A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

Prepared by Pamela C. Dodds, Ph.D., Licensed Professional Geologist
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THE HYDROGEOLOGIC FRAMEWORK AND A RECONNAISSANCE OF GROUND-WATER QUALITY IN THE PIEDMONT PROVINCE OF NORTH CAROLINA, WITH A DESIGN FOR FUTURE STUDY

By Douglas A. Harned

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DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Post Office Box 2857
Raleigh, North Carolina 27602

Copies of this report can be purchased from:

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CONVERSION FACTORS

The following factors may be used to convert the U.S. customary units published in this report to the International System of Units (SI).

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Velocity	
inch per hour (in./hr)	25.4	millimeter per hour (mm/hr)
foot per day (ft/d)	0.3048	meter per day (m/d)
	Mass	
pound (lb)	0.4536	kilogram (kg)
	Volume per area	
gallons per acre	0.009353	cubic meters per square hectometer (m^3/hm^2)
	Temperature	
degree Fahrenheit (°F)	5/9 (°F-32)	degree Celsius (°C)

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

THE HYDROGEOLOGIC FRAMEWORK AND A RECONNAISSANCE OF GROUND-WATER QUALITY IN THE PIEDMONT PROVINCE OF NORTH CAROLINA, WITH A DESIGN FOR FUTURE STUDY

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ABSTRACT

The U.S. Geological Survey is investigating the relation of ground-water quality and land use in the regolith and fractured rock ground-water system of the North Carolina Piedmont. The initial phase of this study provides a description of the ground-water flow system and a review of available ground-water data and formulates hypotheses that guide the design of a water-quality monitoring network for study of selected areas.

In the Piedmont, the solid igneous and metamorphic bedrock grades upward into unweathered fractured rock that is covered by a transition zone of highly-fractured, partially weathered rock, clay-rich saprolite, and the soil. The fractured bedrock, transition zone, saprolite, and soil make up a complex flow system.

A review of available ground-water quality data shows a lack of information about organic compounds and trace metals and changes in ground-water quality with depth. Land use, soils, and geology significantly influence ground-water quality.

The hypotheses that need to be tested in the next study phase are: (1) that ground-water contamination can be related to land use, and (2) that the transition zone between bedrock and regolith serves as a primary transmitter of contaminants.

Monitoring of basins containing industrial, urban, residential, and agricultural land uses in future studies will help define the relation of ground-water quality to land use. Water quality at different depths in the flow system and in streams during base flow needs to be identified.

INTRODUCTION

The Piedmont province of the eastern United States is one of the country's more developed and populated areas, with an ever-growing need for high-quality water supplies. Yet little is known about the ground-water system and the quality of its waters, because most major water supplies in the Piedmont have been developed from surface-water sources. Well yields in the igneous and metamorphic fractured rock system of the Piedmont are generally low compared to wells in many sedimentary rock terranes, so that use of ground water as a supply in the Piedmont generally has been restricted to individually owned domestic wells or small municipal and industrial supplies. However, in North Carolina more than half of the population in the Piedmont depends on ground water from private wells as the source for their water for domestic use (Heath and Giese, 1980).

Approximately 44 percent of streamflow in the Piedmont is ground-water discharge (Harned and Daniel, 1987). Nearly all of the baseflow in Piedmont streams is ground-water discharge. Therefore, quality of the ground water directly affects the quality of surface water.

Because most favorable surface-water sites have been developed and because concerns about environmental impacts of reservoir construction, inter-basin transfer of water, and declining surface-water quality have multiplied, interest in the use of ground water for larger supplies has been rekindled. Recent studies by Richardson (1982), Cressler and others (1983), Daniel and Sharpless (1983), and Daniel (1985) have focused on the potential of ground-water supply in the Piedmont. Other studies have stressed issues of ground-water quality management (LeGrand, 1984; Mew, 1985). However, there has been no regional study designed to assess ground-water quality in the Piedmont.

Very little is known about the nature and extent of ground-water contamination in the Piedmont province of North Carolina. Therefore, to define contamination, an understanding of the background water quality is essential. Currently, background ground-water quality data consist of analyses of major ions, with a few analyses of heavy metals and even fewer of organic compounds.

The Toxic Waste--Ground-Water Contamination Program of the U.S. Geological Survey is conducting a series of ground-water appraisals throughout the United States (Helsel and Ragone, 1984). As part of this program, the ground-water quality of areas of widely differing geohydrology, climate, and land uses is being examined with the objective of developing a national assessment. The principal hypothesis of the program is that levels of ground-water contamination can be related to land-use. The two-phased study in North Carolina, which focuses on segments of the North Carolina Piedmont, is geared to allow transfer of information to the rest of the Piedmont province by statistically associating ground-water quality with land use, geology, and soil characteristics.

Purpose and Scope

The purpose of this report is to describe the hydrogeologic framework, present an inventory and preliminary analysis of available ground-water quality data and potential sources of ground-water contamination, and propose a design for the second phase of the study. Geohydrologic information on the region is presented, including a conceptual model of the flow system and hypotheses about contaminant movement through the system. An evaluation of available ground-water quality data is presented and a program of sampling, designed to associate land use with ground-water quality is proposed.

Method of Study

The available ground-water data that were reviewed included data collected from shallow wells between 1978 and 1980 in a program of the North Carolina Department of Natural Resources and Community Development (NRCD). The data collection effort of the NRCD study centered in the western Piedmont. The data include: (1) physical and chemical characteristics of the ground water, such as temperature, conductance, pH, concentrations of major ionic constituents, metals concentrations, and selected analyses of nutrient concentrations; (2) lithologic logs; and (3) well characteristics, such as well depth and water level at time of sampling. In addition, because stream water is virtually all ground-water discharge at baseflow, data from studies that examined water-quality characteristics of streams at baseflow have been considered. A study by Eddins and Crawford (1984) includes low-flow sample analyses of major ionic constituents, nutrients, and metals for Mecklenburg County.

Additional data were collected specifically for the first phase of this study during January and February 1985. Samples collected in Mecklenburg and Guilford Counties were scanned for presence of organic compounds and a suite of 43 elements, including many trace metals. This information was collected to help select possible sites for detailed analysis in future study.

Historical data, collected during Geological Survey cooperative studies spanning from 1946-76, was included in the data set generated from this study. However, historical data were not used in the data analysis for this report.

The evaluation of data in this report is limited to summary presentation of certain constituents using frequency histograms, simple non-parametric analysis of variance, and Duncan multiple-range testing. A more detailed analysis of the data set is reserved for future study, which would also include additional collection of water samples from a network specifically designed to define ground-water quality.

A review of the hydrogeology of the Piedmont includes a summary of earlier work by LeGrand (1967), Heath (1984), and Daniel (1987). Temperature profile logs for several wells located in Guilford County were run to test one of the flow hypotheses of the study.

Acknowledgments

M. Groves and R. Crouch conducted the NRCD study during 1978-80 that collected much of the data that was compiled for this report. Richard Peace, of the NRCD Mooresville Regional office at the time of this study, provided access to this data.

The Climate, Topography, Geology, and Well Logs sections were written by Alexander Cardinell and Ronald Coble.

DESCRIPTION OF STUDY AREA

The Piedmont of North Carolina (fig. 1) is part of the Piedmont province as described by Fenneman (1938) that extends from New Jersey to Alabama and lies between the Blue Ridge and Coastal Plain provinces. The Piedmont province of North Carolina, shown in figure 1, is approximately 20,000 square miles or about 23 percent of the total Piedmont region of the eastern United States. The Piedmont widens to the south, reaching its maximum width of nearly 200 miles in North Carolina. The province occupies approximately 41 percent of the State.

Climate

The North Carolina Piedmont lies within a humid, subtropical climate region. The temperature is moderate, seldom dropping to zero degrees Fahrenheit in the winter and occasionally rising above 100 degrees in the summer. Mean annual temperatures range from 58 to 61 degrees Fahrenheit, with January the coldest and July the hottest month (Eder and others, 1983). The growing season, which is defined as that period without killing frosts, lasts from mid-April to the end of October, an average of about 200 days.

The average annual precipitation in the Piedmont of North Carolina ranges from 43 to 60 inches. Generally, the greatest monthly precipitation occurs during the summer months, and the least precipitation occurs in October or November. Although rainfall is heaviest in the summer, evaporation and transpiration losses are greatest then also; consequently, there is little ground-water recharge during this season.

Topography

The Piedmont is an ancient erosional surface developed, for the most part, on crystalline igneous and metamorphic rock. The Piedmont province is bordered on the east by the Fall Line, which is the western boundary of the Coastal Plain province, and on the west by the Blue Ridge front (fig. 1). The Fall Line represents the boundary where the soft, sedimentary rocks of the Coastal Plain give way to the harder crystalline rocks of the Piedmont. The Blue Ridge front is a prominent topographic feature generally thought to have resulted from displacement associated with faulting.

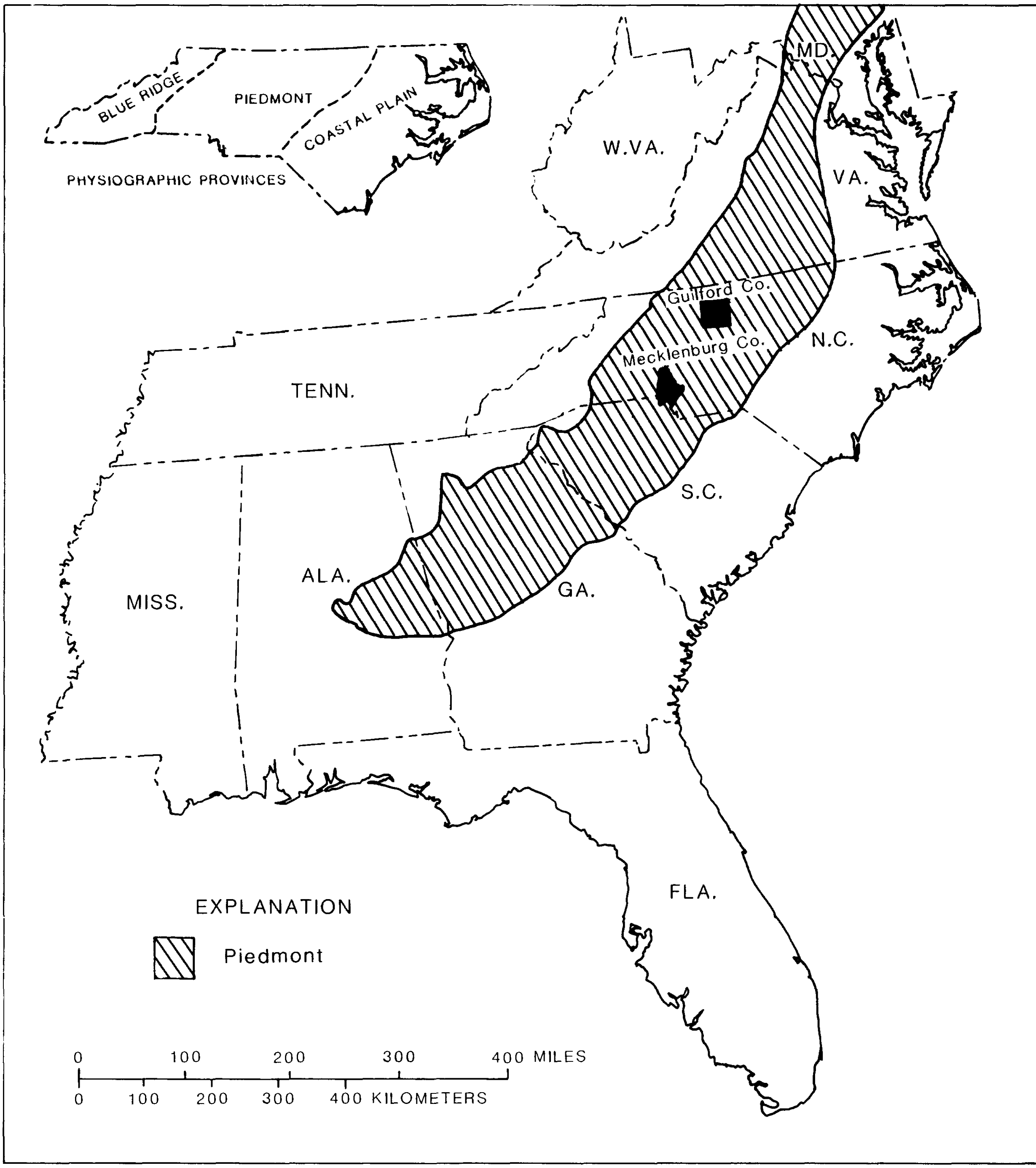


Figure 1.--The Piedmont province of the eastern United States and the physiographic provinces of North Carolina.

The Piedmont consists of low, rounded hills and long, rolling northeast-trending ridges with up to a few hundred feet of local relief. Land elevation gradually rises from about 150 feet above sea level along the Piedmont's eastern boundary to 1,900 feet along the western boundary at the foot of the Blue Ridge front.

The rolling topography is the result of streams acting on rocks of unequal resistance. Isolated hills with summit heights standing above the upland surface are remnants of extremely erosion-resistant rock. In contrast to the topography of the crystalline-rock terrane of most of the Piedmont, erosion has produced low lands in the soft sedimentary rocks of the Triassic basins.

The typical Piedmont topographic surface described by Fenneman (1938) is practically all hillside or valley side. The region has a well integrated drainage system and, in nearly all aspects, qualifies as having reached topographic maturity as defined by Thornbury (1954). LeGrand (1958 and 1984) notes that in the network of closely spaced perennial streams the upland divide is everywhere less than a mile and commonly less than half a mile from a valley.

Geology

The geology of the North Carolina Piedmont province is very complex; the bedrock consists of folded and fractured metamorphosed sedimentary and igneous basement rocks. Intruded into these metamorphic rocks are lesser bodies of unmetamorphosed igneous rocks. Typical bedrock lithologies include granite, gneiss, schist, quartzite, slate, and phyllite. Downfaulted into the basement complex are several basins (Triassic basins), which are grabens where sedimentary rock occurs.

The regional geology of the Piedmont basement is only generally understood. The crystalline igneous and metamorphic sequences may have undergone two or three regional metamorphic events and as many as four major deformation events from the Precambrian through the Paleozoic. The complex nature and variable degrees of metamorphism found in the Piedmont make precise dating of these events impossible at present. More detailed discussions of recent hypotheses for these events can be found elsewhere

(Ragland and others, 1983; Farrar, 1985; Russell and others, 1985; Wehr and Grover, 1985). Various periods of plate tectonic activity, along with the associated formation of rift margins, are believed to be responsible for these events. The Piedmont can be divided into northeast trending parallel geologic belts. Traversing from the southeast, the major geologic belts are the Carolina slate belt, the Raleigh belt, the Charlotte belt, the Kings Mountain belt, and the Inner Piedmont belt (Daniel, 1987).

The rock-type classification scheme based on lithologic and geohydrologic properties developed by Daniel (1987) for the Piedmont and Blue Ridge provinces of North Carolina has been used in this study. The near-surface earth materials of the Piedmont consist of a three-stage system which, from top to bottom, contains (1) a regolith zone, (2) a transition zone, and (3) underlying fractured crystalline bedrock (fig. 2).

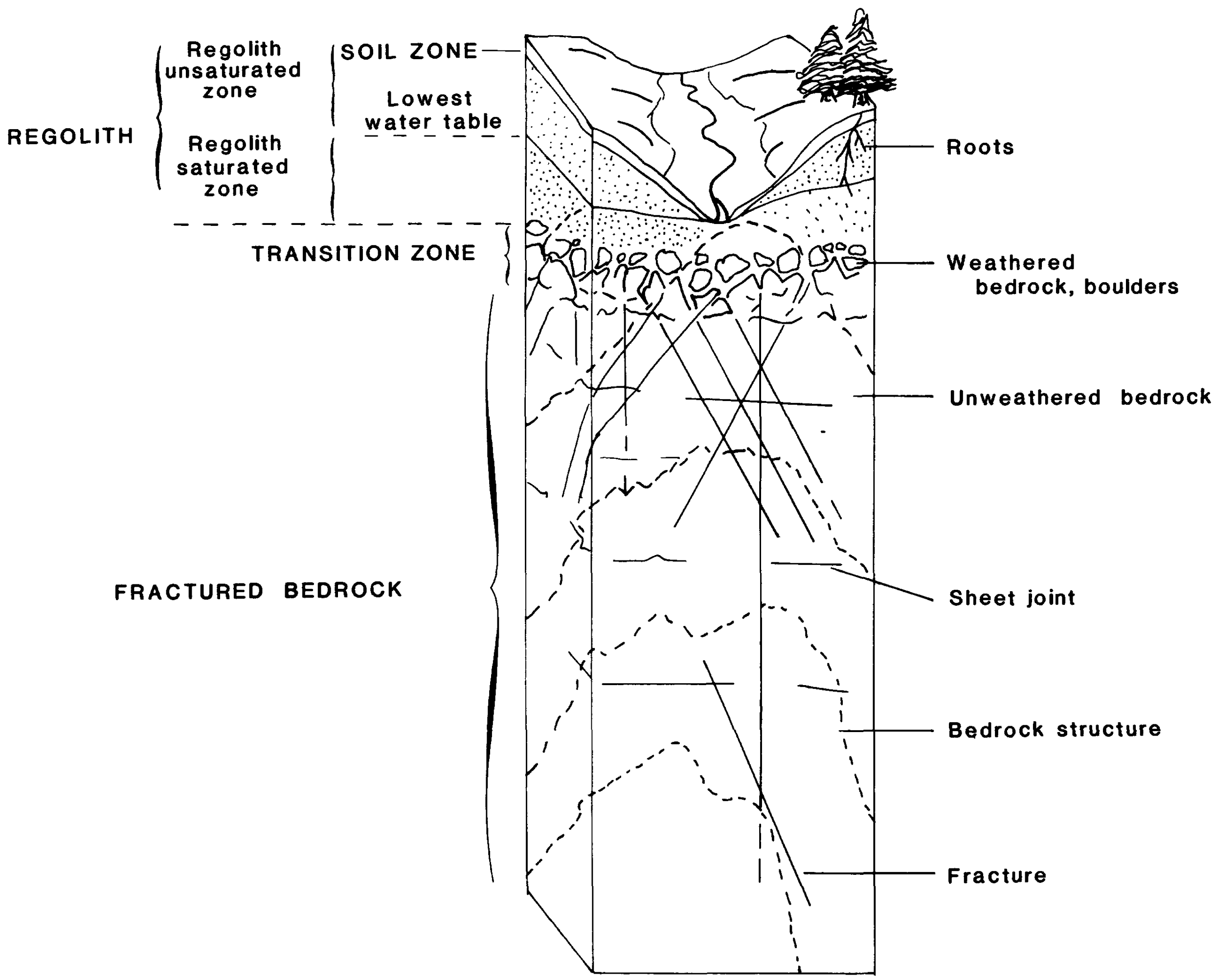


Figure 2.--Conceptual structure of the Piedmont ground-water system (modified from Heath, 1984).

Collectively, the uppermost layer is the regolith, which is composed of saprolite, alluvium, and soil (Daniel and Sharpless, 1983). The regolith zone consists of an unconsolidated or semiconsolidated mixture of clay and fragmental material ranging in grain size from silt to boulders.

Saprolite is the clay-rich, residual material derived from in-place weathering of bedrock. Saprolite deposits represent leached deposits and, being granular material with principal openings between grabens, differ significantly in texture and chemical composition from the parent rock which is unweathered, crystalline rock having principal openings along fractures. Since saprolite is the product of in-place weathering of the parent bedrock, some of the textural features of that bedrock are retained within the saprolite. Evidence of relic quartz veins, dikes, and shear zones are commonly seen in outcrops. Alluvial deposits are unconsolidated sediments deposited by streams and rivers. Soil is referred to as the natural medium for the growth of plants. Saprolite is the dominant deposit in this unconsolidated zone, with soil deposits generally restricted to the uppermost layer, and alluvium deposits restricted to locations of current and former stream channels and river beds.

The transition zone is where unconsolidated material grades into bedrock and consists of saprolite and partially weathered bedrock. Here, particle size ranges from silts and clays to large boulders of unweathered bedrock. The thickness of this zone depends a great deal on the texture and composition of the parent rock. The best defined transitional zones are usually associated with highly foliated metamorphic parent rock, while those of massive igneous rocks are often poorly defined or nonexistent (C.C. Daniel, III, U.S. Geological Survey, oral commun., 1985). In the Piedmont, 90 percent of the records for cased bedrock wells show combined thicknesses of 97 feet or less for the regolith and transition zones (Daniel, 1987).

The uppermost part of the Piedmont crystalline bedrock contains numerous closely spaced fractures which can be related to the local and regional tectonic history of the area. As a general rule, very few fractures occur in the Piedmont bedrock at depths greater than 400 feet (LeGrand, 1967).

Soils

Most Piedmont soils have formed largely from saprolite derived from the underlying parent rocks. Some soils have developed on stream-valley alluvium. Soils are a product of their local and regional environment. Geology, geomorphology, and climate, in addition to topography, moisture, and vegetation, influence the characteristics of soil cover. Combinations of factors give rise to a number of diverse soils that fit into locally and regionally recurring patterns.

Daniels and others (1984) classified four major soil systems within the Piedmont based on the major kinds of bedrock:

1. The felsic crystalline terrains composed largely of granite, gneiss, mica gneiss, and schist;
2. The Carolina slate belt of bedded argillites, felsic volcanics, and mafic volcanics;
3. The Triassic basins with mudstones, sandstones, shales, and conglomerates; and
4. The mixed mafic and felsic rocks; a complex area of granites, diorites, gabbros, and other rocks.

In the felsic crystalline area, most deeper soil horizons are clayey, but some soils originating from the coarser grained rocks, such as granite, have clay-loam or loamy-sand deeper horizons. Soils derived from Carolina slates have high silt contents, overlie relatively thin saprolite layers in comparison with the felsic crystalline area, and have low permeability in the deeper horizons. Triassic basin soils have more swelling clays in their deeper horizons than other soils. The mafic soils (from mafic dikes) are plastic and usually a reddish color.

In this study, physical parameters of soils, including permeability and available water capacity provided by the U.S. Soil Conservation Service (1978), were used to construct the detailed data base necessary to compare ground-water quality characteristics with soil type. These parameters have been included in the data set but were not used in the data analysis.

Land Use

Land Use Data Analysis maps (LUDA maps; Anderson and others, 1976) provide data on a regional scale for land use in the Piedmont. These maps were generated in the early 1970's using remote-sensing satellite data.

Estimates of the relative amount of area covered by the different land-use types were determined from LUDA maps. Land-use types lying along the 78-, 80-, and 82-degree meridians, and along the 35- and 36-degree parallels were determined from the North Carolina LUDA maps. First, the distances along each latitude or longitude line for each land-use type were measured and totaled. Then, the total for each land use was divided by the total for all the lines sampled to give a percent of the total area covered by each land use. The result of these calculations are shown in table 1. This analysis indicates that about 65 percent of the North Carolina Piedmont land area is forest, about 25 percent is crop land, and about 6 percent is urban and residential.

Table 1.--*Approximate percentages of major land uses of the Piedmont of North Carolina*
[LUDA, Land Use Data Analysis]

LUDA land use	Piedmont percent
Residential and farm buildings	4.2
Commercial and services	.67
Industrial	.23
Transportation, communications, and utilities	.34
Mixed urban	.32
Other urban or built-up land	.59
Cropland and pastures	25
Deciduous forest	24
Evergreen forest	10
Mixed forest	32
Reservoirs	1.2
Forested wetland	.85
Transitional areas	.36
Other	.24

Land-use data from Anderson and others, 1976.

HYDROGEOLOGIC FRAMEWORK AND CONCEPTUAL MODEL OF THE FLOW SYSTEM

Heath's (1984) concept of the ground-water system for the Piedmont and Blue Ridge provinces has been adopted as the conceptual model for this study with slight modifications to emphasize the transition zone between the regolith zone and the bedrock.

The fundamental structure of the ground-water system is shown in figure 2. The components of the system are:

1. The unsaturated zone in the regolith, which generally contains the organic layers of the surface soil;
2. The saturated zone in the regolith;
3. The transition zone between the regolith and bedrock; and
4. The fractured crystalline bedrock system.

Regolith Unsaturated Zone

The unsaturated zone extends from the land surface down to the water table, which is the top of the saturated zone. The pore spaces of the regolith in the unsaturated zone contain both air and water. The unsaturated zone usually ranges from 5 to 50 feet in thickness. Daniel (1987) found a mean depth to the water table of 31.3 feet in an examination of 2,326 Piedmont wells. Water moves down from the land surface through the soil zone by intergranular flow through the larger pore spaces and passages left by burrows or decayed roots. Roots from surface vegetation can grow to 30 feet below land surface but more commonly spread laterally near the surface. At the base of the soil zone, which is generally 3 to 8 feet thick, the average grain size abruptly decreases with a corresponding decrease in pore size as the water enters the saprolite (C.C. Daniel, III, U.S. Geological Survey, written commun., 1985). At this point water movement may also be diverted somewhat by relic structures of foliation or folds in the saprolite, which are remnants from the parent rock.

The total porosity of soil is commonly around 55 percent, and its specific yield is about 40 percent (Heath, 1983). Saprolite has a total porosity of 35 to 50 percent near land surface (fig. 3), which decreases at depth, and a specific yield of 20 percent (Daniel and Sharpless, 1983).

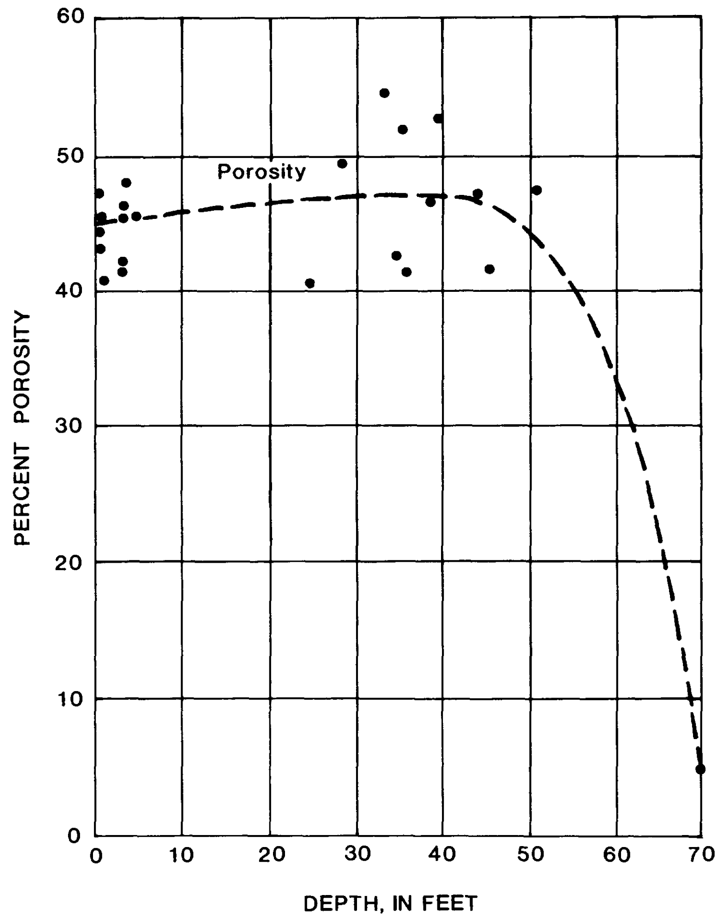


Figure 3.--Relation of porosity of saprolite with depth (after Stewart, 1962).

Topsoil in Piedmont soils to a depth of 7 to 10 inches was reported to have a mean hydraulic conductivity of 5.7 inches per hour (11.4 feet per day), and the subsoil, 7 to 20 inches below land surface, has a mean hydraulic conductivity 1.8 inches per hour (3.6 feet per day) (Lutz, 1969). These values are in line with the hydraulic conductivity values for saprolite reported by Heath (1980) that range from 0.5 to 10 inches per hour (1 to 20 feet per day). However, the hydraulic conductivity of saprolite is not the same in all directions. This anistropy may take the form of preferential permeability along the direction of relic structures within the saprolite.

Regolith Saturated Zone

The regolith saturated zone is that interval below the water table and above the transition zone. Daniel has calculated the median saturated thickness of the regolith and transition zone from records of 1,749 water-supply wells in the Piedmont of North Carolina to be 13 feet (Daniel, 1987). The median saturated thickness was shown to be a function of topography: beneath draws and valleys, it was 28 feet thick; below slopes and flats, it was 15 feet; and beneath hills and ridges, it was 9 feet.

The saturated regolith provides the bulk of the water storage within the Piedmont ground-water system (Heath, 1980). This concept is illustrated in figure 4. In the Piedmont ground-water system, the regolith has a specific yield of around 20 percent (Daniel and Sharpless, 1983), whereas the porosity of the bedrock ranges from 0.01 to 2 percent (Heath, 1984). The depth-porosity relation described by Stewart (1962) is shown in figure 3. The amount of ground water in storage as a function of the saturated thickness of the regolith has been calculated by Daniel (C.C. Daniel, III, U.S. Geological Survey, written commun., 1985) and is presented as figure 5.

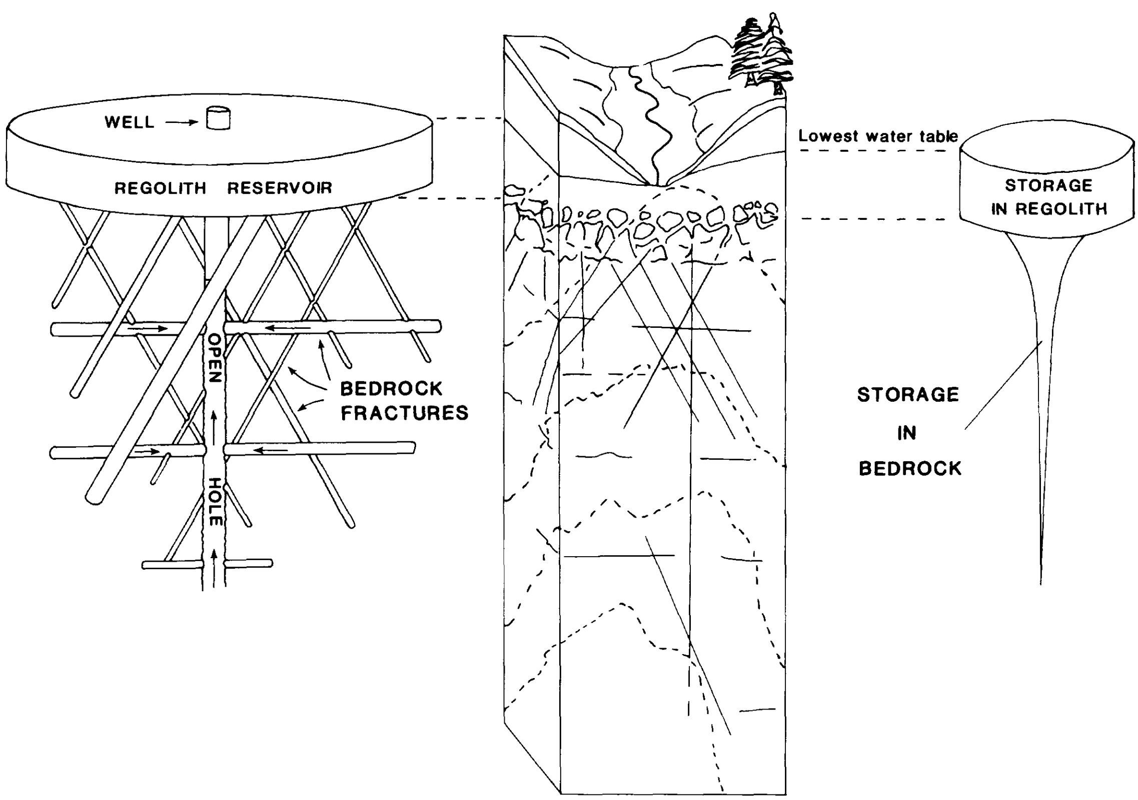


Figure 4.--Water storage within, and the reservoir-pipeline conceptual model of the Piedmont ground-water system (modified from Heath, 1984).

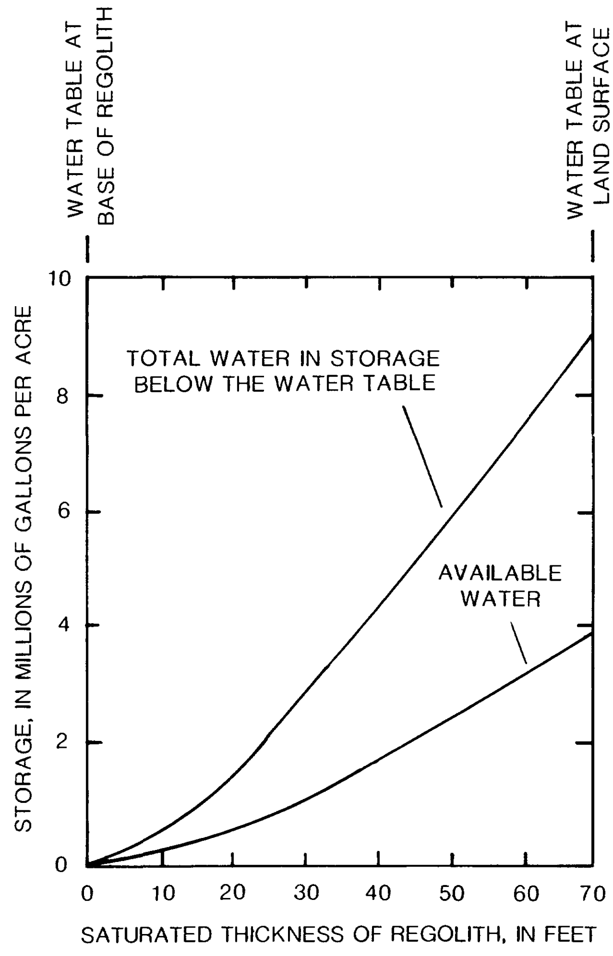


Figure 5.--Relation of ground-water storage and saturated thickness (after C.C. Daniel, III, U.S. Geological Survey, written commun., 1986).

As illustrated in figure 4, the regolith serves as a reservoir supplying water to interconnected fractures within the bedrock. In general, wells in the Piedmont are cased through the regolith, with open hole through enough of the bedrock to intercept enough fractures to furnish acceptable yields. The bedrock fractures serve as pipelines between the well and the regolith reservoir.

The depth to water table is largely a function of topography. Based on data from 2,326 water-supply wells, the median water level in wells located in draws and valleys is 20 feet, in slopes and flats 25 feet, and in hills and ridges 32 feet (Daniel, 1987). Depth to water table at any one place varies with ground-water recharge and continual discharge. An example of the response of water level due to variation in rainfall is shown in figure 6. In this example, ground-water recharge (in excess of discharge) resulting from heavy rains in late winter, when evapotranspiration is low, is reflected by a peak in the water-table hydrograph appearing a few days after heavy rainfall in late March. The time after a storm that the peak appears in the water level is directly related to the vertical hydraulic conductivity of the material in the unsaturated zone and the depth to water table. The hydrograph also shows that little recharge took place during the growing season (April through September) even though the area received significant rainfall during these months. The declining water level indicates continuing ground-water discharge that is not equaled or exceeded by recharge until fall, when evapotranspiration is low. Similar seasonal

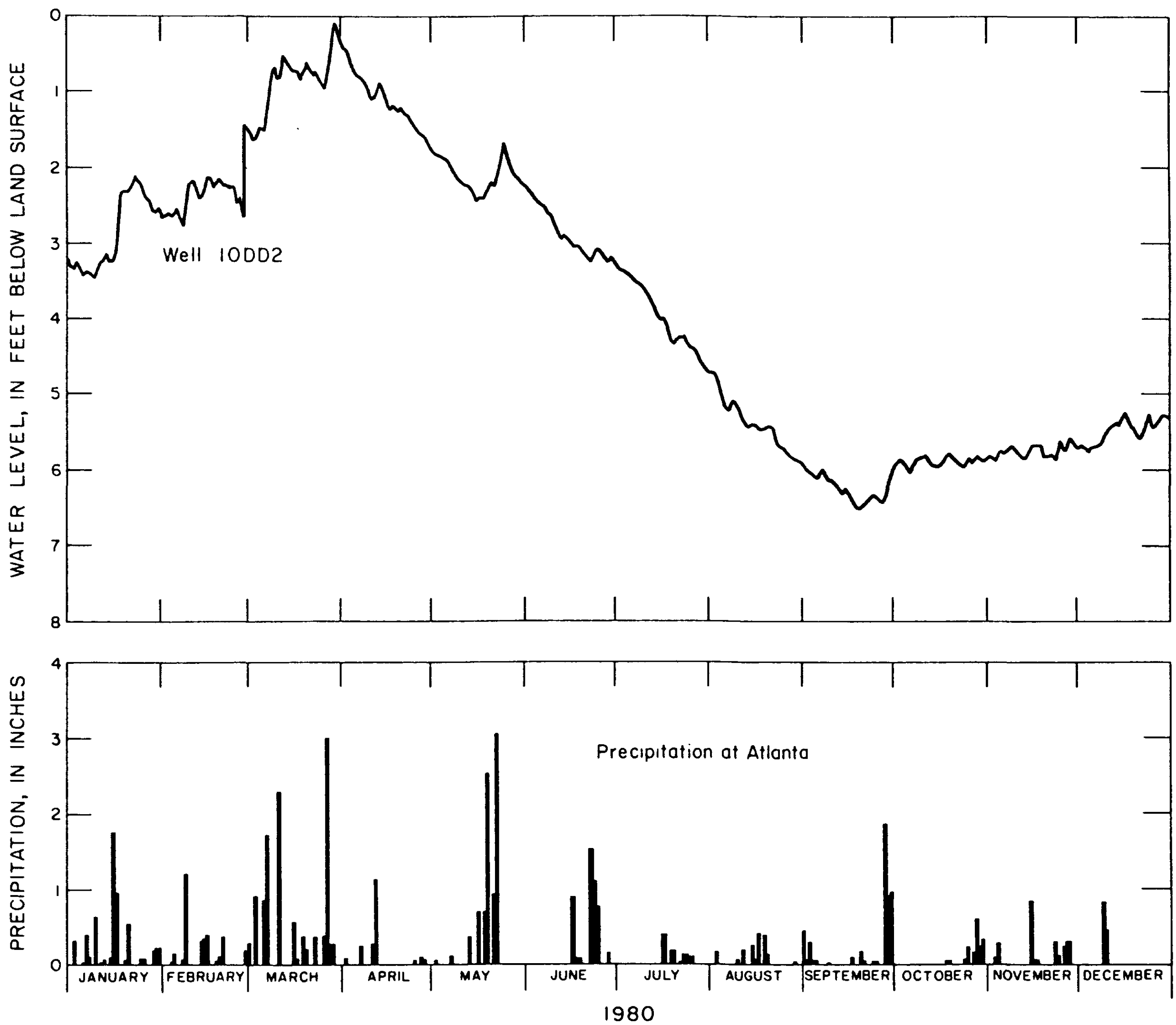


Figure 6.--Response of water-level change to rainfall (from Cressler and others, 1983).

fluctuations of the water table are also shown in the hydrograph for a well located in Iredell County, North Carolina (fig. 7).

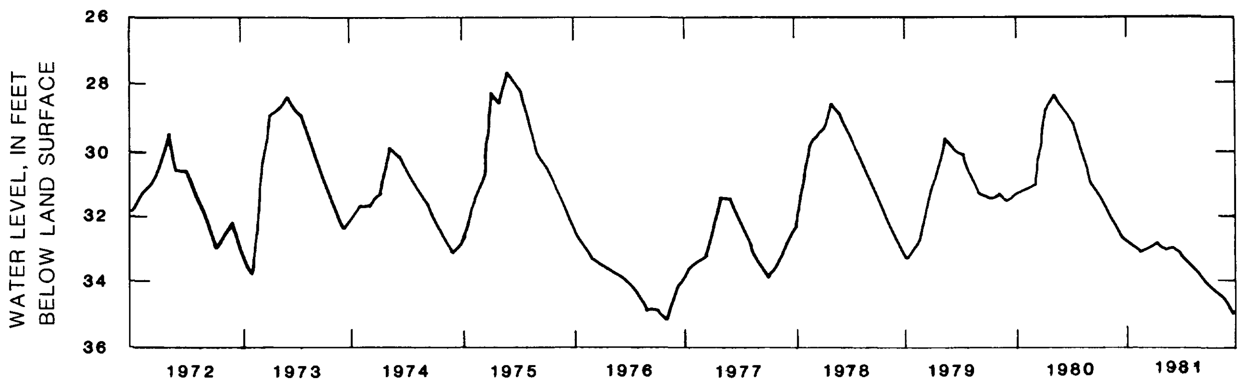


Figure 7.--Seasonal fluctuations in water-table depth in a well in Iredell County, North Carolina (from LeGrand, 1984).

Transition Zone

At the base of the regolith there is generally a transition zone of weathered rock, boulders, and saprolite. Careful augering of three wells showed this transition zone to be approximately 15 feet thick at the Guilford County, North Carolina, test site shown in figure 8 (C.C. Daniel, III, U.S. Geological Survey, written commun., 1985). This zone has been found in Georgia, Maryland, and North Carolina and reported by Stewart (1962), Nutter and Otton (1969), and Daniel (C.C. Daniel, III, U.S. Geological Survey, written commun., 1985), respectively. They describe this zone as being more permeable than the upper regolith and slightly more permeable than the soil zone. This observation is substantiated by reports from well drillers of so-called "first water" (C.C. Daniel, III, U.S. Geological Survey, written commun., 1985) in drillers' logs (Nutter and Otton, 1969).

The high permeability of the transition zone is probably due to incomplete weathering in the upper regolith. Chemical alteration of the bedrock has progressed to a stage of minute fracturing of the crystalline rock, yet it has not progressed so far that the rock minerals have been altered to clays, which would clog the tiny fractures (C.C. Daniel, III,

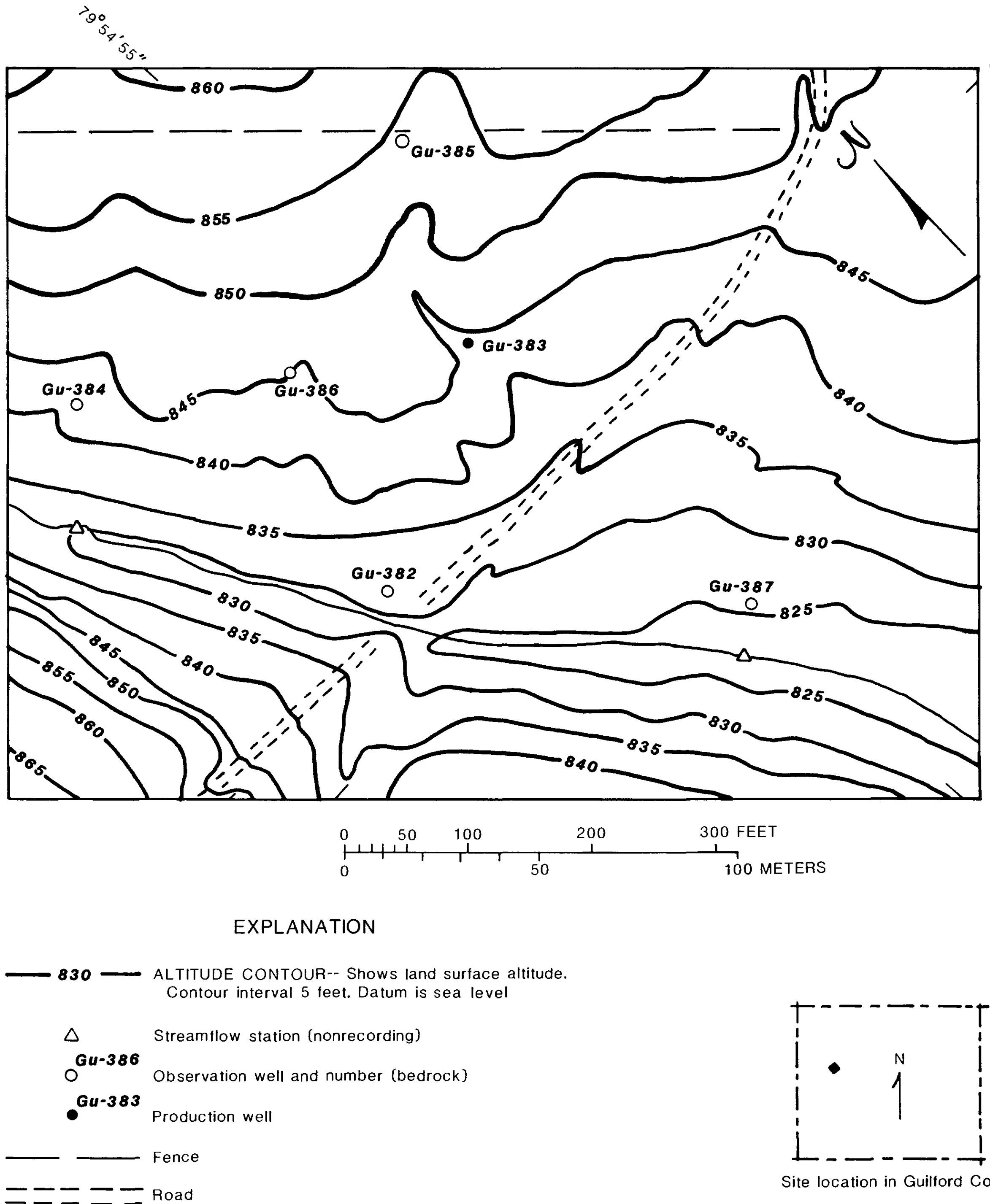


Figure 8.--Locations of data-collection sites and topography at the Greensboro-High Point Regional Airport test site (from Daniel and Sharpless, 1983).

U.S. Geological Survey, written commun., 1985). An idealized weathering profile by Nutter and Otton shown in figure 9 illustrates the effect of degree of weathering on permeability.

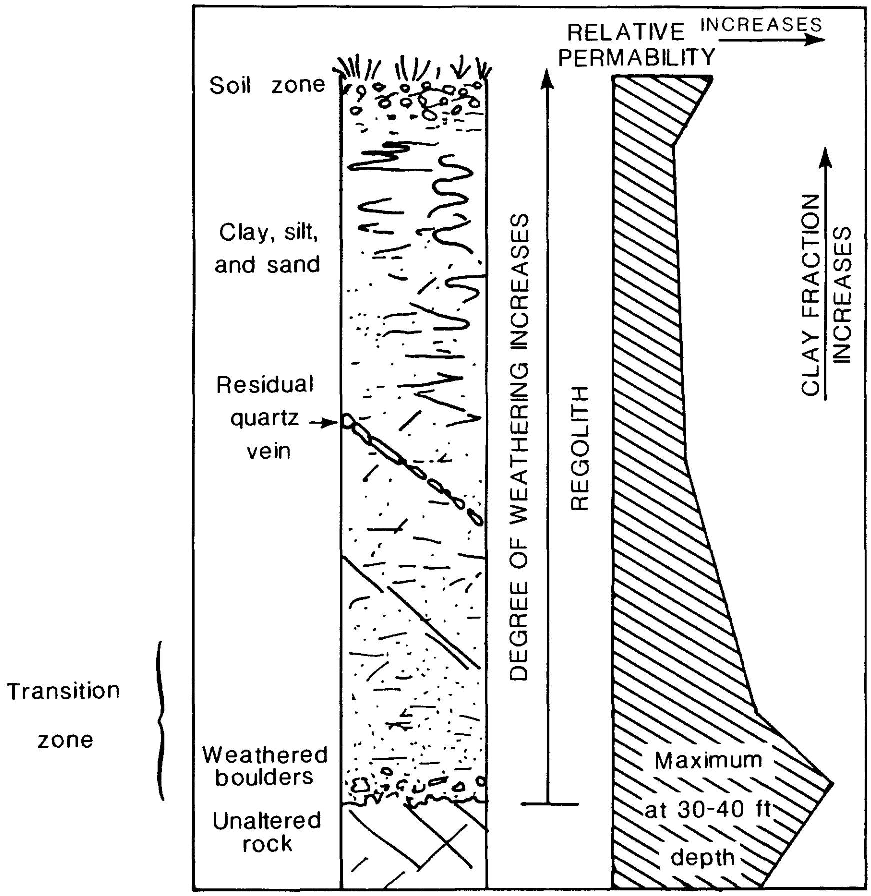


Figure 9.--An idealized weathering profile through the regolith showing relative permeability (after Nutter and Otton, 1969).

The presence of a high-permeability zone on top of the bedrock may create a zone of concentrated flow within the ground-water system. Daniel (C.C. Daniel, III, U.S. Geological Survey, written commun., 1985) cites the case where well drillers find water in the transition zone, yet end up with a dry hole after setting casing through the regolith and transition zone into the unweathered bedrock. In this case, the ground water occurs primarily in the transition zone, where there is poor connection between the regolith reservoir, the bedrock fracture pipeline system, and the well. Daniel comments that the transition zone may serve as an interval where relatively rapid movement of contaminated ground water can take place.

Fractured Bedrock

Ground-water flow within the crystalline bedrock occurs within fracture systems. LeGrand (1967) discussed what he considered to be the six common types of fracture patterns (fig. 10) that influence yields to wells. These fractures are reported to be more common near the surface and beneath valleys, draws, and surface depressions (Heath, 1980), and are considered to be zones of weakness that allowed the initial development of valleys and draws at these locations. Fracture openings are wider near the bedrock surface and decrease in size and number with depth due to increasing lithostatic pressure.

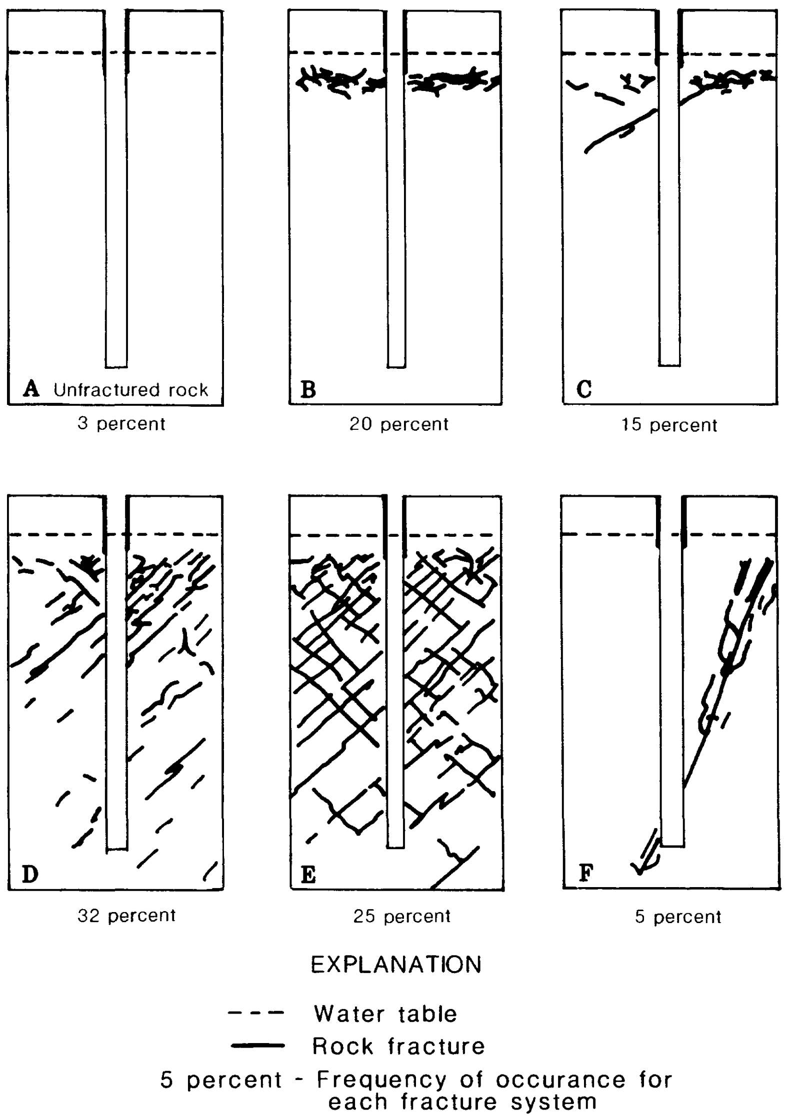


Figure 10.--Six common types of fracture systems in the Piedmont (from LeGrand, 1967).

Heath indicates that few fractures below 300 to 400 feet from land surface contain substantial amounts of water, and that those which do bear water at depth are probably associated with faults. However, Cressler and others (1983) found that for the Atlanta, Georgia, area, nearly horizontal stress-relief fractures at depths of 400 feet or more were often associated with high-yielding wells. When surface material is removed by erosion, nearly horizontal stress-relief fractures develop and widen in response to the reduction in compressional stress. Daniel also reports high-yielding wells at depths over 500 feet in the North Carolina Piedmont (Daniel, 1987). Fractures are planar features oriented along zones of lithologic and structural weakness. Water can move along the fractures with relative ease to discharge points such as wells or to natural discharge areas in stream valleys. Non-horizontal fractures may account for dramatically asymmetrical patterns of water-level decline that may be seen around a pumped well or the more rapid movement of water and contaminants in one direction than in another, creating aniostrophy in the bedrock aquifer. The hydrologic conductivity of the fractured bedrock is generally 0.001 to 3 feet per day (Heath, 1984). The primary porosity of the bedrock ranges from about 0.01 to 2 percent (Heath, 1984).

In general, the mineral assemblages determine the degree to which water will dissolve aquifer material. For example, quartz is resistant to chemical weathering and will dissolve much more slowly than less resistant ferromagnesium minerals such as biotite and hornblende and numerous iron minerals such as pyrite and magnetite. Generally, the mafic igneous rocks such as diorite-gabbro contain more ferromagnesium minerals and are more susceptible to chemical solution than the minerals of felsic rocks such as granite. Weathering of the ferromagnesium minerals produce solution openings and channels in the mafic rock units.

Ground water from a typical granite, composed largely of sodium and potassium feldspars, should have relatively high concentrations of sodium bicarbonate. Calcium and magnesium bicarbonate concentrations can be high in ground water moving through mafic rocks, such as gabbro, which is composed largely of calcium feldspars and ferromagnesium minerals. Ground water from certain metavolcanic and mica-schist units contain high concentrations of iron (Hem, 1970). However, these simple relationships are complicated if there is mixing of waters from adjacent rock types of different compositions or if the host rock is intermediate in composition.

Because the natural chemical quality of ground water is affected by the minerals in the regolith and bedrock, which form the hydrogeologic framework for the Piedmont ground-water system, the natural water quality should be considered when attempting to determine water-quality differences resulting from different land uses. The significance of the effects of geology and soils on the ground-water quality are described in the data-analysis section of the report.

Flow Hypotheses

Several aspects of the ground-water flow system in the Piedmont are particularly significant geochemically. In describing ground-water recharge and discharge and the functions of a ground-water system, Heath (1983, p. 14) states:

> Hydraulically, this system serves two functions: it stores water to the extent of its porosity, and it transmits water from recharge areas to discharge areas. Thus, a ground-water system serves as both a reservoir and a conduit.
>
> Water enters ground-water systems in recharge areas and moves through them, as dictated by hydraulic gradients and hydraulic conductivities, to discharge areas.
>
> In the humid part of the country, recharge occurs in all interstream areas--that is, in all areas except along streams and their adjoining flood plains. The streams and flood plains are, under most conditions, discharge areas.

These general conditions are assumed to apply in the Piedmont of North Carolina.

The generalized flow system in the Piedmont as represented in figure 11 occurs within a closely-spaced network of streams typical of the mature topography of the Piedmont. Ground-water flow is toward these streams, and the shape of the water table mimics the topography of the land surface,

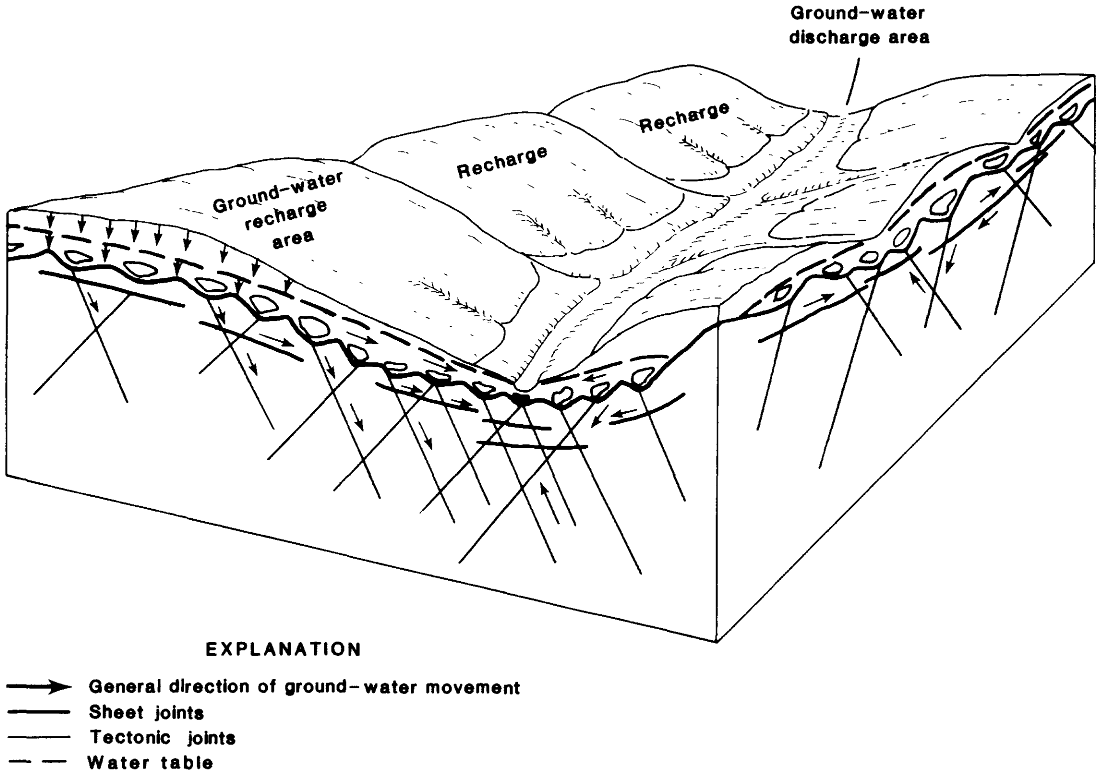


Figure 11.--Generalized ground-water flow system in the Piedmont (from Heath, 1980).

although with subdued relief. Thus, surface topography can be used to predict the natural direction of ground-water flow. The distance between the point where a drop of water or waste enters the system and the point where it discharges into the stream down slope is commonly less than a half mile (LeGrand, 1958). Most of the natural flow in the system is probably confined to the upper 30 feet of bedrock, where fractures are concentrated, and the overlying transition zone, which apparently has the highest hydraulic conductivity of any part of the hydrogeologic system (C.C. Daniel, III, U.S. Geological Survey, written commun., 1985). However, flow probably also occurs in the deeper fractured system in a manner harder to predict by local surface topography. In the deeper system, regional topography or structural features may result in flow over long distances and long ground-water residence times in the fractured rock.

The ground-water flow system in the Piedmont is directly connected to the surface-water system. The annual contribution of ground water to total streamflow for 11 streams flowing through the Piedmont is estimated to average 44 percent (Harned and Daniel, 1987). Consequently, it is a concern that ground-water contamination will eventually discharge to streams that are water-supply sources.

Because of the interconnection of the ground- and surface-water systems in the Piedmont, a drainage basin large enough to contain a perennial stream can serve as a basic unit for the description of ground-water quality (LeGrand, 1984). Each drainage basin is a flow-system cell similar to, and yet separate from, surrounding basins. Although not all of the ground-water flow for a particular area is confined within a single drainage basin, it should be possible to generalize, with a reasonable degree of confidence, about ground-water quality of larger regions from data collected in small drainage basins. This is a basic assumption used in this study.

Hypotheses about the Piedmont ground-water flow system relevant to this and future studies of the system include:

1. The transition zone between bedrock and regolith serves as a primary transmitter of contaminated ground water. The regolith serves as the principal reservoir of ground-water contamination.
2. Attenuation of ground-water contamination in the regolith is related to the degree of weathering and composition of regolith material and the hydraulic conductivity, gradient, and porosity of the material.
3. The velocity of contaminant movement can be highest within the fractured bedrock system, particularly under stressed conditions.
4. The deeper zones in basement rock generally contain the best quality water in the system due to contaminant attenuation in the regolith.
5. Geomorphological analysis can be used to identify fracture zones that help predict general subsurface-flow patterns of ground-water contamination. These methods can be verified with surface geophysical techniques.

Transition-Zone Studies

There have been some initial tests of the hypothesis that the transition zone is a principal conduit of ground-water movement and ground-water contamination. Daniel was the first investigator to focus on the transition zone and has done some initial test drilling, well construction, and well logging to define its characteristics. In particular, temperature logs run in several wells located in Cary and in Guilford County, North

Carolina, may be used to identify greater movement of water within the transition zone (Daniel and Sharpless, 1983).

Borehole geophysical log data were collected in June 1983 from five bedrock wells (Gu-382, Gu-383, Gu-385, Gu-386, Gu-387) located at a test site (fig. 8) in the Greensboro-High Point Regional Airport area by Daniel and Sharpless (1983). Well depths ranged from 200 feet to 275 feet. The borehole geophysical data from these five wells were collected in order to refine current knowledge of subsurface geology and hydrologic parameters in the test-site area. The data collected included natural gamma-ray logs, porosity logs, temperature logs, televiewer logs, and caliper logs. Temperature logs also were collected at all five well sites in March 1985.

Well-log data collected at the test site agree with the results of other well-log studies conducted in other sections of the Piedmont (Stewart, 1962). The bulk of the material in the upper 40 and 50 feet penetrated by these wells is unconsolidated regolith. Here, total porosities are as high as 60 percent and generally decrease significantly below this depth. The gamma ray logs identified most clay-rich zones in the saprolite, as well as zones of feldspars and micaceous minerals in bedrock. The temperature logs were evaluated in order to (1) obtain geothermal-gradient profiles in the bedrock wells, and (2) determine to what extent temperature profiles in an open borehole might delineate zones of ground-water entrance or movement. Nutter and Otton (1969) conducted a similar evaluation of temperature logs collected from wells located in the Maryland Piedmont detecting seasonal effects of temperature change on ground water in the first 60 feet below land surface.

The upper segments of temperature profile logs collected at well Gu-383 at the Greensboro-High Point test site in June 1983 and in March 1985 are shown in figure 12. Note the pronounced cool-water temperature bulge in June 1983 from 21 to 52 feet.

Only a slight cool-water temperature deflections were detected on temperature logs collected in March 1985 (fig. 12). Initial comparisons of recorded surface-water temperature data collected in North Carolina for the winter of 1982-83 (Gunter and others, 1984) and for the winter of 1984-85 indicate that the winter of 1982-83 may have been slightly cooler than the winter of 1984-85. The temperature profile in figure 12 may suggest that warmer water recharged the ground-water system in 1985 than in 1983 due to slightly milder winter conditions. It is interesting to note that the uppermost portions of the temperature curves (0 to 20 feet) have opposite slopes. These near-surface temperature curves may reflect the actual surface temperature conditions present when the logs were collected.

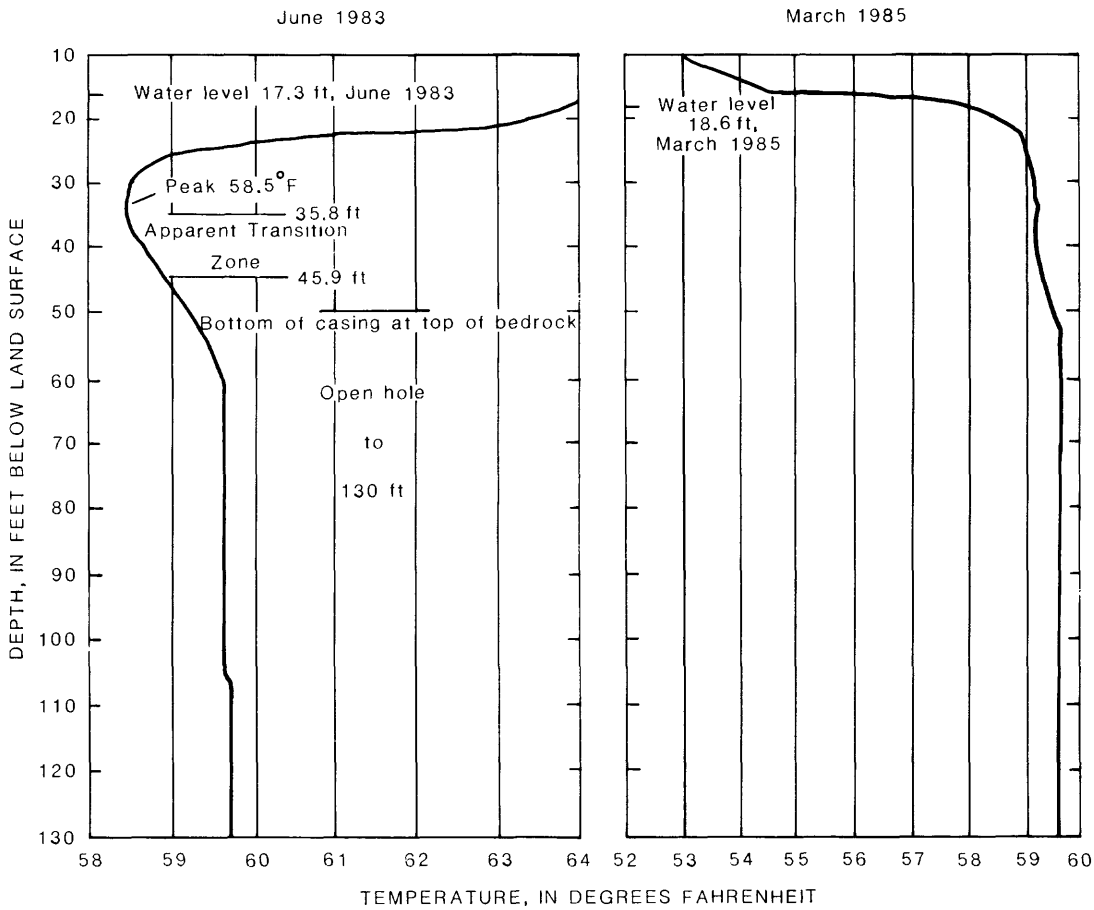


Figure 12.--Temperature logs for well Gu-383, June 1983 and March 1985, located at the Greensboro-High Point Regional Airport.

A more complete data base is needed in the Piedmont province in order to determine to what extent seasonal variations do affect ground-water temperatures and if the subsurface temperatures can provide evidence of greater flow in the transition zone than in the other zones.

POTENTIAL SOURCES OF GROUND-WATER CONTAMINATION

Assessment of potential sources of contamination is fundamental to the management of the ground-water resource. As part of this assessment process, Mew (1985) has developed a ranking system to evaluate ground-water contamination sources and has evaluated the NRCD's inventory of sources that has been compiled over the last 10 years. This inventory includes data on ownership, location, type of operation, type of waste, type of disposal facility or source, status of the source, monitoring, confirmation of ground-water contamination, data-base cross references, and regulatory history.

The waste-source inventory identified over 3,000 potential sources of ground-water contamination in North Carolina. Contamination has been verified at 240 of these sites. A subset of 592 sources from the inventory, containing only the confirmed contamination sources, the highest ranked sources, and the monitored sources was examined by Mew (1985). Two hundred and fifty-one of these sources are located in the Piedmont. Percentages of potential and confirmed sources of ground-water contamination by type for these 251 sources are shown in figure 13. Landfills, waste lagoons, and underground tanks make up most of the sources of ground-water contamination of concern.

The 1983 annual report of hazardous waste (North Carolina Department of Human Resources, Division of Health Services, 1984) states that within the State of North Carolina there were 618 facilities, each of which generated 2,200 pounds or more per month of hazardous waste. In addition, 111 facilities either treated, stored, or disposed of 2,200 pounds or more of hazardous waste. The majority of the waste generators and the waste handlers are in the Piedmont counties with Mecklenburg County (fig. 1) having the greatest number (86).

WATER-QUALITY DATA BASE

One of the principal objectives of this study has been to construct a data set containing the available data on ground-water quality in the Piedmont of North Carolina. Well locations of the combined data set are shown in figure 14.

The data set constructed during this reconnaissance study provides a strong base for current and future ground-water quality study. The construction, editing, and analysis of information contained in this data

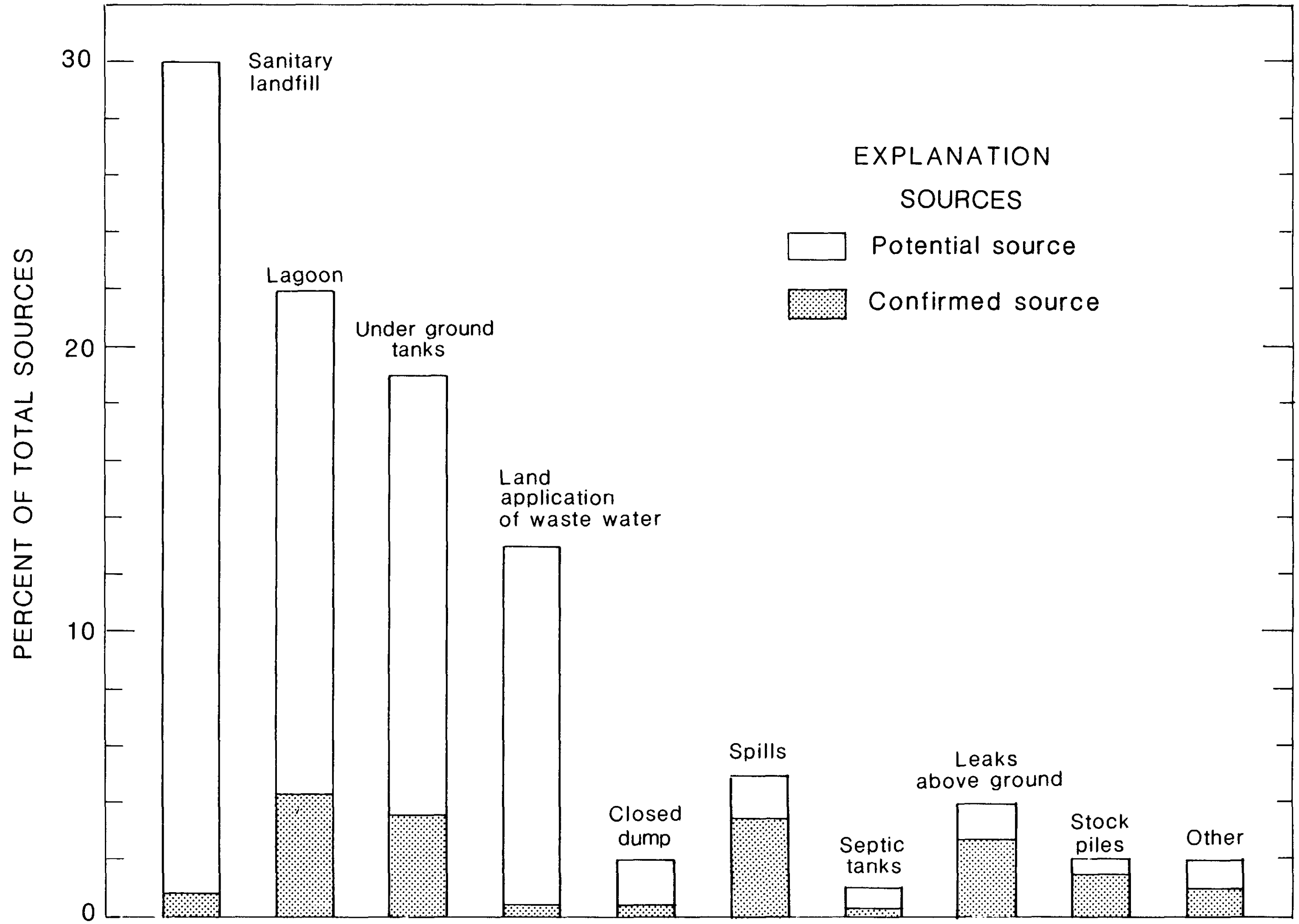


Figure 13.--Percent of ground-water contamination sources, confirmed and potential, by type, for the 251 high ranking sources in the Piedmont.

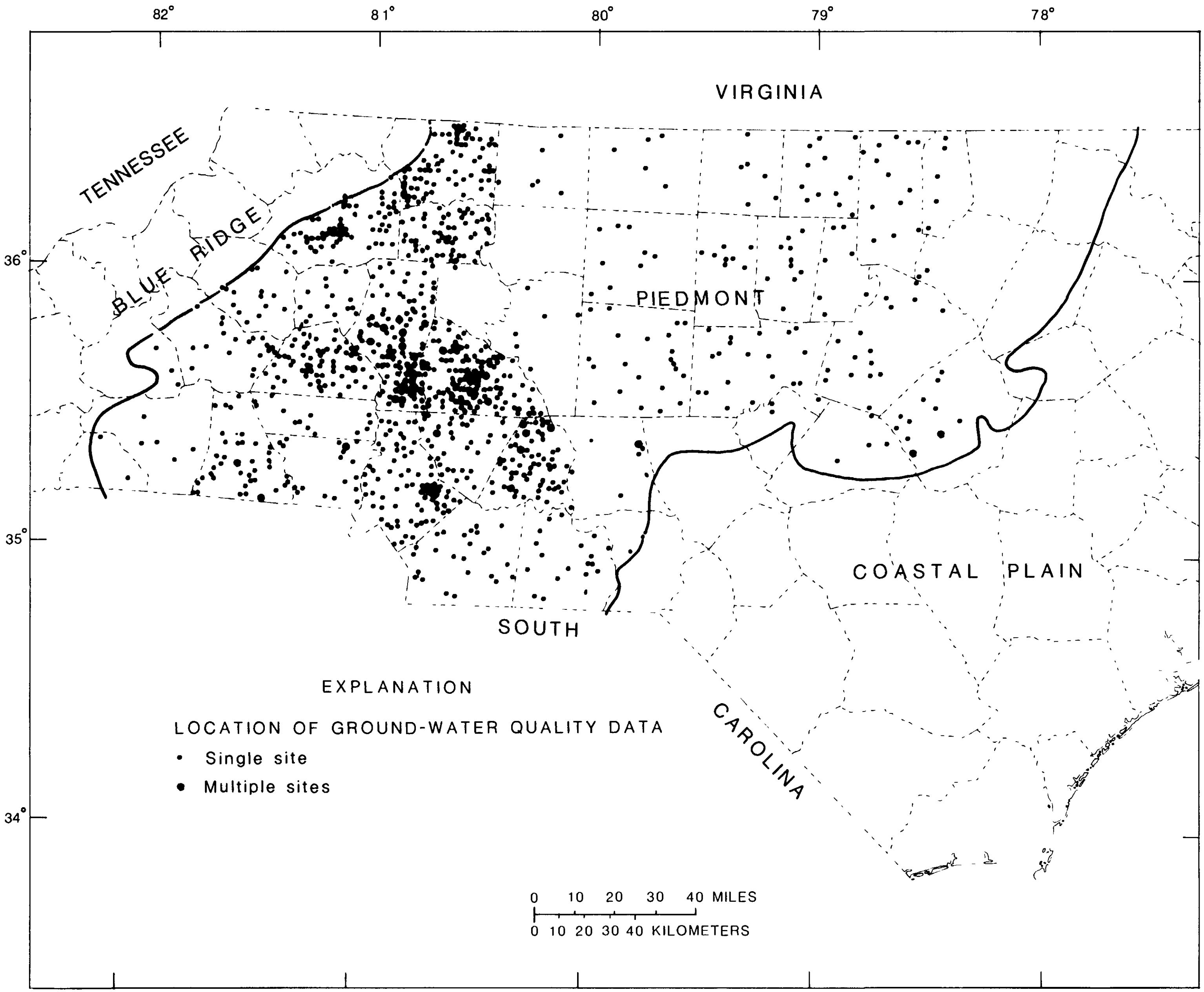


Figure 14.--Locations of available ground-water quality data in the Piedmont of North Carolina.

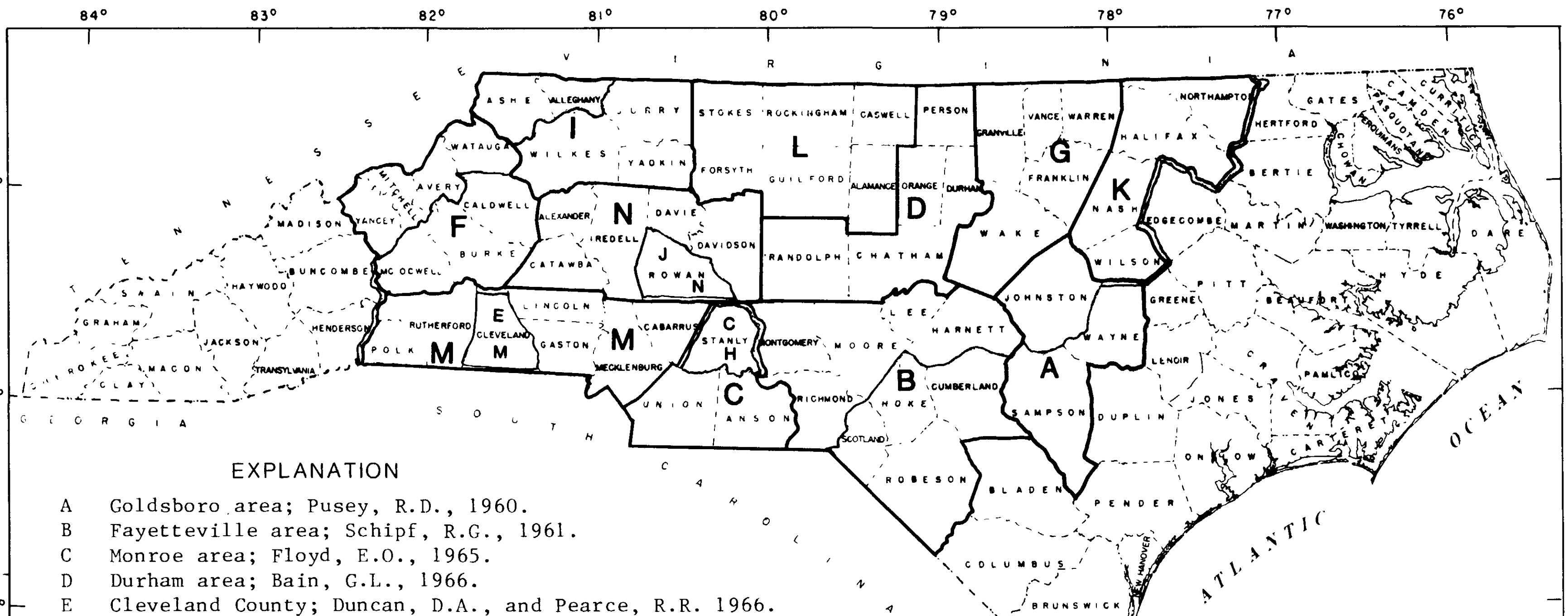
set is an ongoing process, and much additional work can be done to enhance its usefulness. Data on organic constituents and more trace-element data need to be collected and added to the data set.

Two principal sources of data form the bulk of the Piedmont ground-water-quality data set. The primary source is historical data, collected mainly during U.S. Geological Survey cooperative studies and published in numerous publications of the NRCD and preceding agencies. A map showing the coverage of the Piedmont province by these reports is shown in figure 15. Another important source of data has been unpublished results of ground-water analyses made for the U.S. Environmental Protection Agency (EPA) 208 Planning Study of 1978-80 (208 Study). The 208 Study, which was directed by NRCD, produced laboratory analyses of shallow ground-water quality at nearly 600 sites. The recently initiated NRCD baseline water-quality network (Perry Nelson, North Carolina Department of Natural Resources and Community Development, written commun., 1985) is an important source of information for background water quality. Data from this ongoing study will also be added to the data set.

Data from recent and ongoing U.S. Geological Survey studies are an important part of information currently available on ground water in the Piedmont. Recent U.S. Geological Survey studies provide one of the few sources of analyses of constituents such as heavy metals and organics, but even this source is limited to only a few land-use types. One U.S. Geological Survey study in particular, the city of Charlotte and Mecklenburg County urban hydrology study (Eddins and Crawford, 1984), has been instrumental to site selection. It provides detailed information on county-wide water quality of streams during low-flow periods.

The ongoing U.S. Geological Survey study of Charlotte-Mecklenburg County urban hydrology includes quarterly sampling of 24 monitoring wells in landfills around Charlotte, 10 privately-owned wells near the landfills, and streams draining landfill and residential areas.

Simmons and Heath (1979) examined baseline water quality from undeveloped basins all around North Carolina at both high and low flows. Low-flow data from this study can be used as an indicator of ground-water quality in undeveloped areas.



EXPLANATION

A Goldsboro area; Pusey, R.D., 1960.
B Fayetteville area; Schipf, R.G., 1961.
C Monroe area; Floyd, E.O., 1965.
D Durham area; Bain, G.L., 1966.
E Cleveland County; Duncan, D.A., and Pearce, R.R. 1966.
F Morganton area; Sumsion, C.T., and Laney, R.L., 1967.
G Raleigh area; May, V.J., and Thomas, J.D., 1968.
H Stanly County; Berry, E.L., 1970.
I Northwestern North Carolina; Peace, R.R., Jr., and Link, D.R., 1971
J Rowan County; Groves, M.R., 1976.
K Halifax area; Mundorff, M.J., 1946,
L Greensboro area; Mundorff, M.J., 1948.
M Charlotte area; LeGrand, H.E., and Mundorff, M.J., 1952.
N Statesville area; LeGrand, H.E., 1954.

Figure 15.--Regional ground-water investigations in the Piedmont of North Carolina.

A study of the ground-water development potential in the Piedmont and Blue Ridge areas of North Carolina is the source of the geologic data used in correlation analysis with ground-water quality data, as well as much hydrologic framework information used in this study.

An ongoing U.S. Geological Survey study of the effects of land-management practices on sediment and chemical transport via streams in Guilford County, North Carolina, includes an examination of soil-water and ground-water quality in a tobacco-growing area.

DATA ANALYSIS

The data-analysis objective of the current study is to test the set of available ground-water quality data for relations between water quality and land use, geology, and soil characteristics. This was done using simple non-parametric analysis of variance (ANOVA) on the ranks of the data. In addition, some characterization of the data set is appropriate. However, a more complete description and analysis of the data is reserved for future study.

The data collected for the 208 Study was used for this study because the water samples were collected over a period of 3 years and analyzed at the same laboratory, and the land uses associated with the sampling sites were known. This data set is well suited for testing by ANOVA, because the effect of uncontrollable variance due to analyses at different laboratories at different periods of time is not a factor.

The 402 wells included in the 208 Study were quite shallow, with a mean depth of 27.7 feet. Daniel (1985) reports that in his survey of the North Carolina Piedmont and Blue Ridge the mean well depth for 5,221 wells is 154.0 feet, and the mean for 4,408 domestic wells is 123.6 feet. The Blue Ridge area has a similar hydrogeologic flow system to the Piedmont; therefore, wells from the Blue Ridge should not substantially differ in well characteristics from Piedmont wells. The 208 Study wells were augered in the regolith deep enough to obtain a water sample from just below the water table. The mean depth of the water table is 18.2 feet below land surface for the 208 Study. Daniel reports that the overall Piedmont and Blue Ridge mean water level in water-supply wells is 32.3 feet below land surface (n =

2,825). Water-supply wells used in Daniel's study tended to be deeper than the shallow 208 Study wells and generally had water-levels lower than those in shallow wells nearby. This indicates that in much of the area there is a downward gradient from the shallow part of the system to the deeper fractured rock system.

Water-Quality Data

An analysis of available ground-water quality data indicates that shallow ground water in the Piedmont generally is a slightly acidic (median pH, 6.5) sodium bicarbonate-type water with dissolved solids concentrations less than 100 milligrams per liter (mg/L). However, the water-quality data base contains analyses of contaminated as well as natural ground waters. Dissolved solids concentrations exceed 500 mg/L in a number of the analyses and exceed 1,000 mg/L in a few. Values of pH ranged from less than 2.0 units to as high as 10.8 units. Those samples with high dissolved-solids concentrations and extreme pH values were generally from wells in urban and industrial areas where the ground water has been contaminated.

Frequency histograms for pH, alkalinity, specific conductance, and dissolved solids concentrations in ground waters in the Piedmont are shown in figures 16-19. The histogram for pH is bell-shaped with most values falling between a pH of 5.5 and 7.5. Histograms for alkalinity, specific conductance, and dissolved solids are more log normal in shape with most values of alkalinity (as $CaCO_3$) less than 60 mg/L, most specific conductance values less than 200 microsiemens, and most dissolved solids concentrations less than 100 mg/L.

Independent Variables

Three different variables that may influence ground-water quality have been included in the data set: land use, geology, and soil type. The principal variable of interest in this study is land use. However, in defining the influences of land use on ground-water quality, it is important to account for the effects of other variables which may complicate analysis. Therefore, the variables of geology and soils have been added to the data set.

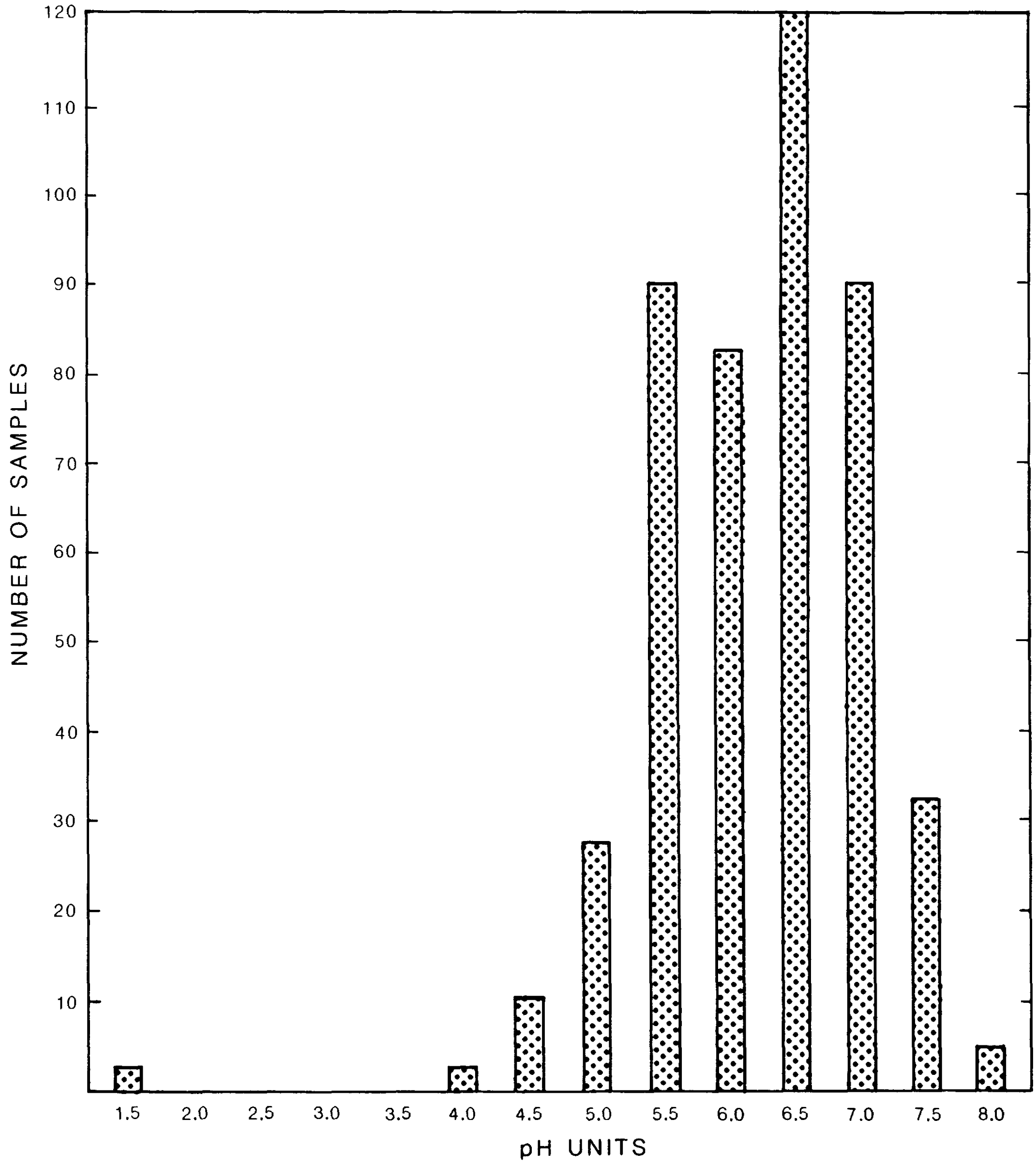


Figure 16.--A frequency histogram for pH.

Land use is represented in the data set in two forms. The Land-Use Data Analysis (LUDA) land-use type (Anderson and others, 1976) and the 208 Study land-use type have both been entered for each well location. The different categorizations of land uses produce two distinctly different ways of sorting the data set.

Bedrock geology, as compiled by Daniel (1987), was used in defining the rock type for each well. Most of the wells are located in regions of the metavolcanic and metaigneous rock types.

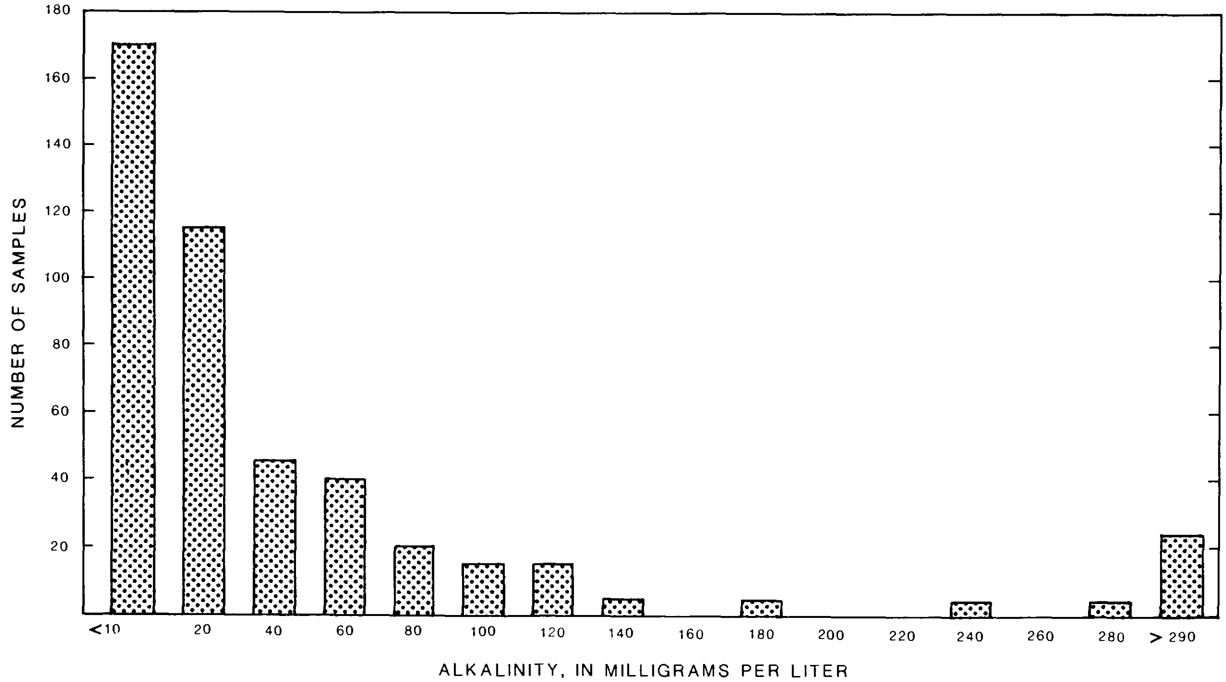


Figure 17.--A frequency histogram for alkalinity.

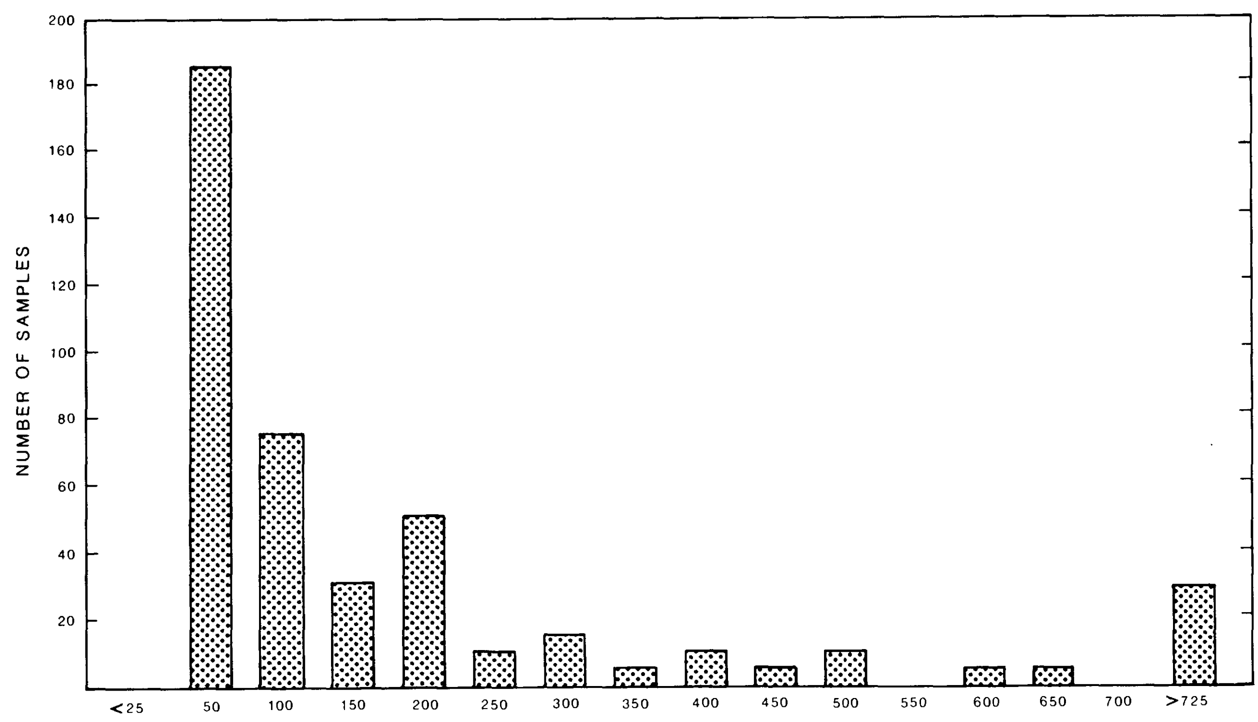


Figure 18.--A frequency histogram for specific conductance.

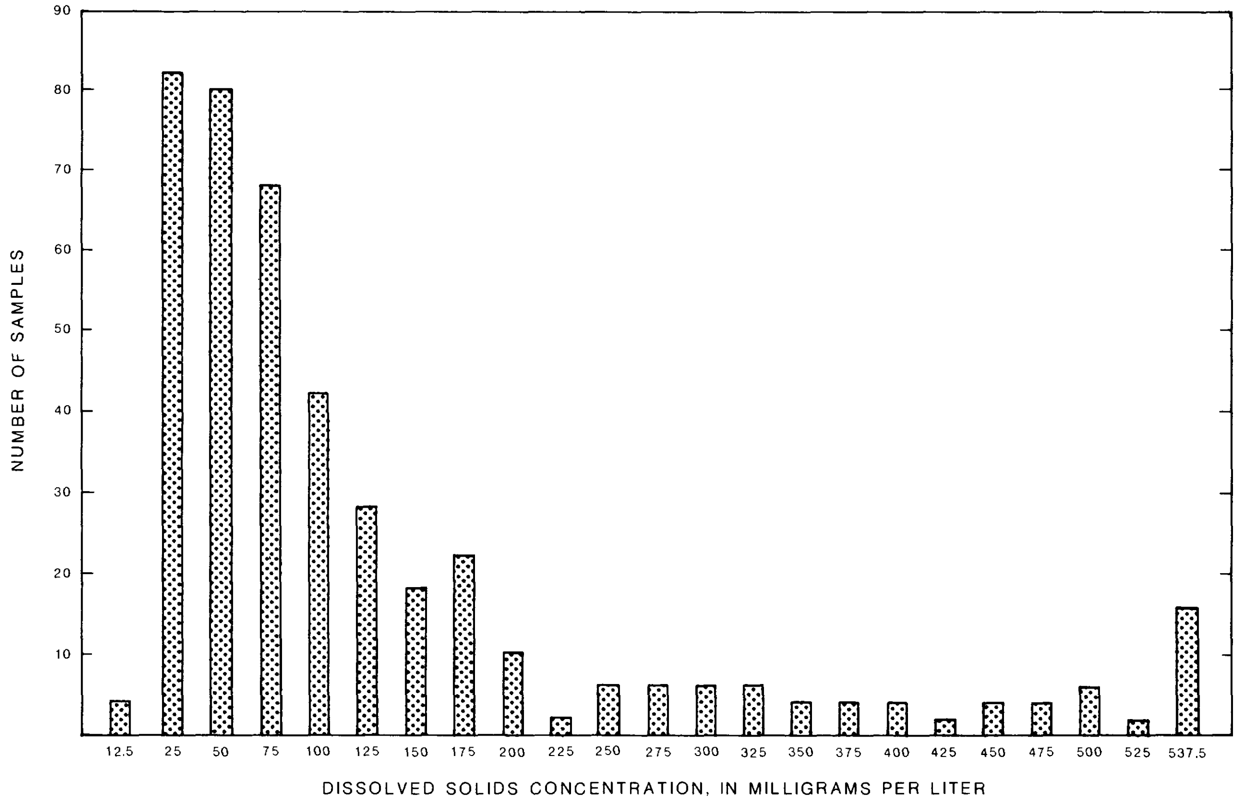


Figure 19.--A frequency histogram for dissolved-solids concentration.

Soil type at each well location was determined using the U.S. Soil Conservation Service (1978) soil classification system. The variables of soil type and rock type are not completely independent of each other since soils are usually derived from the underlying parent rock. However, in this analysis, soils and geology have been treated as separate variables simply to test if they affect ground-water quality.

Analysis of Variance

Non-parametric analysis of variance (ANOVA) on ranked data is used in this investigation to help define the relation between land use and ground-water quality. Helsel and Ragone (1984) describe the application of analysis of variance in the frame of reference of the U.S. Geological Survey ground-water quality appraisal program. Basically, one factor non-parametric ANOVA is a test for the comparison of means of the ranks of the concentrations. In other words, are the differences in the means of the concentrations of constituents in water due to chance variation alone, or are they the result of land use?

To test the null hypothesis that the means do not vary because of the effects of land use, the ratio:

$$F = \frac{\text{(Total variance) - (Within land-use region variance)}}{\text{(Within land-use region variance)}}$$

is calculated and compared to the F ratio that would be expected if the null hypothesis were true. If probability (PR) is low, then the effect investigated (land use, etc.) is significant, and the null hypothesis is rejected.

The results of analysis of variance of the water-quality constituents and the four independent variables are shown in table 2. Many of the F statistic values shown in table 2 for all the independent variables are significantly larger than the F values that might be produced by chance alone. In other words, for many of the water-quality constituents, the null hypothesis is rejected, land use, geology, and soil type do indeed influence ground-water quality for many constituents.

Simple analysis of variance has shown that there is at least one subgroup mean for land use, geology, and soils that has a variance significantly different from the variance that might be expected from chance. The next step is to find out which of the subgroup ranked means tested are significantly different from one another. One technique that can be used to show the subgroups that are significantly different from the others is the Duncan multiple-range test (Duncan, 1955).

The Duncan procedure sorts the subgroup means into groups that are statistically different from one another. When applied to the land use, geology, and soils classifications for this study, the Duncan analysis produced up to 4 out of 20 groups of different soil types, 3 out of 4 for the 208 Study land use, 3 out of the 15 LUDA classes of land use categories, and up to 4 groups of rock types that were found to be statistically different from one another out of 14 rock types. In other words, the test indicated that, in future analyses, combining of some of the land use, geology, and soils catagories may be appropriate. The results of the Duncan

Table 2.--*Summary of analysis of variance of the water-quality constituents and the four independent variables*

[F, the ratio: $\frac{\text{(total variance) - (within land use region variance)}}{\text{(within land use region variance)}}$; PR, critical probability level; *, indicates significance at the 0.05 critical probability level]

Constituents	Independent variables											
	208-study land use			LUDA land use			Geology			Soil		
	F	PR	Number of observations	F	PR	Number of observations	F	PR	Number of observations	F	PR	Number of observations
Alkalinity (4.5)	13.02	0.0001*	473	1.75	0.0432*	435	5.17	0.0001*	435	1.87	0.0153*	419
Alkalinity (8)	3.11	.0260*	473	1.04	.4131	435	1.83	.0421*	435	.15	1.000	419
Aluminum	18.66	.0001*	469	.58	.8796	435	3.87	.0001*	435	1.47	.0912	420
Ammonia	28.44	.0001*	179	1.24	.2622	158	2.72	.0059*	158	2.71	.0025*	156
Bicarbonate	12.72	.0001*	471	1.70	.0535	435	4.72	.0001*	435	1.85	.0167*	419
Calcium	8.44	.0001*	469	3.38	.0001*	433	6.17	.0001*	433	3.44	.0001*	418
Carbonate	2.36	.0700	471	.11	1.000	435	.77	.6849	435	.10	1.000	419
Chloride	7.27	.0001*	471	3.88	.0001*	433	10.28	.0001*	433	3.54	.0001*	417
Copper	.14	.9319	177	2.11	.0275*	155	.44	.9228	155	.45	.8693	143
Dissolved solids	4.27	.0057*	416	2.77	.0006*	383	9.07	.0001*	383	4.92	.0001*	376
Fluoride	3.70	.0119*	442	.48	.9449	407	1.40	.1620	407	.93	.5445	400
Hardness (carbon)	11.95	.0001*	472	3.53	.0001*	435	10.66	.0001*	435	4.47	.0001*	419
Iron	11.56	.0001*	469	.75	.7281	434	1.08	.3744	434	.65	.8652	419
Lead	2.26	.0814	178	.15	.9989	156	.31	.9693	156	.33	.9614	144
Lithium	.32	.8139	468	.09	1.000	435	.11	1.000	435	.05	1.000	420
Magnesium	12.04	.0001*	469	.09	1.000	435	8.48	.0001*	433	3.43	.0001*	418
Manganese	21.42	.0001*	470	2.52	.0019*	433	2.40	.0052*	435	2.15	.0036*	420
Nitrite + nitrate	9.32	.0001*	457	1.51	.1027	428	3.40	.0002*	424	1.58	.0660	408
pH (field)	.72	.5465	286	1.89	.0363*	268	3.84	.0001*	269	2.00	.0122*	258
pH (lab)	2.05	.1048	465	1.23	.2498	428	2.22	.0127*	428	1.16	.2860	413
Potassium	1.64	.1786	466	.84	.6279	433	4.85	.0001*	433	1.04	.4129	418
Silica	1.89	.1295	424	1.50	.1067	390	5.74	.0001*	390	2.54	.0005*	383
Sodium	8.60	.0001*	468	3.29	.0001*	434	6.96	.0001*	434	3.88	.0001*	419
Specific conductance	20.42	.0001*	436	2.69	.0009*	413	7.96	.0001*	414	2.83	.0001*	400
Sulfate	11.07	.0001*	417	1.49	.1111	383	7.06	.0001*	383	2.74	.0002*	376
Temperature	6.31	.0004*	359	1.96	.0195*	433	4.73	.0001*	434	1.87	.0148*	418
Total phosphorus	4.79	.0029*	455	1.02	.4287	422	1.34	.1985	422	.93	.5363	406
Zinc	.31	.8184	180	1.69	.0884	157	2.26	.0212*	157	1.09	.3751	145

test suggest that the separate LUDA categories for urban areas could be grouped together. The 208 Study land-use data fared a little better, showing more separation of the subgroups than the LUDA data.

The ANOVA results shown in table 2 used 208 Study data land-use classifications of industrial, mixed urban, residential, and undeveloped. A finer division of these land-use classes into 17 categories produced similar results to the grouped classes with up to 4 Duncan groupings. The industrial land-use category was associated with the highest constituent concentrations followed generally by the mixed urban, residential and undeveloped land-use categories. Definition of the land-use catagories for the 208 Study data was based on information on the well locations. Therefore, a quantitative breakdown of the exact land uses represented by each of the classifications or categories is not possible. The industrial land use includes waste-water treatment plants, landfills, and manufacturing plants. The mixed-urban category includes a potpourri of commercial, retail, and urban land uses. The residential category includes both high and low density housing areas. The undeveloped land-use classification includes forests, fields, cropland, and farms.

A more detailed analysis of the data set is reserved for future study. As the current set of data is supplemented with organic constituents and more trace-element data, the information that can be gleaned from the data set by statistical analysis will increase.

NEED FOR ADDITIONAL STUDY

One of the principal objectives of this study has been to design a ground-water sampling program to test the relation between ground-water quality and land use. Definition of the relation of ground-water quality to land use will allow extrapolation of the data to a larger scale, giving an overall projection of ground-water quality within the Piedmont province based on land use.

The assembly of available information about the flow system and ground-water quality has led to the formulation of the following hypotheses about the system.

1. Land use.--Different land-use types are associated with different ground-water chemistry characteristics. The amount of ground-water contamination in the regolith and bedrock-fracture system is related to each land-use type. These relations can be mathematically defined to a level that allows statistical prediction and numerical modeling.

2. Contaminant-flow system.--The transition zone between bedrock and regolith serves as a primary transmitter of ground water and contaminated ground water. The regolith serves as the principal reservoir of contaminated ground water.
   a. Attenuation of ground-water contaminants in the regolith is related to the degree of weathering and composition of regolith material.
   b. The velocity of contaminant movement can be highest within the fractured-bedrock system, particularly under stressed conditions.
   c. The deeper zones in basement rock generally contain the best quality water in the system due to contaminant attenuation in the regolith and shallow fractures.
   d. Geomorphological analysis can be used to find fracture zones that help predict general subsurface-flow patterns of ground-water contamination. These methods can be verified with geophysical techniques.

3. Natural ground-water quality.--Ground-water quality is related to soil type and geology. Identification of measurable soil and geological characteristics that affect ground-water quality will allow a better characterization of the relation of land use to water quality.

Network Design

A ground-water quality monitoring network designed to test these hypotheses can provide:

1. Detailed information that can be used to refine understanding of the flow system;
2. Data that can give a regional picture of the effects of land use on water quality.

A hypothetical drainage basin (LeGrand, 1984) with multiple-contamination sources (fig. 20) illustrates the complexity of sampling to determine ground-water quality on an areal basis. The ground-water contamination from point sources such as spills and small waste lagoons is generally local and detectable only if wells are placed near the source and in the contaminant plume. Contamination from nonpoint sources, however, such as application of pesticides to farm fields, may be areal in extent but locally dilute and difficult to detect in any particular well.

Helsel and Ragone (1984) provide guidelines for experimental design within the framework of the U.S. Geological Survey national program of ground-water quality assessment. These guidelines stress the importance of:

1. <u>Representative sampling of study areas to give a characterization of overall basin ground-water quality</u>. In this respect, large localized sources such as landfills within the study area should be described separately, possibly by a separate monitoring program.

2. <u>Random sampling to reduce error in statistical testing of the data</u>. After a group of wells has been located within the study area to give representative hydrologic and geochemical coverage of the area, these wells should be randomly sampled to reduce bias in the data from any one particular well or series of wells.

3. <u>Maximization of the ability to detect effects given a limited number of samples</u>. The principal effect of interest is the influence of land use on water quality. Given a number of regions of different land uses, we wish to find:
    a. If there are significant water-quality differences between the land uses;

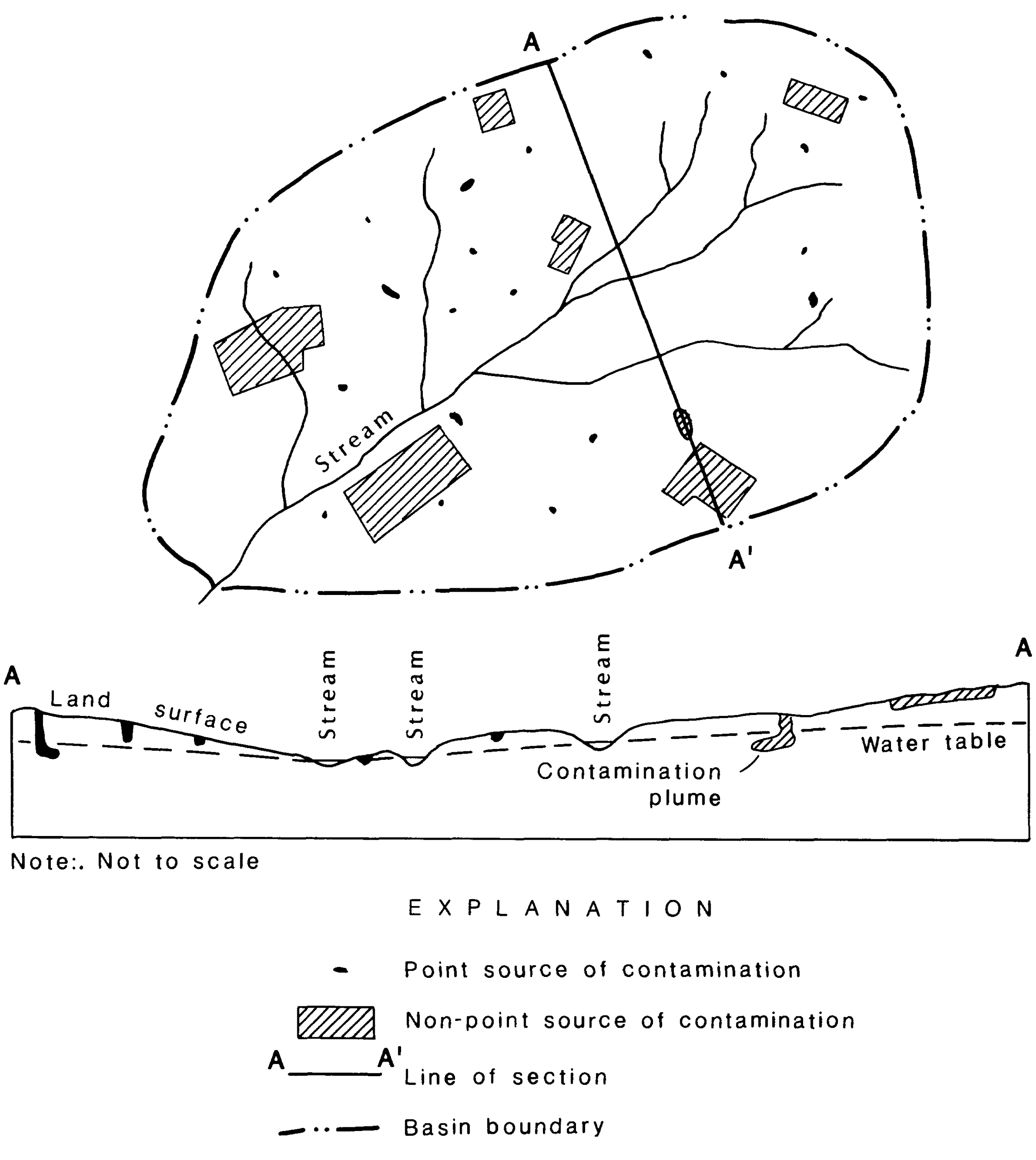


Figure 20.--A hypothetical drainage basin with multiple contamination sources (after LeGrand, 1984).

b. If there are significant areal variations in water quality in any particular land use (Significant variance between wells may obscure detection of differences between land uses. Additional sampling may improve definition of this variance); and

c. If there is significant variation over time in water quality in samples from any one well. (Significant variance between samples from a single well may obscure detection of differences between land uses. Additional sampling may improve definition of this variance.)

Once estimates for variance in concentrations between wells and variance of concentrations in the same well are known, the number of wells needed per area and the number of samples needed per well can be optimized for a given cost and number of study areas (Sokal and Rohlf, 1969; Helsel and Ragone, 1984).

Data Collection

To test the land-use and contaminant flow-system hypotheses, additional information about ground-water quality will need to be collected. In addition, special studies are needed to further refine the conceptual model of the hydrologic framework. As part of the study design, monitoring of (1) four different areas representing old industrial, new industrial, mixed urban, and residential land uses in Mecklenburg County, (2) an agricultural land-use area in Guilford County, and (3) two other sites to refine the framework are planned.

The monitoring will consist of three principal sampling programs:

1. Sampling of existing wells in and outside of the principal study areas;
2. Sampling from wells constructed specifically for the sampling program within the principal study areas; and
3. Sampling of baseflow of streams within the study areas.

There is very little information in available data bases about wells in and near the study areas. One of the first tasks of the study will be to identify the wells within the area that can be sampled. It is likely that few of these wells will be usable in the monitoring network. Domestic water-supply wells are usually cased to the fractured rock, bypassing the zones hypothesized to be most susceptible to ground-water contamination.

Usable sampling wells will be supplemented with new wells constructed specifically for this study. The goal will be to establish a network of wells which sample areas representative of particular land uses. Each well will sample a cell in the geohydrologic system. The locations of these cells will generally be in downgradient areas of the land uses under study. Wells will be installed to sample the upper part of the saturated regolith and the transition zone.

The resultant network of wells will be sampled during an initial sampling period to define spacial water-quality variability related to land use. Sampling wells open to different zones and multiple sampling in individual wells will be used to estimate within-well variability.

After the initial period of sampling, smaller groups of wells will be randomly selected from the group of wells sampling the shallow zones, the group sampling the transition zone, and the group sampling the deeper zone. Each of these three subgroups of wells will then be sampled periodically so that water-quality variation over time may be defined.

Sampling of streams during baseflow periods in basins and subbasins within the study areas will accompany sampling of wells. The sampling intervals will be nonuniform, depending on the streamflow conditions at the time of scheduled well-sampling trips.

Sampling Methods

The complexity of sampling to determine ground-water quality on a regional basis is further complicated by the difficulty of correctly measuring substances such as metals or organic substances in extremely low concentrations in the ground-water system. Wells within the network need to be designed to allow sampling of the desired zones without contamination from other zones or the casing materials. The sampling protocol will consider such factors as: sampling frequency, well diameter, sampling device used, amount of water to be removed from the well before sample collection, depth in water column that the sample is taken, bottle types and composition, sample filtering in the field, movement of sample from sampling device to the sample bottle, sample preservation, time limits required on delivery of samples to the laboratory, and quality control (Nacht, 1983).

In the initial assessment of water quality in a study area it is necessary to define which contaminants are present in the system in measurable amounts. Laboratory analyses of major inorganic constituents and nutrients combined with hydrocarbon and trace-element scans will be used to define the suite of constituents to be tested for in the following period of periodic sampling. Due to the high cost of sample analysis for organic constituents and trace metals, the assessment will begin with a relatively inexpensive scan or semi-qualitative method that indicates if contaminants are present (Helsel and Ragone, 1984). One such technique, the gas chromatograph-flame ionization detector (GC-FID) scan, is designed to detect the presence of hydrocarbons. Another technique, neutron-activation analysis (NAA), is a low-cost method that measures concentrations of a suite of elements, including many trace metals, and has very low detection limits for these elements.

During a GC-FID scan, the gas chromatograph separates organic compounds within the sample, delivering a stream of components of the sample to the flame-ionization detector (F. Cardinali, U.S. Geological Survey, oral commun., 1985). The sample stream comes out of the gas chromatograph and goes into a hydrogen flame, where the organic compounds are burned, producing ions and a current flow that is proportional to the amount of organic chemical present. This current can be detected and displayed. Standards and blanks are run to allow comparison and detection of laboratory contamination.

Careful comparative examination of the chromatographs of the series of samples, standards, and blanks may indicate that organic substances are in the sample that may warrant further investigation. The GC-FID scan can detect organic compounds, and in particular hydrocarbons, at levels of 0.5 micrograms per liter. GC-FID scans have been used in this study during the process of site selection. The technique will provide a means in the proposed monitoring studies of screening samples prior to substance-specific analysis.

In NAA, the sample is first irradiated by neutrons in a nuclear reactor (Kimberley and Bellis, 1985). The slightly radioactive sample produces gamma rays for each decaying radioisotope which can be detected. The rate of production of gamma rays for each induced radioisotope is proportional to its concentration. Spectral analysis is necessary in this analysis.

The elemental analysis produced by a complete NAA scan includes a variety of trace elements rarely tested for in traditional atomic-absorption spectrophotometry. These rare elements can individually be indicators of contamination or, in combination, can provide a signature that may be used to characterize ground water at a study location. Concentrations of 43 different elements are measured in a complete NAA scan.

Gas chromatograph-flame ionization detector and NAA scans provide a means to help define the suite of constituents to be tested for in later sampling. These scans, combined with laboratory analyses of major inorganic constituents and nutrients, will be useful in determining what constituents need to be tested for in the following period of random sampling.

Special Studies

The special-study program is designed primarily to test the principal hypothesis of the study that levels of ground-water contamination can be related to land use. However, to address the hypotheses about the contaminant-flow system, and especially the role of the transition zone in that system, a few additional special studies are proposed. These studies tie into other current U.S. Geological Survey research.

The distribution of solutes within the ground-water system is three dimensional. A vertical definition of water-quality variation within the ground-water flow system is necessary to describe solute distribution within the flow system on a local scale and to understand regional or basin-wide contaminant movement. To study the vertical variation in water quality in the regolith fractured-rock system, a nest of wells, each with a short screen interval at different depths, can be installed in areas where there is known ground-water contamination. Sampling of these well-nest sites, coupled with careful identification of the nature of the regolith and fractured-rock system at a site, will test the hypothesis that the transition zone plays a particularly important role in the contaminant-flow system.

Temperature logs can be used to detect seasonal effects on ground-water temperatures in the shallower parts of a borehole and to indicate ground-water flow (Nutter and Otton, 1969). However, a more complete data base is needed in the Piedmont province in order to determine the extent seasonal variations affect near-surface ground-water temperatures and if the subsurface temperatures provide evidence of greater flow in the transition zone than the other zones. One possible approach would be to run temperature logs monthly over a 1- to 2-year span at an established test site with a known regolith-bedrock profile. Another approach is to place thermocouples in key boreholes at the test site to record ground-water temperatures at various borehole depths for various time periods. The goal is to obtain enough temperature-profile information to test the hypothesis that differential flow within the regolith and fractured-rock system affects ground-water temperature.

SUMMARY AND CONCLUSIONS

The objective of this study is to evaluate the quality of ground water in the combined regolith and fractured-rock ground-water system in the North Carolina Piedmont and to develop and test hypotheses regarding the relationship of contamination to land use. This is a two-phase study. The first phase is the reconnaissance of available data and design of a monitoring program. The second phase is the implementation of that monitoring program and analysis of data from that program. This report documents of the progress of the first phase of the study.

The igneous and metamorphic rocks of the Piedmont are mantled by a cover of their own weathering products. The unweathered massive bedrock of about 400 feet below land surface grades upwards into fractured rock, then weathered rock with boulders of less weathered parent rock, followed by clay-rich saprolite (an unconsolidated material which contains remnant structure of the parent rock), and finally the soil horizons. In floodplains, streams rework the erodible material, sorting it into layered unconsolidated deposits. The mantle of weathered material, soil, and alluvium is generally called the regolith. In the Piedmont, the regolith is usually 30-60 feet thick. The regolith and underlying fractured rocks combine to make up a complex, multi-media flow system. The components of the system are:

1. The unsaturated zone in the regolith,
2. The saturated zone in the regolith,
3. The transition zone, and
4. The fractured-bedrock system.

The saturated thickness in the regolith provides the bulk of the water storage within the Piedmont ground-water system. The regolith serves as a reservoir supplying water to interconnected fractures within the bedrock. At the base of the regolith there is generally a zone of weathered rock, boulders, and saprolite. This transition zone has high permeability relative to other zones, and it may create a high-flow zone within the ground-water flow system.

On a regional scale, prediction of the natural direction of ground-water flow can be related to surface topography. Since most of the natural flow is probably confined to the upper 30 feet of bedrock, where there are the most fractures, and the transition zone, the distance between the point where a drop of water or waste enters the system is commonly less than a half mile from where that drop may eventually discharge to a stream (LeGrand, 1958). The perennial-stream drainage basin is essentially a complete flow-system cell, similar to and yet generally separate from surrounding basins.

Available sources of data on ground-water quality in the Piedmont of North Carolina have been identified and are being combined into a data set which also includes data on regional characteristics of the Piedmont such as land use, soils, and geology. The bulk of the data currently in the data set was collected between 1978 and 1980 in a program of the North Carolina Department of Natural Resources and Community Development (NRCD). Historical data, published in numerous publications of the North Carolina Department of Natural Resources and preceding agencies, most of which were U.S. Geological Survey cooperative studies, are also a primary source of data for this study.

Available land-use data were obtained from LUDA land-use maps, from the Mecklenburg County Planning Department, and the 208 Study. About 65 percent of the North Carolina Piedmont land area is forest, about 25 percent is cropland, and about 6 percent is urban and residential.

Several current U.S. Geological Survey studies have provided valuable information during the first phase of the investigation. One study in particular, the Charlotte and Mecklenburg County study (Eddins and Crawford, 1984), has been instrumental in the selection of possible second-phase study sites and has provided detailed information on county-wide water quality of streams during baseflow periods.

The set of ground-water quality data constructed during this reconnaissance study provides a strong base for current and future ground-water quality study. The construction, editing, and analysis of information contained in this data set is an ongoing process. The data set contains over 1,800 water-quality observations. The wells included in the 208 Study were shallow, with a mean depth of 27.7 feet. The mean depth of the water table was 18.2 feet below land surface for the 208 Study.

Temperature and pH show bell-shaped normal distributions. The other water-quality constituents show distributions that appear to be log-normal in shape.

Three different variables that may influence ground-water quality have been included in the data set. The variables of land use, geology, and soil type are all likely to affect water quality. The principal variable of interest in this study is land use. However, in defining the influences of land use on ground-water quality, it is important to account for the effects of other variables which may complicate analyses. Therefore, the variables of geology and soils have been added to the data set.

Non-parametric analysis of variance of the water-quality data indicates that land use, soil type, and geology influence ground-water quality for many constituents. The results of the Duncan multiple-range test suggest that the separate LUDA catagories for urban areas could be grouped together.

These are the hypotheses which need to be tested by further study:

1. Land use.--The amount of ground-water contamination in the regolith and bedrock-fracture system is related to land use. Each land-use type may be characterized by a particular ground-water chemistry.

2. Contaminant-flow system.--
    a. The transition zone between bedrock and regolith serves as a primary transmitter of contaminated

ground water. The regolith serves as the principal reservoir of ground-water contamination.

b. Attenuation of ground-water contaminants is related to the degree of weathering and composition of regolith material and the hydraulic conductivity, gradient, and porosity of the material.

c. Ground-water contaminants generally move in the direction of ground-water flow and at various rates depending upon water solubility.

d. The deeper zones in basement rock generally contain the best quality water in the system due to contaminant attenuation in the regolith.

e. Geomorphological analysis can be used to identify fracture zones that help predict general subsurface-flow patterns of ground-water contamination. These methods can be verified with surface geophysical techniques.

3. Natural ground-water quality.--Water quality is related to soil type and geology, and the relation can be quantified.

Future study is considered for four different land uses in Mecklenburg County, North Carolina. Drainage basins containing old industrial, new industrial, mixed urban, and residential land uses have been identified as potential study sites. Ground water from these basins will be collected from a network of wells augered to the top of the saturated zone and into the transition zone. Sampling wells open to different zones through the regolith and fractured rock system will test the hypothesis that the transition zone between the regolith and the fractured rock is a primary transmitter of contaminated ground water.

Gas chromatograph-flame ionization detector and NAA scans will be combined with selected laboratory analyses of volatile organic compounds and analyses of major inorganic constituents and nutrients in the initial period of sampling to define the suite of compounds to be tested for in the following period of random sampling. Sampling of baseflow of stream basins and subbasins within the study areas will accompany sampling of wells. The sampling intervals will be nonuniform, depending on the baseflow conditions at the time of scheduled well-sampling trips.

The Mecklenburg County studies will be coupled with other ongoing U.S. Geological Survey studies in the Piedmont. A study of ground-water quality in Guilford County, North Carolina, will provide information about agricultural land uses. A study in Mecklenburg County relating land use to surface-water quality will provide additional detailed land-use information, as well as results relevant to the proposed ground-water study.

The data collected from the Mecklenburg and Guilford County studies will be combined with the set of available ground-water quality data and used to test for correlations between land use and ground-water quality. The hypothesis that land use can be used to estimate regional ground-water quality will be tested using non-parametric analysis of variance. Comparison of results to other areas with known water-quality characteristics will allow verification of the predictive models.

REFERENCES

Anderson, J.R., Hardy, E.E., Roach, J.T., and Witmer, R.E., 1976, A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 28 p.

Bain, G.L., 1966, Geology and ground-water resources of the Durham area, North Carolina: North Carolina Department of Water Resources Ground-Water Bulletin 7, 147 p.

Berry, E.L., 1970, Ground-water quality in Stanly County, North Carolina: North Carolina Department of Water and Air Resources Ground-Water Circular 15, 24 p.

Cressler, C.W., Thurmond, C.J., and Hester, W.G., 1983, Ground water in the greater Atlanta region, Georgia: Georgia Department of Natural Resources, U.S. Environmental Protection Agency, and The Georgia Geologic Survey, in cooperation with U.S. Geological Survey, Information Circular 63, 143 p.

Daniel, C.C., III, 1985, Statistical analysis of water-well records from the Piedmont and Blue Ridge of North Carolina: Implications for well-site selection and well design (abs.), Geological Society of America Abstracts with Programs, v. 17, no. 2, p. 86-87.

______1987, Statistical analysis relating well yield to construction practices and siting of wells in the Piedmont and Blue Ridge provinces of North Carolina: U.S. Geological Survey Water-Resources Investigations Report 86-4132, 54 p.

Daniel, C.C., III, and Sharpless, N.B., 1983, Ground-water supply potential and procedures for well-site selection Upper Cape Fear River Basin, Cape Fear River Basin Study 1981-83: North Carolina Department of Natural Resources and Community Development and U.S. Water Resources Council in cooperation with U.S. Geological Survey, 73 p.

Daniels, R.B., Kleiss, H.J., Boul, S.W., Byrd, H.J., and Phillips, J.A., 1984, Soil systems in North Carolina: North Carolina Agricultural Research Service, North Carolina State University, Bulletin 467, 77 p.

Duncan, D.B., 1955, Multiple range and multiple F tests: Biometrics, v. 11, p. 1-42.

Duncan, D.A., and Peace, R.R., Jr., 1966, Ground-water resources of Cleveland County, North Carolina: North Carolina Department of Water Resources Ground-Water Bulletin 11, 65 p.

Eddins, W.H., and Crawford, J.K., 1984, Reconnaissance of water-quality characteristics of streams in the city of Charlotte and Mecklenburg County, North Carolina: U.S. Geological Survey Water-Resources Investigations Report 84-4308, 105 p.

Eder, B.K., Davis, J.M., and Robinson, P.J., 1983, Variations in monthly precipitation over North Carolina: North Carolina Climate Program Office, North Carolina State University, Raleigh, N. C., Report No. 185, 50 p.

Farrar, S.S., 1985, Tectonic evolution of the easternmost Piedmont, North Carolina: Geological Society of America Bulletin, v. 96, p. 362-380.

Fenneman, N.M., 1938, Physiography of eastern United States: McGraw-Hill Book Co., New York, p. 121-123.

Floyd, E.O., 1965, Geology and ground-water resources of the Monroe area, North Carolina: North Carolina Department of Water Resources Ground-Water Bulletin 5, 109 p.

Groves, M.R., 1976, Preliminary report on ground-water resources of Rowan County, North Carolina: North Carolina Department of Natural and Economic Resources Ground-Water Bulletin 22, 63 p.

Gunter, H.C., Hill, C.L., and Dillard, T.E., 1984, Water-resources data North Carolina, water year 1983: U.S. Geological Survey Water-Data Report NC-83-1, 534 p.

Harned, D.A., and Daniel, C.C., III, 1987, Ground-water component of Piedmont streams *in* Implications for ground-water supply systems and land-use planning: GSA Abstracts with Programs, v. 19, no. 2, February 1987.

Heath, R.C., 1980, Basic elements of ground-water hydrology with reference to conditions in North Carolina: U.S. Geological Survey Water-Resources Open-File Report 80-44, 856 p.

_____1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

_____1984, Ground-water regions of the United States: U.S. Geological Survey Water-Supply Paper 2242, 78 p.

Heath, R.C., and Giese, G.L., 1980, What about ground water in western North Carolina: are large supplies feasible?: U.S. Geological Survey Pamphlet.

Helsel, D.R., and Ragone, S.E., 1984, A work plan for ground-water quality appraisals of the toxic-waste ground-water contamination program: U.S. Geological Survey Water-Resources Investigations Report 84-4217, 33 p.

Hem, J.D., 1970, Study and interpretation of the chemical characteristics of natural water, 2nd ed: U.S. Geological Survey Water-Supply Paper 1473, 363 p.

Kimberley, M.M., and Bellis, B.J., 1985, Neutron-activation analysis of ground water around a chemical-waste landfill in the North Carolina Piedmont: abs., 1985 Triangle Conference on Environmental Technology, Raleigh, N.C.

LeGrand, H.E., 1954, Geology and ground water in the Statesville area, North Carolina: North Carolina Department of Conservation and Development Bulletin 68, 68 p.

_____1958, Chemical character of water in the igneous and metamorphic rocks of North Carolina: Economic Geology, v. 53, no. 12, p. 179-189.

_____1967, Ground water of the Piedmont and Blue Ridge provinces in the southeastern states: U.S. Geological Survey Circular 538, 11 p.

_____1984, Ground water and its contamination in North Carolina with reference to waste management: 92 p.

LeGrand, H.E., and Mundorff, M.J., 1952, Geology and ground water in the Charlotte area, North Carolina: North Carolina Department of Conservation and Development Bulletin 63, 88 p.

Lutz, J.F., 1969, The movement and storage of water in North Carolina soils and the role of soil in determining water quality: Water Resources Research Institute of the University of North Carolina, no. 24, 45 p.

May, V.J., and Thomas, J.D., 1968, Geology and ground-water resources in the Raleigh area, North Carolina: North Carolina Department of Water and Air Resources Ground-Water Bulletin 15, 135 p.

Mew, H.E., Jr., 1985, Ground water contamination and incident management in North Carolina: North Carolina Department of Natural Resources and Community Development, 17 p.

Mundorff, M.J., 1946, Ground water in the Halifax area, North Carolina: North Carolina Department of Conservation and Development Bulletin 51, 76 p.

_____1948, Ground water in the Greensboro area, North Carolina: North Carolina Department of Conservation and Development Bulletin 55, 108 p.

Nacht, S.J., 1983, Monitoring sampling protocol considerations: Ground Water Monitoring Review, v. 3, no. 3, p. 23-29.

North Carolina Department of Human Resources, Division of Health Services, Solid and Hazardous Waste Management Branch, 1984, North Carolina 1983 annual report of hazardous waste generated, stored, treated, or disposed: North Carolina Solid and Hazardous Waste Management Branch Annual Report, 157 p.

Nutter, L.J., and Otton, E.G., 1969, Ground-water occurrence in the Maryland Piedmont: Maryland Geological Survey Report of Investigations no. 10, 56 p.

Peace, R.R., Jr., and Link, D.R., 1971, Geology and ground-water resources of northwestern North Carolina: North Carolina Department of Water and Air Resources Ground-Water Bulletin 19, 135 p.

Pusey, R.D., 1960, Geology and ground water in the Goldsboro area, North Carolina: North Carolina Department of Water Resources Ground-Water Bulletin 2, 72 p.

Ragland, P.C., Hatcher, R.D., Jr., and Whittington, D., 1983, Juxtaposed Mesozoic diabase dike sets from the Carolinas, a preliminary assessment: Geology, v. 11, p. 394-399.

Richardson, C.A., 1982, Ground water in the Piedmont upland of central Maryland: U.S. Geological Survey Water-Supply Paper 2077, 42 p.

Russell, G.S., Russell, C.W., and Farrar, S.S., 1985, Alleghanian deformation and metamorphism in the eastern North Carolina Piedmont: Geological Society of America Bulletin, v. 96, p. 381-387.

Schipf, R.G., 1961, Geology and ground-water resources of the Fayetteville area: North Carolina Department of Water Resources Ground-Water Bulletin 3, 99 p.

Simmons, C.E., and Heath, R.C., 1979, Water-quality characteristics of forested and rural basins in North Carolina: U.S. Geological Survey Water-Supply Paper 2185-B, 33 p.

Sokal, R.R., and Rohlf, F.J., 1969, Biometry: San Francisco, W.H. Freeman, 776 p.

Stewart, J.W., 1962, Water-yielding potential of weathered crystalline rocks at the Georgia Nuclear Laboratory: U.S. Geological Survey Professional Paper 450-B, 2 p.

Sumsion, C.T., and Laney, R.L., 1967, Geology and ground-water resources of the Morganton area: North Carolina Department of Water Resources Ground-Water Bulletin 12, 119 p.

Thornbury, W.D., 1954, Principals of geomorphology: New York, John Wiley and Sons, Inc., p. 135.

U.S. Soil Conservation Service, 1978, General soils map of North Carolina by Watershed: Raleigh, N.C., Soil Conservation Service and the North Carolina Department of Natural Resources and Community Development, 9 sheets.

Wehr, F., and Grover, L., III, 1985, Stratigraphy and tectonics of the Virginia-North Carolina Blue Ridge evolution of a late Proterozoic-early Paleozoic hinge line: Geological Society of America Bulletin, v. 96, p. 285-295.

A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

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CATENA

A classification of natural rivers

David L. Rosgen

Wildland Hydrology, 157649 U. S. Highway 160, Pagosa Springs, CO 81147

Abstract

A classification system for natural rivers is presented in which a morphological arrangement of stream characteristics is organized into relatively homogeneous stream types. This paper describes morphologically similar stream reaches that are divided into 7 major stream type categories that differ in entrenchment, gradient, width/depth ratio, and sinuosity in various landforms. Within each major category are six additional types delineated by dominate channel materials from bedrock to silt/clay along a continuum of gradient ranges. Recent stream type data used to further define classification interrelationships were derived from 450 rivers throughout the U.S, Canada, and New Zealand. Data used in the development of this classification involved a great diversity of hydro-physiographic/geomorphic provinces from small to large rivers and in catchments from headwater streams in the mountains to the coastal plains. A stream hierarchical inventory system is presented which utilizes the stream classification system. Examples for use of this stream classification system for engineering, fish habitat enhancement, restoration and water resource management applications are presented. Specific examples of these applications include hydraulic geometry relations, sediment supply/availability, fish habitat structure evaluation, flow resistance, critical shear stress estimates, shear stress/velocity relations, streambank erodibility potential, management interpretations, sequences of morphological evolution, and river restoration principles.

1. General statement

It has long been a goal of individuals working with rivers to define and understand the processes that influence the pattern and character of river systems. The differences in river systems, as well as their similarities under diverse settings, pose a real challenge for study. One axiom associated with rivers is that what initially appears complex is even more so upon further investigation. Underlying these complexities is an assortment of interrelated variables that determines the dimension, pattern, and profile of the present-day river. The resulting physical appearance and character of the river is a product of adjustment of its boundaries to the current streamflow and sediment regime.

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River form and fluvial process evolved simultaneously and operate through mutual adjustments toward self-stabilization. Obviously, a classification scheme risks over-simplification of a very complex system. While this may appear presumptuous, the effort to categorize river systems by channel morphology is justified in order to achieve, to some extent, the following objectives:

1. Predict a river's behavior from its appearance;
2. Develop specific hydraulic and sediment relations for a given morphological channel type and state;
3. Provide a mechanism to extrapolate site-specific data collected on a given stream reach to those of similar character;
4. Provide a consistent and reproducible frame of reference of communication for those working with river systems in a variety of professional disciplines.

2. Stream classification review

A definition of classification was offered by Platts (1980) where "classification in the strictest sense means ordering or arranging objects into groups or sets on the basis of their similarities or relationships." The effort to classify streams is not new. Davis (1899) first divided streams into three classes based on relative stage of adjustment: youthful, mature, and old age. Additional river classification systems based on qualitative and descriptive delineations were subsequently developed by Melton (1936) and Matthes (1956).

Straight, meandering, and braided patterns were described by Leopold and Wolman (1957). Lane (1957) developed quantitative slope-discharge relationships for braided, intermediate, and meandering streams. A classification based on descriptive and interpretive characteristics was developed by Schumm (1963) where delineation was partly based on channel stability (stable, eroding, or depositing) and mode of sediment transport (mixed load, suspended load, and bedload).

A descriptive classification was also developed by Culbertson et al. (1967) that utilized depositional features, vegetation, braiding patterns, sinuosity, meander scrolls, bank heights, levee formations, and floodplain types. Thornbury (1969) developed a system based on valley types. Patterns were described as antecedent, superposed, consequent, and subsequent. The delineative criteria of these early classification systems required qualitative geomorphic interpretations creating delineative inconsistencies. Khan (1971) developed a quantitative classification for sand-bed streams based on sinuosity, slope, and channel pattern.

To cover a wider range of stream morphologies, a descriptive classification scheme was developed for and applied on Canadian Rivers by Kellerhals et al. (1972, 1976), Galay et al. (1973), and Mollard (1973). The work of these Canadian researchers provides excellent description and interpretation of fluvial features. This scheme has utility both for aerial photo delineation and for describing gradual transitions between classical river types. and to date offers the most detailed and complete list of channel and valley features. The large number of possible interpretative delineations, however, makes this scheme quite complex for general planning objectives.

An attempt to classify rivers in the great plains region using sediment transport, channel stability, and measured channel dimensions was developed by Schumm (1977). Classifying stream systems on the basis of stability is often difficult because of the qualitative criteria can vary widely among observers leading to inconsistencies in the classification. Similarly, data on ratio of bedload to total sediment load as needed in this classification, while useful, often is not readily available to those who need to classify streams.

Brice and Blodgett (1978) described four channel types of: braided, braided point-bar, wide-bend point-bar, and equi-width point-bar. A descriptive inventory of alluvial river channels is well documented by Church and Rood (1983). This data set can be very useful for many purposes including the grouping of rivers based on similar morphological characteristics. Nanson and Croke (1992) presented a classification of flood plains that involved particle size, morphology of channels, and bank materials. This classification has some of the same criteria of channel type as presented in this paper, but is restricted to flood plains. Pickup (1984) describes the relation of sediment source and relative amounts of sediment to various aspects of river type, but is not a classification of channels. Recent documentation by Selby (1985) showed a relationship between the form and gradient of alluvial channels and the type, supply and dominant textures (particle sizes) of sediments. This relationship utilizes the Schumm (1977) classification in that an increase in the ratio of bed material load to total sediment load with a corresponding increase in channel gradient leads to a decrease in stability causing channel patterns to shift from a meandering to braided channel form. In his classification, Selby (1985) treats anastomosed and braided channel patterns similarly. However, the anastomosed rivers are not similar to braided rivers in slope, adjustment processes, stability, ratio of bed material to total load or width/depth ratios as shown by (Smith and Smith, 1980).

Typically, theoretically derived schemes, often do not match observations. To be useful for extrapolation purposes, restoration designs, and prediction, classification schemes should generally represent the physical characteristics of the river. With certain limitations, most of these classification and/or inventory systems met the objectives of their design. However, the requirement for more detailed, reproducible, quantitative applications at various levels of inventory over wide hydro-physiographic provinces has led to further development of classification schemes.

2. Stream classification concepts

The morphology of the present day channel is governed by the laws of physics through observable stream channel features and related fluvial processes. Stream pattern morphology is directly influenced by eight major variables including channel width, depth, velocity, discharge, channel slope, roughness of channel materials, sediment load, and sediment size (Leopold et al., 1964). A change in any one of these variables sets up a series of channel adjustments which lead to a change in

Table 1
Hierarchy of river inventories

Level of detail	Inventory description	Information required	Objectives
I	Broad morphological characterization	Landform, lithology, soils, climate, depositional history, basin relief, valley morphology, river profile morphology, general river pattern	To describe generalized fluvial features using remote sensing and existing inventories of geology, landform evolution, valley morphology, depositional history and associated river slopes, relief and patterns utilized for generalized categories of major stream types and associated interpretations.
II	Morphological description (stream types)	Channel patterns, entrenchment ratio, width/depth ratio, sinuosity, channel material, slope	This level delineates homogeneous stream types that describe specific slopes, channel materials, dimensions and patterns from "reference reach" measurements. Provides a more detailed level of interpretation and extrapolation than Level I.
III	Stream "state" or condition	Riparian vegetation, depositional patterns, meander patterns, confinement features, fish habitat indices, flow regime, river size category, debris occurrence, channel stability index, bank erodibility	The "state" of streams further describes existing conditions that influence the response of channels to imposed change and provide specific information for prediction methodologies (such as stream bank erosion calculations, etc.). Provides for very detailed descriptions and associated prediction/interpretation.
IV	Verification	Involves direct measurements/observations of sediment transport, bank erosion rates, aggradation/degradation processes, hydraulic geometry, biological data such as fish biomass, aquatic insects, riparian vegetation evaluations, etc.	Provides reach-specific information on channel processes. Used to evaluate prediction methodologies; to provide sediment, hydraulic and biological information related to specific stream types; and to evaluate effectiveness of mitigation and impact assessments for activities by stream type.

the others, resulting in channel pattern alteration. Because stream morphology is the product of this integrative process, the variables that are measurable should be used as stream classification criteria.

The directly measurable variables that appear from both theory and experience to govern channel morphology have been included in the present classification procedure. These "delineative criteria" interact with one another to produce a stream's dominant features.

The present classification system has evolved from field observation of hundreds of rivers of various sizes in all the climatic regions of North America, experience in stream restoration, extensive teaching, and practical applications of the classification system by many hydrologists, geomorphologists, fisheries experts, and plant ecologists. Initial efforts to develop the classification procedure began in 1973, and a preliminary version was presented to the scientific community (Rosgen, 1985). The present paper includes notational changes from the earlier publication.

3. Stream classification system

The classification of rivers is an organization of data on stream features into discreet combinations. The level of classification should be commensurate with the initial planning level objective. Because these objectives vary, a hierarchy of stream classification and inventories is desirable because it allows an organization of stream inventory data into levels of resolution from very broad morphological characterizations to discreet, measured, reach-specific descriptions. Each level should include appropriate interpretations that match the inventory specificity. Further, general descriptions and characteristics of stream types should be able to be divided into even more specific levels. The more specific levels should provide indications of stream potential, stability, existing "states", etc., to respond to higher resolution data and interpretations when planning needs change. A proposed stream inventory system, including an integrated stream classification, is shown in Table 1.

Current river "state" and influences on the modern channel by vegetation, flow regime, debris, depositional features, meander patterns, valley and channel confinement, streambank erodibility, channel stability, etc., comprise additional parameters that are considered critical to evaluate by stream type at a more detailed inventory level (Level III). However, for the sake of brevity and clarity, this paper will focus on the first two levels, the broad geomorphic characterization (Level I) and the morphological description (Level II) which incorporates the general character of channel form and related interpretations. Portions of the data used for detailed assessment levels are contained in the sub-type section of the earlier classification paper (Rosgen, 1985).

4.1. Geomorphic characterization (level I)

The purpose of delineation at this level is to provide a broad characterization that integrates the landform and fluvial features of valley morphology with channel relief,

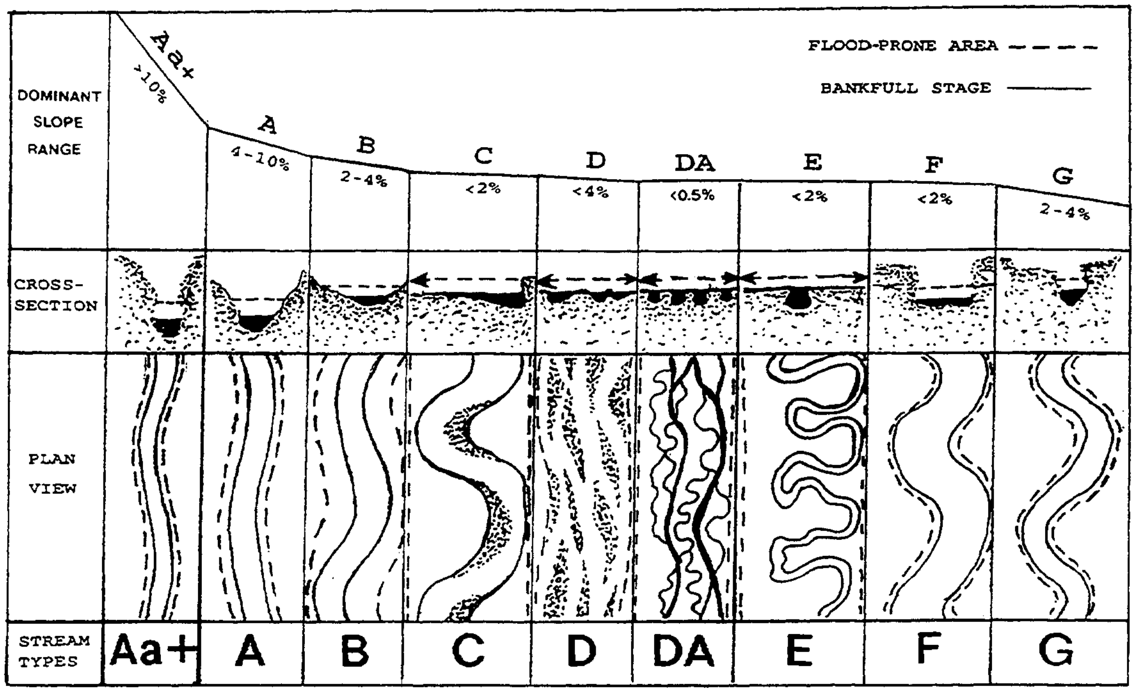


Fig. 1. Longitudinal, cross-sectional and plan views of major stream types.

pattern, shape, and dimension. Level I combines the influences of climate, depositional history, and life zones (desert shrub, alpine, etc.) on channel morphology.

The presence, description, and dimensions of floodplains, terraces, fans, deltas and outwash plains are a few examples of valley features identified. Depositional and erosional history overlay channel patterns at this level. Generalized categories of "stream types" initially can be delineated using broad descriptions of longitudinal profiles, valley and channel cross-sections, and plan-view patterns (see Fig. 1 and Table 2).

Longitudinal profiles

The longitudinal profile, which can be inferred from topographic maps, serves as the basis for breaking the stream reaches into slope categories that reflect profile morphology. For example, the stream types of Aa+ (Fig. 1) are very steep, (greater than 10%), with frequently spaced, vertical drop/scour-pool bed features. They tend to be high debris transport streams, waterfalls, etc. Type A streams are steep (4–10% slope), with steep, cascading, step/pool bed features. Type B streams are riffle-dominated types with "rapids" and infrequently spaced scour-pools at bends or areas of constriction. The C, DA, E and F stream types are gentle-gradient riffle/pool types. Type G streams are "gullies" that typically are step/pool channels. Finally, the D type streams are braided channels of convergence/divergence process that lead to localized, frequently spaced scour/depositional bed forms.

Bed features are consistently found to be related to channel slope. Grant et al. (1990) described bed features of pools, riffles, rapids, cascades, and steps as a function

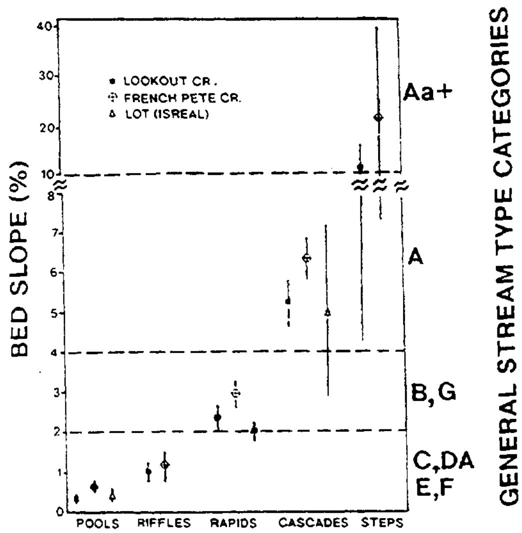


Fig. 2. Relationship of bed slope to bed forms for various stream types (from Grant et al., 1990).

of bed-slope gradient. Using their bed form descriptions, the above described stream types were plotted against the corresponding slope ranges reported by Grant et al. (1990). "Groupings", (Fig. 2), were apparent for riffle/pool stream types (C, E, and F) at less than 2%, rapids at 2–4% in "B" and "G", cascades in slopes 4–10% in type A streams, and steps for slopes 4–40% in types A and Aa+ streams. Because gradient and bed-feature relationships are integral to the delineation of stream type categories, "stream types" are more than just "arbitrary units". Bed morphology can be predicted from stream type by using bed-slope indices.

Cross-section morphology

The shape of the cross-section that would indicate a narrow and deep stream as opposed to a wide and shallow one can be inferred at this broad level. The manner in which the channel is incised in its valley can also be deduced at this level as well as information concerning floodplains, terraces, colluvial slopes, structural control features, confinement (lateral containment), entrenchment (vertical containment), and valley vs. channel dimension. For example, the type A streams are narrow, deep, confined, and, entrenched. The width of the channel and valley are similar. This contrasts with type C streams, where the channel is wider and shallower with a well-developed floodplain and a very broad valley. Type E streams have a narrow and deep channel (low width/depth ratio) but have a very wide and well developed floodplain. Type F streams have wide and shallow channels, but are an entrenched meandering channel type with little to no developed floodplain. Type G channels have low width/depth ratio channels similar to type E streams except they are well entrenched (no floodplain), are steeper, and less sinuous than type E streams (see Fig. 1).

Plan view morphology

The pattern of the river is classed as relatively straight (A stream types), low sinuosity (B stream types), meandering (C stream types), and tortuously meandering

Table 2
Summary of delineative criteria for broad-level classification

Stream type	General description	Entrenchment ratio	W/D ratio	Sinuosity	Slope	Landform/soils/features
Aa+	Very steep, deeply entrenched, debris transport streams.	< 1.4	< 12	1.0 to 1.1	> 0.10	Very high relief. Erosional, bedrock or depositional features; debris flow potential. Deeply entrenched streams. Vertical steps with/deep scour pools; waterfalls.
A	Steep, entrenched, cascading, step/pool streams. High energy/debris transport associated with depositional soils. Very stable if bedrock or boulder dominated channel.	< 1.4	< 12	1.0 to 1.2	0.04 to 0.10	High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools in associated step-pool bed morphology.
B	Moderately entrenched, moderate gradient, riffle dominated channel, with infrequently spaced pools. Very stable plan and profile. Stable banks.	1.4 to 2.2	> 12	> 1.2	0.02 to 0.039	Moderate relief, colluvial deposition and/or residual soils. Moderate entrenchment and W/D ratio. Narrow, gently sloping valleys. Rapids predominate with occasional pools.
C	Low gradient, meandering, point-bar, riffle/pool, alluvial channels with broad, well defined floodplains	> 2.2	> 12	> 1.4	< 0.02	Broad valleys with terraces, in association with floodplains, alluvial soils. Slightly entrenched with well-defined meandering channel. Riffle-pool bed morphology.

D	Braided channel with longitudinal and transverse bars. Very wide channel with eroding banks.	n/a	> 40	n/a	< 0.04	Broad valleys with alluvial and colluvial fans. Glacial debris and depositional features. Active lateral adjustment, with abundance of sediment supply.
DA	Anastomosing (multiple channels) narrow and deep with expansive well vegetated floodplain and associated wetlands. Very gentle relief with highly variable sinuosities. Stable streambanks.	> 4.0	< 40	variable	< 0.005	Broad, low-gradient valleys with fine alluvium and/or lacustrine soils. Anastomosed (multiple channel) geologic control creating fine deposition with well-vegetated bars that are laterally stable with broad wetland floodplains.
E	Low gradient, meandering riffle/pool stream with low width/depth ratio and little deposition. Very efficient and stable. High meander width ratio.	> 2.2	< 12	> 1.5	< 0.02	Broad valley/meadows. Alluvial materials with floodplain. Highly sinuous with stable, well vegetated banks. Riffle-pool morphology with very low width/depth ratio.
F	Entrenched meandering riffle/pool channel on low gradients with high width/depth ratio.	< 1.4	> 12	> 1.4	< 0.02	Entrenched in highly weathered material. Gentle gradients, with a high *W/D* ratio. Meandering, laterally unstable with high bank-erosion rates. Riffle-pool morphology.
G	Entrenched "gulley" step/pool and low width/depth ratio on moderate gradients.	< 1.4	< 12	> 1.2	0.02 to 0.039	Gulley, step-pool morphology with moderate slopes and low *W/D* ratio. Narrow valleys, or deeply incised in alluvial or colluvial materials; i.e., fans or deltas. Unstable, with grade control problems and high bank erosion rates.

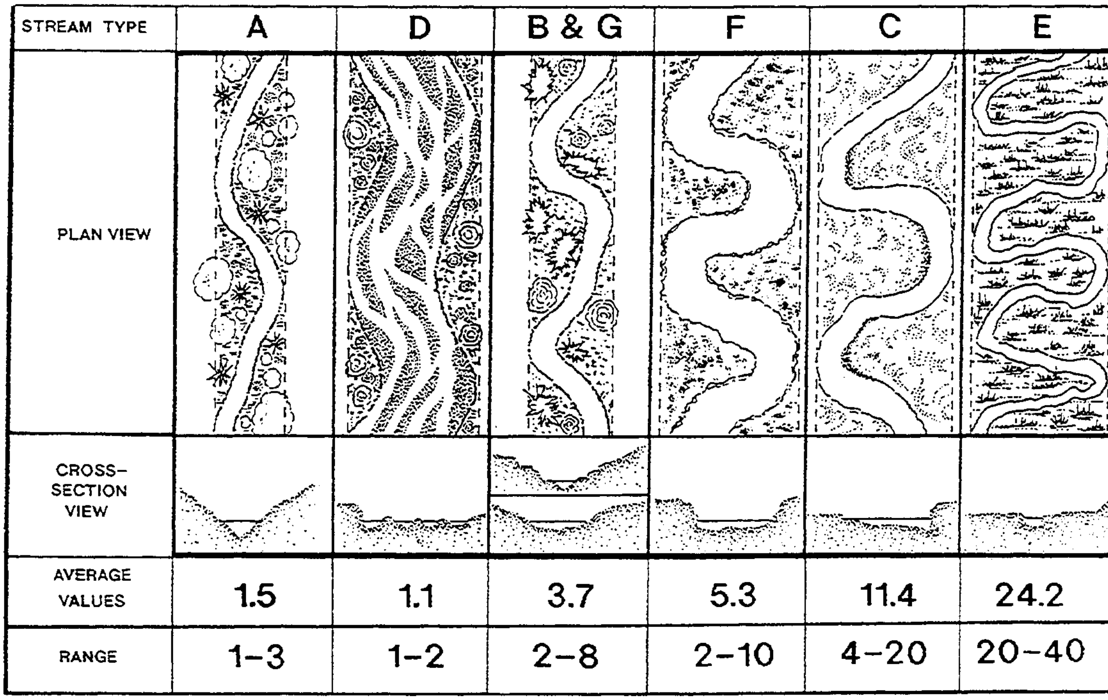


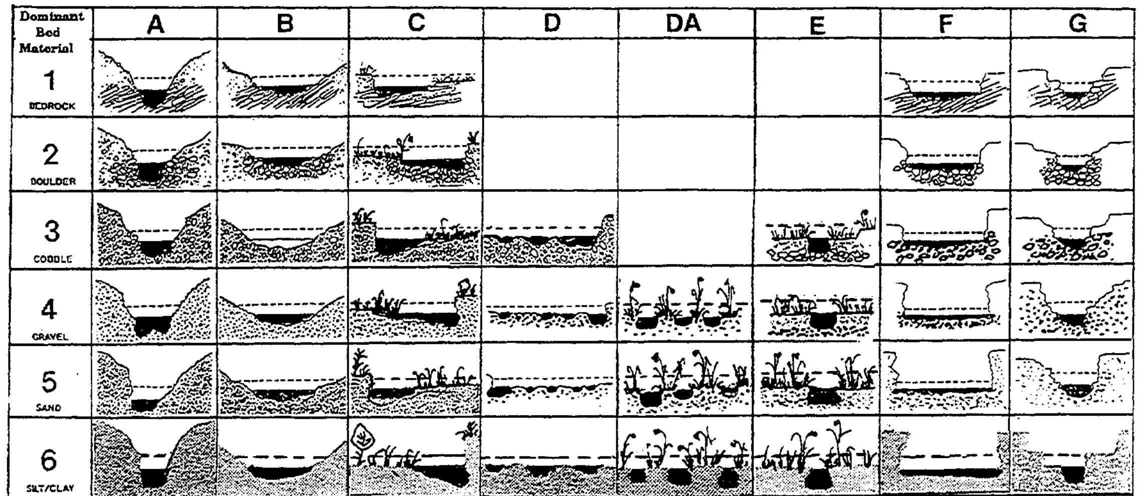
Fig. 3. Meander width ratio (belt width/bankfull width) by stream type categories.

(E stream types). Complex stream patterns are found in the multiple channel, braided (D) and anastomosed (DA) stream types. Sinuosity can be calculated from aerial photographs and often, like slope, serves as a good initial delineation of major stream types. These river patterns have integrated many processes in deriving their present form and thus, provide interpretations of their associated morphology.

Even at this broad level of delineation, consistency of dimension and associated pattern can be observed by broad stream types. Meander width ratio (belt width/ bankfull surface width) was calculated by general categories of stream types for a wide variety of rivers. Measured mean values and ranges by stream type are shown in Fig. 3. Early work by Inglis (1942) and Lane (1957) discussed meander width ratio but the values were so divergent among rivers that the ratio appeared to have little value. When stratified by general stream types, however, the variability appears to be explained by the similarities of the morphological character of the various stream types. This has value not only for classification and broad-level delineations, but also for describing the most probable state of channel pattern in stream restoration work.

Discussion

Interpretations of mode of adjustment — either vertical, lateral, or both — and energy distribution can often be inferred in these broad types. Many variables that are not discrete delineative variables integrate at this level to produce an observable morphology. A good example of this is the influence of a deep sod-root mass on type E streams that produces a low width/depth ratio, low meander length, low radius of curvature, and a high meander width ratio. Vegetation is not singled out for mapping at this level, but is implicit in the resulting morphology. If this vegetation is changed, the width/depth ratio and other features will result in adjustments to the



	A	B	C	D	DA	E	F	G
ENTRH.	<1.4	1.4–2.2	>2.2	N/A	>2.2	>2.2	<1.4	<1.4
SIN.	<1.2	>1.2	>1.4	<1.1	1.1-1.6	>1.5	>1.4	>1.2
W/D	<12	>12	>12	>40	<40	<12	>12	<12
SLOPE	.04–.099	.02–.039	<.02	<.02	<.005	<.02	<.02	.02–.039

Fig. 4. Illustrative guide showing cross-sectional configuration, composition and delineative criteria of major stream types.

type C stream morphology. Detailed vegetative information, however, is obtained at the channel state level (Level III, Table 1).

Delineating broad stream types provides an initial sorting within large basins and allows a general level of interpretation. This leads to organization and prioritization for the next more detailed level of stream classification.

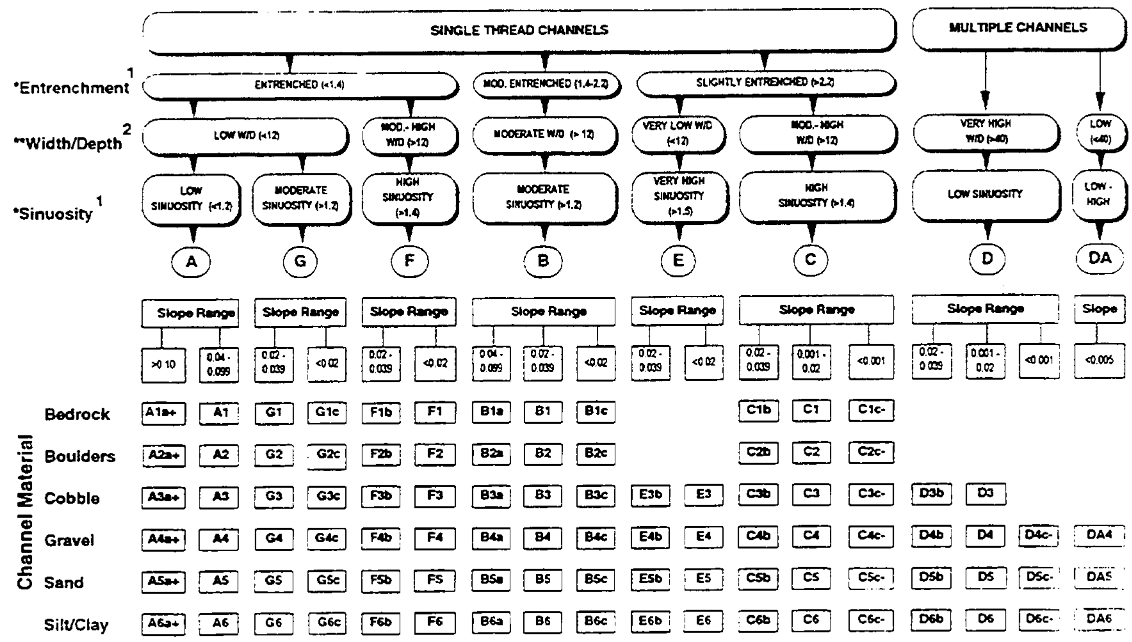
4.2. The morphological description (level II)

General description

This classification scheme is delineated initially into the major, broad, stream categories of A–G as shown in Fig. 1 and Table 2. The stream types are then broken into discreet slope ranges and dominant channel-material particle sizes. The stream types are given numbers related to the median particle size diameter of channel materials such that 1 is bedrock, 2 is boulder, 3 is cobble, 4 is gravel, 5 is sand, and 6 is silt/clay. This initially produces 42 major stream types as shown in (Fig. 4).

A range of values for each criterion is given in the key to classification for 42 major stream types (Fig. 5). The range of values chosen to represent each delineative criterion is based on data from a large assortment of streams throughout the United States, Canada and New Zealand. A recent data set of 450 rivers was statistically used to refine and test previous ranges of delineative criteria as described in the author's earlier publication (Rosgen, 1985).

Histograms were drawn of the distribution of values of each delineative criterion for each channel type. From the histograms of 5 criteria for 42 major stream types, the mean and "frequent range" of values were recorded. The most frequently observed values seemed to group into a recognizable "river form" or morphology. When values



[1] Values can vary by ± 0.2 units as a function of the continuum of physical variables within stream reaches.
[2] Values can vary by ± 2.0 units as a function of the continuum of physical variables within stream reaches.

Fig. 5. Key to classification of natural rivers.

were outside of the range of the "most frequently observed" condition, a distinctly different morphology was identified. As a result, the delineation of unique stream types representing a range of values amongst several variables were established. These variables and their ranges make up the current morphological description of stream types as shown in Figs. 4 and 5.

The classification can be applied to ephemeral as well as perennial channels with little modification. Bankfull stage can be identified in most perennial channels through observable field indicators. Although, these bankfull stage indicators, are often more elusive in ephemeral channels.

The morphological variables can and do change even in short distances along a river channel, due to such influences of change as geology and tributaries. Therefore, the morphological description level incorporates field measurements from selected reaches, so that the stream channel types used here apply only to individual reaches of channel. Data from individual reaches are not averaged over entire basins to describe stream systems. A category may apply to a reach only a few tens of meters or may be applicable to a reach of several kilometers.

Data is obtained from field measurements of representative or "reference reaches." The resultant stream type as delineated can then be extrapolated to other reaches where detailed data is not readily available. In similar valley and lithological types, stream types can often be delineated using these reference reaches through the use of aerial photos, topographic maps, etc.

Continuum concept

When the variables which make up the range of values within a stream type change, there is more often than not, a change in stream type. The ranges in slope, width/depth ratio, entrenchment ratio and sinuosity shown in Fig. 4 span the most frequently observed values. Exceptions occur infrequently, where values of one variable may be outside of the range for a given stream type.

This level recognizes and describes a continuum of river morphology within and between stream types. The continuum is applied where values outside the normal range are encountered but do not warrant a unique stream type. Often the general appearance of the stream and the associated dimensions and patterns of the stream do not change with a minor value change in one of the delineative criteria. For example, slope values as shown in Fig. 5, using the continuum concept, are not "lumped", but rather are sorted by sub-categories of: a+ (steeper than 0.10), a (0.04–0.10), b (0.02–0.039), c (less than 0.02) and c- (less than 0.001).

The application of this concept allows an initial classification of a C4 stream type (a gravel bed, sinuous, high width/depth ratio channel with a well-developed floodplain. If the slope of this stream was less than 0.001, then the stream type would be a C4c−.

Rivers do not always change instantaneously, under a geomorphic exceedance or "threshold". Rather, they undergo a series of channel adjustments over time to accommodate change in the "driving" variables. Their dimensions, profile and pattern reflects on these adjustment processes which are presently responsible for the form of the river. The rate and direction of channel adjustment is a function of the nature and magnitude of the change and the stream type involved. Some streams change very rapidly, while others are very slow in their response.

Delineative criteria

At this level of inventory each reach is characterized by field measurements and validation of the classification. The delineation criteria and ranges for various stream types are shown in Fig. 5. This classification key also represents the sequential process for classification. The classification process starts at the top of the chart (single or multiple thread channels), and proceeds downward through channel materials and slope ranges.

Entrenchment

An important element of the delineation is the interrelationship of the river to its valley and/or landform features. This interrelationship determines whether the river is deeply incised or entrenched in the valley floor or in the deposit feature. Entrenchment is defined as the vertical containment of river and the degree to which it is incised in the valley floor (Kellerhals et al., 1972). This makes an important distinction of whether the flat adjacent to the channel is a frequent floodplain, a terrace (abandoned floodplain) or is outside of a flood-prone area. A quantitative expression of this feature, "entrenchment ratio" was developed by the author so that various mappers could obtain consistent values. The entrenchment ratio is the ratio of the width of the flood-prone area to the bankfull surface width of the channel. The flood-prone area is defined as the width measured at an elevation which is determined at twice the maximum bankfull depth. Field observation shows this elevation to be a frequent

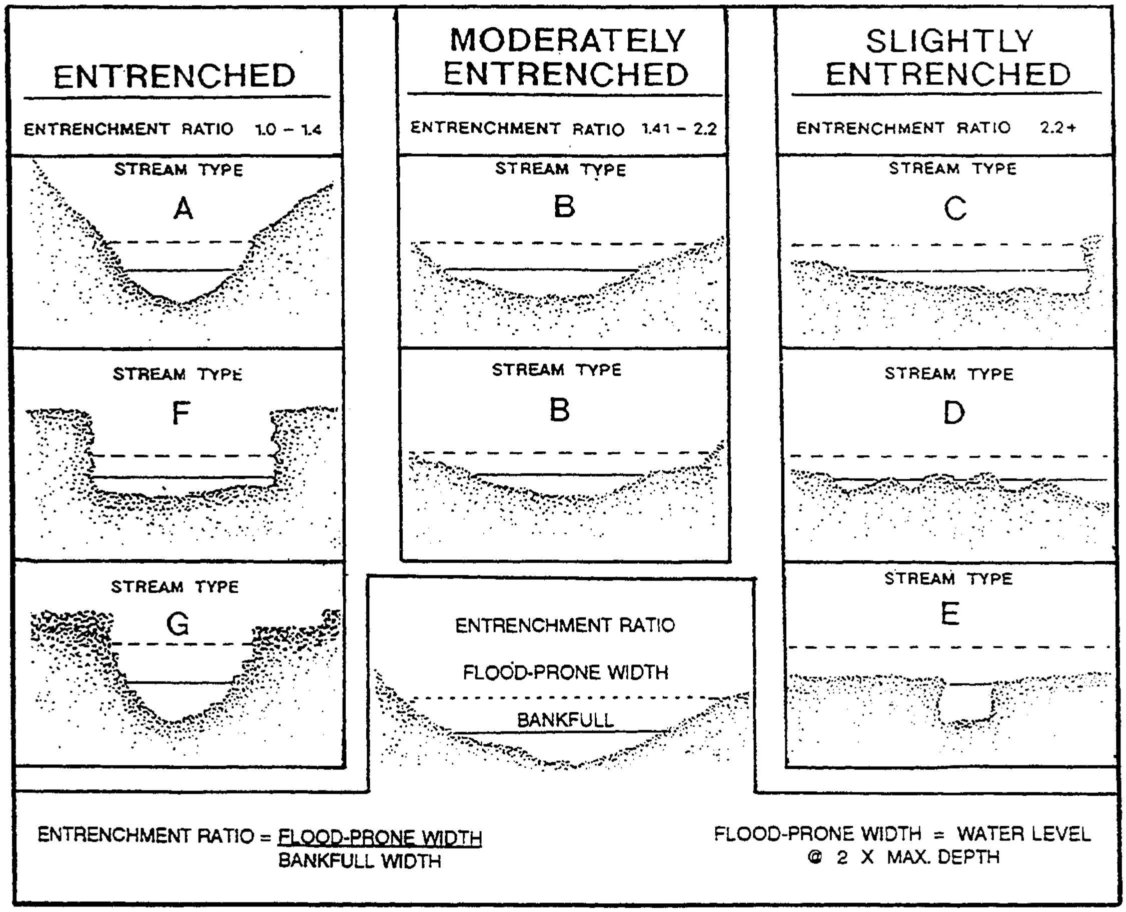


Fig. 6. Examples and calculations of channel entrenchment.

flood (50 year return period) or less, rather than a rare flood elevation. The categories are illustrated in Figs. 4, 5 and 6.

Entrenchment ratios of 1–1.4 represent entrenched streams, 1.41–2.2 represent moderately entrenched streams and ratios greater than 2.2 are slightly entrenched (well-developed floodplain). These categories were empirically derived based on hundreds of streams. As with other criteria, the measured entrenchment ratio value may lie somewhat outside of the classification range. When this occurs, the author applies the continuum concept which allows for a category description where the entrenchment is either greater or less than the most frequently observed value for a given morphology. The continuum allows for a change of \pm 0.2 units where the corresponding delineative criteria still match the range of variables consistent for that type. In this case, all of the other attributes must be considered before assigning a stream type.

Width/depth ratio

The width/depth ratio describes the dimension and shape factor as the ratio of bankfull channel width to bankfull mean depth. Bankfull discharge is defined as the momentary maximum peak flow; one which occurs several days in a year and is often related to the 1.5 year recurrence interval discharge. Specific discussions on the delineation and significance of bankfull discharge are found in Leopold et al. (1964), Dunne and Leopold (1978), and Andrews (1980). Hydraulic geometry and sediment transport relations rely heavily on the frequency and magnitude of bankfull discharge.

Osborn and Stypula (1987) utilized width/depth ratio to characterize stream channels for hydraulic relations using channel boundary shear as a function of channel shape.

For this classification, values of low width/depth ratio are those less than 12. Values greater than 12 are moderate or high. Average values and ranges are shown in the stream type summaries. As in the continuum concept, applied to entrenchment ratio, there is an occasion where width/depth ratio values can vary by ±2 units without showing a different morphology. This does not occur very frequently, but the continuum allows for some flexibility to fit the stream type into a "dominant" morphology.

Sinuosity

Sinuosity is the ratio of stream length to valley length. It can also be described as the ratio of valley slope to channel slope. Mapping sinuosity from aerial photos is often possible, and interpretations can often be made of slope, channel materials, and entrenchment once sinuosity is determined. Values of sinuosity appear to be modified by bedrock control, roads, channel confinement, specific vegetative types, etc. Generally speaking, as gradient and particle size decreases, there is a corresponding increase in sinuosity. The continuum as mentioned earlier also applies and adjustments of + or −0.2 can be applied to this delineative criteria. Meander geometry characteristics are directly related to sinuosity following minimum expenditure of energy concepts. Initial studies by Langbein and Leopold (1966) suggested that a sine generated curve describes symmetrical meander paths. From this observation they predicted the radius of curvature of meander bends from meander wavelength and channel sinuosity. In comparing observed versus predicted values of radius of curvature for 79 streams, Williams (1986) found this relation to be highly correlated when applied to an expanded data set. This demonstrates the interrelationship of sinuosity to meander geometry. Based on such relations and the relative ease of determination, sinuosity was selected as one of the delineative criteria for stream classification.

Channel materials

The bed and bank materials of the river is not only critical for sediment transport and hydraulic influences but also modifies the form, plan and profile of the river. Interpretations of biological function and stability also require this information. Often a good working knowledge of the soils associated with various landforms can predict the channel materials at the broad delineation level. Reliable estimates of the soil characteristics for glacial till, glacial outwash, alluvial fans, river terraces, lacustrine and eolian deposits, and residual soils can be derived from mapped lithology.

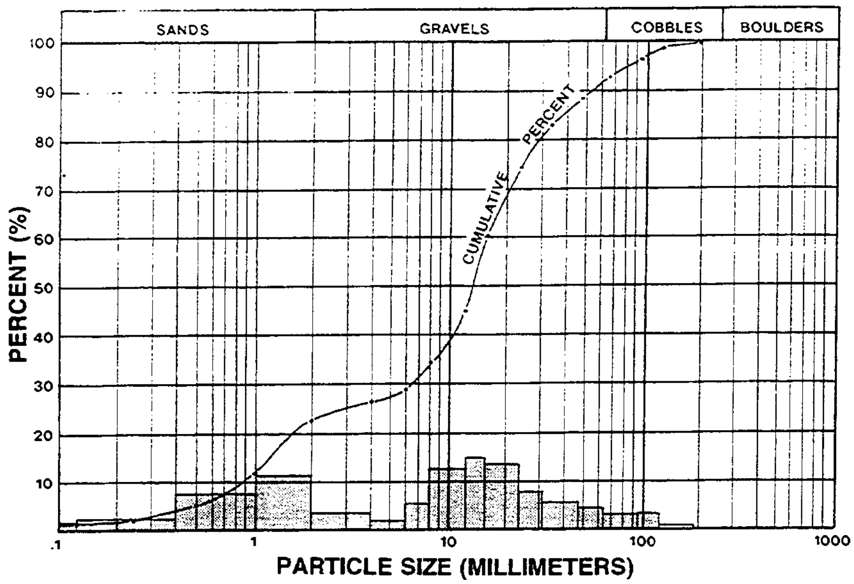


Fig. 7. Channel material sizes showing cumulative and percent distributions.

Field determination of channel materials for this classification system utilizes the "pebble count" method developed by Wolman (1954), with a few modifications to account for bank material and for sand and smaller sizes. This is a determination the frequency distribution of particle sizes that make up the channel. The pebble count data is plotted as cumulative percent and percent of total distribution (Fig. 7). The dominant particle size is identified in the cumulative percent curve as the median size of channel materials or size that 50% of the population is of the same size or finer (D_{50}). The percent distribution shown in Fig. 7 is often used to detect bimodal distributions that may be hidden in cumulative plots. This data is used in biological evaluation, sediment supply assessment, and other interpretative applications.

Slope

Water surface slope is of major importance to the morphological character of the channel and its sediment, hydraulic, and biological function. It is determined by measuring the difference in water surface elevation per unit stream length. Typically, slope is often measured through at least 20 channel widths or two meander wavelengths. As observed with the other delineative variables, slope values less or greater than the most frequently observed ranges can occur. These can occur without a significant change in the other delineative criteria for that stream type. The most frequently observed slope categories and applications of the continuum concept for slope is shown in Fig. 5.

In broad-level delineations, slopes can often be estimated by measuring sinuosity from aerial photos and measuring valley slope from topographic maps (valley slope/sinuosity = channel slope). The basin and associated landform relief can also be used to estimate stream slope ranges, as for example terraces and slopes of alluvial fans.

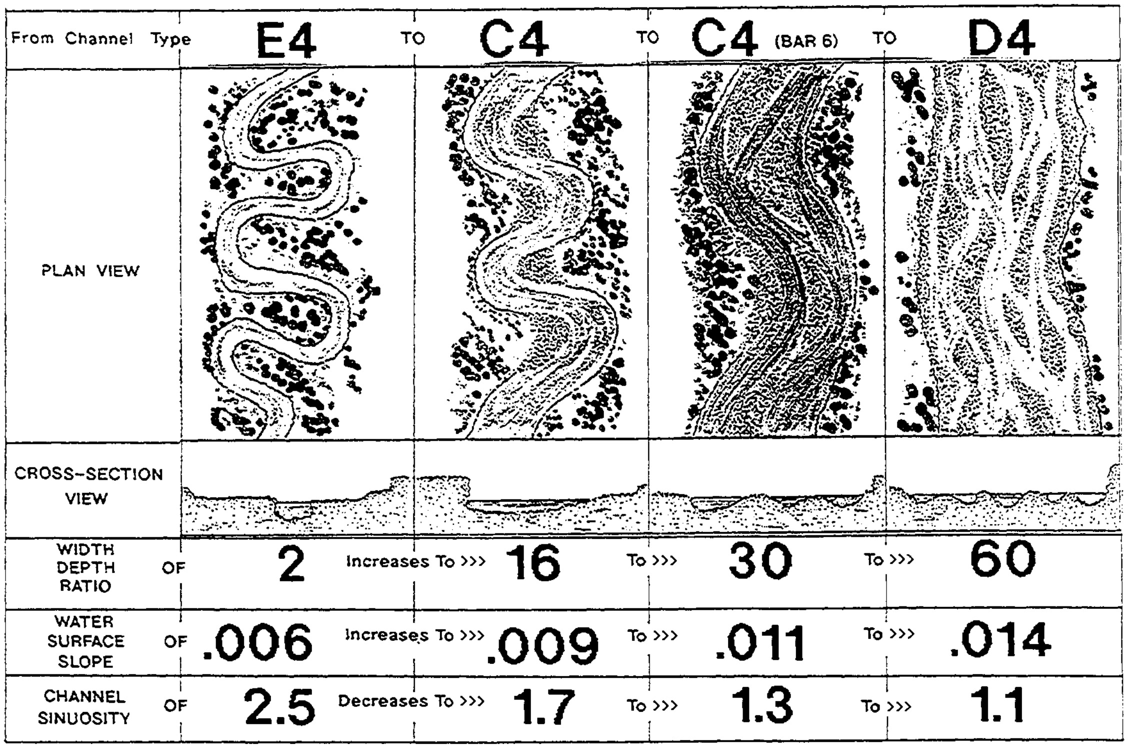


Fig. 8. Progressive stages of channel adjustment due to imposed stream bank instability.

5. Application

Past observations of adjustments of stream systems often provide insight into sensitivity and consequence of change. Stream system changes can be due to flow, sediment, or many of the interrelated variables that have produced the modern channel. If changes produces disequilibrium, similar streams types receiving similar impacts may be expected to respond the same. If the observer knows the stream type of the disturbed reach, and has cross-section, bank erosion, sediment data, riparian vegetation and fisheries data, this information can be used predictively to evaluate the risk and sensitivity to disturbance.

5.1. Evolution of stream types

In reviewing historical aerial photos, observations can be made of progressive stages in channel adjustment. These adjustments occur partially as a result of change in stream-flow magnitude and/or timing, sediment supply and/or size, direct disturbance, and vegetation changes. These observed changes in channel morphology over time can be communicated in terms of stream type changes. For example, due to streambank instability, and a resultant increase in bank erosion rate, the stream increased it's width/depth ratio; decreased sinuosity; increased slope; established a bimodal particle size distribution; increased bar deposition; accelerated bank erosion; and decreased the meander width ratio. These changes can be described more simply

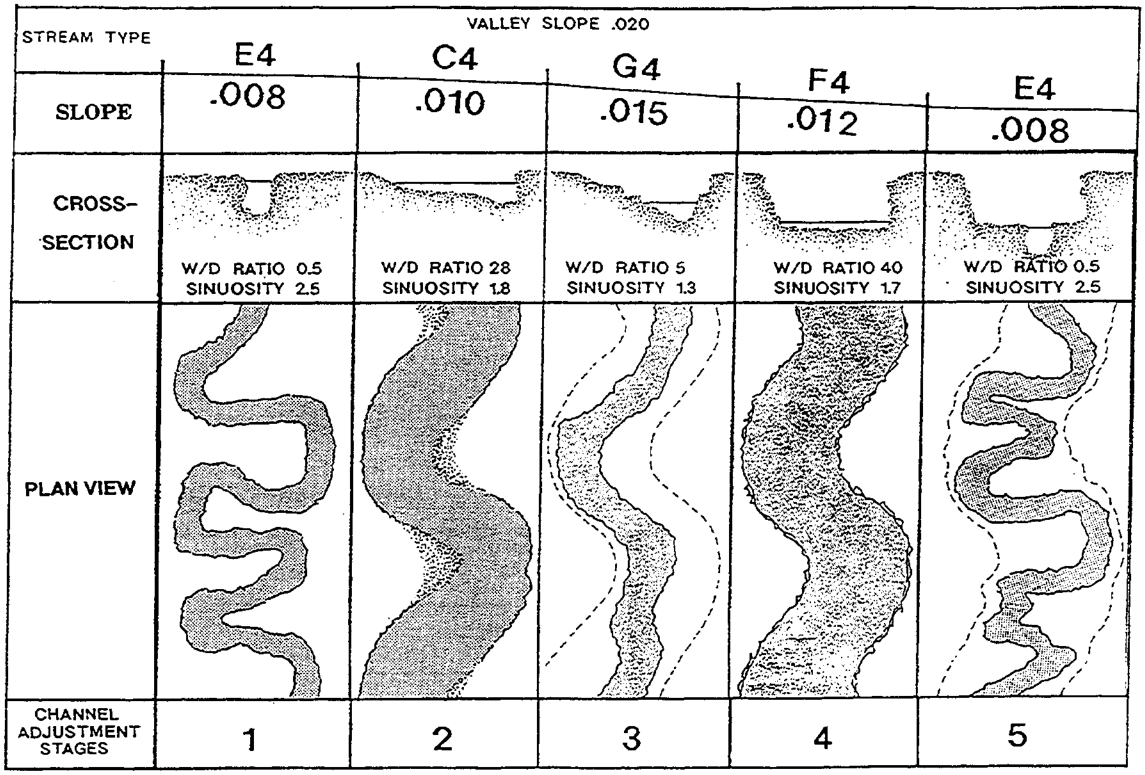


Fig. 9. Evolutionary stages of channel adjustment.

as a series of progressive changes of channel adjustment in stream type from an E4 to C4 to C4 (bar-braided) to D4 (Fig. 8).

Another example of channel adjustment where morphological patterns are changed sufficient to indicate a shift in stream type is shown in Fig. 9. In this scenario, a change in streambank stability led to an increase in width/depth ratio and slope, and a decrease in sinuosity and meander width ratio. As the slope steepened along with a high width/depth ratio, chute cutoffs occurred across large point bars creating a gulley. The stream abandoned its floodplain, decreased the width/depth ratio, steepened the slope and decreased sinuosity. This resulted in a change in base level as all of the tributaries draining into this stream were over-steepened. Sediment from both channel degradation and bank erosion was increased. As the banks continued to erode, the width/depth ratio and sinuosity both increased with a corresponding decrease in slope. The channel was still deeply entrenched, but eventually started to develop a floodplain at a new elevation. This stream eventually evolved under a changed sediment and flow regime into a sinuous, low gradient, low width/depth ratio channel with a well developed floodplain which matched the original morphology, except now exists at a lower elevation in the valley. This case is shown more simply in Fig. 9 as a shift from an E4 stream type to C4 to G4 to F4 and back to an E4 type.

These changes have been well documented throughout western North America due to various reasons including climate change and adverse watershed impacts. The knowledge provided by observing these historical adjustments and the understanding of the tendency of rivers to regain their own stability can assist those restoring disturbed river systems. Often the works of man try to "restore" streams back to a state that does not match the dimension, pattern and slope of the natural, stable form. As stream types change, there are a large number of interpretations associated with these "morphological shifts". Stream types can imply much more than what is initially described in it's alphanumeric title.

5.2. Fish habitat

When physical structures are installed in channels to improve the fish habitat, the adjustment processes that occur sometimes create more damage than habitat. For example, Trail Creek in southeast Colorado, a C4 stream type, had a gabion check dam installed at 80% of the bankfull stage to create a plunge pool for fish. The results were; decreased upstream gradient; width/depth ratio increase; decreased mean bed particle diameter; and decreased competence of the stream to move its own sediment. The longitudinal profile of the river changed creating headward aggradation. With a decrease in slope, there was a corresponding increase in sinuosity that resulted in accelerated lateral channel migration and increased bank erosion. Subsequently, the stream abandoned the original channel and created a "headcut gulley" with a gradient that was twice the valley slope. This converted the C4 stream type to a G4 type in a period of approximately two years. The "new" stream type has abandoned its floodplain, is rejuvenating tributaries headward and creating excess sediment from stream degradation and bank erosion. This disequilibrium caused by the check dam is long-term and has deteriorated the habitat that the structure was initially designed to improve. Unfortunately, structures like this continue to be installed by well-meaning individuals without a clear understanding of channel adjustment processes.

To prevent similar problems and to assist biologists in the selection and evaluation of commonly used in-channel structures, guidelines by stream type were developed (Rosgen and Fittante, 1986). In the development of these guidelines hundreds of fish habitat improvement structures were evaluated for effectiveness and channel response. A stream classification was made for each reach containing a structure. From this data, the authors rated various structures from "excellent" to "poor" for an extensive range of stream types. These guidelines provide "warning flags" of potential adverse adjustments to the river so that technical assistance may be obtained. In this manner, structures may be better designed to not only meet their objectives, but help maintain the stability and function of the river. Fisheries habitat surveys presently integrate this stream classification system (USDA, 1989). The objective for this integration is to determine the potential of the stream reach, current state, and a variety of hydraulic and sediment relations that can be utilized for habitat and biological interpretations.

5.3. Flow resistance

Application of the Manning's equation and the selection of a roughness coefficient N value to predict mean velocity is a common methodology used by engineers and

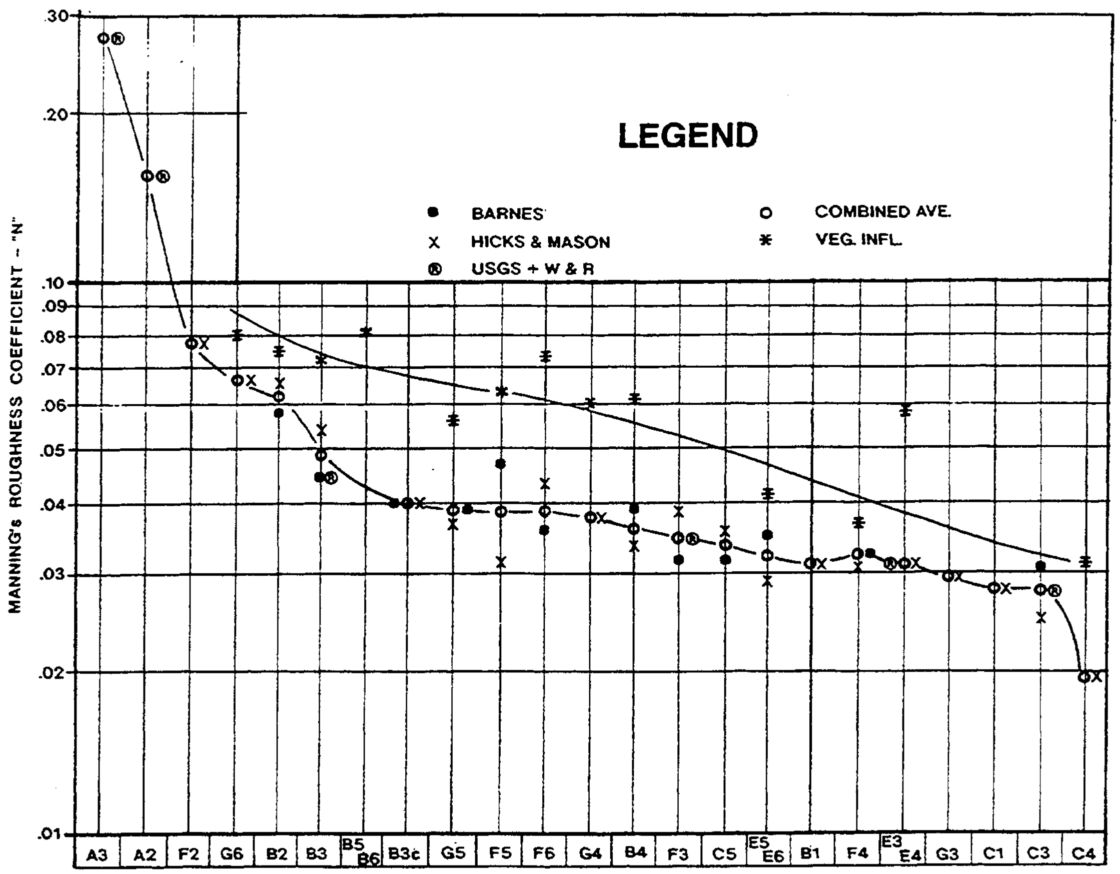


Fig. 10. Bankfull stage roughness coefficients ("N" values) by stream type for 140 streams from the United States and New Zealand.

hydrologists. The lack of consistent criteria for selection of the correct N values, however, creates great variability in the subsequent estimate of flow velocity. Barnes (1967), and Hicks and Mason (1991) produced photographs and a variety of stream data which was primarily a visual comparison approach for the selection of roughness coefficients. However, using these books for a visual estimate of roughness, actually involves looking at various stream types. The author classified each of the 128 streams described in both publications, noted the occurrence of vegetation influence, and plotted the bankfull stage N values by stream type (Fig. 10). The remarkable similarity of N values by stream type for two data bases from two countries revealed another application for estimating a bankfull stage roughness coefficient using stream classification. This may help in developing more consistent roughness estimates and provide an approach for improving stream discharge estimates by using the manning's equation. Roughness values increase as stage decreases, thus, the N values shown in Fig. 10 are for bankfull conditions only. The Hicks and Mason (1991) work is exemplary in terms of evaluating and displaying variations in N with changes in stream discharge. These variations can potentially be developed as a rate of change index for changes in stage by stream type. The influence of vegetation is shown to cause a marked adjustment in values by stream type. As would be expected, this relationship suggests the vegetation influence on roughness is diminished as channel gradient and bed material particle size increase. Stream types essentially integrate those variables affecting roughness, such as; gradient, shape and form resistance, particle size, and relative depth of bankfull discharge to the diameter of the larger particles in the channel. Rather than looking at discrete predictors, stream types integrate the many variables that influence resistance. Another recommended application to roughness estimation is to develop specific relations of roughness and associated velocity as recently developed for "mountain streams" by Jarrett (1984, 1990). In this method, equations were stratified for steeper slopes and cobble/boulder channel materials, using hydraulic radius and slope in the equations. Jarrett's results were valuable in that they produced values much different from most published equations. This work could be even more effective if the stream data were further stratified into stream types and size of stream. In this manner, much like the Manning's N values, equations could be developed using the integrating effects of stream types and thereby advance the state of the art of applications.

5.4. Hydraulic geometry relations

The original work of Leopold and Maddock (1953) made a significant contribution to the applied science in the development of hydraulic geometry relations. The variables of; depth, velocity, and cross-sectional area were quantitatively related to discharge as simple power functions for a given river cross-section. Their findings prompted numerous research efforts over the years. To refine average values of exponents, and to demonstrate the potential for applications of hydraulic geometry relations by stream types, this author assembled stream dimensions, slopes, and hydraulic data for six different stream types having the same discharge and channel materials. The objective was to demonstrate how the shape (width/depth ratio), profile (gradient), plan view (sinuosity), and meander geometry affect the hydraulic geometry relations. For example channel width increases faster than mean depth, with increasing discharge in high width/depth ratio channels. The opposite is true in low width/depth ratio channels. Streamflow values from baseflow of approximately 4 cfs up to bankfull values of 40 cfs were compared for each cross-section, and the corresponding widths, depths, velocities, and cross-sectional area for each stream type were computed. The A3, B3, C3, D3, E3 and F3 stream types selected for comparisons all had a cobble dominated bed-material size. The resultant hydraulic geometry relations for the selected array of stream types at the described flow ranges are shown in Fig. 11. Except for the E3 stream type for the plot of width/discharge, the slope of the plotted relations did not significantly change nearly as much as the intercept values.

6. Shear stress/velocity relations

Using the same data from the six stream types described previously, a "lumped" data base for all stream types from low to high flow was made for the corresponding shear stress ($\tau = \gamma RS$) (Shields, 1936) vs. mean velocity, where; $\tau =$ shear stress,

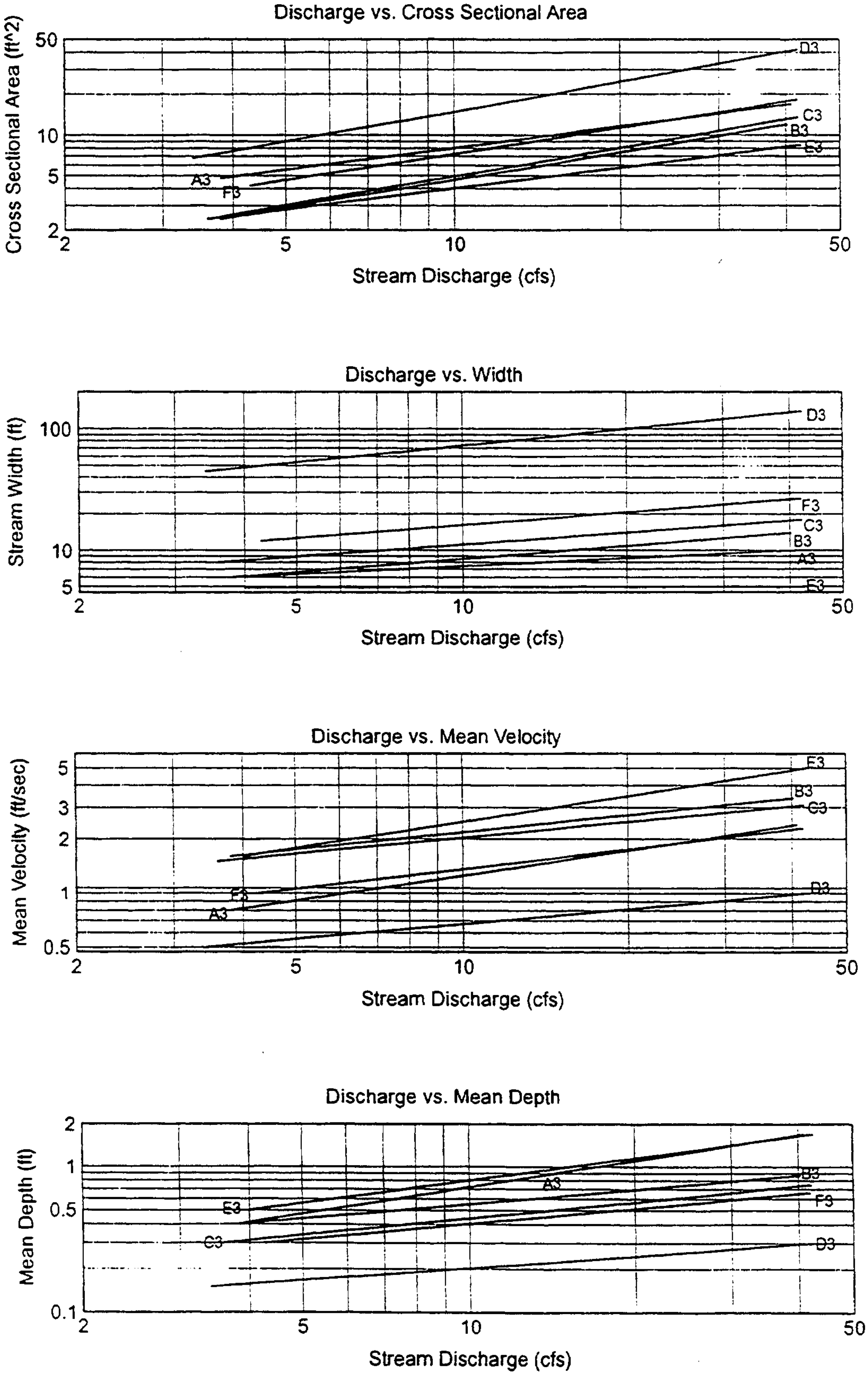


Fig. 11. Hydraulic geometry relations for selected stream types of uniform size.

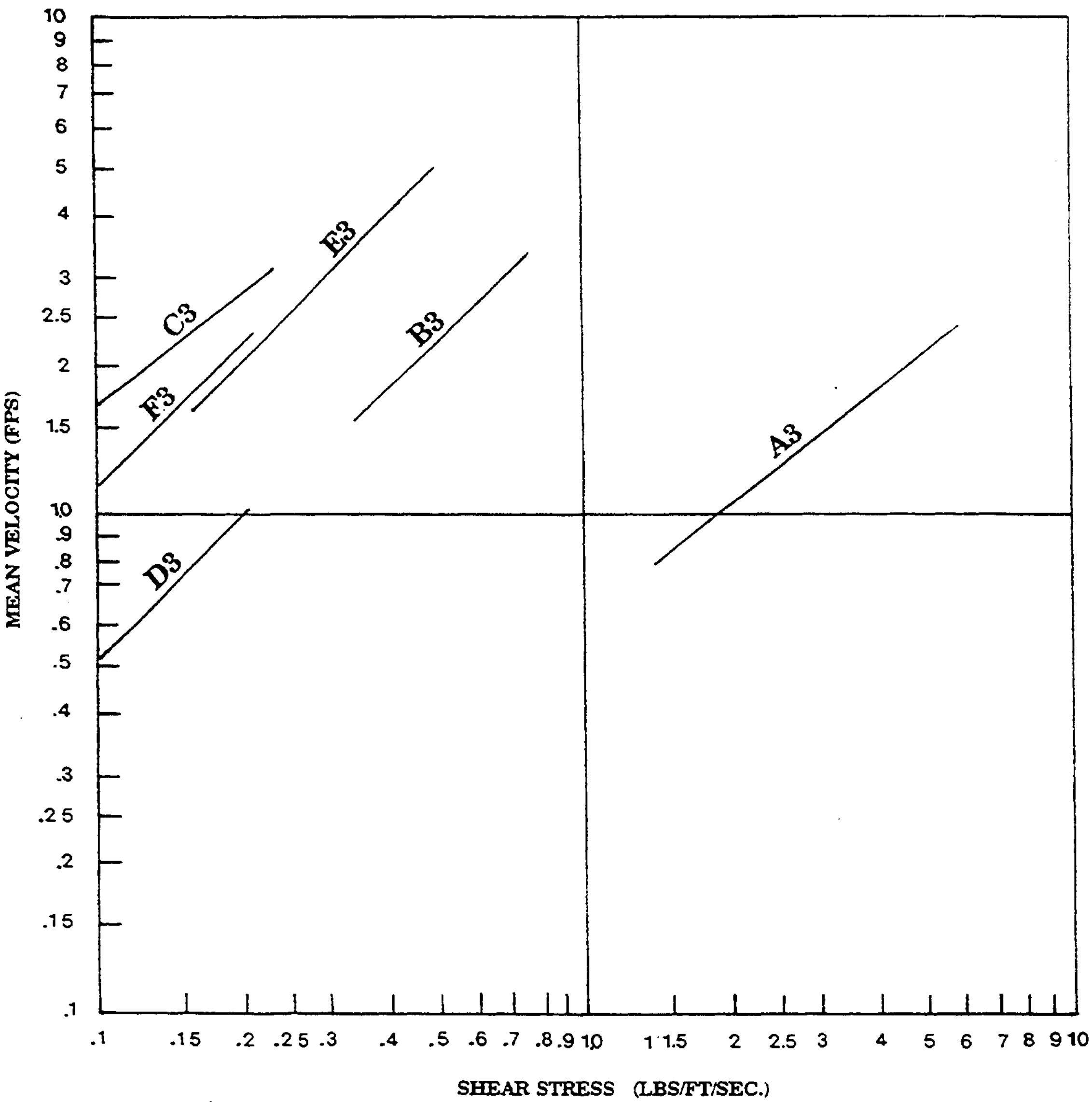


Fig. 12. Relationship of mean velocity vs. shear stress for six stream types from base flow (3–4 cfs) to bankfull discharge (40–41 cfs).

γ = density of water, R = hydraulic radius, and S = channel slope. As expected, a meaningful relation was not found. However, plotting shear stress and velocity stratification by stream type provided a trend that did shows promise (Fig. 12). While more data are needed to establish mathematical and statistical relationships, the comparisons arranged by stream type may have potential for future applications.

6.1. Critical shear stress estimates

Previous investigations of the magnitude of shear stress required to entrain various particle diameters from the stream-bed material have produced a wide range of values. A number of investigators have assumed the critical dimensionless shear

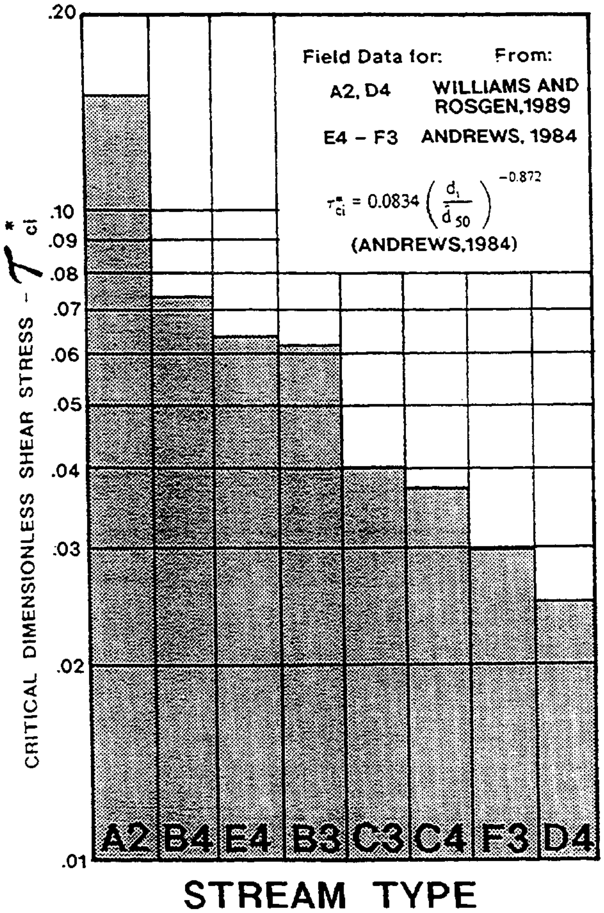


Fig. 13. Relationship of field verification of critical dimensionless shear stress values for various stream types.

stress values of 0.06 for computations of bedload transport using Shield's (1936) criteria (Baker, 1974; Baker and Ritter, 1975; Church, 1978; Bradley and Mears, 1980; Simons and Senturk, 1977; Simons and Li, 1982). In addition, critical dimensionless shear stress values computed from data compiled by Fahnestock (1963), Ritter (1967), and Church (1978) for the entrainment of gravels and cobbles from a natural river-bed, as reported by Andrews (1983) showed a range of approximately 0.02 to 0.25. The mean of the computed values was 0.06, which is the value suggested by Shields (1936).

Andrews (1983) described a relationship where to the ratio of surface (pavement) bed particles to sub-surface (sub-pavement) particles that yielded an estimate of critical dimensionless shear stress values (τ_{ci}*) from 0.02 to 0.28. Additional work using the same equation was applied to several Colorado gravel-bed streams with similar results (Andrews, 1984).

It is sometimes difficult for many engineers to obtain pavement and sub-pavement data along with the required channel hydraulics information to refine critical dimensionless shear stress estimates using the Andrews (1983, 1984) equation. The use of stream types to help bridge this gap of estimating the critical dimensionless shear stress value (τc) has potential where these study streams have been analyzed and classified. The study streams by Andrews (1984) were classified, data compiled and the values of τ_c* (critical dimensionless shear stress) were plotted (Fig. 13). A2 and D4 stream types were obtained from field measurements of bedload sediment and bed-material size distribution for those types (Williams and Rosgen, 1989). Stream types and their morphologic/hydraulic characteristics do not substitute for detailed on-site investigations as described by Andrews (1983, 1984); however, calculations of τ_{ci}* are often made without the benefit of site-specific investigation. Based on the great variability in the estimate of τ_{ci}*, sediment transport prediction errors can be from one to several orders of magnitude. A closer approximation of τ_{ci}* for stream reaches that cannot be investigated in detail, is possible using the extrapolation approach shown in Fig. 13.

A similar analysis has been made but not included here using unit stream power rather than critical shear stress. This analysis again demonstrated that stratification by stream type improved sediment transport/stream power relations as an integrative function of the supply/energy distribution/resistance factors for specific stream types.

6.2. Sediment relations

Stream types have been used to characterize sediment rating curves that reflect sediment supply in relation to stream discharge. For example, a sediment rating curve regression relation for an A2 stream type would have a characteristic low slope and intercept. The sediment rating curve for the C4 stream type, however, has a higher intercept and steeper slope. The author has used this procedure for both suspended and bedload rating curves. These relationships were initially plotted as a function of channel stability ratings as developed by Pfankuch (1975). Applications for cumulative effects analysis for non-point sediment sources utilized this approach (USEPA, 1980). Subsequent comparisons of data with stream type delineations indicated similar relations.

The ratio of bedload to total sediment load can also be stratified by stream type where measured data is available. Ranges of less than 5% bedload to total sediment load for C3 stream types have been reported, but values greater than 75% bedload to total load for G4 stream types have also been measured (Williams and Rosgen, 1989). The "high ratio" bedload streams are the A3, A4, A5, D3, D4, D5, F4, F5, G3, G4, and G5 stream types.

6.3. Management interpretations

The ability to predict a river's behavior from its appearance and to extrapolate information from similar stream types helps in applying the interpretive information in Table 3. These interpretations evaluate various stream types in terms of; sensitivity to disturbance, recovery potential, sediment supply, vegetation controlling influence, and streambank erosion potential. Application of these interpretations can be used for; potential impact assessment, risk analysis, and management direction by stream type. For example, livestock grazing effects were related to stream stability and

Table 3
Management interpretations of various stream types

Stream type	Sensitivity to disturbance [a]	Recovery potential [b]	Sediment supply [c]	Streambank erosion potential	Vegetation controlling influence [d]
A1	very low	excellent	very low	very low	negligible
A2	very low	excellent	very low	very low	negligible
A3	very high	very poor	very high	high	negligible
A4	extreme	very poor	very high	very high	negligible
A5	extreme	very poor	very high	very high	negligible
A6	high	poor	high	high	negligible
B1	very low	excellent	very low	very low	negligible
B2	very low	excellent	very low	very low	negligible
B3	low	excellent	low	low	moderate
B4	moderate	excellent	moderate	low	moderate
B5	moderate	excellent	moderate	moderate	moderate
B6	moderate	excellent	moderate	low	moderate
C1	low	very good	very low	low	moderate
C2	low	very good	low	low	moderate
C3	moderate	good	moderate	moderate	very high
C4	very high	good	high	very high	very high
C5	very high	fair	very high	very high	very high
C6	very high	good	high	high	very high
D3	very high	poor	very high	very high	moderate
D4	very high	poor	very high	very high	moderate
D5	very high	poor	very high	very high	moderate
D6	high	poor	high	high	moderate
DA4	moderate	good	very low	low	very high
DA5	moderate	good	low	low	very high
DA6	moderate	good	very low	very low	very high
E3	high	good	low	moderate	very high
E4	very high	good	moderate	high	very high
E5	very high	good	moderate	high	very high
E6	very high	good	low	moderate	very high
F1	low	fair	low	moderate	low
F2	low	fair	moderate	moderate	low
F3	moderate	poor	very high	very high	moderate
F4	extreme	poor	very high	very high	moderate
F5	very high	poor	very high	very high	moderate
F6	very high	fair	high	very high	moderate
G1	low	good	low	low	low
G2	moderate	fair	moderate	moderate	low
G3	very high	poor	very high	very high	high
G4	extreme	very poor	very high	very high	high
G5	extreme	very poor	very high	very high	high
G6	very high	poor	high	high	high

[a] Includes increases in streamflow magnitude and timing and/or sediment increases.
[b] Assumes natural recovery once cause of instability is corrected.
[c] Includes suspended and bedload from channel derived sources and/or from stream adjacent slopes.
[d] Vegetation that influences width/depth ratio-stability.

sensitivity using stream types (Meyers and Swanson, 1992). They summarized their study results on streams in northern Nevada that "... range managers should consider the stream type when setting local standards, writing management objectives, or determining riparian grazing management strategies."

This interpretive information by stream type can also apply to establishment of watershed and streamside management guidelines dealing with; silvicultural standards, surface disturbance activities, surface disturbance activities, gravel and surface mining activities, riparian management guidelines, debris management, floodplain management, cumulative effects analysis, flow regulation from reservoirs/diversions, etc. An example of the implementation of these guidelines by stream type are shown in the Land and Resource Management Plan (USDA, 1984).

Applications for riparian areas (USDA, 1992), have utilized the stream classification system into their recently developed "Integrated Riparian Evaluation Guide" — Intermountain Region. The classification system was used to help stratify and classify riparian areas based on natural characteristics and existing conditions. It is also used to evaluate the potential risks and sensitivities of riparian areas.

6.4. Restoration

The morphologic variables that interact to form the dimensions, profile and patterns of modern rivers are often the same variables that have been adversely impacted by development and land use activities. To restore the "disturbed" river, the natural stable tendencies must be understood to predict the most probable form. Those who undertake to restore the "disturbed" river must have knowledge of fluvial process, morphology, channel and meander geometry, and the natural tendencies of adjustment toward stability in order to predict the most effective design for long-term stability and function. If one works against these tendencies, restoration is generally not successful. Restoration applications using stream classification and the previously discussed principles are documented in the "Blanco River" case study (National Research Council, 1992).

7. Summary

Rivers are complex natural systems. A necessary and critical task towards the understanding of these complex systems is to continue the river systems research. In the interim, water resource managers must often make decisions and timely predictions without the luxury of a complex and thorough data base. Therefore, a goal for researchers and managers is to properly integrate what has been learned about rivers into a management decision process that can effectively utilize such knowledge. There is often more data collected and available on rivers than is ever applied. Part of the problem is the large number of "pieces" that this data comprises and the difficulty of putting these pieces into meaningful form.

The objective of this stream classification system presented here is to assist in bringing together these "pieces" and the many disciplines working with rivers under a common format — a central theme for comparison, a basis for extrapolation, prediction, and communication. The stream classification system can assist in organizing the observations of river data and of molding the many pieces together into a logical, useable, and reproducible system.

With the recent emphasis on "natural" river restoration or "naturalization" throughout Europe and North America, understanding the potential versus the existing stream type is always a challenge. The dimension of rivers related to the flow, and the patterns, which in turn are related to the dimensions, have to be further stratified by discrete stream types. In this way, the arrangement of the variables that make up the plan, profile and section views of stable stream types that are integrated within their valley's can be emulated. This also involves re-creation of the corresponding appropriate bed morphology associated with individual stream types with the observed sequence of step/pool and/or riffle pool bed features as a function of the bankfull width. The use of meander width ratios by stream type helps to establish the minimum, average and ranges of lateral containment of rivers. This often helps the design engineer/hydrologist determine appropriate widths that need to be accommodated when natural, stable rivers are re-constructed within their valleys. River and floodplain elevations, which need to be constructed, can be often determined by the used of the entrenchment ratio, which depicts the vertical containment of rivers in the landform. Using these integrative, morphological relations by stream type, can avoid the problematic "works" done on streams which create changes in the dimensions, pattern and profile of rivers which are not compatible with the tendencies of the natural stable form.

A classification system is particularly needed to stratify river reaches into groups that may be logically compared. Such stratification reduces scatter that might appear to come from random variation, whereas the scatter often results from attempting to compare items generically different. For example, data developed from empirical relations associated with process oriented research in natural channels such as tractive force relations, resistance and sediment transport equations, etc., can be stratified by stream type. This can help reduce the scatter when applied to stream types different than those from which the relations were developed.

Utilizing quantitative channel morphological indices for a classification procedure insures for consistency in defining stream types among observers for a great diversity of potential applications. The classification presented here may be the first approximation of a system that undoubtedly will be refined over the years with continued experience and knowledge. This stream classification system hopefully can be a vehicle to provide better communication among those studying river systems and promote a better understanding of river processes, helping put principles into practice.

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References

Andrews, E.D., 1980. Effective and bankfull discharges of streams in the Yampa River Basin, Colorado and Wyoming. J. Hydrol., 46: 311–330.

Andrews, E.D., 1983. Entrainment of gravel from natural sorted riverbed material. Geol. Soc. Am. Bull., 94: 1225–1231.

Andrews, E.D., 1984. Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. Geol. Soc. Am. Bull., 95: 371–378.

Baker, V.R., 1974. Paleohydraulic interpretation of Quaternary alluvium near Golden, Colorado. Quat. Res., 4: 94–112.

Baker, V.R. and Ritter, D.F., 1975. Competence of rivers to transport coarse bedload material. Geol. Soc. Am. Bull., 86: 975–978.

Barnes, H.H., 1967. Roughness characteristics of natural channels. U.S. Geol. Survey, Water Supply Paper 1849, 213 pp.

Bradley, W.C. and Mears, A.I., 1980. Calculations of flows needed to transport coarse fraction of Boulder Creek alluvium at Boulder, Colorado. Geol. Soc. Am. Bull., Part II, 91: 1057–1090.

Brice, J.C. and Blodgett, J.C., 1978. Counter Measures for Hydraulic Problems at Bridges. Vol. 1, Analysis and Assessment. Report No. FHWA-RD-78-162, Fed. Highway Admin., Washington, DC, 169 pp.

Church, M., 1978. Paleohydrological reconstructions from a Holocene valley. In: A.D. Miall (Editor.), Fluvial Sedimentology. Can. Soc. Pet. Geol. Mem., 5: 743–772.

Church, M. and Rood, K., 1983. Catalogue of alluvial river channel regime data. Natural Sciences and Engineering Research Council of Canada. Dept. Geology Univ. British Columbia, Vancouver, B.C., Edition 1.0.

Culbertson, D.M., Young, L.E. and Brice, J.C., 1967. Scour and fill in alluvial channels. U.S. Geological Survey, Open File Report, 58 pp.

Davis, W.M., 1899. The geographical cycle. Geogr. J., 14: 481–504.

Dunne, T. and Leopold, L.B., 1978. Water in Environmental Planning. Freeman, San Francisco, CA, 818 pp.

Fahnestock, R.K., 1963. Morphology and hydrology of a glacial stream — White River. Mount Rainier, Washington. U.S. Geol. Survey Prof. Paper 422-A, 70 pp.

Galay, V.J., Kellerhals, R. and Bray, D.I., 1973. Diversity of river types in Canada. In: Fluvial Process and Sedimentation. Proceedings of Hydrology Symposium. National Research Council of Canada, pp. 217–250.

Grant, G.E., Swanson, F.J. and Wolman, M.G., 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. Geol. Soc. Am. Bull., 102: 340–352.

Hicks, D.M. and P.D. Mason, 1991. Roughness characteristics of New Zealand rivers. New Zealand Dept. of Scientific and Industrial Research, Marine and Freshwater, Natural Resources Survey, Wellington, 329 pp.

Inglis, C.C., 1942. Rapid westerly movement of the Kosi River. Central Board of Irrigation, India (Technical), Poona, Bombay, pp. 7 and 8.

Jarrett, R.D., 1984. Hydraulics of high-gradient streams. J. Hydraul. Eng., 110(11): 1519–1539.

Jarrett, R.D., 1990. Hydrologic and hydraulic research in mountain rivers. Water Res. Bull. WARBAQ, 26(3): 419–429.

Kellerhals, R., Neill, C.R. and Bray, D.I., 1972. Hydraulic and geomorphic characteristics of rivers in Alberta. Research Council of Alberta, River Engineering and Surface Hydrology Report 72-1, p. 52.

Kellerhals, R., Church, M. and Bray, D.I., 1976. Classification and analysis of river processes. J. Hydraul. Div., ASCE, 102(HY7): 813–829.

Khan, H.R., 1971. Laboratory studies of alluvial river channel patterns. Ph.D. Dissertation, Dept. of Civil Engineering Department, Colorado State University, Fort Collins, CO.

Lane, E.W., 1957. A study of the shape of channels formed by natural streams flowing in erodible material. Missouri River Division Sediment Series No. 9, U.S. Army Engineer Division, Missouri River, Corps of Engineers, Omaha, NE.

Langbein, W.B. and Leopold, L.B., 1966. River meanders — Theory of minimum variance. U.S. Geol. Survey Prof. Paper No. 422-H, 15 pp.

Leopold, L.B. and Maddock, T., 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geol. Survey Prof. Paper No. 252. Supt. of Docs, U.S. Government Printing Office, Washington, DC, 57 pp.

Leopold, L.B. and Wolman, M.G., 1957. River channel patterns: braided, meandering, and straight. U.S. Geological Survey Prof. Paper 282-B.

Leopold, L.B., Wolman, M.G. and Miller, J.P., 1964. Fluvial processes in geomorphology. Freeman, San Francisco, CA, 522 pp.

Matthes, G., 1956. River engineering. In: P.O. Abbott (Editor), American Civil Engineering Practice. Wiley, New York, Vol. II, pp. 15–56.

Melton, F.A., 1936. An empirical classification of flood-plain streams. Geogr. Rev., 26.

Mollard, J.D., 1973. Air photo interpretation of fluvial features. In: Fluvial Processes and Sedimentation. Research Council of Canada, pp. 341–380.

Meyers, T.J. and Swanson, S., 1992. Variation of stream stability with stream type and livestock bank damage in Northern Nevada. Water Resources Bull. AWRA, 28(4): 743–754.

Nanson, G.C. and Croke, J.C., 1992. A genetic classification of floodplains. In: G.R. Brakenridge and J. Hagedorn (Editors), Floodplain Evolution. Geomorphology, 4: 459–486.

National Research Council, 1992. Restoration of aquatic ecosystems. Restoration case studies. National Academy Press, Washington, DC, pp. 470–477.

Osborn, J.F. and Stypula, J.M., 1987. New models of hydrological and stream channel relationships. In: Erosion and sedimentation in the Pacific Rim. IAHS Publ. No. 165, Oregon State Univ., Corvallis, OR.

Pfankuch, D.J., 1975. Stream reach inventory and channel stability evaluation. USDA Forest Service, R1-75-002. Government Printing Office #696-260/200, Washington DC, 26 pp.

Pickup, G., 1984. Geomorphology of tropical rivers. 1. Landforms, hydrology and sedimentation in the fly and lower Purari, Papua New Guinea. In: A.P. Schick (Editor), Channel Processes, Water, Sediment, Catchment Controls. Catena Suppl., 5: 1–17.

Platts, W.S., 1980. A plea for fishery habitat classification. Fisheries, 5(1): 1–6.

Ritter, J.R., 1967. Bed-material movement. Middle Fork Eel River, California. U.S. Geol. Survey Prof. Paper 575-C, pp. C219–C221.

Rosgen, D.L., 1985. A stream classification system. In: Riparian Ecosystems and Their Management. First North American Riparian Conference. Rocky Mountain Forest and Range Experiment Station, RM-120, pp. 91–95.

Rosgen, D.L. and Fittante, B.L., 1986. Fish habitat structures — A selection guide using stream classification. In: J.G. Miller, J.A. Arway and R.F. Carline (Editors), 5th Trout Stream Habitat Improvement Workshop, Lock Haven Univ., Lock Haven, PA. Penn. Fish Comm. Publics, Hamsburg, PA, pp. 163–179.

Schumm, S.A., 1963. A tentative classification of alluvial river channels. U.S. Geological Survey Circular 477. Washington, DC.

Schumm, S.A., 1977. The Fluvial System. Wiley, New York, 338 pp.

Selby, M.J., 1985. Earth's Changing Surface: an Introduction to Geomorphology. Oxford University Press, Oxford.

Shields, A., 1936. Application of similarity principles and turbulence research to bed-load movement. In: W.P. Ott and J.C. Uchelen (translators), Mitt. Preuss. Verschsanst., Berlin. Wasserbau Schiffbau. California Institute of Technology, Pasadena, CA, Report No. 167, 43 pp.

Simons, D.B. and Senturk, F., 1977. Sediment Transport Technology. Water Resource Publications, Fort Collins, CO, 807 pp.

Simons, D.B. and Li, R.M., 1982. Engineering Analysis of Fluvial Systems. SLA, P.O. Box 1816, Fort Collins, CO.

Smith, D.G. and Smith, N.D., 1980. Sedimentation in anastomosing river systems: examples from alluvial valleys near Banff, Alberta. J. Sediment. Petrol., 50: 157–164.

Thornbury, W.D., 1969. Principles of Geomorphology. 2nd Edition. Wiley, New York.

USDA (U.S. Department of Agriculture), Forest Service, 1984. Land and Resource Management Plan — Arapaho and Roosevelt National Forests and Pawnee Grassland. Fort Collins, CO.

USDA (U.S. Department of Agriculture), Forest Service, 1989. Fisheries Habitat Surveys Handbook. Region 4 — FSH 2609.23. Ogden, UT.

USDA (U.S. Department of Agriculture), Forest Service, 1992. Integrated Riparian Evaluation Guide. Intermountain Region — Ogden, UT.

USEPA (U.S. Environmental Protection Agency), 1980. An approach to water resources evaluation of non-point silvicultural sources. Chap. VI, Total Potential Sediment, D. Rosgen. EPA-600/8-80-012, Athens, GA, pp. 39–41.

Williams, G.W., 1986. River meanders and channel size. J. Hydrol., 88: 147–164.

Williams, G.P. and Rosgen, D.L., 1989. Measured total sediment loads (suspended loads and bedloads) for 93 United States streams. Open File Report 89-67. U.S. Geol. Survey, Denver, CO, 128 pp.

Wolman, M.G., 1954. A method of sampling coarse river-bed material. Trans. Am. Geophys. Union, 35: 951–956.

A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

Prepared by Pamela C. Dodds, Ph.D., Licensed Professional Geologist
Prepared for The Wilderness Society - January 24, 2023

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Hydrologic Unit Maps

United States Geological Survey Water-Supply Paper 2294

USGS
science for a changing world

Hydrologic Unit Maps

By PAUL R. SEABER, F. PAUL KAPINOS,
and GEORGE L. KNAPP

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Hydrologic Unit Maps

By Paul R. Seaber, F. Paul Kapinos, *and* George L. Knapp

Abstract

A set of maps depicting approved boundaries of, and numerical codes for, river-basin units of the United States has been developed by the U.S. Geological Survey. These "Hydrologic Unit Maps" are four-color maps that present information on drainage, culture, hydrography, and hydrologic boundaries and codes of (1) the 21 major water-resources regions and the 222 subregions designated by the U.S. Water Resources Council, (2) the 352 accounting units of the U.S. Geological Survey's National Water Data Network, and (3) the 2,149 cataloging units of the U.S. Geological Survey's "Catalog of Information on Water Data." The maps are plotted on the Geological Survey State base-map series at a scale of 1:500,000 and, except for Alaska, depict hydrologic unit boundaries for all drainage basins greater than 700 square miles (1,813 square kilometers). A complete list of all the hydrologic units, along with their drainage areas, their names, and the names of the States or outlying areas in which they reside, is contained in the report.

These maps and associated codes provide a standardized base for use by water-resources organizations in locating, storing, retrieving, and exchanging hydrologic data, in indexing and inventorying hydrologic data and information, in cataloging water-data acquisition activities, and in a variety of other applications. Because the maps have undergone extensive review by all principal Federal, regional, and State water-resource agencies, they are widely accepted for use in planning and describing water-use and related land-use activities, and in geographically organizing hydrologic data. Examples of these uses are given in the report. The hydrologic unit codes shown on the maps have been approved as a Federal Information Processing Standard for use by the Federal establishment.

INTRODUCTION

This report describes the U.S. Geological Survey's standard map series called "Hydrologic Unit Maps" and presents the codes, names, and boundaries of hydrologic units in the United States and the Caribbean outlying areas. The four-color maps depict a hydrologic system that divides the United States into 21 major regions. These *regions* are currently (1984) further subdivided into 222 *subregions*, 352 *accounting units*, and, finally, into 2,149 *cataloging units*. These four levels of subdivisions, used for the collection and organization of hydrologic data, are referred to as "hydrologic units." The identifying numeric codes associated with these units are "hydrologic unit codes." Each hydrologic unit has been assigned a name; in most cases, the name corresponds to the principal hydrologic feature within the unit. The Hydrologic Unit Maps show drainage, hydrography, culture, and political and hydrologic unit boundaries and codes, thus providing a standard geographic and hydrologic framework for detailed water-resource and related land-resource planning. Also included on the maps are the Federal Information Processing Standards State and county codes (U.S. National Bureau of Standards, 1983).

In recognition that such maps were needed by almost everyone working in water resources in the United States, this set of maps covers the entire United States and the Caribbean outlying areas. The maps, published in a series beginning in 1974 at a scale of 1:500,000 (1 inch equals nearly 8 miles), present twice the detail of previous river-basin maps using the Geological Survey State Map series as a base. They delineate all river basins having a drainage area of at least 700 square miles except for river basins in the State of Alaska. In special instances, river basins of less than 700 square miles have been delineated.

These maps and associated codes provide a standardized base for use by water-resources organizations in locating, storing, retrieving, and exchanging hydrologic data, in indexing and inventorying hydrologic data and information, in cataloging water-data acquisition activities, and in a variety of other applications.

The Hydrologic Unit Map series was initiated in the fall of 1972 by the U.S. Geological Survey's Office of Water Data Coordination, in cooperation with the U.S. Water Resources Council and supported by the U.S. Geological Survey's Resources and Land Information program (Seaber and others, 1975). The need for nationwide standardization by obtaining acceptance of and agreement on the maps by a broad spectrum of water-resource interests was acknowledged from the beginning. Thus, the maps were thoroughly reviewed throughout the country. This paper describes the methods and criteria used to produce the Hydrologic Unit Maps so that the map delineations, coding, and naming system can be understood and used to full advantage. Maintenance, updating, and use of the maps can be accomplished effectively only within a framework of the background, history, and development of the maps.

HISTORY AND DEVELOPMENT

Hydrologic maps available before 1972 were unsatisfactory for many purposes because of inadequate bases or scales as well as lack of agreement about hydrologic subdivisions among Federal, State, and local agencies. Federal and State agencies, Congress and its committees, the "Federal Register," treaties, compacts, adjudications, Presidential Executive orders, river-basin commissions, and others used many incompatible criteria for names, codes, hydrographic boundaries, and river basins (Kammerer, 1969). After many years of use of unsatisfactory and inadequate hydrologic maps, discussions among representatives of Federal and State agencies, initiated in 1972, led to nearly unanimous agreement on the need for a national project to develop uniform and widely acceptable hydrologic boundaries and to present them on nationally consistent base maps. A need for standardization of hydrologic units was evident throughout the country.

Although this project dates from 1972, the national effort to depict hydrologic units really began more than 60 years earlier:

> For the purpose of uniformity in presentation of reports, a general plan has been agreed upon by the U.S. Reclamation Service, the U.S. Weather Bureau, and the U.S. Geological Survey, according to which the area of the United States has been divided into 12 parts whose boundaries coincide with certain natural drainage areas (U.S. Geological Survey, 1910, p. 10).

Several other attempts to produce a set of uniform maps for the Nation were made between 1910 and 1972, although the Geological Survey's 12-part subdivision was generally accepted for publication of water data.

The U.S. Army Corps of Engineers and the U.S. Department of Agriculture have made comprehensive river-basin studies nationwide. The boundaries of these studies are usually as outlined in the 1959–1960 reports of the Senate Select Committee on National Water Resources known as "The Kerr Report" (U.S. Senate, 1959–1960). General river-basin planning policies were established in 1962 by Senate Document 97 prepared under the direction of the President's ad hoc Water Resources Council. These reports led to Public Law 89–80, the Water Resources Planning Act (U.S. Congress, 1965). This act, together with U.S. Bureau of the Budget (1964) Circular A–67 and other events in the mid-1960's and early 1970's provided the impetus for producing the Hydrologic Unit Map series.

The Water Resources Planning Act established the U.S. Water Resources Council and directed it to "maintain a continuing study and prepare an assessment***of the adequacy of supplies of water necessary to meet the water requirements in each water-resource region in the United States***" as well as to "maintain a continuing study of the relation of regional or river-basin plans and programs to the requirements of larger regions of the Nation."

U.S. Bureau of the Budget Circular A–67 prescribed guidelines for coordinating water-data acquisition activities of the more than 30 Federal agencies that collect or use water data and assigned lead-agency responsibility to the Department of the Interior, which in turn delegated these coordinating responsibilities to the Geological Survey.

It was immediately evident that both the Water Resources Council and the U.S. Geological Survey should perform their assigned functions on the basis of precise and systematic definitions of hydrologic areas of appropriate sizes.

The Water Resources Council's program for carrying out its duties was the National Assessment of Water and Related Land Resources. The first national assessment was issued in 1968 (U.S. Water Resources Council, 1968). Early in the program, the council found a need for standard geographic and hydrographic bases to maintain continuity in its assessments. One of the initial tasks in preparing for the second assessment was the delineation of geographic areas suitable for analysis. The regions and subregions were originated primarily by the council to meet this need (U.S. Water Resources Council, 1970).

To discharge its responsibilities as outlined in Circular A–67, the U.S. Geological Survey established the Office of Water Data Coordination to (1) maintain a catalog of information on water data, (2) undertake a continuing review of water-data requirements, (3) prepare a Federal plan for efficient utilization of water-data activities, and (4) design and operate a national water data network. Accounting units and cataloging units were originated by the Geological Survey as part of these responsibilities. The cataloging units used for the Hydrologic Unit Maps supplant an earlier set used by the Geological Survey in its "Catalog of Information on Water Data" (1966–1972).

The current Hydrologic Unit Map boundaries were adapted, in part, from several publications: "Catalog of Information on Water Data" (U.S. Geological Survey, Office of Water Data Coordination, 1973); "Water-Resources Regions and Subregions for the National Assessment of Water and Related Land Resources" (U.S. Water Resources Council, 1970); "Atlas of River Basins of the United States" (U.S. Department of Agriculture, 1963, 1970); "River Basin Maps Showing Hydrologic Stations" (Federal Interagency Committee on Water Resources, 1961); and State planning maps.

The political subdivision code was taken from "Counties and County Equivalents of the States of the United States" presented in Federal Information Processing Standards Publication 6–2, issued by the U.S. National Bureau of Standards (1973). The addition of the Federal Information Processing Standards code to the maps allows data to be cataloged politically as well as hydrologically.

DESCRIPTION OF THE HYDROLOGIC UNITS

Hydrologic Unit Codes

Basically, the United States was divided and subdivided into successively smaller hydrologic units, which were classified into four levels, as shown in figure 1. The hydrologic units are arranged within each other, from the smallest (cataloging units) to the largest (regions). Each hydrologic unit is identified by a unique numeric hydrologic unit code consisting of two to eight digits based on the four levels of classification in the hydrologic unit system.

The first level of classification divides the Nation into 21 major geographic areas, or regions (fig. 2). These geographic areas (hydrologic areas based on surface topography) contain either the drainage area of a major river, such as the Missouri region, or the combined drainage areas of a series of rivers, such as the Texas-Gulf region, which includes a number of rivers draining into the Gulf of Mexico. Eighteen of the regions occupy the land area of the conterminous United States. Alaska is region 19, the Hawaiian Islands constitute region 20, and Puerto Rico and other outlying Caribbean areas are region 21. The Pacific Trust Territories are a potential region 22.

The second level of classification divides the 21 regions into 222 subregions. A subregion includes the area drained by a river system, a reach of a river and its tributaries in that reach, a closed basin(s), or a group of streams forming a coastal drainage area.

The third level of classification subdivides many of the subregions into accounting units. These 352 hydrologic accounting units nest within, or are equivalent to, the subregions. The accounting units are used by the Geological Survey for designing and managing the National Water Data Network. The areal extent of the accounting units is shown on plate 1.

The fourth level of classification is the cataloging unit, the smallest element in the hierarchy of hydrologic units. A cataloging unit is a geographic area representing part or all of a surface drainage basin, a combination of drainage basins, or a distinct hydrologic feature. These units subdivide the subregions and accounting units into smaller areas (approximately 2,150 in the Nation) that are used by the U.S. Geological Survey for cataloging and indexing water-data acquisition activities in the "Catalog of Information on Water Data."

Within this hierarchy, units have been defined so that almost all cataloging units are larger than 700 square

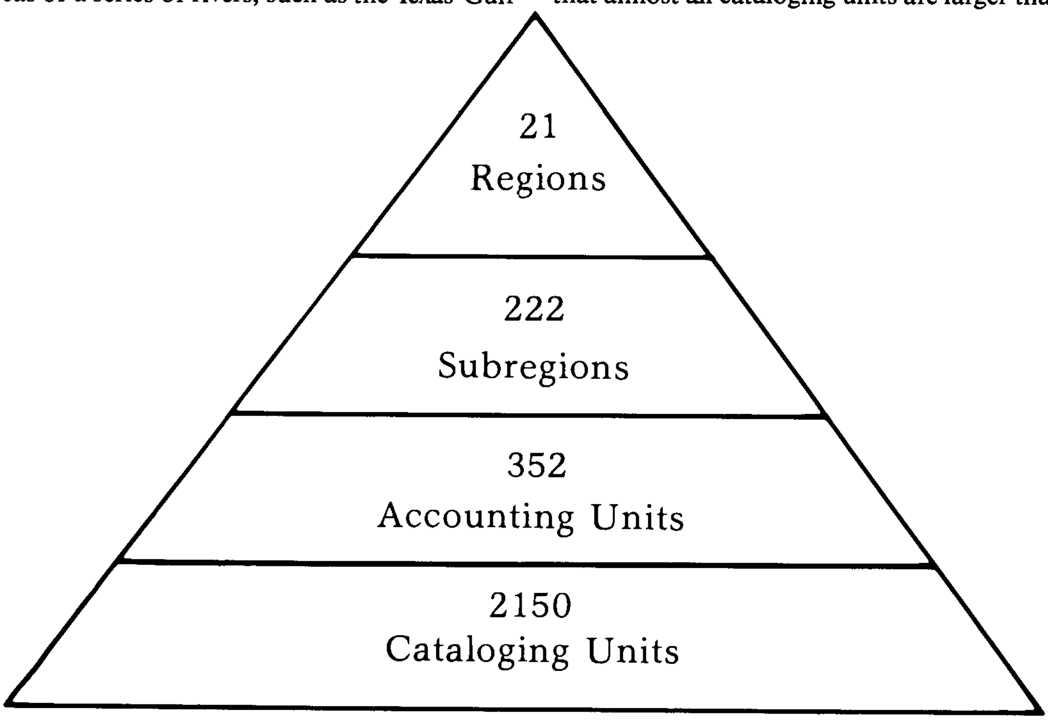


Figure 1. Hierarchy of hydrologic units shown on Hydrologic Unit Maps.

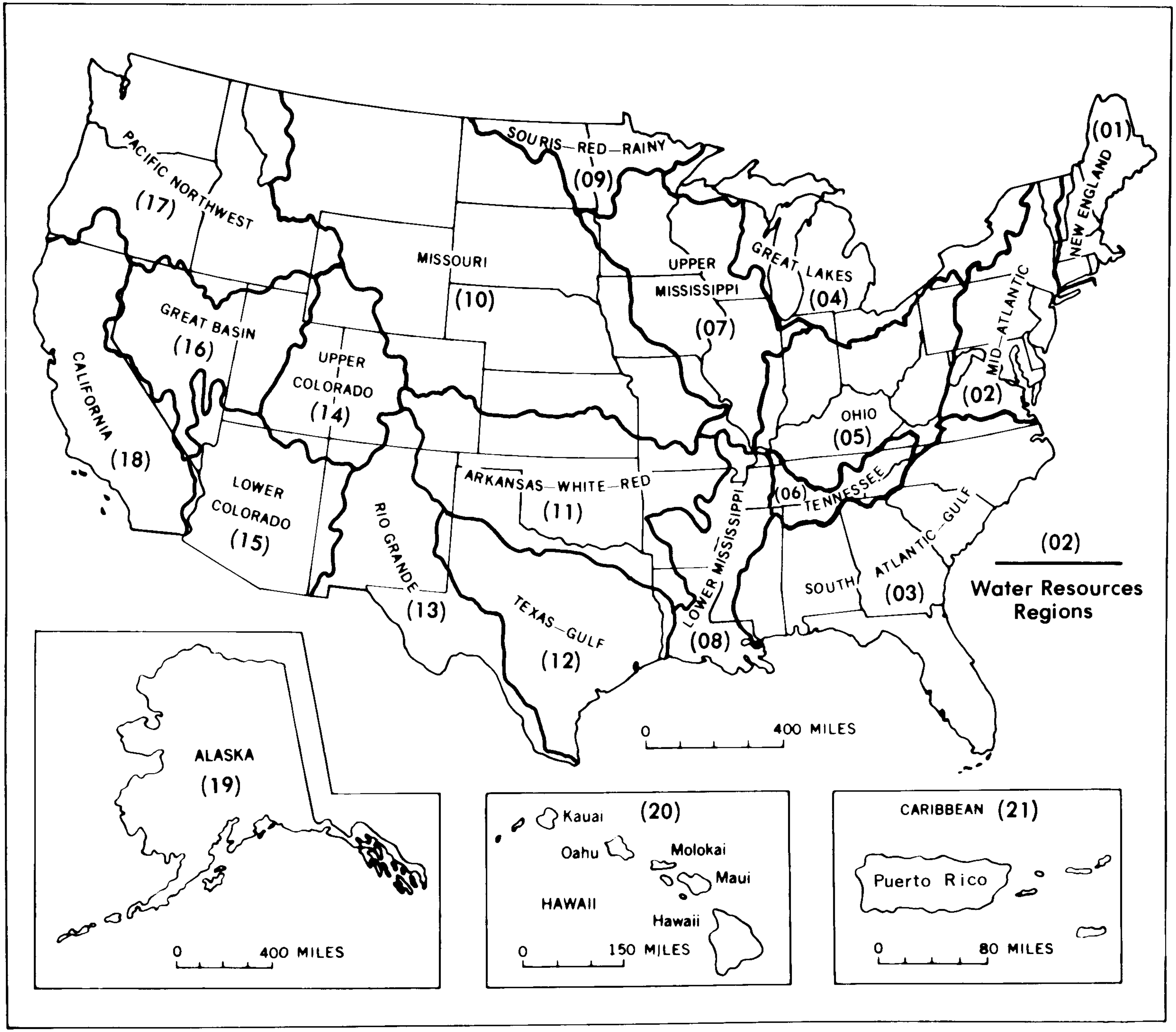


Figure 2. Water-resources regions of the United States.

miles (1,813 square kilometers) in area. In special circumstances, units smaller than 700 square miles are identified on some of the maps.

The boundaries or areal extent of the hydrologic units may be revised at the request of local users, and with the approval of the Geological Survey. Changes are more likely to be made to the cataloging unit boundaries than to boundaries of the regions, subregions, and accounting units.

An eight-digit code uniquely identifies each of the four levels of classification within four two-digit fields. The first two digits identify the water-resources region; the first four digits identify the subregions; the first six digits identify the accounting unit; and the addition of two more digits for the cataloging unit completes the eight-digit code. An example is given below using hydrologic unit code 01080204:

01—the region
0108—the subregion
010802—the accounting unit
01080204—the cataloging unit

A 00 in the two-digit accounting unit field indicates that the accounting unit and the subregion are the same. Likewise, if the cataloging unit code is 00, it is the same as the accounting unit.

Hydrologic Unit Names

In addition to hydrologic unit codes, each hydrologic unit has been assigned a name corresponding to the principal hydrologic feature(s) within the unit. In the absence of such features, the assigned name may reflect a cultural or political feature within the unit. All regions and subregions are uniquely named; however, the accounting units are uniquely named only within each region, and the cataloging units are uniquely named only within each accounting unit. Duplication of some names at the cataloging unit level is unavoidable because a large number of streams found throughout the Nation share the same names.

A complete list of all hydrologic unit codes, their names, the names of the States or outlying areas in which they reside, and their drainage areas is given in table 1 (at back of report).

DESCRIPTION OF THE HYDROLOGIC UNIT MAPS

The Hydrologic Unit Map Series consists of 47 maps on 53 sheets. The maps present 49 States at a scale of 1:500,000, or about 8 miles to the inch (1 centimeter to 5 kilometers). This scale permits most States to be shown on a single map of convenient size. Texas is shown on four sheets, and Montana, Michigan, and California are shown on two sheets each. Three groups of States—Massachusetts, Rhode Island, and Connecticut; Maryland, Delaware, and the District of Columbia; and Vermont and New Hampshire—are combined on a single sheet for each group. Alaska, because of its large size and less accurately defined drainage, is shown at a scale of 1:2,500,000, or about 40 miles to the inch (1 centimeter to 25 kilometers). Puerto Rico is shown on the Caribbean region map at a scale of 1:240,000, or about 4 miles to the inch (1 centimeter to 2.4 kilometers). The other outlying Caribbean areas are shown on this map at scales ranging from 1:250,000 to 1:1,000,000.

In preparing the maps, the best available Geological Survey State base materials were obtained and then modified where necessary to allow matching of hydrologic and political boundaries from sheet to sheet. The resulting set of maps thus provides good uniformity and accuracy on a nationwide basis. The State base is appropriate because water-resources planning and management are largely conducted at the State level. However, the maps are also usable at regional or national levels by such entities as river-basin commissions, water-management districts, and Federal agencies. Because of their uniform scale, the maps can be cut and spliced to form a mosaic of any region or area desired.

Figure 3, a section of the Hydrologic Unit Map for Wisconsin, shows the components depicted by the series. Hydrographic features (streams, lakes, and bays, and their names) are shown in blue; cultural features (political boundaries, geographic coordinates, and names of places) are in black; hydrologic unit boundaries and the eight-digit hydrologic unit codes are in red; and the county codes are in green.

Figure 4 shows the map explanation on a typical Hydrologic Unit Map. It includes the major source references from which the boundaries were adopted, and it illustrates the makeup of the eight-digit hydrologic unit code. A table shows the hydrologic units for the States broken down according to their regions, subregions, accounting units, and cataloging units. The political subdivision code is illustrated with a simple three-digit county code and a two-digit State code.

The Hydrologic Unit Maps have been adopted as "official issue" by the Federal Government. The associated codes and names for identifying hydrologic units in the United States and the Caribbean outlying areas have been adopted as a Geological Survey Data Standard (U.S. Geological Survey, 1982). This is a part of the Geological Survey program for standardizing data elements and representations used in automated earth-science systems.

The proposed codes and names were published in the December 28, 1982, "Federal Register." After a public comment period, the Secretary of Commerce approved the codes and names as a Federal Information Processing Standard on October 25, 1983.

MAP OF HYDROLOGIC UNITS

This new series of U.S. Geological Survey State base maps provide a uniform, nationally consistent set of hydrologic units accurately delineated to show drainage basins down to approximately 700 square miles in area.

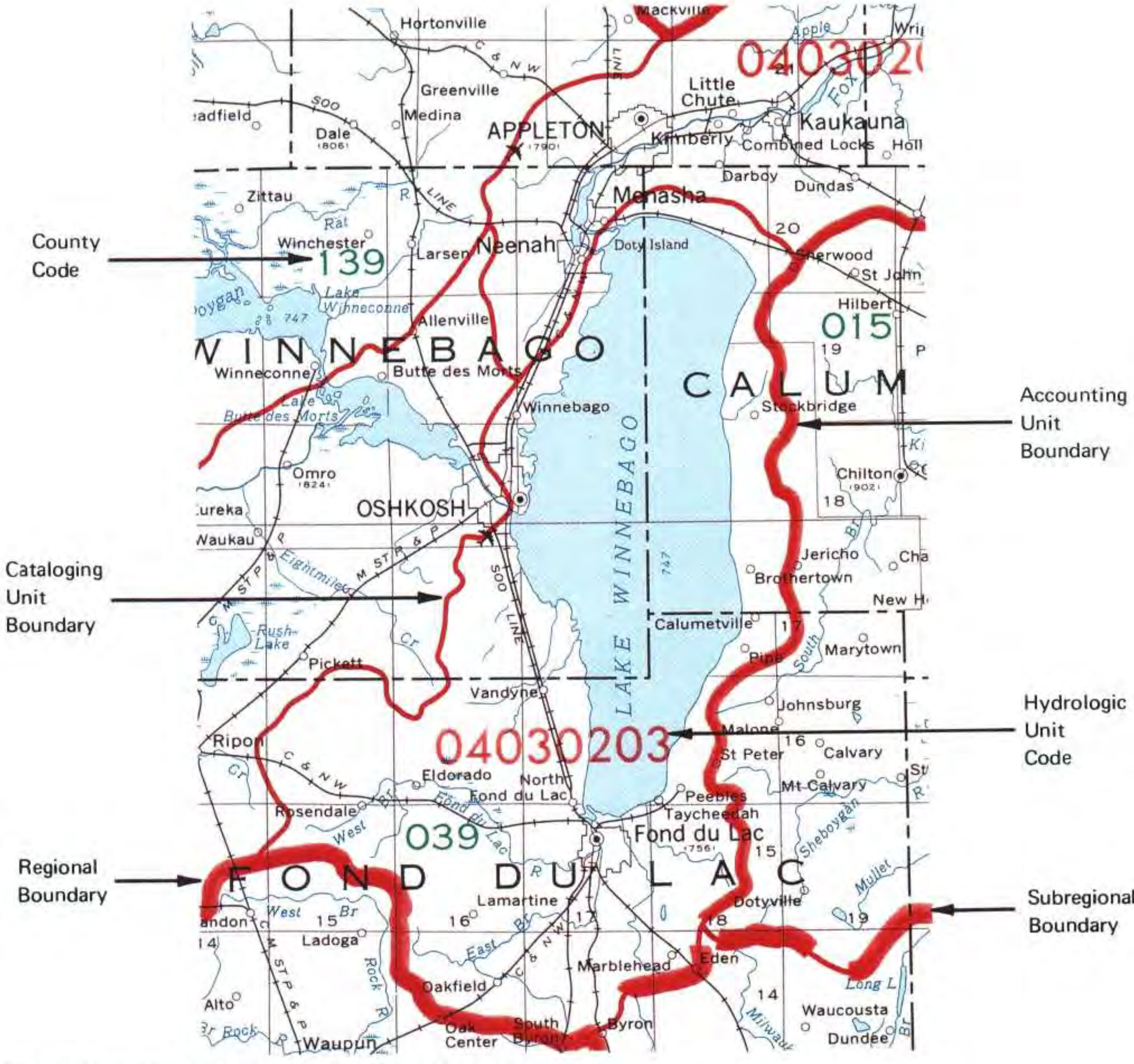


Figure 3. Section of a Hydrologic Unit Map (Wisconsin).

COMPILATION GUIDELINES

The following guidelines were used for preparing and reviewing the Hydrologic Unit Maps. The preparation of draft maps and the initial review process occurred simultaneously because one of the major criteria for producing the maps was local acceptance of the hydrologic units.

EXPLANATION

This map and accompanying table show Hydrologic Units that are basically hydrographic in nature. The Cataloging Units shown will supplant the Cataloging Units previously used by the U.S. Geological Survey in its Catalog of Information on Water Data (1966–72). The previous U.S. Geological Survey Catalog-Indexing System was by map number and letter, such as 49M. The boundaries as shown have been adapted from "The Catalog of Information on Water Data" (1972), "Water Resources Regions and Subregions for the National Assessment of Water and Related Land Resources" by the U.S. Water Resources Council (1970), "River Basins of the United States" by the U.S. Soil Conservation Service (1963, 1970), "River Basin Maps Showing Hydrologic Stations" by the Inter-Agency Committee on Water Resources, Subcommittee on Hydrology (1961), and State planning maps.

The Political Subdivision Code has been adopted from "Counties and County Equivalents of the States of the United States" presented in Federal Information Processing Standards Publication 6-2, issued by the National Bureau of Standards (1973) in which each county or county equivalent is identified by a 2-character State code and a 3-character county code.

The Regions, Subregions and Accounting Units are aggregates of the Cataloging Units. The Regions and Subregions are currently (1974) used by the U.S. Water Resources Council for comprehensive planning, including the National Assessment, and as a standard geographical framework for more detailed water and related land-resources planning. The Accounting Units are those currently (1974) in use by the U.S. Geological Survey for managing the National Water Data Network.

HYDROLOGIC UNIT CODE

Subregional Boundary

Accounting Unit Boundary

Cataloging Unit Boundary

The Regional and Subregional Boundaries serve as Accounting Unit Boundaries as well as Cataloging Unit Boundaries

POLITICAL SUBDIVISION CODE

081

County or County Equivalent Code

The State code for Florida is 12.
The code is not shown on the map.

The following table shows the Hydrologic Units for the State

Region	Subregion	Accounting Unit	Cataloging Unit
03 South Atlantic–Gulf	07	02	04, 05
	08	01	01, 02, 03
		02	01, 02, 03
	09	01	01, 02, 03
		02	01, 02, 03, 04, 05
	10	01	01, 02, 03
		02	01, 02, 03, 04, 05, 06, 07, 08
	11	01	01, 02, 03
		02	01, 02, 03, 05, 06
	12	00	01, 03
	13	00	04, 11, 12, 13, 14
	14	01	01, 02, 03, 04, 05, 06, 07
		02	02, 03
		03	04, 05

Figure 4. Explanation shown on a typical Hydrologic Unit Map.

Basic Criteria

Two basic criteria were used in preparing the maps:

1. All boundaries are hydrologic (hydrographic) in nature within the United States. By legal definition, however, the region and subregion boundaries end or coincide with the U.S. international boundary; thus, this criterion is violated for region and subregion boundaries along the international boundaries with Mexico and

Canada. However, because the boundaries of the cataloging units and accounting units are hydrologic in nature, they can be extended into Mexico and Canada. Essentially, the topography of stream drainage basins was the sole preferred determinant for hydrologic unit boundaries in the United States.

2. All smaller units nest within the next larger unit. All boundaries of units lying in contiguous States match precisely.

Technical Criteria

Most technical criteria used in delineating boundaries were derived from published sources:

1. Principal references. Appendix C of "Notes on Hydrologic Activities," Bulletin 4, by the Federal Interagency Committee on Water Resources, Subcommittee on Hydrology (1951), and "River Mileage Measurement," Bulletin 14, by the U.S. Water Resources Council, Hydrology Subcommittee (1967), were the principal references used in development of the technical criteria and additional specifications.

2. Selection of major areas. Figure 5 depicts types of subregions and accounting units and shows their relationship to cataloging units. In general, the subregional delineations defined by the U.S. Water Resources Council (1970) were used as the principal geographic units with the following exceptions:

a. At a major lake or reservoir, the boundary was placed at the outlet of the impoundment rather than at its head, because the headwaters can vary considerably over a period of time whereas the outlet of the impoundment is usually a fixed point.

b. The location of boundaries at gaging stations, major cities, State lines, tidal or backwater effects, or other so-called strategic hydrologic, political, or cultural points was deemphasized.

c. The boundaries of the Standard Metropolitan Statistical Areas were not used as criteria for defining hydrologic unit boundaries.

d. Relocations of boundaries or subdivisions of principal units defined in the 1970 Water Resources Council publication were made on the recommendations of the designated regional sponsors of the Water Resources Council and State agencies.

3. Size of basins. No maximum-size criterion was specified. However, every unique river basin having a drainage area of more than 700 square miles is delineated, except in Alaska. A "unique river" is defined herein as one that has been given a definitive name by the Board on Geographic Names and is shown and named on Geological Survey base maps. The 700-square-mile criterion was adapted from the Soil Conservation Service's "Atlas of River Basins of the United States" (U.S. Department of Agriculture, 1970).

4. Bays and estuaries. No firm guidelines were developed. However, the U.S. Department of Commerce's publication entitled "Measurement of Geographic Area" (Proudfoot, 1940) was followed where possible and practical.

5. Small coastal islands. No firm guidelines were developed, but individual islands usually were not divided. Again, the criteria in Proudfoot's 1940 publication were used where possible and practical.

6. Closed basins. Closed basins and large noncontributing areas were delineated as separate units if of sufficient size, for example, approximately 700 square miles.

7. Ground-water areas. These areas were assumed to be the same as areas contributing to surface-water flow and thus were not specifically given separate consideration in the development of the maps. The cataloging units are thus more hydrographic than true hydrologic entities.

8. Swamps and depressions. These were designated as separate areas if of sufficient size, for example, approximately 700 square miles.

9. Interbasin flow. Interbasin flow was not considered if it occurs only during flood conditions.

10. Man-induced changes or diversions in natural drainage. Where flow is diverted continually, boundaries were delineated correspondingly. Where flow is diverted partially or intermittently, the boundaries were not adjusted. Levees were considered permanent structures.

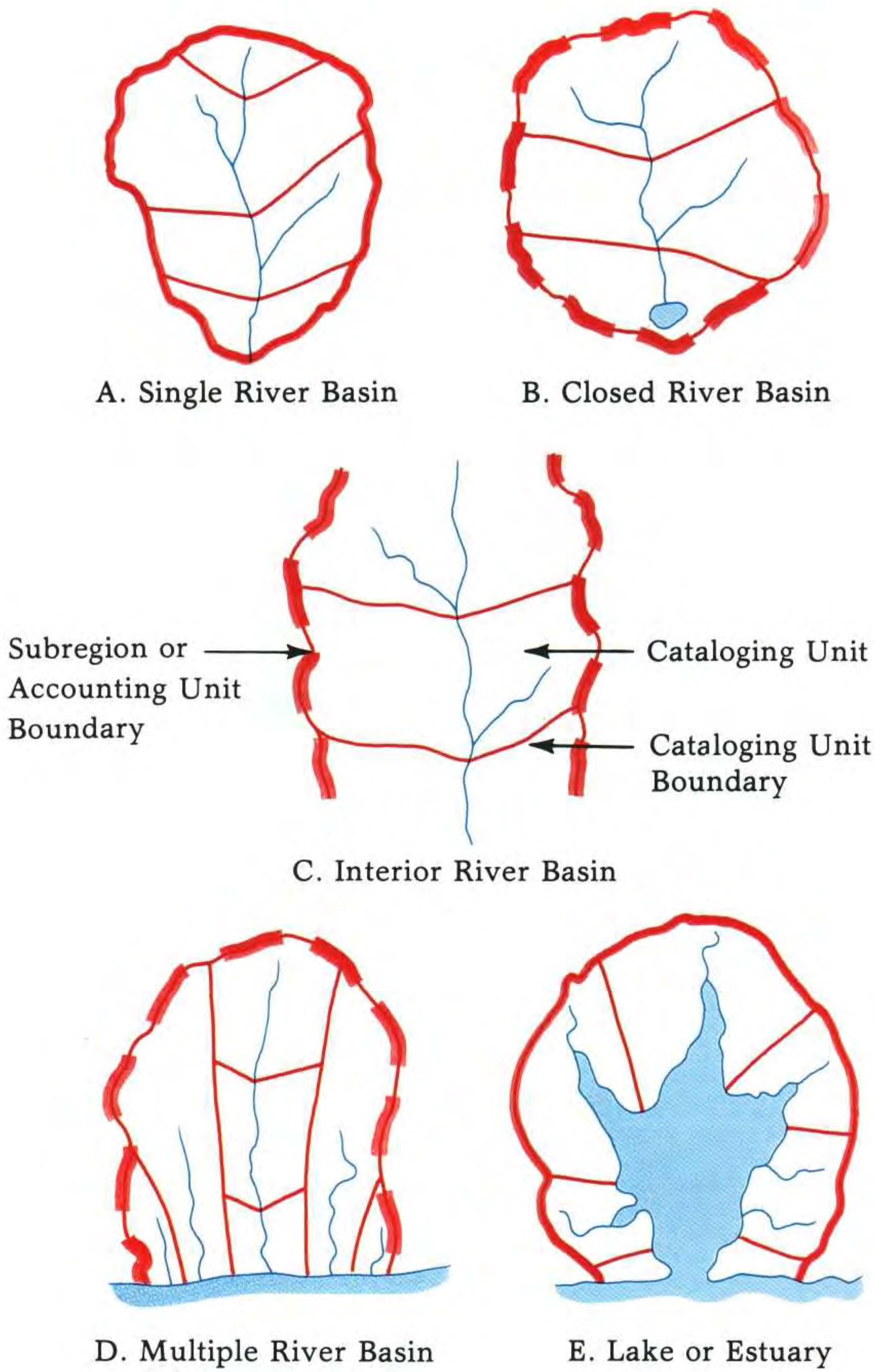
11. Drainage corrections. Drainage corrections to the base maps were made using the best and latest available reference maps, which are the U.S. Geological Survey's standard topographic maps published in 7.5- and 15-minute quadrangles. Unpublished maps approved for publication by the Geological Survey were occasionally used for reference.

Additional Specifications

Coastal Boundaries

Because of the varying and complex State and Federal laws governing the placement of coastal boundaries, closure of the hydrologic units is not shown on the Hydrologic Unit Maps along the coastline of the United States. However, the hydrologic units had to be closed for

Figure 5. Types of subregions and accounting units showing their relationship to the cataloging units.



A. Single River Basin

B. Closed River Basin

C. Interior River Basin

D. Multiple River Basin
(along a sea coast)

E. Lake or Estuary

the purpose of digitizing for computing areal totals. Additional problems arose in the delineation of certain shorelines and coastal areas because the areas of the hydrologic units and corresponding areal totals (county, State, and so forth) should conform as closely as possible to the areal statistics published by the U.S. Bureau of the Census. The resolution of this complex problem is described in U.S. Geological Survey Professional Paper 964 by Anderson and others (1976) and in U.S. Geological Survey Open-File Report 77-555 by George L. Loelkes (1977). Essentially, the U.S. Geological Survey accepted the guidelines for coastal areas developed in "Measurement of Geographic Area" by Malcolm J. Proudfoot (1940). The procedure is explained more fully in Loelkes (1977, p. 18-21).

Code Identification

The region numbers were those assigned by the U.S. Water Resources Council (1970). Subregion numbers, originally assigned in the same publication, were changed, if necessary, to reflect a nationally consistent downstream numbering of units. The accounting unit and cataloging unit numbers and boundaries were developed simultaneously with the maps by the two senior authors. Hydrologic unit numbers for the accounting and cataloging units were assigned in downstream order within each subregion. Where no downstream order was feasible, units were numbered north to south.

The political subdivision code was adopted from Federal Information Processing Standards Publication 6-2, issued by the U.S. National Bureau of Standards (1973). Each county or county equivalent is identified by a two-character State code and a three-character county code. The State code is shown in the map explanation and the three-character county code for each county is shown on the maps.

Digitized Units

The hydrologic unit boundaries were digitized using the scale-stable scribe coat originals of the Hydrologic Unit Maps. The scale of the 1:500,000 base maps was reduced in the digitization to 1:1,000,000. Alaska, Hawaii, and the Caribbean received special treatment. Owing to digitizer-size restrictions and base-map divisions, large States were digitized in several parts and then combined to form full State data bases. A computer program was developed to use with the full State data bases to identify the hydrologic unit code associated with the point location (latitude and longitude) of a data site. Subsequently, the State boundaries were deleted and the individual State data bases were combined to form the national data base. Information on these partial and full data bases can be found in U.S. Geological Survey Circular 817, sequence no's. 145, 173, and 191 (U.S. Geological Survey, 1979).

Drainage Areas

One of the purposes of digitizing the hydrologic unit boundaries on the Hydrologic Unit Maps was to provide a national compilation of drainage areas, which is shown in table 1. The areas originated as routine output from the digitizer are expressed in square inches of digitizer table. All areas were recomputed to square miles. Areas in all regions except Alaska are reported to three significant figures. Areas in Alaska are reported to two significant figures except for the subregions and accounting units, which are rounded to three significant figures.

The areas presented in table 1 have some inherent inaccuracies and should be used with some caution. The inaccuracies include the following: errors in locating the drainage boundaries on original topographic maps; errors in transferring the drainage boundaries to the scale-stable base materials; errors in digitizing the boundaries; errors introduced when partial States or full States were combined into the national data base; errors in rounding the final numbers; and, in the case of Alaska, errors due to the variation in map projections.

Through random comparisons with published drainage area values, it is estimated that the areas listed in table 1 are within 5 percent of the true values as determined by planimetering the same areas on the best available Geological Survey 7.5-minute topographic maps. The areas of the subregions and accounting units are generally subject to a smaller percentage of error than the cataloging units. The areas are presented herein to allow relative comparisons of drainage basin sizes, but not to establish them as official values. The areas listed for hydrologic units along the coasts or the Great Lakes may include both "inland water" and "water other than inland water" as described in Proudfoot (1940) and the U.S. Bureau of the Census (1970).

REVIEW AND APPROVAL

The need for nationwide acceptance of and agreement on the Hydrologic Unit Maps by a broad spectrum of water-resource interests was acknowledged from the beginning of the program. Thus, the hydrologic unit boundaries, codes, and names were reviewed extensively by all principal Federal, regional, and State water-resources agencies across the country during a formal review process established for the map series.

The formal review process consisted of a field review by the four regional and 46 district offices of the U.S. Geological Survey's Water Resources Division, in conjunction with their principal regional, State, and local cooperators, followed by review and approval by the National Planning and Assessment Committee of the Water Resources Council. Approval by the National Planning and Assessment Committee constituted approval by the

Council of Representatives of the Water Resources Council, which had delegated this authority to the committee. The maps received final Water Resources Council approval between 1974 and 1977.

CONFLICTS REGARDING BOUNDARIES

The overriding consideration in resolving any conflicts in boundary locations was to recognize boundaries and subdivisions most widely used and accepted by responsible State, regional, and Federal agencies, as long as the two basic criteria were met.

The Geological Survey's Water Resources Division districts were the prime source and authority for correcting hydrologic boundaries. State, regional, and Federal agencies were relied on for preferred ranking of units as well as delineation of unit boundaries and numbering of units. Boundary locations and ranking of units were essentially determined using professional judgment based on principles of hydrology and cartography.

Some boundary conflicts were resolved by the Water Resources Council after identification and documentation by the Geological Survey. Decisions at this level were limited to those for which agreement could not be reached locally or regionally, or those that were entrenched by law or Executive order. The hydrologic units affected by proposed boundary or numbering changes were documented for the Water Resources Council on a single set of State maps, which showed only those boundaries recommended by the Geological Survey after extensive field review.

All proposed changes in boundaries and numbering during the review process were documented and are on file with the Geological Survey's Office of Water Data Coordination in Reston, Va. This documentation describes the basis for the change, identifies the originator of the proposed change, and explains why each change was accepted or rejected. Minor undisputed changes in hydrologic boundaries made on the basis of hydrography or topography were not formally documented but are on file with the Geological Survey. Changes in previous boundary lines were not considered conflicts if all interested parties concurred with the changes, and if the changes were made in accordance with the criteria and specifications listed previously.

MAINTENANCE AND UPDATING

There is currently no plan to revise the Hydrologic Unit Maps except to correct major errors. Boundary, code, or name revisions can be accepted only from a responsible water-resources agency, whereas any user may notify the Geological Survey of errors on the maps. All changes in the hydrologic units, as cited in table 1 and in U.S. Geological Survey Circular 878–A (U.S. Geological Survey, 1982), are subject to approval by the Geological Survey.

Recommendations for changes and questions concerning the list of entities and codes shown in table 1 should be addressed to the Office of Water Data Coordination, which then will process all necessary amendments:

U.S. Geological Survey
Water Resources Division
Office of Water Data Coordination
417 National Center
Reston, VA 22092

USES

The Hydrologic Unit Maps have been used and applied by many other agencies and are being increasingly adopted by them for official uses. They have lasting value in planning activities relating to land and associated water resources, and in organizing and disseminating data, on both a geographic and hydrologic basis. The maps are suitable for use in conjunction with computer graphics and for automatic plotting of station locations and other areal data.

For data collection, storage, and manipulation, a standard coding system is necessary for efficient use and dissemination. The Geological Survey uses the coding system to document all its water-data collection activities and efforts. The boundaries of the hydrologic units have been digitized for more efficient use with data processing and automatic plotting machines.

Other Federal agencies using the hydrologic units for codifying and displaying the data that were collected locally and nationwide include the Forest Service, U.S. Army Corps of Engineers, Soil Conservation Service, Fish and Wildlife Service, National Park Service, Council on Environmental Quality, and National Weather Service, as well as regional, State, and local agencies.

National Water Data Network

The entire activity involving water-data collection, handling, storage, and dissemination in the United States can be thought of as a national water-data system. This system embraces all Federal and non-Federal water-data activities that contribute to meeting the general need for water information to support planning and operating water-related programs. All organized activities concerned with collecting water data on and beneath the Earth's surface for this national system can be considered as the National Water Data Network. The Hydrologic Unit Maps show boundaries of discrete elements of this surface-water network.

Cataloging and Coordinating Data

The Hydrologic Unit Maps are used for geographically locating the data sites indexed in the National Water Data Exchange Program and the "Catalog of Information on Water Data" and, therefore, constitute an important part of this data service.

Cataloging and coordinating play major roles in establishing design objectives for the National Water Data Network and provide the necessary basic information for planning, refining, and updating the network.

The "Catalog of Information on Water Data" was established by the Geological Survey in 1966 from information on some 60,000 activities supplied by more than 200 Federal, State, and local agencies and universities in the United States and by the Water Survey of Canada. The catalog is a file of information about water-data activities; it is not a compilation of the collected water data.

In response to the increasing needs of the water-data user community, the Geological Survey established the National Water Data Exchange in 1976 to enhance the exchange of water data between collector and user. The Master Water Data Index, a computerized file developed and maintained by the National Water Data Exchange, identifies sites for which water data are available, the location of these sites, the organizations collecting the data, the types of data available, and the frequency of measurement of each major type of data. The number of activities identified in the Master Water Data Index has grown to about 400,000, representing more than 400 organizations. For example, the Geological Survey, through the National Water Data Exchange, has incorporated the hydrologic unit codes into its computer system to enable all its members to have rapid access to data holdings that consist of more than a billion water-resource measurements.

Other Uses of Hydrologic Unit Maps

The Hydrologic Unit Maps have been used by both Government agencies and private firms. The following is a partial listing of uses and users.

The Soil Conservation Service has adopted the Hydrologic Unit Maps as a base for collecting data in its natural-resource inventories and surveys. The Soil Conservation Service data are coded so that they can be stored and retrieved on the basis of hydrologic units. The addition of a hyphen and a three-digit Soil Conservation Service watershed code to the eight-digit code (for example, 05120107–014) makes the Hydrologic Unit Map coding system applicable to areas delineated as part of the implementation of Public Law 83–566. As time and resources permit, the State conservationists of the Soil Conservation Service are putting the three-digit watershed coding system into effect as a supplement to the national hydrologic unit code.

The Geological Survey's National Mapping Division uses the hydrologic unit boundaries and coding system in its land-use and land-cover mapping program. Under this program, the conterminous States will be covered on the 1:250,000 scale map series over the next several years. All boundaries are again checked on the latest available accurate topographic maps, in order to ensure accuracy at this enlarged scale. The specifications for the land-use and land-cover and associated maps are given in Loelkes (1977). A further description of these maps is given in Anderson and others (1976). These Geological Survey land-use maps show (1) land use and cover, (2) Federal land ownership, (3) political units, (4) hydrologic units, (5) census county subdivisions, and (6) State land ownership.

The U.S. Fish and Wildlife Service is using the Hydrologic Unit Maps as bases on which to overprint its Stream Evaluation Map Series. The latter maps, provided to assist Federal and State agencies and water users in assessing the impact of proposed water-development projects on existing fishery resources, are a cooperative effort by the U.S. Department of the Interior, the U.S. Environmental Protection Agency, and the State Fish and Wildlife Departments of Colorado, Idaho, Montana, Nebraska, Nevada, North Dakota, Oklahoma, South Dakota, Texas, Utah, and Wyoming. The Fish and Wildlife Service, in conjunction with the Forest Service, has published another set of nationwide maps entitled "Ecoregion, Land-Surface Form and Hydrologic Unit Maps of the United States" (Bailey and Cushwa, 1982).

The Environmental Protection Agency is using the coding system in its storage and retrieval system, as well as in its River-Reach File. The River-Reach File is a computerized catalog of streams of the United States for organizing water-resources statistics and related information. In addition, it contains the digitized traces of streams, lakes, coastlines, and basin boundaries and provides a framework for simulated routing of streamflow and pollutants through the Nation's river systems. Computerized hard-copy displays and interactive graphics displays are available from the Environmental Protection Agency.

The Forest Service is using the maps to manage the resource data available for national forests. It is also using the maps as a base for the ongoing Inventory of Federal Reserved Water Rights. The National Park Service and the Bureau of Land Management are also using the maps for their portion of the Inventory of Federal Reserved Water Rights.

The U.S. Department of Energy has contracted with the Hanford Engineering Development Laboratory for the development of a Water Use Information System to help plan energy strategy. The system, which came on line in 1979, contains data on electrical generating plants and surface-water resources; additional capabilities will be added later. The system uses the Hydrologic Unit Maps as its base and provides data for each cataloging unit in the United States. These data can, of course, be aggregated into larger units and are also tabulated for each county and State. The water-resources element of the information system will contain four groups of data: area description, surface water, ground water, and oceans and bays.

The National Weather Service is using the maps for coding its meteorological data sites, and the U.S. Bureau of Commerce has used the maps as a base for its irrigation census. The Geological Survey is using the maps for its nationwide water-use program.

Many States use hydrologic subdivisions so small that it was not deemed advisable for nationwide consistency, or possible because of scale, to adopt their smallest recommended units on the Hydrologic Unit Maps. The plates used for the preparation of the maps are available to States and regional agencies, through the Geological Survey, for use in overprinting their own hydrologic, planning, or water-management units. Agencies in Florida and Minnesota have already printed their own maps with smaller units added to the base map.

Their sales record indicates that the Hydrologic Unit Maps have widespread use for planning water-related activities, as well as in organizing and disseminating data on a hydrologic, geographic, and political basis. The maps have been accepted by many Federal, State, and regional agencies, and the codes have been a published in the "Federal Register" and were approved as a Federal Standard in 1983. Their suitability for computer plotting of station locations and other areal data, and the ability to combine them into any size desired, has increased their value.

SUMMARY

The Hydrologic Unit Maps depict basic hydrologic and political areal planning units of the United States, thus providing a standard, uniform geographical framework for water-resource and related land-resource planning. Their use has standardized, nationwide, not only the boundaries of planning activities, but also the organization and dissemination of data. Most of the differences among Federal, regional, State, and local water-resource agencies as to location, size, and extent of hydrologic unit boundaries have been resolved as a result of intensive and extensive review. The maps will generally require only minor changes for future editions, mainly for correction of errors or for further subdivision of the *cataloging units.*

SELECTED BIBLIOGRAPHY

Anderson, J.R., Hardy, E.E., Roach, J.T., and Witmer, R.E., 1976, A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 28 p.

Bailey, R.G., and Cushwa, C.T., 1982, Ecoregion, land-surface form and hydrologic unit maps of the United States: Biological Services Program, U.S. Fish and Wildlife Service, Publication OBS-82/09, 3 maps.

Federal Interagency Committee on Water Resources, Subcommittee on Hydrology, 1951 [rev. 1963], Notes on hydrologic activities—Interagency coordination of drainage area data: Bulletin 4, 28 p.

______1961, Notes on hydrologic activities—River basin maps showing hydrologic stations: Bulletin 11, 79 maps.

Federal Interagency River Basin Committee, Subcommittee on Hydrology, 1947 [rev. 1949], River basin maps showing hydrologic stations: 79 maps.

Kammerer, J.C., 1969, Delineation of major water regions in the conterminous United States, 1908–68: U.S. Geological Survey, Water Resources Review, January 1969, p. 10.

Langford, R.H., and Kapinos, F.P., 1979, The national water data network: A case history: Water Resources Research, v. 15, no. 6, p. 1687–1691.

Loelkes, G.L., Jr., 1977, Specifications for land use and land cover and associated maps: U.S. Geological Survey Open-File Report 77–555, 115 p.

Piper, A.M., 1965, Has the United States enough water?: U.S. Geological Survey Water-Supply Paper 1797, 27 p. [1966].

Proudfoot, M.J., 1940, Measurement of geographic area: U.S. Department of Commerce, Bureau of the Census, p. 37–51.

Seaber, P.R., Kapinos, F.P., and Shanton, J.A., 1975, U.S. Geological Survey State Hydrologic Unit Maps: Geoscience Information—Proceedings of the Geosciences Information Society, v. 5, p. 41–53.

U.S. Bureau of the Budget, 1964, Coordination of Federal activities in the acquisition of certain water data: Circular A–67, 4 p.

U.S. Bureau of the Census, 1970, Areas of the United States: U.S. Department of Commerce, Bureau of the Census, Area Measurement Reports no. 1–52.

U.S. Congress, 1965, Water Resources Planning Act, Public Law 89–80, 79 Stat. 244, 11 p.

U.S. Department of Agriculture, 1963, Atlas of river basins of the United States: Soil Conservation Service, 79 maps.

______1967, Conservation needs inventory: Soil Conservation Service, 211 p.

______1970, Atlas of river basins of the United States: Soil Conservation Service, 82 maps.

______1980, Soil, water, and related resources in the United States: Status, conditions, and trends, Parts I–II: 624 p.

U.S. Geological Survey, 1910, Surface-water supply of the United States, 1907–08, Part 1, North Atlantic Coast: U.S. Geological Survey Water-Supply Paper 241, 356 p.

______1979, Scientific and technical, spatial, and bibliographic data bases of the U.S. Geological Survey: U.S. Geological Survey Circular 817, 223 entries.

———1982, A U.S. Geological Survey data standard, Codes for the identification of hydrologic units in the United States and the Caribbean outlying areas: U.S. Geological Survey Circular 878-A, 115 p.

U.S. Geological Survey, Office of Water Data Coordination, 1973, Catalog of information on water data—1972 edition: Reston, Va. (21 v. by region, 86 maps showing location of water-quality stations, and 86 maps showing location of streamflow and stage stations).

U.S. National Bureau of Standards, 1973, Counties and county equivalents of the States of the United States: U.S. Department of Commerce, Federal Information Processing Standards (FIPS) Publication 6-2, 35 p.

———1983, Codes for the identification of hydrologic units in the United States and the Caribbean outlying areas: Federal Information Processing Standards Publication 103: U.S. Deparment of Commerce.

U.S. Senate, Select Committee on National Water Resources, 1959-1960, Water resources activities in the United States (U.S. 86th Congress): Washington, D.C., U.S. Government Printing Office, 3 v., 31 prints.

U.S. Water Resources Council, 1968, The Nation's water resources, Parts 1-7, The first national assessment of the Water Resources Council: Washington, D.C., 414 p.

———1970, Water resources regions and subregions for the National Assessment of Water and Related Land Resources: Washington, D.C., 188 p.

———1978, The Nation's water resources, Parts 1-5, The second national water assessment by the U.S. Water Resources Council: Washington, D.C. (6 pt., 3 stat. app.)

U.S. Water Resources Council, Hydrology Subcommittee, 1967 [rev. 1968], River mileage measurement: Bulletin 14, 17 p.

Table 1. Hydrologic unit codes, descriptions, names, and drainage areas

	Water-resources region	*Page*
01.	New England	17
02.	Mid-Atlantic	18
03.	South Atlantic-Gulf	20
04.	Great Lakes	24
05.	Ohio	27
06.	Tennessee	30
07.	Upper Mississippi	31
08.	Lower Mississippi	33
09.	Souris-Red-Rainy	36
10.	Missouri	37
11.	Arkansas-White-Red	42
12.	Texas-Gulf	46
13.	Rio Grande	48
14.	Upper Colorado	50
15.	Lower Colorado	51
16.	Great Basin	53
17.	Pacific Northwest	55
18.	California	58
19.	Alaska	61
20.	Hawaii	62
21.	Caribbean	63

REGION 01 NEW ENGLAND REGION — THE DRAINAGE WITHIN THE UNITED STATES THAT ULTIMATELY DISCHARGES INTO: (A) THE BAY OF FUNDY; (B) THE ATLANTIC OCEAN WITHIN AND BETWEEN THE STATES OF MAINE AND CONNECTICUT; (C) LONG ISLAND SOUND NORTH OF THE NEW YORK-CONNECTICUT STATE LINE; AND (D) THE RIVIERE ST. FRANCOIS, A TRIBUTARY OF THE ST. LAWRENCE RIVER. INCLUDES ALL OF MAINE, NEW HAMPSHIRE AND RHODE ISLAND AND PARTS OF CONNECTICUT, MASSACHUSETTS, NEW YORK, AND VERMONT.

SUBREGION 0101 — ST. JOHN: THE ST. JOHN RIVER BASIN WITHIN THE UNITED STATES. MAINE.
AREA = 7330 SQ.MI.

ACCOUNTING UNIT 010100 — ST. JOHN. MAINE.
AREA = 7330 SQ.MI.

CATALOGING UNITS
01010001 — UPPER ST. JOHN. MAINE. AREA = 2120 SQ.MI.
01010002 — ALLAGASH. MAINE. AREA = 1250 SQ.MI.
01010003 — FISH. MAINE. AREA = 908 SQ.MI.
01010004 — AROOSTOOK. MAINE. AREA = 2420 SQ.MI.
01010005 — MEDUXNEKEAG. MAINE. AREA = 634 SQ.MI.

SUBREGION 0102 — PENOBSCOT: THE PENOBSCOT RIVER BASIN. MAINE.
AREA = 8610 SQ.MI.

ACCOUNTING UNIT 010200 — PENOBSCOT. MAINE.
AREA = 8610 SQ.MI.

CATALOGING UNITS
01020001 — WEST BRANCH PENOBSCOT. MAINE. AREA = 2150 SQ.MI.
01020002 — EAST BRANCH PENOBSCOT. MAINE. AREA = 1130 SQ.MI.
01020003 — MATTAWAMKEAG. MAINE. AREA = 1510 SQ.MI.
01020004 — PISCATAQUIS. MAINE. AREA = 1460 SQ.MI.
01020005 — LOWER PENOBSCOT. MAINE. AREA = 2360 SQ.MI.

SUBREGION 0103 — KENNEBEC: THE KENNEBEC RIVER BASIN, INCLUDING PART OF MERRYMEETING BAY. MAINE.
AREA = 5900 SQ.MI.

ACCOUNTING UNIT 010300 — KENNEBEC. MAINE.
AREA = 5900 SQ.MI.

CATALOGING UNITS
01030001 — UPPER KENNEBEC. MAINE. AREA = 1570 SQ.MI.
01030002 — DEAD. MAINE. AREA = 878 SQ.MI.
01030003 — LOWER KENNEBEC. MAINE. AREA = 3450 SQ.MI.

SUBREGION 0104 — ANDROSCOGGIN: THE ANDROSCOGGIN RIVER BASIN, INCLUDING PART OF MERRYMEETING BAY. MAINE, NEW HAMPSHIRE.
AREA = 3530 SQ.MI.

ACCOUNTING UNIT 010400 — ANDROSCOGGIN. MAINE, NEW HAMPSHIRE.
AREA = 3530 SQ.MI.

CATALOGING UNITS
01040001 — UPPER ANDROSCOGGIN. MAINE, NEW HAMPSHIRE. AREA = 1470 SQ.MI.
01040002 — LOWER ANDROSCOGGIN. MAINE, NEW HAMPSHIRE. AREA = 2060 SQ.MI.

SUBREGION 0105 — MAINE COASTAL: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE MAINE-NEW BRUNSWICK INTERNATIONAL BOUNDARY TO CAPE SMALL, MAINE, INCLUDING THE ST. CROIX RIVER BASIN WITHIN THE UNITED STATES. MAINE.
AREA = 7130 SQ.MI.

ACCOUNTING UNIT 010500 — MAINE COASTAL. MAINE.
AREA = 7130 SQ.MI.

CATALOGING UNITS
01050001 — ST. CROIX. MAINE. AREA = 999 SQ.MI.
01050002 — MAINE COASTAL. MAINE. AREA = 4880 SQ.MI.
01050003 — ST. GEORGE-SHEEPSCOT. MAINE. AREA = 1250 SQ.MI.

SUBREGION 0106 — SACO: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM CAPE SMALL, MAINE TO THE MERRIMACK RIVER BASIN BOUNDARY. MAINE, NEW HAMPSHIRE, MASSACHUSETTS.
AREA = 4330 SQ.MI.

ACCOUNTING UNIT 010600 — SACO. MAINE, NEW HAMPSHIRE, MASSACHUSETTS.
AREA = 4330 SQ.MI.

CATALOGING UNITS
01060001 — PRESUMPSCOT. MAINE. AREA = 1240 SQ.MI.
01060002 — SACO. MAINE, NEW HAMPSHIRE. AREA = 1690 SQ.MI.
01060003 — PISCATAQUA-SALMON FALLS. MAINE, NEW HAMPSHIRE, MASSACHUSETTS. AREA = 1400 SQ.MI.

SUBREGION 0107 — MERRIMACK: THE MERRIMACK RIVER BASIN. MASSACHUSETTS, NEW HAMPSHIRE.
AREA = 4980 SQ.MI.

ACCOUNTING UNIT 010700 — MERRIMACK. MASSACHUSETTS, NEW HAMPSHIRE.
AREA = 4980 SQ.MI.

CATALOGING UNITS
01070001 — PEMIGEWASSET. NEW HAMPSHIRE. AREA = 1000 SQ.MI.
01070002 — MERRIMACK. MASSACHUSETTS, NEW HAMPSHIRE. AREA = 2300 SQ.MI.
01070003 — CONTOOCOOK. NEW HAMPSHIRE. AREA = 757 SQ.MI.
01070004 — NASHUA. MASSACHUSETTS, NEW HAMPSHIRE. AREA = 525 SQ.MI.
01070005 — CONCORD. MASSACHUSETTS. AREA = 401 SQ.MI.

SUBREGION 0108 — CONNECTICUT: THE CONNECTICUT RIVER BASIN. CONNECTICUT, MASSACHUSETTS, NEW HAMPSHIRE, VERMONT.
AREA = 11100 SQ.MI.

ACCOUNTING UNIT 010801 — UPPER CONNECTICUT: THE CONNECTICUT RIVER BASIN ABOVE VERNON DAM. NEW HAMSPHIRE, VERMONT.
AREA = 6120 SQ.MI.

CATALOGING UNITS —
01080101 — UPPER CONNECTICUT. NEW HAMPSHIRE VERMONT. AREA = 1990 SQ.MI.
01080102 — PASSUMPSIC. VERMONT.. AREA = 496 SQ.MI.
01080103 — WAITS. VERMONT. AREA = 441 SQ.MI.
01080104 — UPPER CONNECTICUT-MASCOMA. NEW HAMPSHIRE, VERMONT. AREA = 1460 SQ.MI.
01080105 — WHITE. VERMONT. AREA = 703 SQ.MI.
01080106 — BLACK-OTTAUQUECHEE. VERMONT. AREA = 418 SQ.MI.
01080107 — WEST. VERMONT. AREA = 612 SQ.MI.

ACCOUNTING UNIT 010802 — LOWER CONNECTICUT: THE CONNECTICUT RIVER BASIN BELOW VERNON DAM. CONNECTICUT, MASSACHUSETTS, NEW HAMPSHIRE, VERMONT.
AREA = 4960 SQ.MI.

CATALOGING UNITS
01080201 — MIDDLE CONNECTICUT. MASSACHUSETTS, NEW HAMPSHIRE, VERMONT. AREA = 999 SQ.MI.
01080202 — MILLER. MASSACHUSETTS, NEW HAMSPHIRE. AREA = 391 SQ.MI.
01080203 — DEERFIELD. MASSACHUSETTS, VERMONT. AREA = 658 SQ.MI.
01080204 — CHICOPEE. MASSACHUSETTS. AREA = 725 SQ.MI.
01080205 — LOWER CONNECTICUT. CONNECTICUT, MASSACHUSETTS. AREA = 1090 SQ.MI.
01080206 — WESTFIELD. CONNECTICUT, MASSACHUSETTS. AREA = 505 SQ.MI.
01080207 — FARMINGTON. CONNECTICUT, MASSACHUSETTS. AREA = 590 SQ.MI.

SUBREGION 0109 — MASSACHUSETTS-RHODE ISLAND COASTAL: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE MERRIMACK RIVER BASIN BOUNDART TO AND INCLUDING THE PAWCATUCK RIVER BASIN. CONNECTICUT, MASSACHUSETTS, RHODE ISLAND.
AREA = 5510 SQ.MI.

REGION 01: NEW ENGLAND — Continued

ACCOUNTING UNIT 010900 — MASSACHUSETTS-RHODE ISLAND COASTAL. CONNECTICUT, MASSACHUSETTS, RHODE ISLAND.
AREA = 5510 SQ.MI.

CATALOGING UNITS 01090001 — CHARLES. MASSACHUSETTS.
AREA = 1130 SQ.MI.
01090002 — CAPE COD. MASSACHUSETTS, RHODE ISLAND.
AREA = 2220 SQ.MI.
01090003 — BLACKSTONE. MASSACHUSETTS, RHODE ISLAND.
AREA = 451 SQ.MI.
01090004 — NARRAGANSETT. MASSACHUSETTS, RHODE ISLAND.
AREA = 1330 SQ.MI.
01090005 — PAWCATUCK-WOOD. CONNECTICUT, RHODE ISLAND.
AREA = 383 SQ.MI.

SUBREGION 0110 — CONNECTICUT COASTAL: THE COASTAL DRAINAGE INTO LONG ISLAND SOUND FROM THE PAWCATUCK RIVER BASIN BOUNDARY TO AND INCLUDING THE BYRAM RIVER BASIN, EXCLUDING THE CONNECTICUT RIVER BASIN, AND INCLUDING LONG ISLAND SOUND NORTH OF THE NEW YORK-CONNECTICUT STATE LINE. CONNECTICUT, MASSACHUSETTS, NEW YORK, RHODE ISLAND.
AREA = 5080 SQ.MI.

ACCOUNTING UNIT 011000 — CONNECTICUT COASTAL. CONNECTICUT, MASSACHUSETTS, NEW YORK, RHODE ISLAND.
AREA = 5080 SQ.MI.

CATALOGING UNITS 01100001 — QUINEBAUG. CONNECTICUT, MASSACHUSETTS, RHODE ISLAND.
AREA = 729 SQ.MI.
01100002 — SHETUCKET. CONNECTICUT, MASSACHUSETTS.
AREA = 517 SQ.MI.
01100003 — THAMES. CONNECTICUT.
AREA = 381 SQ.MI.
01100004 — QUINNIPIAC. CONNECTICUT.
AREA = 516 SQ.MI.
01100005 — HOUSATONIC. CONNECTICUT, MASSACHUSETTS, NEW YORK.
AREA = 1930 SQ.MI.
01100006 — SAUGATUCK. CONNECTICUT, NEW YORK.
AREA = 436 SQ.MI.
01100007 — LONG ISLAND SOUND. CONNECTICUT.
AREA = 568 SQ.MI.

SUBREGION 0111 — ST. FRANCOIS: THE RIVIERE ST. FRANCOIS BASIN WITHIN THE UNITED STATES. VERMONT.
AREA = 590 SQ.MI.

ACCOUNTING UNIT 011100 — ST. FRANCOIS. VERMONT.
AREA = 590 SQ.MI.

CATALOGING UNIT 01110000 — ST. FRANCOIS. VERMONT.
AREA = 590 SQ.MI.

REGION 02 MID ATLANTIC REGION — THE DRAINAGE WITHIN THE UNITED STATES THAT ULTIMATELY DISCHARGES INTO: (A) THE ATLANTIC OCEAN WITHIN AND BETWEEN THE STATES OF NEW YORK AND VIRGINIA; (B) LONG ISLAND SOUND SOUTH OF THE NEW YORK-CONNECTICUT STATE LINE; AND (C) THE RIVIERE RICHELIEU, A TRIBUTARY OF THE ST. LAWRENCE RIVER. INCLUDES ALL OF DELAWARE AND NEW JERSEY AND THE DISTRICT OF COLUMBIA, AND PARTS OF CONNECTICUT, MARYLAND, MASSACHUSETTS, NEW YORK, PENNSYLVANIA, VERMONT, VIRGINIA, AND WEST VIRGINIA.

SUBREGION 0201 — RICHELIEU: THE RIVIERE RICHELIEU BASIN, INCLUDING LAKE CHAMPLAIN DRAINAGE, WITHIN THE UNITED STATES. NEW YORK, VERMONT.
AREA = 7720 SQ.MI.

ACCOUNTING UNIT 020100 — RICHELIEU. NEW YORK, VERMONT.
AREA = 7720 SQ.MI.

CATALOGING UNITS 02010001 — LAKE GEORGE. NEW YORK, VERMONT.
AREA = 1390 SQ.MI.
02010002 — OTTER. VERMONT.
AREA = 1090 SQ.MI.
02010003 — WINOOSKI. VERMONT.
AREA = 1220 SQ.MI.
02010004 — AUSABLE. NEW YORK.
AREA = 1070 SQ.MI.
02010005 — LAMOILLE. VERMONT.
AREA = 1130 SQ.MI.
02010006 — GREAT CHAZY-SARANAC. NEW YORK.
AREA = 1110 SQ.MI.
02010007 — MISSISQUOI. VERMONT.
AREA = 707 SQ.MI.

SUBREGION 0202 — UPPER HUDSON: THE HUDSON RIVER BASIN TO AND INCLUDING THE POPOLOPEN BROOK BASIN JUST UPSTREAM FROM BEAR MOUNTAIN BRIDGE. NEW JERSEY, NEW YORK, MASSACHUSETTS, VERMONT.
AREA = 12500 SQ.MI.

ACCOUNTING UNIT 020200 — UPPER HUDSON. NEW JERSEY, NEW YORK, MASSACHUSETTS, VERMONT.
AREA = 12500 SQ.MI.

CATALOGING UNITS 02020001 — UPPER HUDSON. NEW YORK.
AREA = 1630 SQ.MI.
02020002 — SACANDAGA. NEW YORK.
AREA = 1050 SQ.MI.
02020003 — HUDSON-HOOSIC. NEW YORK, MASSACHUSETTS, VERMONT.
AREA = 1880 SQ.MI.
02020004 — MOHAWK. NEW YORK.
AREA = 2550 SQ.MI.
02020005 — SCHOHARIE. NEW YORK.
AREA = 927 SQ.MI.
02020006 — MIDDLE HUDSON. MASSACHUSETTS, NEW YORK.
AREA = 2390 SQ.MI.
02020007 — RONDOUT. NEW JERSEY, NEW YORK.
AREA = 1190 SQ.MI.
02020008 — HUDSON-WAPPINGER. NEW YORK.
AREA = 928 SQ.MI.

SUBREGION 0203 — LOWER HUDSON-LONG ISLAND: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE BYRAM RIVER BASIN BOUNDARY, TO THE MANASQUAN RIVER BASIN BOUNDARY, INCLUDING THE HUDSON RIVER BASIN DOWNSTREAM FROM THE POPOLOPEN BROOK BASIN BOUNDARY, LONG ISLAND AND BLOCK ISLAND SOUNDS SOUTH OF THE NEW YORK-CONNECTICUT STATE LINE, AND LONG ISLAND. CONNECTICUT, NEW JERSEY, NEW YORK.
AREA = 6360 SQ.MI.

ACCOUNTING UNIT 020301 — LOWER HUDSON: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE BYRAM RIVER BASIN BOUNDARY, TO THE MANASQUAN RIVER BASIN BOUNDARY, INCLUDING THE HUDSON RIVER BASIN DOWNSTREAM FROM THE POPOLOPEN BROOK BASIN BOUNDARY, AND LONG ISLAND SOUND IN WESTCHESTER AND BRONX COUNTIES, NEW YORK, BUT EXCLUDING LONG ISLAND AND BLOCK ISLAND SOUNDS SOUTH OF THE NEW YORK-CONNECTICUT STATE LINE AND LONG ISLAND. CONNECTICUT, NEW JERSEY, NEW YORK.
AREA = 3790 SQ.MI.

CATALOGING UNITS 02030101 — LOWER HUDSON. CONNECTICUT, NEW JERSEY, NEW YORK.
AREA = 720 SQ.MI.
02030102 — BRONX. NEW YORK.
AREA = 190 SQ.MI.
02030103 — HACKENSACK-PASSAIC. NEW JERSEY, NEW YORK.
AREA = 1120 SQ.MI.
02030104 — SANDY HOOK-STATEN ISLAND. NEW JERSEY, NEW YORK.
AREA = 679 SQ.MI.
02030105 — RARITAN. NEW JERSEY.
AREA = 1080 SQ.MI.

ACCOUNTING UNIT 020302 — LONG ISLAND: LONG ISLAND AND LONG ISLAND AND BLOCK ISLAND SOUNDS SOUTH OF THE NEW YORK-CONNECTICUT STATE LINE, BUT EXCLUDING LONG ISLAND SOUND IN WESTCHESTER AND BRONX COUNTIES, NEW YORK. NEW YORK.
AREA = 2580 SQ.MI.

CATALOGING UNITS 02030201 — NORTHERN LONG ISLAND. NEW YORK.
AREA = 915 SQ.MI.
02030202 — SOUTHERN LONG ISLAND. NEW YORK.
AREA = 1660 SQ.MI.

SUBREGION 0204 — DELAWARE: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM AND INCLUDING THE MANASQUAN RIVER BASIN TO AND INCLUDING THE DELAWARE RIVER BASIN WHICH INCLUDES DELAWARE BAY. DELAWARE, MARYLAND, NEW JERSEY, NEW YORK, PENNSYLVANIA.
AREA = 15500 SQ.MI.

ACCOUNTING UNIT 020401 — UPPER DELAWARE: THE DELAWARE RIVER BASIN UPSTREAM FROM THE FALL LINE (HIGHEST TIDAL EFFECT OF THE DELAWARE RIVER) AT TRENTON, NEW JERSEY. NEW JERSEY, NEW YORK, PENNSYLVANIA.
AREA = 6800 SQ.MI.

CATALOGING UNITS 02040101 — UPPER DELAWARE. NEW YORK, PENNSYLVANIA.
AREA = 1180 SQ.MI.
02040102 — EAST BRANCH DELAWARE. NEW YORK.
AREA = 828 SQ.MI.
02040103 — LACKAWAXEN. PENNSYLVANIA.
AREA = 587 SQ.MI.
02040104 — MIDDLE DELAWARE-MONGAUP-BRODHEAD. NEW JERSEY, NEW YORK, PENNSYLVANIA.
AREA = 1520 SQ.MI.
02040105 — MIDDLE DELAWARE-MUSCONETCONG. NEW JERSEY, PENNSYLVANIA.
AREA = 1330 SQ.MI.
02040106 — LEHIGH. PENNSYLVANIA.
AREA = 1350 SQ.MI.

ACCOUNTING UNIT 020402 — LOWER DELAWARE: THE DELAWARE RIVER BASIN DOWNSTREAM FORM THE FALL LINE AT TRENTON, NEW JERSEY, INCLUDING DELAWARE BAY. DELAWARE, MARYLAND, NEW JERSEY, PENNSYLVANIA.
AREA = 6650 SQ.MI.

CATALOGING UNITS 02040201 — CROSSWICKS-NESHAMINY. NEW JERSEY, PENNSYLVANIA.
AREA = 521 SQ.MI.
02040202 — LOWER DELAWARE. NEW JERSEY, PENNSYLVANIA.
AREA = 1050 SQ.MI.
02040203 — SCHUYLKILL. PENNSYLVANIA.
AREA = 1900 SQ.MI.
02040204 — DELAWARE BAY. NEW JERSEY.
AREA = 744 SQ.MI.
02040205 — BRANDYWINE-CHRISTINA. DELAWARE, MARYLAND, PENNSYLVANIA.
AREA = 745 SQ.MI.
02040206 — COHANSEY-MAURICE. NEW JERSEY.
AREA = 1060 SQ.MI.
02040207 — BROADKILL-SMYRNA. DELAWARE.
AREA = 628 SQ.MI.

ACCOUNTING UNIT 020403 — NEW JERSEY COASTAL: THE COASTAL DRAINAGE IN NEW JERSEY FROM AND INCLUDING THE MANASQUAN RIVER BASIN TO THE DELAWARE BAY DRAINAGE BOUNDARY. NEW JERSEY.
AREA = 2070 SQ.MI.

CATALOGING UNITS 02040301 — MULLICA-TOMS. NEW JERSEY
AREA = 1350 SQ.MI.
02040302 — GREAT EGG HARBOR. NEW JERSEY.
AREA = 717 SQ.MI.

SUBREGION 0205 — SUSQUEHANNA: THE SUSQUEHANNA RIVER BASIN. MARYLAND, NEW YORK, PENNSYLVANIA.
AREA = 27200 SQ.MI.

ACCOUNTING UNIT 020501 — UPPER SUSQUEHANNA: THE SUSQUEHANNA RIVER BASIN ABOVE THE CONFLUENCE WITH THE WEST BRANCH SUSQUENHANNA RIVER BASIN. NEW YORK, PENNSYLVANIA.
AREA = 11200 SQ.MI.

CATALOGING UNITS 02050101 — UPPER SUSQUEHANNA. NEW YORK, PENNSYLVANIA.
AREA = 2260 SQ.MI.
02050102 — CHENANGO. NEW YORK.
AREA = 1580 SQ.MI.
02050103 — OWEGO-WAPPASENING. NEW YORK, PENNSYLVANIA.
AREA = 1040 SQ.MI.
02050104 — TIOGA. NEW YORK, PENNSYLVANIA.
AREA = 1370 SQ.MI.
02050105 — CHEMUNG. NEW YORK, PENNSYLVANIA.
AREA = 1200 SQ.MI.
02050106 — UPPER SUSQUEHANNA-TUNKHANNOCK. PENNSYLVANIA.
AREA = 1980 SQ.MI.
02050107 — UPPER SUSQUEHANNA-LACKAWANNA. PENNSYLVANIA.
AREA = 1760 SQ.MI.

ACCOUNTING UNIT 020502 — WEST BRANCH SUSQUEHANNA: THE WEST BRANCH SUSQUEHANNA RIVER BASIN. PENNSYLVANIA.
AREA = 6920 SQ.MI.

CATALOGING UNITS 02050201 — UPPER WEST BRANCH SUSQUEHANNA. PENNSYLVANIA.
AREA = 1590 SQ.MI.
02050202 — SINNEMAHONING. PENNSYLVANIA.
AREA = 1020 SQ.MI.
02050203 — MIDDLE WEST BRANCH SUSQUEHANNA. PENNSYLVANIA.
AREA = 768 SQ.MI.
02050204 — BALD EAGLE. PENNSYLVANIA.
AREA = 765 SQ.MI.
02050205 — PINE. PENNSYLVANIA.
AREA = 970 SQ.MI.
02050206 — LOWER WEST BRANCH SUSQUEHANNA. PENNSYLVANIA.
AREA = 1810 SQ.MI.

ACCOUNTING UNIT 020503 — LOWER SUSQUEHANNA: THE SUSQUEHANNA RIVER BASIN BELOW THE CONFLUENCE WITH THE WEST BRANCH SUSQUEHANNA RIVER BASIN. MARYLAND, PENNSYLVANIA.
AREA = 9080 SQ.MI.

CATALOGING UNITS 02050301 — LOWER SUSQUEHANNA-PENNS. PENNSYLVANIA.
AREA = 1430 SQ.MI.
02050302 — UPPER JUNIATA. PENNSYLVANIA.
AREA = 973 SQ.MI.
02050303 — RAYSTOWN. PENNSYLVANIA.
AREA = 937 SQ.MI.
02050304 — LOWER JUNIATA. PENNSYLVANIA.
AREA = 1450 SQ.MI.
02050305 — LOWER SUSQUEHANNA-SWATARA. PENNSYLVANIA.
AREA = 1850 SQ.MI.
02050306 — LOWER SUSQUEHANNA. MARYLAND, PENNSYLVANIA.
AREA = 2440 SQ.MI.

SUBREGION 0206 — UPPER CHESAPEAKE: THE CHESAPEAKE BAY AND ITS TRIBUTARY DRAINAGE NORTH OF THE MARYLAND-VIRGINIA STATE LINE INCLUDING THE POCOMOKE RIVER DRAINAGE, EXCLUDING THE SUSQUEHANNA AND POTOMAC RIVER BASINS; AND THE COASTAL DRAINAGE FROM THE DELAWARE BAY DRAINAGE BOUNDARY TO CHINCOTEAGUE INLET ON THE DELMARVA PENINSULA. DELAWARE, MARYLAND, VIRGINIA, AND PENNSYLVANIA.
AREA = 8980 SQ.MI.

ACCOUNTING UNIT 020600 — UPPER CHESAPEAKE. DELAWARE, MARYLAND, VIRGINIA, AND PENNSYLVANIA.
AREA = 8980 SQ.MI.

CATALOGING UNITS 02060001 — UPPER CHESAPEAKE BAY. MARYLAND.
AREA = 1270 SQ.MI.
02060002 — CHESTER-SASSAFRAS. DELAWARE, MARYLAND, PENNSYLVANIA.
AREA = 1290 SQ.MI.
02060003 — GUNPOWDER-PATAPSCO. MARYLAND, PENNSYLVANIA.
AREA = 1370 SQ.MI.
02060004 — SEVERN. MARYLAND.
AREA = 325 SQ.MI.
02060005 — CHOPTANK. DELAWARE, MARYLAND.
AREA = 931 SQ.MI.
02060006 — PATUXENT. MARYLAND.
AREA = 922 SQ.MI.
02060007 — BLACKWATER-WICOMICO. DELAWARE, MARYLAND.
AREA = 537 SQ.MI.
02060008 — NANTICOKE. DELAWARE, MARYLAND.
AREA = 821 SQ.MI.
02060009 — POCOMOKE. DELAWARE, MARYLAND, VIRGINIA.
AREA = 771 SQ.MI.
02060010 — CHINCOTEAGUE. DELAWARE, MARYLAND, VIRGINIA.
AREA = 742 SQ.MI.

SUBREGION 0207 — POTOMAC: THE POTOMAC RIVER BASIN. DISTRICT OF COLUMBIA, MARYLAND, PENNSYLVANIA, VIRGINIA, WESY VIRGINIA.
AREA = 14600 SQ.MI.

ACCOUNTING UNIT 020700 — POTOMAC. DISTRICT OF COLUMBIA, MARYLAND, PENNSYLVANIA, VIRGINIA, WEST VIRGINIA.
AREA = 14600 SQ.MI.

CATALOGING UNITS 02070001 — SOUTH BRANCH POTOMAC. WEST VIRGINIA, VIRGINIA.
AREA = 1490 SQ.MI.
02070002 — NORTH BRANCH POTOMAC. MARYLAND, WEST VIRGINIA, PENNSYLVANIA.
AREA = 1360 SQ.MI.
02070003 — CACAPON-TOWN. MARYLAND, PENNSYLVANIA, WEST VIRGINIA.
AREA = 1200 SQ.MI.
02070004 — CONOCOCHEAGUE-OPEQUON. MARYLAND, PENNSYLVANIA, VIRGINIA, WEST VIRGINIA.
AREA = 2250 SQ.MI.
02070005 — SOUTH FORK SHENANDOAH. VIRGINIA.
AREA = 1660 SQ.MI.
02070006 — NORTH FORK SHENANDOAH. VIRGINIA, WEST VIRGINIA.
AREA = 1040 SQ.MI.
02070007 — SHENANDOAH. VIRGINIA, WEST VIRGINIA.
AREA = 359 SQ.MI.
02070008 — MIDDLE POTOMAC-CATOCTIN. DISTRICT OF COLUMBIA, VIRGINIA, MARYLAND.
AREA = 1210 SQ.MI.
02070009 — MONOCACY. MARYLAND, PENNSYLVANIA.
AREA = 962 SQ.MI.
02070010 — MIDDLE POTOMAC-ANACOSTIA-OCCOQUAN. DISTRICT OF COLUMBIA, MARYLAND, VIRGINIA.
AREA = 1280 SQ.MI.
02070011 — LOWER POTOMAC. MARYLAND, VIRGINIA.
AREA = 1800 SQ.MI.

SUBREGION 0208 — LOWER CHESAPEAKE: THE CHESAPEAKE BAY AND ITS TRIBUTARY DRAINAGE SOUTH OF THE MARYLAND-VIRGINIA STATE LINE EXCLUDING THE POCOMOKE RIVER DRAINAGE; AND THE COASTAL DRAINAGE FROM CHINCOTEAGUE INLET ON THE DELMARVA PENINSULA TO THE BACK BAY DRAINAGE BOUNDARY. VIRGINIA, WEST VIRGINIA.
AREA = 18500 SQ.MI.

ACCOUNTING UNIT 020801 — LOWER CHESAPEAKE.--THE CHESAPEAKE BAY AND ITS TRIBUTARY DRAINAGE SOUTH OF THE MARYLAND-VIRGINIA STATE LINE EXCLUDING THE POCOMOKE RIVER DRAINAGE, AND EXCLUDING THE JAMES RIVER BASIN; AND THE COASTAL DRAINAGE FROM CHINCOTEAGUE INLET ON THE DELMARVA PENINSULA TO THE BACK BAY DRAINAGE BOUNDARY. VIRGINIA.
AREA = 8320 SQ.MI.

CATALOGING UNITS 02080101 — LOWER CHESAPEAKE BAY. VIRGINIA.
AREA = 1390 SQ.MI.
02080102 — GREAT WICOMICO-PIANKATANK. VIRGINIA
AREA = 605 SQ.MI.
02080103 — RAPIDAN-UPPER RAPPAHANNOCK. VIRGINIA.
AREA = 1530 SQ.MI.
02080104 — LOWER RAPPAHANNOCK. VIRGINIA.
AREA = 1160 SQ.MI.
02080105 — MATTAPONI. VIRGINIA.
AREA = 901 SQ.MI.
02080106 — PAMUNKEY. VIRGINIA.
AREA = 1450 SQ.MI.
02080107 — YORK. VIRGINIA.
AREA = 275 SQ.MI.
02080108 — LYNNHAVEN-POQUOSON. VIRGINIA.
AREA = 213 SQ.MI.
02080109 — WESTERN LOWER DELMARVA. VIRGINIA.
AREA = 338 SQ.MI.
02080110 — EASTERN LOWER DELMARVA. VIRGINIA.
AREA = 457 SQ.MI.

ACCOUNTING UNIT 020802 — JAMES: THE JAMES RIVER BASIN. VIRGINIA, WEST VIRGINIA.
AREA = 10200 SQ.MI.

CATALOGING UNITS 02080201 — UPPER JAMES. VIRGINIA, WEST VIRGINIA.
AREA = 2210 SQ.MI.
02080202 — MAURY. VIRGINIA.
AREA = 818 SQ.MI.
02080203 — MIDDLE JAMES-BUFFALO. VIRGINIA.
AREA = 1990 SQ.MI.
02080204 — RIVANNA. VIRGINIA.
AREA = 758 SQ.MI.
02080205 — MIDDLE JAMES-WILLIS. VIRGINIA.
AREA = 948 SQ.MI.
02080206 — LOWER JAMES. VIRGINIA.
AREA = 1440 SQ.MI.
02080207 — APPOMATTOX. VIRGINIA.
AREA = 1590 SQ.MI.
02080208 — HAMPTON ROADS. VIRGINIA.
AREA = 425 SQ.MI.

REGION 03 SOUTH ATLANTIC-GULF REGION—THE DRAINAGE THAT ULTIMATELY DISCHARGES INTO: (A) THE ATLANTIC OCEAN WITHIN AND BETWEEN THE STATES OF VIRGINIA AND FLORIDA; (B) THE GULF OF MEXICO WITHIN AND BETWEEN THE STATES OF FLORIDA AND LOUISIANA; AND (C) THE ASSOCIATED WATERS. INCLUDES ALL OF FLORIDA AND SOUTH CAROLINA, AND PARTS OF ALABAMA, GEORGIA, LOUISIANA, MISSISSIPPI, NORTH CAROLINA, TENNESSEE, AND VIRGINIA.

SUBREGION 0301 — CHOWAN-ROANOKE: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM AND INCLUDING THE BACK BAY DRAINAGE TO OREGON INLET. VIRGINIA, NORTH CAROLINA.
AREA = 18300 SQ.MI.

ACCOUNTING UNIT 030101 — ROANOKE: THE ROANOKE RIVER BASIN. NORTH CAROLINA, VIRGINIA.
AREA = 9680 SQ.MI.

CATALOGING UNITS 03010101 — UPPER ROANOKE. VIRGINIA.
AREA = 2180 SQ.MI.
03010102 — MIDDLE ROANOKE. NORTH CAROLINA, VIRGINIA.
AREA = 1750 SQ.MI.
03010103 — UPPER DAN. NORTH CAROLINA, VIRGINIA.
AREA = 2040 SQ.MI.
03010104 — LOWER DAN. NORTH CAROLINA, VIRGINIA.
AREA = 1240 SQ.MI.
03010105 — BANISTER. VIRGINIA.
AREA = 590 SQ.MI.
03010106 — ROANOKE RAPIDS. NORTH CAROLINA, VIRGINIA.
AREA = 590 SQ.MI.
03010107 — LOWER ROANOKE. NORTH CAROLINA.
AREA = 1290 SQ.MI.

ACCOUNTING UNIT 030102 — ALBEMARLE-CHOWAN: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM AND INCLUDING THE BACK BAY DRAINAGE TO OREGON INLET, EXCLUDING THE ROANOKE RIVER BASIN. NORTH CAROLINA, VIRGINIA.
AREA = 8650 SQ.MI.

CATALOGING UNITS 03010201 — NOTTOWAY. NORTH CAROLINA, VIRGINIA.
AREA = 1700 SQ.MI.
03010202 — BLACKWATER. NORTH CAROLINA, VIRGINIA.
AREA = 744 SQ.MI.
03010203 — CHOWAN. NORTH CAROLINA, VIRGINIA.
AREA = 857 SQ.MI.
03010204 — MEHERIIN. NORTH CAROLINA, VIRGINIA.
AREA = 1600 SQ.MI.
03010205 — ALBEMARLE. NORTH CAROLINA, VIRGINIA.
AREA = 3750 SQ.MI.

SUBREGION 0302 — NEUSE-PAMLICO: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM OREGON INLET TO BROWNS INLET. NORTH CAROLINA.
AREA = 13100 SQ.MI.

ACCOUNTING UNIT 030201 — PAMLICO: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM OREGON INLET TO BROWNS INLET, EXCLUDING THE NEUSE RIVER BASIN. NORTH CAROLINA.
AREA = 7470 SQ.MI.

CATALOGING UNITS 03020101 — UPPER TAR. NORTH CAROLINA.
AREA = 1280 SQ.MI.
03020102 — FISHING. NORTH CAROLINA
AREA = 876 SQ.MI.
03020103 — LOWER TAR. NORTH CAROLINA.
AREA = 967 SQ.MI.
03020104 — PAMLICO. NORTH CAROLINA
AREA = 1140 SQ.MI.
03020105 — PAMLICO SOUND. NORTH CAROLINA.
AREA = 2060 SQ.MI.
03020106 — BOGUE-CORE SOUNDS. NORTH CAROLINA.
AREA = 1150 SQ.MI.

ACCOUNTING UNIT 030202 — NEUSE: THE NEUSE RIVER BASIN. NORTH CAROLINA.
AREA = 5590 SQ.MI.

CATALOGING UNITS 03020201 — UPPER NEUSE. NORTH CAROLINA.
AREA = 2380 SQ.MI.
03020202 — MIDDLE NEUSE. NORTH CAROLINA.
AREA = 1080 SQ.MI.
03020203 — CONTENTNEA. NORTH CAROLINA.
AREA = 1010 SQ.MI.
03020204 — LOWER NEUSE. NORTH CAROLINA.
AREA = 1120 SQ.MI.

SUBREGION 0303 — CAPE FEAR: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM BROWNS INLET TO AND INCLUDING THE CAPE FEAR RIVER BASIN. NORTH CAROLINA.
AREA = 9700 SQ.MI.

ACCOUNTING UNIT 030300 — CAPE FEAR. NORTH CAROLINA.
AREA = 9700 SQ.MI.

CATALOGING UNITS 03030001 — HEW. NORTH CAROLINA.
AREA = 613 SQ.MI.
03030002 — HAW. NORTH CAROLINA.
AREA = 1690 SQ.MI.
03030003 — DEEP. NORTH CAROLINA.
AREA = 1430 SQ.MI.
03030004 — UPPER CAPE FEAR. NORTH CAROLINA.
AREA = 1630 SQ.MI.
03030005 — LOWER CAPE FEAR. NORTH CAROLINA.
AREA = 1030 SQ.MI.
03030006 — BLACK. NORTH CAROLINA.
AREA = 1570 SQ.MI.
03030007 — NORTHEAST CAPE FEAR. NORTH CAROLINA.
AREA = 1740 SQ.MI.

SUBREGION 0304 — PEE DEE: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE CAPE FEAR RIVER BASIN BOUNDARY TO THE SANTEE RIVER BASIN BOUNDARY.
NORTH CAROLINA, SOUTH CAROLINA, VIRGINIA.
AREA = 18500 SQ.MI.

ACCOUNTING UNIT 030401 — UPPER PEE DEE: THE PEE DEE RIVER BASIN ABOVE BLEWETT FALLS LAKE DAM.
NORTH CAROLINA, SOUTH CAROLINA, VIRGINIA.
AREA = 6800 SQ.MI.

CATALOGING UNITS 03040101 — UPPER YADKIN. NORTH CAROLINA, VIRGINIA.
AREA = 2420 SQ.MI.
03040102 — SOUTH YADKIN. NORTH CAROLINA.
AREA = 915 SQ.MI.
03040103 — LOWER YADKIN. NORTH CAROLINA.
AREA = 1180 SQ.MI.
03040104 — UPPER PEE DEE. NORTH CAROLINA, SOUTH CAROLINA.
AREA = 861 SQ.MI.
03040105 — ROCKY, NORTH CAROLINA, SOUTH CAROLINA.
AREA = 1420 SQ.MI.

ACCOUNTING UNIT 030402 — LOWER PEE DEE: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE CAPE FEAR RIVER BASIN BOUNDARY TO THE SANTEE RIVER BASIN BOUNDARY, EXCLUDING THE PEE DEE RIVER BASIN ABOVE BLEWETT FALLS DAM.
NORTH CAROLINA, SOUTH CAROLINA.
AREA = 11700 SQ.MI.

CATALOGING UNITS 03040201 — LOWER PEE DEE. NORTH CAROLINA, SOUTH CAROLINA.
AREA = 2830 SQ.MI.
03040202 — LYNCHES. NORTH CAROLINA, SOUTH CAROLINA.
AREA = 1390 SQ.MI.
03040203 — LUMBER. NORTH CAROLINA, SOUTH CAROLINA.
AREA = 1750 SQ.MI.
03040204 — LITTLE PEE DEE. NORTH CAROLINA, SOUTH CAROLINA.
AREA = 1340 SQ.MI.
03040205 — BLACK. SOUTH CAROLINA.
AREA = 2040 SQ.MI.
03040206 — WACCAMAW. NORTH CAROLINA, SOUTH CAROLINA.
AREA = 1640 SQ.MI.
03040207 — CAROLINA COASTAL-SAMPIT. NORTH CAROLINA, SOUTH CAROLINA.
AREA = 682 SQ.MI.

SUBREGION 0305 — EDISTO-SANTEE: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM AND INCLUDING THE SANTEE RIVER BASIN TO THE SAVANNAH RIVER BASIN BOUNDARY.
NORTH CAROLINA, SOUTH CAROLINA.
AREA = 23600 SQ.MI.

ACCOUNTING UNIT 030501 — SANTEE: THE SANTEE RIVER BASIN.
NORTH CAROLINA, SOUTH CAROLINA.
AREA = 15300 SQ.MI.

CATALOGING UNITS 03050101 — UPPER CATAWBA. NORTH CAROLINA, SOUTH CAROLINA.
AREA = 2350 SQ.MI.
03050102 — SOUTH FORK CATAWBA. NORTH CAROLINA.
AREA = 657 SQ.MI.
03050103 — LOWER CATAWBA. NORTH CAROLINA, SOUTH CAROLINA.
AREA = 1370 SQ.MI.
03050104 — WATEREE. SOUTH CAROLINA.
AREA = 1210 SQ.MI.
03050105 — UPPER BROAD. NORTH CAROLINA, SOUTH CAROLINA.
AREA = 2480 SQ.MI.
03050106 — LOWER BROAD. SOUTH CAROLINA.
AREA = 1290 SQ.MI.
03050107 — TYGER. SOUTH CAROLINA.
AREA = 809 SQ.MI.

REGION 03: SOUTH ATLANTIC-GULF -- Continued

03050108 — ENOREE. SOUTH CAROLINA.
AREA = 731 SQ.MI.
03050109 — SALUDA. SOUTH CAROLINA.
AREA = 2480 SQ.MI.
03050110 — CONGAREE. SOUTH CAROLINA.
AREA = 708 SQ.MI.
03050111 — LAKE MARION. SOUTH CAROLINA.
AREA = 543 SQ.MI.
03050112 — SANTEE. SOUTH CAROLINA.
AREA = 718 SQ.MI.

ACCOUNTING UNIT 030502 — EDISTO-SOUTH CAROLINA COASTAL: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE SANTEE RIVER BASIN BOUNDARY TO THE SAVANNAH RIVER BASIN BOUNDARY.
SOUTH CAROLINA.
AREA = 8210 SQ.MI.

CATALOGING UNITS 03050201 — COOPER. SOUTH CAROLINA.
AREA = 837 SQ.MI.
03050202 — SOUTH CAROLINA COASTAL. SOUTH CAROLINA.
AREA = 955 SQ.MI.
03050203 — NORTH FORK EDISTO. SOUTH CAROLINA.
AREA = 750 SQ.MI.
03050204 — SOUTH FORK EDISTO. SOUTH CAROLINA.
AREA = 865 SQ.MI.
03050205 — EDISTO. SOUTH CAROLINA.
AREA = 846 SQ.MI.
03050206 — FOUR HOLE SWAMP. SOUTH CAROLINA.
AREA = 627 SQ.MI.
03050207 — SALKEHATCHIE. SOUTH CAROLINA.
AREA = 1000 SQ.MI.
03050208 — BROAD-ST. HELENA. SOUTH CAROLINA.
AREA = 2330 SQ.MI.

SUBREGION 0306 — OGEECHEE-SAVANNAH: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM AND INCLUDING THE SAVANNAH RIVER BASIN TO THE ALTAMAHA RIVER BASIN BOUNDARY.
GEORGIA, NORTH CAROLINA, SOUTH CAROLINA.
AREA = 16300 SQ.MI.

ACCOUNTING UNIT 030601 — SAVANNAH: THE SAVANNAH RIVER BASIN.
GEORGIA, NORTH CAROLINA, SOUTH CAROLINA.
AREA = 10400 SQ.MI.

CATALOGING UNITS 03060101 — SENECA. NORTH CAROLINA, SOUTH CAROLINA.
AREA = 1020 SQ.MI.
03060102 — TUGALOO. GEORGIA, NORTH CAROLINA, SOUTH CAROLINA.
AREA = 995 SQ.MI.
03060103 — UPPER SAVANNAH. GEORGIA, SOUTH CAROLINA.
AREA = 1830 SQ.MI.
03060104 — BROAD. GEORGIA.
AREA = 1500 SQ.MI.
03060105 — LITTLE. GEORGIA.
AREA = 766 SQ.MI.
03060106 — MIDDLE SAVANNAH. GEORGIA, SOUTH CAROLINA.
AREA = 1850 SQ.MI.
03060107 — STEVENS. SOUTH CAROLINA.
AREA = 734 SQ.MI.
03060108 — BRIER. GEORGIA.
AREA = 830 SQ.MI.
03060109 — LOWER SAVANNAH. GEORGIA, SOUTH CAROLINA.
AREA = 916 SQ.MI.

ACCOUNTING UNIT 030602 — OGEECHEE: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE SAVANNAH RIVER BASIN BOUNDARY TO THE ALTAMAHA RIVER BASIN BOUNDARY. GEORGIA.
AREA = 5830 SQ.MI.

CATALOGING UNITS 03060201 — UPPER OGEECHEE. GEORGIA.
AREA = 1820 SQ.MI.
03060202 — LOWER OGEECHEE. GEORGIA.
AREA = 1220 SQ.MI.
03060203 — CANOOCHEE. GEORGIA.
AREA = 1420 SQ.MI.
03060204 — OGEECHEE COASTAL. GEORGIA.
AREA = 1370 SQ.MI.

SUBREGION 0307 — ALTAMAHA - ST. MARYS: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM AND INCLUDING THE ALTAMAHA RIVER BASIN TO THE ST. JOHNS RIVER BASIN BOUNDARY. FLORIDA, GEORGIA.
AREA = 20500 SQ.MI.

ACCOUNTING UNIT 030701 — ALTAMAHA: THE ALTAMAHA RIVER BASIN.
GEORGIA.
AREA = 14200 SQ.MI.

CATALOGING UNITS 03070101 — UPPER OCONEE. GEORGIA.
AREA = 2920 SQ.MI.
03070102 — LOWER OCONEE. GEORGIA.
AREA = 2400 SQ.MI.

03070103 — UPPER OCMULGEE. GEORGIA.
AREA = 2980 SQ.MI.
03070104 — LOWER OCMULGEE. GEORGIA.
AREA = 2280 SQ.MI.
03070105 — LITTLE OCMULGEE. GEORGIA.
AREA = 818 SQ.MI.
03070106 — ALTAMAHA. GEORGIA.
AREA = 1510 SQ.MI.
03070107 — OHOOPEE. GEORGIA.
AREA = 1340 SQ.MI.

ACCOUNTING UNIT 030702 — ST. MARYS - SATILLA: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE ALTAMAHA RIVER BASIN BOUNDARY TO THE ST. JOHNS RIVER BASIN BOUNDARY. FLORIDA, GEORGIA.
AREA = 6220 SQ.MI.

CATALOGING UNITS 03070201 — SATILLA. GEORGIA.
AREA = 2630 SQ.MI.
03070202 — LITTLE SATILLA. GEORGIA.
AREA = 773 SQ.MI.
03070203 — CUMBERLAND-ST. SIMONS. GEORGIA.
AREA = 768 SQ.MI.
03070204 — ST. MARYS. FLORIDA, GEORGIA.
AREA = 1610 SQ.MI.
03070205 — NASSAU. FLORIDA.
AREA = 439 SQ.MI.

SUBREGION 0308 — ST. JOHNS: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM AND INCLUDING THE ST. JOHNS RIVER BASIN TO ST. LUCIE INLET. FLORIDA.
AREA = 11600 SQ.MI.

ACCOUNTING UNIT 030801 — ST. JOHNS: THE ST. JOHNS RIVER BASIN. FLORIDA.
AREA = 9360 SQ.MI.

CATALOGING UNITS 03080101 — UPPER ST. JOHNS. FLORIDA.
AREA = 3700 SQ.MI.
03080102 — OKLAWAHA. FLORIDA.
AREA = 2860 SQ.MI.
03080103 — LOWER ST. JOHNS. FLORIDA.
AREA = 2800 SQ.MI.

ACCOUNTING UNIT 030802 — EAST FLORIDA COASTAL: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE ST. JOHNS RIVER BASIN BOUNDARY TO ST. LUCIE INLET. FLORIDA.
AREA = 2190 SQ.MI.

CATALOGING UNITS 03080201 — DAYTONA - ST. AUGUSTINE. FLORIDA.
AREA = 760 SQ.MI.
03080202 — CAPE CANAVERAL. FLORIDA.
AREA = 760 SQ.MI.
03080203 — VERO BEACH. FLORIDA.
AREA = 670 SQ.MI.

SUBREGION 0309 — SOUTHERN FLORIDA: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM ST. LUCIE INLET TO AND INCLUDING THE CALOOSAHATCHEE RIVER BASIN, AND INTERIOR DRAINAGE SOUTH OF THE ST. JOHNS AND PEACE RIVER BASINS. FLORIDA.
AREA = 18700 SQ.MI.

ACCOUNTING UNIT 030901 — KISSIMMEE: THE KISSIMMEE RIVER BASIN AND INTERIOR DRAINAGE INTO LAKE OKEECHOBEE FROM THE NORTH. FLORIDA.
AREA = 4210 SQ.MI.

CATALOGING UNITS 03090101 — KISSIMMEE. FLORIDA.
AREA = 3010 SQ.MI.
03090102 — NORTHERN OKEECHOBEE INFLOW. FLORIDA.
AREA = 282 SQ.MI.
03090103 — WESTERN OKEECHOBEE INFLOW. FLORIDA.
AREA = 918 SQ.MI.

ACCOUNTING UNIT 030902 — SOUTHERN FLORIDA: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM ST. LUCIE INLET TO AND INCLUDING THE CALOOSAHATCHEE RIVER BASIN, AND INTERIOR DRAINAGE SOUTH OF THE ST. JOHNS AND PEACE RIVER BASINS, EXCLUDING THE KISSIMMEE RIVER BASIN AND INTERIOR DRAINAGE INTO LAKE OKEECHOBEE FROM THE NORTH. FLORIDA.
AREA = 14500 SQ.MI.

CATALOGING UNITS 03090201 — LAKE OKEECHOBEE. FLORIDA.
AREA = 727 SQ.MI.
03090202 — EVERGLADES. FLORIDA.
AREA = 8400 SQ.MI.
03090203 — FLORIDA BAY-FLORIDA KEYS. FLORIDA.
AREA = 1230 SQ.MI.
03090204 — BIG CYPRESS SWAMP. FLORIDA.
AREA = 2710 SQ.MI.
03090205 — CALOOSAHATCHEE. FLORIDA.
AREA = 1420 SQ.MI.

REGION 03: SOUTH ATLANTIC-GULF — Continued

SUBREGION 0310 — PEACE-TAMPA BAY: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE CALOOSAHATCHEE RIVER BASIN BOUNDARY TO AND INCLUDING THE WITHLACOOCHEE RIVER BASIN. FLORIDA.
AREA = 10000 SQ.MI.

ACCOUNTING UNIT 031001 — PEACE: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE CALOOSAHATCHEE RIVER BASIN BOUNDARY TO GASPARILLA PASS. FLORIDA.
AREA = 3610 SQ.MI.

CATALOGING UNITS 03100101 — PEACE. FLORIDA.
AREA = 2420 SQ.MI.
03100102 — MYAKKA. FLORIDA.
AREA = 606 SQ.MI.
03100103 — CHARLOTTE HARBOR. FLORIDA.
AREA = 587 SQ.MI.

ACCOUNTING UNIT 031002 — TAMPA BAY: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM GASPARILLA PASS TO AND INCLUDING THE WITHLACOOCHEE RIVER BASIN. FLORIDA.
AREA = 6410 SQ.MI.

CATALOGING UNITS 03100201 — SARASOTA BAY. FLORIDA.
AREA = 428 SQ.MI.
03100202 — MANATEE. FLORIDA.
AREA = 375 SQ.MI.
03100203 — LITTLE MANATEE. FLORIDA.
AREA = 217 SQ.MI.
03100204 — ALAFIA. FLORIDA.
AREA = 434 SQ.MI.
03100205 — HILLSBOROUGH. FLORIDA.
AREA = 678 SQ.MI.
03100206 — TAMPA BAY. FLORIDA.
AREA = 894 SQ.MI.
03100207 — CRYSTAL-PITHLACHASCOTEE. FLORIDA.
AREA = 1290 SQ.MI.
03100208 — WITHLACOOCHEE. FLORIDA.
AREA = 2090 SQ.MI.

SUBREGION 0311 — SUWANNEE: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE WITHLACOOCHEE RIVER BASIN BOUNDARY TO AND INCLUDING THE AUCILLA RIVER BASIN. FLORIDA, GEORGIA.
AREA = 13800 SQ.MI.

ACCOUNTING UNIT 031101 — AUCILLA-WACCASASSA: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE WITHLACOOCHEE RIVER BASIN BOUNDARY TO AND INCLUDING THE AUCILLA RIVER BASIN, EXCLUDING THE SUWANNEE RIVER BASIN. FLORIDA, GEORGIA.
AREA = 3870 SQ.MI.

CATALOGING UNITS 03110101 — WACCASASSA. FLORIDA.
AREA = 936 SQ.MI.
03110102 — ECONFINA-STEINHATCHEE. FLORIDA.
AREA = 1930 SQ.MI.
03110103 — AUCILLA. FLORIDA, GEORGIA.
AREA = 1000 SQ.MI.

ACCOUNTING UNIT 031102 — SUWANNEE: THE SUWANNEE RIVER BASIN. FLORIDA, GEORGIA.
AREA = 9930 SQ.MI.

CATALOGING UNITS 03110201 — UPPER SUWANNEE. FLORIDA, GEORGIA.
AREA = 2720 SQ.MI.
03110202 — ALAPAHA. FLORIDA, GEORGIA.
AREA = 1840 SQ.MI.
03110203 — WITHLACOOCHEE. FLORIDA, GEORGIA.
AREA = 1510 SQ.MI.
03110204 — LITTLE. GEORGIA.
AREA = 884 SQ.MI.
03110205 — LOWER SUWANNEE. FLORIDA.
AREA = 1590 SQ.MI.
03110206 — SANTA FE. FLORIDA.
AREA = 1390 SQ.MI.

SUBREGION 0312 — OCHLOCKONEE: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE AUCILLA RIVER BASIN BOUNDARY TO AND INCLUDING THE OCHLOCKONEE RIVER BASIN. FLORIDA, GEORGIA.
AREA = 3650 SQ.MI.

ACCOUNTING UNIT 031200 — OCHLOCKONEE. FLORIDA. GEORGIA.
AREA = 3650 SQ.MI.

CATALOGING UNITS 03120001 — APALACHEE BAY-ST. MARKS. FLORIDA, GEORGIA.
AREA = 1180 SQ.MI.
03120002 — UPPER OCHLOCKONEE. GEORGIA.
AREA = 925 SQ.MI.
03120003 — LOWER OCHLOCKONEE. FLORIDA, GEORGIA.
AREA = 1540 SQ.MI.

SUBREGION 0313 — APALACHICOLA: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE OCHLOCKONEE RIVER BASIN BOUNDARY TO AND INCLUDING THE APALACHICOLA RIVER BASIN AND THE DRAINAGE INTO APALACHICOLA BAY. ALABAMA, FLORIDA, GEORGIA.
AREA = 20500 SQ.MI.

ACCOUNTING UNIT 031300 — APALACHICOLA. ALABAMA, FLORIDA, GEORGIA.
AREA = 20500 SQ.MI.

CATALOGING UNITS
03130001 — UPPER CHATTAHOOCHEE. GEORGIA.
AREA = 1560 SQ.MI.
03130002 — MIDDLE CHATTAHOOCHEE-LAKE HARDING. ALABAMA, GEORGIA.
AREA = 3060 SQ.MI.
03130003 — MIDDLE CHATTAHOOCHEE-WALTER F. GEORGE RESERVOIR. ALABAMA, GEORGIA.
AREA = 2880 SQ.MI.
03130004 — LOWER CHATTAHOOCHEE. ALABAMA, FLORIDA, GEORGIA.
AREA = 1300 SQ.MI.
03130005 — UPPER FLINT. GEORGIA.
AREA = 2630 SQ.MI.
03130006 — MIDDLE FLINT. GEORGIA.
AREA = 1570 SQ.MI.
03130007 — KINCHAFOONEE-MUCKALEE. GEORGIA.
AREA = 1090 SQ.MI.
03130008 — LOWER FLINT. GEORGIA.
AREA = 1290 SQ.MI.
03130009 — ICHAWAYNOCHAWAY. GEORGIA.
AREA = 1110 SQ.MI.
03130010 — SPRING. GEORGIA.
AREA = 778 SQ.MI.
03130011 — APALACHICOLA. FLORIDA, GEORGIA.
AREA = 1130 SQ.MI.
03130012 — CHIPOLA. ALABAMA, FLORIDA.
AREA = 1270 SQ.MI.
03130013 — NEW. FLORIDA.
AREA = 569 SQ.MI.
03130014 — APALACHICOLA BAY. FLORIDA.
AREA = 266 SQ.MI.

SUBREGION 0314 — CHOCTAWHATCHEE - ESCAMBIA: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE APALACHICOLA BAY DRAINAGE BOUNDARY TO THE MOBILE BAY DRAINAGE BOUNDARY. ALABAMA, FLORIDA.
AREA = 15000 SQ.MI.

ACCOUNTING UNIT 031401 — FLORIDA PANHANDLE COASTAL: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE APALACHICOLA BAY DRAINAGE BOUNDARY TO THE MOBILE BAY DRAINAGE BOUNDARY, EXCLUDING THE CHOCTAWHATCHEE AND ESCAMBIA RIVER BASINS. ALABAMA, FLORIDA, GEORGIA.
AREA = 6060 SQ.MI.

CATALOGING UNITS
03140101 — ST. ANDREW-ST. JOSEPH BAYS. FLORIDA.
AREA = 1350 SQ.MI.
03140102 — CHOCTAWHATCHEE BAY. FLORIDA.
AREA = 699 SQ.MI.
03140103 — YELLOW. ALABAMA, FLORIDA.
AREA = 1380 SQ.MI.
03140104 — BLACKWATER. ALABAMA, FLORIDA.
AREA = 860 SQ.MI.
03140105 — PENSACOLA BAY. FLORIDA.
AREA = 543 SQ.MI.
03140106 — PERDIDO. ALABAMA, FLORIDA.
AREA = 913 SQ.MI.
03140107 — PERDIDO BAY. ALABAMA, FLORIDA.
AREA = 313 SQ.MI.

ACCOUNTING UNIT 031402 — CHOCTAWHATCHEE: THE CHOCTAWHATCHEE RIVER BASIN. ALABAMA, FLORIDA.
AREA = 4670 SQ.MI.

CATALOGING UNITS
03140201 — UPPER CHOCTAWHATCHEE. ALABAMA.
AREA = 1560 SQ.MI.
03140202 — PEA. ALABAMA, FLORIDA.
AREA = 1550 SQ.MI.
03140203 — LOWER CHOCTAWHATCHEE. ALABAMA, FLORIDA.
AREA = 1560 SQ.MI.

ACCOUNTING UNIT 031403 — ESCAMBIA: THE ESCAMBIA RIVER BASIN. ALABAMA, FLORIDA.
AREA = 4290 SQ.MI.

CATALOGING UNITS
03140301 — UPPER CONECUH. ALABAMA.
AREA = 853 SQ.MI.
03140302 — PATSALIGA. ALABAMA.
AREA = 593 SQ.MI.
03140303 — SEPULGA. ALABAMA.
AREA = 1050 SQ.MI.
03140304 — LOWER CONECUH. ALABAMA, FLORIDA.
AREA = 1010 SQ.MI.
03140305 — ESCAMBIA. ALABAMA, FLORIDA.
AREA = 780 SQ.MI.

REGION 03: SOUTH ATLANTIC-GULF — Continued

SUBREGION 0315 — ALABAMA: THE ALABAMA RIVER BASIN. ALABAMA, GEORGIA, TENNESSEE.
AREA = 22700 SQ.MI.

ACCOUNTING UNIT 031501 — COOSA-TALLAPOOSA: THE ALABAMA RIVER BASIN ABOVE THE CONFLUENCE OF AND INCLUDING THE COOSA AND TALLAPOOSA RIVER BASINS. ALABAMA, GEORGIA, TENNESSEE.
AREA = 14800 SQ.MI.

CATALOGING UNITS
03150101 — CONASAUGA. GEORGIA, TENNESSEE.
AREA = 723 SQ.MI.
03150102 — COOSAWATTEE. GEORGIA.
AREA = 848 SQ.MI.
03150103 — OOSTANAULA. GEORGIA.
AREA = 557 SQ.MI.
03150104 — ETOWAH. GEORGIA.
AREA = 1850 SQ.MI.
03150105 — UPPER COOSA. ALABAMA, GEORGIA.
AREA = 1610 SQ.MI.
03150106 — MIDDLE COOSA. ALABAMA.
AREA = 2580 SQ.MI.
03150107 — LOWER COOSA. ALABAMA.
AREA = 1910 SQ.MI.
03150108 — UPPER TALLAPOOSA. ALABAMA, GEORGIA.
AREA = 1400 SQ.MI.
03150109 — MIDDLE TALLAPOOSA. ALABAMA.
AREA = 1590 SQ.MI.
03150110 — LOWER TALLAPOOSA. ALABAMA.
AREA = 1700 SQ.MI.

ACCOUNTING UNIT 031502 — ALABAMA: THE ALABAMA RIVER BASIN BELOW THE CONFLUENCE OF THE COOSA AND TALLAPOOSA RIVER BASINS. ALABAMA.
AREA = 7950 SQ.MI.

CATALOGING UNITS
03150201 — UPPER ALABAMA. ALABAMA.
AREA = 2430 SQ.MI.
03150202 — CAHABA. ALABAMA.
AREA = 1850 SQ.MI.
03150203 — MIDDLE ALABAMA. ALABAMA.
AREA = 2250 SQ.MI.
03150204 — LOWER ALABAMA. ALABAMA.
AREA = 1420 SQ.MI.

SUBREGION 0316 — MOBILE - TOMBIGBEE: THE DRAINAGE INTO MOBILE BAY EXCLUDING THE ALABAMA RIVER BASIN. ALABAMA, MISSISSIPPI.
AREA = 21900 SQ.MI.

ACCOUNTING UNIT 031601 — BLACK WARRIOR - TOMBIGBEE: THE TOMBIGBEE RIVER BASIN ABOVE THE CONFLUENCE WITH AND INCLUDING THE BLACK WARRIOR RIVER BASIN. ALABAMA, MISSISSIPPI.
AREA = 15400 SQ.MI.

CATALOGING UNITS
03160101 — UPPER TOMBIGBEE. ALABAMA, MISSISSIPPI.
AREA = 1790 SQ.MI.
03160102 — TOWN. MISSISSIPPI.
AREA = 689 SQ.MI.
03160103 — BUTTAHATCHEE. ALABAMA, MISSISSIPPI.
AREA = 863 SQ.MI.
03160104 — TIBBEE. MISSISSIPPI.
AREA = 1100 SQ.MI.
03160105 — LUXAPALLILA. ALABAMA, MISSISSIPPI.
AREA = 798 SQ.MI.
03160106 — MIDDLE TOMBIGBEE-LUBBUB. ALABAMA, MISSISSIPPI.
AREA = 1650 SQ.MI.
03160107 — SIPSEY. ALABAMA.
AREA = 788 SQ.MI.
03160108 — NOXUBEE. ALABAMA, MISSISSIPPI.
AREA = 1400 SQ.MI.
03160109 — MULBERRY. ALABAMA.
AREA = 1380 SQ.MI.
03160110 — SIPSEY FORK. ALABAMA.
AREA = 1010 SQ.MI.
03160111 — LOCUST. ALABAMA.
AREA = 1210 SQ.MI.
03160112 — UPPER BLACK WARRIOR. ALABAMA.
AREA = 1250 SQ.MI.
03160113 — LOWER BLACK WARRIOR. ALABAMA.
AREA = 1450 SQ.MI.

ACCOUNTING UNIT 031602 — MOBILE BAY- TOMBIGBEE: THE DRAINAGE INTO MOBILE BAY EXCLUDING THE ALABAMA RIVER BASIN, THE TOMBIGBEE RIVER BASIN ABOVE THE CONFLUENCE WITH THE BLACK WARRIOR RIVER, AND THE BLACK WARRIOR RIVER BASIN. ALABAMA, MISSISSIPPI.
AREA = 6500 SQ.MI.

REGION 03: SOUTH ATLANTIC-GULF — Continued

CATALOGING UNITS 03160201 — MIDDLE TOMBIGBEE-CHICKASAW. ALABAMA, MISSISSIPPI.
AREA = 2090 SQ.MI.
03160202 — SUCARNOOCHEE. ALABAMA, MISSISSIPPI.
AREA = 956 SQ.MI.
03160203 — LOWER TAMBIGBEE. ALABAMA.
AREA = 1600 SQ.MI.
03160204 — MOBILE - TENSAW. ALABAMA.
AREA = 972 SQ.MI.
03160205 — MOBILE BAY. ALABAMA.
AREA = 883 SQ.MI.

SUBREGION 0317 — PASCAGOULA: THE COASTAL DRAINAGE AND ASSOCIATED WATERS IN ALABAMA AND MISSISSIPPI NORTH AND EAST OF THE LOUISIANA-MISSISSIPPI STATE LINE FROM THE MOBILE BAY DRAINAGE BOUNDARY TO THE PEARL RIVER BASIN BOUNDARY. ALABAMA, MISSISSIPPI.
AREA = 12100 SQ.MI.

ACCOUNTING UNIT 031700 — PASCAGOULA. ALABAMA. MISSISSIPPI.
AREA = 12100 SQ.MI.

CATALOGING UNITS 03170001 — CHUNKY-OKATIBBEE. MISSISSIPPI.
AREA = 907 SQ.MI.
03170002 — UPPER CHICKASAWHAY. ALABAMA, MISSISSIPPI.
AREA = 1480 SQ.MI.
03170003 — LOWER CHICKASAWHAY. ALABAMA, MISSISSIPPI.
AREA = 671 SQ.MI.
03170004 — UPPER LEAF. MISSISSIPPI.
AREA = 1760 SQ.MI.
03170005 — LOWER LEAF. MISSISSIPPI.
AREA = 1820 SQ.MI.
03170006 — PASCAGOULA. MISSISSIPPI.
AREA = 620 SQ.MI.
03170007 — BLACK. MISSISSIPPI.
AREA = 1290 SQ.MI.
03170008 — ESCATAWPA. ALABAMA, MISSISSIPPI.
AREA = 1080 SQ.MI.
03170009 MISSISSIPPI COASTAL. ALABAMA, MISSISSIPPI.
AREA = 2480 SQ.MI.

SUBREGION 0318 — PEARL: THE PEARL RIVER BASIN. LOUISIANA, MISSISSIPPI.
AREA = 8730 SQ.MI.

ACCOUNTING UNIT 031800 — PEARL. LOUISIANA, MISSISSIPPI.
AREA = 8730 SQ.MI.

CATALOGING UNITS 03180001 — UPPER PEARL. MISSISSIPPI.
AREA = 2490 SQ.MI.
03180002 — MIDDLE PEARL-STRONG. MISSISSIPPI.
AREA = 1990 SQ.MI.
03180003 — MIDDLE PEARL-SILVER. MISSISSIPPI.
AREA = 1220 SQ.MI.
03180004 — LOWER PEARL. LOUISIANA. MISSISSIPPI.
AREA = 1810 SQ.MI.
03180005 — BOGUE CHITTO. LOUISIANA, MISSISSIPPI.
AREA = 1220 SQ.MI.

REGION 04 GREAT LAKES REGION — THE DRAINAGE WITHIN THE UNITED STATES THAT ULTIMATELY DISCHARGES INTO: (A) THE GREAT LAKES SYSTEM, INCLUDING THE LAKE SURFACES, BAYS, AND ISLANDS; AND (B) THE ST. LAWRENCE RIVER TO THE RIVIERE RICHELIEU DRAINAGE BOUNDARY. INCLUDES PARTS OF ILLINOIS, INDIANA, MICHIGAN, MINNESOTA, NEW YORK, OHIO, PENNSYLVANIA, AND WISCONSIN.

SUBREGION 0401 — WESTERN LAKE SUPERIOR: THE DRAINAGE INTO LAKE SUPERIOR WITHIN THE UNITED STATES FROM THE ONTARIO-MINNESOTA INTERNATIONAL BOUNDARY TO AND INCLUDING THE MONTREAL RIVER BASIN. MICHIGAN, MINNESOTA, WISCONSIN.
AREA = 9240 SQ.MI.

ACCOUNTING UNIT 040101 — NORTHWESTERN LAKE SUPERIOR: THE DRAINAGE INTO LAKE SUPERIOR WITHIN THE UNITED STATES FROM THE ONTARIO-MINNESOTA INTERNATIONAL BOUNDARY TO THE ST. LOUIS RIVER BASIN BOUNDARY. MINNESOTA.
AREA = 2260 SQ.MI.

CATALOGING UNITS 04010101 — BAPTISM-BRULE. MINNESOTA.
AREA = 1620 SQ.MI.
04010102 — BEAVER-LESTER. MINNESOTA.
AREA = 635 SQ.MI.

ACCOUNTING UNIT 040102 — ST. LOUIS: THE ST. LOUIS RIVER BASIN. MINNESOTA, WISCONSIN.
AREA = 3810 SQ.MI.

CATALOGING UNITS 04010201 — ST. LOUIS. MINNESOTA, WISCONSIN.
AREA = 3010 SQ.MI.
04010202 — CLOQUET. MINNESOTA.
AREA = 796 SQ.MI.

ACCOUNTING UNIT 040103 — SOUTHWESTERN LAKE SUPERIOR: THE DRAINAGE INTO LAKE SUPERIOR FROM THE ST. LOUIS RIVER BASIN BOUNDARY TO AND INCLUDING THE MONTREAL RIVER BASIN. MICHIGAN, MINNESOTA, WISCONSIN.
AREA = 3180 SQ.MI.

CATALOGING UNITS 04010301 — BEARTRAP-NEMADJI. MINNESOTA, WISCONSIN.
AREA = 1850 SQ.MI.
04010302 — BAD-MONTREAL. MICHIGAN, WISCONSIN.
AREA = 1330 SQ.MI.

SUBREGION 0402 — SOUTHERN LAKE SUPERIOR-LAKE SUPERIOR: THE DRAINAGE INTO LAKE SUPERIOR WITHIN THE UNITED STATES FROM THE MONTREAL RIVER BASIN BOUNDARY TO THE SOO LOCKS AT SAULT SAINTE MARIE, AND LAKE SUPERIOR WITHIN THE UNITED STATES, INCLUDING ITS BAYS AND ISLANDS. MICHIGAN, MINNESOTA, WISCONSIN.
AREA = 28600 SQ.MI.

ACCOUNTING UNIT 040201 — SOUTHCENTRAL LAKE SUPERIOR: THE DRAINAGE INTO LAKE SUPERIOR FROM THE MONTREAL RIVER BASIN BOUNDARY TO AND INCLUDING THE CARP RIVER BASIN. MICHIGAN, WISCONSIN.
AREA = 5210 SQ.MI.

CATALOGING UNITS 04020101 — BLACK-PRESQUE ISLE. MICHIGAN, WISCONSIN.
AREA = 1030 SQ.MI.
04020102 — ONTONAGON. MICHIGAN, WISCONSIN.
AREA = 1390 SQ.MI.
04020103 — KEWEENAW PENINSULA. MICHIGAN.
AREA = 1130 SQ.MI.
04020104 — STURGEON. MICHIGAN.
AREA = 710 SQ.MI.
04020105 — DEAD-KELSEY. MICHIGAN.
AREA = 946 SQ.MI.

ACCOUNTING UNIT 040202 — SOUTHEASTERN LAKE SUPERIOR: THE DRAINAGE INTO LAKE SUPERIOR WITHIN THE UNITED STATES FROM THE CARP RIVER BASIN BOUNDARY TO THE SOO LOCKS AT SAULT SAINTE MARIE. MICHIGAN.
AREA = 2340 SQ.MI.

CATALOGING UNITS 04020201 — BETSY-CHOCOLAY. MICHIGAN.
AREA = 1180 SQ.MI.
04020202 — TAHQUAMENON. MICHIGAN.
AREA = 832 SQ.MI.
04020203 — WAISKA. MICHIGAN.
AREA = 324 SQ.MI.

ACCOUNTING UNIT 040203 — LAKE SUPERIOR: LAKE SUPERIOR WITHIN THE UNITED STATES, INCLUDING ITS BAYS AND ISLANDS. MICHIGAN, MINNESOTA, WISCONSIN.
AREA = 21100 SQ.MI.

CATALOGING UNIT 04020300 — LAKE SUPERIOR. MICHIGAN. MINNESOTA, WISCONSIN.
AREA = 21100 SQ.MI.

SUBREGION 0403 — NORTHWESTERN LAKE MICHIGAN: THE DRAINAGE INTO LAKE MICHIGAN FROM THE MILWAUKEE RIVER BASIN BOUNDARY TO THE MANISTIQUE RIVER BASIN BOUNDARY. MICHIGAN, WISCONSIN.
AREA = 18700 SQ.MI.

ACCOUNTING UNIT 040301 — NORTHWESTERN LAKE MICHIGAN: THE DRAINAGE INTO LAKE MICHIGAN FROM THE MILWAUKEE RIVER BASIN BOUNDARY TO THE MANISTIQUE RIVER BASIN BOUNDARY, EXCLUDING THE FOX RIVER BASIN. MICHIGAN, WISCONSIN.
AREA = 12400 SQ.MI.

CATALOGING UNITS
04030101 — MANITOWOC-SHEBOYGAN. WISCONSIN.
AREA = 1650 SQ.MI.
04030102 — DOOR-KEWAUNEE. WISCONSIN.
AREA = 776 SQ.MI.
04030103 — DUCK-PENSAUKEE. WISCONSIN.
AREA = 483 SQ.MI.
04030104 — OCONTO. WISCONSIN.
AREA = 1040 SQ.MI.
04030105 — PESHTIGO. WISCONSIN.
AREA = 1170 SQ.MI.
04030106 — BRULE. MICHIGAN, WISCONSIN.
AREA = 1060 SQ.MI.
04030107 — MICHIGAMME. MICHIGAN.
AREA = 734 SQ.MI.
04030108 — MENOMINEE. MICHIGAN, WISCONSIN.
AREA = 2310 SQ.MI.
04030109 — CEDAR-FORD. MICHIGAN.
AREA = 1010 SQ.MI.
04030110 — ESCANABA. MICHIGAN.
AREA = 935 SQ.MI.
04030111 — TACOOSH-WHITEFISH. MICHIGAN.
AREA = [illegible]6 SQ.MI.
04030112 — FISHDAM-STURGEON. MICHIGAN.
AREA = 556 SQ.MI.

ACCOUNTING UNIT 040302 — FOX: THE FOX RIVER BASIN. WISCONSIN.
AREA = 6340 SQ.MI.

CATALOGING UNITS
04030201 — UPPER FOX. WISCONSIN.
AREA = 1610 SQ.MI.
04030202 — WOLF. WISCONSIN.
AREA = 3720 SQ.MI.
04030203 — LAKE WINNEBAGO. WISCONSIN.
AREA = 570 SQ.MI.
04030204 — LOWER FOX. WISCONSIN.
AREA = 438 SQ.MI.

SUBREGION 0404 — SOUTHWESTERN LAKE MICHIGAN. THE DRAINAGE INTO LAKE MICHIGAN FROM THE ST. JOSEPH RIVER BASIN BOUNDARY TO AND INCLUDING THE MILWAUKEE RIVER BASIN. ILLINOIS, INDIANA, MICHIGAN, WISCONSIN.
AREA = 1970 SQ.MI.

ACCOUNTING UNIT 040400 — SOUTHWESTERN LAKE MICHIGAN. ILLINOIS, INDIANA, MICHIGAN, WISCONSIN.
AREA = 1970 SQ.MI.

CATALOGING UNITS
04040001 — LITTLE CALUMET-GALIEN. ILLINOIS, INDIANA, MICHIGAN.
AREA = 705 SQ.MI.
04040002 — PIKE-ROOT. ILLINOIS, WISCONSIN.
AREA = 399 SQ.MI.
04040003 — MILWAUKEE. WISCONSIN.
AREA = 861 SQ.MI.

SUBREGION 0405 — SOUTHEASTERN LAKE MICHIGAN: THE DRAINAGE INTO LAKE MICHIGAN FROM AND INCLUDING THE ST. JOSEPH RIVER BASIN TO AND INCLUDING THE GRAND RIVER BASIN. INDIANA, MICHIGAN.
AREA = 12800 SQ.MI.

ACCOUNTING UNIT 040500 — SOUTHEASTERN LAKE MICHIGAN. INDIANA, MICHIGAN.
AREA = 12800 SQ.MI.

CATALOGING UNITS
04050001 — ST. JOSEPH. INDIANA, MICHIGAN
AREA = 4670 SQ.MI.
04050002 — BLACK-MACATAWA. MICHIGAN.
AREA = 600 SQ.MI.
04050003 — KALAMAZOO. MICHIGAN.
AREA = 2030 SQ.MI.
04050004 — UPPER GRAND. MICHIGAN.
AREA = 1730 SQ.MI.
04050005 — MAPLE. MICHIGAN.
AREA = 924 SQ.MI.
04050006 — LOWER GRAND. MICHIGAN.
AREA = 1990 SQ.MI.
04050007 — THORNAPPLE. MICHIGAN.
AREA = 874 SQ.MI.

SUBREGION 0406 — NORTHEASTERN LAKE MICHIGAN-LAKE MICHIGAN: THE DRAINAGE INTO LAKE MICHIGAN FROM THE GRAND RIVER BASIN BOUNDARY TO AND INCLUDING THE MANISTIQUE RIVER BASIN, AND LAKE MICHIGAN, INCLUDING ITS BAYS AND ISLANDS. ILLINOIS, INDIANA, MICHIGAN, WISCONSIN.
AREA = 33600 SQ.MI.

ACCOUNTING UNIT 040601 — NORTHEASTERN LAKE MICHIGAN: THE DRAINAGE INTO LAKE MICHIGAN FROM THE GRAND RIVER BASIN BOUNDARY TO AND INCLUDING THE MANISTIQUE RIVER BASIN. MICHIGAN.
AREA = 11300 SQ.MI.

CATALOGING UNITS
04060101 — PERE MARQUETTE-WHITE. MICHIGAN.
AREA = 2100 SQ.MI.
04060102 — MUSKEGON. MICHIGAN.
AREA = 2680 SQ.MI.
04060103 — MANISTEE. MICHIGAN.
AREA = 1970 SQ.MI.
04060104 — BETSIE-PLATTE. MICHIGAN.
AREA = 819 SQ.MI.
04060105 — BOARDMAN-CHARLEVOIX. MICHIGAN.
AREA = 1650 SQ.MI.
04060106 — MANISTIQUE. MICHIGAN.
AREA = 1480 SQ.MI.
04060107 — BREVOORT-MILLECOQUINS. MICHIGAN.
AREA = 578 SQ.MI.

ACCOUNTING UNIT 040602 — LAKE MICHIGAN: LAKE MICHIGAN, INCLUDING ITS BAYS AND ISLANDS. ILLINOIS, INDIANA, MICHIGAN, WISCONSIN.
AREA = 22300 SQ.MI.

CATALOGING UNITS
04060200 — LAKE MICHIGAN. ILLINOIS, INDIANA, MICHIGAN, WISCONSIN.
AREA = 22300 SQ.MI.

SUBREGION 0407 — NORTHWESTERN LAKE HURON: THE DRAINAGE INTO LAKE HURON WITHIN THE UNITED STATES FROM THE SOO LOCKS AT SAULT SAINTE MARIE TO AND INCLUDING THE AU SABLE RIVER BASIN. MICHIGAN.
AREA = 7110 SQ.MI.

ACCOUNTING UNIT 040700 — NORTHWESTERN LAKE HURON. MICHIGAN.
AREA = 7110 SQ.MI.

CATALOGING UNITS
04070001 — ST. MARYS. MICHIGAN.
AREA = 853 SQ.MI.
04070002 — CARP-PINE. MICHIGAN.
AREA = 641 SQ.MI.
04070003 — LONE LAKE-OCQUEOC. MICHIGAN.
AREA = 810 SQ.MI.
04070004 — CHEBOYGAN. MICHIGAN.
AREA = 918 SQ.MI.
04070005 — BLACK. MICHIGAN.
AREA = 618 SQ.MI.
04070006 — THUNDER BAY. MICHIGAN.
AREA = 1270 SQ.MI.
04070007 — AU SABLE. MICHIGAN.
AREA = 2000 SQ.MI.

SUBREGION 0408 — SOUTHWESTERN LAKE HURON-LAKE HURON: THE DRAINAGE INTO LAKE HURON WITHIN THE UNITED STATES, FROM THE AU SABLE RIVER BASIN BOUNDARY TO THE ST. CLAIR RIVER BASIN BOUNDARY AT THE MOUTH OF LAKE HURON, AND LAKE HURON WITHIN THE UNITED STATES, INCLUDING ITS BAYS AND ISLANDS. MICHIGAN.
AREA = 18000 SQ.MI.

ACCOUNTING UNIT 040801 — SOUTHWESTERN LAKE HURON: THE DRAINAGE INTO LAKE HURON WITHIN THE UNITED STATES FROM THE AU SABLE RIVER BASIN BOUNDARY TO THE ST. CLAIR RIVER BASIN BOUNDARY AT THE MOUTH OF LAKE HURON, EXCLUDING THE SAGINAW RIVER BASIN. MICHIGAN.
AREA = 2960 SQ.MI.

CATALOGING UNITS
04080101 — AU GRES-RIFLE. MICHIGAN.
AREA = 1030 SQ.MI.
04080102 — KAWKAWLIN-PI[illegible] MICHIGAN.
AREA = [illegible]3 SQ.MI.
04080103 — PIGEON-WISCOGGIN. MICHIGAN.
AREA = 853 SQ.MI.
04080104 — BIRCH-WILLOW. MICHIGAN.
AREA = 572 SQ.MI.

ACCOUNTING UNIT 040802 — SAGINAW: THE SAGINAW RIVER BASIN. MICHIGAN.
AREA = 6160 SQ.MI.

CATALOGING UNITS
04080201 — TITTABAWASSEE. MICHIGAN.
AREA = 1430 SQ.MI.
04080202 — PINE. MICHIGAN.
AREA = 1040 SQ.MI.
04080203 — SHIAWASSEE. MICHIGAN.
AREA = 1220 SQ.MI.

04080204 — FLINT. MICHIGAN.
AREA = 1340 SQ.MI.
04080205 — CASS. MICHIGAN.
AREA = 881 SQ.MI.
04080206 — SAGINAW. MICHIGAN.
AREA = 250 SQ.MI.

ACCOUNTING UNIT 040803 — LAKE HURON: LAKE HURON WITHIN THE UNITED STATES, INCLUDING ITS BAYS AND ISLANDS. MICHIGAN.
AREA = 8920 SQ.MI.

CATALOGING UNIT 04080300 — LAKE HURON. MICHIGAN.
AREA = 8920 SQ.MI.

SUBREGION 0409 — ST. CLAIR-DETROIT: THE ST. CLAIR AND DETROIT RIVER BASINS WITHIN THE UNITED STATES FROM THE MOUTH OF LAKE HURON TO AND INCLUDING THE HURON RIVER BASIN, AND LAKE ST. CLAIR WITHIN THE UNITED STATES. MICHIGAN.
AREA = 3960 SQ.MI.

ACCOUNTING UNIT 040900 — ST. CLAIR-DETROIT. MICHIGAN.
AREA = 3960 SQ.MI.

CATALOGING UNITS 04090001 — ST. CLAIR. MICHIGAN.
AREA = 1210 SQ.MI.
04090002 — LAKE ST. CLAIR. MICHIGAN.
AREA = 413 SQ.MI.
04090003 — CLINTON. MICHIGAN.
AREA = 742 SQ.MI.
04090004 — DETROIT. MICHIGAN.
AREA = 685 SQ.MI.
04090005 — HURON. MICHIGAN.
AREA = 909 SQ.MI.

SUBREGION 0410 — WESTERN LAKE ERIE: THE DRAINAGE INTO LAKE ERIE FROM THE HURON RIVER BASIN BOUNDARY TO AND INCLUDING THE VERMILION RIVER BASIN. INDIANA, MICHIGAN, OHIO.
AREA = 11900 SQ.MI.

ACCOUNTING UNIT 041000 — WESTERN LAKE ERIE. INDIANA, MICHIGAN, OHIO.
AREA = 11900 SQ.MI.

CATALOGING UNITS 04100001 — OTTAWA-STONY. MICHIGAN, OHIO.
AREA = 689 SQ.MI.
04100002 — RAISIN. MICHIGAN, OHIO.
AREA = 1070 SQ.MI.
04100003 — ST. JOSEPH. INDIANA, MICHIGAN, OHIO.
AREA = 1060 SQ.MI.
04100004 — ST. MARYS. INDIANA, OHIO.
AREA = 820 SQ.MI.
04100005 — UPPER MAUMEE. INDIANA, OHIO.
AREA = 385 SQ.MI.
04100006 — TIFFIN. MICHIGAN, OHIO.
AREA = 781 SQ.MI.
04100007 — AUGLAIZE. INDIANA, OHIO.
AREA = 1660 SQ.MI.
04100008 — BLANCHARD. OHIO.
AREA = 757 SQ.MI.
04100009 — LOWER MAUMEE. OHIO.
AREA = 1080 SQ.MI.
04100010 — CEDAR-PORTAGE. OHIO.
AREA = 958 SQ.MI.
04100011 — SANDUSKY. OHIO.
AREA = 1850 SQ.MI.
04100012 — HURON-VERMILION. OHIO.
AREA = 754 SQ.MI.

SUBREGION 0411 — SOUTHERN LAKE ERIE: THE DRAINAGE INTO LAKE ERIE FROM THE VERMILION RIVER BASIN BOUNDARY TO AND INCLUDING THE ASHTABULA RIVER BASIN. OHIO, PENNSYLVANIA.
AREA = 3030 SQ.MI.

ACCOUNTING UNIT 041100 — SOUTHERN LAKE ERIE. OHIO, PENNSYLVANIA.
AREA = 3030 SQ.MI.

CATALOGING UNITS 04110001 — BLACK-ROCKY. OHIO.
AREA = 888 SQ.MI.
04110002 — CUYAHOGA. OHIO.
AREA = 804 SQ.MI.
04110003 — ASHTABULA-CHAGRIN. OHIO, PENNSYLVANIA.
AREA = 630 SQ.MI.
04110004 — GRAND. OHIO.
AREA = 710 SQ.MI.

SUBREGION 0412 — EASTERN LAKE ERIE-LAKE ERIE: THE DRAINAGE INTO LAKE ERIE WITHIN THE UNITED STATES FROM THE ASHTABULA RIVER BASIN BOUNDARY TO AND INCLUDING THE NIAGARA RIVER BASIN, AND LAKE ERIE WITHIN THE UNITED STATES, INCLUDING ITS BAYS AND ISLANDS. MICHIGAN, NEW YORK, OHIO, PENNSYLVANIA.
AREA = 7740 SQ.MI.

ACCOUNTING UNIT 041201 — EASTERN LAKE ERIE: THE DRAINAGE INTO LAKE ERIE WITHIN THE UNITED STATES FROM THE ASHTABULA RIVER BASIN BOUNDARY TO AND INCLUDING THE NIAGARA RIVER BASIN. NEW YORK, OHIO, PENNSYLVANIA.
AREA = 2930 SQ.MI.

CATALOGING UNITS 04120101 — CHAUTAUQUA-CONNEAUT. NEW YORK, OHIO, PENNSYLVANIA.
AREA = 874 SQ.MI.
04120102 — CATTARAUGUS. NEW YORK.
AREA = 548 SQ.MI.
04120103 — BUFFALO-EIGHTEENMILE. NEW YORK.
AREA = 732 SQ.MI.
04120104 — NIAGARA. NEW YORK.
AREA = 774 SQ.MI.

ACCOUNTING UNIT 041202 — LAKE ERIE: LAKE ERIE WITHIN THE UNITED STATES, INCLUDING ITS BAYS AND ISLANDS. MICHIGAN, NEW YORK, OHIO, PENNSYLVANIA.
AREA = 4810 SQ.MI.

CATALOGING UNIT 04120200 — LAKE ERIE. MICHIGAN, NEW YORK, OHIO, PENNSYLVANIA.
AREA = 4810 SQ.MI.

SUBREGION 0413 — SOUTHWESTERN LAKE ONTARIO: THE DRAINAGE INTO LAKE ONTARIO FROM THE NIAGARA RIVER BASIN BOUNDARY TO AND INCLUDING THE GENESEE RIVER BASIN. NEW YORK, PENNSYLVANIA.
AREA = 3540 SQ.MI.

ACCOUNTING UNIT 041300 — SOUTHWESTERN LAKE ONTARIO. NEW YORK, PENNSYLVANIA.
AREA = 3540 SQ.MI.

CATALOGING UNITS 04130001 — OAK ORCHARD-TWELVEMILE. NEW YORK.
AREA = 1040 SQ.MI.
04130002 — UPPER GENESEE. NEW YORK, PENNSYLVANIA.
AREA = 1430 SQ.MI.
04130003 — LOWER GENESEE. NEW YORK.
AREA = 1070 SQ.MI.

SUBREGION 0414 — SOUTHEASTERN LAKE ONTARIO: THE DRAINAGE INTO LAKE ONTARIO FROM THE GENESEE RIVER BASIN BOUNDARY TO AND INCLUDING THE STONY CREEK BASIN. NEW YORK.
AREA = 6710 SQ.MI.

ACCOUNTING UNIT 041401 — SOUTHEASTERN LAKE ONTARIO: THE DRAINAGE INTO LAKE ONTARIO FROM THE GENESEE RIVER BASIN BOUNDARY TO AND INCLUDING THE STONY CREEK BASIN, EXCLUDING THE OSWEGO RIVER BASIN. NEW YORK.
AREA = 1680 SQ.MI.

CATALOGING UNITS 04140101 — IRONDEQUOIT-NINEMILE. NEW YORK.
AREA = 708 SQ.MI.
04140102 — SALMON-SANDY. NEW YORK.
AREA = 969 SQ.MI.

ACCOUNTING UNIT 041402 — OSWEGO: THE OSWEGO RIVER BASIN. NEW YORK.
AREA = 5030 SQ.MI.

CATALOGING UNITS 04140201 — SENECA. NEW YORK.
AREA = 3430 SQ.MI.
04140202 — ONEIDA. NEW YORK.
AREA = 1470 SQ.MI.
04140203 — OSWEGO. NEW YORK.
AREA = 131 SQ.MI.

SUBREGION 0415 — NORTHEASTERN LAKE ONTARIO-LAKE ONTARIO-ST. LAWRENCE: THE DRAINAGE INTO LAKE ONTARIO AND THE ST. LAWRENCE RIVER BASIN WITHIN THE UNITED STATES FROM THE STONY CREEK BASIN BOUNDARY TO AND INCLUDING THE ENGLISH RIVER BASIN, AND LAKE ONTARIO WITHIN THE UNITED STATES, INCLUDING ITS BAYS AND ISLANDS. NEW YORK.
AREA = 11400 SQ.MI.

ACCOUNTING UNIT 041501 — NORTHEASTERN LAKE ONTARIO: THE DRAINAGE INTO LAKE ONTARIO FROM THE STONY CREEK BASIN BOUNDARY TO THE DRAINAGE BOUNDARY OF THE ST. LAWRENCE RIVER AT THE MOUTH OF LAKE ONTARIO. NEW YORK.
AREA = 2300 SQ.MI.

CATALOGING UNITS 04150101 — BLACK. NEW YORK.
AREA = 1920 SQ.MI.
04150102 — CHAUMONT-PERCH. NEW YORK.
AREA = 380 SQ.MI.

ACCOUNTING UNIT 041502 — LAKE ONTARIO: LAKE ONTARIO WITHIN THE UNITED STATES, INCLUDING ITS BAYS AND ISLANDS. NEW YORK.
AREA = 3430 SQ.MI.

CATALOGING UNIT 04150200 — LAKE ONTARIO. NEW YORK.
AREA = 3430 SQ.MI.

ACCOUNTING UNIT 041503 — ST. LAWRENCE: THE DRAINAGE INTO THE ST. LAWRENCE RIVER BASIN WITHIN THE UNITED STATES FROM THE MOUTH OF LAKE ONTARIO TO AND INCLUDING THE ENGLISH RIVER BASIN. NEW YORK.
AREA = 5650 SQ.MI.

CATALOGING UNITS
04150301 — UPPER ST. LAWRENCE. NEW YORK.
AREA = 506 SQ.MI.
04150302 — OSWEGATCHIE. NEW YORK.
AREA = 1040 SQ.MI.
04150303 — INDIAN. NEW YORK.
AREA = 558 SQ.MI.
04150304 — GRASS. NEW YORK.
AREA = 630 SQ.MI.
04150305 — RAQUETTE. NEW YORK.
AREA = 1250 SQ.MI.
04150306 — ST. REGIS. NEW YORK.
AREA = 853 SQ.MI.
04150307 — ENGLISH-SALMON. NEW YORK.
AREA = 811 SQ.MI.

REGION 05 OHIO REGION — THE DRAINAGE OF THE OHIO RIVER BASIN, EXCLUDING THE TENNESSEE RIVER BASIN. INCLUDES PARTS OF ILLINOIS, INDIANA, KENTUCKY, MARYLAND, NEW YORK, NORTH CAROLINA, OHIO, PENNSYLVANIA, TENNESSEE, VIRGINIA AND WEST VIRGINIA.

SUBREGION 0501 — ALLEGHENY: THE ALLEGHENY RIVER BASIN. PENNSYLVANIA, NEW YORK.
AREA = 11600 SQ.MI.

ACCOUNTING UNIT 050100 — ALLEGHENY. PENNSYLVANIA, NEW YORK.
AREA = 11600 SQ.MI.

CATALOGING UNITS
05010001 — UPPER ALLEGHENY. PENNSYLVANIA, NEW YORK.
AREA = 2560 SQ.MI.
05010002 — CONEWANGO. PENNSYLVANIA, NEW YORK.
AREA = 888 SQ.MI.
05010003 — MIDDLE ALLEGHENY-TIONESTA. PENNSYLVANIA.
AREA = 1670 SQ.MI.
05010004 — FRENCH. PENNSYLVANIA, NEW YORK.
AREA = 1210 SQ.MI.
05010005 — CLARION. PENNSYLVANIA.
AREA = 1230 SQ.MI.
05010006 — MIDDLE ALLEGHENY-REDBANK. PENNSYLVANIA.
AREA = 1680 SQ.MI.
05010007 — CONEMAUGH. PENNSYLVANIA.
AREA = 1350 SQ.MI.
05010008 — KISKIMINETAS. PENNSYLVANIA.
AREA = 500 SQ.MI.
05010009 — LOWER ALLEGHENY. PENNSYLVANIA.
AREA = 479 SQ.MI.

SUBREGION 0502 — MONONGAHELA: THE MONONGAHELA RIVER BASIN. MARYLAND, PENNSYLVANIA, WEST VIRGINIA.
AREA = 7310 SQ.MI.

ACCOUNTING UNIT 050200 — MONONGAHELA. MARYLAND, PENNSYLVANIA, WEST VIRGINIA.
AREA = 7310 SQ.MI.

CATALOGING UNITS
05020001 — TYGART VALLEY. WEST VIRGINIA.
AREA = 1380 SQ.MI.
05020002 — WEST FORK. WEST VIRGINIA.
AREA = 877 SQ.MI.
05020003 — UPPER MONONGAHELA. PENNSYLVANIA, WEST VIRGINIA.
AREA = 463 SQ.MI.
05020004 — CHEAT. PENNSYLVANIA, WEST VIRGINIA.
AREA = 1410 SQ.MI.
05020005 — LOWER MONONGAHELA. PENNSYLVANIA, WEST VIRGINIA.
AREA = 1450 SQ.MI.
05020006 — YOUGHIOGHENY. MARYLAND, PENNSYLVANIA, WEST VIRGINIA.
AREA = 1730 SQ.MI.

SUBREGION 0503 — UPPER OHIO: THE OHIO RIVER BASIN BELOW THE CONFLUENCE OF THE ALLEGHENY AND MONONGAHELA RIVER BASINS TO THE CONFLUENCE WITH THE KANAWHA RIVER BASIN, EXCLUDING THE MUSKINGUM RIVER BASIN. OHIO, PENNSYLVANIA, WEST VIRGINIA.
AREA = 13200 SQ.MI.

ACCOUNTING UNIT 050301 — UPPER OHIO-BEAVER. THE OHIO RIVER BASIN BELOW THE CONFLUENCE OF THE ALLEGHENY AND MONONGAHELA RIVER BASINS TO LOCK AND DAM 14. OHIO, PENNSYLVANIA, WEST VIRGINIA.
AREA = 6570 SQ.MI.

CATALOGING UNITS
05030101 — UPPER OHIO. OHIO, PENNSYLVANIA, WEST VIRGINIA.
AREA = 1950 SQ.MI.
05030102 — SHENANGO. OHIO, PENNSYLVANIA.
AREA = 1050 SQ.MI.
05030103 — MAHONING. OHIO, PENNSYLVANIA.
AREA = 1130 SQ.MI.
05030104 — BEAVER. PENNSYLVANIA.
AREA = 108 SQ.MI.
05030105 — CONNOQUENESSING. PENNSYLVANIA.
AREA = 837 SQ.MI.
05030106 — UPPER OHIO-WHEELING. OHIO, PENNSYLVANIA, WEST VIRGINIA.
AREA = 1490 SQ.MI.

ACCOUNTING UNIT 050302 — UPPER OHIO-LITTLE KANAWHA: THE OHIO RIVER BASIN FROM LOCK AND DAM 14 TO THE CONFLUENCE WITH THE KANAWHA RIVER BASIN, EXCLUDING THE MUSKINGUM RIVER BASIN. OHIO, WEST VIRGINIA.
AREA = 6660 SQ.MI.

CATALOGING UNITS
05030201 — LITTLE MUSKINGUM-MIDDLE ISLAND. OHIO, WEST VIRGINIA.
AREA = 1800 SQ.MI.
05030202 — UPPER OHIO-SHADE. OHIO, WEST VIRGINIA.
AREA = 1390 SQ.MI.
05030203 — LITTLE KANAWHA. WEST VIRGINIA.
AREA = 2300 SQ.MI.

05030204 — HOCKING. OHIO.
AREA = 1170 SQ.MI.

SUBREGION 0504 — MUSKINGUM: THE MUSKINGUM RIVER BASIN. OHIO.
AREA = 7980 SQ.MI.

ACCOUNTING UNIT 050400 — MUSKINGUM. OHIO.
AREA = 7980 SQ.MI.

CATALOGING UNITS 05040001 — TUSCARAWAS. OHIO.
AREA = 2580 SQ.MI.
05040002 — MOHICAN. OHIO.
AREA = 981 SQ.MI.
05040003 — WALHONDING. OHIO.
AREA = 1250 SQ.MI.
05040004 — MUSKINGUM. OHIO.
AREA = 1540 SQ.MI.
05040005 — WILLS. OHIO.
AREA = 843 SQ.MI.
05040006 — LICKING. OHIO.
AREA = 786 SQ.MI.

SUBREGION 0505 — KANAWHA: THE KANAWHA RIVER BASIN. NORTH CAROLINA, VIRGINIA, WEST VIRGINIA.
AREA = 12200 SQ.MI.

ACCOUNTING UNIT 050500 — KANAWHA. NORTH CAROLINA, VIRGINIA, WEST VIRGINIA.
AREA = 12200 SQ.MI.

CATALOGING UNITS 05050001 — UPPER NEW. NORTH CAROLINA, VIRGINIA.
AREA = 2900 SQ.MI.
05050002 — MIDDLE NEW. VIRGINIA, WEST VIRGINIA.
AREA = 1650 SQ.MI.
05050003 — GREENBRIER. WEST VIRGINIA.
AREA = 1650 SQ.MI.
05050004 — LOWER NEW. WEST VIRGINIA.
AREA = 692 SQ.MI.
05050005 — GAULEY. WEST VIRGINIA.
AREA = 1420 SQ.MI.
05050006 — UPPER KANAWHA. WEST VIRGINIA.
AREA = 522 SQ.MI.
05050007 — ELK. WEST VIRGINIA.
AREA = 1530 SQ.MI.
05050008 — LOWER KANAWHA. WEST VIRGINIA.
AREA = 940 SQ.MI.
05050009 — COAL. WEST VIRGINIA.
AREA = 893 SQ.MI.

SUBREGION 0506 — SCIOTO: THE SCIOTO RIVER BASIN. OHIO.
AREA = 6440 SQ.MI.

ACCOUNTING UNIT 050600 — SCIOTO. OHIO.
AREA = 6440 SQ.MI.

CATALOGING UNITS 05060001 — UPPER SCIOTO. OHIO.
AREA = 3160 SQ.MI.
05060002 — LOWER SCIOTO. OHIO.
AREA = 2150 SQ.MI.
05060003 — PAINT. OHIO.
AREA = 1130 SQ.MI.

SUBREGION 0507 — BIG SANDY-GUYANDOTTE: THE BIG SANDY AND GUYANDOTTE RIVER BASINS. KENTUCKY, VIRGINIA, WEST VIRGINIA.
AREA = 5900 SQ.MI.

ACCOUNTING UNIT 050701 — GUYANDOTTE: THE GUYANDOTTE RIVER BASIN. WEST VIRGINIA.
AREA = 1680 SQ.MI.

CATALOGING UNITS 05070101 — UPPER GUYANDOTTE. WEST VIRGINIA.
AREA = 945 SQ.MI.
05070102 — LOWER GUYANDOTTE. WEST VIRGINIA.
AREA = 738 SQ.MI.

ACCOUNTING UNIT 050702 — BIG SANDY: THE BIG SANDY RIVER BASIN. KENTUCKY, VIRGINIA, WEST VIRGINIA.
AREA = 4210 SQ.MI.

CATALOGING UNITS 05070201 — TUG. KENTUCKY, VIRGINIA, WEST VIRGINIA.
AREA = 1520 SQ.MI.
05070202 — UPPER LEVISA. KENTUCKY, VIRGINIA.
AREA = 1200 SQ.MI.
05070203 — LOWER LEVISA. KENTUCKY.
AREA = 1090 SQ.MI.
05070204 — BIG SANDY. KENTUCKY, WEST VIRGINIA.
AREA = 402 SQ.MI.

SUBREGION 0508 — GREAT MIAMI: THE GREAT MIAMI RIVER BASIN. INDIANA, OHIO.
AREA = 5330 SQ.MI.

ACCOUNTING UNIT 050800 — GREAT MIAMI. INDIANA, OHIO.
AREA = 5330 SQ.MI.

CATALOGING UNITS 05080001 — UPPER GREAT MIAMI. INDIANA, OHIO.
AREA = 2480 SQ.MI.
05080002 — LOWER GREAT MIAMI. INDIANA, OHIO.
AREA = 1390 SQ.MI.
05080003 — WHITEWATER. INDIANA, OHIO.
AREA = 1460 SQ.MI.

SUBREGION 0509 — MIDDLE OHIO: THE OHIO RIVER BASIN BELOW THE CONFLUENCE WITH THE KANAWHA RIVER BASIN TO THE CONFLUENCE WITH THE KENTUCKY RIVER BASIN, EXCLUDING THE BIG SANDY, GREAT MIAMI, GUYANDOTTE, KENTUCKY, LICKING AND SCIOTO RIVER BASINS. INDIANA, KENTUCKY, OHIO, WEST VIRGINIA.
AREA = 8850 SQ.MI.

ACCOUNTING UNIT 050901 — MIDDLE OHIO-RACCOON: THE OHIO RIVER BASIN BELOW THE CONFLUENCE WITH THE KANAWHA RIVER BASIN TO RIVER MILE 359.3 (FORMERLY LOCK AND DAM 31) ON THE OHIO RIVER, EXCLUDING THE BIG SANDY, GUYANDOTTE, AND SCIOTO RIVER BASINS. KENTUCKY, OHIO, WEST VIRGINIA.
AREA = 3630 SQ.MI.

CATALOGING UNITS 05090101 — RACCOON-SYMMES. OHIO, WEST VIRGINIA.
AREA = 1450 SQ.MI.
05090102 — TWELVEPOLE. WEST VIRGINIA.
AREA = 444 SQ.MI.
05090103 — LITTLE SCIOTO-TYGARTS. KENTUCKY, OHIO.
AREA = 1020 SQ.MI.
05090104 — LITTLE SANDY. KENTUCKY.
AREA = 713 SQ.MI.

ACCOUNTING UNIT 050902 — MIDDLE OHIO-LITTLE MIAMI: THE OHIO RIVER BASIN FROM RIVER MILE 359.3 (FORMERLY LOCK AND DAM 31) ON THE OHIO RIVER TO THE CONFLUENCE WITH THE KENTUCKY RIVER BASIN, EXCLUDING THE GREAT MIAMI, KENTUCKY AND LICKING RIVER BASINS. INDIANA, KENTUCKY, OHIO.
AREA = 5220 SQ.MI.

CATALOGING UNITS 05090201 — OHIO BRUSH-WHITEOAK. KENTUCKY, OHIO.
AREA = 2110 SQ.MI.
05090202 — LITTLE MIAMI. OHIO.
AREA = 1710 SQ.MI.
05090203 — MIDDLE OHIO-LAUGHERY. INDIANA, KENTUCKY, OHIO.
AREA = 1400 SQ.MI.

SUBREGION 0510 — KENTUCKY-LICKING: THE LICKING AND KENTUCKY RIVER BASINS. KENTUCKY.
AREA = 10500 SQ.MI.

ACCOUNTING UNIT 051001 — LICKING: THE LICKING RIVER BASIN. KENTUCKY.
AREA = 3660 SQ.MI.

CATALOGING UNITS 05100101 — LICKING. KENTUCKY.
AREA = 2740 SQ.MI.
05100102 — SOUTH FORK LICKING. KENTUCKY.
AREA = 915 SQ.MI.

ACCOUNTING UNIT 051002 — KENTUCKY: THE KENTUCKY RIVER BASIN. KENTUCKY.
AREA = 6870 SQ.MI.

CATALOGING UNITS 05100201 — NORTH FORK KENTUCKY. KENTUCKY.
AREA = 1310 SQ.MI.
05100202 — MIDDLE FORK KENTUCKY. KENTUCKY.
AREA = 552 SQ.MI.
05100203 — SOUTH FORK KENTUCKY. KENTUCKY.
AREA = 741 SQ.MI.
05100204 — UPPER KENTUCKY. KENTUCKY.
AREA = 1070 SQ.MI.
05100205 — LOWER KENTUCKY. KENTUCKY.
AREA = 3200 SQ.MI.

SUBREGION 0511 — GREEN: THE GREEN RIVER BASIN. KENTUCKY, TENNESSEE.
AREA = 9140 SQ.MI.

ACCOUNTING UNIT 051100 — GREEN. KENTUCKY, TENNESSEE.
AREA = 9140 SQ.MI.

CATALOGING UNITS 05110001 — UPPER GREEN. KENTUCKY.
AREA = 3130 SQ.MI.
05110002 — BARREN. KENTUCKY, TENNESSEE.
AREA = 2230 SQ.MI.
05110003 — MIDDLE GREEN. KENTUCKY.
AREA = 1010 SQ.MI.
05110004 — ROUGH. KENTUCKY.
AREA = 1070 SQ.MI.
05110005 — LOWER GREEN. KENTUCKY.
AREA = 911 SQ.MI.
05110006 — POND. KENTUCKY.
AREA = 784 SQ.MI.

SUBREGION 0512 — WABASH: THE WABASH RIVER BASIN. ILLINOIS, INDIANA, OHIO.
AREA = 32600 SQ.MI.

ACCOUNTING UNIT 051201 — WABASH: THE WABASH RIVER BASIN, EXCLUDING THE PATOKA AND WHITE RIVER BASINS. ILLINOIS, INDIANA, OHIO.
AREA = 20500 SQ.MI.

CATALOGING UNITS
05120101 — UPPER WABASH. INDIANA, OHIO. AREA = 1570 SQ.MI.
05120102 — SALAMONIE. INDIANA. AREA = 541 SQ.MI.
05120103 — MISSISSINEWA. INDIANA, OHIO. AREA = 811 SQ.MI.
05120104 — EEL. INDIANA. AREA = 811 SQ.MI.
05120105 — MIDDLE WABASH-DEER. INDIANA. AREA = 654 SQ.MI.
05120106 — TIPPECANOE. INDIANA. AREA = 1930 SQ.MI.
05120107 — WILDCAT. INDIANA. AREA = 797 SQ.MI.
05120108 — MIDDLE WABASH-LITTLE VERMILION. ILLINOIS, INDIANA. AREA = 2230 SQ.MI.
05120109 — VERMILION. ILLINOIS, INDIANA. AREA = 1410 SQ.MI.
05120110 — SUGAR. INDIANA. AREA = 818 SQ.MI.
05120111 — MIDDLE WABASH-BUSSERON. ILLINOIS, INDIANA. AREA = 2000 SQ.MI.
05120112 — EMBARRAS. ILLINOIS. AREA = 2430 SQ.MI.
05120113 — LOWER WABASH. ILLINOIS, INDIANA. AREA = 1300 SQ.MI.
05120114 — LITTLE WABASH. ILLINOIS. AREA = 2120 SQ.MI.
05120115 — SKILLET. ILLINOIS. AREA = 1060 SQ.MI.

ACCOUNTING UNIT 051202 — PATOKA-WHITE. THE PATOKA AND WHITE RIVER BASINS. INDIANA.
AREA = 12100 SQ.MI.

CATALOGING UNITS
05120201 — UPPER WHITE. INDIANA. AREA = 2700 SQ.MI.
05120202 — LOWER WHITE. INDIANA. AREA = 1650 SQ.MI.
05120203 — EEL. INDIANA. AREA = 1200 SQ.MI.
05120204 — DRIFTWOOD. INDIANA. AREA = 1150 SQ.MI.
05120205 — FLATROCK-HAW. INDIANA. AREA = 578 SQ.MI.
05120206 — UPPER EAST FORK WHITE. INDIANA. AREA = 806 SQ.MI.
05120207 — MUSCATATUCK. INDIANA. AREA = 1130 SQ.MI.
05120208 — LOWER EAST FORK WHITE. INDIANA. AREA = 2030 SQ.MI.
05120209 — PATOKA. INDIANA. AREA = 854 SQ.MI.

SUBREGION 0513 — CUMBERLAND: THE CUMBERLAND RIVER BASIN. KENTUCKY, TENNESSEE.
AREA = 17700 SQ.MI.

ACCOUNTING UNIT 051301 — UPPER CUMBERLAND: THE CUMBERLAND RIVER BASIN ABOVE THE CONFLUENCE WITH AND INCLUDING THE CANEY FORK BASIN. KENTUCKY, TENNESSEE.
AREA = 10600 SQ.MI.

CATALOGING UNITS
05130101 — UPPER CUMBERLAND. KENTUCKY, TENNESSEE. AREA = 2300 SQ.MI.
05130102 — ROCKCASTLE. KENTUCKY. AREA = 760 SQ.MI.
05130103 — UPPER CUMBERLAND-LAKE CUMBERLAND. KENTUCKY, TENNESSEE. AREA = 1870 SQ.MI.
05130104 — SOUTH FORK CUMBERLAND. KENTUCKY, TENNESSEE. AREA = 1360 SQ.MI.
05130105 — OBEY. KENTUCKY, TENNESSEE. AREA = 932 SQ.MI.
05130106 — UPPER CUMBERLAND-CORDELL HULL RESERVOIR. TENNESSEE. AREA = 782 SQ.MI.
05130107 — COLLINS. TENNESSEE. AREA = 795 SQ.MI.
05130108 — CANEY. TENNESSEE. AREA = 1780 SQ.MI.

ACCOUNTING UNIT 051302 — LOWER CUMBERLAND: THE CUMBERLAND RIVER BASIN BELOW THE CONFLUENCE WITH THE CANEY FORK BASIN. KENTUCKY, TENNESSEE.
AREA = 7150 SQ.MI.

REGION 05: OHIO -- Continued

CATALOGING UNITS
05130201 — LOWER CUMBERLAND-OLD HICKORY LAKE. TENNESSEE. AREA = 975 SQ.MI.
05130202 — LOWER CUMBERLAND-SYCAMORE. TENNESSEE. AREA = 642 SQ.MI.
05130203 — STONES. TENNESSEE. AREA = 921 SQ.MI.
05130204 — HARPETH. TENNESSEE. AREA = 861 SQ.MI.
05130205 — LOWER CUMBERLAND. KENTUCKY, TENNESSEE. AREA = 2300 SQ.MI.
05130206 — RED. KENTUCKY, TENNESSEE. AREA = 1450 SQ.MI.

SUBREGION 0514 — LOWER OHIO: THE OHIO RIVER BASIN BELOW THE CONFLUENCE WITH THE KENTUCKY RIVER BASIN, TO THE CONFLUENCE WITH THE MISSISSIPPI RIVER, EXCLUDING THE CUMBERLAND, GREEN, TENNESSEE, AND WABASH RIVER BASINS. ILLINOIS, INDIANA, KENTUCKY.
AREA = 12500 SQ.MI.

ACCOUNTING UNIT 051401 — LOWER OHIO-SALT. THE OHIO RIVER BASIN BELOW THE CONFLUENCE WITH THE KENTUCKY RIVER BASIN, TO RIVER MILE 703.((FORMERLY LOCK AND DAM 45) ON THE OHIO RIVER. INDIANA, KENTUCKY.
AREA = 6000 SQ.MI.

CATALOGING UNITS
05140101 — SILVER-LITTLE KENTUCKY. INDIANA, KENTUCKY. AREA = 1240 SQ.MI.
05140102 — SALT. KENTUCKY. AREA = 1450 SQ.MI.
05140103 — ROLLING FORK. KENTUCKY. AREA = 1430 SQ.MI.
05140104 — BLUE-SINKING. KENTUCKY, INDIANA. AREA = 1880 SQ.MI.

ACCOUNTING UNIT 051402 — LOWER OHIO: THE OHIO RIVER BASIN FROM RIVER MILE 703.0 (FORMERLY LOCK AND DAM 45) ON THE OHIO RIVER TO THE CONFLUENCE WITH THE MISSISSIPPI RIVER, EXCLUDING THE CUMBERLAND, GREEN, TENNESSEE, AND WABASH RIVER BASINS. ILLINOIS, INDIANA, KENTUCKY.
AREA = 6480 SQ.MI.

CATALOGING UNITS
05140201 — LOWER OHIO-LITTLE PIGEON. INDIANA, AREA = 1370 SQ.MI.
05140202 — HIGHLAND-PIGEON. INDIANA, KENTUCKY. AREA = 1000 SQ.MI.
05140203 — LOWER OHIO-BAY. ILLINOIS, KENTUCKY. AREA = 1090 SQ.MI.
05140204 — SALINE. ILLINOIS. AREA = 1160 SQ.MI.
05140205 — TRADEWATER. KENTUCKY. AREA = 936 SQ.MI.
05140206 — LOWER OHIO. ILLINOIS, KENTUCKY. AREA = 928 SQ.MI.

REGION 06 TENNESSEE REGION — THE DRAINAGE OF THE TENNESSEE RIVER BASIN. INCLUDES PARTS OF ALABAMA, GEORGIA, KENTUCKY, MISSISSIPPI, NORTH CAROLINA, TENNESSEE, AND VIRGINIA.

SUBREGION 0601 — UPPER TENNESSEE: THE TENNESSEE RIVER BASIN ABOVE WATTS BAR DAM. GEORGIA, NORTH CAROLINA, TENNESSEE, VIRGINIA.
AREA = 17200 SQ.MI.

ACCOUNTING UNIT 060101 — FRENCH BROAD-HOLSTON: THE TENNESSEE RIVER BASIN ABOVE THE CONFLUENCE OF AND INCLUDING THE FRENCH BROAD AND HOLSTON RIVER BASINS. NORTH CAROLINA, TENNESSEE, VIRGINIA.
AREA = 8820 SQ.MI.

CATALOGING UNITS
06010101 — NORTH FORK HOLSTON. TENNESSEE, VIRGINIA.
AREA = 708 SQ.MI.
06010102 — SOUTH FORK HOLSTON. TENNESSEE, VIRGINIA.
AREA = 1170 SQ.MI.
06010103 — WATAUGA. NORTH CAROLINA, TENNESSEE.
AREA = 870 SQ.MI.
06010104 — HOLSTON. TENNESSEE.
AREA = 990 SQ.MI.
06010105 — UPPER FRENCH BROAD. NORTH CAROLINA, TENNESSEE.
AREA = 1870 SQ.MI.
06010106 — PIGEON. NORTH CAROLINA, TENNESSEE.
AREA = 679 SQ.MI.
06010107 — LOWER FRENCH BROAD. TENNESSEE.
AREA = 792 SQ.MI.
06010108 — NOLICHUCKY. NORTH CAROLINA, TENNESSEE.
AREA = 1740 SQ.MI.

ACCOUNTING UNIT 060102 — UPPER TENNESSEE: THE TENNESSEE RIVER BASIN ABOVE WATTS BAR DAM, EXCLUDING THE FRENCH BROAD AND HOLSTON RIVER BASINS. GEORGIA, NORTH CAROLINA, TENNESSEE, VIRGINIA.
AREA = 8360 SQ.MI.

CATALOGING UNITS
06010201 — WATTS BAR LAKE. TENNESSEE.
AREA = 1340 SQ.MI.
06010202 — UPPER LITTLE TENNESSEE. GEORGIA, NORTH CAROLINA.
AREA = 839 SQ.MI.
06010203 — TUCKASEGEE. NORTH CAROLINA.
AREA = 731 SQ.MI.
06010204 — LOWER LITTLE TENNESSEE. NORTH CAROLINA, TENNESSEE.
AREA = 1050 SQ.MI.
06010205 — UPPER CLINCH. TENNESSEE, VIRGINIA.
AREA = 1970 SQ.MI.
06010206 — POWELL. TENNESSEE, VIRGINIA.
AREA = 939 SQ.MI.
06010207 — LOWER CLINCH. TENNESSEE.
AREA = 620 SQ.MI.
06010208 — EMORY. TENNESSEE.
AREA = 866 SQ.MI.

SUBREGION 0602 — MIDDLE TENNESSEE-HIWASSEE: THE TENNESSEE RIVER BASIN BELOW WATTS BAR DAM TO AND INCLUDING THE SEQUATCHIE RIVER BASIN. ALABAMA, GEORGIA, NORTH CAROLINA, TENNESSEE.
AREA = 5160 SQ.MI.

ACCOUNTING UNIT 060200 — MIDDLE TENNESSEE-HIWASSEE. ALABAMA, GEORGIA, NORTH CAROLINA, TENNESSEE.
AREA = 5160 SQ.MI.

CATALOGING UNITS
06020001 — MIDDLE TENNESSEE-CHICKAMAUGA. ALABAMA, GEORGIA, TENNESSEE.
AREA = 1870 SQ.MI.
06020002 — HIWASSEE. GEORGIA, NORTH CAROLINA, TENNESSEE.
AREA = 2060 SQ.MI.
06020003 — OCOEE. GEORGIA, NORTH CAROLINA, TENNESSEE.
AREA = 648 SQ.MI.
06020004 — SEQUATCHIE. TENNESSEE.
AREA = 586 SQ.MI.

SUBREGION 0603 — MIDDLE TENNESSEE-ELK: THE TENNESSEE RIVER BASIN BELOW THE CONFLUENCE WITH THE SEQUATCHIE RIVER BASIN TO PICKWICK DAM. ALABAMA, GEORGIA, MISSISSIPPI, TENNESSEE.
AREA = 10300 SQ.MI.

ACCOUNTING UNIT 060300 — MIDDLE TENNESSEE-ELK. ALABAMA, GEORGIA, MISSISSIPPI, TENNESSEE.
AREA = 10300 SQ.MI.

CATALOGING UNITS
06030001 — GUNTERSVILLE LAKE. ALABAMA, GEORGIA, TENNESSEE.
AREA = 1990 SQ.MI.
06030002 — WHEELER LAKE. ALABAMA, TENNESSEE.
AREA = 2890 SQ.MI.
06030003 — UPPER ELK. ALABAMA, TENNESSEE.
AREA = 1270 SQ.MI.

06030004 — LOWER ELK. ALABAMA, TENNESSEE.
AREA = 950 SQ.MI.
06030005 — PICKWICK LAKE. ALABAMA, MISSISSIPPI, TENNESSEE.
AREA = 2270 SQ.MI.
06030006 — BEAR. ALABAMA, MISSISSIPPI.
AREA = 930 SQ.MI.

SUBREGION 0604 — LOWER TENNESSEE: THE TENNESSEE RIVER BASIN BELOW PICKWICK DAM. KENTUCKY, MISSISSIPPI, TENNESSEE.
AREA = 8010 SQ.MI.

ACCOUNTING UNIT 060400 — LOWER TENNESSEE: KENTUCKY, MISSISSIPPI, TENNESSEE.
AREA = 8010 SQ.MI.

CATALOGING UNITS
06040001 — LOWER TENNESSEE-BEECH. MISSISSIPPI, TENNESSEE.
AREA = 2080 SQ.MI.
06040002 — UPPER DUCK. TENNESSEE.
AREA = 1160 SQ.MI.
06040003 — LOWER DUCK. TENNESSEE.
AREA = 1540 SQ.MI.
06040004 — BUFFALO. TENNESSEE.
AREA = 731 SQ.MI.
06040005 — KENTUCKY LAKE. KENTUCKY, TENNESSEE.
AREA = 1810 SQ.MI.
06040006 — LOWER TENNESSEE. KENTUCKY, TENNESSEE.
AREA = 689 SQ.MI.

REGION 07 UPPER MISSISSIPPI REGION — THE DRAINAGE OF THE MISSISSIPPI RIVER BASIN ABOVE THE CONFLUENCE WITH THE OHIO RIVER, EXCLUDING THE MISSOURI RIVER BASIN. INCLUDES PARTS OF ILLINOIS, INDIANA, IOWA, MICHIGAN, MINNESOTA, MISSOURI, SOUTH DAKOTA, AND WISCONSIN.

SUBREGION 0701 — MISSISSIPPI HEADWATERS: THE MISSISSIPPI RIVER BASIN ABOVE THE CONFLUENCE WITH THE ST. CROIX RIVER BASIN, EXCLUDING THE MINNESOTA RIVER BASIN. MINNESOTA.
AREA = 20200 SQ.MI.

ACCOUNTING UNIT 070101 — MISSISSIPPI HEADWATERS: THE MISSISSIPPI RIVER BASIN ABOVE BLANCHARD DAM. MINNESOTA.
AREA = 11700 SQ.MI.

CATALOGING UNITS 07010101 — MISSISSIPPI HEADWATERS. MINNESOTA.
AREA = 2010 SQ.MI.
AREA = 1390 SQ.MI.
07010103 — PRAIRIE-WILLOW. MINNESOTA.
AREA = 2060 SQ.MI.
07010104 — ELK-NOKASIPPI. MINNESOTA.
AREA = 1680 SQ.MI.
07010105 — PINE. MINNESOTA.
AREA = 774 SQ.MI.
07010106 — CROW WING. MINNESOTA.
AREA = 1970 SQ.MI.
07010107 — REDEYE. MINNESOTA.
AREA = 893 SQ.MI.
07010108 — LONG PRAIRIE. MINNESOTA.
AREA = 904 SQ.MI.

ACCOUNTING UNIT 070102 — UPPER MISSISSIPPI-CROW-RUM: THE MISSISSIPPI RIVER BASIN BELOW BLANCHARD DAM AND ABOVE THE CONFLUENCE WITH THE ST. CROIX RIVER BASIN, EXCLUDING THE MINNESOTA RIVER BASIN. MINNESOTA.
AREA = 8520 SQ.MI.

CATALOGING UNITS 07010201 — PLATTE-SPUNK. MINNESOTA.
AREA = 1020 SQ.MI.
07010202 — SAUK. MINNESOTA.
AREA = 1020 SQ.MI.
07010203 — CLEARWATER-ELK. MINNESOTA.
AREA = 1100 SQ.MI.
07010204 — CROW. MINNESOTA.
AREA = 1460 SQ.MI.
07010205 — SOUTH FORK CROW. MINNESOTA.
AREA = 1280 SQ.MI.
07010206 — TWIN CITIES. MINNESOTA.
AREA = 1080 SQ.MI.
07010207 — RUM. MINNESOTA.
AREA = 1560 SQ.MI.

SUBREGION 0702 — MINNESOTA: THE MINNESOTA RIVER BASIN. IOWA, MINNESOTA, SOUTH DAKOTA.
AREA = 16800 SQ.MI.

ACCOUNTING UNIT 070200 — MINNESOTA. IOWA, MINNESOTA, SOUTH DAKOTA.
AREA = 16800 SQ.MI.

CATALOGING UNITS 07020001 — UPPER MINNESOTA. MINNESOTA, SOUTH DAKOTA.
AREA = 1980 SQ.MI.
07020002 — POMME DE TERRE. MINNESOTA.
AREA = 901 SQ.MI.
07020003 — LAC QUI PARLE. SOUTH DAKOTA, MINNESOTA.
AREA = 1070 SQ.MI.
07020004 — HAWK-YELLOW MEDICINE. MINNESOTA.
AREA = 2040 SQ.MI.
07020005 — CHIPPEWA. MINNESOTA.
AREA = 2070 SQ.MI.
07020006 — REDWOOD. MINNESOTA.
AREA = 715 SQ.MI.
07020007 — MIDDLE MINNESOTA. MINNESOTA.
AREA = 1360 SQ.MI.
07020008 — COTTONWOOD. MINNESOTA.
AREA = 1290 SQ.MI.
07020009 — BLUE EARTH. IOWA, MINNESOTA.
AREA = 1570 SQ.MI.
07020010 — WATONWAN. MINNESOTA.
AREA = 835 SQ.MI.
07020011 — LE SUEUR. MINNESOTA.
AREA = 1110 SQ.MI.
07020012 — LOWER MINNESOTA. MINNESOTA.
AREA = 1810 SQ.MI.

SUBREGION 0703 — ST. CROIX: THE ST. CROIX RIVER BASIN. MINNESOTA, WISCONSIN.
AREA = 7750 SQ.MI.

ACCOUNTING UNIT 070300 — ST. CROIX. MINNESOTA, WISCONSIN.
AREA = 7750 SQ.MI.

CATALOGING UNITS 07030001 — UPPER ST. CROIX. MINNESOTA, WISCONSIN.
AREA = 2030 SQ.MI.
07030002 — NAMEKAGON. WISCONSIN.
AREA = 1030 SQ.MI.

07030003 — KETTLE. MINNESOTA.
AREA = 1060 SQ.MI.
07030004 — SNAKE. MINNESOTA.
AREA = 1020 SQ.MI.
07030005 — LOWER ST. CROIX. MINNESOTA, WISCONSIN.
AREA = 2610 SQ.MI.

SUBREGION 0704 — UPPER MISSISSIPPI-BLACK-ROOT: THE MISSISSIPPI RIVER BASIN BELOW THE CONFLUENCE WITH THE ST. CROIX RIVER BASIN TO AND INCLUDING THE ROOT RIVER BASIN WEST OF THE MISSISSIPPI RIVER AND THE LA CROSSE RIVER BASIN EAST OF THE MISSISSIPPI RIVER, EXCLUDING THE CHIPPEWA RIVER BASIN. IOWA, MINNESOTA, WISCONSIN.
AREA = 10700 SQ.MI.

ACCOUNTING UNIT 070400 — UPPER MISSISSIPPI-BLACK-ROOT. IOWA, MINNESOTA, WISCONSIN.
AREA = 10700 SQ.MI.

CATALOGING UNITS 07040001 — RUSH-VERMILLION. MINNESOTA, WISCONSIN.
AREA = 1100 SQ.MI.
07040002 — CANNON. MINNESOTA.
AREA = 1480 SQ.MI.
07040003 — BUFFALO-WHITEWATER. MINNESOTA, WISCONSIN.
AREA = 1370 SQ.MI.
07040004 — ZUMBRO. MINNESOTA.
AREA = 1430 SQ.MI.
07040005 — TREMPEALEAU. WISCONSIN.
AREA = 720 SQ.MI.
07040006 — LA CROSSE-PINE. MINNESOTA, WISCONSIN.
AREA = 678 SQ.MI.
07040007 — BLACK. WISCONSIN.
AREA = 2270 SQ.MI.
07040008 — ROOT. IOWA, MINNESOTA.
AREA = 1670 SQ.MI.

SUREGION 0705 — CHIPPEWA: THE CHIPPEWA RIVER BASIN. MICHIGAN, WISCONSIN.
AREA = 9570 SQ.MI.

ACCOUNTING UNIT 070500 — CHIPPEWA. MICHIGAN, WISCONSIN.
AREA = 9570 SQ.MI.

CATALOGING UNITS 07050001 — UPPER CHIPPEWA. WISCONSIN.
AREA = 1940 SQ.MI.
07050002 — FLAMBEAU. MICHIGAN, WISCONSIN.
AREA = 1190 SQ.MI.
07050003 — SOUTH FORK FLAMBEAU. WISCONSIN.
AREA = 767 SQ.MI.
07050004 — JUMP. WISCONSIN.
AREA = 848 SQ.MI.
07050005 — LOWER CHIPPEWA. WISCONSIN.
AREA = 2040 SQ.MI.
07050006 — EAU CLAIRE. WISCONSIN.
AREA = 871 SQ.MI.
07050007 — RED CEDAR. WISCONSIN.
AREA = 1910 SQ.MI.

SUBREGION 0706 — UPPER MISSISSIPPI-MAQUOKETA-PLUM: THE MISSISSIPPI RIVER BASIN BELOW THE ROOT RIVER BASIN WEST OF THE MISSISSIPPI RIVER AND THE LA CROSSE RIVER BASIN EAST OF THE MISSISSIPPI RIVER TO LOCK AND DAM 13, EXCLUDING THE WISCONSIN RIVER BASIN. ILLINOIS, IOWA, MINNESTOA, WISCONSIN.
AREA = 8610 SQ.MI.

ACCOUNTING UNIT 070600 — UPPER MISSISSIPPI-MAQUOKETA-PLUM. ILLINOIS, IOWA, MINNESOTA, WISCONSIN.
AREA = 8610 SQ.MI.

CATALOGING UNITS 07060001 — COON-YELLOW. IOWA, MINNESOTA, WISCONSIN.
AREA = 1440 SQ.MI.
07060002 — UPPER IOWA. IOWA, MINNESOTA.
AREA = 1010 SQ.MI.
07060003 — GRANT-LITTLE MAQUOKETA. IOWA, WISCONSIN.
AREA = 1110 SQ.MI.
07060004 — TURKEY. IOWA.
AREA = 1690 SQ.MI.
07060005 — APPLE-PLUM. ILLINOIS, IOWA, WISCONSIN.
AREA = 1490 SQ.MI.
07060006 — MAQUOKETA. IOWA.
AREA = 1870 SQ.MI.

SUBREGION 0707 — WISCONSIN: THE WISCONSIN RIVER BASIN. MICHIGAN, WISCONSIN.
AREA = 11900 SQ.MI.

ACCOUNTING UNIT 070700 — WISCONSIN. MICHIGAN, WISCONSIN.
AREA = 11900 SQ.MI.

CATALOGING UNITS 07070001 — UPPER WISCONSIN. MICHIGAN, WISCONSIN.
AREA = 2190 SQ.MI.
07070002 — LAKE DUBAY. WISCONSIN.
AREA = 2690 SQ.MI.
07070003 — CASTLE ROCK. WISCONSIN.
AREA = 3250 SQ.MI.
07070004 — BARABOO. WISCONSIN.
AREA = 660 SQ.MI.
07070005 — LOWER WISCONSIN. WISCONSIN.
AREA = 2360 SQ.MI.
07070006 — KICKAPOO. WISCONSIN.
AREA = 753 SQ.MI.

SUBREGION 0708 — UPPER MISSISSIPPI-IOWA-SKUNK-WAPSIPINICON: THE MISSISSIPPI RIVER BASIN BELOW LOCK AND DAM 13 TO THE CONFLUENCE WITH THE DES MOINES RIVER BASIN, EXCLUDING THE ROCK RIVER BASIN. ILLINOIS, IOWA, MINNESOTA.
AREA = 22800 SQ.MI.

ACCOUNTING UNIT 070801 — UPPER MISSISSIPPI-SKUNK-WAPSIPINICON: THE MISSISSIPPI RIVER BASIN BELOW LOCK AND DAM 13 TO THE CONFLUENCE WITH THE DES MOINES RIVER BASIN, EXCLUDING THE IOWA AND ROCK RIVER BASINS. ILLINOIS, IOWA, MINNESOTA.
AREA = 10200 SQ.MI.

CATALOGING UNITS 07080101 — COPPERAS-DUCK. ILLINOIS, IOWA.
AREA = 1040 SQ.MI.
07080102 — UPPER WAPSIPINICON. IOWA, MINNESOTA.
AREA = 1550 SQ.MI.
07080103 — LOWER WAPSIPINICON. IOWA.
AREA = 967 SQ.MI.
07080104 — FLINT-HENDERSON. ILLINOIS, IOWA.
AREA = 2350 SQ.MI.
07080105 — SOUTH SKUNK. IOWA.
AREA = 1840 SQ.MI.
07080106 — NORTH SKUNK. IOWA.
AREA = 883 SQ.MI.
07080107 — SKUNK. IOWA.
AREA = 1610 SQ.MI.

ACCOUNTING UNIT 070802 — IOWA: THE IOWA RIVER BASIN. IOWA, MINNESOTA.
AREA = 12600 SQ.MI.

CATALOGING UNITS 07080201 — UPPER CEDAR. IOWA, MINNESOTA.
AREA = 1730 SQ.MI.
07080202 — SHELL ROCK. IOWA, MINNESOTA.
AREA = 1060 SQ.MI.
07080203 — WINNEBAGO. IOWA, MINNESOTA.
AREA = 704 SQ.MI.
07080204 — WEST FORK CEDAR. IOWA.
AREA = 850 SQ.MI.
07080205 — MIDDLE CEDAR. IOWA.
AREA = 2410 SQ.MI.
07080206 — LOWER CEDAR. IOWA.
AREA = 1060 SQ.MI.
07080207 — UPPER IOWA. IOWA.
AREA = 1430 SQ.MI.
07080208 — MIDDLE IOWA. IOWA.
AREA = 1670 SQ.MI.
07080209 — LOWER IOWA. IOWA.
AREA = 1670 SQ.MI.

SUBREGION 0709 — ROCK: THE ROCK RIVER BASIN. ILLINOIS, WISCONSIN.
AREA = 10900 SQ.MI.

ACCOUNTING UNIT 070900 — ROCK. ILLINOIS, WISCONSIN.
AREA = 10900 SQ.MI.

CATALOGING UNITS 07090001 — UPPER ROCK. ILLINOIS, WISCONSIN.
AREA = 2920 SQ.MI.
07090002 — CRAWFISH. WISCONSIN.
AREA = 788 SQ.MI.
07090003 — PECATONICA. ILLINOIS, WISCONSIN.
AREA = 1870 SQ.MI.
07090004 — SUGAR. ILLINOIS, WISCONSIN.
AREA = 748 SQ.MI.
07090005 — LOWER ROCK. ILLINOIS, WISCONSIN.
AREA = 2180 SQ.MI.
07090006 — KISHWAUKEE. ILLINOIS, WISCONSIN.
AREA = 1260 SQ.MI.
07090007 — GREEN. ILLINOIS.
AREA = 1120 SQ.MI.

SUBREGION 0710 — DES MOINES: THE DES MOINES RIVER BASIN. IOWA, MINNESOTA, MISSOURI.
AREA = 14400 SQ.MI.

ACCOUNTING UNIT 071000 — DES MOINES. IOWA, MINNESOTA, MISSOURI.
AREA = 14400 SQ.MI.

REGION 07: UPPER MISSISSIPPI — Continued

CATALOGING UNITS 07100001 — DES MOINES HEADWATERS. MINNESOTA.
AREA = 1250 SQ.MI.
07100002 — UPPER DES MOINES. IOWA, MINNESOTA.
AREA = 1100 SQ.MI.
07100003 — EAST FORK DES MOINES. IOWA, MINNESOTA.
AREA = 1310 SQ.MI.
07100004 — MIDDLE DES MOINES. IOWA.
AREA = 1690 SQ.MI.
07100005 — BOONE. IOWA.
AREA = 910 SQ.MI.
07100006 — NORTH RACCOON. IOWA.
AREA = 2460 SQ.MI.
07100007 — SOUTH RACCOON. IOWA.
AREA = 1130 SQ.MI.
07100008 — LAKE RED ROCK. IOWA.
AREA = 2400 SQ.MI.
07100009 — LOWER DES MOINES. IOWA, MISSOURI.
AREA = 2110 SQ.MI.

SUBREGION 0711 — UPPER MISSISSIPPI-SALT: THE MISSISSIPPI RIVER BASIN BELOW THE CONFLUENCE WITH THE DES MOINES RIVER BASIN TO THE CONFLUENCE WITH THE MISSOURI RIVER BASIN, EXCLUDING THE ILLINOIS RIVER BASIN. ILLINOIS, IOWA, MISSOURI.
AREA = 9970 SQ.MI.

ACCOUNTING UNIT 071100 — UPPER MISSISSIPPI-SALT. ILLINOIS, IOWA, MISSOURI.
AREA = 9970 SQ.MI.

CATALOGING UNITS 07110001 — BEAR-WYACONDA. ILLINOIS, IOWA, MISSOURI.
AREA = 1710 SQ.MI.
07110002 — NORTH FABIUS. IOWA, MISSOURI.
AREA = 930 SQ.MI.
07110003 — SOUTH FABIUS. MISSOURI.
AREA = 623 SQ.MI.
07110004 — THE SNY. ILLINOIS, MISSOURI.
AREA = 1960 SQ.MI.
07110005 — NORTH FORK SALT. MISSOURI.
AREA = 895 SQ.MI.
07110006 — SOUTH FORK SALT. MISSOURI.
AREA = 1190 SQ.MI.
07110007 — SALT. MISSOURI.
AREA = 780 SQ.MI.
07110008 — CUIVRE. MISSOURI.
AREA = 1250 SQ.MI.
07110009 — PERUQUE-PIASA. ILLINOIS, MISSOURI.
AREA = 633 SQ.MI.

SUBREGION 0712 — UPPER ILLINOIS: THE ILLINOIS RIVER BASIN ABOVE THE CONFLUENCE OF AND INCLUDING THE FOX RIVER BASIN. ILLINOIS, INDIANA, MICHIGAN, WISCONSIN.
AREA = 10900 SQ.MI.

ACCOUNTING UNIT 071200 — UPPER ILLINOIS. ILLINOIS, INDIANA, MICHIGAN, WISCONSIN.
AREA = 10900 SQ.MI.

CATALOGING UNITS 07120001 — KANKAKEE. ILLINOIS, INDIANA, MICHIGAN.
AREA = 3010 SQ.MI.
07120002 — IROQUOIS. ILLINOIS, INDIANA.
AREA = 2110 SQ.MI.
07120003 — CHICAGO. ILLINOIS, INDIANA.
AREA = 622 SQ.MI.
07120004 — DES PLAINES. ILLINOIS, WISCONSIN.
AREA = 1440 SQ.MI.
07120005 — UPPER ILLINOIS. ILLINOIS.
AREA = 1010 SQ.MI.
07120006 — UPPER FOX. ILLINOIS, WISCONSIN.
AREA = 1570 SQ.MI.
07120007 — LOWER FOX. ILLINOIS.
AREA = 1090 SQ.MI.

SUBREGION 0713 — LOWER ILLINOIS: THE ILLINOIS RIVER BASIN BELOW THE CONFLUENCE OF THE FOX RIVER BASIN. ILLINOIS.
AREA = 17700 SQ.MI.

ACCOUNTING UNIT 071300 — LOWER ILLINOIS. ILLINOIS.
AREA = 17700 SQ.MI.

CATALOGING UNITS 07130001 — LOWER ILLINOIS-SENACHWINE LAKE. ILLINOIS.
AREA = 1950 SQ.MI.
07130002 — VERMILION. ILLINOIS.
AREA = 1290 SQ.MI.
07130003 — LOWER ILLINOIS-LAKE CHAUTAUQUA. ILLINOIS.
AREA = 1520 SQ.MI.
07130004 — MACKINAW. ILLINOIS.
AREA = 1130 SQ.MI.
07130005 — SPOON. ILLINOIS.
AREA = 1860 SQ.MI.
07130006 — UPPER SANGAMON. ILLINOIS.
AREA = 1420 SQ.MI.
07130007 — SOUTH FORK SANGAMON. ILLINOIS.
AREA = 1130 SQ.MI.
07130008 — LOWER SANGAMON. ILLINOIS.
AREA = 928 SQ.MI.

07130009 — SALT. ILLINOIS.
AREA = 1890 SQ.MI.
07130010 — LA MOINE. ILLINOIS.
AREA = 1340 SQ.MI.
07130011 — LOWER ILLINOIS. ILLINOIS.
AREA = 2280 SQ.MI.
07130012 — MACOUPIN. ILLINOIS.
AREA = 966 SQ.MI.

SUBREGION 0714 — UPPER MISSISSIPPI-KASKASKIA-MERAMEC: THE MISSISSIPPI RIVER BASIN BELOW THE CONFLUENCE WITH AND EXCLUDING THE MISSOURI RIVER BASIN TO THE CONFLUENCE WITH THE OHIO RIVER. ILLINOIS, MISSOURI.
AREA = 16900 SQ.MI.

ACCOUNTING UNIT 071401 — UPPER MISSISSIPPI-MERAMEC: THE MISSISSIPPI RIVER BASIN BELOW THE CONFLUENCE WITH AND EXCLUDING THE MISSOURI RIVER BASIN TO THE CONFLUENCE WITH THE OHIO RIVER, EXCLUDING THE KASKASKIA RIVER BASIN. ILLINOIS, MISSOURI.
AREA = 11200 SQ.MI.

CATALOGING UNITS 07140101 — CAHOKIA-JOACHIM. ILLINOIS, MISSOURI.
AREA = 1650 SQ.MI.
07140102 — MERAMEC. MISSOURI.
AREA = 2130 SQ.MI.
07140103 — BOURBEUSE. MISSOURI.
AREA = 838 SQ.MI.
07140104 — BIG. MISSOURI.
AREA = 955 SQ.MI.
07140105 — UPPER MISSISSIPPI-CAPE GIRARDEAU. ILLINOIS. MISSOURI.
AREA = 1690 SQ.MI.
07140106 — BIG MUDDY. ILLINOIS.
AREA = 2350 SQ.MI.
07140107 — WHITEWATER. MISSOURI.
AREA = 1210 SQ.MI.
07140108 — CACHE. ILLINOIS.
AREA = 352 SQ.MI.

ACCOUNTING UNIT 071402 — KASKASKIA: THE KASKASKIA RIVER BASIN. ILLINOIS.
AREA = 5700 SQ.MI.

CATALOGING UNITS 07140201 — UPPER KASKASKIA. ILLINOIS.
AREA = 1540 SQ.MI.
07140202 — MIDDLE KASKASKIA. ILLINOIS.
AREA = 1680 SQ.MI.
07140203 — SHOAL. ILLINOIS.
AREA = 879 SQ.MI.
07140204 — LOWER KASKASKIA. ILLINOIS.
AREA = 1600 SQ.MI.

REGION 08 LOWER MISSISSIPPI REGION — THE DRAINAGE OF: (A) THE MISSISSIPPI RIVER BELOW ITS CONFLUENCE WITH THE OHIO RIVER, EXCLUDING THE ARKANSAS, RED, AND WHITE RIVER BASINS ABOVE THE POINTS OF HIGHEST BACKWATER EFFECT OF THE MISSISSIPPI RIVER IN THOSE BASINS; AND (B) COASTAL STREAMS THAT ULTIMATELY DISCHARGE INTO THE GULF OF MEXICO FROM THE PEARL RIVER BASIN BOUNDARY TO THE SABINE RIVER AND SABINE LAKE DRAINAGE BOUNDARY. INCLUDES PARTS OF ARKANSAS, KENTUCKY LOUISIANA, MISSISSIPPI, MISSOURI, AND TENNESSEE.

SUBREGION 0801 — LOWER MISSISSIPPI-HATCHIE: THE MISSISSIPPI RIVER BASIN FROM THE CONFLUENCE OF THE OHIO RIVER TO AND INCLUDING THE HORN LAKE CREEK BASIN, BUT EXCLUDING THE DRAINAGE WEST OF THE WEST-BANK LEVEE ALONG THE MISSISSIPPI RIVER. ARKANSAS, KENTUCKY, MISSISSIPPI, MISSOURI, AND TENNESSEE.
AREA = 11000 SQ.MI.

ACCOUNTING UNIT 080101 — LOWER MISSISSIPPI-MEMPHIS: THE MISSISSIPPI ALLUVIAL LANDS LYING IN THE FLOOD PLAIN OF THE PRESENT CHANNEL OF THE MISSISSIPPI RIVER BETWEEN THE WEST-BANK LEVEE AND THE DRAINAGE BOUNDARIES OF THE MAJOR TRIBUTARIES ALONG THE EAST BANK, FROM THE CONFLUENCE OF THE OHIO RIVER TO HORN LAKE CREEK. ARKANSAS, KENTUCKY, MISSISSIPPI, MISSOURI, AND TENNESSEE.
AREA = 1110 SQ.MI.

CATALOGING UNIT 08010100 — LOWER MISSISSIPPI-MEMPHIS. ARKANSAS, KENTUCKY, MISSISSIPPI, MISSOURI, AND TENNESSEE.
AREA = 1110 SQ.MI.

ACCOUNTING UNIT 080102 — HATCHIE-OBION: THE DRAINAGE BASINS EAST OF THE MISSISSIPPI RIVER FROM THE OHIO RIVER BASIN TO AND INCLUDING THE HORN LAKE CREEK BASIN, BUT EXCLUDING THE ALLUVIAL LANDS LYING IN THE FLOOD PLAIN OF THE PRESENT CHANNEL OF THE MISSISSIPPI RIVER EAST OF THE WEST-BANK LEVEE. KENTUCKY, MISSISSIPPI, AND TENNESSEE.
AREA = 9910 SQ.MI.

CATALOGING UNITS 08010201 — BAYOU DE CHIEN-MAYFIELD. KENTUCKY, TENNESSEE.
AREA = 957 SQ.MI.
08010202 — OBION. KENTUCKY, TENNESSEE.
AREA = 1310 SQ.MI.
08010203 — SOUTH FORK OBION. TENNESSEE.
AREA = 1150 SQ.MI.
08010204 — NORTH FORK FORKED DEER. TENNESSEE.
AREA = 952 SQ.MI.
08010205 — SOUTH FORK FORKED DEER. TENNESSEE.
AREA = 1050 SQ.MI.
08010206 — FORKED DEER. TENNESSEE.
AREA = 70 SQ.MI.
08010207 — UPPER HATCHIE. MISSISSIPPI, TENNESSEE.
AREA = 1130 SQ.MI.
08010208 — LOWER HATCHIE. MISSISSIPPI, TENNESSEE.
AREA = 1460 SQ.MI.
08010209 — LOOSAHATCHIE. TENNESSEE.
AREA = 736 SQ.MI.
08010210 — WOLF. MISSISSIPPI, TENNESSEE.
AREA = 813 SQ.MI.
08010211 — HORN LAKE-NONCONNAH. MISSISSIPPI, TENNESSEE.
AREA = 281 SQ.MI.

SUBREGION 0802 — LOWER MISSISSIPPI - ST. FRANCIS: THE MISSISSIPPI RIVER BASIN FROM THE HORN LAKE CREEK BASIN ON THE EAST BANK TO AND INCLUDING THE ARKANSAS AND WHITE RIVER BASINS BELOW THE POINTS OF HIGHEST BACKWATER EFFECT OF THE MISSISSIPPI RIVER; EXCLUDING ALL DRAINAGE EAST OF THE EAST-BANK LEVEE BELOW THE HORN LAKE CREEK BASIN. ARKANSAS, MISSISSIPPI, AND MISSOURI.
AREA = 16700 SQ.MI.

ACCOUNTING UNIT 080201 — LOWER MISSISSIPPI-HELENA: THE MISSISSIPPI ALLUVIAL LANDS LYING IN THE FLOOD PLAIN OF THE PRESENT CHANNEL OF THE MISSISSIPPI RIVER BETWEEN THE EAST-BANK LEVEE AND THE LEVEES OR THE DRAINAGE BOUNDARIES OF THE MAJOR TRIBUTARIES ALONG THE WEST BANK, FROM HORN LAKE CREEK TO THE ARKANSAS RIVER. ARKANSAS, MISSISSIPPI.
AREA = 566 SQ.MI.

CATALOGING UNIT 08020100 — LOWER MISSISSIPPI-HELENA. ARKANSAS, MISSISSIPPI.
AREA = 566 SQ.MI.

ACCOUNTING UNIT 080202 — ST. FRANCIS: THE ST. FRANCIS RIVER BASIN AND ALL MAN-MADE DIVERSIONS INTO THE BASIN. ARKANSAS, MISSOURI.
AREA = 9040 SQ.MI.

CATALOGING UNITS 08020201 — NEW MADRID-ST. JOHNS. MISSOURI.
AREA = 703 SQ.MI.
08020202 — UPPER ST. FRANCIS. MISSOURI.
AREA = 1280 SQ.MI.
08020203 — LOWER ST. FRANCIS. ARKANSAS, MISSOURI.
AREA = 3480 SQ.MI.
08020204 — LITTLE RIVER DITCHES. ARKANSAS.
AREA = 2620 SQ.MI.
08020205 — L'ANGUILLE. ARKANSAS.
AREA = 961 SQ.MI.

ACCOUNTING UNIT 080203 — LOWER WHITE: THE WHITE RIVER BASIN BELOW THE LITTLE RED RIVER BASIN. ARKANSAS, MISSOURI.
AREA = 5410 SQ.MI.

CATALOGING UNITS 08020301 — LOWER WHITE-BAYOU DES ARC. ARKANSAS.
AREA = 1110 SQ.MI.
08020302 — CACHE. ARKANSAS, MISSOURI.
AREA = 2000 SQ.MI.
08020303 — LOWER WHITE. ARKANSAS.
AREA = 1360 SQ.MI.
08020304 — BIG. ARKANSAS.
AREA = 943 SQ.MI.

ACCOUNTING UNIT 080204 — LOWER ARKANSAS: THE ARKANSAS RIVER BASIN BELOW THE PLUM BAYOU BASIN. ARKANSAS.
AREA = 1690 SQ.MI.

CATALOGING UNITS 08020401 — LOWER ARKANSAS. ARKANSAS.
AREA = 700 SQ.MI.
08020402 — BAYOU METO. ARKANSAS.
AREA = 993 SQ.MI.

SUBREGION 0803 — LOWER MISSISSIPPI - YAZOO: THE MISSISSIPPI RIVER BASIN FROM THE ARKANSAS RIVER BASIN TO AND INCLUDING THE YAZOO RIVER BASIN; EXCLUDING ALL DRAINAGE WEST OF THE WEST-BANK LEVEE BELOW THE ARKANSAS RIVER BASIN. ARKANSAS, LOUISIANA, MISSISSIPPI, AND TENNESSEE.
AREA = 14100 SQ.MI.

ACCOUNTING UNIT 080301 — LOWER MISSISSIPPI-GREENVILLE: THE MISSISSIPPI ALLUVIAL LANDS LYING IN THE FLOOD PLAIN OF THE PRESENT CHANNEL OF THE MISSISSIPPI RIVER BETWEEN THE EAST-BANK AND THE WEST-BANK LEVEES, FROM THE ARKANSAS RIVER TO THE YAZOO RIVER. ARKANSAS, MISSISSIPPI.
AREA = 629 SQ.MI.

CATALOGING UNIT 08030100 — LOWER MISSISSIPPI-GREENVILLE. ARKANSAS, LOUISIANA, MISSISSIPPI.
AREA = 629 SQ.MI.

ACCOUNTING UNIT 080302 — YAZOO: THE YAZOO RIVER BASIN. LOUISIANA, MISSISSIPPI, TENNESSEE.
AREA = 13500 SQ.MI.

CATALOGING UNITS 08030201 — LITTLE TALLAHATCHIE. MISSISSIPPI.
AREA = 1640 SQ.MI.
08030202 — TALLAHATCHIE. MISSISSIPPI.
AREA = 1010 SQ.MI.
08030203 — YOCONA. MISSISSIPPI.
AREA = 752 SQ.MI.
08030204 — COLDWATER. MISSISSIPPI, TENNESSEE.
AREA = 1920 SQ.MI.
08030205 — YALOBUSHA. MISSISSIPPI.
AREA = 2310 SQ.MI.
08030206 — UPPER YAZOO. MISSISSIPPI.
AREA = 1560 SQ.MI.
08030207 — BIG SUNFLOWER. MISSISSIPPI.
AREA = 3120 SQ.MI.
08030208 — LOWER YAZOO. LOUISIANA, MISSISSIPPI.
AREA = 222 SQ.MI.
08030209 — DEER-STEELE. LOUISIANA, MISSISSIPPI.
AREA = 938 SQ.MI.

SUBREGION 0804 — LOWER RED - OUACHITA: THE RED RIVER BASIN BELOW THE BAYOU RIGOLETTE BASIN, EXCLUDING THE BOEUF AND TENSAS RIVER BASINS. ARKANSAS, LOUISIANA.
AREA = 20500 SQ.MI.

ACCOUNTING UNIT 080401 — UPPER OUACHITA: THE OUACHITA RIVER BASIN ABOVE THE TWO BAYOU BASIN. ARKANSAS.
AREA = 5380 SQ.MI.

CATALOGING UNITS 08040101 — OUACHITA HEADWATERS. ARKANSAS.
AREA = 1550 SQ.MI.
08040102 — UPPER OUACHITA. ARKANSAS.
AREA = 1750 SQ.MI.

REGION 08: LOWER MISSISSIPPI — Continued

08040103 — LITTLE MISSOURI. ARKANSAS.
AREA = 2080 SQ.MI.

ACCOUNTING UNIT 080402 — LOWER OUACHITA: THE OUACHITA RIVER BASIN BELOW AND INCLUDING THE TWO BAYOU BASIN. ARKANSAS, LOUISIANA.
AREA = 10700 SQ.MI.

CATALOGING UNITS 08040201 — LOWER OUACHITA-SMACKOVER. ARKANSAS.
AREA = 1810 SQ.MI.
08040202 — LOWER OUACHITA-BAYOU DE LOUTRE. ARKANSAS, LOUISIANA.
AREA = 1300 SQ.MI.
08040203 — UPPER SALINE. ARKANSAS.
AREA = 1710 SQ.MI.
08040204 — LOWER SALINE. ARKANSAS.
AREA = 1510 SQ.MI.
08040205 — BAYOU BARTHOLOMEW. ARKANSAS, LOUISIANA.
AREA = 1680 SQ.MI.
08040206 — BAYOU D'ARBONNE. ARKANSAS, LOUISIANA.
AREA = 1930 SQ.MI.
08040207 — LOWER OUACHITA. LOUISIANA.
AREA = 759 SQ.MI.

ACCOUNTING UNIT 080403 — LOWER RED: THE RED RIVER BASIN BELOW THE BAYOU RIGOLETTE BASIN, EXCLUDING THE BOEUF, OUACHITA, AND TENSAS RIVER BASINS. LOUISIANA.
AREA = 4400 SQ.MI.

CATALOGING UNITS 08040301 — LOWER RED. LOUISIANA.
AREA = 898 SQ.MI.
08040302 — CASTOR. LOUISIANA.
AREA = 966 SQ.MI.
08040303 — DUGDEMONA. LOUISIANA.
AREA = 927 SQ.MI.
08040304 — LITTLE. LOUISIANA.
AREA = 987 SQ.MI.
08040305 — BLACK. LOUISIANA.
AREA = 84 SQ.MI.
08040306 — BAYOU COCODRIE. LOUISIANA.
AREA = 542 SQ.MI.

SUBREGION 0805 — BOEUF-TENSAS: THE BOEUF AND TENSAS RIVER BASINS. ARKANSAS, LOUISIANA.
AREA = 5300 SQ.MI.

ACCOUNTING UNIT 080500 — BOEUF-TENSAS. ARKANSAS, LOUISIANA.
AREA = 5300 SQ.MI.

CATALOGING UNITS 08050001 — BOEUF. ARKANSAS, LOUISIANA.
AREA = 2890 SQ.MI.
08050002 — BAYOU MACON. ARKANSAS, LOUISIANA.
AREA = 1060 SQ.MI.
08050003 — TENSAS. LOUISIANA.
AREA = 1350 SQ.MI.

SUBREGION 0806 — LOWER MISSISSIPPI - BIG BLACK: THE MISSISSIPPI RIVER BASIN FROM THE YAZOO RIVER BASIN TO THE LOWER OLD RIVER DRAINAGE BOUNDARY, BUT EXCLUDING ALL THE DRAINAGE WEST OF THE WEST-BANK LEVEE ALONG THE MISSISSIPPI RIVER. LOUISIANA, MISSISSIPPI.
AREA = 7100 SQ.MI.

ACCOUNTING UNIT 080601 — LOWER MISSISSIPPI-NATCHEZ: THE MISSISSIPPI ALLUVIAL LANDS LYING IN THE FLOOD PLAIN OF THE PRESENT CHANNEL OF THE MISSISSIPPI RIVER BETWEEN THE WEST-BANK LEVEE AND THE DRAINAGE BOUNDARIES OF THE MAJOR TRIBUTARIES ALONG THE EAST BANK, FROM THE THE YAZOO RIVER TO THE LOWER OLD RIVER. LOUISIANA, MISSISSIPPI.
AREA = 548 SQ.MI.

CATALOGING UNIT 08060100 — LOWER MISSISSIPPI-NATCHEZ. LOUISIANA, MISSISSIPPI.
AREA = 548 SQ.MI.

ACCOUNTING UNIT 080602 — BIG BLACK - HOMOCHITTO: THE DRAINAGE BASINS EAST OF THE MISSISSIPPI RIVER FROM THE YAZOO RIVER BASIN TO AND INCLUDING THE BUFFALO RIVER BASIN, BUT EXCLUDING THE ALLUVIAL LANDS LYING IN THE FLOOD PLAIN OF THE PRESENT CHANNEL OF THE MISSISSIPPI RIVER EAST OF WEST-BANK LEVEE. LOUISIANA, MISSISSIPPI.
AREA = 6550 SQ.MI.

CATALOGING UNITS 08060201 — UPPER BIG BLACK. MISSISSIPPI.
AREA = 1470 SQ.MI.
08060202 — LOWER BIG BLACK. LOUISIANA, MISSISSIPPI.
AREA = 1900 SQ.MI.
08060203 — BAYOU PIERRE. LOUISIANA, MISSISSIPPI.
AREA = 1070 SQ.MI.

08060204 — COLES CREEK. LOUISIANA, MISSISSIPPI.
AREA = 551 SQ.MI.
08060205 — HOMOCHITTO. MISSISSIPPI.
AREA = 1220 SQ.MI.
08060206 — BUFFALO. MISSISSIPPI.
AREA = 343 SQ.MI.

SUBREGION 0807 — LOWER MISSISSIPPI-LAKE MAUREPAS: THE MISSISSIPPI RIVER BASIN FROM THE LOWER OLD RIVER DRAINAGE BOUNDARY TO THE BONNET CARRE FLOODWAY, AND INCLUDING THE LOWER GRAND RIVER BASIN WEST OF THE WEST-BANK LEVEE. LOUISIANA, MISSISSIPPI.
AREA = 5870 SQ.MI.

ACCOUNTING UNIT 080701 — LOWER MISSISSIPPI-BATON ROUGE: THE MISSISSIPPI ALLUVIAL LANDS LYING IN THE FLOOD PLAIN OF THE PRESENT CHANNEL OF THE MISSISSIPPI RIVER BETWEEN THE WEST-BANK LEVEE AND THE EAST-BANK LEVEE OR THE DRAINAGE BOUNDARIES OF THE MAJOR TRIBUTARIES ALONG THE EAST BANK, FROM THE LOWER OLD RIVER TO THE BONNET CARRE FLOODWAY. LOUISIANA.
AREA = 270 SQ.MI.

CATALOGING UNIT 08070100 — LOWER MISSISSIPPI-BATON ROUGE. LOUISIANA.
AREA = 270 SQ.MI.

ACCOUNTING UNIT 080702 — LAKE MAUREPAS: THE DRAINAGE BASINS EAST OF THE MISSISSIPPI RIVER FROM THE BUFFALO RIVER BASIN TO THE BONNET CARRE FLOODWAY, BUT EXCLUDING THE MISSISSIPPI ALLUVIAL LANDS EAST OF THE WEST-BANK LEVEE; AND INCLUDING DRAINAGE FROM THE NORTH INTO LAKE PONTCHARTRAIN, EAST TO AND INCLUDING THE TANGIPAHOA RIVER BASIN. LOUISIANA, MISSISSIPPI.
AREA = 4810 SQ.MI.

CATALOGING UNITS 08070201 — BAYOU SARA-THOMPSON. LOUISIANA, MISSISSIPPI.
AREA = 698 SQ.MI.
08070202 — AMITE. LOUISIANA, MISSISSIPPI.
AREA = 1890 SQ.MI.
08070203 — TICKFAW. LOUISIANA, MISSISSIPPI.
AREA = 729 SQ.MI.
08070204 — LAKE MAUREPAS. LOUISIANA.
AREA = 719 SQ.MI.
08070205 — TANGIPAHOA. LOUISIANA, MISSISSIPPI.
AREA = 771 SQ.MI.

ACCOUNTING UNIT 080703 — LOWER GRAND: THE LOWER GRAND RIVER BASIN. LOUISIANA.
AREA = 792 SQ.MI.

CATALOGING UNIT 08070300 — LOWER GRAND. LOUISIANA.
AREA = 792 SQ.MI.

SUBREGION 0808 — LOUISIANA COASTAL: THE LOUISIANA COASTAL DRAINAGE, INCLUDING ISLANDS AND ASSOCIATED WATERS, SOUTH OF THE RED RIVER BASIN BOUNDARY AND WEST OF THE EAST-BANK LEVEE OF THE ATCHAFALAYA BASIN FLOODWAY, TO THE SABINE RIVER AND SABINE LAKE DRAINAGE BOUNDARY. LOUISIANA.
AREA = 14000 SQ.MI.

ACCOUNTING UNIT 080801 — ATCHAFALAYA - VERMILION: THE LOUISIANA COASTAL DRAINAGE, INCLUDING ISLANDS AND ASSOCIATED WATERS, SOUTH OF THE RED RIVER BASIN BOUNDARY AND WEST OF THE EAST-BANK LEVEE OF THE ATCHAFALAYA BASIN FLOODWAY, TO AND INCLUDING THE DRAINAGE INTO VERMILION BAY. LOUISIANA.
AREA = 5900 SQ.MI.

CATALOGING UNITS 08080101 — ATCHAFALAYA. LOUISIANA.
AREA = 1930 SQ.MI.
08080102 — BAYOU TECHE. LOUISIANA.
AREA = 2210 SQ.MI.
08080103 — VERMILION. LOUISIANA.
AREA = 1760 SQ.MI.

ACCOUNTING UNIT 080802 — CALCASIEU - MERMENTAU: THE LOUISIANA COASTAL DRAINAGE AND ASSOCIATED WATERS, FROM THE VERMILION BAY DRAINAGE BOUNDARY TO THE SABINE RIVER AND SABINE LAKE DRAINAGE BOUNDARY. LOUISIANA.
AREA = 8120 SQ.MI.

CATALOGING UNITS 08080201 — MERMENTAU HEADWATERS. LOUISIANA.
AREA = 1400 SQ.MI.
08080202 — MERMENTAU. LOUISIANA.
AREA = 2390 SQ.MI.
08080203 — UPPER CALCASIEU. LOUISIANA.
AREA = 1550 SQ.MI.
08080204 — WHISKY CHITTO. LOUISIANA.
AREA = 884 SQ.MI.

REGION 08: LOWER MISSISSIPPI — Continued

08080205 — WEST FORK CALCASIEU. LOUISIANA.
AREA = 818 SQ.MI.
08080206 — LOWER CALCASIEU. LOUISIANA.
AREA = 1080 SQ.MI.

SUBREGION 0809 — LOWER MISSISSIPPI: THE MISSISSIPPI RIVER BELOW THE BONNET CARRE FLOODWAY, AND THE COASTAL DRAINAGE, INCLUDING ISLANDS AND ASSOCIATED WATERS, FROM THE PEARL RIVER BASIN BOUNDARY AND THE MISSISSIPPI-LOUISIANA STATE LINE TO THE EAST-BANK LEVEE OF THE ATCHAFALAYA BASIN FLOODWAY, EXCLUDING THE DRAINAGE FROM THE NORTH INTO LAKE PONTCHARTRAIN, EAST TO THE TCHEFUNCTA RIVER DRAINAGE BOUNDARY; AND EXCLUDING THE LOWER GRAND RIVER BASIN. LOUISIANA.
AREA = 9460 SQ.MI.

ACCOUNTING UNIT 080901 — LOWER MISSISSIPPI-NEW ORLEANS: THE MISSISSIPPI RIVER BELOW THE BONNET CARRE FLOODWAY, INCLUDING THE MISSISSIPPI DELTA. LOUISIANA.
AREA = 587 SQ.MI.

CATALOGING UNIT 08090100 — LOWER MISSISSIPPI-NEW ORLEANS. LOUISIANA.
AREA = 587 SQ.MI.

ACCOUNTING UNIT 080902 — LAKE PONTCHARTRAIN: LAKE PONTCHARTRAIN AND THE COASTAL DRAINAGE, INCLUDING ISLANDS AND ASSOCIATED WATERS, FROM THE PEARL RIVER BASIN BOUNDARY AND THE MISSISSIPPI-LOUISIANA STATE LINE TO THE EAST-BANK LEVEE OF THE MISSISSIPPI RIVER, EXCLUDING THE DRAINAGE FROM THE NORTH INTO LAKE PONTCHARTRAIN, EAST TO THE TCHEFUNCTA RIVER DRAINAGE BOUNDARY. LOUISIANA.
AREA = 3520 SQ.MI.

CATALOGING UNITS 08090201 — LIBERTY BAYOU-TCHEFUNCTA. LOUISIANA.
AREA = 708 SQ.MI.
08090202 — LAKE PONTCHARTRAIN. LOUISIANA.
AREA = 648 SQ.MI.
08090203 — EASTERN LOUISIANA COASTAL. LOUISIANA.
AREA = 2160 SQ.MI.

ACCOUNTING UNIT 080903 — CENTRAL LOUISIANA COASTAL: THE COASTAL DRAINAGE, INCLUDING ISLANDS AND ASSOCIATED WATERS, FROM THE WEST-BANK LEVEE OF THE MISSISSIPPI RIVER TO THE EAST-BANK LEVEE OF THE ATCHAFALAYA BASIN FLOODWAY; EXCLUDING THE LOWER GRAND RIVER BASIN. LOUISIANA.
AREA = 5350 SQ.MI.

CATALOGING UNITS 08090301 — EAST CENTRAL LOUISIANA COASTAL. LOUISIANA.
AREA = 2460 SQ.MI.
08090302 — WEST CENTRAL LOUISIANA COASTAL. LOUISIANA.
AREA = 2890 SQ.MI.

REGION 09 SOURIS-RED-RAINY REGION -- THE DRAINAGE WITHIN THE UNITED STATES OF THE LAKE OF THE WOODS AND THE RAINY, RED, AND SOURIS RIVER BASINS THAT ULTIMATELY DISCHARGES INTO LAKE WINNIPEG AND HUDSON BAY. INCLUDES PARTS OF MINNESOTA, NORTH DAKOTA, AND SOUTH DAKOTA.

SUBREGION 0901 — SOURIS: THE SOURIS RIVER BASIN WITHIN THE UNITED STATES. NORTH DAKOTA.
AREA = 9150 SQ.MI.

ACCOUNTING UNIT 090100 — SOURIS. NORTH DAKOTA.
AREA = 9150 SQ.MI.

CATALOGING UNITS
09010001 — UPPER SOURIS. NORTH DAKOTA. AREA = 2340 SQ.MI.
09010002 — DES LACS. NORTH DAKOTA. AREA = 1030 SQ.MI.
09010003 — LOWER SOURIS. NORTH DAKOTA. AREA = 2260 SQ.MI.
09010004 — WILLOW. NORTH DAKOTA. AREA = 1850 SQ.MI.
09010005 — DEEP. NORTH DAKOTA. AREA = 1670 SQ.MI.

SUBREGION 0902 — RED: THE RED RIVER BASIN WITHIN THE UNITED STATES INCLUDING THE DEVILS LAKE CLOSED BASIN. MINNESOTA, NORTH DAKOTA, SOUTH DAKOTA.
AREA = 39800 SQ.MI.

ACCOUNTING UNIT 090201 — UPPER RED: THE RED RIVER BASIN ABOVE THE CONFLUENCE OF AND INCLUDING THE GOOSE AND MARSH RIVER BASINS, EXCLUDING THE SHEYENNE RIVER BASIN AND THE DEVILS LAKE CLOSED BASIN. MINNESOTA, NORTH DAKOTA, SOUTH DAKOTA.
AREA = 12200 SQ.MI.

CATALOGING UNITS
09020101 — BOIS DE SIOUX. MINNESOTA, NORTH DAKOTA, SOUTH DAKOTA. AREA = 1140 SQ.MI.
09020102 — MUSTINKA. MINNESOTA. AREA = 825 SQ.MI.
09020103 — OTTER TAIL. MINNESOTA. AREA = 1980 SQ.MI.
09020104 — UPPER RED. MINNESOTA, NORTH DAKOTA. AREA = 594 SQ.MI.
09020105 — WESTERN WILD RICE. NORTH DAKOTA, SOUTH DAKOTA. AREA = 2380 SQ.MI.
09020106 — BUFFALO. MINNESOTA. AREA = 1150 SQ.MI.
09020107 — ELM-MARSH. MINNESOTA, NORTH DAKOTA. AREA = 1150 SQ.MI.
09020108 — EASTERN WILD RICE. MINNESOTA. AREA = 1670 SQ.MI.
09020109 — GOOSE. NORTH DAKOTA. AREA = 1280 SQ.MI.

ACCOUNTING UNIT 090202 — DEVILS LAKE-SHEYENNE: THE SHEYENNE RIVER BASIN AND THE DEVILS LAKE CLOSED BASIN DRAINAGE. NORTH DAKOTA.
AREA = 11000 SQ.MI.

CATALOGING UNITS
09020201 — DEVILS LAKE. NORTH DAKOTA. AREA = 3700 SQ.MI.
09020202 — UPPER SHEYENNE. NORTH DAKOTA. AREA = 1940 SQ.MI.
09020203 — MIDDLE SHEYENNE. NORTH DAKOTA. AREA = 2070 SQ.MI.
09020204 — LOWER SHEYENNE. NORTH DAKOTA. AREA = 1640 SQ.MI.
09020205 — MAPLE. NORTH DAKOTA. AREA = 1620 SQ.MI.

ACCOUNTING UNIT 090203 — LOWER RED: THE RED RIVER BASIN WITHIN THE UNITED STATES BELOW THE CONFLUENCE OF THE GOOSE AND MARSH RIVER BASINS. MINNESOTA, NORTH DAKOTA.
AREA = 16600 SQ.MI.

CATALOGING UNITS
09020301 — SANDHILL-WILSON. MINNESOTA, NORTH DAKOTA. AREA = 1130 SQ.MI.
09020302 — RED LAKES. MINNESOTA. AREA = 2040 SQ.MI.
09020303 — RED LAKE. MINNESOTA. AREA = 1450 SQ.MI.
09020304 — THIEF. MINNESOTA. AREA = 994 SQ.MI.
09020305 — CLEARWATER. MINNESOTA. AREA = 1350 SQ.MI.
09020306 — GRAND MARAIS-RED. MINNESOTA, NORTH DAKOTA. AREA = 482 SQ.MI.
09020307 — TURTLE. NORTH DAKOTA. AREA = 714 SQ.MI.
09020308 — FOREST. NORTH DAKOTA. AREA = 875 SQ.MI.
09020309 — SNAKE. MINNESOTA. AREA = 953 SQ.MI.
09020310 — PARK. NORTH DAKOTA. AREA = 1080 SQ.MI.

09020311 — LOWER RED. MINNESOTA, NORTH DAKOTA. AREA = 1320 SQ.MI.
09020312 — TWO RIVERS. MINNESOTA. AREA = 958 SQ.MI.
09020313 — PEMBINA. NORTH DAKOTA. AREA = 2020 SQ.MI.
09020314 — ROSEAU. MINNESOTA. AREA = 1230 SQ.MI.

SUBREGION 0903 — RAINY: THE RAINY RIVER BASIN AND LAKE OF THE WOODS DRAINAGE WITHIN THE UNITED STATES. MINNESOTA.
AREA = 11400 SQ.MI.

ACCOUNTING UNIT 090300 — RAINY. MINNESOTA.
AREA = 11400 SQ.MI.

CATALOGING UNITS
09030001 — RAINY HEADWATERS. MINNESOTA. AREA = 2540 SQ.MI.
09030002 — VERMILION. MINNESOTA. AREA = 1080 SQ.MI.
09030003 — RAINY LAKE. MINNESOTA. AREA = 908 SQ.MI.
09030004 — UPPER RAINY. MINNESOTA. AREA = 529 SQ.MI.
09030005 — LITTLE FORK. MINNESOTA. AREA = 1880 SQ.MI.
09030006 — BIG FORK. MINNESOTA. AREA = 2070 SQ.MI.
09030007 — RAPID. MINNESOTA. AREA = 867 SQ.MI.
09030008 — LOWER RAINY. MINNESOTA. AREA = 292 SQ.MI.
09030009 — LAKE OF THE WOODS. MINNESOTA. AREA = 1220 SQ.MI.

REGION 10 MISSOURI REGION — THE DRAINAGE WITHIN THE UNITED STATES OF: (A) THE MISSOURI RIVER BASIN, (B) THE SASKATCHEWAN RIVER BASIN, AND (C) SEVERAL SMALL CLOSED BASINS. INCLUDES ALL OF NEBRASKA AND PARTS OF COLORADO, IOWA, KANSAS, MINNESOTA, MISSOURI, MONTANA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING.

SUBREGION 1001 — SASKATCHEWAN: THE SASKATCHEWAN RIVER BASIN WITHIN THE UNITED STATES. MONTANA.
AREA = 697 SQ.MI.

ACCOUNTING UNIT 100100 — SASKATCHEWAN. MONTANA.
AREA = 697 SQ.MI.

CATALOGING UNITS 10010001 — BELLY. MONTANA.
AREA = 192 SQ.MI.
10010002 — ST. MARY. MONTANA.
AREA = 505 SQ.MI.

SUBREGION 1002 — MISSOURI HEADWATERS: THE HEADWATERS OF THE MISSOURI RIVER BASIN ABOVE THE CONFLUENCE OF AND INCLUDING THE GALLATIN, JEFFERSON, AND MADISON RIVER BASINS. MONTANA, WYOMING.
AREA = 14100 SQ.MI.

ACCOUNTING UNIT 100200 — MISSOURI HEADWATERS. MONTANA, WYOMING.
AREA = 14100 SQ.MI.

CATALOGING UNITS 10020001 — RED ROCK. MONTANA.
AREA = 2330 SQ.MI.
10020002 — BEAVERHEAD. MONTANA.
AREA = 1460 SQ.MI.
10020003 — RUBY. MONTANA.
AREA = 988 SQ.MI.
10020004 — BIG HOLE. MONTANA.
AREA = 2790 SQ.MI.
10020005 — JEFFERSON. MONTANA.
AREA = 1340 SQ.MI.
10020006 — BOULDER. MONTANA.
AREA = 754 SQ.MI.
10020007 — MADISON. MONTANA, WYOMING.
AREA = 2570 SQ.MI.
10020008 — GALLATIN. MONTANA, WYOMING.
AREA = 1820 SQ.MI.

SUBREGION 1003 — MISSOURI-MARIAS: THE MISSOURI RIVER BASIN BELOW THE CONFLUENCE OF THE GALLATIN, JEFFERSON, AND MADISON RIVER BASINS TO AND INCLUDING THE MARIAS RIVER BASIN. MONTANA.
AREA = 20100 SQ.MI.

ACCOUNTING UNIT 100301 — UPPER MISSOURI: THE MISSOURI RIVER BASIN BELOW THE CONFLUENCE OF THE GALLATIN, JEFFERSON, AND MADISON RIVER BASINS TO, BUT EXCLUDING THE MARIAS RIVER BASIN. MONTANA.
AREA = 10900 SQ.MI.

CATALOGING UNITS 10030101 — UPPER MISSOURI. MONTANA.
AREA = 3370 SQ.MI.
10030102 — UPPER MISSOURI-DEARBORN. MONTANA.
AREA = 2680 SQ.MI.
10030103 — SMITH. MONTANA.
AREA = 2020 SQ.MI.
10030104 — SUN. MONTANA.
AREA = 2000 SQ.MI.
10030105 — BELT. MONTANA.
AREA = 806 SQ.MI.

ACCOUNTING UNIT 100302 — MARIAS: THE MARIAS RIVER BASIN. MONTANA.
AREA = 9180 SQ.MI.

CATALOGING UNITS 10030201 — TWO MEDICINE. MONTANA.
AREA = 1320 SQ.MI.
10030202 — CUT BANK. MONTANA.
AREA = 1230 SQ.MI.
10030203 — MARIAS. MONTANA.
AREA = 3680 SQ.MI.
10030204 — WILLOW. MONTANA.
AREA = 985 SQ.MI.
10030205 — TETON. MONTANA.
AREA = 1960 SQ.MI.

SUBREGION 1004 — MISSOURI-MUSSELSHELL: THE MISSOURI RIVER BASIN BELOW THE CONFLUENCE OF THE MARIAS RIVER BASIN TO FORT PECK DAM. MONTANA.
AREA = 23700 SQ.MI.

ACCOUNTING UNIT 100401 — FORT PECK LAKE. THE MISSOURI RIVER BASIN BELOW THE CONFLUENCE OF THE MARIAS RIVER BASIN TO FORT PECK DAM, EXCLUDING THE MUSSELSHELL RIVER BASIN. MONTANA.
AREA = 14100 SQ.MI.

CATALOGING UNITS 10040101 — BULLWHACKER-DOG. MONTANA.
AREA = 1930 SQ.MI.
10040102 — ARROW. MONTANA.
AREA = 1220 SQ.MI.
10040103 — JUDITH. MONTANA.
AREA = 2780 SQ.MI.

10040104 — FORT PECK RESERVOIR. MONTANA.
AREA = 5350 SQ.MI.
10040105 — BIG DRY. MONTANA.
AREA = 1550 SQ.MI.
10040106 — LITTLE DRY. MONTANA.
AREA = 1250 SQ.MI.

ACCOUNTING UNIT 100402 — MUSSELSHELL: THE MUSSELSHELL RIVER BASIN. MONTANA.
AREA = 9570 SQ.MI.

CATALOGING UNITS 10040201 — UPPER MUSSELSHELL. MONTANA.
AREA = 4050 SQ.MI.
10040202 — MIDDLE MUSSELSHELL. MONTANA.
AREA = 1920 SQ.MI.
10040203 — FLATWILLOW. MONTANA.
AREA = 692 SQ.MI.
10040204 — BOX ELDER. MONTANA.
AREA = 1190 SQ.MI.
10040205 — LOWER MUSSELSHELL. MONTANA.
AREA = 1720 SQ.MI.

SUBREGION 1005 — MILK: THE MILK RIVER BASIN WITHIN THE UNITED STATES, INCLUDING THE WILD HORSE LAKE CLOSED BASIN. MONTANA.
AREA = 15300 SQ.MI.

ACCOUNTING UNIT 100500 — MILK. MONTANA.
AREA = 15300 SQ.MI.

CATALOGING UNITS 10050001 — MILK HEADWATERS. MONTANA.
AREA = 520 SQ.MI.
10050002 — UPPER MILK. MONTANA.
AREA = 1040 SQ.MI.
10050003 — WILD HORSE LAKE. MONTANA.
AREA = 91 SQ.MI.
10050004 — MIDDLE MILK. MONTANA.
AREA = 3390 SQ.MI.
10050005 — BIG SANDY. MONTANA.
AREA = 851 SQ.MI.
10050006 — SAGE. MONTANA.
AREA = 1050 SQ.MI.
10050007 — LODGE. MONTANA.
AREA = 244 SQ.MI.
10050008 — BATTLE. MONTANA.
AREA = 485 SQ.MI.
10050009 — PEOPLES. MONTANA.
AREA = 735 SQ.MI.
10050010 — COTTONWOOD. MONTANA.
AREA = 926 SQ.MI.
10050011 — WHITEWATER. MONTANA.
AREA = 536 SQ.MI.
10050012 — LOWER MILK. MONTANA.
AREA = 1740 SQ.MI.
10050013 — FRENCHMAN. MONTANA.
AREA = 286 SQ.MI.
10050014 — BEAVER. MONTANA.
AREA = 1750 SQ.MI.
10050015 — ROCK. MONTANA.
AREA = 878 SQ.MI.
10050016 — PORCUPINE. MONTANA.
AREA = 750 SQ.MI.

SUBREGION 1006 — MISSOURI-POPLAR: THE MISSOURI RIVER BASIN WITHIN THE UNITED STATES FROM FORT PECK DAM TO THE CONFLUENCE WITH THE YELLOWSTONE RIVER BASIN. MONTANA.
AREA = 10800 SQ.MI.

ACCOUNTING UNIT 100600 — MISSOURI-POPLAR. MONTANA.
AREA = 10800 SQ.MI.

CATALOGING UNITS 10060001 — PRAIRIE ELK-WOLF. MONTANA.
AREA = 2040 SQ.MI.
10060002 — REDWATER. MONTANA.
AREA = 2140 SQ.MI.
10060003 — POPLAR. MONTANA.
AREA = 1310 SQ.MI.
10060004 — WEST FORK POPLAR. MONTANA.
AREA = 863 SQ.MI.
10060005 — CHARLIE-LITTLE MUDDY. MONTANA, NORTH DAKOTA.
AREA = 1200 SQ.MI.
10060006 — BIG MUDDY. MONTANA, NORTH DAKOTA.
AREA = 2590 SQ.MI.
10060007 — BRUSH LAKE CLOSED BASIN. MONTANA, NORTH DAKOTA.
AREA = 680 SQ.MI.

SUBREGION 1007 — UPPER YELLOWSTONE: THE YELLOWSTONE RIVER BASIN ABOVE THE CONFLUENCE WITH THE BIGHORN RIVER BASIN. MONTANA, WYOMING.
AREA = 14400 SQ.MI.

ACCOUNTING UNIT 100700 — UPPER YELLOWSTONE. MONTANA, WYOMING.
AREA = 14400 SQ.MI.

CATALOGING UNITS 10070001 — YELLOWSTONE HEADWATERS. MONTANA, WYOMING.
AREA = 2600 SQ.MI.
10070002 — UPPER YELLOWSTONE. MONTANA, WYOMING.
AREA = 2940 SQ.MI.
10070003 — SHIELDS. MONTANA.
AREA = 853 SQ.MI.
10070004 — UPPER YELLOWSTONE-LAKE BASIN. MONTANA.
AREA = 1580 SQ.MI.
10070005 — STILLWATER. MONTANA.
AREA = 1060 SQ.MI.
10070006 — CLARKS FORK YELLOWSTONE. MONTANA, WYOMING.
AREA = 2770 SQ.MI.
10070007 — UPPER YELLOWSTONE-POMPEYS PILLAR. MONTANA.
AREA = 2000 SQ.MI.
10070008 — PRYOR. MONTANA.
AREA = 608 SQ.MI.

SUBREGION 1008 — BIG HORN: THE BIG HORN RIVER BASIN. MONTANA, WYOMING.
AREA = 22800 SQ.MI.

ACCOUNTING UNIT 100800 — BIG HORN. MONTANA, WYOMING.
AREA = 22800 SQ.MI.

CATALOGING UNITS 10080001 — UPPER WIND. WYOMING.
AREA = 2540 SQ.MI.
10080002 — LITTLE WIND. WYOMING.
AREA = 1090 SQ.MI.
10080003 — POPO AGIE. WYOMING.
AREA = 798 SQ.MI.
10080004 — MUSKRAT. WYOMING.
AREA = 735 SQ.MI.
10080005 — LOWER WIND. WYOMING.
AREA = 1710 SQ.MI.
10080006 — BADWATER. WYOMING.
AREA = 844 SQ.MI.
10080007 — UPPER BIGHORN. WYOMING.
AREA = 3450 SQ.MI.
10080008 — NOWOOD. WYOMING.
AREA = 1990 SQ.MI.
10080009 — GREYBULL. WYOMING.
AREA = 1150 SQ.MI.
10080010 — BIG HORN LAKE. MONTANA, WYOMING.
AREA = 1800 SQ.MI.
10080011 — DRY. WYOMING.
AREA = 438 SQ.MI.
10080012 — NORTH FORK SHOSHONE. WYOMING.
AREA = 853 SQ.MI.
10080013 — SOUTH FORK SHOSHONE. WYOMING.
AREA = 659 SQ.MI.
10080014 — SHOSHONE. MONTANA, WYOMING.
AREA = 1490 SQ.MI.
10080015 — LOWER BIGHORN. MONTANA.
AREA = 1970 SQ.MI.
10080016 — LITTLE BIGHORN. MONTANA, WYOMING.
AREA = 1290 SQ.MI.

SUBREGION 1009 — POWDER-TONGUE: THE POWDER AND TONGUE RIVER BASINS. MONTANA, WYOMING.
AREA = 18800 SQ.MI.

ACCOUNTING UNIT 100901 — TONGUE: THE TONGUE RIVER BASIN. MONTANA, WYOMING.
AREA = 5390 SQ.MI.

CATALOGING UNITS 10090101 — UPPER TONGUE. MONTANA, WYOMING.
AREA = 2530 SQ.MI.
10090102 — LOWER TONGUE. MONTANA.
AREA = 2860 SQ.MI.

ACCOUNTING UNIT 100902 — POWDER: THE POWDER RIVER BASIN. MONTANA, WYOMING.
AREA = 13400 SQ.MI.

CATALOGING UNITS 10090201 — MIDDLE FORK POWDER. WYOMING.
AREA = 1020 SQ.MI.
10090202 — UPPER POWDER. WYOMING.
AREA = 2500 SQ.MI.
10090203 — SOUTH FORK POWDER. WYOMING.
AREA = 1210 SQ.MI.
10090204 — SALT. WYOMING.
AREA = 800 SQ.MI.
10090205 — CRAZY WOMAN. WYOMING.
AREA = 921 SQ.MI.
10090206 — CLEAR. WYOMING.
AREA = 1150 SQ.MI.
10090207 — MIDDLE POWDER. MONTANA, WYOMING.
AREA = 1060 SQ.MI.
10090208 — LITTLE POWDER. MONTANA, WYOMING.
AREA = 2030 SQ.MI.
10090209 — LOWER POWDER. MONTANA.
AREA = 1890 SQ.MI.
10090210 — MIZPAH. MONTANA.
AREA = 802 SQ.MI.

SUBREGION 1010 — LOWER YELLOWSTONE: THE YELLOWSTONE RIVER BASIN BELOW THE CONFLUENCE WITH THE BIG HORN RIVER BASIN, EXCLUDING THE TONGUE AND POWDER RIVER BASINS. MONTANA, NORTH DAKOTA.
AREA = 14000 SQ.MI.

ACCOUNTING UNIT 101000 — LOWER YELLOWSTONE. MONTANA, NORTH DAKOTA.
AREA = 14000 SQ.MI.

CATALOGING UNITS 10100001 — LOWER YELLOWSTONE-SUNDAY. MONTANA.
AREA = 4800 SQ.MI.
10100002 — BIG PORCUPINE. MONTANA.
AREA = 879 SQ.MI.
10100003 — ROSEBUD. MONTANA.
AREA = 1310 SQ.MI.
10100004 — LOWER YELLOWSTONE. MONTANA, NORTH DAKOTA.
AREA = 5430 SQ.MI.
10100005 — O'FALLON. MONTANA.
AREA = 1590 SQ.MI.

SUBREGION 1011 — MISSOURI-LITTLE MISSOURI: THE MISSOURI RIVER BASIN BELOW THE CONFLUENCE WITH THE YELLOWSTONE RIVER BASIN TO GARRISON DAM. MONTANA, NORTH DAKOTA, SOUTH DAKOTA, WYOMING.
AREA = 17300 SQ.MI.

ACCOUNTING UNIT 101101 — LAKE SAKAKAWEA: THE MISSOURI RIVER BASIN BELOW THE CONFLUENCE WITH THE YELLOWSTONE RIVER BASIN TO GARRISON DAM, EXCLUDING THE LITTLE MISSOURI RIVER BASIN. NORTH DAKOTA.
AREA = 7740 SQ.MI.

CATALOGING UNITS 10110101 — LAKE SAKAKAWEA. NORTH DAKOTA.
AREA = 6790 SQ.MI.
10110102 — LITTLE MUDDY. NORTH DAKOTA.
AREA = 953 SQ.MI.

ACCOUNTING UNIT 101102 — LITTLE MISSOURI: THE LITTLE MISSOURI RIVER BASIN. MONTANA, NORTH DAKOTA, SOUTH DAKOTA, WYOMING.
AREA = 9550 SQ.MI.

CATALOGING UNITS 10110201 — UPPER LITTLE MISSOURI. MONTANA, NORTH DAKOTA, SOUTH DAKOTA, WYOMING.
AREA = 3490 SQ.MI.
10110202 — BOXELDER. MONTANA, NORTH DAKOTA, SOUTH DAKOTA.
AREA = 1210 SQ.MI.
10110203 — MIDDLE LITTLE MISSOURI. MONTANA, NORTH DAKOTA.
AREA = 2180 SQ.MI.
10110204 — BEAVER. MONTANA, NORTH DAKOTA.
AREA = 871 SQ.MI.
10110205 — LOWER LITTLE MISSOURI. NORTH DAKOTA.
AREA = 1800 SQ.MI.

SUBREGION 1012 — CHEYENNE: THE CHEYENNE RIVER BASIN ABOVE THE NORMAL OPERATING POOL OF LAKE OAHE. MONTANA, NEBRASKA, SOUTH DAKOTA, WYOMING.
AREA = 24300 SQ.MI.

ACCOUNTING UNIT 101201 — CHEYENNE: THE CHEYENNE RIVER BASIN ABOVE THE NORMAL OPERATING POOL OF LAKE OAHE, EXCLUDING THE BELLE FOURCHE RIVER BASIN. NEBRASKA, SOUTH DAKOTA, WYOMING.
AREA = 17000 SQ.MI.

CATALOGING UNITS 10120101 — ANTELOPE. WYOMING.
AREA = 1030 SQ.MI.
10120102 — DRY FORK CHEYENNE. WYOMING.
AREA = 484 SQ.MI.
10120103 — UPPER CHEYENNE. WYOMING.
AREA = 1430 SQ.MI.
10120104 — LANCE. WYOMING.
AREA = 1090 SQ.MI.
10120105 — LIGHTNING. WYOMING.
AREA = 1010 SQ.MI.
10120106 — ANGOSTURA RESERVOIR. NEBRASKA, SOUTH DAKOTA, WYOMING.
AREA = 1410 SQ.MI.
10120107 — BEAVER. SOUTH DAKOTA, WYOMING.
AREA = 1700 SQ.MI.
10120108 — HAT. NEBRASKA, SOUTH DAKOTA, WYOMING.
AREA = 971 SQ.MI.
10120109 — MIDDLE CHEYENNE-SPRING. SOUTH DAKOTA.
AREA = 2110 SQ.MI.
10120110 — RAPID. SOUTH DAKOTA.
AREA = 725 SQ.MI.
10120111 — MIDDLE CHEYENNE-ELK. SOUTH DAKOTA.
AREA = 1560 SQ.MI.
10120112 — LOWER CHEYENNE. SOUTH DAKOTA.
AREA = 1630 SQ.MI.
10120113 — CHERRY. SOUTH DAKOTA.
AREA = 1870 SQ.MI.

ACCOUNTING UNIT 101202 — BELLE FOURCHE: THE BELLE FOURCHE RIVER BASIN. MONTANA, SOUTH DAKOTA, WYOMING.
AREA = 7290 SQ.MI.

CATALOGING UNITS 10120201 — UPPER BELLE FOURCHE. SOUTH DAKOTA, WYOMING.
AREA = 2920 SQ.MI.
10120202 — LOWER BELLE FOURCHE. MONTANA, SOUTH DAKOTA, WYOMING.
AREA = 3290 SQ.MI.
10120203 — REDWATER. SOUTH DAKOTA, WYOMING.
AREA = 1080 SQ.MI.

SUBREGION 1013 — MISSOURI-OAHE: THE MISSOURI RIVER BASIN FROM GARRISON DAM TO OAHE DAM, EXCLUDING THE CHEYENNE RIVER BASIN ABOVE THE NORMAL OPERATING POOL OF LAKE OAHE. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 37400 SQ.MI.

ACCOUNTING UNIT 101301 — LAKE OAHE: THE MISSOURI RIVER BASIN FROM GARRISON DAM TO OAHE DAM, EXCLUDING THE CHEYENNE RIVER BASIN ABOVE THE NORMAL OPERATING POOL OF LAKE OAHE AND THE CANNONBALL, GRAND, HEART, KNIFE, AND MOREAU RIVER BASINS. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 16700 SQ.MI.

CATALOGING UNITS 10130101 — PAINTED WOODS-SQUARE BUTTE. NORTH DAKOTA.
AREA = 2410 SQ.MI.
10130102 — UPPER LAKE OAHE. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 3860 SQ.MI.
10130103 — APPLE. NORTH DAKOTA.
AREA = 3670 SQ.MI.
10130104 — BEAVER. NORTH DAKOTA.
AREA = 1050 SQ.MI.
10130105 — LOWER LAKE OAHE. SOUTH DAKOTA.
AREA = 3570 SQ.MI.
10130106 — WEST MISSOURI COTEAU. NORTH DAKOTA SOUTH DAKOTA.
AREA = 2100 SQ.MI.

ACCOUNTING UNIT 101302 — CANNONBALL-HEART-KNIFE: THE CANNONBALL, HEART, AND KNIFE RIVER BASINS. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 10300 SQ.MI.

CATALOGING UNITS 10130201 — KNIFE. NORTH DAKOTA.
AREA = 2530 SQ.MI.
10130202 — UPPER HEART. NORTH DAKOTA.
AREA = 1730 SQ.MI.
10130203 — LOWER HEART. NORTH DAKOTA.
AREA = 1640 SQ.MI.
10130204 — UPPER CANNONBALL. NORTH DAKOTA.
AREA = 1640 SQ.MI.
10130205 — CEDAR. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 1840 SQ.MI.
10130206 — LOWER CANNONBALL. NORTH DAKOTA.
AREA = 899 SQ.MI.

ACCOUNTING UNIT 101303 — GRAND-MOREAU: THE GRAND AND MOREAU RIVER BASINS ABOVE THE NORMAL OPERATING POOL OF LAKE OAHE. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 10400 SQ.MI.

CATALOGING UNITS 10130301 — NORTH FORK GRAND. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 1280 SQ.MI.
10130302 — SOUTH FORK GRAND. SOUTH DAKOTA.
AREA = 1820 SQ.MI.
10130303 — GRAND. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 2430 SQ.MI.
10130304 — SOUTH FORK MOREAU. SOUTH DAKOTA.
AREA = 1010 SQ.MI.
10130305 — UPPER MOREAU. SOUTH DAKOTA.
AREA = 1550 SQ.MI.
10130306 — LOWER MOREAU. SOUTH DAKOTA.
AREA = 2340 SQ.MI.

SUBREGION 1014 — MISSOURI-WHITE: THE MISSOURI RIVER BASIN FROM OAHE DAM TO FORT RANDALL DAM. NEBRASKA, SOUTH DAKOTA.
AREA = 20200 SQ.MI.

ACCOUNTING UNIT 101401 — FORT RANDALL RESERVOIR: THE MISSOURI RIVER BASIN FROM OAHE DAM TO FORT RANDALL DAM, EXCLUDING THE WHITE RIVER BASIN ABOVE THE NORMAL OPERATING POOL OF THE FORT RANDALL RESERVOIR. SOUTH DAKOTA.
AREA = 10400 SQ.MI.

CATALOGING UNITS 10140101 — FORT RANDALL RESERVOIR. SOUTH DAKOTA.
AREA = 4390 SQ.MI.

10140102 — BAD. SOUTH DAKOTA.
AREA = 3170 SQ.MI.
10140103 — MEDICINE KNOLL. SOUTH DAKOTA.
AREA = 941 SQ.MI.
10140104 — MEDICINE. SOUTH DAKOTA.
AREA = 687 SQ.MI.
10140105 — CROW. SOUTH DAKOTA.
AREA = 1170 SQ.MI.

ACCOUNTING UNIT 101402 — WHITE: THE WHITE RIVER BASIN ABOVE THE NORMAL OPERATING POOL OF THE FORT RANDALL RESERVOIR. NEBRASKA, SOUTH DAKOTA.
AREA = 9870 SQ.MI.

CATALOGING UNITS 10140201 — UPPER WHITE. NEBRASKA, SOUTH DAKOTA.
AREA = 3810 SQ.MI.
10140202 — MIDDLE WHITE. SOUTH DAKOTA.
AREA = 2400 SQ.MI.
10140203 — LITTLE WHITE. NEBRASKA, SOUTH DAKOTA.
AREA = 1580 SQ.MI.
10140204 — LOWER WHITE. SOUTH DAKOTA.
AREA = 2080 SQ.MI.

SUBREGION 1015 — NIOBRARA: THE NIOBRARA RIVER BASIN AND THE PONCA CREEK BASIN. NEBRASKA, SOUTH DAKOTA, WYOMING.
AREA = 13900 SQ.MI.

ACCOUNTING UNIT 101500 — NIOBRARA. NEBRASKA, SOUTH DAKOTA, WYOMING.
AREA = 13900 SQ.MI.

CATALOGING UNITS 10150001 — PONCA. NEBRASKA, SOUTH DAKOTA.
AREA = 776 SQ.MI.
10150002 — NIOBRARA HEADWATERS. NEBRASKA, WYOMING.
AREA = 1460 SQ.MI.
10150003 — UPPER NIOBRARA. NEBRASKA, SOUTH DAKOTA.
AREA = 4180 SQ.MI.
10150004 — MIDDLE NIOBRARA. NEBRASKA, SOUTH DAKOTA.
AREA = 3480 SQ.MI.
10150005 — SNAKE. NEBRASKA.
AREA = 876 SQ.MI.
10150006 — KEYA PAHA. NEBRASKA, SOUTH DAKOTA.
AREA = 1710 SQ.MI.
10150007 — LOWER NIOBRARA. NEBRASKA.
AREA = 1460 SQ.MI.

SUBREGION 1016 — JAMES: THE JAMES RIVER BASIN. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 21500 SQ.MI.

ACCOUNTING UNIT 101600 — JAMES. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 21500 SQ.MI.

CATALOGING UNITS 10160001 — JAMES HEADWATERS. NORTH DAKOTA.
AREA = 1780 SQ.MI.
10160002 — PIPESTEM. NORTH DAKOTA.
AREA = 1050 SQ.MI.
10160003 — UPPER JAMES. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 4280 SQ.MI.
10160004 — ELM. NORTH DAKOTA, SOUTH DAKOTA.
AREA = 1600 SQ.MI.
10160005 — MUD. SOUTH DAKOTA.
AREA = 648 SQ.MI.
10160006 — MIDDLE JAMES. SOUTH DAKOTA.
AREA = 3610 SQ.MI.
10160007 — EAST MISSOURI COTEAU. SOUTH DAKOTA.
AREA = 904 SQ.MI.
10160008 — SNAKE. SOUTH DAKOTA.
AREA = 1500 SQ.MI.
10160009 — TURTLE. SOUTH DAKOTA.
AREA = 1380 SQ.MI.
10160010 — NORTH BIG SIOUX COTEAU. SOUTH DAKOTA.
AREA = 1250 SQ.MI.
10160011 — LOWER JAMES. SOUTH DAKOTA.
AREA = 3480 SQ.MI.

SUBREGION 1017 — MISSOURI-BIG SIOUX: THE MISSOURI RIVER BASIN FROM FORT RANDALL DAM TO AND INCLUDING THE BIG SIOUX RIVER BASIN, BUT EXCLUDING THE PONCA CREEK, NIOBRARA RIVER, AND JAMES RIVER BASINS. IOWA, MINNESOTA, NEBRASKA, SOUTH DAKOTA.
AREA = 13900 SQ.MI.

ACCOUNTING UNIT 101701 — LEWIS AND CLARK LAKE: THE MISSOURI RIVER BASIN FROM FORT RANDALL DAM TO THE BIG SIOUX RIVER BASIN, BUT EXCLUDING THE PONCA CREEK, NIOBRARA RIVER, AND JAMES RIVER BASINS. NEBRASKA, SOUTH DAKOTA.
AREA = 5860 SQ.MI.

CATALOGING UNITS 10170101 — LEWIS AND CLARK LAKE. NEBRASKA, SOUTH DAKOTA.
AREA = 3210 SQ.MI.

10170102 — VERMILLION. SOUTH DAKOTA.
AREA = 2240 SQ.MI.
10170103 — SOUTH BIG SIOUX COTEAU. SOUTH DAKOTA.
AREA = 405 SQ.MI.

ACCOUNTING UNIT 101702 — BIG SIOUX: THE BIG SIOUX RIVER BASIN. IOWA, MINNESOTA, SOUTH DAKOTA.
AREA = 8030 SQ.MI.

CATALOGING UNITS 10170201 — MIDDLE BIG SIOUX COTEAU. SOUTH DAKOTA.
AREA = 1210 SQ.MI.
10170202 — UPPER BIG SIOUX. MINNESOTA, SOUTH DAKOTA.
AREA = 1970 SQ.MI.
10170203 — LOWER BIG SIOUX. IOWA, MINNESOTA, SOUTH DAKOTA.
AREA = 3110 SQ.MI.
10170204 — ROCK. IOWA, MINNESOTA.
AREA = 1740 SQ.MI.

SUBREGION 1018 — NORTH PLATTE: THE NORTH PLATTE RIVER BASIN. COLORADO, NEBRASKA, WYOMING.
AREA = 30900 SQ.MI.

ACCOUNTING UNIT 101800 — NORTH PLATTE. COLORADO, NEBRASKA, WYOMING.
AREA = 30900 SQ.MI.

CATALOGING UNITS 10180001 — NORTH PLATTE HEADWATERS. COLORADO.
AREA = 1420 SQ.MI.
10180002 — UPPER NORTH PLATTE. COLORADO, WYOMING.
AREA = 2880 SQ.MI.
10180003 — PATHFINDER-SEMINOE RESERVOIRS. WYOMING.
AREA = 980 SQ.MI.
10180004 — MEDICINE BOW. WYOMING.
AREA = 1430 SQ.MI.
10180005 — LITTLE MEDICINE BOW. WYOMING.
AREA = 1030 SQ.MI.
10180006 — SWEETWATER. WYOMING.
AREA = 2880 SQ.MI.
10180007 — MIDDLE NORTH PLATTE-CASPER. WYOMING.
AREA = 3490 SQ.MI.
10180008 — GLENDO RESERVOIR. WYOMING.
AREA = 2090 SO.MI.
10180009 — MIDDLE NORTH PLATTE-SCOTTS BLUFF. NEBRASKA, WYOMING.
AREA = 5190 SQ.MI.
10180010 — UPPER LARAMIE. COLORADO, WYOMING.
AREA = 2180 SQ.MI.
10180011 — LOWER LARAMIE. WYOMING.
AREA = 2370 SQ.MI.
10180012 — HORSE. NEBRASKA, WYOMING.
AREA = 1650 SQ.MI.
10180013 — PUMPKIN. NEBRASKA, WYOMING.
AREA = 1020 SQ.MI.
10180014 — LOWER NORTH PLATTE. NEBRASKA.
AREA = 2270 SQ.MI.

SUBREGION 1019 — SOUTH PLATTE: THE SOUTH PLATTE RIVER BASIN. COLORADO, NEBRASKA, WYOMING.
AREA = 23900 SQ.MI.

ACCOUNTING UNIT 101900 — SOUTH PLATTE. COLORADO, NEBRASKA, WYOMING.
AREA = 23900 SQ.MI.

CATALOGING UNITS 10190001 — SOUTH PLATTE HEADWATERS. COLORADO.
AREA = 1590 SQ.MI.
10190002 — UPPER SOUTH PLATTE. COLORADO.
AREA = 1820 SQ.MI.
10190003 — MIDDLE SOUTH PLATTE-CHERRY CREEK. COLORADO.
AREA = 2870 SQ.MI.
10190004 — CLEAR. COLORADO.
AREA = 558 SQ.MI.
10190005 — ST. VRAIN. COLORADO.
AREA = 978 SQ.MI.
10190006 — BIG THOMPSON. COLORADO.
AREA = 819 SQ.MI.
10190007 — CACHE LA POUDRE. COLORADO, WYOMING.
AREA = 1910 SQ.MI.
10190008 — LONE TREE-OWL. COLORADO, WYOMING.
AREA = 573 SQ.MI.
10190009 — CROW. COLORADO, WYOMING.
AREA = 1410 SQ.MI.
10190010 — KIOWA. COLORADO.
AREA = 720 SQ.MI.
10190011 — BIJOU. COLORADO.
AREA = 1360 SQ.MI.
10190012 — MIDDLE SOUTH PLATTE-STERLING. COLORADO, NEBRASKA.
AREA = 2900 SQ.MI.

REGION 10: MISSOURI — Continued

10190013 — BEAVER. COLORADO.
AREA = 1080 SQ.MI.
10190014 — PAWNEE. COLORADO.
AREA = 728 SQ.MI.
10190015 — UPPER LODGEPOLE. COLORADO, NEBRASKA, WYOMING.
AREA = 1130 SQ.MI.
10190016 — LOWER LODGEPOLE. COLORADO, NEBRASKA, WYOMING.
AREA = 1350 SQ.MI.
10190017 — SIDNEY DRAW. COLORADO, NEBRASKA, WYOMING.
AREA = 744 SQ.MI.
10190018 — LOWER SOUTH PLATTE. COLORADO, NEBRASKA.
AREA = 1380 SQ.MI.

SUBREGION 1020 — PLATTE: THE PLATTE RIVER BASIN BELOW THE CONFLUENCE OF THE NORTH AND SOUTH PLATTE RIVER BASINS, EXCLUDING THE ELKHORN AND LOUP RIVER BASINS. NEBRASKA.
AREA = 8160 SQ.MI.

ACCOUNTING UNIT 102001 — MIDDLE PLATTE: THE PLATTE RIVER BASIN BELOW THE CONFLUENCE OF THE NORTH AND SOUTH PLATTE RIVER BASINS TO THE CONFLUENCE WITH THE LOUP RIVER BASIN. NEBRASKA.
AREA = 5130 SQ.MI.

CATALOGING UNITS 10200101 — MIDDLE PLATTE-BUFFALO. NEBRASKA.
AREA = 3270 SQ.MI.
10200102 — WOOD. NEBRASKA.
AREA = 736 SQ.MI.
10200103 — MIDDLE PLATTE-PRAIRIE. NEBRASKA.
AREA = 1120 SQ.MI.

ACCOUNTING UNIT 102002 — LOWER PLATTE: THE PLATTE RIVER BASIN BELOW THE CONFLUENCE WITH THE LOUP RIVER BASIN, EXCLUDING THE ELKHORN RIVER BASIN. NEBRASKA.
AREA = 3030 SQ.MI.

CATALOGING UNITS 10200201 — LOWER PLATTE-SHELL. NEBRASKA.
AREA = 879 SQ.MI.
10200202 — LOWER PLATTE. NEBRASKA.
AREA = 531 SQ.MI.
10200203 — SALT. NEBRASKA.
AREA = 1620 SQ.MI.

SUBREGION 1021 — LOUP: THE LOUP RIVER BASIN. NEBRASKA.
AREA = 15000 SQ.MI.

ACCOUNTING UNIT 102100 — LOUP. NEBRASKA.
AREA = 15000 SQ.MI.

CATALOGING UNITS 10210001 — UPPER MIDDLE LOUP. NEBRASKA.
AREA = 1800 SQ.MI.
10210002 — DISMAL. NEBRASKA.
AREA = 2050 SQ.MI.
10210003 — LOWER MIDDLE LOUP. NEBRASKA.
AREA = 1490 SQ.MI.
10210004 — SOUTH LOUP. NEBRASKA.
AREA = 1700 SQ.MI.
10210005 — MUD. NEBRASKA.
AREA = 1000 SQ.MI.
10210006 — UPPER NORTH LOUP. NEBRASKA.
AREA = 2250 SQ.MI.
10210007 — LOWER NORTH LOUP. NEBRASKA.
AREA = 955 SQ.MI.
10210008 — CALAMUS. NEBRASKA.
AREA = 1080 SQ.MI.
10210009 — LOUP. NEBRASKA.
AREA = 1430 SQ.MI.
10210010 — CEDAR. NEBRASKA.
AREA = 1240 SQ.MI.

SUBREGION 1022 — ELKHORN: THE ELKHORN RIVER BASIN. NEBRASKA.
AREA = 6950 SQ.MI.

ACCOUNTING UNIT 102200 — ELKHORN. NEBRASKA.
AREA = 6950 SQ.MI.

CATALOGING UNITS 10220001 — UPPER ELKHORN. NEBRASKA.
AREA = 2880 SQ.MI.
10220002 — NORTH FORK ELKHORN. NEBRASKA.
AREA = 843 SQ.MI.
10220003 — LOWER ELKHORN. NEBRASKA.
AREA = 2180 SQ.MI.
10220004 — LOGAN. NEBRASKA.
AREA = 1050 SQ.MI.

SUBREGION 1023 — MISSOURI-LITTLE SIOUX: THE MISSOURI RIVER BASIN BELOW THE CONFLUENCE WITH THE BIG SIOUX RIVER BASIN TO THE CONFLUENCE WITH THE PLATTE RIVER BASIN. IOWA, MINNESOTA, NEBRASKA.
AREA = 9140 SQ.MI.

ACCOUNTING UNIT 102300 — MISSOURI-LITTLE SIOUX. IOWA, MINNESOTA, NEBRASKA.
AREA = 9140 SQ.MI.

CATALOGING UNITS
10230001 — BLACKBIRD-SOLDIER. IOWA, NEBRASKA.
AREA = 1500 SQ.MI.
10230002 — FLOYD. IOWA.
AREA = 902 SQ.MI.
10230003 — LITTLE SIOUX. IOWA, MINNESOTA.
AREA = 2800 SQ.MI.
10230004 — MONONA-HARRISON DITCH. IOWA.
AREA = 954 SQ.MI.
10230005 — MAPLE. IOWA.
AREA = 747 SQ.MI.
10230006 — BIG PAPILLION-MOSQUITO. IOWA, NEBRASKA.
AREA = 1160 SQ.MI.
10230007 — BOYER. IOWA.
AREA = 1080 SQ.MI.

SUBREGION 1024 — MISSOURI-NISHNABOTNA: THE MISSOURI RIVER BASIN BELOW THE CONFLUENCE WITH THE PLATTE RIVER BASIN TO THE CONFLUENCE WITH THE KANSAS RIVER BASIN. IOWA, KANSAS, MISSOURI, NEBRASKA.
AREA = 13300 SQ.MI.

ACCOUNTING UNIT 102400 — MISSOURI-NISHNABOTNA. IOWA, KANSAS, MISSOURI, NEBRASKA.
AREA = 13300 SQ.MI.

CATALOGING UNITS
10240001 — KEG-WEEPING WATER. IOWA, MISSOURI, NEBRASKA.
AREA = 783 SQ.MI.
10240002 — WEST NISHNABOTNA. IOWA.
AREA = 1650 SQ.MI.
10240003 — EAST NISHNABOTNA. IOWA.
AREA = 1140 SQ.MI.
10240004 — NISHNABOTNA. IOWA, MISSOURI.
AREA = 173 SQ.MI.
10240005 — TARKIO-WOLF. IOWA, KANSAS, MISSOURI, NEBRASKA.
AREA = 1640 SQ.MI.
10240006 — LITTLE NEMAHA. NEBRASKA.
AREA = 881 SQ.MI.
10240007 — SOUTH FORK BIG NEMAHA. KANSAS, NEBRASKA.
AREA = 705 SQ.MI.
10240008 — BIG NEMAHA. KANSAS, NEBRASKA.
AREA = 1190 SQ.MI.
10240009 — WEST NODAWAY. IOWA.
AREA = 782 SQ.MI.
10240010 — NODAWAY. IOWA, MISSOURI.
AREA = 968 SQ.MI.
10240011 — INDEPENDENCE-SUGAR. KANSAS, MISSOURI.
AREA = 915 SQ.MI.
10240012 — PLATTE. IOWA, MISSOURI.
AREA = 1670 SQ.MI.
10240013 — ONE HUNDRED AND TWO. IOWA, MISSOURI.
AREA = 773 SQ.MI.

SUBREGION 1025 — REPUBLICAN: THE REPUBLICAN RIVER BASIN. COLORADO, KANSAS, NEBRASKA.
AREA = 24700 SQ.MI.

ACCOUNTING UNIT 102500 — REPUBLICAN. COLORADO, KANSAS, NEBRASKA.
AREA = 24700 SQ.MI.

CATALOGING UNITS
10250001 — ARIKAREE. COLORADO, KANSAS, NEBRASKA.
AREA = 1710 SQ.MI.
10250002 — NORTH FORK REPUBLICAN. COLORADO, KANSAS, NEBRASKA.
AREA = 3290 SQ.MI.
10250003 — SOUTH FORK REPUBLICAN. COLORADO, KANSAS, NEBRASKA.
AREA = 2720 SQ.MI.
10250004 — UPPER REPUBLICAN. COLORADO, KANSAS, NEBRASKA.
AREA = 2160 SQ.MI.
10250005 — FRENCHMAN. COLORADO, NEBRASKA.
AREA = 1350 SQ.MI.
10250006 — STINKING WATER. COLORADO, NEBRASKA.
AREA = 1470 SQ.MI.
10250007 — RED WILLOW. NEBRASKA.
AREA = 783 SQ.MI.
10250008 — MEDICINE. NEBRASKA.
AREA = 916 SQ.MI.
10250009 — HARLAN COUNTY RESERVOIR. KANSAS, NEBRASKA.
AREA = 1350 SQ.MI.
10250010 — UPPER SAPPA. KANSAS.
AREA = 1020 SQ.MI.
10250011 — LOWER SAPPA. KANSAS, NEBRASKA.
AREA = 644 SQ.MI.
10250012 — SOUTH FORK BEAVER. COLORADO, KANSAS.
AREA = 771 SQ.MI.

10250013 — LITTLE BEAVER. COLORADO, KANSAS.
AREA = 604 SQ.MI.
10250014 — BEAVER. KANSAS, NEBRASKA.
AREA = 731 SQ.MI.
10250015 — PRAIRIE DOG. KANSAS, NEBRASKA.
AREA = 1060 SQ.MI.
10250016 — MIDDLE REPUBLICAN. KANSAS, NEBRASKA.
AREA = 2130 SQ.MI.
10250017 — LOWER REPUBLICAN. KANSAS.
AREA = 1960 SQ.MI.

SUBREGION 1026 — SMOKY HILL: THE SMOKY HILL RIVER BASIN. COLORADO, KANSAS.
AREA = 19800 SQ.MI.

ACCOUNTING UNIT 102600 — SMOKY HILL. COLORADO, KANSAS.
AREA = 19800 SQ.MI.

CATALOGING UNITS
10260001 — SMOKY HILL HEADWATERS. COLORADO, KANSAS.
AREA = 1070 SQ.MI.
10260002 — NORTH FORK SMOKY HILL. COLORADO, KANSAS.
AREA = 734 SQ.MI.
10260003 — UPPER SMOKY HILL. KANSAS.
AREA = 1470 SQ.MI.
10260004 — LADDER. COLORADO, KANSAS.
AREA = 1430 SQ.MI.
10260005 — HACKBERRY. KANSAS.
AREA = 622 SQ.MI.
10260006 — MIDDLE SMOKY HILL. KANSAS.
AREA = 1590 SQ.MI.
10260007 — BIG. KANSAS.
AREA = 852 SQ.MI.
10260008 — LOWER SMOKY HILL. KANSAS.
AREA = 1980 SQ.MI.
10260009 — UPPER SALINE. KANSAS.
AREA = 1910 SQ.MI.
10260010 — LOWER SALINE. KANSAS.
AREA = 1360 SQ.MI.
10260011 — UPPER NORTH FORK SOLOMON. KANSAS.
AREA = 1350 SQ.MI.
10260012 — LOWER NORTH FORK SOLOMON. KANSAS.
AREA = 1330 SQ.MI.
10260013 — UPPER SOUTH FORK SOLOMON. KANSAS.
AREA = 1150 SQ.MI.
10260014 — LOWER SOUTH FORK SOLOMON. KANSAS.
AREA = 1040 SQ.MI.
10260015 — SOLOMON. KANSAS.
AREA = 1880 SQ.MI.

SUBREGION 1027 — KANSAS: THE KANSAS RIVER BASIN, EXCLUDING THE REPUBLICAN AND SMOKY HILL RIVER BASINS. KANSAS, NEBRASKA, MISSOURI.
AREA = 15000 SQ.MI.

ACCOUNTING UNIT 102701 — KANSAS: THE KANSAS RIVER BASIN, EXCLUDING THE BIG BLUE, REPUBLICAN, AND SMOKY HILL RIVER BASINS. KANSAS, MISSOURI.
AREA = 5500 SQ.MI.

CATALOGING UNITS
10270101 — UPPER KANSAS. KANSAS.
AREA = 548 SQ.MI.
10270102 — MIDDLE KANSAS. KANSAS.
AREA = 2160 SQ.MI.
10270103 — DELAWARE. KANSAS.
AREA = 1150 SQ.MI.
10270104 — LOWER KANSAS. KANSAS, MISSOURI.
AREA = 1640 SQ.MI.

ACCOUNTING UNIT 102702 — BIG BLUE: THE BIG BLUE RIVER BASIN. KANSAS, NEBRASKA.
AREA = 9540 SQ.MI.

CATALOGING UNITS
10270201 — UPPER BIG BLUE. NEBRASKA.
AREA = 1080 SQ.MI.
10270202 — MIDDLE BIG BLUE. NEBRASKA.
AREA = 1260 SQ.MI.
10270203 — WEST FORK BIG BLUE. NEBRASKA.
AREA = 1330 SQ.MI.
10270204 — TURKEY. NEBRASKA.
AREA = 725 SQ.MI.
10270205 — LOWER BIG BLUE. KANSAS, NEBRASKA.
AREA = 1650 SQ.MI.
10270206 — UPPER LITTLE BLUE. KANSAS, NEBRASKA.
AREA = 2160 SQ.MI.
10270207 — LOWER LITTLE BLUE. KANSAS, NEBRASKA.
AREA = 1330 SQ.MI.

SUBREGION 1028 — CHARITON-GRAND: THE CHARITON, GRAND, AND LITTLE CHARITON RIVER BASINS. IOWA, MISSOURI.
AREA = 10900 SQ.MI.

ACCOUNTING UNIT 102801 — GRAND: THE GRAND RIVER BASIN. IOWA, MISSOURI.
AREA = 7810 SQ.MI.

CATALOGING UNITS 10280101 — UPPER GRAND. IOWA, MISSOURI.
AREA = 3280 SQ.MI.
10280102 — THOMPSON. IOWA, MISSOURI.
AREA = 2200 SQ.MI.
10280103 — LOWER GRAND. IOWA, MISSOURI.
AREA = 2330 SQ.MI.

ACCOUNTING UNIT 102802 — CHARITON: THE CHARITON AND LITTLE CHARITON RIVER BASINS. IOWA, MISSOURI.
AREA = 3070 SQ.MI.

CATALOGING UNITS 10280201 — UPPER CHARITON. IOWA, MISSOURI.
AREA = 1370 SQ.MI.
10280202 — LOWER CHARITON. MISSOURI.
AREA = 1020 SQ.MI.
10280203 — LITTLE CHARITON. MISSOURI.
AREA = 679 SQ.MI.

SUBREGION 1029 — GASCONADE-OSAGE: THE GASCONADE AND OSAGE RIVER BASINS. KANSAS, MISSOURI.
AREA = 18400 SQ.MI.

ACCOUNTING UNIT 102901 — OSAGE: THE OSAGE RIVER BASIN. KANSAS, MISSOURI.
AREA = 14800 SQ.MI.

CATALOGING UNITS 10290101 — UPPER MARAIS DES CYGNES. KANSAS.
AREA = 2150 SQ.MI.
10290102 — LOWER MARAIS DES CYGNES. KANSAS, MISSOURI.
AREA = 1560 SQ.MI.
10290103 — LITTLE OSAGE. KANSAS, MISSOURI.
AREA = 535 SQ.MI.
10290104 — MARMATON. KANSAS, MISSOURI.
AREA = 1080 SQ.MI.
10290105 — HARRY S. TRUMAN RESERVOIR. MISSOURI.
AREA = 1210 SQ.MI.
10290106 — SAC. MISSOURI.
AREA = 1950 SQ.MI.
10290107 — POMME DE TERRE. MISSOURI.
AREA = 840 SQ.MI.
10290108 — SOUTH GRAND. KANSAS, MISSOURI.
AREA = 1990 SQ.MI.
10290109 — LAKE OF THE OZARKS. MISSOURI.
AREA = 1370 SQ.MI.
10290110 — NIANGUA. MISSOURI.
AREA = 1040 SQ.MI.
10290111 — LOWER OSAGE. MISSOURI.
AREA = 1080 SQ.MI.

ACCOUNTING UNIT 102902 — GASCONADE. THE GASCONADE RIVER BASIN. MISSOURI.
AREA = 3550 SQ.MI.

CATALOGING UNITS 10290201 — UPPER GASCONADE. MISSOURI.
AREA = 1780 SQ.MI.
10290202 — BIG PINEY. MISSOURI.
AREA = 754 SQ.MI.
10290203 — LOWER GASCONADE. MISSOURI.
AREA = 1020 SQ.MI.

SUBREGION 1030 — LOWER MISSOURI: THE MISSOURI RIVER BASIN BELOW THE CONFLUENCE WITH THE KANSAS RIVER BASIN TO THE CONFLUENCE WITH THE MISSISSIPPI RIVER, EXCLUDING THE CHARITON, GASCONADE, GRAND, AND OSAGE RIVER BASINS. KANSAS, MISSOURI.
AREA = 10200 SQ.MI.

ACCOUNTING UNIT 103001 — LOWER MISSOURI-BLACKWATER. THE MISSOURI RIVER BASIN BELOW THE CONFLUENCE WITH THE KANSAS RIVER BASIN TO THE CONFLUENCE WITH THE GASCONADE RIVER BASIN, EXCLUDING THE CHARITON, GASCONADE, GRAND, AND OSAGE RIVER BASINS. KANSAS, MISSOURI.
AREA = 8640 SQ.MI.

CATALOGING UNITS 10300101 — LOWER MISSOURI-CROOKED. KANSAS, MISSOURI.
AREA = 2650 SQ.MI.
10300102 — LOWER MISSOURI-MOREAU. MISSOURI.
AREA = 3360 SQ.MI.
10300103 — LAMINE. MISSOURI.
AREA = 1120 SQ.MI.
10300104 — BLACKWATER. MISSOURI.
AREA = 1510 SQ.MI.

ACCOUNTING UNIT 103002 — LOWER MISSOURI. THE MISSOURI RIVER BASIN BELOW THE CONFLUENCE WITH THE GASCONADE RIVER BASIN TO THE CONFLUENCE WITH THE MISSISSIPPI RIVER. MISSOURI.
AREA = 1590 SQ.MI.

CATALOGING UNIT 10300200 — LOWER MISSOURI. MISSOURI.
AREA = 1590 SQ.MI.

REGION 11 ARKANSAS-WHITE-RED REGION — THE DRAINAGE OF THE ARKANSAS, WHITE, AND RED RIVER BASINS ABOVE THE POINTS OF HIGHEST BACKWATER EFFECT OF THE MISSISSIPPI RIVER. INCLUDES ALL OF OKLAHOMA AND PARTS OF ARKANSAS, COLORADO, KANSAS, LOUISIANA, MISSOURI, NEW MEXICO, AND TEXAS.

SUBREGION 1101 — UPPER WHITE: THE WHITE RIVER BASIN ABOVE AND INCLUDING THE LITTLE RED RIVER BASIN TO THE POINT OF HIGHEST BACKWATER EFFECT OF THE MISSISSIPPI RIVER. ARKANSAS, MISSOURI.
AREA = 22200 SQ.MI.

ACCOUNTING UNIT 110100 — UPPER WHITE. ARKANSAS, MISSOURI.
AREA = 22200 SQ.MI.

CATALOGING UNITS 11010001 — BEAVER RESERVOIR. ARKANSAS, MISSOURI.
AREA = 2540 SQ.MI.
11010002 — JAMES. MISSOURI.
AREA = 1420 SQ.MI.
11010003 — BULL SHOALS LAKE. ARKANSAS, MISSOURI.
AREA = 2600 SQ.MI.
11010004 — MIDDLE WHITE. ARKANSAS.
AREA = 1490 SQ.MI.
11010005 — BUFFALO. ARKANSAS.
AREA = 1330 SQ.MI.
11010006 — NORTH FORK WHITE. ARKANSAS, MISSOURI.
AREA = 1810 SQ.MI.
11010007 — UPPER BLACK. ARKANSAS, MISSOURI.
AREA = 1900 SQ.MI.
11010008 — CURRENT. ARKANSAS, MISSOURI.
AREA = 2600 SQ.MI.
11010009 — LOWER BLACK. ARKANSAS, MISSOURI.
AREA = 760 SQ.MI.
11010010 — SPRING. ARKANSAS, MISSOURI.
AREA = 1210 SQ.MI.
11010011 — ELEVEN POINT. ARKANSAS, MISSOURI.
AREA = 1210 SQ.MI.
11010012 — STRAWBERRY. ARKANSAS.
AREA = 761 SQ.MI.
11010013 — UPPER WHITE-VILLAGE. ARKANSAS.
AREA = 758 SQ.MI.
11010014 — LITTLE RED. ARKANSAS.
AREA = 1790 SQ.MI.

SUBREGION 1102 — UPPER ARKANSAS: THE ARKANSAS RIVER BASIN ABOVE ITS INTERSECT WITH THE COLORADO-KANSAS STATE LINE. COLORADO, KANSAS, NEW MEXICO.
AREA = 24600 SQ.MI.

ACCOUNTING UNIT 110200 — UPPER ARKANSAS. COLORADO, KANSAS, NEW MEXICO.
AREA = 24600 SQ.MI.

CATALOGING UNITS 11020001 — ARKANSAS HEADWATERS. COLORADO.
AREA = 3020 SQ.MI.
11020002 — UPPER ARKANSAS. COLORADO.
AREA = 2280 SQ.MI.
11020003 — FOUNTAIN. COLORADO.
AREA = 917 SQ.MI.
11020004 — CHICO. COLORADO.
AREA = 729 SQ.MI.
11020005 — UPPER ARKANSAS-LAKE MEREDITH. COLORADO.
AREA = 2170 SQ.MI.
11020006 — HUERFANO. COLORADO.
AREA = 1830 SQ.MI.
11020007 — APISHAPA. COLORADO.
AREA = 1060 SQ.MI.
11020008 — HORSE. COLORADO.
AREA = 1400 SQ.MI.
11020009 — UPPER ARKANSAS-JOHN MARTIN RESERVOIR. COLORADO, KANSAS.
AREA = 3770 SQ.MI.
11020010 — PURGATOIRE. COLORADO, NEW MEXICO.
AREA = 3440 SQ.MI.
11020011 — BIG SANDY. COLORADO.
AREA = 1880 SQ.MI.
11020012 — RUSH. COLORADO.
AREA = 1350 SQ.MI.
11020013 — TWO BUTTE. COLORADO.
AREA = 798 SQ.MI.

SUBREGION 1103 — MIDDEL ARKANSAS: THE ARKANSAS RIVER BASIN BELOW ITS INTERSECT WITH THE COLORADO-KANSAS STATE LINE TO AND INCLUDING THE WALNUT RIVER BASIN, INCLUDING THE WHITEWOMAN CREEK CLOSED BASIN. COLORADO, KANSAS.
AREA = 20200 SQ.MI.

ACCOUNTING UNIT 110300 — MIDDLE ARKANSAS. COLORADO, KANSAS.
AREA = 20200 SQ.MI.

CATALOGING UNITS 11030001 — MIDDLE ARKANSAS-LAKE MCKINNEY. COLORADO, KANSAS.
AREA = 2330 SQ.MI.
11030002 — WHITEWOMAN. COLORADO, KANSAS.
AREA = 1370 SQ.MI.
11030003 — ARKANSAS-DODGE CITY. KANSAS.
AREA = 970 SQ.MI.

11030004 — COON-PICKEREL. KANSAS.
AREA = 1600 SQ.MI.
11030005 — PAWNEE. KANSAS.
AREA = 1810 SQ.MI.
11030006 — BUCKNER. KANSAS.
AREA = 902 SQ.MI.
11030007 — UPPER WALNUT CREEK. KANSAS.
AREA = 885 SQ.MI.
11030008 — LOWER WALNUT CREEK. KANSAS.
AREA = 935 SQ.MI.
11030009 — RATTLESNAKE. KANSAS.
AREA = 1280 SQ.MI.
11030010 — GAR-PEACE. KANSAS.
AREA = 559 SQ.MI.
11030011 — COW. KANSAS.
AREA = 938 SQ.MI.
11030012 — LITTLE ARKANSAS. KANSAS.
AREA = 1320 SQ.MI.
11030013 — MIDDLE ARKANSAS-SLATE. KANSAS.
AREA = 1010 SQ.MI.
11030014 — NORTH FORK NINNESCAH. KANSAS.
AREA = 941 SQ.MI.
11030015 — SOUTH FORK NINNESCAH. KANSAS.
AREA = 964 SQ.MI.
11030016 — NINNESCAH. KANSAS.
AREA = 392 SQ.MI.
11030017 — UPPER WALNUT RIVER. KANSAS.
AREA = 957 SQ.MI.
11030018 — LOWER WALNUT RIVER. KANSAS.
AREA = 1000 SQ.MI.

SUBREGION 1104 — UPPER CIMARRON: THE CIMARRON RIVER BASIN FROM ITS HEADWATERS TO THE RIVER'S MOST DOWNSTREAM INTERSECT WITH THE KANSAS-OKLAHOMA STATE LINE, INCLUDING THE BEAR CREEK CLOSED BASIN. COLORADO, KANSAS, NEW MEXICO, OKLAHOMA.
AREA = 12000 SQ.MI.

ACCOUNTING UNIT 110400 — UPPER CIMARRON. COLORADO, KANSAS, NEW MEXICO, OKLAHOMA.
AREA = 12000 SQ.MI.

CATALOGING UNITS 11040001 — CIMARRON HEADWATERS. COLORADO, NEW MEXICO, OKLAHOMA.
AREA = 1730 SQ.MI.
11040002 — UPPER CIMARRON. COLORADO, KANSAS, NEW MEXICO, OKLAHOMA.
AREA = 1750 SQ.MI.
11040003 — NORTH FORK CIMARRON. COLORADO, KANSAS.
AREA = 987 SQ.MI.
11040004 — SAND ARROYO. COLORADO, KANSAS.
AREA = 728 SQ.MI.
11040005 — BEAR. COLORADO, KANSAS.
AREA = 1870 SQ.MI.
11040006 — UPPER CIMARRON-LIBERAL. KANSAS, OKLAHOMA.
AREA = 1720 SQ.MI.
11040007 — CROOKED. KANSAS, OKLAHOMA.
AREA = 1430 SQ.MI.
11040008 — UPPER CIMARRON-BLUFF. KANSAS, OKLAHOMA.
AREA = 1800 SQ.MI.

SUBREGION 1105 — LOWER CIMARRON: THE CIMARRON RIVER BASIN BELOW THE RIVER'S MOST DOWNSTREAM INTERSECT WITH THE KANSAS-OKLAHOMA STATE LINE TO THE CONFLUENCE WITH THE ARKANSAS RIVER, INCLUDING THAT PORTION INUNDATED BY KEYSTONE RESERVOIR. KANSAS, OKLAHOMA.
AREA = 7050 SQ.MI.

ACCOUNTING UNIT 110500 — LOWER CIMARRON. KANSAS, OKLAHOMA.
AREA = 7050 SQ.MI.

CATALOGING UNITS 11050001 — LOWER CIMARRON-EAGLE CHIEF. KANSAS, OKALHOMA.
AREA = 2490 SQ.MI.
11050002 — LOWER CIMARRON-SKELETON. OKLAHOMA.
AREA = 3180 SQ.MI.
11050003 — LOWER CIMARRON. OKLAHOMA.
AREA = 1380 SQ.MI.

SUBREGION 1106 — ARKANSAS - KEYSTONE: THE ARKANSAS RIVER BASIN BELOW THE WALNUT RIVER BASIN TO KEYSTONE DAM, EXCLUDING THE CIMARRON RIVER BASIN. KANSAS, OKLAHOMA.
AREA = 9750 SQ.MI.

ACCOUNTING UNIT 110600 — ARKANSAS - KEYSTONE. KANSAS, OKLAHOMA.
AREA = 9750 SQ.MI.

CATALOGING UNITS 11060001 — KAW LAKE. KANSAS, OKLAHOMA.
AREA = 926 SQ.MI.
11060002 — UPPER SALT FORK ARKANSAS. KANSAS, OKLAHOMA.
AREA = 1080 SQ.MI.
11060003 — MEDICINE LODGE. KANSAS, OKLAHOMA.
AREA = 1280 SQ.MI.
11060004 — LOWER SALT FORK ARKANSAS. KANSAS, OKLAHOMA.
AREA = 2340 SQ.MI.
11060005 — CHIKASKIA. KANSAS, OKLAHOMA.
AREA = 2000 SQ.MI.
11060006 — BLACK BEAR-RED ROCK. OKLAHOMA.
AREA = 2120 SQ.MI.

SUBREGION 1107 — NEOSHO - VERDIGRIS. THE NEOSHO AND VERDIGRIS RIVER BASINS. ARKANSAS, KANSAS, MISSOURI, OKLAHOMA.
AREA = 20500 SQ.MI.

ACCOUNTING UNIT 110701 — VERDIGRIS: THE VERDIGRIS RIVER BASIN. KANSAS, OKLAHOMA.
AREA = 8100 SQ.MI.

CATALOGING UNITS 11070101 — UPPER VERDIGRIS. KANSAS.
AREA = 1160 SQ.MI.
11070102 — FALL. KANSAS.
AREA = 868 SQ.MI.
11070103 — MIDDLE VERDIGRIS. KANSAS, OKLAHOMA.
AREA = 1500 SQ.MI.
11070104 — ELK. KANSAS.
AREA = 673 SQ.MI.
11070105 — LOWER VERDIGRIS. OKLAHOMA.
AREA = 692 SQ.MI.
11070106 — CANEY. KANSAS, OKLAHOMA.
AREA = 2080 SQ.MI.
11070107 — BIRD. OKLAHOMA.
AREA = 1130 SQ.MI.

ACCOUNTING UNIT 110702 — NEOSHO: THE NEOSHO RIVER BASIN. ARKANSAS, KANSAS, MISSOURI, OKLAHOMA.
AREA = 12400 SQ.MI.

CATALOGING UNITS 11070201 — NEOSHO HEADWATERS. KANSAS.
AREA = 1110 SQ.MI.
11070202 — UPPER COTTONWOOD. KANSAS.
AREA = 927 SQ.MI.
11070203 — LOWER COTTONWOOD. KANSAS.
AREA = 968 SQ.MI.
11070204 — UPPER NEOSHO. KANSAS.
AREA = 1360 SQ.MI.
11070205 — MIDDLE NEOSHO. KANSAS, OKLAHOMA.
AREA = 1420 SQ.MI.
11070206 — LAKE O' THE CHEROKEES. ARKANSAS, KANSAS, MISSOURI, OKLAHOMA.
AREA = 911 SQ.MI.
11070207 — SPRING. KANSAS, MISSOURI, OKLAHOMA.
AREA = 2500 SQ.MI.
11070208 — ELK. ARKANSAS, MISSOURI, OKLAHOMA.
AREA = 1010 SQ.MI.
11070209 — LOWER NEOSHO. ARKANSAS, OKLAHOMA.
AREA = 2170 SQ.MI.

SUBREGION 1108 — UPPER CANADIAN: THE CANADIAN RIVER BASIN ABOVE ITS INTERSECT WITH THE NEW MEXICO-TEXAS STATE LINE. COLORADO, NEW MEXICO.
AREA = 12500 SQ.MI.

ACCOUNTING UNIT 110800 — UPPER CANADIAN. COLORADO, NEW MEXICO.
AREA = 12500 SQ.MI.

CATALOGING UNITS 11080001 — CANADIAN HEADWATERS. COLORADO, NEW MEXICO.
AREA = 1730 SQ.MI.
11080002 — CIMARRON. NEW MEXICO.
AREA = 1040 SQ.MI.
11080003 — UPPER CANADIAN. NEW MEXICO.
AREA = 2020 SQ.MI.
11080004 — MORA. NEW MEXICO.
AREA = 1470 SQ.MI.
11080005 — CONCHAS. NEW MEXICO.
AREA = 1030 SQ.MI.
11080006 — UPPER CANADIAN-UTE RESERVOIR. NEW MEXICO, TEXAS.
AREA = 2390 SQ.MI.
11080007 — UTE. NEW MEXICO.
AREA = 2070 SQ.MI.
11080008 — REVUELTO. NEW MEXICO.
AREA = 780 SQ.MI.

SUBREGION 1109 — LOWER CANADIAN: THE CANADIAN RIVER BASIN BELOW ITS INTERSECT WITH THE NEW MEXICO-TEXAS STATE LINE TO THE CONFLUENCE WITH THE ARKANSAS RIVER, INCLUDING THAT PORTION INUNDATED BY EUFAULA LAKE AND ROBERT S. KERR RESERVOIR, BUT EXCLUDING THE NORTH CANADIAN RIVER BASIN. NEW MEXICO, OKLAHOMA, TEXAS.
AREA = 16800 SQ.MI.

ACCOUNTING UNIT 110901 — MIDDLE CANADIAN: THE CANADIAN RIVER BASIN BELOW ITS INTERSECT WITH THE NEW MEXICO-TEXAS STATE LINE TO ITS INTERSECT WITH THE OKLAHOMA-TEXAS STATE LINE. NEW MEXICO, OKLAHOMA, TEXAS.
AREA = 10100 SQ.MI.

CATALOGING UNITS 11090101 — MIDDLE CANADIAN-TRUJILLO. NEW MEXICO, TEXAS.
AREA = 1700 SQ.MI.
11090102 — PUNTA DE AGUA. NEW MEXICO, TEXAS.
AREA = 1560 SQ.MI.
11090103 — RITA BLANCA. NEW MEXICO, OKLAHOMA, TEXAS.
AREA = 1130 SQ.MI.
11090104 — CARRIZO. NEW MEXICO, TEXAS.
AREA = 864 SQ.MI.
11090105 — LAKE MEREDITH. TEXAS.
AREA = 2060 SQ.MI.
11090106 — MIDDLE CANADIAN-SPRING. TEXAS.
AREA = 2780 SQ.MI.

ACCOUNTING UNIT 110902 — LOWER CANADIAN: THE CANADIAN RIVER BASIN BELOW ITS INTERSECT WITH THE OKLAHOMA-TEXAS STATE LINE TO THE CONFLUENCE WITH THE ARKANSAS RIVER, INCLUDING THAT PORTION INUNDATED BY EUFAULA LAKE AND ROBERT S. KERR RESERVOIR, BUT EXCLUDING THE NORTH CANADIAN RIVER BASIN. OKLAHOMA, TEXAS.
AREA = 6750 SQ.MI.

CATALOGING UNITS 11090201 — LOWER CANADIAN-DEER. OKLAHOMA, TEXAS.
AREA = 2010 SQ.MI.
11090202 — LOWER CANADIAN-WALNUT. OKLAHOMA.
AREA = 1800 SQ.MI.
11090203 — LITTLE. OKLAHOMA.
AREA = 976 SQ.MI.
11090204 — LOWER CANADIAN. OKLAHOMA.
AREA = 1960 SQ.MI.

SUBREGION 1110 — NORTH CANADIAN: THE NORTH CANADIAN RIVER BASIN, INCLUDING THAT PORTION INUNDATED BY EUFAULA LAKE. KANSAS, NEW MEXICO, OKLAHOMA, TEXAS.
AREA = 17500 SQ.MI.

ACCOUNTING UNIT 111001 — UPPER BEAVER. THE BEAVER RIVER BASIN TO AND INCLUDING THE HOME CREEK BASIN. KANSAS, NEW MEXICO, OKLAHOMA, TEXAS.
AREA = 7800 SQ.MI.

CATALOGING UNITS 11100101 — UPPER BEAVER. NEW MEXICO, OKLAHOMA, TEXAS.
AREA = 2710 SQ.MI.
11100102 — MIDDLE BEAVER. KANSAS, OKLAHOMA.
AREA = 1280 SQ.MI.
11100103 — COLDWATER. OKLAHOMA, TEXAS.
AREA = 1780 SQ.MI.
11100104 — PALO DURO. OKLAHOMA, TEXAS.
AREA = 2300 SQ.MI.

ACCOUNTING UNIT 111002 — LOWER BEAVER: THE BEAVER RIVER BASIN BELOW THE HOME CREEK BASIN TO AND INCLUDING THE WOLF CREEK BASIN. OKLAHOMA, TEXAS.
AREA = 3590 SQ.MI.

CATALOGING UNITS 11100201 — LOWER BEAVER. OKLAHOMA, TEXAS.
AREA = 1740 SQ.MI.
11100202 — UPPER WOLF. TEXAS.
AREA = 779 SQ.MI.
11100203 — LOWER WOLF. OKLAHOMA, TEXAS.
AREA = 1070 SQ.MI.

ACCOUNTING UNIT 111003 — LOWER NORTH CANADIAN: THE NORTH CANADIAN RIVER BASIN, INCLUDING THAT PORTION INUNDATED BY EUFAULA LAKE, BUT EXCLUDING THE BEAVER RIVER BASIN ABOVE ITS CONFLUENCE WITH THE WOLF CREEK BASIN. OKLAHOMA.
AREA = 6160 SQ.MI.

CATALOGING UNITS 11100301 — MIDDLE NORTH CANADIAN. OKLAHOMA.
AREA = 1770 SQ.MI.
11100302 — LOWER NORTH CANADIAN. OKLAHOMA.
AREA = 1830 SQ.MI.
11100303 — DEEP FORK. OKLAHOMA.
AREA = 2560 SQ.MI.

SUBREGION 1111 — LOWER ARKANSAS: THE ARKANSAS RIVER BASIN BELOW KEYSTONE DAM TO THE POINT OF HIGHEST BACKWATER EFFECT OF THE MISSISSIPPI RIVER BELOW LOCK AND DAM 4 ON THE ARKANSAS RIVER, BUT EXCLUDING THE CANADIAN, NEOSHO, AND VERDIGRIS RIVER BASINS. ARKANSAS, OKLAHOMA.
AREA = 15600 SQ.MI.

ACCOUNTING UNIT 111101 — ROBERT S. KERR RESERVOIR: THE ARKANSAS RIVER BASIN BELOW KEYSTONE DAM TO LOCK AND DAM 13, BUT EXCLUDING THE CANADIAN, NEOSHO, AND VERDIGRIS RIVER BASINS. ARKANSAS. OKLAHOMA.
AREA = 7340 SQ.MI.

REGION 11: ARKANSAS-WHITE-RED — Continued

CATALOGING UNITS 11110101 — POLECAT-SNAKE. OKLAHOMA.
AREA = 1310 SQ.MI.
11110102 — DIRTY-GREENLEAF. OKLAHOMA.
AREA = 769 SQ.MI.
11110103 — ILLINOIS. ARKANSAS, OKLAHOMA.
AREA = 1620 SQ.MI.
11110104 — ROBERT S. KERR RESERVOIR. ARKANSAS, OKLAHOMA.
AREA = 1780 SQ.MI.
11110105 — POTEAU. ARKANSAS, OKLAHOMA.
AREA = 1860 SQ.MI.

ACCOUNTING UNIT 111102 — LOWER ARKANSAS-FOURCHE LA FAVE: THE ARKANSAS RIVER BASIN BELOW LOCK AND DAM 13 TO THE POINT OF HIGHEST BACKWATER EFFECT OF THE MISSISSIPPI RIVER BELOW LOCK AND DAM 4 ON THE ARKANSAS RIVER. ARKANSAS.
AREA = 8300 SQ.MI.

CATALOGING UNITS 11110201 — FROG-MULBERRY. ARKANSAS.
AREA = 1270 SQ.MI.
11110202 — DARDANELLE RESERVOIR. ARKANSAS.
AREA = 1860 SQ.MI.
11110203 — LAKE CONWAY-POINT REMOVE. ARKANSAS.
AREA = 1140 SQ.MI.
11110204 — PETIT JEAN. ARKANSAS.
AREA = 1070 SQ.MI.
11110205 — CADRON. ARKANSAS.
AREA = 751 SQ.MI.
11110206 — FOURCHE LA FAVE. ARKANSAS.
AREA = 1100 SQ.MI.
11110207 — LOWER ARKANSAS-MAUMELLE. ARKANSAS.
AREA = 1100 SQ.MI.

SUBREGION 1112 — RED HEADWATERS: THE NORTH FORK RED RIVER, PRAIRIE DOG TOWN FORK RED RIVER, AND THE SALT FORK RED RIVER BASINS. NEW MEXICO, OKLAHOMA, TEXAS.
AREA = 14600 SQ.MI.

ACCOUNTING UNIT 111201 — PRAIRIE DOG TOWN FORK RED: THE PRAIRIE DOG TOWN FORK RED RIVER BASIN. NEW MEXICO, OKLAHOMA, TEXAS.
AREA = 7630 SQ.MI.

CATALOGING UNITS 11120101 — TIERRA BLANCA. NEW MEXICO, TEXAS.
AREA = 1910 SQ.MI.
11120102 — PALO DURO. NEW MEXICO, TEXAS.
AREA = 966 SQ.MI.
11120103 — UPPER PRAIRIE DOG TOWN FORK RED. TEXAS.
AREA = 2120 SQ.MI.
11120104 — TULE. TEXAS.
AREA = 1100 SQ.MI.
11120105 — LOWER PRAIRIE DOG TOWN FORK RED. OKLAHOMA, TEXAS.
AREA = 1530 SQ.MI.

ACCOUNTING UNIT 111202 — SALT FORK RED: THE SALT FORK RED RIVER BASIN. OKLAHOMA, TEXAS.
AREA = 2000 SQ.MI.

CATALOGING UNITS 11120201 — UPPER SALT FORK RED. TEXAS.
AREA = 740 SQ.MI.
11120202 — LOWER SALT FORK RED. OKLAHOMA, TEXAS.
AREA = 1260 SQ.MI.

ACCOUNTING UNIT 111203 — NORTH FORK RED: THE NORTH FORK RED RIVER BASIN. OKLAHOMA, TEXAS.
AREA = 5000 SQ.MI.

CATALOGING UNITS 11120301 — UPPER NORTH FORK RED. TEXAS.
AREA = 1160 SQ.MI.
11120302 — MIDDLE NORTH FORK RED. OKLAHOMA, TEXAS.
AREA = 1630 SQ.MI.
11120303 — LOWER NORTH FORK RED. OKLAHOMA.
AREA = 1330 SQ.MI.
11120304 — ELM FORK RED. OKLAHOMA, TEXAS.
AREA = 878 SQ.MI.

SUBREGION 1113 — RED - WASHITA: THE RED RIVER BASIN ABOVE DENISON DAM, EXCLUDING THE NORTH FORK RED RIVER, PRAIRIE DOG TOWN FORK RED RIVER, AND THE SALT FORK RED RIVER BASINS. OKLAHOMA, TEXAS.
AREA = 24600 SQ.MI.

ACCOUNTING UNIT 111301 — RED-PEASE: THE RED RIVER BASIN FROM THE PRAIRIE DOG TOWN FORK RED RIVER BASIN TO THE CACHE CREEK BASIN, EXCLUDING THE NORTH FORK RED RIVER AND THE SALT FORK RED RIVER BASINS. OKLAHOMA, TEXAS.
AREA = 5730 SQ.MI.

CATALOGING UNITS 11130101 — GROESBECK-SANDY. OKLAHOMA, TEXAS.
AREA = 1300 SQ.MI.
11130102 — BLUE-CHINA. OKLAHOMA, TEXAS.
AREA = 794 SQ.MI.
11130103 — NORTH PEASE. TEXAS.
AREA = 1460 SQ.MI.
11130104 — MIDDLE PEASE. TEXAS.
AREA = 1420 SQ.MI.
11130105 — PEASE. TEXAS.
AREA = 760 SQ.MI.

ACCOUNTING UNIT 111302 — RED-LAKE TEXOMA: THE RED RIVER BASIN FROM AND INCLUDING THE CACHE CREEK BASIN TO DENISON DAM, INCLUDING THAT PORTION INUNDATED BY LAKE TEXOMA, BUT EXCLUDING THE WASHITA RIVER BASIN. OKLAHOMA, TEXAS.
AREA = 11000 SQ.MI.

CATALOGING UNITS 11130201 — FARMERS-MUD. OKLAHOMA, TEXAS.
AREA = 2340 SQ.MI.
11130202 — CACHE. OKLAHOMA.
AREA = 785 SQ.MI.
11130203 — WEST CACHE. OKLAHOMA.
AREA = 1120 SQ.MI.
11130204 — NORTH WICHITA. TEXAS.
AREA = 1090 SQ.MI.
11130205 — SOUTH WICHITA. TEXAS.
AREA = 702 SQ.MI.
11130206 — WICHITA. TEXAS.
AREA = 1010 SQ.MI.
11130207 — SOUTHERN BEAVER. TEXAS.
AREA = 679 SQ.MI.
11130208 — NORTHERN BEAVER. OKLAHOMA.
AREA = 847 SQ.MI.
11130209 — LITTLE WICHITA. TEXAS.
AREA = 1470 SQ.MI.
11130210 — LAKE TEXOMA. OKLAHOMA, TEXAS.
AREA = 982 SQ.MI.

ACCOUNTING UNIT 111303 — WASHITA. THE WASHITA RIVER BASIN, INCLUDING THAT PORTION INUNDATED BY LAKE TEXOMA. OKLAHOMA.
AREA = 7870 SQ.MI.

CATALOGING UNITS 11130301 — WASHITA HEADWATERS. OKLAHOMA, TEXAS.
AREA = 1460 SQ.MI.
11130302 — UPPER WASHITA. OKLAHOMA.
AREA = 3190 SQ.MI.
11130303 — MIDDLE WASHITA. OKLAHOMA.
AREA = 2490 SQ.MI.
11130304 — LOWER WASHITA. OKLAHOMA.
AREA = 727 SQ.MI.

SUBREGION 1114 — RED-SULPHUR: THE RED RIVER BASIN BELOW DENISON DAM TO AND INCLUDING THE BAYOU RIGOLETTE BASIN AT THE POINT OF HIGHEST BACKWATER EFFECT OF THE MISSISSIPPI RIVER. ARKANSAS, LOUISIANA, OKLAHOMA, TEXAS.
AREA = 27600 SQ.MI.

ACCOUNTING UNIT 111401 — RED-LITTLE: THE RED RIVER BASIN BELOW DENISON DAM TO AND INCLUDING THE LITTLE RIVER BASIN. ARKANSAS, OKLAHOMA, TEXAS.
AREA = 12500 SQ.MI.

CATALOGING UNITS 11140101 — BOIS D'ARC-ISLAND. OKLAHOMA, TEXAS.
AREA = 2010 SQ.MI.
11140102 — BLUE. OKLAHOMA.
AREA = 643 SQ.MI.
11140103 — MUDDY BOGGY. OKLAHOMA.
AREA = 1420 SQ.MI.
11140104 — CLEAR BOGGY. OKLAHOMA.
AREA = 1000 SQ.MI.
11140105 — KIAMICHI. ARKANSAS, OKLAHOMA.
AREA = 1820 SQ.MI.
11140106 — PECAN-WATERHOLE. ARKANSAS, OKLAHOMA, TEXAS.
AREA = 1460 SQ.MI.
11140107 — UPPER LITTLE. OKLAHOMA.
AREA = 1400 SQ.MI.
11140108 — MOUNTAIN FORK. ARKANSAS, OKLAHOMA.
AREA = 821 SQ.MI.
11140109 — LOWER LITTLE. ARKANSAS, OKLAHOMA.
AREA = 1950 SQ.MI.

ACCOUNTING UNIT 111402 — RED-SALINE: THE RED RIVER BASIN BELOW THE LITTLE RIVER BASIN TO AND INCLUDING THE BAYOU RIGOLETTE BASIN AT THE POINT OF HIGHEST BACKWATER EFFECT OF THE MISSISSIPPI RIVER, EXCLUDING THE BIG CYPRESS AND SULPHUR RIVER BASINS. ARKANSAS, LOUISIANA.
AREA = 7740 SQ.MI.

CATALOGING UNITS 11140201 — MCKINNEY-POSTEN BAYOUS. ARKANSAS, LOUISIANA, TEXAS.
AREA = 906 SQ.MI.
11140202 — MIDDLE RED-COUSHATTA. LOUISIANA.
AREA = 276 SQ.MI.
11140203 — LOGGY BAYOU. ARKANSAS, LOUISIANA.
AREA = 1470 SQ.MI.
11140204 — RED CHUTE. LOUISIANA.
AREA = 381 SQ.MI.
11140205 — BODCAU BAYOU. ARKANSAS, LOUISIANA.
AREA = 766 SQ.MI.
11140206 — BAYOU PIERRE. LOUISIANA.
AREA = 1110 SQ.MI.
11140207 — LOWER RED-LAKE IATT. LOUISIANA.
AREA = 1450 SQ.MI.
11140208 — SALINE BAYOU. LOUISIANA.
AREA = 477 SQ.MI.
11140209 — BLACK LAKE BAYOU. LOUISIANA.
AREA = 908 SQ.MI.

ACCOUNTING UNIT 111403 — BIG CYPRESS - SULPHUR. THE CROSS BAYOU AND SULPHUR RIVER BASINS, INCLUDING THE BIG CYPRESS CREEK BASIN. ARKANSAS, LOUISIANA.
AREA = 7310 SQ.MI.

CATALOGING UNITS 11140301 — SULPHUR HEADWATERS. TEXAS.
AREA = 1160 SQ.MI.
11140302 — LOWER SULPHUR. ARKANSAS, TEXAS.
AREA = 1810 SQ.MI.
11140303 — WHITE OAK BAYOU. TEXAS.
AREA = 783 SQ.MI.
11140304 — CROSS BAYOU. ARKANSAS, LOUISIANA, TEXAS.
AREA = 756 SQ.MI.
11140305 — LAKE O'THE PINES. TEXAS.
AREA = 901 SQ.MI.
11140306 — CADDO LAKE. LOUISIANA, TEXAS.
AREA = 1180 SQ.MI.
11140307 — LITTLE CYPRESS. TEXAS.
AREA = 720 SQ.MI.

REGION 12 TEXAS-GULF REGION — THE DRAINAGE THAT DISCHARGES INTO THE GULF OF MEXICO FROM AND INCLUDING SABINE PASS TO THE RIO GRANDE BASIN BOUNDARY. INCLUDES PARTS OF LOUISIANA, NEW MEXICO, AND TEXAS.

SUBREGION 1201 — SABINE: THE SABINE RIVER BASIN ABOVE SABINE LAKE. LOUISIANA, TEXAS.
AREA = 9860 SQ.MI.

ACCOUNTING UNIT 120100 — SABINE. LOUISIANA, TEXAS.
AREA = 9860 SQ.MI.

CATALOGING UNITS 12010001 — UPPER SABINE. TEXAS.
AREA = 1380 SQ.MI.
12010002 — MIDDLE SABINE. LOUISIANA, TEXAS.
AREA = 2760 SQ.MI.
12010003 — LAKE FORK. TEXAS.
AREA = 689 SQ.MI.
12010004 — TOLEDO BEND RESERVOIR. LOUISIANA, TEXAS.
AREA = 2390 SQ.MI.
12010005 — LOWER SABINE. LOUISIANA, TEXAS.
AREA = 2640 SQ.MI.

SUBREGION 1202 — NECHES: THE NECHES RIVER BASIN ABOVE SABINE LAKE. TEXAS.
AREA = 10000 SQ.MI.

ACCOUNTING UNIT 120200 — NECHES. TEXAS.
AREA = 10000 SQ.MI.

CATALOGING UNITS 12020001 — UPPER NECHES. TEXAS.
AREA = 1940 SQ.MI.
12020002 — MIDDLE NECHES. TEXAS.
AREA = 1630 SQ.MI.
12020003 — LOWER NECHES. TEXAS.
AREA = 1130 SQ.MI.
12020004 — UPPER ANGELINA. TEXAS.
AREA = 1610 SQ.MI.
12020005 — LOWER ANGELINA. TEXAS.
AREA = 1940 SQ.MI.
12020006 — VILLAGE. TEXAS.
AREA = 1100 SQ.MI.
12020007 — PINE ISLAND BAYOU. TEXAS.
AREA = 670 SQ.MI.

SUBREGION 1203 — TRINITY: THE TRINITY RIVER BASIN ABOVE TRINITY BAY. TEXAS.
AREA = 18000 SQ.MI.

ACCOUNTING UNIT 120301 — UPPER TRINITY: THE TRINITY RIVER BASIN ABOVE AND INCLUDING THE RICHLAND CREEK BASIN. TEXAS.
AREA = 11800 SQ.MI.

CATALOGING UNITS 12030101 — UPPER WEST FORK TRINITY. TEXAS.
AREA = 1970 SQ.MI.
12030102 — LOWER WEST FORK TRINITY. TEXAS.
AREA = 1510 SQ.MI.
12030103 — ELM FORK TRINITY. TEXAS.
AREA = 1840 SQ.MI.
12030104 — DENTON. TEXAS.
AREA = 727 SQ.MI.
12030105 — UPPER TRINITY. TEXAS.
AREA = 1370 SQ.MI.
12030106 — EAST FORK TRINITY. TEXAS.
AREA = 1300 SQ.MI.
12030107 — CEDAR. TEXAS.
AREA = 1070 SQ.MI.
12030108 — RICHLAND. TEXAS.
AREA = 917 SQ.MI.
12030109 — CHAMBERS. TEXAS.
AREA = 1070 SQ.MI.

ACCOUNTING UNIT 120302 — LOWER TRINITY: THE TRINITY RIVER BASIN BELOW THE RICHLAND CREEK BASIN TO BUT EXCLUDING TRINITY BAY. TEXAS.
AREA = 6210 SQ.MI.

CATALOGING UNITS 12030201 — LOWER TRINITY-TEHUACANA. TEXAS.
AREA = 2140 SQ.MI.
12030202 — LOWER TRINITY-KICKAPOO. TEXAS.
AREA = 3250 SQ.MI.
12030203 — LOWER TRINITY. TEXAS.
AREA = 815 SQ.MI.

SUBREGION 1204 — GALVESTON BAY-SAN JACINTO: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM AND INCLUDING SABINE PASS TO THE BRAZOS RIVER BASIN BOUNDARY, BUT EXCLUDING THE NECHES AND SABINE RIVER BASINS ABOVE SABINE LAKE AND THE TRINITY RIVER BASIN ABOVE TRINITY BAY. LOUISIANA, TEXAS.
AREA = 7980 SQ.MI.

ACCOUNTING UNIT 120401 — SAN JACINTO: THE SAN JACINTO RIVER BASIN ABOVE GALVESTON BAY. TEXAS.
AREA = 3980 SQ.MI.

CATALOGING UNITS 12040101 — WEST FORK SAN JACINTO. TEXAS.
AREA = 1080 SQ.MI.
12040102 — SPRING. TEXAS.
AREA = 760 SQ.MI.
12040103 — EAST FORK SAN JACINTO. TEXAS.
AREA = 1010 SQ.MI.
12040104 — BUFFALO-SAN JACINTO. TEXAS.
AREA = 1130 SQ.MI.

ACCOUNTING UNIT 120402 — GALVESTON BAY-SABINE LAKE: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM AND INCLUDING SABINE PASS TO THE BRAZOS RIVER BASIN BOUNDARY, BUT EXCLUDING THE NECHES AND SABINE RIVER BASINS ABOVE THE SABINE LAKE, THE TRINITY RIVER BASIN ABOVE TRINITY BAY, AND THE SAN JACINTO RIVER ABOVE GALVESTON BAY. LOUISIANA, TEXAS.
AREA = 4000 SQ.MI.

CATALOGING UNITS 12040201 — SABINE LAKE. LOUISIANA, TEXAS.
AREA = 1040 SQ.MI.
12040202 — EAST GALVESTON BAY. TEXAS.
AREA = 795 SQ.MI.
12040203 — NORTH GALVESTON BAY. TEXAS.
AREA = 395 SQ.MI.
12040204 — WEST GALVESTON BAY. TEXAS.
AREA = 1130 SQ.MI.
12040205 — AUSTIN-OYSTER. TEXAS.
AREA = 637 SQ.MI.

SUBREGION 1205 — BRAZOS HEADWATERS: THE BRAZOS RIVER BASIN ABOVE THE CONFLUENCE OF AND INCLUDING THE DOUBLE MOUNTAIN FORK BRAZOS RIVER AND THE SALT FORK BRAZOS RIVER BASINS. NEW MEXICO, TEXAS.
AREA = 14600 SQ.MI.

ACCOUNTING UNIT 120500 — BRAZOS HEADWATERS. NEW MEXICO, TEXAS.
AREA = 14600 SQ.MI.

CATALOGING UNITS 12050001 — YELLOW HOUSE DRAW. NEW MEXICO, TEXAS.
AREA = 3780 SQ.MI.
12050002 — BLACKWATER DRAW. NEW MEXICO, TEXAS.
AREA = 1560 SQ.MI.
12050003 — NORTH FORK DOUBLE MOUNTAIN FORK BRAZOS. TEXAS.
AREA = 1050 SQ.MI.
12050004 — DOUBLE MOUTAIN FORK BRAZOS. TEXAS.
AREA = 2740 SQ.MI.
12050005 — RUNNING WATER DRAW. NEW MEXICO, TEXAS.
AREA = 1620 SQ.MI.
12050006 — WHITE. TEXAS.
AREA = 1690 SQ.MI.
12050007 — SALT FORK BRAZOS. TEXAS.
AREA = 2150 SQ.MI.

SUBREGION 1206 — MIDDLE BRAZOS: THE BRAZOS RIVER BASIN BELOW THE CONFLUENCE OF THE DOUBLE MOUNTAIN FORK BRAZOS RIVER AND THE SALT FORK BRAZOS RIVER BASINS TO AND INCLUDING THE CASTLEMAN CREEK BASIN. TEXAS.
AREA = 15500 SQ.MI.

ACCOUNTING UNIT 120601 — MIDDLE BRAZOS-CLEAR FORK: THE BRAZOS RIVER BASIN BELOW THE CONFLUENCE OF THE DOUBLE MOUNTAIN FORK BRAZOS RIVER AND THE SALT FORK BRAZOS RIVER BASINS TO AND INCLUDING THE CLEAR FORK BRAZOS RIVER BASIN. TEXAS.
AREA = 8220 SQ.MI.

CATALOGING UNITS 12060101 — MIDDLE BRAZOS-MILLERS. TEXAS.
AREA = 2490 SQ.MI.
12060102 — UPPER CLEAR FORK BRAZOS. TEXAS.
AREA = 2730 SQ.MI.
12060103 — PAINT. TEXAS.
AREA = 1080 SQ.MI.
12060104 — LOWER CLEAR FORK BRAZOS. TEXAS.
AREA = 620 SQ.MI.
12060105 — HUBBARD. TEXAS.
AREA = 1300 SQ.MI.

ACCOUNTING UNIT 120602 — MIDDLE BRAZOS-BOSQUE: THE BRAZOS RIVER BASIN BELOW THE CLEAR FORK BRAZOS RIVER BASIN TO AND INCLUDING THE CASTLEMAN CREEK BASIN. TEXAS.
AREA = 7320 SQ.MI.

CATALOGING UNITS 12060201 — MIDDLE BRAZOS-PALO PINTO. TEXAS.
AREA = 3160 SQ.MI.
12060202 — MIDDLE BRAZOS-LAKE WHITNEY. TEXAS.
AREA = 2500 SQ.MI.
12060203 — BOSQUE. TEXAS.
AREA = 418 SQ.MI.
12060204 — NORTH BOSQUE. TEXAS.
AREA = 1240 SQ.MI.

SUBREGION 1207 — LOWER BRAZOS: THE BRAZOS RIVER BASIN BELOW THE CASTLEMAN CREEK BASIN. TEXAS.
AREA = 15600 SQ.MI.

ACCOUNTING UNIT 120701 — LOWER BRAZOS: THE BRAZOS RIVER BASIN BELOW THE CASTLEMAN CREEK BASIN, EXCLUDING THE LITTLE RIVER BASIN. TEXAS.
AREA = 7960 SQ.MI.

CATALOGING UNITS 12070101 — LOWER BRAZOS-LITTLE BRAZOS. TEXAS.
AREA = 2720 SQ.MI.
12070102 — YEGUA. TEXAS.
AREA = 1330 SQ.MI.
12070103 — NAVASOTA. TEXAS.
AREA = 2260 SQ.MI.
12070104 — LOWER BRAZOS. TEXAS.
AREA = 1650 SQ.MI.

ACCOUNTING UNIT 120702 — LITTLE: THE LITTLE RIVER BASIN. TEXAS.
AREA = 7610 SQ.MI.

CATALOGING UNITS 12070201 — LEON. TEXAS.
AREA = 3000 SQ.MI.
12070202 — COWHOUSE. TEXAS.
AREA = 743 SQ.MI.
12070203 — LAMPASAS. TEXAS.
AREA = 1510 SQ.MI.
12070204 — LITTLE. TEXAS.
AREA = 1000 SQ.MI.
12070205 — SAN GABRIEL. TEXAS.
AREA = 1360 SQ.MI.

SUBREGION 1208 — UPPER COLORADO: THE COLORADO RIVER BASIN ABOVE AND INCLUDING THE OAK CREEK BASIN. NEW MEXICO, TEXAS.
AREA = 16000 SQ.MI.

ACCOUNTING UNIT 120800 — UPPER COLORADO. NEW MEXICO, TEXAS.
AREA = 16000 SQ.MI.

CATALOGING UNITS 12080001 — LOST DRAW. NEW MEXICO, TEXAS.
AREA = 2370 SQ.MI.
12080002 — COLORADO HEADWATERS. TEXAS.
AREA = 2680 SQ.MI.
12080003 — MONUMENT-SEMINOLE DRAWS. NEW MEXICO, TEXAS.
AREA = 2680 SQ.MI.
12080004 — MUSTANG DRAW. NEW MEXICO, TEXAS.
AREA = 2640 SQ.MI.
12080005 — JOHNSON DRAW. TEXAS.
AREA = 1910 SQ.MI.
12080006 — SULPHUR SPRINGS DRAW. NEW MEXICO, TEXAS.
AREA = 1720 SQ.MI.
12080007 — BEALS. TEXAS.
AREA = 632 SQ.MI.
12080008 — UPPER COLORADO. TEXAS.
AREA = 1380 SQ.MI.

SUBREGION 1209 — LOWER COLORADO-SAN BERNARD COASTAL: THE COLORADO RIVER BASIN BELOW THE OAK CREEK BASIN; AND THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE BRAZOS RIVER BASIN BOUNDARY TO THE COLORADO RIVER BASIN BOUNDARY. TEXAS.
AREA = 28400 SQ.MI.

ACCOUNTING UNIT 120901 — MIDDLE COLORADO-CONCHO: THE COLORADO RIVER BASIN BELOW THE OAK CREEK BASIN TO AND INCLUDING THE SAN SABA RIVER BASIN. TEXAS.
AREA = 15200 SQ.MI.

CATALOGING UNITS 12090101 — MIDDLE COLORADO-ELM. TEXAS.
AREA = 1160 SQ.MI.
12090102 — SOUTH CONCHO. TEXAS.
AREA = 1350 SQ.MI.
12090103 — MIDDLE CONCHO. TEXAS.
AREA = 2650 SQ.MI.
12090104 — NORTH CONCHO. TEXAS.
AREA = 1510 SQ.MI.
12090105 — CONCHO. TEXAS.
AREA = 1240 SQ.MI.
12090106 — MIDDLE COLORADO. TEXAS.
AREA = 1980 SQ.MI.
12090107 — PECAN BAYOU. TEXAS.
AREA = 1410 SQ.MI.
12090108 — JIM NED. TEXAS.
AREA = 780 SQ.MI.
12090109 — SAN SABA. TEXAS.
AREA = 2330 SQ.MI.
12090110 — BRADY. TEXAS.
AREA = 786 SQ.MI.

ACCOUNTING UNIT 120902 — MIDDLE COLORADO-LLANO: THE COLORADO RIVER BASIN BELOW THE SAN SABA RIVER BASIN TO AND INCLUDING THE ONION CREEK BASIN. TEXAS.
AREA = 8350 SQ.MI.

CATALOGING UNITS 12090201 — BUCHANAN-LYNDON B. JOHNSON LAKES. TEXAS.
AREA = 1260 SQ.MI.
12090202 — NORTH LLANO. TEXAS.
AREA = 942 SQ.MI.
12090203 — SOUTH LLANO. TEXAS.
AREA = 937 SQ.MI.
12090204 — LLANO. TEXAS.
AREA = 2650 SQ.MI.
12090205 — AUSTIN-TRAVIS LAKES. TEXAS.
AREA = 1260 SQ.MI.
12090206 — PEDERNALES. TEXAS.
AREA = 1300 SQ.MI.

ACCOUNTING UNIT 120903 — LOWER COLORADO: THE COLORADO RIVER BASIN BELOW THE ONION CREEK BASIN TO ITS POINT OF DISCHARGE INTO THE GULF OF MEXICO. TEXAS.
AREA = 2930 SQ.MI.

CATALOGING UNITS 12090301 — LOWER COLORADO-CUMMINS. TEXAS.
AREA = 2220 SQ.MI.
12090302 — LOWER COLORADO. TEXAS.
AREA = 706 SQ.MI.

ACCOUNTING UNIT 120904 — SAN BERNARD COASTAL: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE BRAZOS RIVER BASIN BOUNDARY TO THE COLORADO RIVER BASIN BOUNDARY. TEXAS.
AREA = 1920 SQ.MI.

CATALOGING UNITS 12090401 — SAN BERNARD. TEXAS.
AREA = 1050 SQ.MI.
12090402 — EAST MATAGORDA BAY. TEXAS.
AREA = 865 SQ.MI.

SUBREGION 1210 — CENTRAL TEXAS COASTAL: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE COLORADO RIVER BASIN BOUNDARY TO ARANSAS PASS AND THE CORPUS CHRISTI BAY DRAINAGE BOUNDARY. TEXAS.
AREA = 18200 SQ.MI.

ACCOUNTING UNIT 121001 — LAVACA: THE LAVACA RIVER BASIN. TEXAS.
AREA = 2340 SQ.MI.

CATALOGING UNITS 12100101 — LAVACA. TEXAS.
AREA = 903 SQ.MI.
12100102 — NAVIDAD. TEXAS.
AREA = 1440 SQ.MI.

ACCOUNTING UNIT 121002 — GUADALUPE: THE GUADALUPE RIVER BASIN, EXCLUDING THE SAN ANTONIO RIVER BASIN. TEXAS.
AREA = 6040 SQ.MI.

CATALOGING UNITS 12100201 — UPPER GUADALUPE. TEXAS.
AREA = 1450 SQ.MI.
12100202 — MIDDLE GUADALUPE. TEXAS.
AREA = 2160 SQ.MI.
12100203 — SAN MARCOS. TEXAS.
AREA = 1370 SQ.MI.
12100204 — LOWER GUADALUPE. TEXAS.
AREA = 1060 SQ.MI.

ACCOUNTING UNIT 121003 — SAN ANTONIO: THE SAN ANTONIO RIVER BASIN. TEXAS.
AREA = 4270 SQ.MI.

CATALOGING UNITS 12100301 — UPPER SAN ANTONIO. TEXAS.
AREA = 524 SQ.MI.
12100302 — MEDINA. TEXAS.
AREA = 1380 SQ.MI.
12100303 — LOWER SAN ANTONIO. TEXAS.
AREA = 1500 SQ.MI.
12100304 — CIBOLO. TEXAS.
AREA = 861 SQ.MI.

ACCOUNTING UNIT 121004 — CENTRAL TEXAS COASTAL: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM THE COLORADO RIVER BASIN BOUNDARY TO ARANSAS PASS AND THE CORPUS CHRISTI BAY DRAINAGE BOUNDARY, EXCLUDING THE GUADALUPE, LAVACA, AND SAN ANTONIO RIVER BASINS. TEXAS.
AREA = 5540 SQ.MI.

CATALOGING UNITS 12100401 — CENTRAL MATAGORDA BAY. TEXAS.
AREA = 1300 SQ.MI.
12100402 — WEST MATAGORDA BAY. TEXAS.
AREA = 922 SQ.MI.
12100403 — EAST SAN ANTONIO BAY. TEXAS.
AREA = 392 SQ.MI.

12100404 — WEST SAN ANTONIO BAY. TEXAS.
AREA = 155 SQ.MI.
12100405 — ARANSAS BAY. TEXAS.
AREA = 855 SQ.MI.
12100406 — MISSION. TEXAS.
AREA = 1050 SQ.MI.
12100407 — ARANSAS. TEXAS.
AREA = 863 SQ.MI.

SUBREGION 1211 — NUECES-SOUTHWESTERN TEXAS COASTAL: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM ARANSAS PASS, INCLUDING THE CORPUS CHRISTI BAY AND NUECES RIVER DRAINAGES, TO THE RIO GRANDE BASIN BOUNDARY. TEXAS.
AREA = 29000 SQ.MI.

ACCOUNTING UNIT 121101 — NUECES: THE NUECES RIVER BASIN. TEXAS.
AREA = 17000 SQ.MI.

CATALOGING UNITS 12110101 — NUECES HEADWATERS. TEXAS.
AREA = 813 SQ.MI.
12110102 — WEST NUECES. TEXAS.
AREA = 911 SQ.MI.
12110103 — UPPER NUECES. TEXAS.
AREA = 1900 SQ.MI.
12110104 — TURKEY. TEXAS.
AREA = 1590 SQ.MI.
12110105 — MIDDLE NUECES. TEXAS.
AREA = 3400 SQ.MI.
12110106 — UPPER FRIO. TEXAS.
AREA = 2390 SQ.MI.
12110107 — HONDO. TEXAS.
AREA = 1100 SQ.MI.
12110108 — LOWER FRIO. TEXAS.
AREA = 1250 SQ.MI.
12110109 — SAN MIGUEL. TEXAS.
AREA = 869 SQ.MI.
12110110 — ATASCOSA. TEXAS.
AREA = 1420 SQ.MI.
12110111 — LOWER NUECES. TEXAS
AREA = 1370

ACCOUNTING UNIT 121102 — SOUTHWESTERN TEXAS COASTAL: THE COASTAL DRAINAGE AND ASSOCIATED WATERS FROM ARANSAS PASS, INCLUDING THE CORPUS CHRISTI BAY DRAINAGE, TO THE RIO GRANDE BASIN BOUNDARY, EXCLUDING THE NUECES RIVER BASIN. TEXAS.
AREA = 12000 SQ.MI.

CATALOGING UNITS 12110201 — NORTH CORPUS CHRISTI BAY. TEXAS.
AREA = 170 SQ.MI.
12110202 — SOUTH CORPUS CHRISTI BAY. TEXAS.
AREA = 451 SQ.MI.
12110203 — NORTH LAGUNA MADRE. TEXAS.
AREA = 229 SQ.MI.
12110204 — SAN FERNANDO. TEXAS.
AREA = 1350 SQ.MI.
12110205 — BAFFIN BAY. TEXAS.
AREA = 2150 SQ.MI.
12110206 — PALO BLANCO. TEXAS.
AREA = 1010 SQ.MI.
12110207 — CENTRAL LAGUNA MADRE. TEXAS.
AREA = 3650 SQ.MI.
12110208 — SOUTH LAGUNA MADRE. TEXAS.
AREA = 2960 SQ.MI.

REGION 13 RIO GRANDE REGION — THE DRAINAGE WITHIN THE UNITED STATES OF: (A) THE RIO GRANDE BASIN, AND (B) THE SAN LUIS VALLEY, NORTH PLAINS, PLAINS OF SAN AGUSTIN, MIMBRES RIVER, ESTANCIA, JORNADA DEL MUERTO, TULAROSA VALLEY, SALT BASIN, AND OTHER CLOSED BASINS. INCLUDES PARTS OF COLORADO, NEW MEXICO, AND TEXAS.

SUBREGION 1301 — RIO GRANDE HEADWATERS: THE RIO GRANDE BASIN FROM ITS HEADWATERS TO THE RIVER'S INTERSECT WITH THE COLORADO-NEW MEXICO STATE LINE, INCLUDING THE SAN LUIS VALLEY CLOSED BASIN. COLORADO, NEW MEXICO.
AREA = 7580 SQ.MI.

ACCOUNTING UNIT 130100 — RIO GRANDE HEADWATERS. COLORADO, NEW MEXICO.
AREA = 7580 SQ.MI.

CATALOGING UNITS 13010001 — RIO GRANDE HEADWATERS. COLORADO.
AREA = 1320 SQ.MI.
13010002 — ALAMOSA-TRINCHERA. COLORADO, NEW MEXICO.
AREA = 2560 SQ.MI.
13010003 — SAN LUIS. COLORADO.
AREA = 1590 SQ.MI.
13010004 — SAGUACHE. COLORADO.
AREA = 1320 SQ.MI.
13010005 — CONEJOS. COLORADO, NEW MEXICO.
AREA = 790 SQ.MI.

SUBREGION 1302 — RIO GRANDE-ELEPHANT BUTTE: THE RIO GRANDE BASIN FROM THE COLORADO-NEW MEXICO STATE LINE TO AND INCLUDING ELEPHANT BUTTE RESERVOIR, AND INCLUDING THE NORTH PLAINS, JORNADA DEL MUERTO, AND PLAINS OF SAN AGUSTIN CLOSED BASINS. COLORADO, NEW MEXICO.
AREA = 26900 SQ.MI.

ACCOUNTING UNIT 130201 — UPPER RIO GRANDE: THE RIO GRANDE BASIN FROM THE COLORADO-NEW MEXICO STATE LINE TO AND INCLUDING THE GUAJE CANYON DRAINAGE BASIN. COLORADO, NEW MEXICO.
AREA = 6370 SQ.MI.

CATALOGING UNITS 13020101 — UPPER RIO GRANDE. COLORADO, NEW MEXICO.
AREA = 3220 SQ.MI.
13020102 — RIO CHAMA. COLORADO, NEW MEXICO.
AREA = 3150 SQ.MI.

ACCOUNTING UNIT 130202 — RIO GRANDE-ELEPHANT BUTTE: THE RIO GRANDE BASIN BELOW THE GUAJE CANYON DRAINAGE BASIN TO AND INCLUDING ELEPHANT BUTTE RESERVOIR, AND INCLUDING THE NORTH PLAINS, JORNADA DEL MUERTO, AND PLAINS OF SAN AGUSTIN CLOSED BASINS. NEW MEXICO.
AREA = 20500 SQ.MI.

CATALOGING UNITS 13020201 — RIO GRANDE-SANTA FE. NEW MEXICO.
AREA = 1830 SQ.MI.
13020202 — JEMEZ. NEW MEXICO.
AREA = 1040 SQ.MI.
13020203 — RIO GRANDE-ALBUQUERQUE. NEW MEXICO.
AREA = 3200 SQ.MI.
13020204 — RIO PUERCO. NEW MEXICO.
AREA = 2090 SQ.MI.
13020205 — ARROYO CHICO. NEW MEXICO.
AREA = 1360 SQ.MI.
13020206 — NORTH PLAINS. NEW MEXICO.
AREA = 1130 SQ.MI.
13020207 — RIO SAN JOSE. NEW MEXICO.
AREA = 2620 SQ.MI.
13020208 — PLAINS OF SAN AGUSTIN. NEW MEXICO.
AREA = 1970 SQ.MI.
13020209 — RIO SALADO. NEW MEXICO.
AREA = 1390 SQ.MI.
13020210 — JORNADA DEL MUERTO. NEW MEXICO.
AREA = 1800 SQ.MI.
13020211 — ELEPHANT BUTTE RESERVOIR. NEW MEXICO.
AREA = 2110 SQ.MI.

SUBREGION 1303 — RIO GRANDE-MIMBRES: THE DRAINAGE WITHIN THE UNITED STATES OF THE RIO GRANDE BASIN FROM ELEPHANT BUTTE RESERVOIR TO THE JUNCTION OF THE MEXICO, NEW MEXICO, AND TEXAS INTERNATIONAL BOUNDARY, AND INCLUDING THE JORNADA DRAW, MIMBRES RIVER, AND OTHER CLOSED BASINS WEST OF THE RIO GRANDE. NEW MEXICO, TEXAS.
AREA = 11100 SQ.MI.

ACCOUNTING UNIT 130301 — RIO GRANDE-CABALLO: THE DRAINAGE WITHIN THE UNITED STATES OF THE RIO GRANDE BASIN FROM ELEPHANT BUTTE RESERVOIR TO THE JUNCTION OF THE MEXICO, NEW MEXICO, AND TEXAS INTERNATIONAL BOUNDARY, AND INCLUDING THE JORNADA DRAW CLOSED BASIN. NEW MEXICO, TEXAS.
AREA = 4890 SQ.MI.

CATALOGING UNITS 13030101 — CABALLO. NEW MEXICO.
AREA = 1230 SQ.MI.
13030102 — EL PASO-LAS CRUCES. NEW MEXICO, TEXAS.
AREA = 2400 SQ.MI.
13030103 — JORNADA DRAW. NEW MEXICO.
AREA = 1260 SQ.MI.

ACCOUNTING UNIT 130302 — MIMBRES: THE DRAINAGE WITHIN THE UNITED STATES OF THE MIMBRES RIVER AND OTHER CLOSED BASINS WEST OF THE RIO GRANDE. NEW MEXICO.
AREA = 6250 SQ.MI.

CATALOGING UNITS 13030201 — PLAYAS LAKE. NEW MEXICO.
AREA = 1690 SQ.MI.
13030202 — MIMBRES. NEW MEXICO.
AREA = 4560 SQ.MI.

SUBREGION 1304 — RIO GRANDE-AMISTAD: THE DRAINAGE WITHIN THE UNITED STATES OF THE RIO GRANDE BASIN FROM THE JUNCTION OF THE MEXICO, NEW MEXICO, AND TEXAS INTERNATIONAL BOUNDARY TO AND INCLUDING AMISTAD RESERVOIR, BUT EXCLUDING THE PECOS RIVER BASIN. TEXAS.
AREA = 18700 SQ.MI.

ACCOUNTING UNIT 130401 — RIO GRANDE-FORT QUITMAN: THE DRAINAGE WITHIN THE UNITED STATES OF THE RIO GRANDE BASIN FROM THE JUNCTION OF THE MEXICO, NEW MEXICO, AND TEXAS INTERNATIONAL BOUNDARY TO THE COMPACT POINT NEAR FORT QUITMAN. TEXAS.
AREA = 1780 SQ.MI.

CATALOGING UNIT 13040100 — RIO GRANDE-FORT QUITMAN. TEXAS.
AREA = 1780 SQ.MI.

ACCOUNTING UNIT 130402 — RIO GRANDE-AMISTAD: THE DRAINAGE WITHIN THE UNITED STATES OF THE RIO GRANDE BASIN FROM THE COMPACT POINT NEAR FORT QUITMAN TO AND INCLUDING AMISTAD RESERVOIR, BUT EXCLUDING THE PECOS AND DEVILS RIVER BASINS. TEXAS.
AREA = 12700 SQ.MI.

CATALOGING UNITS 13040201 — CIBOLO-RED LIGHT. TEXAS.
AREA = 2170 SQ.MI.
13040202 — ALAMITO. TEXAS.
AREA = 1570 SQ.MI.
13040203 — BLACK HILLS-FRESNO. TEXAS.
AREA = 617 SQ.MI.
13040204 — TERLINGUA. TEXAS.
AREA = 1290 SQ.MI.
13040205 — BIG BEND. TEXAS.
AREA = 1100 SQ.MI.
13040206 — MARAVILLAS. TEXAS.
AREA = 1320 SQ.MI.
13040207 — SANTIAGO DRAW. TEXAS.
AREA = 686 SQ.MI.
13040208 — REAGAN-SANDERSON. TEXAS.
AREA = 724 SQ.MI.
13040209 — SAN FRANCISCO. TEXAS.
AREA = 1020 SQ.MI.
13040210 — LOZIER CANYON. TEXAS.
AREA = 926 SQ.MI.
13040211 — BIG CANYON. TEXAS.
AREA = 823 SQ.MI.
13040212 — AMISTAD RESERVOIR. TEXAS.
AREA = 410 SQ.MI.

ACCOUNTING UNIT 130403 — DEVILS: THE DEVILS RIVER BASIN. TEXAS.
AREA = 4270 SQ.MI.

CATALOGING UNITS 13040301 — UPPER DEVILS. TEXAS.
AREA = 2650 SQ.MI.
13040302 — LOWER DEVILS. TEXAS.
AREA = 893 SQ.MI.
13040303 — DRY DEVILS. TEXAS.
AREA = 729 SQ.MI.

SUBREGION 1305 — RIO GRANDE CLOSED BASINS: THE ESTANCIA, TULAROSA VALLEY, SALT BASIN AND OTHER CLOSED BASINS LYING BETWEEN THE RIO GRANDE AND THE PECOS RIVER BASINS. NEW MEXICO, TEXAS.
AREA = 17500 SQ.MI.

ACCOUNTING UNIT 130500 — RIO GRANDE CLOSED BASINS. NEW MEXICO, TEXAS.
AREA = 17500 SQ.MI.

CATALOGING UNITS 13050001 — WESTERN ESTANCIA. NEW MEXICO.
AREA = 2400 SQ.MI.
13050002 — EASTERN ESTANCIA. NEW MEXICO.
AREA = 517 SQ.MI.
13050003 — TULAROSA VALLEY. NEW MEXICO, TEXAS.
AREA = 6720 SQ.MI.
13050004 — SALT BASIN. NEW MEXICO, TEXAS.
AREA = 7900 SQ.MI.

REGION 13: RIO GRANDE — Continued

SUBREGION 1306 — UPPER PECOS: THE PECOS RIVER BASIN TO BUT EXCLUDING THE DELAWARE RIVER BASIN. NEW MEXICO, TEXAS.
AREA = 23500 SQ.MI.

ACCOUNTING UNIT 130600 — UPPER PECOS. NEW MEXICO, TEXAS.
AREA = 23500 SQ.MI.

CATALOGING UNITS 13060001 — PECOS HEADWATERS. NEW MEXICO.
AREA = 3610 SQ.MI.
13060002 — PINTADA ARROYO. NEW MEXICO.
AREA = 884 SQ.MI.
13060003 — UPPER PECOS. NEW MEXICO.
AREA = 4870 SQ.MI.
13060004 — TAIBAN. NEW MEXICO.
AREA = 725 SQ.MI.
13060005 — ARROYO DEL MACHO. NEW MEXICO.
AREA = 1870 SQ.MI.
13060006 — GALLO ARROYO. NEW MEXICO.
AREA = 745 SQ.MI.
13060007 — UPPER PECOS-LONG ARROYO. NEW MEXICO.
AREA = 2700 SQ.MI.
13060008 — RIO HONDO. NEW MEXICO.
AREA = 1680 SQ.MI.
13060009 — RIO FELIX. NEW MEXICO.
AREA = 994 SQ.MI.
13060010 — RIO PENASCO. NEW MEXICO.
AREA = 1080 SQ.MI.
13060011 — UPPER PECOS-BLACK. NEW MEXICO, TEXAS.
AREA = 4360 SQ.MI.

SUBREGION 1307 — LOWER PECOS: THE PECOS RIVER BASIN FROM AND INCLUDING THE DELAWARE RIVER BASIN TO THE CONFLUENCE WITH THE RIO GRANDE. NEW MEXICO, TEXAS.
AREA = 20800 SQ.MI.

ACCOUNTING UNIT 130700 — LOWER PECOS. NEW MEXICO, TEXAS.
AREA = 20800 SQ.MI.

CATALOGING UNITS 13070001 — LOWER PECOS-RED BLUFF RESERVOIR. NEW MEXICO, TEXAS.
AREA = 4430 SQ.MI.
13070002 — DELAWARE. NEW MEXICO, TEXAS.
AREA = 772 SQ.MI.
13070003 — TOYAH. TEXAS.
AREA = 1030 SQ.MI.
13070004 — SALT DRAW. TEXAS.
AREA = 2040 SQ.MI.
13070005 — BARRILLA DRAW. TEXAS.
AREA = 850 SQ.MI.
13070006 — COYANOSA-HACKBERRY DRAWS. TEXAS.
AREA = 1500 SQ.MI.
13070007 — LANDRETH-MONUMENT DRAWS. NEW MEXICO, TEXAS.
AREA = 4270 SQ.MI.
13070008 — LOWER PECOS. TEXAS.
AREA = 2970 SQ.MI.
13070009 — TUNAS. TEXAS.
AREA = 1010 SQ.MI.
13070010 — INDEPENDENCE. TEXAS.
AREA = 765 SQ.MI.
13070011 — HOWARD DRAW. TEXAS.
AREA = 1120 SQ.MI.

SUBREGION 1308 — RIO GRANDE-FALCON: THE DRAINAGE WITHIN THE UNITED STATES OF THE RIO GRANDE BASIN FROM AMISTAD RESERVOIR TO AND INCLUDING FALCON RESERVOIR. TEXAS.
AREA = 5170 SQ.MI.

ACCOUNTING UNIT 130800 — RIO GRANDE-FALCON. TEXAS.
AREA = 5170 SQ.MI.

CATALOGING UNITS 13080001 — ELM-SYCAMORE. TEXAS.
AREA = 1580 SQ.MI.
13080002 — SAN AMBROSIA-SANTA ISABEL. TEXAS.
AREA = 1760 SQ.MI.
13080003 — INTERNATIONAL FALCON RESERVOIR. TEXAS.
AREA = 1830 SQ.MI.

SUBREGION 1309 — LOWER RIO GRANDE: THE DRAINAGE WITHIN THE UNITED STATES OF THE RIO GRANDE BASIN FROM FALCON RESERVOIR TO THE GULF OF MEXICO. TEXAS.
AREA = 1260 SQ.MI.

ACCOUNTING UNIT 130900 — LOWER RIO GRANDE. TEXAS.
AREA = 1260 SQ.MI.

CATALOGING UNITS 13090001 — LOS OLMOS. TEXAS.
AREA = 1170 SQ.MI.
13090002 — LOWER RIO GRANDE. TEXAS.
AREA = 93 SQ.MI.

REGION 14 UPPER COLORADO REGION — THE DRAINAGE OF: (A) THE COLORADO RIVER BASIN ABOVE THE LEE FERRY COMPACT POINT WHICH IS ONE MILE BELOW THE MOUTH OF THE PARIA RIVER; AND (B) THE GREAT DIVIDE CLOSED BASIN. INCLUDES PARTS OF ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING.

SUBREGION 1401 — COLORADO HEADWATERS: THE COLORADO RIVER BASIN TO BUT EXCLUDING THE BITTER CREEK BASIN, AND EXCLUDING THE GUNNISON RIVER BASIN. COLORADO, UTAH.
AREA = 9730 SQ.MI.

ACCOUNTING UNIT 140100 — COLORADO HEADWATERS: COLORADO, UTAH.
AREA = 9730 SQ.MI.

CATALOGING UNITS 14010001 — COLORADO HEADWATERS. COLORADO.
AREA = 2860 SQ.MI.
14010002 — BLUE. COLORADO.
AREA = 675 SQ.MI.
14010003 — EAGLE. COLORADO.
AREA = 963 SQ.MI.
14010004 — ROARING FORK. COLORADO.
AREA = 1440 SQ.MI.
14010005 — COLORADO HEADWATERS-PLATEAU. UTAH.
AREA = 3090 SQ.MI.
14010006 — PARACHUTE-ROAN. COLORADO.
AREA = 698 SQ.MI.

SUBREGION 1402 — GUNNISON: THE GUNNISON RIVER BASIN. COLORADO.
AREA = 7930 SQ.MI.

ACCOUNTING UNIT 140200 — GUNNISON. COLORADO.
AREA = 7930 SQ.MI.

CATALOGING UNITS 14020001 — EAST-TAYLOR. COLORADO.
AREA = 760 SQ.MI.
14020002 — UPPER GUNNISON. COLORADO.
AREA = 2380 SQ.MI.
14020003 — TOMICHI. COLORADO.
AREA = 1090 SQ.MI.
14020004 — NORTH FORK GUNNISON. COLORADO.
AREA = 959 SQ.MI.
14020005 — LOWER GUNNISON. COLORADO.
AREA = 1630 SQ.MI.
14020006 — UNCOMPAHANGE. COLORADO.
AREA = 1110 SQ.MI.

SUBREGION 1403 — UPPER COLORADO-DOLORES: THE COLORADO RIVER BASIN FROM AND INCLUDING THE BITTER CREEK BASIN TO THE CONFLUENCE WITH THE GREEN RIVER BASIN. COLORADO, UTAH.
AREA = 8250 SQ.MI.

ACCOUNTING UNIT 140300 — UPPER COLORADO-DOLORES. COLORADO, UTAH.
AREA = 8250 SQ.MI.

CATALOGING UNITS 14030001 — WESTWATER CANYON. COLORADO, UTAH.
AREA = 1440 SQ.MI.
14030002 — UPPER DOLORES. COLORADO, UTAH.
AREA = 2140 SQ.MI.
14030003 — SAN MIGUEL. COLORADO.
AREA = 1530 SQ.MI.
14030004 — LOWER DOLORES. COLORADO, UTAH.
AREA = 904 SQ.MI.
14030005 — UPPER COLORADO-KANE SPRINGS. COLORADO, UTAH.
AREA = 2240 SQ.MI.

SUBREGION 1404 — GREAT DIVIDE - UPPER GREEN: THE GREEN RIVER BASIN ABOVE THE CONFLUENCE WITH THE YAMPA RIVER BASIN; AND THE GREAT DIVIDE CLOSED BASIN. UTAH, WYOMING.
AREA = 20600 SO.MI.

ACCOUNTING UNIT 140401 — UPPER GREEN: THE GREEN RIVER BASIN ABOVE THE CONFLUENCE WITH THE YAMPA RIVER BASIN. UTAH, WYOMING.
AREA = 16700 SO.MI.

CATALOGING UNITS 14040101 — UPPER GREEN. WYOMING.
AREA = 2930 SQ.MI.
14040102 — NEW FORK. WYOMING.
AREA = 1220 SQ.MI.
14040103 — UPPER GREEN-SLATE. WYOMING.
AREA = 1480 SQ.MI.
14040104 — BIG SANDY. WYOMING.
AREA = 1810 SQ.MI.
14040105 — BITTER. WYOMING.
AREA = 2200 SQ.MI.
14040106 — UPPER GREEN-FLAMING GORGE RESERVOIR. COLORADO. UTAH, WYOMING.
AREA = 2460 SQ.MI.
14040107 — BLACKS FORK. UTAH, WYOMING.
AREA = 2700 SQ.MI.
14040108 — MUDDY. UTAH, WYOMING.
AREA = 968 SQ.MI.
14040109 — VERMILION. COLORADO, WYOMING.
AREA = 961 SQ.MI.

ACCOUNTING UNIT 140402 — GREAT DIVIDE CLOSED BASIN: THE GREAT DIVIDE CLOSED BASIN. WYOMING.
AREA = 3870 SQ.MI.

CATALOGING UNIT 14040200 — GREAT DIVIDE CLOSED BASIN. WYOMING.
AREA = 3870 SQ.MI.

SUBREGION 1405 — WHITE-YAMPA: THE WHITE AND YAMPA RIVER BASINS. COLORADO, UTAH, WYOMING.
AREA = 13100 SQ.MI.

ACCOUNTING UNIT 140500 — WHITE - YAMPA. COLORADO, UTAH, WYOMING.
AREA = 13100 SQ.MI.

CATALOGING UNITS 14050001 — UPPER YAMPA. COLORADO.
AREA = 2590 SQ.MI.
14050002 — LOWER YAMPA. COLORADO.
AREA = 1550 SQ.MI.
14050003 — LITTLE SNAKE. COLORADO, WYOMING.
AREA = 3060 SQ.MI.
14050004 — MUDDY. WYOMING.
AREA = 1010 SQ.MI.
14050005 — UPPER WHITE. COLORADO.
AREA = 1360 SQ.MI.
14050006 — PICEANCE-YELLOW. COLORADO.
AREA = 904 SQ.MI.
14050007 — LOWER WHITE. COLORADO, UTAH.
AREA = 2670 SQ.MI.

SUBREGION 1406 — LOWER GREEN: THE GREEN RIVER BASIN BELOW THE CONFLUENCE WITH THE YAMPA RIVER BASIN,BUT EXCLUDING THE YAMPA AND WHITE RIVER BASINS. COLORADO, UTAH.
AREA = 14400 SQ.MI.

ACCOUNTING UNIT 140600 — LOWER GREEN. COLORADO, UTAH.
AREA = 14400 SQ.MI.

CATALOGING UNITS 14060001 — LOWER GREEN-DIAMOND. COLORADO, UTAH.
AREA = 961 SQ.MI.
14060002 — ASHLEY-BRUSH. UTAH.
AREA = 637 SQ.MI.
14060003 — DUCHESNE. UTAH.
AREA = 2640 SQ.MI.
14060004 — STRAWBERRY. UTAH.
AREA = 1150 SQ.MI.
14060005 — LOWER GREEN-DESOLATION CANYON. UTAH.
AREA = 1910 SQ.MI.
14060006 — WILLOW. UTAH.
AREA = 957 SQ.MI.
14060007 — PRICE. UTAH.
AREA = 1870 SQ.MI.
14060008 — LOWER GREEN. UTAH.
AREA = 1840 SQ.MI.
14060009 — SAN RAFAEL. UTAH.
AREA = 2390 SQ.MI.

SUBREGION 1407 — UPPER COLORADO-DIRTY DEVIL: THE COLORADO RIVER BASIN BELOW THE CONFLUENCE WITH THE GREEN RIVER BASIN TO THE LEE FERRY COMPACT POINT, BUT EXCLUDING THE SAN JUAN RIVER BASIN. ARIZONA, UTAH.
AREA = 13500 SQ.MI.

ACCOUNTING UNIT 140700 — UPPER COLORADO-DIRTY DEVIL. ARIZONA, UTAH.
AREA = 13500 SQ.MI.

CATALOGING UNITS 14070001 — UPPER LAKE POWELL. UTAH.
AREA = 2820 SQ.MI.
14070002 — MUDDY. UTAH.
AREA = 1530 SQ.MI.
14070003 — FREMONT. UTAH.
AREA = 1940 SQ.MI.
14070004 — DIRTY DEVIL. UTAH.
AREA = 839 SQ.MI.
14070005 — ESCALANTE. UTAH.
AREA = 2000 SQ.MI.
14070006 — LOWER LAKE POWELL. ARIZONA, UTAH.
AREA = 2930 SQ.MI.
14070007 — PARIA. ARIZONA, UTAH.
AREA = 1420 SQ.MI.

SUBREGION 1408 — SAN JUAN: THE SAN JUAN RIVER BASIN. ARIZONA, COLORADO, NEW MEXICO, UTAH.
AREA = 24600 SQ.MI.

ACCOUNTING UNIT 140801 — UPPER SAN JUAN: THE SAN JUAN RIVER BASIN TO AND INCLUDING THE MANCOS RIVER BASIN. ARIZONA, COLORADO, NEW MEXICO.
AREA = 14400 SQ.MI.

CATALOGING UNITS 14080101 — UPPER SAN JUAN. COLORADO, NEW MEXICO.
AREA = 3430 SQ.MI.
14080102 — PIEDRA. COLORADO.
AREA = 662 SQ.MI.
14080103 — BLANCO CANYON. NEW MEXICO.
AREA = 1690 SQ.MI.
14080104 — ANIMAS. COLORADO, NEW MEXICO.
AREA = 1370 SQ.MI.

14080105 — MIDDLE SAN JUAN. ARIZONA, COLORADO, NEW MEXICO.
AREA = 1920 SQ.MI.
14080106 — CHACO. ARIZONA, NEW MEXICO.
AREA = 4510 SQ.MI.
14080107 — MANCOS. COLORADO, NEW MEXICO.
AREA = 795 SQ.MI.

ACCOUNTING UNIT 140802 — LOWER SAN JUAN: THE SAN JUAN RIVER BASIN BELOW THE MANCOS RIVER BASIN TO THE CONFLUENCE WITH THE COLORADO RIVER. ARIZONA, COLORADO, NEW MEXICO, UTAH.
AREA = 10300 SQ.MI.

CATALOGING UNITS 14080201 — LOWER SAN JUAN-FOUR CORNERS. ARIZONA, COLORADO, NEW MEXICO, UTAH.
AREA = 2000 SQ.MI.
14080202 — MCELMO. COLORADO, UTAH.
AREA = 702 SQ.MI.
14080203 — MONTEZUMA. COLORADO, UTAH.
AREA = 1160 SQ.MI.
14080204 — CHINLE. ARIZONA, NEW MEXICO, UTAH.
AREA = 4090 SQ.MI.
14080205 — LOWER SAN JUAN. ARIZONA, UTAH.
AREA = 2320 SQ.MI.

REGION 15 LOWER COLORADO REGION—THE DRAINAGE WITHIN THE UNITED STATES OF: (A) THE COLORADO RIVER BASIN BELOW THE LEE FERRY COMPACT POINT WHICH IS ONE MILE BELOW THE MOUTH OF THE PARIA RIVER; (B) STREAMS THAT ORIGINATE WITHIN THE UNITED STATES AND ULTIMATELY DISCHARGE INTO THE GULF OF CALIFORNIA; AND (C) THE ANIMAS VALLEY, WILLCOX PLAYA, AND OTHER SMALLER CLOSED BASINS. INCLUDES PARTS OF ARIZONA, CALIFORNIA, NEVADA, NEW MEXICO, AND UTAH.

SUBREGION 1501 — LOWER COLORADO-LAKE MEAD: THE COLORADO RIVER BASIN FROM THE LEE FERRY COMPACT POINT TO HOOVER DAM, BUT EXCLUDING THE LITTLE COLORADO RIVER BASIN. ARIZONA, NEVADA, UTAH.
AREA = 29900 SQ.MI.

ACCOUNTING UNIT 150100 — LOWER COLORADO-LAKE MEAD: ARIZONA, NEVADA, UTAH.
AREA = 29900 SQ.MI.

CATALOGING UNITS 15010001 — LOWER COLORADO-MARBLE CANYON. ARIZONA.
AREA = 1430 SQ.MI.
15010002 — GRAND CANYON. ARIZONA.
AREA = 2530 SQ.MI.
15010003 — KANAB. ARIZONA, UTAH.
AREA = 2350 SQ.MI.
15010004 — HAVASU CANYON. ARIZONA.
AREA = 2920 SQ.MI.
15010005 — LAKE MEAD. ARIZONA, NEVADA.
AREA = 2710 SQ.MI.
15010006 — GRAND WASH. ARIZONA, NEVADA.
AREA = 922 SQ.MI.
15010007 — HUALAPAI WASH. ARIZONA.
AREA = 1540 SQ.MI.
15010008 — UPPER VIRGIN. UTAH.
AREA = 2130 SQ.MI.
15010009 — FORT PIERCE WASH. ARIZONA, UTAH.
AREA = 1690 SQ.MI.
15010010 — LOWER VIRGIN. ARIZONA, NEVADA, UTAH.
AREA = 2070 SQ.MI.
15010011 — WHITE. NEVADA.
AREA = 2840 SQ.MI.
15010012 — MUDDY. NEVADA.
AREA = 1750 SQ.MI.
15010013 — MEADOW VALLEY WASH. NEVADA, UTAH.
AREA = 2540 SQ.MI.
15010014 — DETRITAL WASH. ARIZONA.
AREA = 650 SQ.MI.
15010015 — LAS VEGAS WASH. NEVADA.
AREA = 1860 SQ.MI.

SUBREGION 1502 — LITTLE COLORADO: THE LITTLE COLORADO RIVER BASIN. ARIZONA, NEW MEXICO.
AREA = 26900 SQ.MI.

ACCOUNTING UNIT 150200 — LITTLE COLORADO. ARIZONA, NEW MEXICO.
AREA = 26900 SQ.MI.

CATALOGING UNITS 15020001 — LITTLE COLORADO HEADWATERS. ARIZONA, NEW MEXICO.
AREA = 783 SQ.MI.
15020002 — UPPER LITTLE COLORADO. ARIZONA, NEW MEXICO.
AREA = 1590 SQ.MI.
15020003 — CARRIZO WASH. ARIZONA, NEW MEXICO.
AREA = 2210 SQ.MI.
15020004 — ZUNI. ARIZONA, NEW MEXICO.
AREA = 2730 SQ.MI.
15020005 — SILVER. ARIZONA.
AREA = 934 SQ.MI.
15020006 — UPPER PEURCO. ARIZONA, NEW MEXICO.
AREA = 1890 SQ.MI.
15020007 — LOWER PEURCO. ARIZONA.
AREA = 1100 SQ.MI.
15020008 — MIDDLE LITTLE COLORADO. ARIZONA.
AREA = 2450 SQ.MI.
15020009 — LEROUX WASH. ARIZONA.
AREA = 801 SQ.MI.
15020010 — CHEVELON CANYON. ARIZONA.
AREA = 839 SQ.MI.
15020011 — COTTONWOOD WASH. ARIZONA.
AREA = 1610 SQ.MI.
15020012 — CORN-ORAIBI. ARIZONA.
AREA = 864 SQ.MI.
15020013 — POLACCA WASH. ARIZONA.
AREA = 1070 SQ.MI.
15020014 — JADITO WASH. ARIZONA.
AREA = 1050 SQ.MI.
15020015 — CANYON DIABLO. ARIZONA.
AREA = 1200 SQ.MI.
15020016 — LOWER LITTLE COLORADO. ARIZONA.
AREA = 2390 SQ.MI.
15020017 — DINNEBITO WASH. ARIZONA.
AREA = 737 SQ.MI.
15020018 — MOENKOPI WASH. ARIZONA.
AREA = 2640 SQ.MI.

SUBREGION 1503 — LOWER COLORADO: THE COLORADO RIVER BASIN WITHIN THE UNITED STATES BELOW HOOVER DAM, EXCLUDING THE GILA RIVER BASIN. ARIZONA, CALIFORNIA, NEVADA.
AREA = 17000 SQ.MI.

ACCOUNTING UNIT 150301 — LOWER COLORADO: THE COLORADO RIVER BASIN WITHIN THE UNITED STATES BELOW HOOVER DAM, EXCLUDING THE GILA AND BILL WILLIAMS RIVER BASINS. ARIZONA, CALIFORNIA, NEVADA.
AREA = 11600 SQ.MI.

CATALOGING UNITS 15030101 — HAVASU-MOHAVE LAKES. ARIZONA, CALIFORNIA, NEVADA.
AREA = 2740 SQ.MI.
15030102 — PIUTE WASH. CALIFORNIA, NEVADA.
AREA = 1030 SQ.MI.
15030103 — SACRAMENTO WASH. ARIZONA.
AREA = 1290 SQ.MI.
15030104 — IMPERIAL RESERVOIR. ARIZONA, CALIFORNIA.
AREA = 3320 SQ.MI.
15030105 — BOUSE WASH. ARIZONA.
AREA = 1630 SQ.MI.
15030106 — TYSON WASH. ARIZONA.
AREA = 717 SQ.MI.
15030107 — LOWER COLORADO. ARIZONA, CALIFORNIA.
AREA = 267 SQ.MI.
15030108 — YUMA DESERT. ARIZONA.
AREA = 626 SQ.MI.

ACCOUNTING UNIT 150302 — BILL WILLIAMS: THE BILL WILLIAMS RIVER BASIN. ARIZONA.
AREA = 5370 SQ.MI.

CATALOGING UNITS 15030201 — BIG SANDY. ARIZONA.
AREA = 2120 SQ.MI.
15030202 — BURRO. ARIZONA.
AREA = 708 SQ.MI.
15030203 — SANTA MARIA. ARIZONA.
AREA = 1440 SQ.MI.
15030204 — BILL WILLIAMS. ARIZONA.
AREA = 1100 SQ.MI.

SUBREGION 1504 — UPPER GILA: THE GILA RIVER BASIN ABOVE COOLIDGE DAM, INCLUDING THE ANIMAS VALLEY CLOSED BASIN. ARIZONA, NEW MEXICO.
AREA = 15100 SQ.MI.

ACCOUNTING UNIT 150400 — UPPER GILA. ARIZONA, NEW MEXICO.
AREA = 15100 SQ.MI.

CATALOGING UNITS 15040001 — UPPER GILA. NEW MEXICO.
AREA = 2000 SQ.MI.
15040002 — UPPER GILA-MANGAS. ARIZONA, NEW MEXICO.
AREA = 2030 SQ.MI.
15040003 — ANIMAS VALLEY. ARIZONA, NEW MEXICO.
AREA = 2250 SQ.MI.
15040004 — SAN FRANCISCO. ARIZONA, NEW MEXICO.
AREA = 2740 SQ.MI.
15040005 — UPPER GILA-SAN CARLOS RESERVOIR. ARIZONA.
AREA = 2820 SQ.MI.
15040006 — SAN SIMON. ARIZONA, NEW MEXICO.
AREA = 2230 SQ.MI.
15040007 — SAN CARLOS. ARIZONA.
AREA = 1070 SQ.MI.

SUBREGION 1505 — MIDDLE GILA: THE GILA RIVER BASIN WITHIN THE UNITED STATES FROM COOLIDGE DAM TO THE CONFLUENCE WITH THE SALT RIVER BASIN, INCLUDING THE WILLCOX CLOSED BASIN. ARIZONA.
AREA = 16900 SQ.MI.

ACCOUNTING UNIT 150501 — MIDDLE GILA: THE GILA RIVER BASIN FROM COOLIDGE DAM TO THE CONFLUENCE WITH THE SALT RIVER BASIN, EXCLUDING THE SANTA CRUZ AND SAN PEDRO RIVER BASINS AND THE WILLCOX CLOSED BASIN. ARIZONA.
AREA = 3310 SQ.MI.

CATALOGING UNIT 15050100 — MIDDLE GILA. ARIZONA.
AREA = 3310 SQ.MI.

ACCOUNTING UNIT 150502 — SAN PEDRO-WILLCOX: THE SAN PEDRO RIVER BASIN WITHIN THE UNITED STATES AND THE WILLCOX CLOSED BASIN. ARIZONA.
AREA = 5440 SQ.MI.

CATALOGING UNITS 15050201 — WILLCOX PLAYA. ARIZONA.
AREA = 1680 SQ.MI.
15050202 — UPPER SAN PEDRO. ARIZONA.
AREA = 1780 SQ.MI.
15050203 — LOWER SAN PEDRO. ARIZONA.
AREA = 1980 SQ.MI.

ACCOUNTING UNIT 150503 — SANTA CRUZ: THE SANTA CRUZ RIVER BASIN WITHIN THE UNITED STATES. ARIZONA.
AREA = 8190 SQ.MI.

CATALOGING UNITS 15050301 — UPPER SANTA CRUZ. ARIZONA.
AREA = 2210 SQ.MI.

15050302 — RILLITO. ARIZONA.
AREA = 928 SQ.MI.
15050303 — LOWER SANTA CRUZ. ARIZONA.
AREA = 1580 SQ.MI.
15050304 — BRAWLEY WASH. ARIZONA.
AREA = 1390 SQ.MI.
15050305 — AGUIRRE VALLEY. ARIZONA.
AREA = 790 SQ.MI.
15050306 — SANTA ROSA WASH. ARIZONA.
AREA = 1290 SQ.MI.

SUBREGION 1506 — SALT: THE SALT RIVER BASIN. ARIZONA.
AREA = 13700 SQ.MI.

ACCOUNTING UNIT 150601 — SALT: THE SALT RIVER BASIN, EXCLUDING THE VERDE RIVER BASIN. ARIZONA.
AREA = 7120 SQ.MI.

CATALOGING UNITS 15060101 — BLACK. ARIZONA.
AREA = 1240 SQ.MI.
15060102 — WHITE. ARIZONA.
AREA = 656 SQ.MI.
15060103 — UPPER SALT. ARIZONA.
AREA = 2160 SQ.MI.
15060104 — CARRIZO. ARIZONA.
AREA = 695 SQ.MI.
15060105 — TONTO. ARIZONA.
AREA = 1030 SQ.MI.
15060106 — LOWER SALT. ARIZONA.
AREA = 1340 SQ.MI.

ACCOUNTING UNIT 150602 — VERDE: THE VERDE RIVER BASIN. ARIZONA.
AREA = 6590 SQ.MI.

CATALOGING UNITS 15060201 — BIG CHINO-WILLIAMSON VALLEY. ARIZONA.
AREA = 2170 SQ.MI.
15060202 — UPPER VERDE. ARIZONA.
AREA = 2480 SQ.MI.
15060203 — LOWER VERDE. ARIZONA.
AREA = 1940 SQ.MI.

SUBREGION 1507 — LOWER GILA: THE GILA RIVER BASIN BELOW THE CONFLUENCE WITH THE SALT RIVER BASIN TO THE CONFLUENCE WITH THE COLORADO RIVER. ARIZONA.
AREA = 14800 SQ.MI.

ACCOUNTING UNIT 150701 — LOWER GILA-AGUA FRIA: THE GILA RIVER BASIN BELOW THE CONFLUENCE WITH THE SALT RIVER BASIN TO PAINTED ROCK DAM. ARIZONA.
AREA = 7860 SQ.MI.

CATALOGING UNITS 15070101 — LOWER GILA-PAINTED ROCK RESERVOIR. ARIZONA.
AREA = 2090 SQ.MI.
15070102 — AGUA FRIA. ARIZONA.
AREA = 2420 SQ.MI.
15070103 — HASSAYAMPA. ARIZONA.
AREA = 1410 SQ.MI.
15070104 — CENTENNIAL WASH. ARIZONA.
AREA = 1940 SQ.MI.

ACCOUNTING UNIT 150702 — LOWER GILA: THE GILA RIVER BASIN BELOW PAINTED ROCK DAM. ARIZONA.
AREA = 6960 SQ.MI.

CATALOGING UNITS 15070201 — LOWER GILA. ARIZONA.
AREA = 4170 SQ.MI.
15070202 — TENMILE WASH. ARIZONA.
AREA = 1220 SQ.MI.
15070203 — SAN CRISTOBAL WASH. ARIZONA.
AREA = 1570 SQ.MI.

SUBREGION 1508 — SONORA: THE DRAINAGE THAT ORIGINATES WITHIN THE UNITED STATES EAST OF THE COLORADO RIVER BASIN AND ULTIMATELY DISCHARGES INTO THE GULF OF CALIFORNIA. ARIZONA, NEW MEXICO.
AREA = 4830 SQ.MI.

ACCOUNTING UNIT 150801 — RIO SONOYTA: THE DRAINAGE WITHIN THE UNITED STATES OF THE RIO SONOYTA BASIN. ARIZONA.
AREA = 2960 SQ.MI.

CATALOGING UNITS 15080101 — SAN SIMON WASH. ARIZONA.
AREA = 2130 SQ.MI.
15080102 — RIO SONOYTA. ARIZONA.
AREA = 420 SQ.MI.
15080103 — TULE DESERT. ARIZONA.
AREA = 412 SQ.MI.

ACCOUNTING UNIT 150802 — RIO DE LA CONCEPCION: THE DRAINAGE WITHIN THE UNITED STATES OF THE RIO DE LA CONCEPCION BASIN. ARIZONA.
AREA = 125 SQ.MI.

CATALOGING UNIT 15080200 — RIO DE LA CONCEPCION. ARIZONA.
AREA = 125 SQ.MI.

ACCOUNTING UNIT 150803 — RIO DE BAVISPE: THE DRAINAGE WITHIN THE UNITED STATES OF THE RIO DE BAVISPE BASIN. ARIZONA, NEW MEXICO.
AREA = 1740 SQ.MI.

CATALOGING UNITS 15080301 — WHITEWATER DRAW. ARIZONA.
AREA = 1180 SQ.MI.
15080302 — SAN BERNARDINO VALLEY. ARIZONA, NEW MEXICO.
AREA = 416 SQ.MI.
15080303 — CLOVERDALE. NEW MEXICO.
AREA = 145 SQ.MI.

REGION 16 GREAT BASIN REGION — THE DRAINAGE OF THE GREAT BASIN THAT DISCHARGES INTO THE STATES OF UTAH AND NEVADA. INCLUDES PARTS OF CALIFORNIA, IDAHO, NEVADA, OREGON, UTAH, AND WYOMING.

SUBREGION 1601 — BEAR: THE BEAR RIVER BASIN. IDAHO, UTAH, WYOMING.
AREA = 7310 SQ.MI.

ACCOUNTING UNIT 160101 — UPPER BEAR: THE BEAR RIVER BASIN ABOVE STEWART DAM. IDAHO, UTAH, WYOMING.
AREA = 2800 SQ.MI.

CATALOGING UNITS 16010101 — UPPER BEAR. UTAH, WYOMING.
AREA = 1970 SQ.MI.
16010102 — CENTRAL BEAR. IDAHO, UTAH, WYOMING.
AREA = 834 SQ.MI.

ACCOUNTING UNIT 160102 — LOWER BEAR: THE BEAR RIVER BASIN BELOW STEWART DAM. IDAHO, UTAH.
AREA = 4510 SQ.MI.

CATALOGING UNITS 16010201 — BEAR LAKE. IDAHO, UTAH.
AREA = 1220 SQ.MI.
16010202 — MIDDLE BEAR. IDAHO, UTAH.
AREA = 1210 SQ.MI.
16010203 — LITTLE BEAR-LOGAN. IDAHO, UTAH.
AREA = 928 SQ.MI.
16010204 — LOWER BEAR-MALAD. IDAHO, UTAH.
AREA = 1150 SQ.MI.

SUBREGION 1602 — GREAT SALT LAKE: THE GREAT SALT LAKE BASIN EXCLUDING THE BEAR RIVER BASIN. IDAHO, NEVADA, UTAH, WYOMING.
AREA = 28700 SQ.MI.

ACCOUNTING UNIT 160201 — WEBER: THE WEBER RIVER BASIN. UTAH, WYOMING.
AREA = 2430 SQ.MI.

CATALOGING UNITS 16020101 — UPPER WEBER. UTAH, WYOMING.
AREA = 1170 SQ.MI.
16020102 — LOWER WEBER. UTAH.
AREA = 1260 SQ.MI.

ACCOUNTING UNIT 160202 — JORDAN: THE JORDAN RIVER BASIN. UTAH.
AREA = 3830 SQ.MI.

CATALOGING UNITS 16020201 — UTAH LAKE. UTAH.
AREA = 1340 SQ.MI.
16020202 — SPANISH FORK. UTAH.
AREA = 993 SQ.MI.
16020203 — PROVO. UTAH.
AREA = 710 SQ.MI.
16020204 — JORDAN. UTAH.
AREA = 791 SQ.MI.

ACCOUNTING UNIT 160203 — GREAT SALT LAKE: THE GREAT SALT LAKE BASIN, EXCLUDING THE BEAR, WEBER, AND JORDAN RIVER BASINS. IDAHO, NEVADA, UTAH.
AREA = 22400 SQ.MI.

CATALOGING UNITS 16020301 — HAMLIN-SNAKE VALLEYS. NEVADA, UTAH.
AREA = 3100 SQ.MI.
16020302 — PINE VALLEY. UTAH.
AREA = 732 SQ.MI.
16020303 — TULE VALLEY. UTAH.
AREA = 928 SQ.MI.
16020304 — RUSH-TOOELE VALLEYS. UTAH.
AREA = 1180 SQ.MI.
16020305 — SKULL VALLEY. UTAH.
AREA = 798 SQ.MI.
16020306 — SOUTHERN GREAT SALT LAKE DESERT. NEVADA, UTAH.
AREA = 5420 SQ.MI.
16020307 — PILOT-THOUSAND SPRINGS, NEVADA, UTAH.
AREA = 1780 SQ.MI.
16020308 — NORTHERN GREAT SALT LAKE DESERT. NEVADA, UTAH.
AREA = 4650 SQ.MI.
16020309 — CURLEW VALLEY. IDAHO, UTAH.
AREA = 1930 SQ.MI.
16020310 — GREAT SALT LAKE. UTAH.
AREA = 1880 SQ.MI.

SUBREGION 1603 — ESCALANTE DESERT-SEVIER LAKE: THE ESCALANTE DESERT AND THE SEVIER LAKE CLOSED BASINS. NEVADA, UTAH.
AREA = 16200 SQ.MI.

ACCOUNTING UNIT 160300 — ESCALANTE DESERT-SEVIER LAKE: NEVADA, UTAH.
AREA = 16200 SQ.MI.

CATALOGING UNITS 16030001 — UPPER SEVIER. UTAH.
AREA = 1180 SQ.MI.
16030002 — EAST FORK SEVIER. UTAH.
AREA = 1250 SQ.MI.
16030003 — MIDDLE SEVIER. UTAH.
AREA = 1850 SQ.MI.

16030004 — SAN PITCH. UTAH.
AREA = 858 SQ.MI.
16030005 — LOWER SEVIER. UTAH.
AREA = 3970 SQ.MI.
16030006 — ESCALANTE DESERT. NEVADA, UTAH.
AREA = 3270 SQ.MI.
16030007 — BEAVER BOTTOMS-UPPER BEAVER. UTAH.
AREA = 1720 SQ.MI.
16030008 — LOWER BEAVER. UTAH.
AREA = 746 SQ.MI.
16030009 — SEVIER LAKE. UTAH.
AREA = 1330 SQ.MI.

SUBREGION 1604 — BLACK ROCK DESERT-HUMBOLDT: THE HUMBOLDT RIVER BASIN, THE BLACK ROCK DESERT, AND OTHER CLOSED BASINS THAT DISCHARGE INTO NORTHWESTERN NEVADA. CALIFORNIA, NEVADA, OREGON.
AREA = 28300 SQ.MI.

ACCOUNTING UNIT 160401 — HUMBOLDT: THE HUMBOLDT RIVER BASIN. NEVADA.
AREA = 16700 SQ.MI.

CATALOGING UNITS 16040101 — UPPER HUMBOLDT. NEVADA.
AREA = 2720 SQ.MI.
16040102 — NORTH FORK HUMBOLDT. NEVADA.
AREA = 988 SQ.MI.
16040103 — SOUTH FORK HUMBOLDT. NEVADA.
AREA = 1270 SQ.MI.
16040104 — PINE. NEVADA.
AREA = 985 SQ.MI.
16040105 — MIDDLE HUMBOLDT. NEVADA.
AREA = 3180 SQ.MI.
16040106 — ROCK. NEVADA.
AREA = 888 SQ.MI.
16040107 — REESE. NEVADA.
AREA = 2310 SQ.MI.
16040108 — LOWER HUMBOLDT. NEVADA.
AREA = 2590 SQ.MI.
16040109 — LITTLE HUMBOLDT. NEVADA.
AREA = 1740 SQ.MI.

ACCOUNTING UNIT 160402 — BLACK ROCK DESERT: THE BLACK ROCK DESERT AND OTHER CLOSED BASINS THAT DISCHARGE INTO NORTHWESTERN NEVADA. CALIFORNIA, NEVADA, OREGON.
AREA = 11600 SQ.MI.

CATALOGING UNITS 16040201 — UPPER QUINN. NEVADA, OREGON.
AREA = 3480 SQ.MI.
16040202 — LOWER QUINN. NEVADA.
AREA = 3230 SQ.MI.
16040203 — SMOKE CREEK DESERT. CALIFORNIA, NEVADA.
AREA = 2430 SQ.MI.
16040204 — MASSACRE LAKE. CALIFORNIA, NEVADA.
AREA = 1300 SQ.MI.
16040205 — THOUSAND-VIRGIN. NEVADA, OREGON.
AREA = 1150 SQ.MI.

SUBREGION 1605 — CENTRAL LAHONTAN: THE CENTRAL LAHONTAN BASIN CONSISTING OF THE CARSON, TRUCKEE, AND WALKER RIVER BASINS. CALIFORNIA, NEVADA.
AREA = 12500 SQ.MI.

ACCOUNTING UNIT 160501 — TRUCKEE: THE TRUCKEE RIVER BASIN. CALIFORNIA, NEVADA.
AREA = 4710 SQ.MI.

CATALOGING UNITS 16050101 — LAKE TAHOE. CALIFORNIA, NEVADA.
AREA = 505 SQ.MI.
16050102 — TRUCKEE. CALIFORNIA, NEVADA.
AREA = 1190 SQ.MI.
16050103 — PYRAMID-WINNEMUCCA LAKES. NEVADA.
AREA = 1370 SQ.MI.
16050104 — GRANITE SPRINGS VALLEY. NEVADA.
AREA = 1640 SQ.MI.

ACCOUNTING UNIT 160502 — CARSON: THE CARSON RIVER BASIN. CALIFORNIA, NEVADA.
AREA = 3930 SQ.MI.

CATALOGING UNITS 16050201 — UPPER CARSON. CALIFORNIA, NEVADA.
AREA = 934 SQ.MI.
16050202 — MIDDLE CARSON. NEVADA.
AREA = 843 SQ.MI.
16050203 — CARSON DESERT. NEVADA.
AREA = 2150 SQ.MI.

ACCOUNTING UNIT 160503 — WALKER: THE WALKER RIVER BASIN. CALIFORNIA, NEVADA.
AREA = 3920 SQ.MI.

CATALOGING UNITS 16050301 — EAST WALKER. CALIFORNIA, NEVADA.
AREA = 1080 SQ.MI.

REGION 16: GREAT BASIN — Continued

16050302 — WEST WALKER. CALIFORNIA, NEVADA.
AREA = 992 SQ.MI.
16050303 — WALKER. NEVADA.
AREA = 1010 SQ.MI.
16050304 — WALKER LAKE. NEVADA.
AREA = 835 SQ.MI.

SUBREGION 1606 — CENTRAL NEVADA DESERT BASINS: THE CLOSED DESERT BASINS THAT DISCHARGE INTO SOUTH CENTRAL NEVADA. CALIFORNIA, NEVADA.
AREA = 47100 SQ.MI.

ACCOUNTING UNIT 160600 — CENTRAL NEVADA DESERT BASINS: CALIFORNIA, NEVADA.
AREA = 47100 SQ.MI.

CATALOGING UNITS 16060001 — DIXIE VALLEY. NEVADA.
AREA = 3990 SQ.MI.
16060002 — GABBS VALLEY. NEVADA.
AREA = 2060 SQ.MI.
16060003 — SOUTHERN BIG SMOKY VALLEY. NEVADA.
AREA = 2030 SQ.MI.
16060004 — NORTHERN BIG SMOKY VALLEY. NEVADA.
AREA = 1890 SQ.MI.
16060005 — DIAMOND-MONITOR VALLEYS. NEVADA.
AREA = 3070 SQ.MI.
16060006 — LITTLE SMOKY-NEWARK VALLEYS. NEVADA.
AREA = 1430 SQ.MI.
16060007 — LONG-RUBY VALLEYS. NEVADA.
AREA = 4060 SQ.MI.
16060008 — SPRING-STEPTOE VALLEYS. NEVADA.
AREA = 5240 SQ.MI.
16060009 — DRY LAKE VALLEY. NEVADA.
AREA = 2160 SQ.MI.
16060010 — FISH LAKE-SODA SPRING VALLEYS. CALIFORNIA, NEVADA.
AREA = 2720 SQ.MI.
16060011 — RALSTON-STONE CABIN VALLEYS. NEVADA.
AREA = 3190 SQ.MI.
16060012 — HOT CREEK-RAILROAD VALLEYS. NEVADA.
AREA = 4660 SQ.MI.
16060013 — CACTUS-SARCOBATUS FLATS. NEVADA.
AREA = 2720 SQ.MI.
16060014 — SAND SPRING-TIKABOO VALLEYS. NEVADA.
AREA = 5070 SQ.MI.
16060015 — IVANPAH-PAHRUMP VALLEYS. CALIFORNIA, NEVADA.
AREA = 2830 SQ.MI.

REGION 17 PACIFIC NORTHWEST REGION — THE DRAINAGE WITHIN THE UNITED STATES THAT ULTIMATELY DISCHARGES INTO: (A) THE STRAITS OF GEORGIA AND OF JUAN DE FUCA, AND (B) THE PACIFIC OCEAN WITHIN THE STATES OF OREGON AND WASHINGTON; AND THAT PART OF THE GREAT BASIN WHOSE DISCHARGE IS INTO THE STATE OF OREGON. INCLUDES ALL OF WASHINGTON AND PARTS OF CALIFORNIA, IDAHO, MONTANA, NEVADA, OREGON, UTAH, AND WYOMING.

SUBREGION 1701 — KOOTENAI-PEND OREILLE-SPOKANE: THE KOOTENAI, PEND OREILLE, AND SPOKANE RIVER BASINS WITHIN THE UNITED STATES. IDAHO, MONTANA, AND WASHINGTON.
AREA = 36600 SQ.MI.

ACCOUNTING UNIT 170101 — KOOTENAI: THE KOOTENAI RIVER BASIN WITHIN THE UNITED STATES. IDAHO, MONTANA.
AREA = 4850 SQ.MI.

CATALOGING UNITS
17010101 — UPPER KOOTENAI. IDAHO, MONTANA. AREA = 2290 SQ.MI.
17010102 — FISHER. MONTANA. AREA = 843 SQ.MI.
17010103 — YAAK. MONTANA. AREA = 630 SQ.MI.
17010104 — LOWER KOOTENAI. IDAHO, MONTANA. AREA = 887 SQ.MI.
17010105 — MOYIE. IDAHO, MONTANA. AREA = 203 SQ.MI.

ACCOUNTING UNIT 170102 — PEND OREILLE: THE PEND OREILLE RIVER BASIN WITHIN THE UNITED STATES. IDAHO, MONTANA, AND WASHINGTON.
AREA = 25100 SQ.MI.

CATALOGING UNITS
17010201 — UPPER CLARK FORK. MONTANA. AREA = 2320 SQ.MI.
17010202 — FLINT-ROCK. MONTANA. AREA = 1400 SQ.MI.
17010203 — BLACKFOOT. MONTANA. AREA = 2340 SQ.MI.
17010204 — MIDDLE CLARK FORK. MONTANA. AREA = 1970 SQ.MI.
17010205 — BITTERROOT. MONTANA. AREA = 2860 SQ.MI.
17010206 — NORTH FORK FLATHEAD. MONTANA. AREA = 967 SQ.MI.
17010207 — MIDDLE FORK FLATHEAD. MONTANA. AREA = 1160 SQ.MI.
17010208 — FLATHEAD LAKE. MONTANA. AREA = 1160 SQ.MI.
17010209 — SOUTH FORK FLATHEAD. MONTANA. AREA = 1690 SQ.MI.
17010210 — STILLWATER. MONTANA. AREA = 830 SQ.MI.
17010211 — SWAN. MONTANA. AREA = 748 SQ.MI.
17010212 — LOWER FLATHEAD. MONTANA. AREA = 2010 SQ.MI.
17010213 — LOWER CLARK FORK. IDAHO, MONTANA. AREA = 2330 SQ.MI.
17010214 — PEND OREILLE LAKE. IDAHO, WASHINGTON. AREA = 1240 SQ.MI.
17010215 — PRIEST. IDAHO, WASHINGTON. AREA = 983 SQ.MI.
17010216 — PEND OREILLE. IDAHO, WASHINGTON. AREA = 1080 SQ.MI.

ACCOUNTING UNIT 170103 — SPOKANE: THE SPOKANE RIVER BASIN. IDAHO, WASHINGTON.
AREA = 6680 SQ.MI.

CATALOGING UNITS
17010301 — UPPER COEUR D'ALENE. IDAHO AREA = 905 SQ.MI.
17010302 — SOUTH FORK COEUR D'ALENE. IDAHO. AREA = 297 SQ.MI.
17010303 — COEUR D'ALENE LAKE. IDAHO, WASHINGTON. AREA = 663 SQ.MI.
17010304 — ST. JOE. IDAHO. AREA = 1860 SQ.MI.
17010305 — UPPER SPOKANE. IDAHO, WASHINGTON. AREA = 609 SQ.MI.
17010306 — HANGMAN. IDAHO, WASHINGTON. AREA = 714 SQ.MI.
17010307 — LOWER SPOKANE. WASHINGTON. AREA = 904 SQ.MI.
17010308 — LITTLE SPOKANE. IDAHO, WASHINGTON. AREA = 723 SQ.MI.

SUBREGION 1702 — UPPER COLUMBIA: THE COLUMBIA RIVER BASIN WITHIN THE THE UNITED STATES ABOVE THE CONFLUENCE WITH THE SNAKE RIVER BASIN, EXCLUDING THE YAKIMA RIVER BASIN. WASHINGTON.
AREA = 22600 SQ.MI.

ACCOUNTING UNIT 170200 — UPPER COLUMBIA. WASHINGTON.
AREA = 22600 SQ.MI.

CATALOGING UNITS
17020001 — FRANKLIN D. ROOSEVELT LAKE. WASHINGTON. AREA = 2170 SQ.MI.
17020002 — KETTLE. WASHINGTON. AREA = 966 SQ.MI.

17020003 — COLVILLE. WASHINGTON. AREA = 1030 SQ.MI.
17020004 — SANPOIL. WASHINGTON. AREA = 1080 SQ.MI.
17020005 — CHIEF JOSEPH. WASHINGTON. AREA = 1390 SQ.MI.
17020006 — OKANOGAN. WASHINGTON. AREA = 1640 SQ.MI.
17020007 — SIMILKAMEEN. WASHINGTON. AREA = 671 SQ.MI.
17020008 — METHOW. WASHINGTON. AREA = 1820 SQ.MI.
17020009 — LAKE CHELAN. WASHINGTON. AREA = 955 SQ.MI.
17020010 — UPPER COLUMBIA-ENTIAT. WASHINGTON. AREA = 1520 SQ.MI.
17020011 — WENATCHEE. WASHINGTON. AREA = 1350 SQ.MI.
17020012 — MOSES COULEE. WASHINGTON. AREA = 926 SQ.MI.
17020013 — UPPER CRAB. WASHINGTON. AREA = 1860 SQ.MI.
17020014 — BANKS LAKE. WASHINGTON. AREA = 609 SQ.MI.
17020015 — LOWER CRAB. WASHINGTON. AREA = 2510 SQ.MI.
17020016 — UPPER COLUMBIA-PRIEST RAPIDS. WASHINGTON. AREA = 2070 SQ.MI.

SUBREGION 1703 — YAKIMA. THE YAKIMA RIVER BASIN. WASHINGTON.
AREA = 6210 SQ.MI.

ACCOUNTING UNIT 170300 — YAKIMA. WASHINGTON.
AREA = 6210 SQ.MI.

CATALOGING UNITS
17030001 — UPPER YAKIMA. WASHINGTON. AREA = 2130 SQ.MI.
17030002 — NACHES. WASHINGTON. AREA = 1130 SQ.MI.
17030003 — LOWER YAKIMA, WASHINGTON. AREA = 2950 SQ.MI.

SUBREGION 1704 — UPPER SNAKE: THE SNAKE RIVER BASIN TO AND INCLUDING THE CLOVER CREEK BASIN. IDAHO, NEVADA, UTAH, WYOMING.
AREA = 35600 SQ.MI.

ACCOUNTING UNIT 170401 — SNAKE HEADWATERS: THE SNAKE RIVER BASIN ABOVE KELLY MOUNTAIN. IDAHO, WYOMING.
AREA = 5690 SQ.MI.

CATALOGING UNITS
17040101 — SNAKE HEADWATERS. WYOMING. AREA = 1680 SQ.MI.
17040102 — GROS VENTRE. WYOMING. AREA = 638 SQ.MI.
17040103 — GREYS-HOBOCK. WYOMING. AREA = 1570 SQ.MI.
17040104 — PALISADES. IDAHO, WYOMING. AREA = 915 SQ.MI.
17040105 — SALT. IDAHO, WYOMING. AREA = 887 SQ.MI.

ACCOUNTING UNIT 170402 — UPPER SNAKE: THE SNAKE RIVER BASIN FROM KELLY MOUNTAIN TO AND INCLUDING THE CLOVER CREEK BASIN. IDAHO, NEVADA, UTAH, WYOMING.
AREA = 29900 SQ.MI.

CATALOGING UNITS
17040201 — IDAHO FALLS. IDAHO. AREA = 1140 SQ.MI.
17040202 — UPPER HENRYS. IDAHO, WYOMING. AREA = 1090 SQ.MI.
17040203 — LOWER HENRYS. IDAHO, WYOMING. AREA = 1040 SQ.MI.
17040204 — TETON. IDAHO, WYOMING. AREA = 1130 SQ.MI.
17040205 — WILLOW. IDAHO. AREA = 645 SQ.MI.
17040206 — AMERICAN FALLS. IDAHO. AREA = 2850 SQ.MI.
17040207 — BLACKFOOT. IDAHO. AREA = 1080 SQ.MI.
17040208 — PORTNEUF. IDAHO. AREA = 1320 SQ.MI.
17040209 — LAKE WALCOTT. IDAHO. AREA = 3670 SQ.MI.
17040210 — RAFT. IDAHO, UTAH. AREA = 1470 SQ.MI.
17040211 — GOOSE. IDAHO, NEVADA, UTAH. AREA = 1150 SQ.MI.
17040212 — UPPER SNAKE-ROCK. IDAHO. AREA = 2440 SQ.MI.
17040213 — SALMON FALLS. IDAHO, NEVADA. AREA = 2120 SQ.MI.
17040214 — BEAVER-CAMAS. IDAHO. AREA = 982 SQ.MI.
17040215 — MEDICINE LODGE. IDAHO. AREA = 952 SQ.MI.

17040216 — BIRCH. IDAHO.
AREA = 692 SQ.MI.
17040217 — LITTLE LOST. IDAHO.
AREA = 957 SQ.MI.
17040218 — BIG LOST. IDAHO.
AREA = 1900 SQ.MI.
17040219 — BIG WOOD. IDAHO.
AREA = 1460 SQ.MI.
17040220 — CAMAS. IDAHO.
AREA = 672 SQ.MI.
17040221 — LITTLE WOOD. IDAHO.
AREA = 1120 SQ.MI.

SUBREGION 1705 — MIDDLE SNAKE: THE SNAKE RIVER BASIN BELOW THE CLOVER CREEK BASIN TO HELLS CANYON DAM. IDAHO, NEVADA, OREGON.
AREA = 36700 SQ.MI.

ACCOUNTING UNIT 170501 — MIDDLE SNAKE-BOISE: THE SNAKE RIVER BASIN BELOW THE CLOVER CREEK BASIN TO AND INCLUDING THE WEISER RIVER BASIN. IDAHO, NEVADA, OREGON.
AREA = 32600 SQ.MI.

CATALOGING UNITS 17050101 — C. J. STRIKE RESERVOIR. IDAHO.
AREA = 2150 SQ.MI.
17050102 — BRUNEAU. IDAHO, NEVADA.
AREA = 3290 SQ.MI.
17050103 — MIDDLE SNAKE-SUCCOR. IDAHO, OREGON.
AREA = 2280 SQ.MI.
17050104 — UPPER OWYHEE. IDAHO, NEVADA.
AREA = 2110 SQ.MI.
17050105 — SOUTH FORK OWYHEE. IDAHO, NEVADA, OREGON.
AREA = 1860 SQ.MI.
17050106 — EAST LITTLE OWYHEE. IDAHO. NEVADA, OREGON.
AREA = 910 SQ.MI.
17050107 — MIDDLE OWYHEE. IDAHO, NEVADA, OREGON.
AREA = 1460 SQ.MI.
17050108 — JORDAN. IDAHO, OREGON.
AREA = 1270 SQ.MI.
17050109 — CROOKED-RATTLESNAKE. OREGON.
AREA = 1340 SQ.MI.
17050110 — LOWER OWYHEE. OREGON.
AREA = 2000 SQ.MI.
17050111 — NORTH AND MIDDLE FORKS BOISE. IDAHO.
AREA = 761 SQ.MI.
17050112 — BOISE-MORES. IDAHO.
AREA = 620 SQ.MI.
17050113 — SOUTH FORK BOISE. IDAHO.
AREA = 1300 SQ.MI.
17050114 — LOWER BOISE. IDAHO.
AREA = 1330 SQ.MI.
17050115 — MIDDLE SNAKE-PAYETTE. IDAHO, OREGON.
AREA = 294 SQ.MI.
17050116 — UPPER MALHEUR. OREGON.
AREA = 2430 SQ.MI.
17050117 — LOWER MALHEUR. OREGON.
AREA = 927 SQ.MI.
17050118 — BULLY. OREGON.
AREA = 577 SQ.MI.
17050119 — WILLOW. OREGON.
AREA = 773 SQ.MI.
17050120 — SOUTH FORK PAYETTE. IDAHO.
AREA = 813 SQ.MI.
17050121 — MIDDLE FORK PAYETTE. IDAHO.
AREA = 338 SQ.MI.
17050122 — PAYETTE. IDAHO.
AREA = 1240 SQ.MI.
17050123 — NORTH FORK PAYETTE. IDAHO.
AREA = 912 SQ.MI.
17050124 — WEISER. IDAHO.
AREA = 1660 SQ.MI.

ACCOUNTING UNIT 170502 — MIDDLE SNAKE-POWDER: THE SNAKE RIVER BASIN BELOW THE WEISER RIVER BASIN TO HELLS CANYON DAM. IDAHO, OREGON.
AREA = 4100 SQ.MI.

CATALOGING UNITS 17050201 — BROWNLEE RESERVOIR. IDAHO, OREGON.
AREA = 1290 SQ.MI.
17050202 — BURNT. OREGON.
AREA = 1090 SQ.MI.
17050203 — POWDER. OREGON.
AREA = 1720 SQ.MI.

SUBREGION 1706 — LOWER SNAKE: THE SNAKE RIVER BASIN BELOW HELLS CANYON DAM TO ITS CONFLUENCE WITH THE COLUMBIA RIVER. IDAHO, OREGON, WASHINGTON.
AREA = 35200 SQ.MI.

REGION 17: PACIFIC NORTHWEST — Continued

ACCOUNTING UNIT 170601 — LOWER SNAKE: THE SNAKE RIVER BASIN BELOW HELLS CANYON DAM TO ITS CONFLUENCE WITH THE COLUMBIA RIVER, EXCLUDING THE SALMON AND CLEARWATER RIVER BASINS. IDAHO, OREGON, WASHINGTON.
AREA = 11800 SQ.MI.

CATALOGING UNITS 17060101 — HELLS CANYON. IDAHO, OREGON.
AREA = 545 SQ.MI.
17060102 — IMNAHA. OREGON.
AREA = 855 SQ.MI.
17060103 — LOWER SNAKE-ASOTIN. IDAHO, OREGON, WASHINGTON.
AREA = 711 SQ.MI.
17060104 — UPPER GRANDE RONDE. OREGON.
AREA = 1650 SQ.MI.
17060105 — WALLOWA. OREGON.
AREA = 950 SQ.MI.
17060106 — LOWER GRANDE RONDE. OREGON, WASHINGTON.
AREA = 1530 SQ.MI.
17060107 — LOWER SNAKE-TUCANNON. WASHINGTON.
AREA = 1480 SQ.MI.
17060108 — PALOUSE. IDAHO, WASHINGTON.
AREA = 2360 SQ.MI.
17060109 — ROCK. IDAHO, WASHINGTON.
AREA = 962 SQ.MI.
17060110 — LOWER SNAKE. WASHINGTON.
AREA = 731 SQ.MI.

ACCOUNTING UNIT 170602 — SALMON: THE SALMON RIVER BASIN. IDAHO.
AREA = 14000 SQ.MI.

CATALOGING UNITS 17060201 — UPPER SALMON. IDAHO.
AREA = 2410 SQ.MI.
17060202 — PAHSIMEROI. IDAHO.
AREA = 825 SQ.MI.
17060203 — MIDDLE SALMON-PANTHER. IDAHO.
AREA = 1810 SQ.MI.
17060204 — LEMHI. IDAHO.
AREA = 1270 SQ.MI.
17060205 — UPPER MIDDLE FORK SALMON. IDAHO.
AREA = 1490 SQ.MI.
17060206 — LOWER MIDDLE FORK SALMON. IDAHO.
AREA = 1370 SQ.MI.
17060207 — MIDDLE SALMON-CHAMBERLAIN. IDAHO.
AREA = 1700 SQ.MI.
17060208 — SOUTH FORK SALMON. IDAHO.
AREA = 1310 SQ.MI.
17060209 — LOWER SALMON. IDAHO.
AREA = 1240 SQ.MI.
17060210 — LITTLE SALMON. IDAHO.
AREA = 582 SQ.MI.

ACCOUNTING UNIT 170603 — CLEARWATER: THE CLEARWATER RIVER BASIN. IDAHO, WASHINGTON.
AREA = 9420 SQ.MI.

CATALOGING UNITS 17060301 — UPPER SELWAY. IDAHO.
AREA = 997 SQ.MI.
17060302 — LOWER SELWAY. IDAHO.
AREA = 1030 SQ.MI.
17060303 — LOCHSA. IDAHO.
AREA = 1180 SQ.MI.
17060304 — MIDDLE FORK CLEARWATER. IDAHO.
AREA = 213 SQ.MI.
17060305 — SOUTH FORK CLEARWATER. IDAHO.
AREA = 1170 SQ.MI.
17060306 — CLEARWATER. IDAHO, WASHINGTON.
AREA = 2340 SQ.MI.
17060307 — UPPER NORTH FORK CLEARWATER. IDAHO.
AREA = 1320 SQ.MI.
17060308 — LOWER NORTH FORK CLEARWATER. IDAHO.
AREA = 1170 SQ.MI.

SUBREGION 1707 — MIDDLE COLUMBIA: THE COLUMBIA RIVER BASIN BELOW THE CONFLUENCE WITH THE SNAKE RIVER BASIN TO BONNEVILLE DAM. OREGON, WASHINGTON.
AREA = 29800 SQ.MI.

ACCOUNTING UNIT 170701 — MIDDLE COLUMBIA: THE COLUMBIA RIVER BASIN BELOW THE CONFLUENCE WITH THE SNAKE RIVER BASIN TO BONNEVILLE DAM, EXCLUDING THE DESCHUTES AND JOHN DAY RIVER BASINS. OREGON, WASHINGTON.
AREA = 11200 SQ.MI.

CATALOGING UNITS 17070101 — MIDDLE COLUMBIA-LAKE WALLULA. OREGON, WASHINGTON.
AREA = 2550 SQ.MI.
17070102 — WALLA WALLA. OREGON, WASHINGTON.
AREA = 1750 SQ.MI.
17070103 — UMATILLA. OREGON.
AREA = 2540 SQ.MI.
17070104 — WILLOW. OREGON.
AREA = 881 SQ.MI.
17070105 — MIDDLE COLUMBIA-HOOD. OREGON, WASHINGTON.
AREA = 2170 SQ.MI.
17070106 — KLICKITAT. WASHINGTON.
AREA = 1330 SQ.MI.

ACCOUNTING UNIT 170702 — JOHN DAY: THE JOHN DAY RIVER BASIN. OREGON.
AREA = 7910 SQ.MI.

CATALOGING UNITS 17070201 — UPPER JOHN DAY. OREGON.
AREA = 2130 SQ.MI.
17070202 — NORTH FORK JOHN DAY. OREGON.
AREA = 1830 SQ.MI.
17070203 — MIDDLE FORK JOHN DAY. OREGON.
AREA = 785 SQ.MI.
17070204 — LOWER JOHN DAY. OREGON.
AREA = 3160 SQ.MI.

ACCOUNTING UNIT 170703 — DESCHUTES: THE DESCHUTES RIVER BASIN. OREGON.
AREA = 10700 SQ.MI.

CATALOGING UNITS 17070301 — UPPER DESCHUTES. OREGON.
AREA = 2140 SQ.MI.
17070302 — LITTLE DESCHUTES. OREGON.
AREA = 1020 SQ.MI.
17070303 — BEAVER-SOUTH FORK. OREGON.
AREA = 1530 SQ.MI.
17070304 — UPPER CROOKED. OREGON.
AREA = 1150 SQ.MI.
17070305 — LOWER CROOKED. OREGON.
AREA = 1840 SQ.MI.
17070306 — LOWER DESCHUTES. OREGON.
AREA = 2300 SQ.MI.
17070307 — TROUT. OREGON.
AREA = 695 SQ.MI.

SUBREGION 1708 — LOWER COLUMBIA: THE COLUMBIA RIVER BASIN BELOW BONNEVILLE DAM, EXCLUDING THE WILLAMETTE RIVER BASIN. OREGON, WASHINGTON.
AREA = 6250 SQ.MI.

ACCOUNTING UNIT 170800 — LOWER COLUMBIA. OREGON, WASHINGTON.
AREA = 6250 SQ.MI.

CATALOGING UNITS 17080001 — LOWER COLUMBIA-SANDY. OREGON, WASHINGTON.
AREA = 1110 SQ.MI.
17080002 — LEWIS. WASHINGTON.
AREA = 1080 SQ.MI.
17080003 — LOWER COLUMBIA-CLATSKANIE. OREGON, WASHINGTON.
AREA = 896 SQ.MI.
17080004 — UPPER COWLITZ. WASHINGTON.
AREA = 1030 SQ.MI.
17080005 — LOWER COWLITZ. WASHINGTON.
AREA = 1460 SQ.MI.
17080006 — LOWER COLUMBIA. OREGON, WASHINGTON.
AREA = 672 SQ.MI.

SUBREGION 1709 — WILLAMETTE: THE WILLAMETTE RIVER BASIN. OREGON.
AREA = 11400 SQ.MI.

ACCOUNTING UNIT 170900 — WILLAMETTE. OREGON.
AREA = 11400 SQ.MI.

CATALOGING UNITS 17090001 — MIDDLE FORK WILLAMETTE. OREGON.
AREA = 1350 SQ.MI.
17090002 — COAST FORK WILLAMETTE. OREGON.
AREA = 664 SQ.MI.
17090003 — UPPER WILLAMETTE. OREGON.
AREA = 1830 SQ.MI.
17090004 — MCKENZIE. OREGON.
AREA = 1360 SQ.MI.
17090005 — NORTH SANTIAM. OREGON.
AREA = 771 SQ.MI.
17090006 — SOUTH SANTIAM. OREGON.
AREA = 1050 SQ.MI.
17090007 — MIDDLE WILLAMETTE. OREGON.
AREA = 700 SQ.MI.
17090008 — YAMHILL. OREGON.
AREA = 770 SQ.MI.
17090009 — MOLALLA-PUDDING. OREGON.
AREA = 883 SQ.MI.
17090010 — TUALATIN. OREGON.
AREA = 718 SQ.MI.
17090011 — CLACKAMAS. OREGON.
AREA = 935 SQ.MI.
17090012 — LOWER WILLAMETTE. OREGON.
AREA = 407 SQ.MI.

SUBREGION 1710 — OREGON-WASHINGTON COASTAL: THE DRAINAGE INTO THE DRAINAGE BOUNDARY TO THE SMITH RIVER BASIN BOUNDARY, EXCLUDING THE COLUMBIA RIVER BASIN. CALIFORNIA, OREGON, WASHINGTON.
AREA = 23200 SQ.MI.

ACCOUNTING UNIT 171001 — WASHINGTON COASTAL: THE DRAINAGE INTO THE PACIFIC OCEAN FROM THE STRAIT OF JUAN DE FUCA DRAINAGE BOUNDARY TO THE COLUMBIA RIVER BASIN BOUNDARY. WASHINGTON.
AREA = 6240 SQ.MI.

REGION 17: PACIFIC NORTHWEST — Continued

CATALOGING UNITS 17100101 — HOH-QUILLAYUTE. WASHINGTON.
AREA = 1230 SQ.MI.
17100102 — QUEETS-QUINAULT. WASHINGTON.
AREA = 1190 SQ.MI.
17100103 — UPPER CHEHALIS. WASHINGTON.
AREA = 1310 SQ.MI.
17100104 — LOWER CHEHALIS. WASHINGTON.
AREA = 838 SQ.MI.
17100105 — GRAYS HARBOR. WASHINGTON.
AREA = 568 SQ.MI.
17100106 — WILLAPA BAY. WASHINGTON.
AREA = 1100 SQ.MI.

ACCOUNTING UNIT 171002 — NORTHERN OREGON COASTAL: THE DRAINAGE INTO THE PACIFIC OCEAN FROM THE COLUMBIA RIVER BASIN BOUNDARY TO THE UMPQUA RIVER BASIN BOUNDARY. OREGON.
AREA = 4310 SQ.MI.

CATALOGING UNITS 17100201 — NECANICUM. OREGON.
AREA = 129 SQ.MI.
17100202 — NEHALEM. OREGON.
AREA = 860 SQ.MI.
17100203 — WILSON-TRUSK-NESTUCCU. OREGON.
AREA = 973 SQ.MI.
17100204 — SILETZ-YAQUINA. OREGON.
AREA = 753 SQ.MI.
17100205 — ALSEA. OREGON.
AREA = 697 SQ.MI.
17100206 — SIUSLAW. OREGON.
AREA = 769 SQ.MI.
17100207 — SILTCOOS. OREGON.
AREA = 129 SQ.MI.

ACCOUNTING UNIT 171003 — SOUTHERN OREGON COASTAL: THE DRAINAGE INTO THE PACIFIC OCEAN FROM AND INCLUDING THE UMPQUA RIVER BASIN TO THE SMITH RIVER BASIN BOUNDARY. CALIFORNIA, OREGON.
AREA = 12600 SQ.MI.

CATALOGING UNITS 17100301 — NORTH UMPQUA. OREGON.
AREA = 1350 SQ.MI.
17100302 — SOUTH UMPQUA. OREGON.
AREA = 1790 SQ.MI.
17100303 — UMPQUA. OREGON.
AREA = 1500 SQ.MI.
17100304 — COOS. OREGON.
AREA = 739 SQ.MI.
17100305 — COQUILLE. OREGON.
AREA = 1030 SQ.MI.
17100306 — SIXES. OREGON.
AREA = 467 SQ.MI.
17100307 — UPPER ROGUE. OREGON.
AREA = 1610 SQ.MI.
17100308 — MIDDLE ROGUE. OREGON.
AREA = 885 SQ.MI.
17100309 — APPLEGATE. CALIFORNIA, OREGON.
AREA = 759 SQ.MI.
17100310 — LOWER ROGUE. OREGON.
AREA = 898 SQ.MI.
17100311 — ILLINOIS. CALIFORNIA, OREGON.
AREA = 981 SQ.MI.
17100312 — CHETCO. CALIFORNIA, OREGON.
AREA = 630 SQ.MI.

SUBREGION 1711 — PUGET SOUND: THE DRAINAGE WITHIN THE UNITED STATES THAT DISCHARGES INTO: (A) PUGET SOUND AND THE STRAITS OF GEORGIA AND OF JUAN DE FUCA; AND (B) THE FRASER RIVER BASIN. WASHINGTON.
AREA = 16800 SQ.MI.

ACCOUNTING UNIT 171100 — PUGET SOUND. WASHINGTON.
AREA = 16800 SQ.MI.

CATALOGING UNITS 17110001 — FRASER. WASHINGTON.
AREA = 249 SQ.MI.
17110002 — STRAIT OF GEORGIA. WASHINGTON.
AREA = 955 SQ.MI.
17110003 — SAN JUAN ISLANDS. WASHINGTON.
AREA = 626 SQ.MI.
17110004 — NOOKSACK. WASHINGTON.
AREA = 795 SQ.MI.
17110005 — UPPER SKAGIT. WASHINGTON.
AREA = 1630 SQ.MI.
17110006 — SAUK. WASHINGTON.
AREA = 741 SQ.MI.
17110007 — LOWER SKAGIT. WASHINGTON.
AREA = 447 SQ.MI.
17110008 — STILLAGUAMISH. WASHINGTON.
AREA = 704 SQ.MI.
17110009 — SKYKOMISH. WASHINGTON.
AREA = 853 SQ.MI.
17110010 — SNOQUALMIE. WASHINGTON.
AREA = 693 SQ.MI.
17110011 — SNOHOMISH. WASHINGTON.
AREA = 278 SQ.MI.
17110012 — LAKE WASHINGTON. WASHINGTON.
AREA = 619 SQ.MI.

17110013 — DUWAMISH. WASHINGTON.
AREA = 487 SQ.MI.
17110014 — PUYALLUP. WASHINGTON.
AREA = 996 SQ.MI.
17110015 — NISQUALLY. WASHINGTON.
AREA = 726 SQ.MI.
17110016 — DESCHUTES. WASHINGTON.
AREA = 168 SQ.MI.
17110017 — SKOKOMISH. WASHINGTON.
AREA = 248 SQ.MI.
17110018 — HOOD CANAL. WASHINGTON.
AREA = 957 SQ.MI.
17110019 — PUGET SOUND. WASHINGTON.
AREA = 2550 SQ.MI.
17110020 — DUNGENESS-ELWHA. WASHINGTON.
AREA = 1270 SQ.MI.
17110021 — CRESCENT-HOKO. WASHINGTON.
AREA = 774 SQ.MI.

SUBREGION 1712 — OREGON CLOSED BASINS: THE DRAINAGE OF THE GREAT BASIN THAT DISCHARGES INTO THE STATE OF OREGON. CALIFORNIA, NEVADA, OREGON.
AREA = 17300 SQ.MI.

ACCOUNTING UNIT 171200 — OREGON CLOSED BASINS. CALIFORNIA, NEVADA, OREGON.
AREA = 17300 SQ.MI.

CATALOGING UNITS 17120001 — HARNEY-MALHEUR LAKES. OREGON.
AREA = 1420 SQ.MI.
17120002 — SILVIES. OREGON.
AREA = 1310 SQ.MI.
17120003 — DONNER UND BLITZEN. OREGON.
AREA = 765 SQ.MI.
17120004 — SILVER. OREGON.
AREA = 1670 SQ.MI.
17120005 — SUMMER LAKE. OREGON.
AREA = 4100 SQ.MI.
17120006 — LAKE ABERT. OREGON.
AREA = 1020 SQ.MI.
17120007 — WARNER LAKES. CALIFORNIA, NEVADA, OREGON.
AREA = 1900 SQ.MI.
17120008 — GUANO. NEVADA, OREGON.
AREA = 2970 SQ.MI.
17120009 — ALVORD LAKE. NEVADA, OREGON.
AREA = 2110 SQ.MI.

REGION 18 CALIFORNIA REGION — (A) THE DRAINAGE WITHIN THE UNITED STATES THAT ULTIMATELY DISCHARGES INTO THE PACIFIC OCEAN WITHIN THE STATE OF CALIFORNIA; AND (B) THOSE PARTS OF THE GREAT BASIN (OR OTHER CLOSED BASINS) THAT DISCHARGE INTO THE STATE OF CALIFORNIA. INCLUDES PARTS OF CALIFORNIA, NEVADA, AND OREGON.

SUBREGION 1801 — KLAMATH-NORTHERN CALIFORNIA COASTAL. THE DRAINAGE INTO THE PACIFIC OCEAN FROM AND INCLUDING THE SMITH RIVER BASIN TO AND INCLUDING THE STEMPLE CREEK BASIN. CALIFORNIA, OREGON.
AREA = 24800 SQ.MI.

ACCOUNTING UNIT 180101 — NORTHERN CALIFORNIA COASTAL. THE DRAINAGE INTO THE PACIFIC OCEAN FROM AND INCLUDING THE SMITH RIVER BASIN TO AND INCLUDING THE STEMPLE CREEK BASIN, EXCLUDING THE KLAMATH RIVER BASIN. CALIFORNIA, OREGON.
AREA = 9230 SQ.MI.

CATALOGING UNITS 18010101 — SMITH. CALIFORNIA, OREGON.
AREA = 788 SQ.MI.
18010102 — MAD-REDWOOD. CALIFORNIA.
AREA = 1130 SQ.MI.
18010103 — UPPER EEL. CALIFORNIA.
AREA = 697 SQ.MI.
18010104 — MIDDLE FORK EEL. CALIFORNIA.
AREA = 747 SQ.MI.
18010105 — LOWER EEL. CALIFORNIA.
AREA = 1510 SQ.MI.
18010106 — SOUTH FORK EEL. CALIFORNIA.
AREA = 678 SQ.MI.
18010107 — MATTOLE. CALIFORNIA.
AREA = 485 SQ.MI.
18010108 — BIG-NAVARRO-GARCIA. CALIFORNIA.
AREA = 1230 SQ.MI.
18010109 — GUALALA-SALMON. CALIFORNIA.
AREA = 343 SQ.MI.
18010110 — RUSSIAN. CALIFORNIA.
AREA = 1470 SQ.MI.
18010111 — BODEGA BAY. CALIFORNIA.
AREA = 147 SQ.MI.

ACCOUNTING UNIT 180102 — KLAMATH. THE KLAMATH RIVER BASIN. CALIFORNIA, OREGON.
AREA = 15500 SQ.MI.

CATALOGING UNITS 18010201 — WILLIAMSON. OREGON.
AREA = 1430 SQ.MI.
18010202 — SPRAGUE. OREGON.
AREA = 1600 SQ.MI.
18010203 — UPPER KLAMATH LAKE. OREGON.
AREA = 738 SQ.MI.
18010204 — LOST. CALIFORNIA, OREGON.
AREA = 2960 SQ.MI.
18010205 — BUTTE. CALIFORNIA, OREGON.
AREA = 601 SQ.MI.
18010206 — UPPER KLAMATH. CALIFORNIA, OREGON.
AREA = 1400 SQ.MI.
18010207 — SHASTA. CALIFORNIA.
AREA = 791 SQ.MI.
18010208 — SCOTT. CALIFORNIA.
AREA = 802 SQ.MI.
18010209 — LOWER KLAMATH. CALIFORNIA, OREGON.
AREA = 1520 SQ.MI.
18010210 — SALMON. CALIFORNIA.
AREA = 748 SQ.MI.
18010211 — TRINITY. CALIFORNIA.
AREA = 2010 SQ.MI.
18010212 — SOUTH FORK TRINITY. CALIFORNIA.
AREA = 926 SQ.MI.

SUBREGION 1802 — SACRAMENTO. THE SACRAMENTO RIVER BASIN AND DRAINAGE INTO GOOSE LAKE. CALIFORNIA, OREGON.
AREA = 27600 SQ.MI.

ACCOUNTING UNIT 180200 — UPPER SACRAMENTO: THE SACRAMENTO RIVER BASIN TO AND INCLUDING SHASTA LAKE AND DRAINAGE INTO GOOSE LAKE. CALIFORNIA, OREGON.
AREA = 7650 SQ.MI.

CATALOGING UNITS 18020001 — GOOSE LAKE. CALIFORNIA, OREGON.
AREA = 1080 SQ.MI.
18020002 — UPPER PIT. CALIFORNIA.
AREA = 2620 SQ.MI.
18020003 — LOWER PIT. CALIFORNIA.
AREA = 2690 SQ.MI.
18020004 — MCCLOUD. CALIFORNIA.
AREA = 674 SQ.MI.
18020005 — SACRAMENTO HEADWATERS. CALIFORNIA.
AREA = 587 SQ.MI.

ACCOUNTING UNIT 180201 — LOWER SACRAMENTO: THE SACRAMENTO RIVER BASIN BELOW SHASTA DAM. CALIFORNIA.
AREA = 19900 SQ.MI.

CATALOGING UNITS 18020101 — SACRAMENTO-LOWER COW-LOWER CLEAR. CALIFORNIA.
AREA = 419 SQ.MI.
18020102 — LOWER COTTONWOOD. CALIFORNIA.
AREA = 328 SQ.MI.

18020103 — SACRAMENTO-LOWER THOMES. CALIFORNIA.
AREA = 1120 SQ.MI.
18020104 — SACRAMENTO-STONE CORRAL. CALIFORNIA.
AREA = 1850 SQ.MI.
18020105 — LOWER BUTTE. CALIFORNIA.
AREA = 593 SQ.MI.
18020106 — LOWER FEATHER. CALIFORNIA.
AREA = 681 SQ.MI.
18020107 — LOWER YUBA. CALIFORNIA.
AREA = 34 SQ.MI.
18020108 — LOWER BEAR. CALIFORNIA.
AREA = 100 SQ.MI.
18020109 — LOWER SACRAMENTO. CALIFORNIA.
AREA = 1720 SQ.MI.
18020110 — LOWER CACHE. CALIFORNIA.
AREA = 190 SQ.MI.
18020111 — LOWER AMERICAN. CALIFORNIA.
AREA = 299 SQ.MI.
18020112 — SACRAMENTO-UPPER CLEAR. CALIFORNIA.
AREA = 269 SQ.MI.
18020113 — COTTONWOOD HEADWATERS. CALIFORNIA.
AREA = 602 SQ.MI.
18020114 — UPPER ELDER-UPPER THOMES. CALIFORNIA.
AREA = 328 SQ.MI.
18020115 — UPPER STONY. CALIFORNIA.
AREA = 731 SQ.MI.
18020116 — UPPER CACHE. CALIFORNIA.
AREA = 939 SQ.MI.
18020117 — UPPER PUTAH. CALIFORNIA.
AREA = 558 SQ.MI.
18020118 — UPPER COW-BATTLE. CALIFORNIA.
AREA = 832 SQ.MI.
18020119 — MILL-BIG CHICO. CALIFORNIA.
AREA = 896 SQ.MI.
18020120 — UPPER BUTTE. CALIFORNIA.
AREA = 202 SQ.MI.
18020121 — NORTH FORK FEATHER. CALIFORNIA.
AREA = 1190 SQ.MI.
18020122 — EAST BRANCH NORTH FORK FEATHER. CALIFORNIA.
AREA = 1010 SQ.MI.
18020123 — MIDDLE FORK FEATHER. CALIFORNIA.
AREA = 1350 SQ.MI.
18020124 — HONCUT HEADWATERS. CALIFORNIA.
AREA = 107 SQ.MI.
18020125 — UPPER YUBA. CALIFORNIA.
AREA = 1290 SQ.MI.
18020126 — UPPER BEAR. CALIFORNIA.
AREA = 361 SQ.MI.
18020127 — UPPER COON-UPPER AUBURN. CALIFORNIA.
AREA = 89 SQ.MI.
18020128 — NORTH FORK AMERICAN. CALIFORNIA.
AREA = 998 SQ.MI.
18020129 — SOUTH FORK AMERICAN. CALIFORNIA.
AREA = 843 SQ.MI.

SUBREGION 1803 — TULARE-BUENA VISTA LAKES: THE DRAINAGE INTO THE TULARE AND BUENA VISTA LAKE CLOSED BASINS. CALIFORNIA.
AREA = 16200 SQ.MI.

ACCOUNTING UNIT 180300 — TULARE-BUENA VISTA LAKES. CALIFORNIA.
AREA = 16200 SQ.MI.

CATALOGING UNITS 18030001 — UPPER KERN. CALIFORNIA.
AREA = 1070 SQ.MI.
18030002 — SOUTH FORK KERN. CALIFORNIA.
AREA = 964 SQ.MI.
18030003 — MIDDLE KERN-UPPER TEHACHAPI-GRAPEVINE. CALIFORNIA.
AREA = 1310 SQ.MI.
18030004 — UPPER POSO. CALIFORNIA.
AREA = 268 SQ.MI.
18030005 — UPPER DEER-UPPER WHITE. CALIFORNIA.
AREA = 345 SQ.MI.
18030006 — UPPER TULE. CALIFORNIA.
AREA = 410 SQ.MI.
18030007 — UPPER KAWEAH. CALIFORNIA.
AREA = 828 SQ.MI.
18030008 — MILL. CALIFORNIA.
AREA = 156 SQ.MI.
18030009 — UPPER DRY. CALIFORNIA.
AREA = 124 SQ.MI.
18030010 — UPPER KING. CALIFORNIA.
AREA = 1520 SQ.MI.
18030011 — UPPER LOS GATOS-AVENAL. CALIFORNIA.
AREA = 702 SQ.MI.
18030012 — TULARE-BUENA VISTA LAKES. CALIFORNIA.
AREA = 8510 SQ.MI.

SUBREGION 1804 — SAN JOAQUIN: THE SAN JOAQUIN RIVER BASIN. CALIFORNIA.
AREA = 15600 SQ.MI.

REGION 18: CALIFORNIA — Continued

ACCOUNTING UNIT 180400 — SAN JOAQUIN. CALIFORNIA.
AREA = 15600 SQ.MI.

CATALOGING UNITS 18040001 — MIDDLE SAN JOAQUIN-LOWER CHOWCHILLA. CALIFORNIA.
AREA = 2640 SQ.MI.
18040002 — MIDDLE SAN JOAQUIN-LOWER MERCED-LOWER STANISLAUS. CALIFORNIA.
AREA = 1830 SQ.MI.
18040003 — SAN JOAQUIN DELTA. CALIFORNIA.
AREA = 938 SQ.MI.
18040004 — LOWER CALAVERAS-MORMON SLOUGH. CALIFORNIA.
AREA = 235 SQ.MI.
18040005 — LOWER COSUMNES-LOWER MOKELUMNE. CALIFORNIA.
AREA = 747 SQ.MI.
18040006 — UPPER SAN JOAQUIN. CALIFORNIA.
AREA = 1680 SQ.MI.
18040007 — UPPER CHOWCHILLA-UPPER FRESNO. CALIFORNIA.
AREA = 938 SQ.MI.
18040008 — UPPER MERCED. CALIFORNIA.
AREA = 1080 SQ.MI.
18040009 — UPPER TUOLUMNE. CALIFORNIA.
AREA = 1600 SQ.MI.
18040010 — UPPER STANISLAUS. CALIFORNIA.
AREA = 971 SQ.MI.
18040011 — UPPER CALAVERAS. CALIFORNIA.
AREA = 383 SQ.MI.
18040012 — UPPER MOKELUMNE. CALIFORNIA.
AREA = 764 SQ.MI.
18040013 — UPPER COSUMNES. CALIFORNIA.
AREA = 632 SQ.MI.
18040014 — PANOCHE-SAN LUIS RESERVOIR. CALIFORNIA.
AREA = 1120 SQ.MI.

SUBREGION 1805 — SAN FRANCISCO BAY: THE DRAINAGE INTO THE PACIFIC OCEAN FROM THE STEMPLE CREEK BASIN BOUNDARY TO AND INCLUDING THE PESCADERO CREEK BASIN, EXCLUDING THE SACRAMENTO AND SAN JOAQUIN RIVER BASINS. CALIFORNIA.
AREA = 4470 SQ.MI.

ACCOUNTING UNIT 180500 — SAN FRANCISCO BAY. CALIFORNIA.
AREA = 4470 SQ.MI.

CATALOGING UNITS 18050001 — SUISUN BAY. CALIFORNIA.
AREA = 644 SQ.MI.
18050002 — SAN PABLO BAY. CALIFORNIA.
AREA = 1200 SQ.MI.
18050003 — COYOTE. CALIFORNIA.
AREA = 831 SQ.MI.
18050004 — SAN FRANCISCO BAY. CALIFORNIA.
AREA = 1200 SQ.MI.
18050005 — TOMALES-DRAKE BAYS. CALIFORNIA.
AREA = 339 SQ.MI.
18050006 — SAN FRANCISCO COASTAL SOUTH. CALIFORNIA.
AREA = 256 SQ.MI.

SUBREGION 1806 — CENTRAL CALIFORNIA COASTAL: THE DRAINAGE INTO THE PACIFIC OCEAN FROM THE PESCADERO CREEK BASIN BOUNDARY TO AND INCLUDING THE RINCON CREEK BASIN. CALIFORNIA.
AREA = 11400 SQ.MI.

ACCOUNTING UNIT 180600 — CENTRAL CALIFORNIA COASTAL. CALIFORNIA.
AREA = 11400 SQ.MI.

CATALOGING UNITS 18060001 — SAN LORENZO-SOQUEL. CALIFORNIA.
AREA = 374 SQ.MI.
18060002 — PAJARO. CALIFORNIA.
AREA = 1290 SQ.MI.
18060003 — CARRIZO PLAIN. CALIFORNIA.
AREA = 440 SQ.MI.
18060004 — ESTRELLA. CALIFORNIA.
AREA = 930 SQ.MI.
18060005 — SALINAS. CALIFORNIA.
AREA = 3250 SQ.MI.
18060006 — CENTRAL COASTAL. CALIFORNIA.
AREA = 1070 SQ.MI.
18060007 — CUYAMA. CALIFORNIA.
AREA = 1130 SQ.MI.
18060008 — SANTA MARIA. CALIFORNIA.
AREA = 675 SQ.MI.
18060009 — SAN ANTONIO. CALIFORNIA.
AREA = 219 SQ.MI.
18060010 — SANTA YNEZ. CALIFORNIA.
AREA = 893 SQ.MI.
18060011 — ALISAL-ELKHORN SLOUGHS. CALIFORNIA.
AREA = 232 SQ.MI.
18060012 — CARMEL. CALIFORNIA.
AREA = 305 SQ.MI.

18060013 — SANTA BARBARA COASTAL. CALIFORNIA.
AREA = 381 SQ.MI.
18060014 — SANTA BARBARA CHANNEL ISLANDS. CALIFORNIA.
AREA = 187 SQ.MI.

SUBREGION 1807 — SOUTHERN CALIFORNIA COASTAL: THE DRAINAGE WITHIN THE UNITED STATES THAT DISCHARGES INTO THE PACIFIC OCEAN FROM THE RINCON CREEK BASIN BOUNDARY TO THE CALIFORNIA-BAJA CALIFORNIA INTERNATIONAL BOUNDARY. CALIFORNIA.
AREA = 11100 SQ.MI.

ACCOUNTING UNIT 180701 — VENTURA-SAN GABRIEL COASTAL: THE DRAINAGE INTO THE PACIFIC OCEAN FROM THE RINCON CREEK BASIN BOUNDARY TO AND INCLUDING THE SAN GABRIEL RIVER BASIN. CALIFORNIA.
AREA = 4530 SQ.MI.

CATALOGING UNITS 18070101 — VENTURA. CALIFORNIA.
AREA = 279 SQ.MI.
18070102 — SANTA CLARA. CALIFORNIA.
AREA = 1610 SQ.MI.
18070103 — CALLEGUAS. CALIFORNIA.
AREA = 377 SQ.MI.
18070104 — SANTA MONICA BAY. CALIFORNIA.
AREA = 575 SQ.MI.
18070105 — LOS ANGELES. CALIFORNIA.
AREA = 819 SQ.MI.
18070106 — SAN GABRIEL. CALIFORNIA.
AREA = 713 SQ.MI.
18070107 — SAN PEDRO CHANNEL ISLANDS. CALIFORNIA.
AREA = 154 SQ.MI.

ACCOUNTING UNIT 180702 — SANTA ANA: THE DRAINAGE INTO THE PACIFIC OCEAN FROM THE SAN GABRIEL RIVER BASIN BOUNDARY TO THE MORO CANYON DRAINAGE BOUNDARY NEAR LAGUNA BEACH. CALIFORNIA.
AREA = 2680 SQ.MI.

CATALOGING UNITS 18070201 — SEAL BEACH. CALIFORNIA.
AREA = 90 SQ.MI.
18070202 — SAN JACINTO. CALIFORNIA.
AREA = 757 SQ.MI.
18070203 — SANTA ANA. CALIFORNIA.
AREA = 1680 SQ.MI.
18070204 — NEWPORT BAY. CALIFORNIA.
AREA = 154 SQ.MI.

ACCOUNTING UNIT 180703 — LAGUNA-SAN DIEGO COASTAL: THE DRAINAGE WITHIN THE UNITED STATES THAT DISCHARGES INTO THE PACIFIC OCEAN FROM AND INCLUDING THE MORO CANYON DRAINAGE BASIN NEAR LAGUNA BEACH TO THE CALIFORNIA-BAJA CALIFORNIA INTERNATIONAL BOUNDARY. CALIFORNIA.
AREA = 3860 SQ.MI.

CATALOGING UNITS 18070301 — ALISO-SAN ONOFRE. CALIFORNIA.
AREA = 498 SQ.MI.
18070302 — SANTA MARGARITA. CALIFORNIA.
AREA = 731 SQ.MI.
18070303 — SAN LUIS REY-ESCONDIDO. CALIFORNIA.
AREA = 766 SQ.MI.
18070304 — SAN DIEGO. CALIFORNIA.
AREA = 1390 SQ.MI.
18070305 — COTTONWOOD-TIJUANA. CALIFORNIA.
AREA = 477 SQ.MI.

SUBREGION 1808 — NORTH LAHONTAN: THE DRAINAGE EAST OF THE SIERRA NEVADA AND NORTH OF THE TRUCKEE RIVER BASIN WHICH INCLUDES THE LAHONTON CLOSED BASINS THAT DISCHARGE INTO CALIFORNIA. CALIFORNIA, NEVADA.
AREA = 4480 SQ.MI.

ACCOUNTING UNIT 180800 — NORTH LAHONTAN. CALIFORNIA, NEVADA.
AREA = 4480 SQ.MI.

CATALOGING UNITS 18080001 — SURPRISE VALLEY. CALIFORNIA, NEVADA.
AREA = 878 SQ.MI.
18080002 — MADELINE PLAINS. CALIFORNIA, NEVADA.
AREA = 835 SQ.MI.
18080003 — HONEY-EAGLE LAKES. CALIFORNIA, NEVADA.
AREA = 2770 SQ.MI.

SUBREGION 1809 — NORTHERN MOJAVE-MONO LAKE: THE CLOSED DESERT BASINS THAT DISCHARGE INTO SOUTH CENTRAL CALIFORNIA, INCLUDING MONO LAKE, OWENS LAKE, DEATH VALLEY, AND THE UPPER MOJAVE DESERT. CALIFORNIA, NEVADA.
AREA = 28000 SQ.MI.

ACCOUNTING UNIT 180901 — MONO-OWENS LAKES. THE MONO LAKE AND OWENS LAKE CLOSED BASINS. CALIFORNIA, NEVADA.
AREA = 4310 SQ.MI.

CATALOGING UNITS 18090101 — MONO LAKE. CALIFORNIA, NEVADA.
AREA = 1070 SQ.MI.
18090102 — CROWLEY LAKE. CALIFORNIA, NEVADA.
AREA = 1900 SQ.MI.
18090103 — OWENS LAKE. CALIFORNIA.
AREA = 1340 SQ.MI.

ACCOUNTING UNIT 180902 — NORTHERN MOJAVE: THE CLOSED DESERT BASINS THAT DISCHARGE INTO SOUTH CENTRAL CALIFORNIA, INCLUDING DEATH VALLEY AND THE UPPER MOJAVE DESERT, EXCLUDING MONO LAKE AND OWENS LAKE. CALIFORNIA, NEVADA.
AREA = 23600 SQ.MI.

CATALOGING UNITS 18090201 — EUREKA-SALINE VALLEYS. CALIFORNIA, NEVADA.
AREA = 1640 SQ.MI.
18090202 — UPPER AMARGOSA. CALIFORNIA, NEVADA.
AREA = 3340 SQ.MI.
18090203 — DEATH VALLEY-LOWER AMARGOSA. CALIFORNIA, NEVADA.
AREA = 5330 SQ.MI.
18090204 — PANAMINT VALLEY. CALIFORNIA.
AREA = 1600 SQ.MI.
18090205 — INDIAN WELLS-SEARLES VALLEYS. CALIFORNIA.
AREA = 2020 SQ.MI.
18090206 — ANTELOPE-FREMONT VALLEYS. CALIFORNIA.
AREA = 3310 SQ.MI.
18090207 — COYOTE-CUDDEBACK LAKES. CALIFORNIA.
AREA = 1820 SQ.MI.
18090208 — MOJAVE. CALIFORNIA.
AREA = 4580 SQ.MI.

SUBREGION 1810 — SOUTHERN MOJAVE-SALTON SEA: THE CLOSED DESERT BASINS IN SOUTHEASTERN CALIFORNIA, INCLUDING THE LOWER MOJAVE DESERT AND THE SALTON SEA. CALIFORNIA.
AREA = 16000 SQ.MI.

ACCOUNTING UNIT 181001 — SOUTHERN MOJAVE: THE LOWER MOJAVE DESERT. CALIFORNIA.
AREA = 8700 SQ.MI.

CATALOGING UNIT 18100100 — SOUTHERN MOJAVE. CALIFORNIA.
AREA = 8700 SQ.MI.

ACCOUNTING UNIT 181002 — SALTON SEA: THE SALTON SEA CLOSED BASIN. CALIFORNIA.
AREA = 7250 SQ.MI.

CATALOGING UNIT 18100200 — SALTON SEA. CALIFORNIA.
AREA = 7250 SQ.MI.

REGION 19 ALASKA REGION — THE DRAINAGE WITHIN THE STATE OF ALASKA. INCLUDES ALL OF ALASKA.

SUBREGION 1901 — ARCTIC SLOPE: THE NORTH SLOPE DRAINAGE WITHIN THE UNITED STATES THAT DISCHARGES INTO THE ARCTIC OCEAN, INCLUDING THE BAYS, ISLANDS, AND ASSOCIATED WATERS, FROM THE ALASKA-YUKON INTERNATIONAL BOUNDARY TO CAPE LISBURNE. ALASKA.
AREA = 81000 SQ.MI.

ACCOUNTING UNIT 190100 — ARCTIC SLOPE. ALASKA.
AREA = 81000 SQ.MI.

CATALOGING UNITS 19010001 — EAST ARCTIC SLOPE. ALASKA.
AREA = 24000 SQ.MI.
19010002 — COLVILLE. ALASKA.
AREA = 23000 SQ.MI.
19010003 — WEST ARCTIC SLOPE. ALASKA.
AREA = 34000 SQ.MI.

SUBREGION 1902 — NORTHWEST ALASKA: THE COASTAL DRAINAGE FROM CAPE LISBURNE TO THE YUKON RIVER BASIN BOUNDARY, INCLUDING THE BAYS, SOUNDS, ISLANDS, AND ASSOCIATED WATERS; AND ST. LAWRENCE ISLAND. ALASKA.
AREA = 75000 SQ.MI.

ACCOUNTING UNIT 190200 — NORTHWEST ALASKA. ALASKA.
AREA = 75000 SQ.MI.

CATALOGING UNITS 19020001 — KOTZEBUE SOUND. ALASKA.
AREA = 49000 SQ.MI.
19020002 — NORTON SOUND-ST. LAWRENCE ISLAND. ALASKA.
AREA = 26000 SQ.MI.

SUBREGION 1903 — YUKON: THE YUKON RIVER BASIN WITHIN THE UNITED STATES, INCLUDING ITS DELTA. ALASKA.
AREA = 204000 SQ.MI.

ACCOUNTING UNIT 190300 — YUKON. ALASKA.
AREA = 204000 SQ.MI.

CATALOGING UNITS 19030001 — FORTYMILE-WHITE. ALASKA.
AREA = 9700 SQ.MI.
19030002 — UPPER YUKON. ALASKA.
AREA = 60000 SQ.MI.
19030003 — MIDDLE YUKON. ALASKA.
AREA = 21000 SQ.MI.
19030004 — TANANA. ALASKA.
AREA = 44000 SQ.MI.
19030005 — KOYUKUK. ALASKA.
AREA = 32000 SQ.MI.
19030006 — LOWER YUKON. ALASKA.
AREA = 37000 SQ.MI.

SUBREGION 1904 — SOUTHWEST ALASKA: THE COASTAL DRAINAGE FROM THE YUKON RIVER BASIN BOUNDARY TO KUPREANOF POINT ON THE ALASKA PENINSULA, INCLUDING THE BAYS, ISLANDS, AND ASSOCIATED WATERS; AND THE ISLANDS OF ST. MATTHEW, NUNIVAK AND PRIBILOF, AND ALL OF THE ALEUTIAN ISLANDS. ALASKA.
AREA = 124000 SQ.MI.

ACCOUNTING UNIT 190400 — SOUTHWEST ALASKA. ALASKA.
AREA = 124000 SQ.MI.

CATALOGING UNITS 19040001 — KUSKOKWIM BAY-NUNIVAK ISLAND-ST. MATTHEW ISLAND. ALASKA.
AREA = 61000 SQ.MI.
19040002 — BRISTOL BAY. ALASKA.
AREA = 43000 SQ.MI.
19040003 — ALEUTIAN-PRIBILOF ISLANDS. ALASKA.
AREA = 20000 SQ.MI.

SUBREGION 1905 — SOUTH CENTRAL ALASKA: THE COASTAL DRAINAGE WITHIN THE UNITED STATES FROM KUPREANOF POINT ON THE ALASKA PENINSULA TO THE ALASKA-YUKON INTERNATIONAL BOUNDARY AND SOUTHWARD TO POINT RIOU, INCLUDING THE BAYS, ISLANDS, SOUNDS, AND ASSOCIATED WATERS. ALASKA.
AREA = 99000 SQ.MI.

ACCOUNTING UNIT 190500 — SOUTH CENTRAL ALASKA. ALASKA.
AREA = 99000 SQ.MI.

CATALOGING UNITS 19050001 — KODIAK-SHELIKOF. ALASKA.
AREA = 12000 SQ.MI.
19050002 — COOK INLET. ALASKA.
AREA = 47000 SQ.MI.
19050003 — GULF OF ALASKA. ALASKA.
AREA = 40000 SQ.MI.

SUBREGION 1906 — SOUTHEAST ALASKA: THE COASTAL DRAINAGE WITHIN THE UNITED STATES FROM POINT RIOU TO THE ALAKSA-BRITISH COLUMBIA INTERNATIONAL BOUNDARY, INCLUDING THE BAYS, ISLANDS, SOUNDS, AND ASSOCIATED WATERS. ALASKA.
AREA = 49000 SQ.MI.

ACCOUNTING UNIT 190600 — SOUTHEAST ALASKA. ALASKA.
AREA = 49000 SQ.MI.

CATALOGING UNIT 19060000 — SOUTHEAST ALASKA. ALASKA.
AREA = 49000 SQ.MI.

REGION 20 HAWAII REGION — THE DRAINAGE WITHIN THE STATE OF HAWAII. INCLUDES ALL OF HAWAII.

SUBREGION 2001 — HAWAII: THE DRAINAGE ON THE ISLAND OF HAWAII; AND ASSOCIATED WATERS. HAWAII.
AREA = 4030 SQ.MI.

ACCOUNTING UNIT 200100 — HAWAII. HAWAII.
AREA = 4030 SQ.MI.

CATALOGING UNIT 20010000 — HAWAII. HAWAII.
AREA = 4030 SQ.MI.

SUBREGION 2002 — MAUI: THE DRAINAGE ON THE ISLAND OF MAUI; AND ASSOCIATED WATERS. HAWAII.
AREA = 730 SQ.MI.

ACCOUNTING UNIT 200200 — MAUI. HAWAII.
AREA = 730 SQ.MI.

CATALOGING UNIT 20020000 — MAUI. HAWAII.
AREA = 730 SQ.MI.

SUBREGION 2003 — KAHOOLAWE: THE DRAINAGE ON THE ISLAND OF KAHOOLAWE; AND ASSOCIATED WATERS. HAWAII.
AREA = 45 SQ.MI.

ACCOUNTING UNIT 200300 — KAHOOLAWE. HAWAII.
AREA = 45 SQ.MI.

CATALOGING UNIT 20030000 — KAHOOLAWE. HAWAII.
AREA = 45 SQ.MI.

SUBREGION 2004 — LANAI: THE DRAINAGE ON THE ISLAND OF LANAI; AND ASSOCIATED WATERS. HAWAII.
AREA = 140 SQ.MI.

ACCOUNTING UNIT 200400 — LANAI. HAWAII.
AREA = 140 SQ.MI.

CATALOGING UNIT 20040000 — LANAI. HAWAII.
AREA = 140 SQ.MI.

SUBREGION 2005 — MOLOKAI: THE DRAINAGE ON THE ISLAND OF MOLOKAI; AND ASSOCIATED WATERS. HAWAII.
AREA = 260 SQ.MI.

ACCOUNTING UNIT 200500 — MOLOKAI. HAWAII.
AREA = 260 SQ.MI.

CATALOGING UNIT 20050000 — MOLOKAI. HAWAII.
AREA = 260 SQ.MI.

SUBREGION 2006 — OAHU: THE DRAINAGE ON THE ISLAND OF OAHU; AND ASSOCIATED WATERS. HAWAII.
AREA = 630 SQ.MI.

ACCOUNTING UNIT 200600 — OAHU. HAWAII.
AREA = 630 SQ.MI.

CATALOGING UNIT 20060000 — OAHU. HAWAII.
AREA = 630 SQ.MI.

SUBREGION 2007 — KAUAI: THE DRAINAGE ON THE ISLAND OF KAUAI; AND ASSOCIATED WATERS. HAWAII.
AREA = 560 SQ.MI.

ACCOUNTING UNIT 200700 — KAUAI. HAWAII.
AREA = 560 SQ.MI.

CATALOGING UNIT 20070000 — KAUAI. HAWAII.
AREA = 560 SQ.MI.

SUBREGION 2008 — NIIHAU: THE DRAINAGE ON THE ISLANDS OF NIIHAU AND KAULA; AND ASSOCIATED WATERS. HAWAII.
AREA = 72 SQ.MI.

ACCOUNTING UNIT 200800 — NIIHAU. HAWAII.
AREA = 72 SQ.MI.

CATALOGING UNIT 20080000 — NIIHAU. HAWAII.
AREA = 72 SQ.MI.

SUBREGION 2009 — NORTHWESTERN HAWAIIAN ISLANDS: THE DRAINAGE ON KURE, LAYSAN, LISIANSKI, NECKER, AND NIHOA ISLANDS; GARDNER PINNACLES; MARO, AND PEARL AND HERMES REEFS; FRENCH FRIGATE SHOALS; AND OTHER ISLETS, REEFS, AND ASSOCIATED WATERS NORTHWEST OF NIIPAU ISLAND. HAWAII.
AREA = < 10 SQ.MI.

ACCOUNTING UNIT 200900 — NORTHWESTERN HAWAIIAN ISLANDS. HAWAII.
AREA = < 10 SQ.MI.

CATALOGING UNIT 20090000 — NORTHWESTERN HAWAIIAN ISLANDS. HAWAII.
AREA = < 10 SQ.MI.

REGION 21 CARIBBEAN REGION — THE DRAINAGE WITHIN: (A) THE COMMONWEALTH OF PUERTO RICO; (B) THE VIRGIN ISLANDS OF THE UNITED STATES; AND (C) OTHER UNITED STATES CARIBBEAN OUTLYING AREAS. INCLUDES LAND AREAS OVER WHICH THE UNITED STATES HAS SOME DEGREE OF INTEREST, JURISDICTION, OR SOVEREIGNTY.

SUBREGION 2101 — PUERTO RICO: THE DRAINAGE AND ASSOCIATED WATERS WITHIN THE COMMONWEALTH OF PUERTO RICO.
PUERTO RICO.
AREA = 3480 SQ.MI.

ACCOUNTING UNIT 210100 — PUERTO RICO. COMMONWEALTH OF PUERTO RICO.
AREA = 3480 SQ.MI.

CATALOGING UNITS 21010001 — INTERIOR PUERTO RICO.
PUERTO RICO.
AREA = 404 SQ.MI.
21010002 — CIBUCO-GUAJATACA. PUERTO RICO.
AREA = 566 SQ.MI.
21010003 — CULEBRINAS-GUANAJIBO. PUERTO RICO.
AREA = 504 SQ.MI.
21010004 — SOUTHERN PUERTO RICO.
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21010005 — EASTERN PUERTO RICO. PUERTO RICO.
AREA = 1067 SQ.MI.
21010006 — PUERTO RICAN ISLANDS. PUERTO RICO.
AREA = 92 SQ.MI.

SUBREGION 2102 — VIRGIN ISLANDS: THE DRAINAGE AND ASSOCIATED WATERS WITHIN THE VIRGIN ISLANDS OF THE UNITED STATES.
U.S. VIRGIN ISLANDS.
AREA = 133 SQ.MI.

ACCOUNTING UNIT 210200 — VIRGIN ISLANDS. U.S. VIRGIN ISLANDS.
AREA = 133 SQ.MI.

CATALOGING UNITS 21020001 — ST. JOHN-ST. THOMAS.
U.S. VIRGIN ISLANDS.
AREA = 51 SQ.MI.
21020002 — ST. CROIX. U.S. VIRGIN ISLANDS.
AREA = 82 SQ.MI.

SUBREGION 2103 — CARIBBEAN OUTLYING AREAS: THE DRAINAGE AND ASSOCIATED WATERS WITHIN THE CANAL ZONE, NAVASSA ISLAND, AND RANCADOR AND SERRANA BANKS.
AREA = 650 SQ.MI.

ACCOUNTING UNIT 210300 — CARIBBEAN OUTLYING AREAS.
AREA = 650 SQ.MI.

CATALOGING UNITS 21030001 — CANAL ZONE. PANAMA CANAL ZONE.
AREA = 647 SQ.MI.
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21030003 — RONCADOR-SERRANA. RONCADOR AND SERRANA BANKS.
AREA = < 1 SQ.MI.

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A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

Prepared by Pamela C. Dodds, Ph.D., Licensed Professional Geologist
Prepared for The Wilderness Society - January 24, 2023

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February 21, 2023

Geological Society of America Bulletin

HYPSOMETRIC (AREA-ALTITUDE) ANALYSIS OF EROSIONAL TOPOGRAPHY

ARTHUR N STRAHLER

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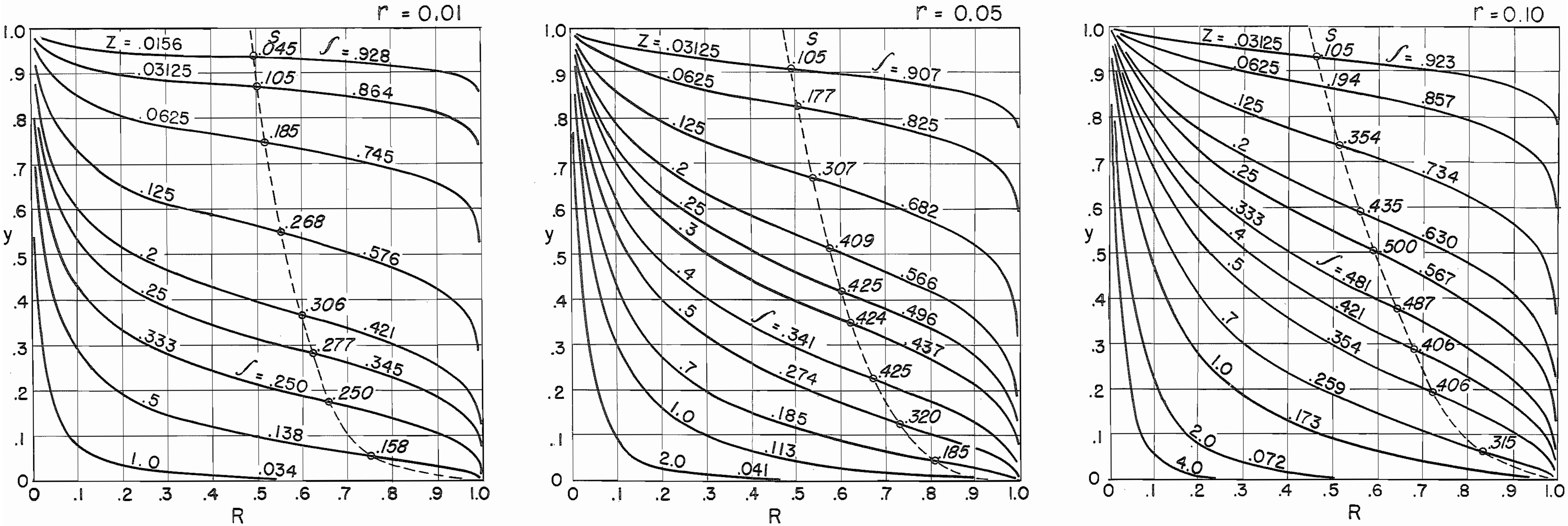


MODEL HYPSOMETRIC FUNCTION FOR DRAINAGE BASINS

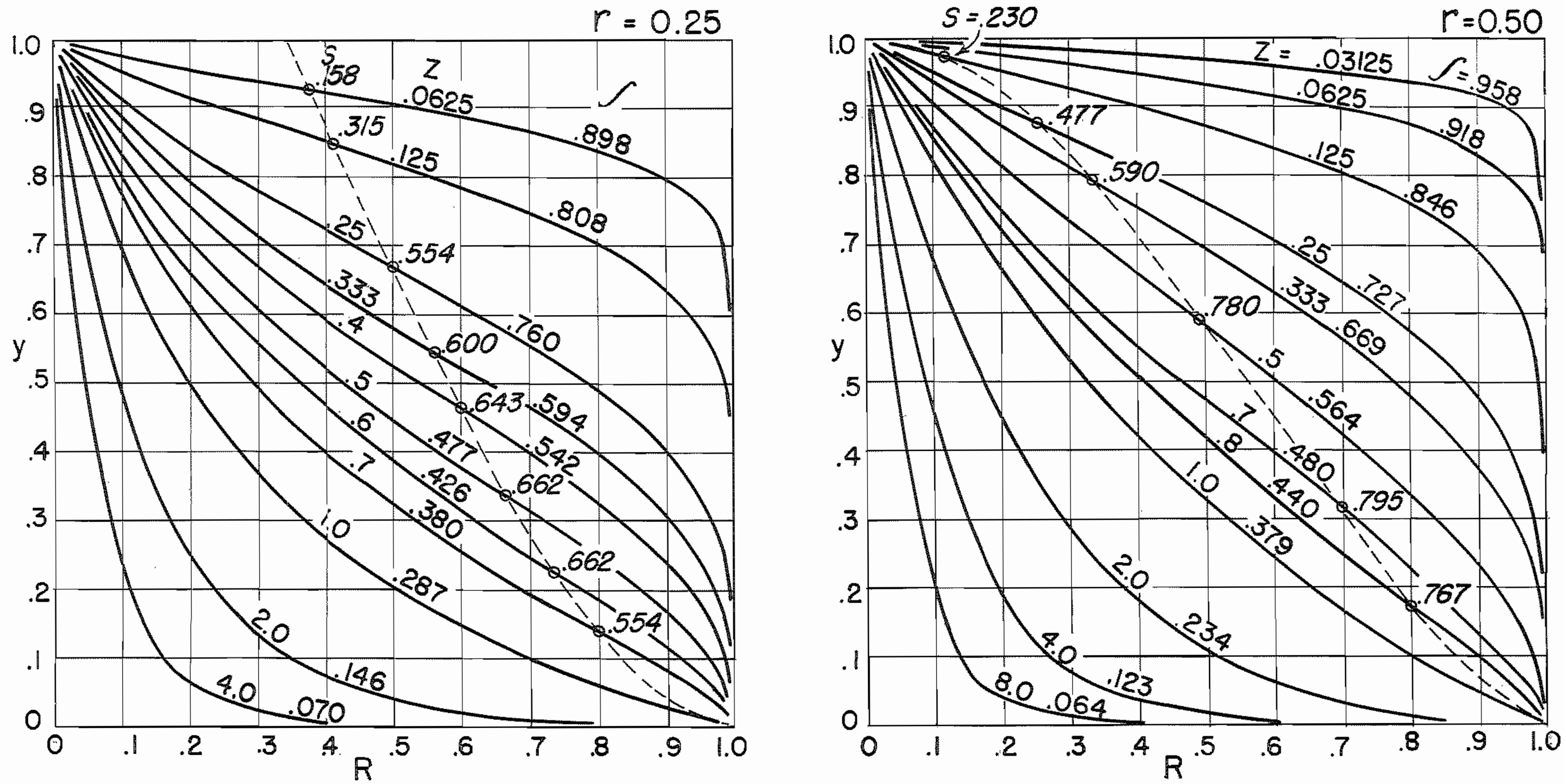
$$y = \left[\frac{d-x}{x} \cdot \frac{a}{d-a}\right]^z$$

Representative curves of five families, each family produced by a different value of r, where $r = \frac{a}{d}$.

Abscissa scaled in terms of percent, R, where $R = \frac{x-a}{d-a}$

S = Slope of curve at inflection point

$\int$ = Hypsometric integral



MODEL HYPSOMETRIC CURVES FOR FIVE VALUES OF r

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HYPSOMETRIC (AREA-ALTITUDE) ANALYSIS OF EROSIONAL TOPOGRAPHY

By Arthur N. Strahler

Abstract

The percentage hypsometric curve (area-altitude curve) relates horizontal cross-sectional area of a drainage basin to relative elevation above basin mouth. By use of dimensionless parameters, curves can be described and compared irrespective of true scale. Curves show distinctive differences both in sinuosity of form and in proportionate area below the curve, here termed the hypsometric integral. A simple three-variable function provides a satisfactory series of model curves to which most natural hypsometric curves can be fitted. The hypsometric curve can be equated to a mean ground-slope curve if length of contour belt is taken into account.

Stages of youth, maturity, and old age in regions of homogeneous rock give a distinctive series of hypsometric forms, but mature and old stages give identical curves unless monadnock masses are present. It is therefore proposed that this terminology be replaced by one consisting of an inequilibrium stage, an equilibrium stage, and a monadnock phase.

Detailed morphometric analysis of basins in five sample areas in the equilibrium stage show distinctive, though small, differences in hypsometric integrals and curve forms. In general, drainage basin height, slope steepness, stream channel gradient, and drainage density show a good negative correlation with mean integrals. Lithologic and structural differences between areas or recent minor uplifts may account for certain curve differences. Regions of strong horizontal structural benching give a modified series of hypsometric curves.

Practical applications of hypsometric analysis are foreseen in hydrology, soil erosion and sedimentation studies, and military science.

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Introduction

Topography produced by stream-channel erosion and associated processes of weathering, mass movement, and sheet runoff is extremely complex, both in the geometry of the forms themselves and in the interrelations of the processes which produce the forms. Although the fluvial-erosional landforms constitute the largest proportion of the earth's land surfaces and therefore deserve intensive study, only in recent years have investigations moved from the rather limited phase of simple visual observation and generalized verbal descriptions to the more productive but vastly more refractory phase of quantitative description and dynamic analysis.

Dynamic-quantitative studies require, first, a thorough morphological analysis in order that the form elements of a landscape may be separated, quantitatively described, and compared from region to region. Drainage network characteristics and channel gradients, slope profile forms, declivities and lengths, drainage densities, and hypsometric properties are among the general classes of morphological information for which standardized measures must be set up so that the essential differences and similarities between regions can be understood. Second, the topographic forms must be related quantitatively to the rates and intensities of the denudational processes. These relationships may take the form of empirical equations derived by methods of mathematical statistics from the observational data, or deduced mathematical models whose validity is sustained by observed values.

The material in the present paper is merely one very small part of the morphological analysis. It concerns the investigation of hypsometric properties of small drainage basins—that is, area-altitude relationships and the manner in which mass is distributed within a drainage basin.

Some parts of this paper represent work supported by the Penrose Bequest, Project Grant 525-48; but the greater part of the investigation was supported by the Office of Naval Research under Contract N6 ONR 271, Task Order 30, Project No. NR 089-042.

The writer is greatly indebted to Dr. W. W. Rubey, Chairman of the National Research Council, and Dr. Luna B. Leopold, Water Resources Division of the U. S. Geological Survey, for critically reading the manuscript and making many suggestions for its clarification. Mr. James L. Lubkin of the Columbia School of Engineering developed the model hypsometric function; Professor Robert Bechhofer and his staff of the Statistical Consulting Service of Columbia University advised the author on testing procedures.

Principles of Hypsometric Analysis

Hypsometric Curve in Absolute Units

Hypsometric analysis is the study of the distribution of ground surface area, or horizontal cross-sectional area, of a landmass with respect to elevation. The simplest form of hypsometric curve (hypsographic curve) is that in absolute units of measure. On the ordinate is plotted elevation in feet or meters; on the abscissa the area in square miles or kilometers lying above a contour of given elevation. The areas used are therefore those of horizontal slices of the topography at any given level. This method produces a cumulative curve, any point on which expresses the total area (reduced to horizontal projection) lying above that plane.

The absolute hypsometric curve has been used in regional geomorphic studies to show the presence of extensive summit flatness or terracing, where the surfaces lies approximately horizontal. Where these surfaces have a pronounced regional slope, they may not appear on the curve. Because a good topographic map, from which the hypsometric curve was prepared, will usually show these features, the justification for an elaborate hypsometric process for interpreting geomorphic history is doubtful.

For analysis of the form quality of erosional topography, use of absolute units is unsatisfactory because areas of different size and relief cannot be compared, and the slope of the curve depends on the arbitrary selection of scales. To overcome these difficulties, it is desirable to use dimensionless parameters independent of absolute scale of topographic features.

Percentage Hypsometric Curve

Hypsometric analysis, in general use for calculation of hydrologic information (Langbein *et al.*, 1947), takes a complete drainage basin above a selected point on a main stream as the area of study. The present study of form qualities of erosional topography likewise uses natural drainage basins, whether single or composite, on the assumption that the form of each drainage basin results from the interaction of slope-wasting and channel-deepening processes within the limits of the drainage divide, and hence that each basin should be treated as a unit.

Most drainage basins in homogeneous materials are pear-shaped in outline, with lateral divides converging to a clearly defined constriction, or mouth (Horton, 1941, p. 303). For hypsometric study, a geometric unit of reference consists of a solid bounded on the sides by the vertical projection of the basin perimeter and on the top and base by parallel planes passing through the summit and mouth respectively (Fig. 1). Although both of these reference planes may be expected to change as the basin is denuded, they are real points which can always be determined.

The percentage hypsometric method used in this investigation relates the area enclosed between a given contour and the upper (headward) segment of the basin perimeter to the height of that contour above the basal plane. The method has been used by Langbein (1947) for hydrologic investigations. Two ratios are involved (Fig. 1): (1) ratio of area between the contour and the upper perimeter (Area a) to total drainage basin area (Area A), represented by the abscissa on the coordinate system. (2) Ratio of height of contour above base (h) to total height of basin (H), represented by values of the ordinate.

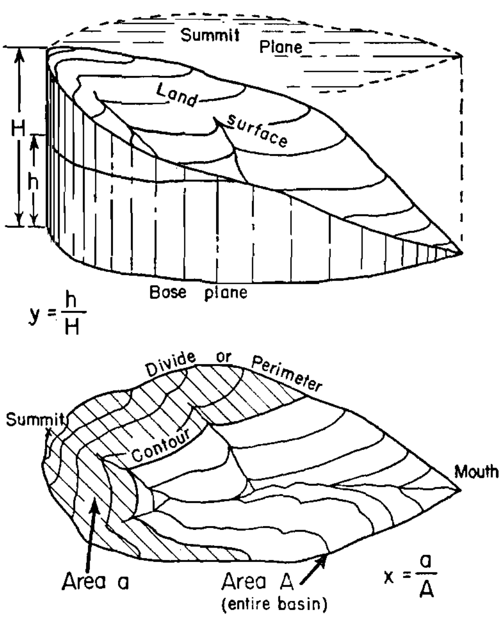

FIGURE 1.—FIGURE OF REFERENCE IN PERCENTAGE HYPSOMETRIC ANALYSIS
Showing derivation of the dimensionless parameters used in Figure 2.

The resulting hypsometric curve (Fig. 2) permits the comparison of forms of basins of different sizes and elevations. It expresses simply the manner in which the volume lying beneath the ground surface is distributed from base to top. The curve must always originate in the upper left-hand corner of the square ($x = 0$, $y = 1$) and reach the lower right-hand corner ($x = 1$, $y = 0$). It may, however, take any one of a variety of paths between these points, depending upon the distribution of the landmass from base to top.

Method of Obtaining Hypsometric Data

Actual measurement and calculation of hypsometric data have been done by the writer in the following steps: First, the drainage basin is selected and outlined. Selection of the basin is influenced by the purpose of the investigation, which may call for a study of the first-order drainage basins or of composite basins whose trunk streams have an order of 3, 4, or higher.[1] Having made this decision, the operator draws in the drainage divide on the map. The divide is carried down to the stream at its point of junction with a stream of the same or higher order.

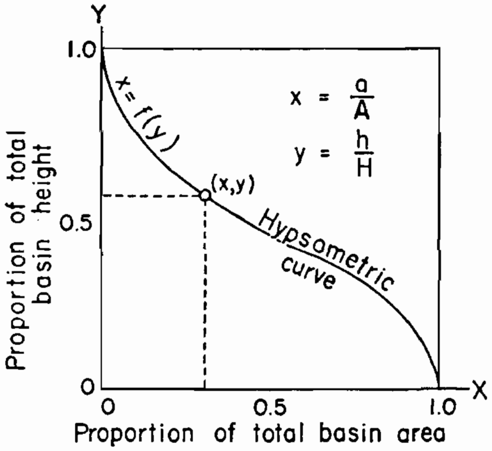

FIGURE 2.—THE PERCENTAGE HYPSOMETRIC CURVE

With a polar planimeter, the operator measures first the area of the entire basin, then the areas enclosed between each contour and the upper perimeter. Ratios are computed and will range from 1.0 to 0.0. Where relief is strong and contours closely crowded, every second or fifth contour is used, except near the summit where all available contours are used. Obviously the value of hypsometric analysis depends on use of sufficiently accurate and large-scale maps for the drainage basins involved. Where texture is fine and unit basins very small, special field maps on a large scale must first be surveyed.

Height ratios are obtained by first determining the total range between basin mouth and summit point. The height of each measured contour above the mouth elevation is then determined and ratios to total basin height computed. These will range from 0.0 to 1.0 in inverse series to the area ratios.

The ratios are plotted on any convenient cross-section paper and the curve drawn smoothly with the aid of a draftsman's curve. For purposes of comparison with model curves illustrated in Plate 1, cross-section paper of 10 divisions per ½ inch should be used, allotting a square 5 inches wide to the hypsometric graph.

Integration of the Hypsometric Function

In order to calculate the volume of earth material contained between the ground surface and the bottom and sides of the figure of reference (Fig. 1), the landmass may be thought of as consisting of horizontal slabs (Fig. 3). The total volume, V, consists of the sum of all slabs. The volume of one slab, ΔV, is obtained by multiplying the area of the slab, a, by its thickness, Δh. Following the mathematical principle of integration, the entire volume may be stated by the expression

$$\text{I} \qquad V = \int_{\text{base el}}^{\text{summit el}} a\,dh.$$

If we now divide both sides of this equation by H and A, which are constant terms,

$$\frac{V}{HA} = \frac{1}{HA}\int_{\text{base el}}^{\text{summit el}} a\,dh$$

or

$$\frac{V}{HA} = \int_{\text{base el}}^{\text{summit el}} \frac{a}{A}\,d\left(\frac{h}{H}\right)$$

This expresses the ratio of volume lying beneath the surface, V, to the entire volume of the reference figure, HA. Because $\frac{a}{A} = x$, and $\frac{h}{H} = y$, by our definition, then

$$\text{II} \qquad \frac{V}{HA} = \int_0^{1.0} x\,dy.$$

[1] Stream orders have been defined by Horton (1945, p. 281–283), but the writer has followed a somewhat different system of determining orders: The smallest, or "finger-tip", channels constitute the first-order segments. For the most part these carry wet-weather streams and are normally dry. A second-order segment is formed by the junction of any two first-order streams; a third-order segment is formed by the joining of any two second-order streams, etc. This method avoids the necessity of subjective decisions, inherent in Horton's method, and assures that there will be only one stream bearing the highest order number.

Thus, if the hypsometric function, $x = f(y)$, is integrated between the limits of $x = 0$ and $x = 1.0$, a measure of landmass volume remaining with respect to volume of the entire reference solid is obtained. This integral is here designated the hypsometric integral and is equivalent to the ratio of area under the hypsometric curve to the area of the entire square. It is expressed in percentage units and can be obtained from any percentage hypsometric curve by measuring the area under the curve with a planimeter. Whether the integration is of the function $y = f(x)$ or $x = f(y)$ is of no consequence. The latter function was used in this explanation because the unit slabs of volume are thought of as being horizontal, rather than vertical.

As discussed elsewhere in this paper, both the form of the hypsometric curve and the value of the integral are important elements in topographic form and show marked variations in regions differing in stage of development and geologic structure.

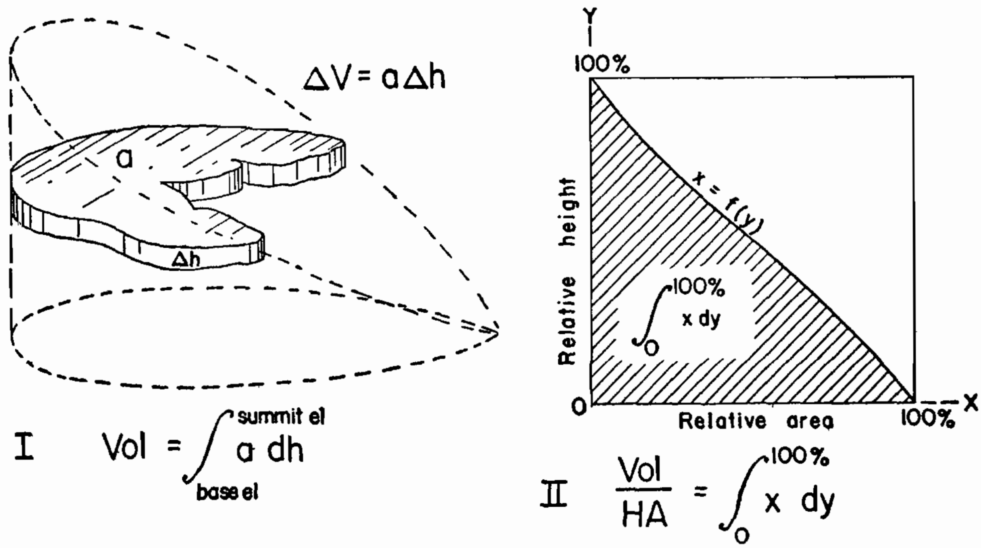

FIGURE 3.—INTEGRATION OF THE HYPSOMETRIC FUNCTION
And meaning of hypsometric integral.

A Model Hypsometric Function

It is desirable to find a relatively simple, yet flexible function which may be fitted to any natural hypsometric curve. This is necessary so that certain mathematical operations can be performed to obtain information useful in hydrologic and other applications.

Inspection of a large number of hypsometric curves has shown that the majority are s-shaped. An up-concavity is commonly present in the upper part; a convexity in the lower part. Sinuosity varies greatly so that the slopes of the curves at their inflection points have a wide range. It is therefore necessary to use an equation having two parameters, one to vary the hypsometric integral, the other to control the sinuosity.

A function[2] which meets these requirements fairly well is

$$\text{III} \qquad y = \left[\frac{d-x}{x} \cdot \frac{a}{d-a}\right]^z$$

where a and d are constants, d always greater than a, and the exponent z, positive or zero (Fig. 4). All curves pass through A and B. The slope of the curve at its inflection point depends on the ratio $\frac{a}{d}$, hereinafter designated r. The general location of the curve depends upon the exponent z.

[2] The writer is indebted to Mr. James Leigh Lubkin of the School of Engineering of Columbia University for developing this equation. It was adapted from a somewhat similar equation used by Hunter Rouse (1937, p. 536) to describe the distribution of suspended load in a stream.

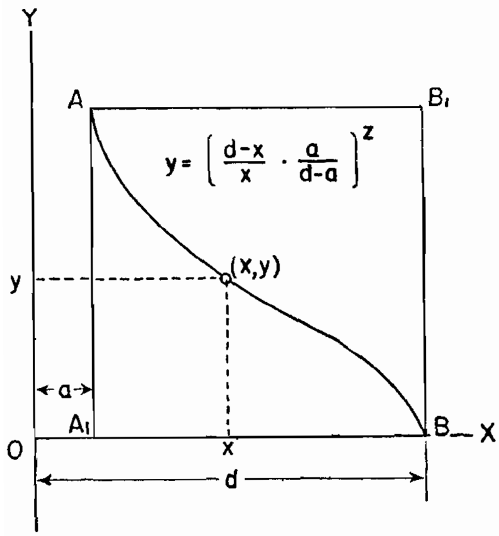

FIGURE 4.—MODEL HYPSOMETRIC FUNCTION

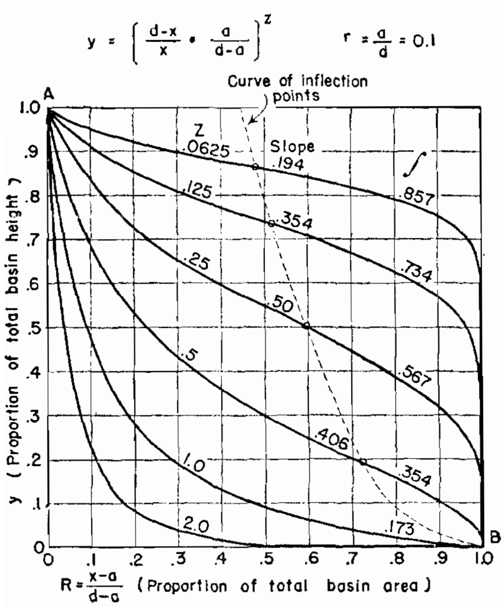

FIGURE 5.—FAMILY OF CURVES FOR THE VALUE, $r = 0.1$

For selected values of z. Given alse are the integrals and the slope of each curve at its inflection point. (Other curve families are given in Plate 1.)

In order to have a percentage scale on the abscissa, conforming with the percentage hypsometric function as previously defined, a modification of equation III is introduced. It is desired that the scale of values on the abscissa as shown in Figure 4 should range from 0 at $x = a$ to 1.0 at $x = d$. This percentage, R is therefore expressed as

$$R = \frac{x - a}{d - a}.$$

In subsequent illustrations of the model hypsometric equation (Figs. 5, 6; Pl. 1) the abscissa appears scaled in terms of R.

To plot a family of model curves having one particular degree of sinuosity, a value of r is selected; curves within each family are then obtained by using different values of the exponent, z.[3]

As an illustration of a family of curves, that particular family in which $r = 0.1$ is given in Figure 5. Curves for several values of z, ranging from 0.0625 to 2.0, are shown. Plate 1 gives five families of curves and can be used for fitting of natural curves by inspection. Curves represented by this model function have the following characteristics (1) The curves are s-shaped where $z < 1$, but are of simple concave-up form where $z > 1$. (2) Where $z < 1$, curves entering at A have a slope, whereas they are tangent to the vertical through the point B.

Decreasing the value of r increases the degree of sinuosity of the curve, thereby reducing the slope of the curve in the region of inflection. This effect may be seen by studying individual curves for the families $r =$ 0.01, 0.05, 0.1, 0.25, and 0.5 (Fig. 6). For comparison, five curves were selected whose integral is approximately the same.

It is not practical to obtain the hypsometric integrals of theoretical curves by mathematical procedures, hence these were obtained by the writer by planimeter measurement for all curves plotted. On each model curve (Pl. 1), the integral is given. The values are only approximate, being subject to errors in measure-

[3] For plotting, the following form of equation III can be used:

$$\text{IV} \quad y = \left[\frac{r}{1 - r}\right]^z \left[\frac{1}{(1 - r)\,R + r} - 1\right]^z$$

where r and R are as defined above. For a given curve, r and z are constants; hence, by substituting a series of values of R ranging from 0 to 1.0, the corresponding values of y may be obtained.

ment as well as errors in plotting the curves from which they were measured.

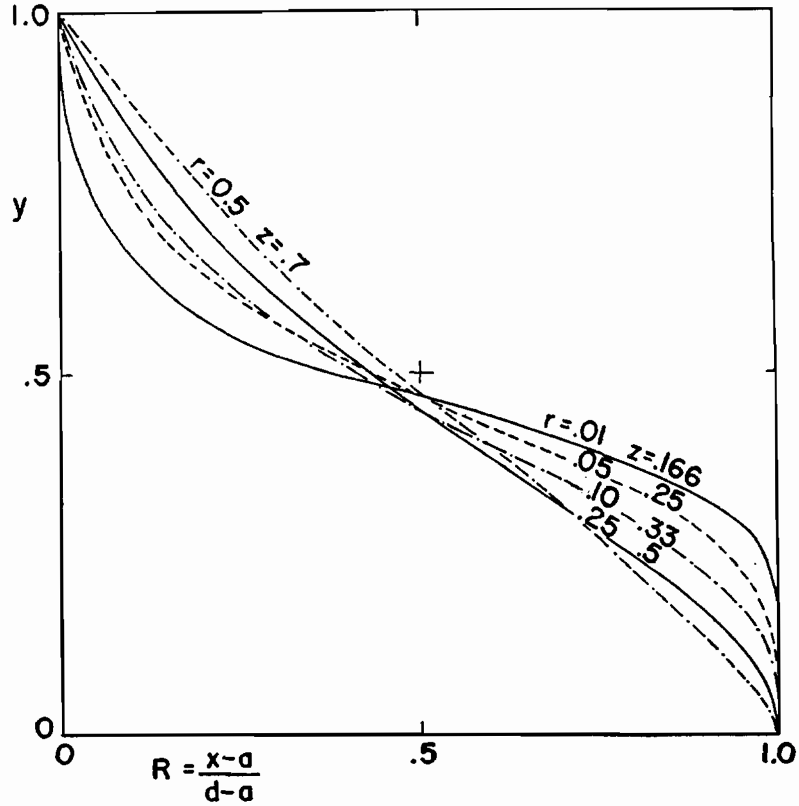

FIGURE 6.—COMPARISON OF SEVERAL CURVE FAMILIES

Showing the effect of varying the value of r in the model hypsometric function. Integrals of these curves are approximately the same.

Because one method of fitting model curves to natural hypsometric curves involves the matching of integrals, it is desirable to have a means of obtaining from a given integral the exponent, z, of a particular model curve which possesses that integral. A graphic solution is shown in Figure 7. Given an integral, measured by planimeter from a natural hypsometric curve, and having selected by inspection the curve family whose value of r gives the closest fit as to shape, one can read the desired value of z.

Inflection Points and Slopes

The point of inflection on any of the model hypsometric curves where z is less than 1.0 may be obtained by the usual method of setting the second derivative of the function equal to 0. For plotting, it is convenient to find the inflection point in terms of R in Equation IV, as the following equation:

$$\text{V} \qquad R_i = \frac{1 + z - 2r}{2\,(1 - r)}$$

where R_i is the value of R at which the curve inflects. Inflection points and the curves on which they lie are shown on the graphs for the several values of r (Fig. 5; Pl. 1).

Inflection points have morphological significance on hypsometric curves because they mark the level at which the rate of decrease of mass upwards changes from an increasingly rapid rate of decrease to a diminishing rate of decrease. Further investigation may prove this feature to be related to dynamic factors, such as the relative importance of sheet runoff

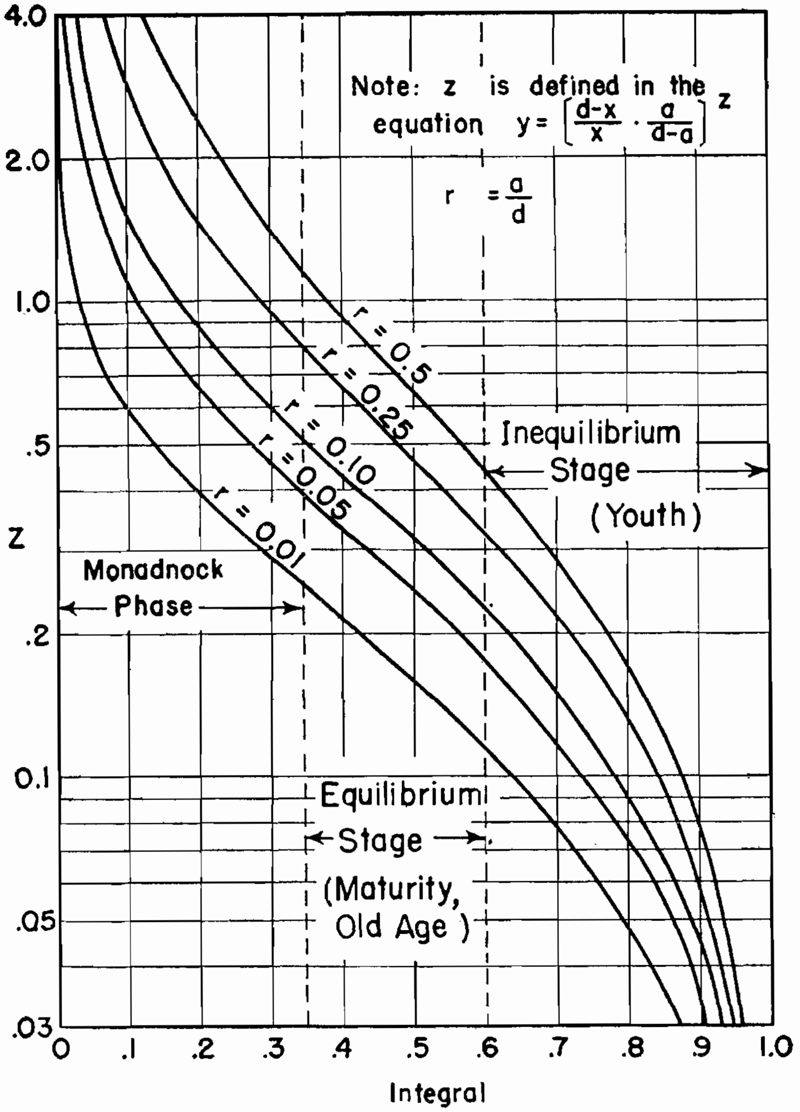

FIGURE 7.—GRAPHIC SOLUTION OF INTEGRALS AND EXPONENTS
For curve families produced by five selected values of r. (See Plate 1 for further data.)

and creep at higher levels compared to channel erosion at lower levels.

While the position of the inflection point on a natural hypsometric curve is greatly affected by chance irregularities of form not significant in the gross aspect of the drainage basin, the slope of the curve in the general region of the inflection can be expected to be a reliable form element. Comparisons of the curve families show that slope at the inflection point is steep where r has high values and diminishes as r decreases. For the curve family $r = 0.5$, the slopes approach 80 per cent near the center of the diagram, while for the family $r = 0.01$ they are reduced to about 30 per cent.

Hypsometric slope at the inflection point is thus a form characteristic which can be rapidly determined and used as one means of fitting natural to model curves. When the slope of the natural curve in the vicinity of its inflection point has been measured, the curve can be matched to the family having a similar slope.

Then, by matching integrals, the particular value of z can be determined.

Precise values of slope at inflection points can be determined from Equation IV by taking the first derivative of the function and substituting for R the various values of these inflection points already obtained. In view of the labor of calculation involved and the fact that exact values are not required for any uses of hypsometric analysis thus far made, the slopes listed opposite each integral on the graphs were determined by direct angular measurement from the graphs. These are, of course, subject to errors in the use of the protractor on a curve drawn through a number of plotted points.

Relation of Hypsometric Curve to Ground Slope

Characteristics of the hypsometric curve are closely related to ground-slope characteristics of a drainage basin. This is evident from the fact that steepening of slopes in the mid-section of a basin will be accompanied by a more rapid rate of change of elevation with respect to change of horizontal cross-sectional area of the basin. One might, at first thought, suppose that steep parts of the hypsometric curve would coincide with belts of relatively steep slopes, gently sloping parts of the curve with gentle ground slopes. Unfortunately the relationship is not so simple. Figure 8 shows a small drainage basin; Figure 9 is the corresponding hypsometric curve. The curve has a gentle slope in the upper part, corresponding with a broad divide area on the map. The steep intermediate part of the hypsometric curve corresponds with steep valley wall slopes in the mid-section of the basin. But the very lowest part of the curve is steepest of all in the region corresponding to the mouth area of the basin, whereas the contours of the map show that the ground slopes are less here than in the mid-section of the basin. The additional factor is, of course, the length of the belt between successive pairs of contours. ("Length" refers to distance along the contour.) Only if each contour belt is the same length can steepness of ground slope vary directly as steepness of hypsometric curve. In Figure 10, all contours have the same length, and the slope profile is identical with the hypsometric curve. Obviously a drainage basin cannot fulfill this condition while narrowing to a mouth through which all drainage is discharged by a narrow channel; a shortening of the length of contours to a minimum approaching zero is required as the drainage basin is followed to its mouth. At the upper end of the drainage basin, the contours can maintain nearly equal length up to the divide (which may be horizontal), but normally the contour length diminishes here, too, to approach zero on the highest peak. Thus the characteristic steepening of hypsometric curves both at the lower and upper ends in mature topography is explained by the diminishing contour lengths.

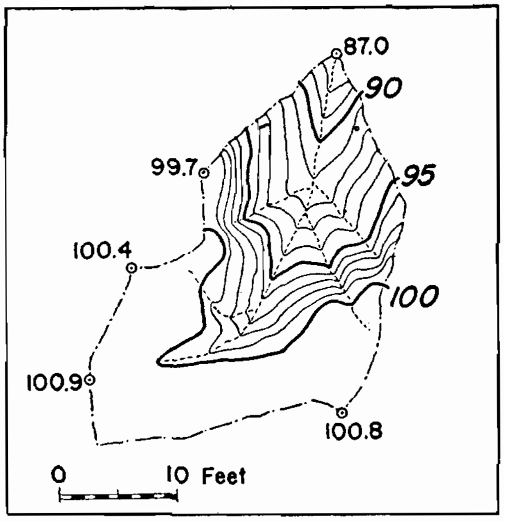

FIGURE 8—SMALL DRAINAGE BASIN IN BADLANDS, PERTH AMBOY, NEW JERSEY

From a special large-scale topographical survey.

To relate hypsometric curve to ground slope it is necessary to take contour length into account. First, the length of each contour line is measured. For each belt of ground between two successive contours the lengths of the upper and lower contours are added and the sum divided into two, giving a rough mean length for the contour belt (Fig. 11). Next the area of the contour belt is measured by planimeter. Dividing area of the contour belt by mean length gives a rough mean width (horizontal distance) for the belt. Now, by dividing the contour interval by the mean width we can

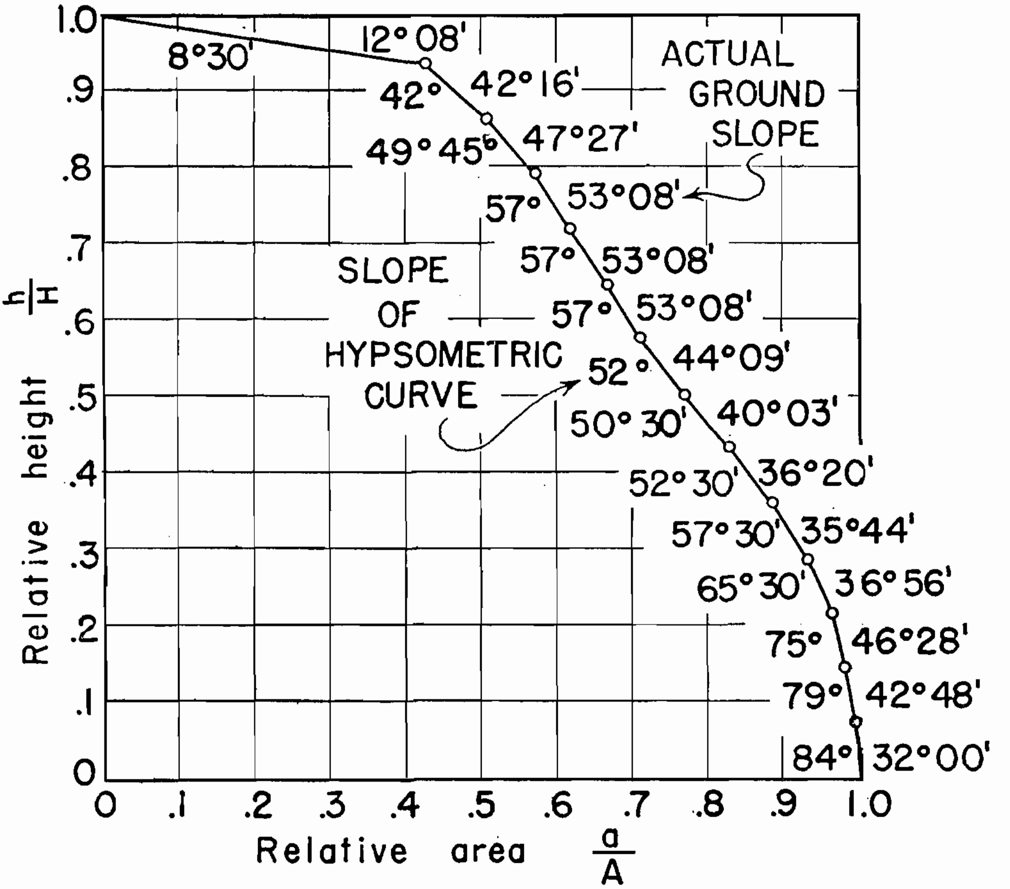

FIGURE 9.—HYPSOMETRIC CURVE OF BASIN SHOWN IN FIGURE 8
Showing relation between slope of segments of hypsometric curve and actual mean ground slopes of corresponding segments.

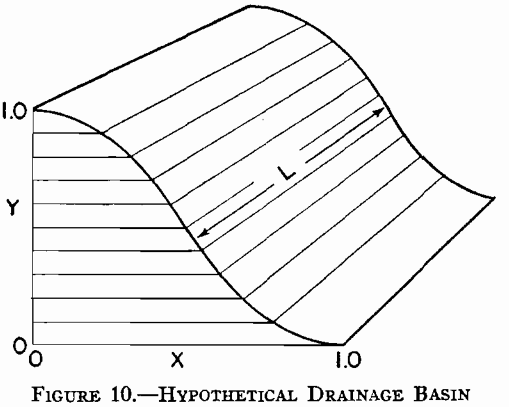

FIGURE 10.—HYPOTHETICAL DRAINAGE BASIN
In which slope of hypsometric curve is identical with ground-slope curve.

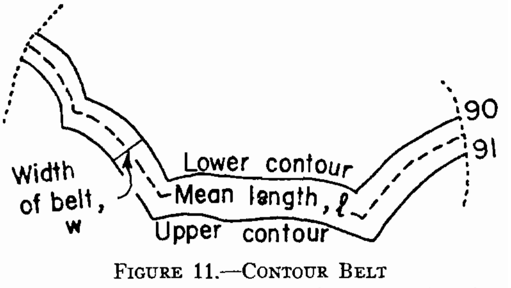

FIGURE 11.—CONTOUR BELT
Showing method of calculating mean length, width, and slope of contour belt.

determine the mean slope of the ground within this particular contour belt, for, $\tan \alpha = \frac{h}{w}$,

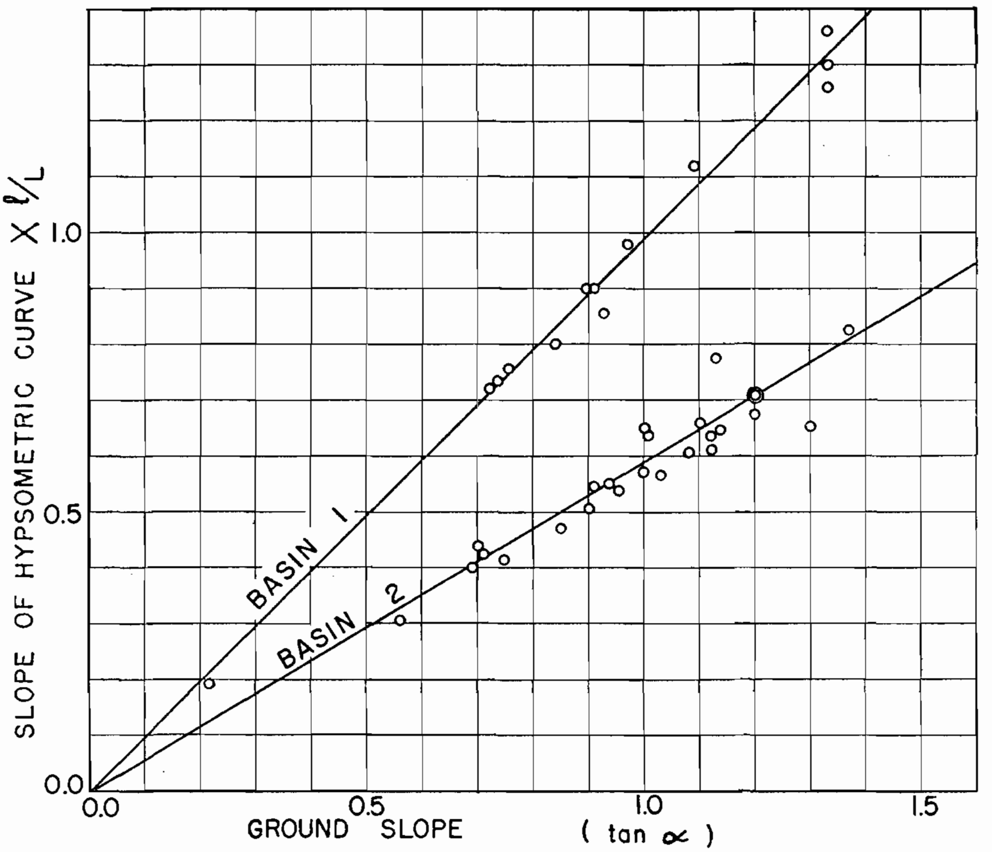

FIGURE 12.—CORRELATION OF MEAN GROUND SLOPES AND ADJUSTED SLOPES OF HYPSOMETRIC CURVE SEGMENTS
Basin 1 same as that in Figures 8 and 9.

where
α is angle of ground slope,
h is contour interval
w is mean width of the belt measured in horizontal projection.

Values of mean slope angle for the basin shown in Figure 8 are written directly on the hypsometric curve (Fig. 9) opposite the particular segments to which they relate. The calculated mean slope figures compared with the slope of the hypsometric curve shows rough correspondence only in the upper part. If, however, we correlate the mean ground slope figures with the contour map of the basin, the slope angles vary as the spacing of the contours, being highest in the midsection, where slopes up to 53° are found.

Relationship of hypsometric curve to mean ground slopes may be summarized by the following equation, which takes into account relative length of each contour belt.

VI $$\frac{l}{L}\tan\theta = \kappa\tan\alpha$$

where θ = slope of hypsometric curve
α = mean ground slope
l = contour length at given relative height
L = length of longest contour in basin
κ = a constant

To test the usefulness of this equation, the values of ground slope have been plotted against corresponding values of hypsometric curve slope for each contour interval of the drainage basin (Fig. 12, Basin 1). Also plotted on Figure 12 are corresponding data for a second drainage

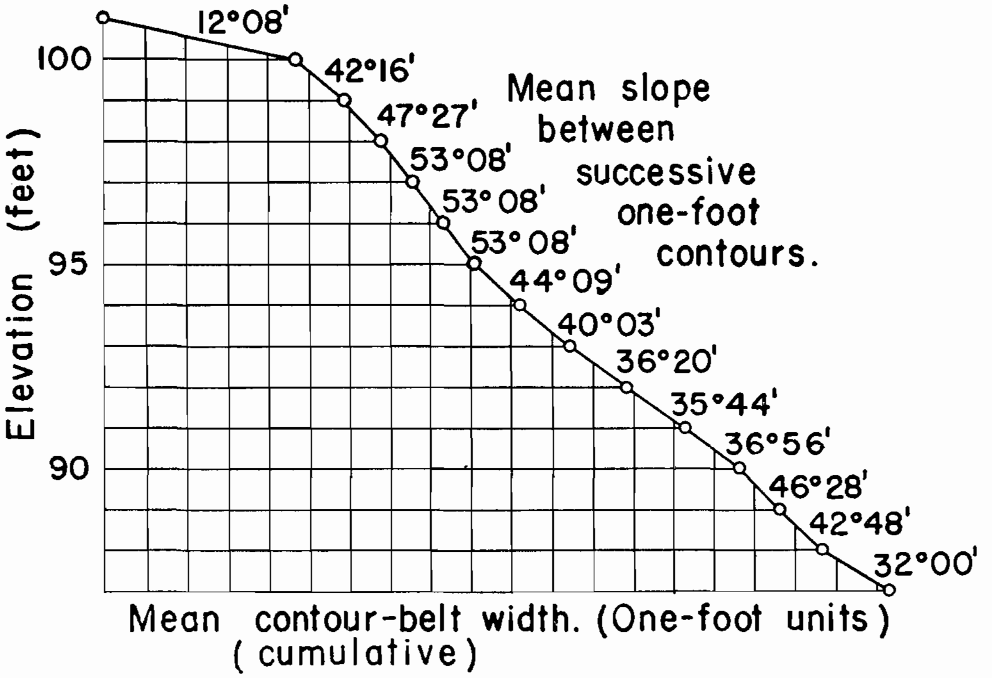

FIGURE 13.—TRUE MEAN-SLOPE CURVE OF BASIN SHOWN IN FIGURE 8
Abscissa and ordinate on same scale.

basin which is in the equilibrium (mature) stage of development and has a narrow divide ridge crest. Note that the two curves, which were fitted by inspection, pass through the origin but have markedly different slopes, which may be attributed to the difference in stage of development of the two basins. The tangent function is extremely sensitive to small errors of horizontal measurement, and, because the range of error in measurement from the map is relatively large, the values are subject to considerable variation. Hence these correlation diagrams should be thought of as only demonstrating the general validity of Equation VI.

A profile of the true mean ground slope (Fig. 13) is a cumulative plot of mean-slope angles for each contour belt. This curve differs from the hypsometric curve of the same basin (Fig. 9) in that the mean-slope curve is plotted with absolute values, the scale of feet being the same on both ordinate and abscissa. By use of this curve, ground slope distribution with respect to height can be depicted for direct visual analysis, inasmuch as the slope of the curve is the actual mean ground slope.

GEOMORPHIC APPLICATIONS OF HYPSOMETRIC ANALYSIS

The Geomorphic Cycle

The hypsometric curve exhibits its widest range of forms in the sequence of drainage basins commencing with early youth (inequilibrium stage), progressing through full maturity (equilibrium stage), and attaining temporarily the monadnock phase of old age.

A drainage basin in youth is shown in Figure 14. It is from the Maryland coastal plain where a large proportion of upland surface has not yet been transformed into valley-wall slopes. The hypsometric curve has a very high integral, 79.5%, indicating that about four-fifths of the landmass of the reference solid remains. Despite the bold convexity of the curve through its central and lower parts, the upper end has the concavity typical of nearly all normal drainage basins, and shows that some relief does exist in the broad divide areas.

Figure 15 represents a small drainage basin in fully mature topography of the Verdugo

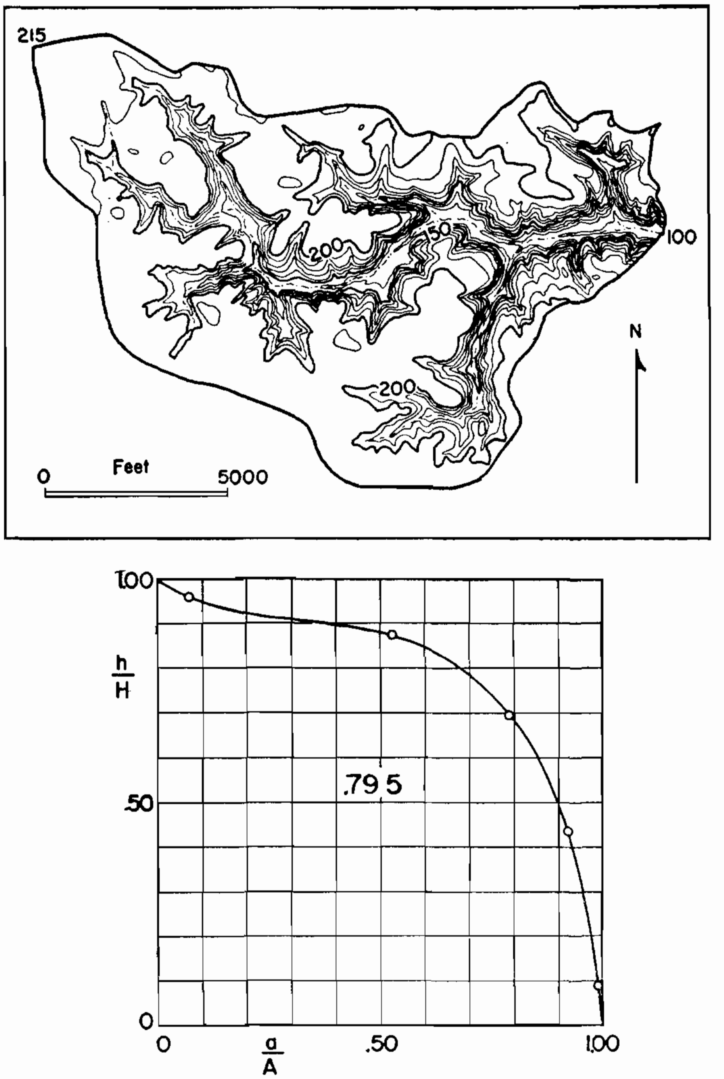

FIGURE 14.—INEQUILIBRIUM (YOUTHFUL) STAGE

Drainage basin of Campbell Creek on the Maryland Coastal Plain (above) with its hypsometric curve (below). From Yellow Tavern Quadrangle, Virginia, U. S. Geological Survey, 1:31,680.

Hills, southern California. Here divides are narrow and no vestiges remain of an original surface. The hypsometric curve passes approximately across the center of the diagram, with a hypsometric integral of 43%, and is smoothly s-shaped. This particular curve is typical of third- or fourth-order basins in relatively homogeneous rocks.

In late mature and old stages of topography, despite the attainment of low relief, the hypsometric curve shows no significant variations from the mature form, and a low integral results only where monadnocks remain. For example, a drainage basin in northern Alabama where low relief has developed on weak shales and limestones, but with prominent monadnock masses of sandstone which are outliers of a retreating escarpment, has a strongly concave hypsometric curve; the integral, 17.6%, is unusually low (Fig. 16). After monad-

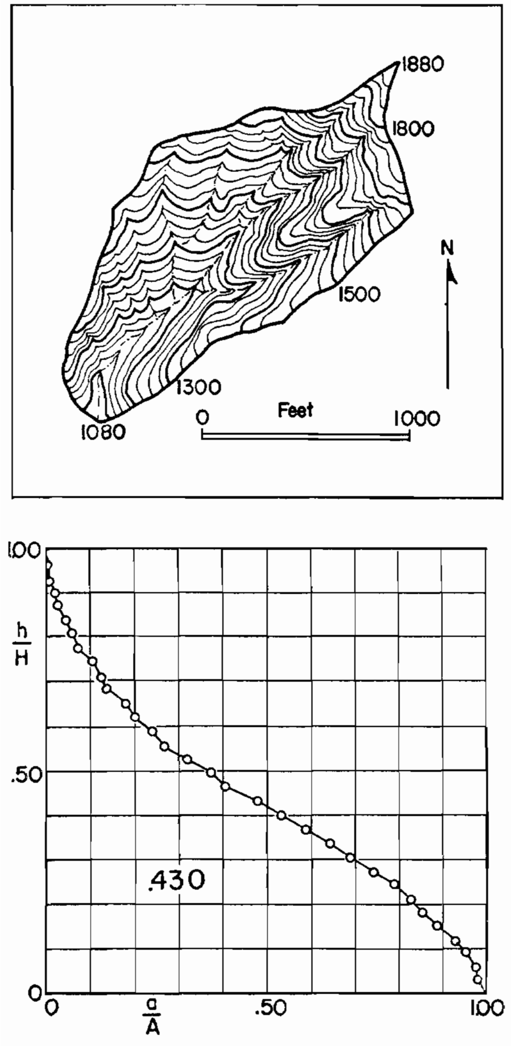

FIGURE 15.—EQUILIBRIUM (MATURE) STAGE
A small drainage basin in the Verdugo Hills, near Burbank, California (above), corresponding hypsometric curve (below). From Sunland Quadrangle, California, U. S. Geological Survey, 1:24,000.

nock masses are removed, the hypsometric curve may be expected to revert to a middle position with integrals in the general range of 40% to 60%.

From the standpoint of hypsometric analysis, the development of the drainage basin in a normal fluvial cycle seems to consist of two major stages only; (1) an inequilibrium stage of early development, in which slope transformations are taking place rapidly as the drainage system is expanded and ramified. (2) An equilibrium stage in which a stable hypsometric curve is developed and maintained in a steady state as relief slowly diminishes. The monadnock phase with abnormally low hypsometric integral, when it does occur, can be regarded as transitory, because removal of the monadnock will result in restoration of the curve to the equilibrium form.

Figure 7 shows relations of hypsometric integral, curve form, and stage of development. Values of z are plotted against hypsometric integrals for each of five families of curves represented by five values of r. From inspection of many natural hypsometric curves and the corresponding maps, the writer estimates that transition from the inequilibrium (youthful) stage to the equilibrium (mature) stage corresponds roughly to a hypsometric integral of 60%, but that where monadnocks become conspicuous features the integrals drop below 35%. These two percentages have, therefore, been used as tentative boundaries of the stages in Figure 7.

The hypsometric curve of the equilibrium stage is an expression of the attainment of a steady state in the processes of erosion and transportation within the fluvial system and its contributing slopes (Strahler, 1950). In this state, a system of channel slopes and valley-wall slopes has been developed which is most efficiently adapted to the reduction of the landmass with available erosional forces, balanced against the resistive forces of cohesion maintained by the bedrock, soil, and plant cover. The basins are no longer expanding in area; they are in contact with similar basins on all sides. The general similarity among hypsometric curves of regions in the equilibrium stage, despite great differences in relief, drainage density, climate, vegetation, soils, and lithology, seems to show that the distribution of mass with respect to height normally follows the s-shaped model hypsometric curve with its upper concavity and lower convexity.

Characteristics of the Equilibrium Stage

Five areas were selected which showed a great range of relief, and for which excellent large-scale topographic maps and air photographs were available. Within each area, six basins of the third or fourth order were outlined and the hypsometric curves plotted for each. A mean curve for each area was obtained

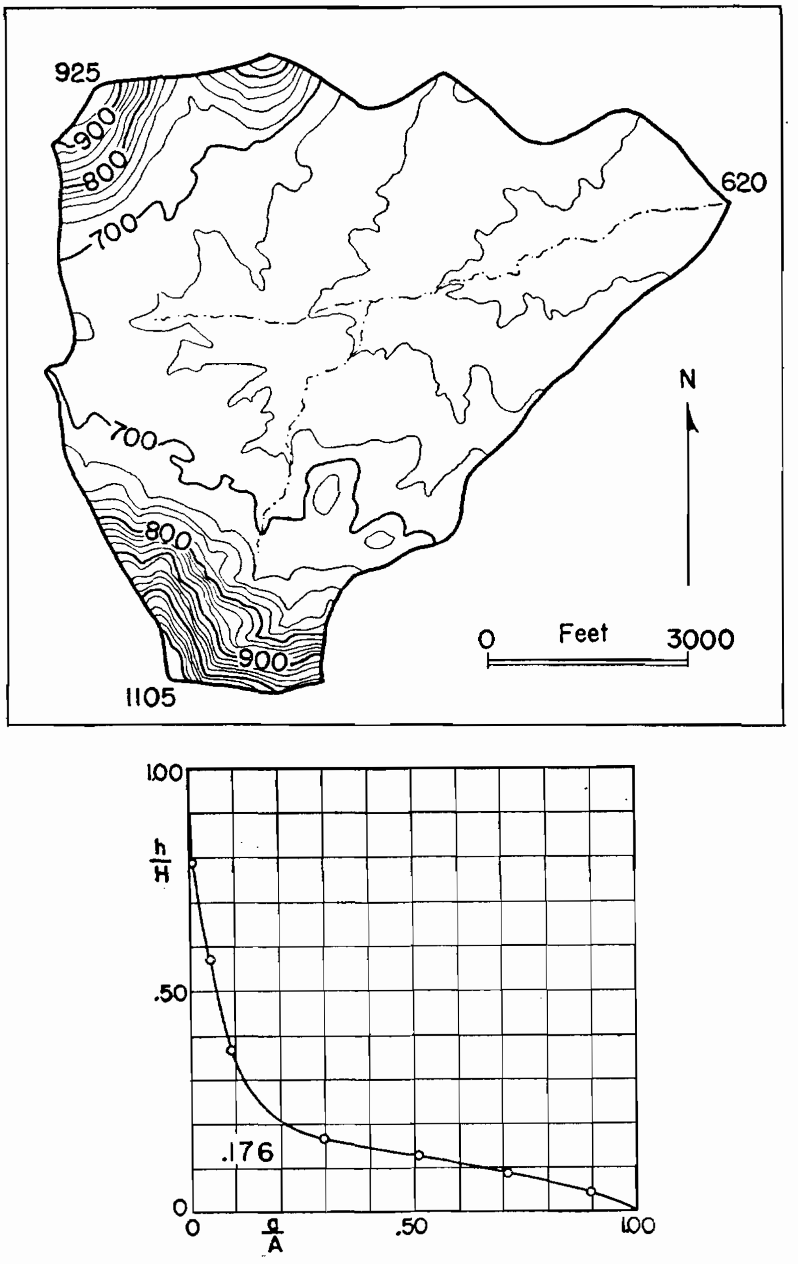

FIGURE 16.—MONADNOCK PHASE

Drainage basin of Atwood Branch, Newburgh Quadrangle, Alabama (above) showing remnants of retreating sandstone escarpment; corresponding hypsometric curve (below).

by plotting the arithmetic means of the ordinates of the six individual basin curves at every ten per cent division on the abscissa (Fig. 17). Figure 18 shows one drainage basin from each of the five areas; that basin was selected whose hypsometric curve most closely follows the mean curve shown in Figure 17. In this way the reader can visualize the appearance of a drainage basin embodying the characteristics of the mean hypsometric curve. Table 1 gives additional data relating to composition of the drainage systems.

The five areas selected are all areas of dendritic drainage, largely free from significant structural control. Long-continued fluvial erosion has removed all traces of flat interstream uplands and it is assumed that the basins are stable in form and that the total regimen of erosion and transportation processes is in a steady state. In relief, lithology and rock structure, vegetation, and climate, however, the five areas differ widely. Extremely low relief on weak Pliocene deposits of the Citronelle formation in western Louisiana is represented by the second area; low relief on Precambrian Wissahickon schists of the Piedmont Province in Virginia by the first area: moderate relief developed on cherts and cherty limestones of the Ozark Plateau province is exemplified by the third area. Extremely rugged terrain of strong relief and steep slopes on deeply weathered metasediments of the lower coastal ranges of the Los Angeles region is seen in the fourth area; great relief with moderately steep slopes on deeply weathered Precambrian Wissahickon schists of the southern flank of the Great Smoky Mountains in the fifth area.

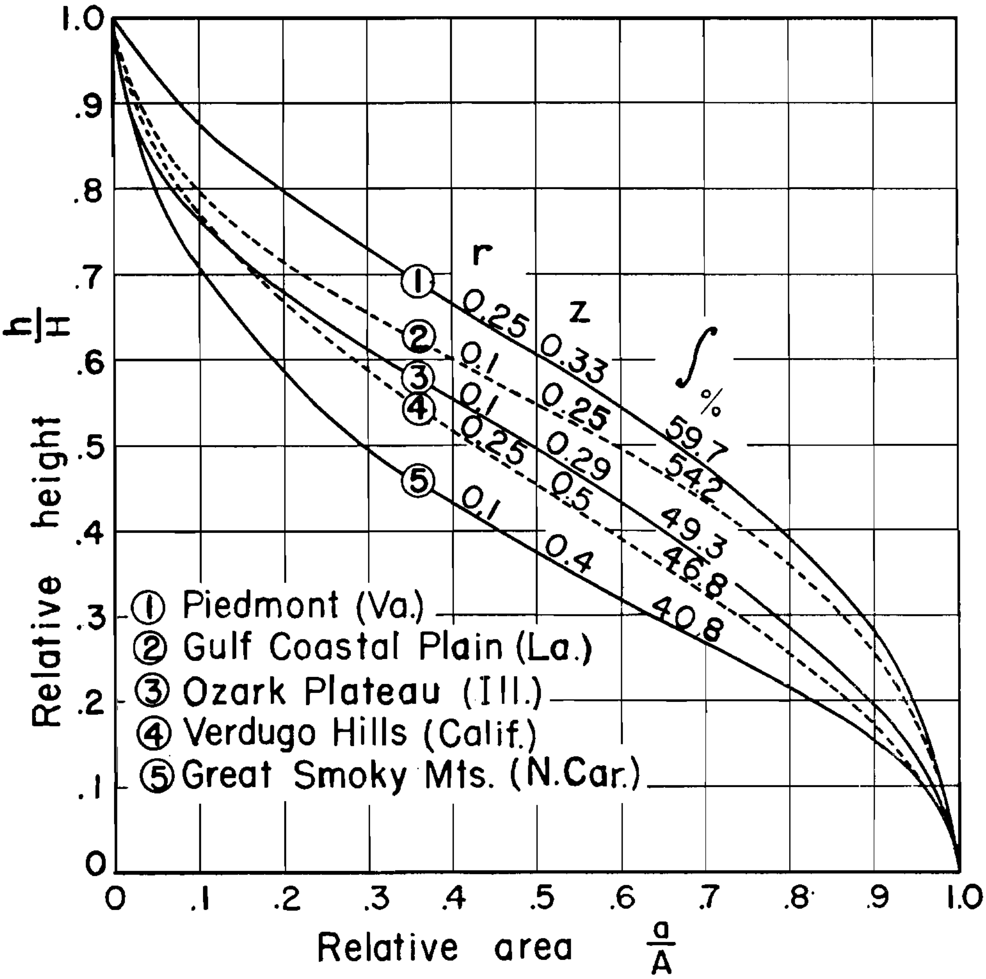

FIGURE 17.—MEAN HYPSOMETRIC CURVES OF FIVE AREAS IN THE EQUILIBRIUM STAGE

Curve 1: from Belmont Quadrangle, Virginia, U.S.A.M.S. 1:25,000. Curve 2: from Mittie Quadrangle, Louisiana, U. S. Geological Survey, 1:24,000. Curve 3: Wolf Lake Quadrangle, Illinois, U. S. Geological Survey, 1:24,000. Curve 4: La Crescenta, Glendale and Sunland Quadrangles, California, U. S. Geological Survey, 1:24,000. Curve 5: Judson and Bryson Quadrangles, North Carolina, T.V.A., 1:24,000.

Investigation of the five areas involved:

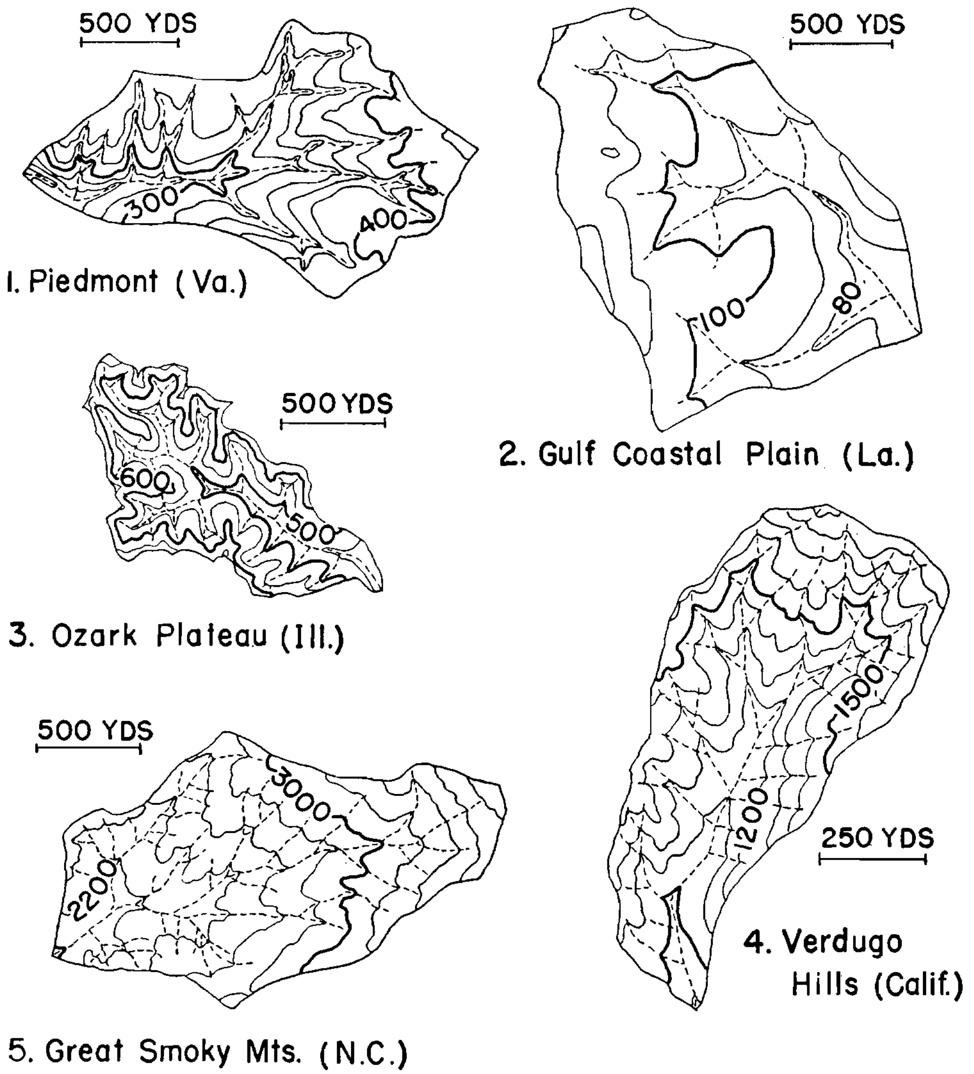

FIGURE 18.—REPRESENTATIVE BASINS FROM FIVE SAMPLE AREAS

[Showing the one drainage basin whose hypsometric curve most closely fits the sample mean curve of Figure 17. Localities as described in Figure 17.

(1) analysis of the hypsometric curves, similarities and differences, and their degree of resemblance to the model hypsometric function; (2) a comparison of hypsometric data with other categories of data, such as drainage network and slope characteristics. It was hoped that significant differences in the hypsometric curves could be correlated with significant differences in other drainage basin characteristics, and that this might provide clues to causative factors determining the hypsometric properties of mature topography.

The mean curves shown in Figure 17 have appreciable differences both in hypsometric integral and in form. The mean curves were fitted to the theoretical function by inspection, and the apparent best fits are described on the curves and in Table 1 by values of r and z. All five curves were best described by the families having r values 0.1 or 0.25 and we may infer that mature topography in relatively homogeneous materials tends to fall within this general range. Fit was very good for curves 1 and 5, but was good only in the inflection

TABLE 1. MORPHOMETRIC DATA

LOCALITIES INVESTIGATED		STREAM NUMBERS						STREAM LENGTHS				
	Quadrangle	Total number of Streams of each order				Bifurcation Ratios: r_b		Mean length of Stream segments of each order: Miles			Length Ratios	
		Σn_1	Σn_2	Σn_3	Σn_4	$\Sigma n_1 / \Sigma n_2$	$\Sigma n_2 / \Sigma n_3$	l_1	l_2	l_3	l_2 / l_1	l_3 / l_2
1.Piedmont	Belmont, Va. USAMS 1:25,000	141	34	6	0	4.15	5.67	0.234	0.345	1.130	1.47	3.27
2.Gulf Coastal Plain	Mittie, La. USGS 1:24,000	96	27	8	(2)	3.55	3.37	0.260	0.427	0.844	1.65	1.97
3.Ozark Plateau	Wolf Lake, Ill. USGS 1:24,000	198	38	10	(4)	5.21	3.80	0.099	0.132	0.368	1.33	2.79
4.Verdugo Hills	Glendale, Sunland, Cal. USGS 1:24,000	201	38	9	0	5.29	4.22	0.062	0.116	0.295	1.87	2.54
5.Great Smokies	Bryson, Judson, N.C. USGS 1:24,000	389	87	24	6	4.47	3.62	0.115	0.185	0.269	1.61	1.60

zone and at one end in the other three. All natural hypsometric curves suffer from some degree of misfitness at the lower end owing to the development of a valley-bottom flat which prevents the curve from approaching the value of 1.0 on the abscissa as closely as on the model curves.

All five mean curves show a similar slope in the inflection zone. This ranges from 0.52 to 0.65 (27½° to 33°), and may prove to be a common characteristic of the mature or equilibrium form, along with the tendency to resemble the family of curves having values of r of 0.1 to 0.25. Note also that the location of the inflection point of the curve is generally higher for the areas of low relief (Nos. 1–3) than in the areas of great relief (Nos. 4 and 5). Within any one of the families of model curves, the inflection point likewise moves down as the integral diminishes, but in the five mean curves shown here the inflection points all tend to be located higher than in the model curves to which they were fitted.

Because each of the mean curves represents a sample of only six basins, and the differences, while conspicuous on the graph, are not great, it might well prove that the differences between integrals are not statistically significant, but might result from expectable variations inherent in small samples despite the fact that no real differences exist from one area to the other as regards the hypsometric characteristics. We must assume first that the sampling was randomized. In actual fact, basins were selected which appeared most representative of the general facies of the area as a whole. None was discarded or added after data analysis was begun. At the time of selection the writer was not aware of possible differences in hypsometric or other form characteristics which might later appear, nor did he have in mind any particular trend which he expected the analysis to reveal. The selection, therefore while not mechanically randomized, is thought to be free of conscious prejudice.

Table 2 gives the sample mean, estimated standard deviation of the population (s), and standard error of the mean ($s_{\bar{x}}$) for each sample, consisting of the hypsometric integrals of the six individual basin curves. The table also shows the percentage probabilities of any two samples being drawn from a population with the same mean. The significance test is based upon the t distribution, which is used for small samples. In this instance all tests involved samples of 6 and the table of t is entered under the heading of 10 degrees of freedom. The probability stated is that representing the area for Five Sample Areas

DRAINAGE DENSITY				CHANNEL GRADIENTS		GROUND SLOPES		HYPSOMETRIC CURVE			
Total Area of 6 basins in each locality (sq. mi.)	Total Stream Lengths ΣL (miles)	$D_d = \frac{\Sigma L}{A}$	Mean basin height H (feet)	Mean Stream Gradient of 3rd order Streams: % (tan)	Degrees	Valley-Wall Slopes, Mean value Degrees	%	Mean Sub-surface Integral $\int$	Best fit to model hypso. function r	Z	Slope of Hypsometric curve at inflection point %
7.47	51.59	6.90	175.0	0.0113	0° 39'	9.9°	.1745	.5968	0.25	.333	.6009
9.58	44.40	4.64	61.0	0.0033	0° 10'	3.4°	.0594	.5420	0.10	.25	.5317
2.26	31.10	13.78	326.0	0.0352	1° 52'	28° 15'	.537	.4928	0.10	.29	.5890
0.77	20.28	26.17	875.8	0.2246	12° 40'	44.7°	.9896	.4684	0.25	.50	.6494
5.14	72.71	14.16	1880.2	0.1233	7° 02'	41° 15'	.867	.4084	0.10	.40	.5206

Table 2. Statistical Data for Mean Integrals of Five Areas*

LOCALITY	MEAN INTEGRAL %	S	$S_{\bar{x}}$
1. PIEDMONT, VA.	59.27	6.55	2.67
2. GULF COASTAL PLAIN, LA.	54.01	5.20	2.12
3. OZARK PLATEAU, ILL.	48.91	5.67	2.31
4. VERDUGO HILLS, CAL.	46.52	4.58	1.87
5. GREAT SMOKY N. CAR.	40.61	5.88	2.40

PROBABILITY (pair bracketed)	
1–2	.16
2–3	.14
3–4	.44
4–5	.08
1–3	.016
2–4	.026
3–5	.036
1–4	.005
2–5	.004
1–5	<.001

*Showing means, estimated standard deviation of the population, s, and standard error of the mean, $s_{\bar{x}}$, as estimated from the sample. Probability figures refer to results of t tests of significance of difference in sample means of each pair indicated by bracket. Although integrals are here ranked in descending order, as in Figure 17, the probability figures have no relationship to ranking significance. Probability figure tells only the percentage of times that sample means drawn repeatedly from the same pair of areas will differ by this amount or more through chance variations in sampling alone, assuming that no real difference in the two population means actually exists.

under both tails of the t distribution curve, and hence tells the probability of obtaining differences of sample means as great as, or greater than, the observed differences, with the possibility of either mean being the larger.

Note that, in Table 2, no significant difference is found between means of any two samples whose mean integrals differ by only 5 or 6% or less, but is present when the means differ by 8% or more. While we cannot easily determine the significance of the ranking, or the probability of rearrangements being likely to occur in the ranking if similar samples of six basins were repeatedly drawn, we can perhaps safely infer that any two consecutive members of the series might readily reverse their order if another set of samples was taken, but that it is most unlikely that one of the last two members of the series could switch places with the first two.

Relation of Hypsometric Forms to Drainage Forms

It is not immediately apparent just why any two integrals of the mean hypsometric curves should differ significantly, or why they should fall into the general sequence which they take. In an effort to obtain clues to this problem, measurement was made of the stream number and length characteristics, drainage density, slopes, relief, and stream gradients. These data are tabulated in Table 1. A number of observations relating to correlation, or lack of correlation, among the various form factors of the topography are as follows:

In general, drainage basin height, slope steepness, stream channel gradients and drainage density show a good but negative correlation with the integral of the hypsometric curve. We may say that mature basins of low relief, gentle slopes, gentle stream gradients, and low drainage density tend to have relatively high integrals; that areas of strong relief, steep slopes, steep stream gradients, and high drainage density tend to give relatively low integrals in the average drainage basin of the third or fourth order. Table 1 bears this out well if over-all trend of the series is considered, but the values of areas 1 and 2 are in reverse order, as are the values of areas 4 and 5. As already stated, however, differences of integral in these two pairs of samples are not significant (see Table 2) and they might easily exchange positions on the list if another sample were taken. What is significant is that Nos. 1 and 2 show very much lower values of drainage density, basin height, slope steepness, and stream gradient than do Nos. 4 and 5, while No. 3 occupies an intermediate position in all cases.

No correlation seems to exist between hypsometric integrals and either bifurcation ratios or length ratios (Figs. 19, 20). Horton (1945, p. 290) states that bifurcation ratios range from about 2 for flat or rolling country up to 3 or 4 for mountainous regions. The writer's data, based on large-scale maps checked in the field or by stereoscopic study of air photographs, show not only considerably higher ratios, but a complete lack of correlation of ratio with relief. Horton's data were taken from comparatively crude, small-scale maps and he must have omitted a large proportion of the stream channels of first and second order which actually exist.

A positive correlation is evident between the average length of the stream segments of any given order in each area and the corresponding mean hypsometric integrals. Figure 20, in which mean stream lengths are plotted against order numbers, shows progressive decline in stream length from left to right, in the same order as that in which the integrals diminish. Although reversals occur in the trends of the first and second order lengths, the values for areas 1 and 2 are always higher than those of areas 3, 4 and 5.

Because length of stream segments tends to become less as drainage density increases, it is only to be expected that the first two areas, whose texture is coarse, would have longer stream segments than the last three areas, whose texture is much finer. Now, since the mean integrals decrease as drainage density increases, the effect is to give a positive correlation between mean stream segment lengths and mean hypsometric integrals.

Geologic Factors Affecting Equilibrium Forms

Turning from a purely quantitative analysis of the various categories of morphometric data to a qualitative approach, there are several topographic and geologic factors apparent to the investigator to which he can attribute certain of the differences in hypsometric curve forms.

The extreme members of the series (curves 1 and 5, Fig. 17) are developed on essentially similar types of rock, mapped as the Wissahickon schist. A t test of significance of difference of sample mean integrals (Table 2) shows a probability less than .001, leading us to discard the hypothesis that both samples have

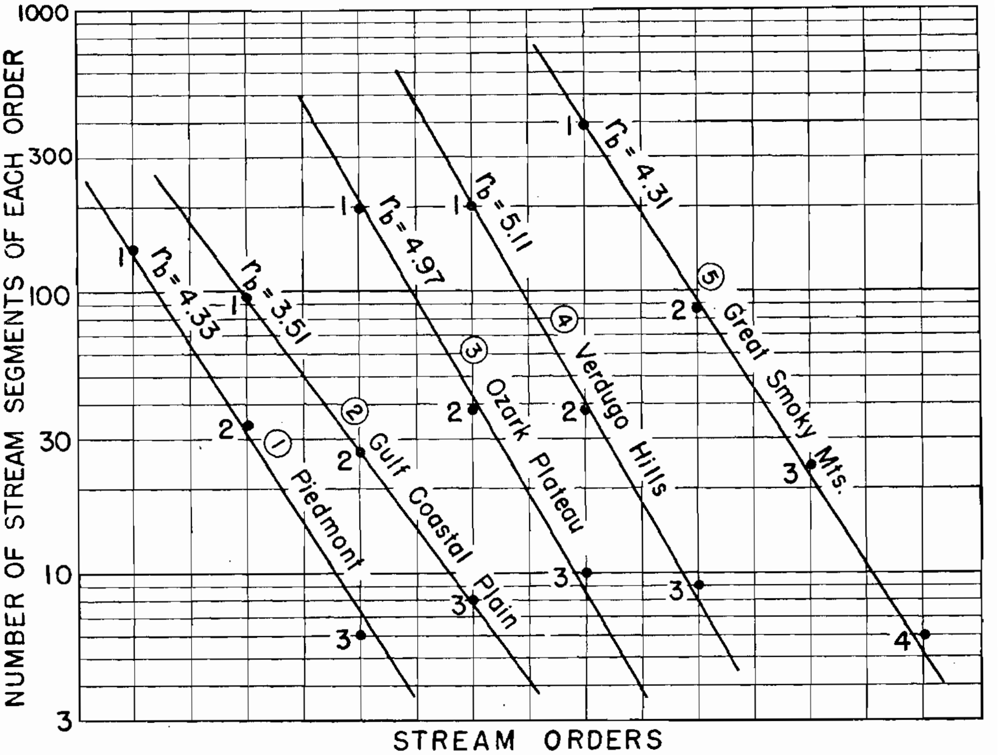

FIGURE 19.—STREAM NUMBERS AND BIFURCATION RATIOS FOR FIVE SAMPLE AREAS

Fitted curve has slope of bifurcation ratio, r_b, whose mean value is given for each area. Number beside each dot is order number.

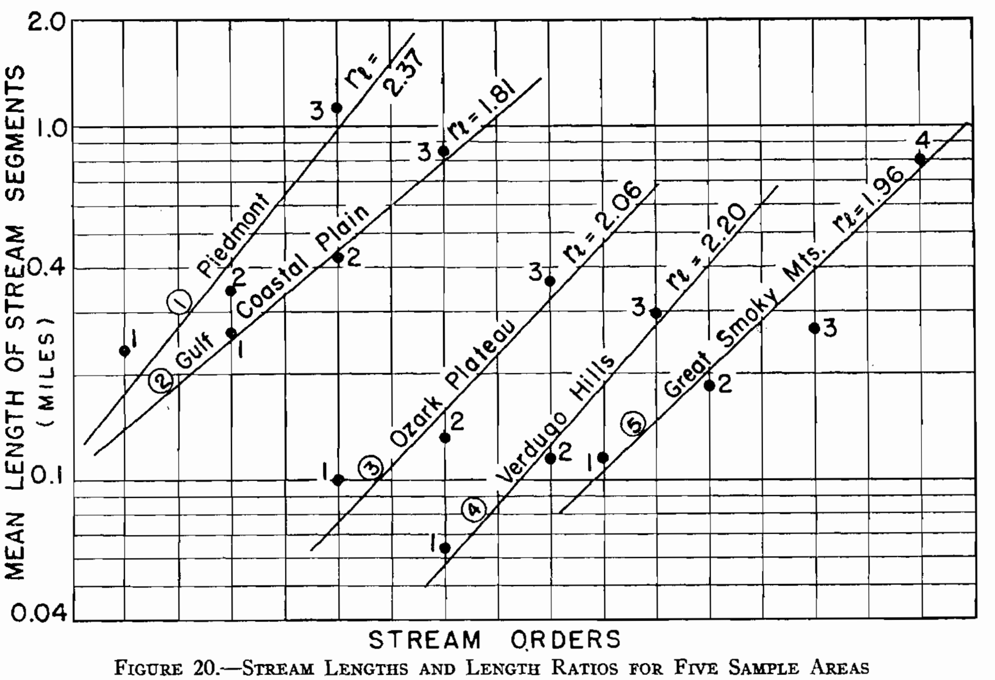

FIGURE 20.—STREAM LENGTHS AND LENGTH RATIOS FOR FIVE SAMPLE AREAS

Fitted curve has slope of length ratio, r_l, averaged for each area. Number beside each dot is order number.

the same popalation mean. The hypothesis that similarity of rock gives similarity of integral is not sustained. Some other cause (or causes) has produced a significant difference in the mean hypsometric integrals.

Cause of the hypsometric curve differences may lie in the geomorphic histories of the two areas. The Piedmont locality is thought to have been reduced to a peneplain, then dissected into a rolling topography of low relief in the present cycle. If so, the high integral (almost 0.60) may be an expression of submaturity, with extensive divide areas as yet not entirely transformed into the equilibrium slopes of the mature stage. But neither field examination nor map-air photograph study shows a distinctive unconsumed upland element, such as one is accustomed to seeing, for example, on the Maryland coastal plain (Fig. 14) or in the older drift plains of the middle west where maturity is being approached. Instead, the divides are broadly rounded and nothing suggests a composite topography involving two distinct cycles. The high integral of this hypsometric curve may, however, mean that, following the attainment of an equilibrium system, an acceleration of stream corrasion associated with increasing relief set in, perhaps induced by regional upwarping and an over-all steepening of gradient of east-flowing master streams. Do we have here a manifestation of the Penckian principle of waxing development (*aufsteigende Entwicklung*)?

The basins in the south flank of the Great Smoky Mountains produce a mean hypsometric curve with an unusually low integral, about 0.40 (Fig. 17). The inflection point is located low on the curve, and the upper two-thirds of the curve takes a broadly concave form. The topographic maps show a noticeable steepening of slopes above the level of 2800–3000 feet occurring at about 40%–50% of the basin height. The steepening of slopes with higher elevation is not sharply defined, as instructural benching found in a region of horizontal strata, but may be caused by differences in rate of rock weathering at low and high altitudes. For example, if rate of alteration of the feldspars and ferromagnesian minerals were appreciably faster in the warmer temperatures of the valleys, an opening out of the valley bottoms might perhaps be expected.

Among localities 2, 3, and 4, hypsometric differences are not strong. The curves of the Ozark Plateau basins and those of the Verdugo Hills basins are remarkably similar, with no significant difference statistically (Table 2), despite the fact that the Ozark Plateau is a region of flat-lying Paleozoic chert and cherty limestone with an over-all uniformity of summit levels, whereas the Verdugo Hills are part of a rugged, up-faulted mountain block consisting of metamorphosed sediments and intrusive bodies. The Ozark curve departs from the theoretical function at the upper end, where an excessive concavity is developed. This may be an expression of the sapping of weaker formations from beneath more resistant beds near the summit, a condition which might be expected in horizontal sedimentary strata.

The hypsometric curve of the Louisiana Gulf Coastal Plain locality has a relatively high integral, 0.54, but is otherwise quite conventional in appearance. Such small relief and faint slopes prevail here that very little of value can be discerned from the topographic map or air photographs. The area is located within the belt assigned to the Montgomery Terrace of Sangamon age by Fisk (1939, p. 193) at elevations from 120 to 140 feet. The surface is underlain by the sandy Citronelle formation. The high integral might perhaps be explained by a submature condition, in which insufficient time has elapsed for attainment of full maturity. As in the Piedmont locality, however, nothing in the topography suggests remnants of an initial surface not as yet completely consumed. The high integral may perhaps be a reflection of slightly accelerated stream erosion rates as a result of recently accelerated southward tilting of the region associated with epeirogenic uplifts (Fisk, 1939, p. 199) and might perhaps be a manifestation of waxing development (*aufsteigende Entwicklung*). At the present elementary stage of our investigations of the quantitative characteristics of erosional topography, we lack criteria for distinguishing among hypsometric curve forms modified by epeirogenic crustal movements, those modified by rejuvenations induced by falling sea level, and those representing stages in attainment of equilibrium under stable crustal and sea level conditions.

Influence of Horizontal Structure

It is obvious that drainage basins developed in horizontally layered rocks, whether sedimentary strata or lavas, will have strongly modified hypsometric curves if there are marked differences in rock resistance on a scale which is large in proportion to the height of the basin. In the region of cherts and cherty limestones of the Ozark Plateau Province, described above as one of the mature areas in apparently homogeneous materials, structural benching did not seem to produce any conspicuous influence in the hypsometric form. Let us turn, then, to a contrasting example, where structural control is predominant: the regions of cliffs, buttes, and mesas of the southern Mesa Verde, located in northwestern New Mexico, within the Rattlesnake and Chimney Rock quadrangles.

Figure 21 compares three hypsometric curves. The first is of a drainage basin about 4 square miles in extent consisting of a deeply-incised canyon surrounded by a stripped structural surface of low relief. The canyon is cut into the Mesa Verde sandstones and represents a deep re-entrant into the ragged escarpment rising above a broad lowland of weak Mancos shales. As we might expect, the hypsometric curve has a high integral, 68%, and resembles the curve of a youthful region in the inequilibrium stage of development, except for a considerable degree of relief in the upper part of the basin, above the flattened part of the curve which represents the break from canyon walls to stripped surface. In the normal curve of the young basin (Fig. 14), relief on the interstream areas is much less, as we would expect of an initial surface of deposition.

The second curve in Figure 21 shows an abnormally low integral, 33%. This basin is almost entirely in Mancos shale, which extends out from the base of the escarpment but includes a small remnant of the Mesa Verde sandstone, Chimney Rock, rising strikingly from the shale plain. This basin represents a stage in retreat of a cliff line in which the resistant bed is all but completely removed. It is in virtually the same phase as the monadnock phase of the normal cycle (Fig. 16).

The third curve, intermediate between the first and second, represents a basin entirely underlain by the Mancos shale, well out beyond the limits of the escarpment. Here no vestiges remain of the overlying resistant formation and the basin is in a virtually homogeneous

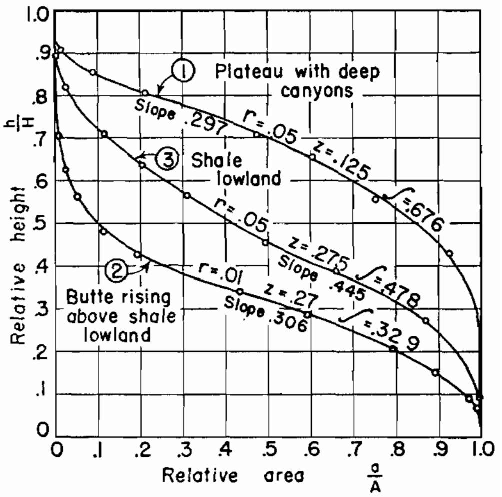

FIGURE 21.—HYPSOMETRIC CURVES OF THREE BASINS IN MESA VERDE REGION, NORTHWESTERN NEW MEXICO

From Chimney Rock Quadrangle, New Mexico, U. S. Geological Survey, 1:62,500.

weak material. Here, as is normal in the equilibrium stage, the integral is close to 50% and the curve has a smooth, s-shaped form which is well described by the model hypsometric function with the values $r = 0.05$, $z = .275$.

To summarize the effect of massive, resistant horizontal strata of an erosional escarpment upon the hypsometric function: a high integral characterizes the early phases of development in the zone of canyon dissection close to the cliffs; the integral drops to low values as the proportion of basin of low relief on weak rock increases and the remnants of resistant rock diminish; and finally, when the basin is entirely in weak rock, the curve reverts to the normal form of the equilibrium stage.

A good example of the modified hypsometric curve resulting from the presence of a massive, resistant formation above a weaker rock is found in the dissected plateau near Soissons, France, north and south of the Aisne River. There the Tertiary chalk forms an extensive interstream upland surface at 170–200 meters elevation. The Aisne and its immediate tributaries have cut into weak sands and clays be-

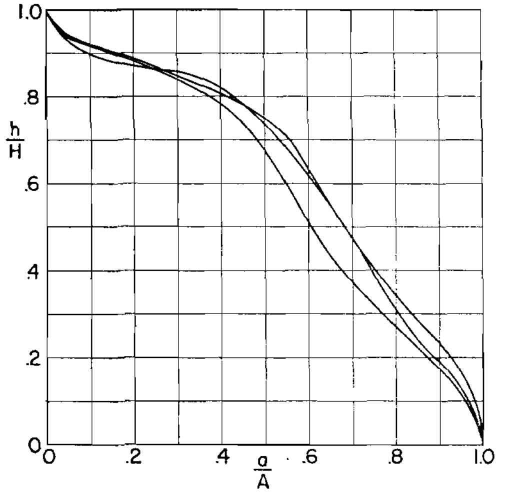

FIGURE 22.—HYPSOMETRIC CURVES OF THREE BASINS NEAR SOISSONS, FRANCE

Showing influence of a resistant chalk formation upon curve form. From Soissons Quadrangle, France, 1:50,000.

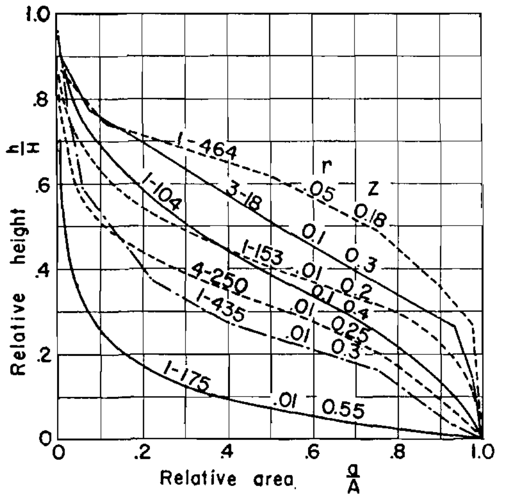

FIGURE 23.—HYPSOMETRIC CURVES OF LARGE DRAINAGE BASINS

From Langbein (1947). Values of r and z, added by writer, were fitted by inspection.

neath the chalk, giving the drainage basins steep inner slopes but very gentle slopes on the extensive divides. Curves of three third-order basins ranging from 14–26 square kilometers in area differ slightly in integral, but are remarkably alike in form (Fig. 22). Note that the resistant chalk produces a high integral and a pronounced convexity in the upper third of the curve. This curve has a double inflection and does not fit the model hypsometric function.

PRACTICAL APPLICATIONS OF HYPSOMETRIC ANALYSIS

The hypsometric analysis of drainage basins has several applications, both hydrologic and topographic. Langbein (1947) applied the percentage hypsometric curve to a number of New England drainage basins (Fig. 23) of a much larger order of size than those analyzed here, but the curves have basically similar forms and can be described by the model hypsometric function. On Figure 23 the values of r and z are given for the best fit. Fit ranges from fair to excellent, and the results are satisfactory considering that most of these basins lie in a glaciated area combined with complex structure.

Referring to practical value of hypsometric data in hydrology, Langbein states (1947, p. 141):

> "For example, snow surveys generally show an increase in depth of cover and water equivalent with increase in altitude; the area-altitude relation provides a means for estimating the mean depth of snow or its water equivalent over a drainage basin. Barrows (1933) describes a significant variation in annual precipitation and runoff in the Connecticut River Basin with respect to altitude. The obvious variation in temperature with change in altitude is further indication of the utility of the area-altitude distribution curve."

Another application might be found in the calculation of sediment load derived from a small drainage basin in relation to slope. Because the hypsometric function combines the value of slope and surface area at any elevation of the basin, it might help obtain more precise calculations of expected source of maximum sediment derived from surface runoff in a typical basin of a given order of magnitude.

Dr. Luna B. Leopold (personal communication) has applied the hypsometric method to analysis of the relationship of vegetative cover to the areal distribution of surface exposed to erosion in the Rio Puerco watershed, New Mexico. Because of distinctive vertical zoning of grassland, woodland, and forest, the relative surface areas underlain by each vegetative type can be described by the hypsometric function, which can thus be used as a basis for calculation. Furthermore, because rainfall increases with elevation, the hypsometric function can be used to calculate the total area subject to a given amount of rainfall.

A military application of the hypsometric method is foreseen in the use of the hypsometric integral as a term descriptive of the character of the terrain in quantitative terms. A high integral, such as that in Figure 14 would indicate extensive interstream areas of low relief, suitable to the rapid movement of mechanized forces, but with the valleys forming small narrow pockets suitable for defense and not readily observed from outside. A medium integral would indicate that the land surface was almost entirely in slope, which might be steep in a given region, and lacking in extensive belts of easy trafficability, either in the valley floors or along the divides. A very low integral would mean the development of extensive interconnected valley floors adapted to rapid movement, but with isolated hill summits which would offer defense positions with wide visibility. Obviously these terrain characteristics can be seen at a glance from any contour topographic map, and hypsometric analysis would be of value only in quantitative calculations using empirical formulas in which each aspect of the terrain is given a numerical statement.

Planning of soil erosion control measures and land utilization may profit from topographic analysis in which such terrain elements as hypsometric qualities, slope steepness, and drainage density are quantitatively stated.

References Cited

Barrows, H. K. (1933) *Precipitation and runoff and altitude relations for Connecticut River*, Am. Geophys. Union, Tr., 14th Ann. Meeting, p. 396–406.

Fisk, H. N. (1939) *Depositional terrace slopes in Louisiana*, Jour. Geomorph., vol. 2, p. 181–200.

Horton, R. E. (1941) *Sheet erosion—present and past*, Am. Geophys. Union, Tr., *Symposium on dynamics of land erosion*, 1941, p. 299–305.

—— (1945) *Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology*, Geol. Soc. Am., Bull., vol. 56, p. 275–370.

Langbein, W. B. *et al.* (1947) *Topographic characteristics of drainage basins*, U. S. Geol. Survey, W.-S. Paper 968-C, p. 125–157.

Rouse, Hunter (1937) *Modern conceptions of the mechanics of fluid turbulence*, Am. Soc. Civ. Eng. Tr., vol. 109, p. 523–543.

Strahler, A. N. (1950) *Equilibrium theory of erosional slopes approached by frequency distribution analysis*, Am. Jour. Sci., vol. 248, p. 673–696, 800–814.

Department of Geology, Columbia University, New York 27, N. Y.

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A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

Prepared by Pamela C. Dodds, Ph.D., Licensed Professional Geologist
Prepared for The Wilderness Society - January 24, 2023

REFERENCE 5

February 21, 2023

UNIFIED STREAM METHODOLOGY

for use in Virginia

U.S. Army Corps of Engineers, Norfolk District
Virginia Department of Environmental Quality

January 2007

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Acronyms

A_F	Adjustment Factor
CC	Compensation Credit
CI	Condition Index
COE	United States Army Corps of Engineers
CR	Compensation Requirement
DEQ	Virginia Department of Environmental Quality
IF	Impact Factor
LB	Left Bank
L_I	Length of Impact Reach
RB	Right Bank
RCI	Reach Condition Index
SAR	Stream Assessment Reach
USM	Unified Stream Methodology

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Introduction

The Unified Stream Methodology (USM) is a collaborative effort between the U.S. Army Corps of Engineers, Norfolk District (COE) and the Virginia Department of Environmental Quality (DEQ). The purpose of this Manual is to describe a method to rapidly assess what the stream compensation requirements would be for permitted stream impacts and the amount of "credits" obtainable through implementation of various stream compensation practices. The Manual describes a process to: 1) assign a **Reach Condition Index (RCI)** to the stream to be impacted; 2) assess the type or severity of impact; 3) determine the compensation requirement; and, 4) determine what types of and the amount of the various compensation practices that will satisfy the compensation requirement. This manual may be used for projects requiring stream compensation under the COE regulatory program and the DEQ's Virginia Water Protection Permit Program (VWPP). This Manual and USM forms can be found on the COE and DEQ webpages US Army Corps of Engineers - Norfolk District and Virginia DEQ - Wetlands.

This method is not intended to take the place of project specific review and discussion, which may result in adjustments to the compensation requirements or credits obtained through application of this process. This method can be applied to stream compensation projects performed on-site, off-site, for a stream mitigation bank, or for an in-lieu fee fund project, thereby, ensuring a standard application for evaluating and crediting all stream compensation projects. This Manual is to be used in wadeable intermittent or perennial streams statewide. The following circumstances require special consideration:

Concrete, Gabion-lined or Riprap Channels

Jurisdictional streams that are entirely contained within concrete, gabion-lined, or riprap channels and do not have normal stream features (sedimentation, vegetation) will be reviewed on a case-by-case basis. Compensation for impacts to these stream channels will generally not be required. However, impacts to these streams will still need to be included in the impact area for permitting purposes. The following photos provide examples of these channel types.

Concrete-lined Channel

Riprap-lined Channel

If these streams have established a naturalized stream cross-section, with normal stream features (sedimentation, vegetation), the agencies may require compensation and the USM would then be required.

Relocated Stream Channels

Streams that will be relocated using the principles of natural channel design may be considered self-mitigating in most cases, eliminating the need to apply the USM. The relocated stream must be designed and constructed to mimic the functions and values of the impacted stream, at a minimum. All relocated streams must be stable. However, if the relocated stream results in a reduced stream length or function, compensation may be required for the difference between pre- and post-construction stream length/function.

Jurisdictional Ephemeral Streams

"Ephemeral Streams" are defined as streams that have flowing water only during and for a short duration after, precipitation events in a typical year. Ephemeral streambeds are located above the groundwater table year-round. Groundwater is not a source of water for the stream. Rainfall runoff is the primary water source for these streams. Jurisdictional ephemeral streams have the presence of an ordinary high watermark.

Ephemeral streams will be reviewed on a case-by-case basis. In the event that compensation is required for impacts to ephemeral streams, the **RCI** is determined by evaluating <u>only</u> the Riparian Buffer Parameter (Section 1.2 and Form 1). The **Condition Index (CI)** calculated from this evaluation is then divided by two (2) to obtain the **RCI**. Proceed to Section 2.0 of this Manual

Organization of USM

This Manual is divided into six sections, summarized below. The sections represent the basic types of analyses that are performed, including assessing existing conditions, characterizing proposed impacts, determining compensation requirements, evaluating precompensation conditions, determining compensation credit, and evaluating total compensation credit.

Section 1 - Stream Impact Site Assessment describes a method to rapidly assess and assign a Reach Condition Index (**RCI**) to a stream reach proposed for impact.

Section 2 - Stream Impact Factor Assessment presents a procedure for characterizing proposed impacts to a stream.

Section 3 - Determining Stream Compensation Requirements explains the method for calculating the compensation required for stream impacts. The factors used in this calculation are the stream assessment **RCI** (Section 1), the type of **Impact Factor (IF)** (Section 2), and the linear feet of impact.

Section 4 – Precompensation Evaluation provides information in evaluating the precompensation stream reach and outlines the components of the conceptual compensation plan.

Section 5 - Determining Compensation Credit explains the various methods by which stream impacts may be compensated and the process for determining credit provided by stream compensation proposals.

Section 6 – Evaluating Total Compensation Credit explains the method for calculating the linear feet of credit obtained after review of stream compensation plans. The factors used in this calculation are the activities credit (Section 5), linear footage of the compensation stream, and any applicable adjustment factors (Section 5).

USM Process

This process can be divided into six steps, outlined below:

Step 1 – Stream Impact Site Assessments

- Determine Length of Assessment Reach
- Perform Assessment and determine applicable Condition Index (**CI**)
  - Channel Condition = 1 – 3
  - Riparian Buffer = 0.5 – 1.5
  - In-Stream Habitat = 0.5 – 1.5
  - Channel Alteration = 0.5 – 1.5
- Calculate Reach Condition Index (**RCI**) using Equation 2
  - **RCI** = (Sum of all **CIs**) ÷ 5

Step 2 – Stream Impact Factor Assessment

- Obtain Impact Factor (**IF**) from Table 1
  - Severe = 1.0
  - Significant = 0.75
  - Moderate = 0.5
  - Negligible = 0

Step 3 – Determine Stream Compensation Requirement

- Calculate Compensation Requirement (**CR**) using Equation 3
  - **CR** = Length of Impact ($\mathbf{L_I}$) × Reach Condition Index (**RCI**) × Impact Factor (**IF**)

Step 4 – Precompensation Evaluation

- Assess Existing Conditions
- Develop Conceptual Plan

Step 5 – Determine Compensation Credit

- Determine Compensation Credit (**CC**) for Applicable Compensation Activities
  - Restoration = 1 credit per foot
  - Enhancement = 0.09 – 0.3 credits per foot per bank
  - Riparian Areas = 0 – 0.4 credits per foot
- Apply Applicable Adjustment Factors ($\mathbf{A_F}$)
  - Rare, Threatened, and Endangered Species or Communities = 0.1 – 0.3
  - Livestock Exclusion = 0.1 – 0.3
  - Watershed Preservation = 0.1 – 0.3

Step 6 – Evaluate Compensation Credit

- Calculate Total Compensation Credit (**Total CC**) using Equation 4
  - **Total CC** = Sum [Restoration Credit + Enhancement Credit + Riparian Buffer Credit + Adjustment Factor ($\mathbf{A_F}$) Credit]
- **Total CC** must be = **Total CR**

1.0 Stream Impact Site Assessment

Impacts are proposed in various qualities of streams. Therefore, it is important to assess the quality of the stream reach being impacted and use that as a factor in determining the **Compensation Requirements (CR)**. There are numerous methodologies that arrive at a numerical index to use as an indicator of stream quality. This assessment is not intended to be a substitute for more detailed stream studies that may be undertaken to determine stream quality, water chemistry, or biological conditions.

Stream impact projects may need to be divided into multiple **Stream Assessment Reaches (SAR)**. The length of the **SAR** is determined by significant changes in one or more of the following four parameters: 1) Channel Condition, 2) Riparian Buffer, 3) In-Stream Habitat, and 4) Channel Alteration. The **Stream Assessment Form (Form 1),** included in Appendix A, is used to record this information for each reach.

1.1 Channel Condition Parameter

Under most circumstances, channels respond to disturbances or changes in flow regime in a sequential, predictable manner. The way a stream responds to changes by degrading to a lower elevation and eventually re-stabilizing at that lower elevation (Figure 1) is the basic premise behind the stream channel evolutionary process. The differing stages of this process can be directly correlated with the current state of stream stability. The purpose of evaluating **Channel Condition** is to determine the current condition of the channel cross-section, as it relates to this evolutionary process, and to make a correlation to the current state of stream stability. These evolutionary processes apply to the majority of stream systems and assessment reaches due to the fact that the majority of stream systems are degrading, aggrading, healing, or stable.
A channel's condition can be determined by visually assessing certain geomorphological indicators. These indicators include channel incision, access to original or recently created floodplains, channel widening, channel depositional features, rooting depth compared to streambed elevation, streambank vegetative protection, and streambank erosion. Each of the categories describes a particular combination of the state of these geomorphological indicators which generally correspond to a stream channel stability condition at some stage in the evolution process.

1.1.1 Channel Condition Categories

Channel Condition is an assessment of the cross-section of the stream, along the stream reach. The channel condition of each **SAR** is assessed using the following five categories. A **Condition Index (CI)** is given for each category; however, there may be rare cases where the stream lies between the descriptions. In these cases, a **CI** between those provided may be used. The Evaluator needs to identify the prevailing channel condition or problem (erosion, deposition, disconnection to the floodplain) and record the associated score in the **CI** box for the channel condition parameter**.**

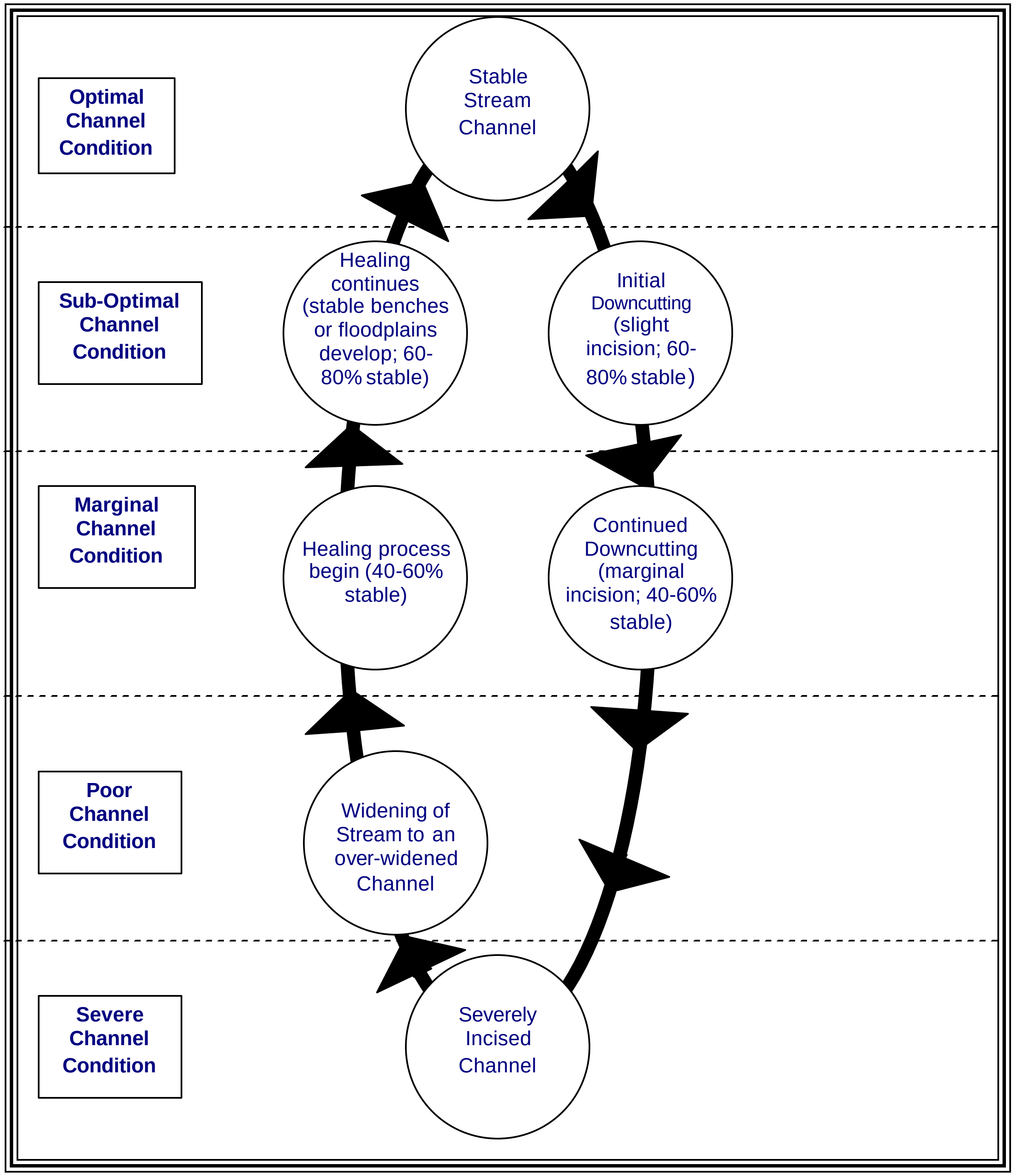
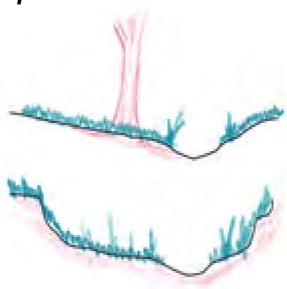


Figure 1: The relationship between the channel evolution and USM Channel Condition

Optimal



These channels show very little incision and little or no evidence of active erosion or unprotected banks. 80-100% of both banks are stable. Vegetative surface protection may be prominent on 80-100% of the banks or natural rock stability present along the majority of the banks.

AND/OR

Stable point bars and bankfull benches are present (when appropriate for the stream type). These channels are stable and have access to their original floodplain or fully developed wide bankfull benches. Mid-channel bars, and transverse bars should be few. If transient sediment deposition is present, it covers less than 10% of the stream bottom.

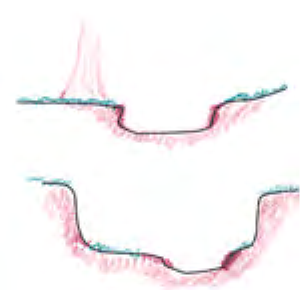
Suboptimal

These channels are slightly incised and contain few areas of active erosion or unprotected banks. The majority of both banks are stable (60-80%). Vegetative surface protection may be prominent along 60-80% of the banks or natural rock stability present along the majority of both banks.

AND/OR

Depositional features (point bars, mid-channel bars, transverse bars, and bankfull benches) are likely present (when appropriate for the stream type) and most are contributing to stability. The bankfull and low flow channels (when appropriate for the stream type) are well defined. This stream likely has access to bankfull benches, or newly developed floodplains along portions of the reach. If transient sediment is present, it affects or buries 10-40% of the stream bottom.

Marginal



These channels are often incised, but to a lesser degree than the ***Severe*** and ***Poor*** channel conditions. The banks are more stable than the stream cross sections in the ***Severe*** or ***Poor*** condition due to lower bank slopes. Erosional scars may be present on 40-60% of both banks. Vegetative surface protection may be present on 40-60% of the banks. The streambanks may consist of some vertical or undercut banks. While portions of the bankfull channel may still widen, other portions have begun to narrow in an attempt to obtain stable dimensions.

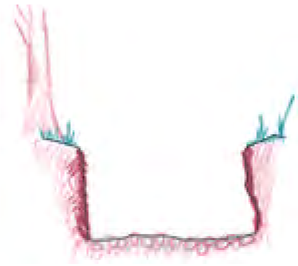
AND/OR

Between 40-60% of the natural stream bed or bottom (pools and riffles) is covered by substantial sediment deposition. Sediment depositional features may be temporary and transient in nature, and may contribute to channel instability. However, depositional features (point bars, mid-channel bars, transverse bars, and bank full benches), that contribute to stability, may be forming or present in the appropriate stream types.

AND/OR

Channels that have experienced historic incision but may be relatively stable (banks and channel) at their existing elevation. These channels may have a V-shape and no connection to their floodplain. Vegetative surface protection is present on greater than 40% of the banks but evidence of instability can be observed in unvegetated areas. Marginal V-shaped channels have depositional features (point bars, mid-channel bars, transverse bars, and bank full benches), which contribute to stability.

Poor



These channels are overwidened and are incised. These channels are vertically and/or laterally unstable. They are more likely to widen rather than incise further. The majority of both banks are near vertical with shallow to moderate root depths. Erosional scars may be present on 60-80% of the banks. Vegetative surface protection may be present on 20-40% of both banks, and is insufficient to prevent significant erosion from continuing.

AND/OR

Between 60-80% of the natural stream bed or bottom (pools and riffles) is covered by substantial sediment deposition. Sediment depositional features are temporary and transient in nature, and are likely contributing to channel instability.

AND/OR

Channels that have experienced historic incision but may be relatively stable (banks and channel) at their existing elevation. These channels may have a V-shape and no connection to their floodplain. Vegetative surface protection is present on greater than 40% of the banks but evidence of instability can be observed in unvegetated areas. Depositional features (point bars, mid-channel bars, transverse bars, and bank full benches), which contribute to stability are absent.

Severe

These channels are deeply incised (or excavated) with vertical and/or lateral instability and will likely continue to incise and widen. Incision is severe enough that flow is contained within the banks during heavy rainfall events (i.e. the stream does not have access to its floodplain). The streambed elevation may be below the average rooting depth within the banks and the majority of both banks may be vertical or undercut. Vegetative surface protection may be present on less than 20% of the banks and is not preventing erosion from continuing. Obvious bank sloughing may be present. Erosional scars or raw banks may be present on 80-100% of the banks.

AND/OR

These channels are aggrading and have an excessive sediment supply that is filling the channel with alluvium, impeding its flow. Greater than 80% of the natural stream bed or bottom (pools and riffles) is covered by substantial sediment deposition that is likely contributing to channel instability. Multiple thread channels and/or subterranean flow may be present in certain aggrading channels. Note: Stable multiple thread channels naturally occur in some low-gradient streams and should not be given a *Severe* Parameter Condition.

1.1.2 Channel Condition Photographs

(see USM Photo File)

1.2 Riparian Buffer Parameter

This Parameter is not intended to be a detailed vegetative cover survey, but instead, is a qualitative evaluation of the cover types that make up the riparian buffer. The **CI** for this parameter is determined by evaluating what cover type occupies what percent of the total riparian buffer area for each side of the stream channel within the **SAR**. The total riparian buffer assessment area (on each side of the stream channel) is calculated by multiplying the length of the **SAR** by 100 feet. The left bank (LB) and right bank (RB) are determined by facing downstream. The Riparian Buffer measurement is taken along the ground and is not an aerial distance from the stream bank.

The ideal riparian buffer would be homogenous with a mature hardwood forest occupying 100% of the assessment area. If the buffer is heterogeneous (example: 33% forested, 33% cropland, and 34% pavement), it is possible that the buffer could contain multiple condition categories. In that case, each condition category present within the buffer is scored and weighted by the percent it occupies within the buffer. An estimate of the percent area that each cover type occupies may be made from visual estimates made on-the-ground or by measuring each different area to obtain its dimensions. Multiple intrusions of roads, parks, houses, etc., into the 100-foot zone may require more detailed measurements to determine percentages. The observed cover types should be categorized and scored accordingly, based upon the parameter category descriptions.

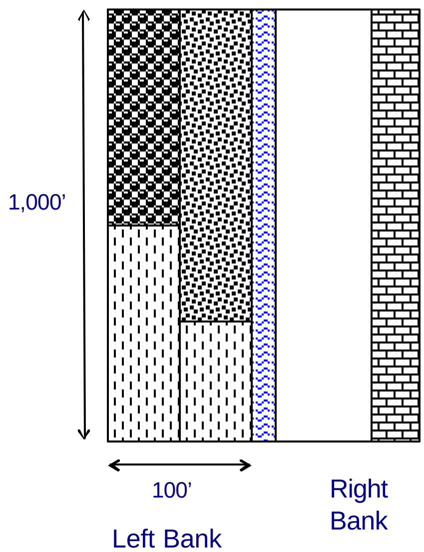
EQUATION 1: The equation is as follows:

Left Bank **CI** =SUM (%Area*Score)*0.01

Right Bank **CI** =SUM(%Area*Score)*0.01

Riparian **CI** = (Left Bank **CI** + Right Bank **CI**) / 2

The following example (Example 1) provides further details on how to assess this parameter.



Forested Buffer with 30% Canopy Cover and herbaceous understory (**Low Suboptimal** - Score of 1.1)

Forested Buffer with 30% Canopy Cover and herbaceous and shrub understory (**High Suboptimal** - Score of 1.2)

Forested Buffer with > 60% Canopy Cover (**Optimal** - Score of 1.5)

Maintained Grasses (**High Poor** - Score of 0.6)

Impervious Area (**Low Poor** - Score of 0.5)

Stream

For this example, the Evaluator considers each area within the 100’ buffer. On both sides of the stream an area of 100,000 square feet (sf) (100’ wide X 1,000’ long) is assessed using USM.

An area 60 feet wide and 1,000 feet long (60,000 sf) is located on the Right Bank and is assessed as Low Suboptimal. 60,000 sf is 60% of 100,000 sf. Therefore, 60 is entered into Right Bank Percent Area row of the Assessment Form and the Low Suboptimal Score (1.1) is entered below the 60 in the Score row. [60% X 1.1 X 0.01 = 0.66]

An area 40’ wide and 1,000’ long (40,000 sf) is located on the Right Bank and is assessed as Low Poor. 40,000 sf is 40% of 100,000 sf. Therefore, 40 is entered into Right Bank Percent Area row of the Assessment Form and the Low Poor Score (0.5) is entered below the 40 in the Score row. [40% X 0.5 X 0.01 = 0.20]

An area 50’ wide and 500’ long (25,000 sf) is located on the Left Bank and is assessed as Optimal. 25,000 is 25% of 100,000 sf. Therefore, 25 is entered into Left Bank Percent Area row of the Assessment Form and the Optimal Score (1.5) is entered below the 25 in the Score row. [25% X 1.5 X 0.01= 0.375]

An area of 50’ wide and 500’ long (25,000 sf) is located on the Left Bank and is assessed as High Poor. Another area 50’ wide and 250’ long (12,500 sf) is also located on the Left Bank and is assessed as High Poor. These two areas equal 37,500 sf and comprise 37.5% of 100,000 sf. Therefore, 37.5 is entered into Left Bank Percent Area row of the Assessment Form and the High Poor Score (0.6) is entered below the 37.5 in the Score row. [37.5% X 0.6 X 0.01 = 0.225]

An area 50’ wide and 750’ long (37,500 sf) is located on the Left Bank and is assessed as High Suboptimal. 37,500 sf is 37.5% of 100,000 sf. Therefore, 37.5 is entered into Left Bank Percent Area row of the Assessment Form and the High Suboptimal Score (1.2) is entered below the 37.5 in the Score row. [37.5% X 1.2 X 0.01 = 0.45]

The CI for each bank is the sum of all the Percent Area X Score products. The Right Bank CI is 0.86. The Left Bank CI is 1.05. These two bank CIs are then averaged, resulting in the Parameter CI of 0.955 or 0.96.

RB % Area	60%	40%		RB CI	
Score	1.1	0.5		0.86	
					Buffer CI
LB % Area	25%	37.5%	37.5	LB CI	0.96
Score	1.5	0.6	1.2	1.05	

Example 1: Riparian Buffer Assessment Example

1.2.1 Riparian Buffer Categories

The **SAR** is assessed for the condition of the **Riparian Buffer** using the following four Categories. The dominance of invasive species will lowers the CI by one category.

Optimal

Tree stratum (dbh > 3 inches) present, with > 60% tree canopy cover. Wetlands located within the riparian areas are scored as optimal.

Suboptimal

High Suboptimal: Riparian areas with tree stratum (dbh > 3 inches) present, with 30% to 60% tree canopy cover and containing both herbaceous and shrub layers or a non-maintained understory.

Low Suboptimal: Riparian areas with tree stratum (dbh > 3 inches) present, with 30% to 60% tree canopy cover and a maintained understory. Recent cutover (dense vegetation).

Marginal

High Marginal: Non-maintained, dense herbaceous vegetation with either a shrub layer or a tree layer (dbh > 3 inches) present, with <30% tree canopy cover.

Low Marginal: Non-maintained, dense herbaceous vegetation, riparian areas lacking shrub and tree stratum, areas of hay production, and ponds or open water areas. If trees are present, tree stratum (dbh >3 inches) present, with <30% tree canopy cover with maintained understory.

Poor

High Poor: Lawns, mowed, and maintained areas, nurseries; no-till cropland; actively grazed pasture, sparsely vegetated non-maintained area, recently seeded and stabilized, or other comparable condition.

Low Poor: Impervious surfaces, mine spoil lands, denuded surfaces, row crops, active feed lots, trails, or other comparable conditions.

1.2.2 Riparian Buffer Parameter Photographs

(see USM Photo File)

1.3 In-stream Habitat Parameter

The **In-Stream Habitat** assessment considers the habitat suitability for effective colonization or use by fish, amphibians, and/or macroinvertebrates. This parameter does not consider the abundance or types of organisms present, nor does it consider the water chemistry and/or quality of the stream. Other factors beyond those measured in this methodology (i.e. watershed conditions) also affect the presence and diversity of aquatic organisms. Therefore, evaluation of this parameter seeks to assess the suitability of physical elements within the stream reach to support aquatic organisms.

This Parameter includes the relative quantity and variety of natural structures in the stream, such as cobble (riffles), large rocks, fallen trees, logs and branches, persistent leaf packs, and undercut banks; available as refugia, feeding, or sites for spawning and nursery functions of aquatic macrofauna. A wide variety and/or abundance of instream habitat features provide macroinvertebrates and fish with a large number of niches, thus increasing species diversity. As variety and abundance of cover decreases, habitat structure becomes monotonous, diversity decreases, and the potential for recovery following disturbance decreases. Riffles and runs are critical for maintaining a variety and abundance of benthic organisms and serve as spawning and feeding refugia for certain fish. The extent and quality of the riffle is an important factor in the support of a healthy biological condition. Riffles and runs offer habitat diversity through a variety of particle sizes. Snags and submerged logs are also productive habitat structures for macroinvertebrate colonization and fish refugia.

This parameter does not establish a percent slope for distinguishing between high and low gradient streams. Therefore, the Evaluator has to know whether a high or low gradient stream is being assessed. Generally speaking, low gradient streams occur in the Coastal Plain, wetland / marsh conditions, or wet meadows, and do not contain riffles. High gradient streams generally have alternating riffles and pools, with gravel or cobble present in the riffles. Typically, most streams west of the Fall Line are high gradient making the majority of streams in Virginia high gradient, with the exception of streams in the Coastal Plain and low gradient streams flowing through wetlands or wet meadows throughout the state. Headwater stream channels have intermittent hydrologic regimes and may not have the diversity of habitat features found in higher order stream channels. Hyporheic flow may comprise all of the flow in intermittent streams during dry times of the year. A high gradient stream should not be scored lower because there is not submerged aquatic vegetation. Likewise, a low gradient stream should not be scored lower because it does not contain riffles.

High Gradient Streams

Physical elements of high gradient stream systems that enhance a stream's ability to support aquatic organisms and are indicative of habitat diversity include the following:

1. A varied mixture of substrate sizes (i.e., sand, gravel, cobbles, and boulders).
2. Low amount of highly mobile substrate material – While most streambed substrate mobilizes under a particular discharge, substrate that remains immobile during the more consistent and frequent discharges provides stable habitat that fish and macroinvertebrates can utilize throughout differing stages of their lifecycles.
3. Low Embeddedness of substrate material – Embeddedness is the extent to which rocks (gravel, cobble, and boulders) and snags are covered by silt, sand, or mud on the stream bottom. As rocks and snags become embedded, there is less area available for colonization for macroinvertebrates and less fish habitat. Generally, the less embedded each particle is, the more surface area available to macroinvertebrates and fish. Additionally, less embeddedness indicates less large-scale sediment movement and deposition. (Observations of embeddedness are taken in the upstream and central portions of riffles and cobble substrate areas.)
4. A varied combination of water velocities and depths (riffles and pools) - More combinations of velocity and depth patterns provide increased habitat diversity.
5. The presence of woody and leafy debris (fallen trees, logs, branches, leaf packs, etc.), root mats, large rocks, and undercut banks (below bankfull).
6. The provision of shade protection by overhanging vegetation.
7. The Hyporheic zone is wet within 12" of ground surface.

Low Gradient Streams

Physical elements of low gradient stream systems that enhance a stream's ability to support aquatic organisms and are indicative of habitat diversity include the following:

1. A varied mixture of substrate materials (i.e., sand and gravel) in pools – Varied substrate materials support a higher diversity of organisms than mud or bedrock.
2. Submerged aquatic vegetation in pools – Will also support a higher diversity of organisms.
3. The presence of woody and leafy debris (fallen trees, logs, branches, leaf packs, etc.), root mats, and undercut banks (below bankfull).
4. The provision of shade protection by overhanging vegetation.

5. The Hyporheic zone is wet within 12” of ground surface.

A diverse and abundant assemblage of these features promotes the potential for colonization by diverse and abundant epifaunal and fish communities.

1.3.1 In-Stream Habitat Categories

The **SAR** is assessed for the condition of **In-Stream Habitat** using the following four Categories. The Evaluator selects the category most representative of the **SAR**. These categories are abbreviated on Form 1.

Optimal
Physical Elements that enhance a stream’s ability to support aquatic organisms are present in greater than 50% of the reach. Substrate is favorable for colonization by a diverse and abundant epifaunal community, and there are many suitable areas for epifaunal colonization and/or fish cover.

Suboptimal
Physical Elements that enhance a stream’s ability to support aquatic organisms are present in 30-50% of the reach. Conditions are mostly desirable, and are generally suitable for full colonization by a moderately diverse and abundant epifaunal community.

Marginal
Physical Elements that enhance a stream’s ability to support aquatic organisms are present in 10-30% of the reach. Conditions are generally suitable for partial colonization by epifaunal and/or fish communities.

Poor
Physical Elements that enhance a stream’s ability to support aquatic organisms are present in less than 10% of the reach. Conditions are generally unsuitable for colonization by epifaunal and/or fish communities.

1.3.2 In-stream Habitat Parameter Photographs

(see USM Photo File)

1.4 Channel Alteration Parameter

This Parameter considers direct impacts to the stream channel from anthropogenic sources. The **SAR** may or may not have been altered throughout its entire length.

Examples of channel alterations evaluated in this Parameter that may disrupt the natural conditions of the stream include, but are not limited to the following:

1. Straightening of channel or other channelization
2. Stream crossings (bridges and bottomless culverts)
3. Riprap along streambank or in streambed
4. Concrete, gabions, or concrete blocks along streambank
5. Manmade embankments on streambanks, including spoil piles
6. Constrictions to stream channel or immediate flood prone area
7. Livestock impacted channels (i.e., hoof tread, livestock in stream)

It is important to note that this Parameter evaluates the physical alteration, separate from the impact the alteration is having on the assessment reach. Any impact to the assessment reach resulting from the alteration (i.e. scouring, head cuts, vertical banks, etc.) is accounted for in the **Channel Condition** Parameter. Any revegetation or natural re-stabilization of the channel is also accounted for in the **Channel Condition** Parameter. For example, consider two assessment reaches, each with similar bridges: the first reach shows no adverse effects to the stream channel or banks; the second shows significant scouring. The alteration is the bridge, not the effects of the bridge; therefore it is the length of bridge relative to the length of the assessment reach that is evaluated. The shorter the assessment reach, the higher percentage of alteration.

The presence of a structure does not necessarily result in a reduced score. For instance, a bridge that completely spans the floodplain would not be considered an alteration. Also, the Evaluator is cautioned not to make assumptions about past alterations. Incision can be mistaken for channelization.

1.4.1 Channel Alteration Categories

The **SAR** is assessed for the extent of channel alterations using the following four Categories. The Evaluator selects the category most representative of the assessment reach. This is recorded in Section 4 of Form 1.

Negligible
Channelization, dredging, alteration, or hardening absent. Stream has unaltered pattern or has normalized.

Minor
High Minor: Less than 20% of the stream reach is disrupted by any of the channel alterations listed above. Alteration or channelization present, usually adjacent to structures, (such as bridge abutments or culverts); evidence of past alteration, (i.e., channelization) may be present, but stream pattern and stability have recovered; recent alteration is not present.

Low Minor: Between 20-40% of the stream reach is disrupted by any of the channel alterations listed above. Alteration or channelization present, usually adjacent to structures, (such as bridge abutments or culverts); evidence of past alteration, (i.e., channelization) may be present, but stream pattern and stability have recovered; recent alteration is not present.

Moderate
High Moderate: Between 40 - 60% of reach is disrupted by any of the channel alterations listed above. If the stream has been channelized, normal stable stream meander pattern has not recovered.

Low Moderate: Between 60 - 80% of reach is disrupted by any of the channel alterations listed in the parameter guidelines. If the stream has been channelized, normal stable stream meander pattern has not recovered.

Severe
Greater than 80% of reach is disrupted by any of the channel alterations listed above. Greater than 80% of banks shored with gabion, riprap, or cement. Channels entirely lined with riprap.

1.4.2 Channel Alteration Parameter Photographs

(see USM Photo File)

1.5 Reach Condition Index (RCI)

The **Reach Condition Index (RCI)** is a numerical value placed on the stream assessment reach using the **Condition Indices (CIs)** determined for each Parameter during the stream assessment. The **RCI** values range from 0.5-1.5 and result from a weighted average of the **CIs**. The average is weighted to reflect the fact that **Channel Condition** is valued twice that of other individual Parameters because a stream's physical stability heavily influences its condition. The following equation is used to determine the **RCI**:

Equation 2 RCI = (Sum of all CIs) ÷ 5

If multiple reaches are assessed the Evaluator may use the **Stream Assessment Summary Form (Form 2)** to record multiple **RCIs** and later determine the **Compensation Requirement (CR)**.

2.0 STREAM IMPACT FACTOR ASSESSMENT

Permitted impacts result in varying levels of impairment to streams. Different types of impacts can therefore be classified based on the degree to which they are expected to impair the stream. Table 1 depicts a wide array of impacts categorized into four Impact Classifications (Severe, Significant, Moderate, Negligible). Each Impact Classification has a corresponding **Impact Factor (IF)**. As depicted in Table 1, the more severe the impact, the higher the **IF**. Therefore, an activity considered to have a *Severe* impact has the highest **IF** of 1.0, representing an activity that is presumed to have a complete or near-complete loss of all beneficial stream functions. Conversely, an activity considered to have Negligible impacts has an **IF** of 0. These activities will not require stream compensation; however they are included in Table 1 to show that if impacts can be minimized to the point that the impact activity falls into the *Negligible* classification, then stream compensation is not required.

The **IF** obtained from Table 1 is used on the Stream Impact Assessment Form (Form1) and the Stream Assessment Summary Form (Form 2) included in Appendix A to calculate the **Total Compensation Requirement (Total CR)** for the project. By using the Impact Classifications and incorporating **IF's** into the equation, the impacts resulting in greater impairment require more compensation than impacts resulting in lesser impairment. Additionally, this serves as an incentive to decrease the degree of impact and ultimately the **CR**.

If an impact is not listed, then best professional judgment must be used in determining the most applicable Impact Classification. If multiple impacts occur within the **SAR**, the highest applicable **IF** is used for that reach.

Table 1: Impact Factor Table

Impact Activity **	*Impact Factor*
Severe Elimination or filling of stream channel Impoundments (flooding of stream channel) Hardening of stream bed (i.e., concrete, gabions, concrete blocks, riprap, countersunk & non-countersunk culverts) [1,2] Channel Alteration: (i.e., modifications to profile or habitat features; straightening or adverse sinuosity modifications; modifications to cross-section or width/depth ratio through widening or narrowing bankfull channel, deepening bankfull channel, channel constriction)	1.0
Significant Hardening of stream banks (i.e., concrete, gabions, concrete blocks, riprap, bottomless culverts and other similar structures)	0.75
Moderate Bridges with piers in the stream channel. Regulator's discretion is used to determine if piers result in stream channel impacts.	0.5
Negligible Bridges or other similar structures associated with roadways or trails causing no permanent impacts to stream channels, including no riprap lining, no piers, no widening, or no constriction of stream channels.	0

** Other activities not listed above that "alter the physical, chemical, or biological properties of stream channels" shall be considered on a case-by-case basis.

[1] The addition of floodplain culverts may reduce the Impact Factor from Severe to Significant.

[2] The requirement to countersink culverts does not apply to extensions or maintenance of existing culverts that are not countersunk, to floodplain culverts being placed above ordinary high water, to culverts being placed on bedrock, or to culverts required to be placed on slopes 5% or greater.

Notes:

1. For bridges resulting in no permanent impacts, floodplain culverts are encouraged and may be assessed as a minimization measure or compensation for other impacts on the same stream in the vicinity of the bridge at the agency personnel's discretion.

2.1 Impact Factor Photographs

(see USM Photo File)

3.0 Determining Stream Compensation Requirements

The stream **Compensation Requirement (CR)** for a project is determined after the following three steps have been performed:

1) Determine the length of impact **(L_I)**;

2) Complete Form 1 to obtain the **RCI**;

3) Classify the type of impact and determine the appropriate **IF** (Table 1).

The total Length of Impact **(L_I)** equals the original length of stream being impacted, not the length of stream remaining after the impacts. For example, if 500 feet of stream is straightened resulting in 400' of stream, then 500' is the impact length.

The **CR** is calculated using the following equation:

EQUATION 3:

$$\text{Compensation Requirement (CR)} = L_I \times RCI \times IF$$

Where,

CR = compensation credits required

L_I = length of impact (in linear feet)

RCI = Reach Condition Index (Form 1)

IF = Impact Factor (Table 1)

To determine the **CR**, the length of impact **(L_I)** is multiplied by the **RCI** obtained from Form 1 and by the appropriate **IF** obtained from Table 1. Form 1 is used to generate the **CR** for each reach evaluated. If more than one reach will be impacted, the individual **$L_{I's}$** and their corresponding **CR's** may be summed on Form 2.

4.0 Precompensation Evaluation and Stream Conceptual Mitigation Plan

In order to develop a conceptual stream mitigation plan, it is necessary to first research the stream's watershed and its history to determine the cause and extent of its deficiencies. The following questions should be answered to help identify and document the specific deficiencies to be addressed within a stream reach.

1. What is the stream name?
2. What is the reach length to be evaluated? Provide a USGS topographic map with the location of the stream reach clearly identified.
3. What is the stream order?

4. What is the approximate drainage area?
5. Describe the existing watershed and the estimated proposed land use for that watershed (ie: percent residential, percent forested, percent commercial, percent cleared/logged, percent industrial, percent agricultural, other)?
6. Describe the existing riparian buffer (ie: mature forested, herbaceous and shrub layers present in understory, utility easements present, understory maintained, lawns, impervious surfaces, active row crops, etc.)? Provide the estimated percentage of the total riparian area comprised of each cover type.
7. What is the estimated bankfull width?
8. What is the estimated bank height?
9. Is the channel high gradient or low gradient?
10. Does the channel appear to have natural sinuosity or does it appear that the channel pattern has been altered?
11. Does the channel appear to be aggrading, degrading, or stable?
12. Describe the sediment supply (ie: extreme, very high, high, etc.)
13. Are the streambanks eroding? Over what percentage of the reach?
14. Are headcuts present within the reach?
15. Provide a general narrative overview of the existing stream deficiencies and the proposed necessary restoration or enhancement measures to be taken to address those deficiencies.
16. What are the goals and objectives of the mitigation, and how will the mitigation plan meet those goals and objectives?
17. The Stream Impact Assessment Form can be used to further document the existing condition of the mitigation site.

4.1 Conceptual Compensatory Mitigation Plan

In Section 5.0 the **Compensation Credit (CC)** for conceptual stream compensation plans is determined. The Evaluator needs to be familiar with the Compensation Activities and Adjustment Factors described in Sections 5.1 – 5.4 and submit the necessary information needed to determine **CC**. Sections 5.1 – 5.4 describe the process for crediting the Compensation Activities and Adjustment Factors and state the necessary information needed to complete the Compensation Crediting Form (Form 3). Note: Additional information may be required per COE & DEQ regulations/permits.

- Section 5.1: Restoration
  - The length (in linear feet) of stream channel to be restored

- Section 5.2: Enhancement
  - The length (in linear feet) of stream channel expected to benefit from and be influenced by instream structures
  - The length (in linear feet) of each streambank expected to benefit from and be influenced by habitat structures
  - The length (in linear feet) of each streambank that will have bankfull bench creation
  - The length (in linear feet) of each streambank that will have the banks laid back
  - The length (in linear feet) of each streambank that will have bioremediation techniques used
  - The length (in linear feet) of each streambank that will have streambank plantings

- Section 5.3: Riparian Buffer
  - The percent of the inner and outer 100’ buffers of each streambank that will be re-established
  - The percent of the inner and outer 100’ buffers of each streambank that will be planted heavily
  - The percent of the inner and outer 100’ buffers of each streambank that will have light or supplemental planting

- The percent of the inner and outer 100' buffers of each streambank that will be preserved only

- Section 5.4: Adjustment Factors
  - Rare, Threatened, and Endangered Species or Communities
    - The name of the species being protected
    - The indicator status of the species
    - The amount the proposed activity will aid or protect that species
    - Whether an activity will protect habitat or known locations of a species
    - The connection to other wildlife corridors
    - The number of species to be benefited

  - Livestock Exclusion
    - The length of time livestock have had access to the stream

      The number of livestock excluded
    - The expected water quality improvements provided by the project

  - Watershed Preservation
    - The nature of the restriction
    - The level of preservation or protection provided
    - The benefit to the stream system

5.0 Determining Compensation Crediting

The Total **Compensation Requirement (CR)** computed in Section 3.0 and on Form 2 represents the total stream compensation credits required for the project.

This section describes the methods and alternatives for fulfilling the **CR** for both onsite and offsite compensation, and explains the crediting process. Using this process, ensures that crediting on-site and off-site compensation projects, evaluating and approving stream compensation banks through the Mitigation Bank Review Team, and in-lieu fee fund projects are all credited in the same manner. This process does not include a method for crediting out-of-kind compensation activities such as removing effluent/straight pipes, correcting acid mine drainage, or removing fish blockages. These activities may serve to fulfill the **CR** in certain situations, but will be credited on a case-by-case basis.

The process categorizes compensation methods and utilizes a Compensation Crediting Form (Form 3), included in Appendix B, to determine the **CC** for various levels of stream and riparian buffer preservation, enhancement, and restoration activities. The **CC** is refined by applying the appropriate **Adjustment Factors (A_F)** to the credits obtained through the various activities.

The following is a step-wise summary of the procedure for calculating the **CC's** obtained from a stream compensation plan:

- Enter the project number, project name, locality, Cowardin classification, HUC, date, stream compensation length, name of evaluators, stream name, and reach ID number.

- If restoration is proposed, then enter the length of stream channel to be restored in the appropriate box on Form 3. The length is multiplied by the credit and restoration credit is calculated.

- If Enhancement with Instream Structures is proposed, determine the affected length. Enter this length in the appropriate box on form 3. The length is multiplied by the credit for Instream Structures.

- If other Enhancement activities are proposed, determine which techniques will be employed, and enter the corresponding length and credit, for each bank, in the appropriate boxes on Form 3. The length of each proposed activity is multiplied by the credit for each activity. The sum of credits provided by each of the activities and the credit provided by Instream Structures result in a total enhancement credit and is entered in the appropriate box of Form 3.

- Determine the riparian buffer area and enter the percent area for the inner 100 and its corresponding credit for each bank in the appropriate box on Form 3. The percent area is multiplied by the credit. The sum of these products for each bank results in the credit for that bank. The right bank and left bank credits are then averaged to obtain an average per-foot credit for the work being done on the reach. This average credit is then multiplied by the total length of the stream reach to obtain the total riparian credit for that particular reach. This calculation is repeated for the outer 100' (100'-200').

- Determine which adjustment factors apply to the project and enter the corresponding length and credit in the appropriate box on Form 3. The length is multiplied by the credit and the amount of the additional credit is calculated. The sum of additional credits provided by each is entered in the appropriate box of Form 3.

- The total credits generated under each activity are added together and result in the total credit.

Methods employed to improve or protect streams include a wide range of activities aimed at preserving, enhancing, stabilizing, or restoring various stream functions. Some of these methods require greater efforts and provide greater benefits than others. When these methods are proposed as stream compensation, the amount of effort required and the resulting benefits from such activities must be taken into account when determining the amount of **CC** granted. Therefore, the amount of **CC** is based on the activity, the expected level of improvement to stream function and quality, and the amount of effort required and methods employed.

This section demonstrates how to credit design components included in the compensation plan. Compensation Crediting is determined by using the USM Compensation Crediting Form (Form 3). The complexity of the project will dictate the number of forms required to be completed. The needed improvements should be based on an assessment of the existing stream deficiencies.

This USM method does not determine whether or not a compensation proposal/plan is appropriate. Agency personnel will rely on the information provided in the Precompensation Evaluation, the conceptual compensation plan, knowledge of the site, natural stream channel design techniques, and best professional judgment to make that determination. Form 3 is utilized simply to calculate the credit provided by each activity on a given reach and any adjustment factors. It should be noted that no credit will be given for unnecessary techniques and/or structures.

The following provides details on compensation practices and guidelines for using the USM Compensation Crediting Form (Form 3).

5.1 Restoration (1 CC per foot)

Restoration is the process of converting an unstable, altered, or degraded stream corridor, including flood-prone areas, to a natural stable condition considering recent and future watershed conditions. This process should be based on a reference condition/reach for the stream valley type and includes restoring the appropriate geomorphic dimension (cross-section), pattern (sinuosity), and profile (channel slope). This process supports reestablishing the streams biological and chemical integrity, including transport of the water and sediment produced by its watershed in order to achieve dynamic equilibrium.

An analysis of the existing geomorphological parameters of the compensation stream is compared to those in a stable reference stream. Natural stream channel design methods and calculations are then applied to result in a stable stream dimension, pattern, and profile that maintains itself within the natural variability of the design parameters. Restoration activities utilizing the natural stream channel design approach typically address the following:

1. Deficiencies in sinuosity, radius of curvature, belt width, meander length
2. Deficiencies in spacing, lengths, and depths for riffles, runs, pools, & glides
3. Restore appropriate critical shear stress
4. Deficiencies in slopes for channel, riffles, runs, pools, & glides
5. Deficiencies in width-depth ratio and cross-sectional area

Situations that readily lend themselves to inclusion in the Restoration Category include Priority 1, 2, or 3 relocations and restorations as described in *A Geomorphological Approach to Restoration of Incised Rivers*, Rosgen 1997[1]. The following provides additional information on these Priorities:

Priority 1 Restoration[1]
Priority 1 Restoration is defined as stream channel restoration that involves the re-establishment of a channel on the original floodplain, using a relic channel or constructing a new channel. The new channel is designed and constructed with the proper dimension, pattern, and profile characteristics for a stable stream. The existing, incised channel is either backfilled or made into discontinuous oxbow lakes level with the new floodplain elevation. (Rosgen, 1997)

Priority 2 Restoration[1]
Priority 2 Restoration is defined as stream channel restoration that involves re-establishment of a new floodplain at the existing level or higher but not at the original level. The new channel is designed and constructed with the proper dimension, pattern, and profile characteristics for a stable stream. (Rosgen, 1997)

Priority 3 Restoration[1]
Priority 3 Restoration is defined as stream channel restoration to a channel without an active floodplain but with a flood prone area (Rosgen, 1997). However, the channel restoration must involve establishing proper dimension, pattern, and profile. Some sites may present difficulties in reestablishing a sinuous pattern when they are laterally contained or have limitations in available belt width. This is often caused by utilities, infrastructure, and other floodplain encroachments. Such physical constraints often favor the creation of a step/pool bed morphology with less sinuosity (associated with Priority 3) over a riffle/pool bed morphology with greater sinuosity (associated with Priorities 1 & 2). It is necessary to consider the available belt width and the slope of the proposed stream when designing the appropriate stream type that is suitable for that

[1] Rosgen, David. 1997. *A Geomorphological Approach to Restoration of Incised Rivers*. Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision. 11pp.

situation. Information should be provided showing that the appropriate dimension, pattern, and profile are being restored for the proposed stream type in that particular situation.

The compensation plan narrative needs to describe, and the plan design sheets need to clearly demarcate, the stream channel length (in linear feet) and stream reaches to be restored, as defined above. The restoration length should be recorded in the appropriate box on Form 3 then it is multiplied by 1.0 resulting in the restoration credit.

Restoration Restrictions:

1. **No enhancement activities can be coupled with restoration on the same linear foot of stream channel.**

2. **The difference between projects that are credited as Restoration and projects that are credited as Enhancement, is whether or not changes are necessary to address the current channel's dimension, pattern, and profile, as described for each of the Priorities, to produce a stable channel. All three geomorphic variables are required to be addressed, with noted pattern limitations for Priority 3, in order to receive Restoration credit. Enhancement credit is given in all other situations when only two geomorphic variables are addressed to produce a stable channel.**

5.1.1 Restoration Photographs

(see USM Photo File)

5.2 Enhancement

Enhancement Activities include physical alterations to the channel that do not constitute Restoration but that directly augment channel stability, water quality, and stream ecology in accordance with a reference condition, where appropriate. These activities may include in-stream and/or streambank activities, but in total fall short of restoring one or more of the geomorphic variables: dimension, pattern and profile. There are 6 activities included in this category: 1) Instream Structures (cross vanes, j hooks, etc.), 2) Habitat Structures (fish boards, root wads, etc), 3) Bankfull Bench Creation, 4) Laying Back Banks, 5) Bioremediation Techniques, and 6) Stream Bank Planting.

These compensation activities <u>directly</u> improve the stability of, or enhance the streambanks, streambed, and in-stream habitat by physically manipulating them.

Instream Structures (0.3 credit per foot of effect)
This activity includes structures that are specifically designed and result in grade control and/or bank stabilization. Accepted structures include, but are not limited to, cross-vanes, j-hook vanes, native material revetments, W rock weirs, rock vortex weirs, log-vanes, constructed riffles, and step-pools. These structures may be created out of appropriate sized rock or logs, boulders or cobbles based on the size of the stream and the flow regime. Structures not listed will be considered on case-by-case basis. Normally, a pool is constructed in combination with these structures, however, if one is not constructed this does not alter the credit provided.

The compensation plan needs to state, and clearly demarcate, the length (in linear feet) of stream channel and reaches of stream channel expected to benefit from and be influenced by the structures. Record this length in the appropriate box on Form 3. This length is multiplied by 0.3 and the credit is calculated.

Habitat Structures (0.1 credit per foot per bank)
This activity includes structures designed specifically for habitat creation. Although, Instream Structures typically provide habitat, they are constructed for channel stability and will not receive credit for Habitat Structures. Habitat Structures do not typically contribute to channel stability. Accepted structures include, but are not limited to, submerged shelters, fish boards or bank cover, floating log structures, root wads, and half-log cover. Riffle and pool complexes and over hanging vegetation do not qualify for credit in this activity.

The compensation plan should state, and the plan sheets should clearly demarcate, the length (in linear feet) of stream channel where habitat structures are proposed. This length is recorded in the appropriate bank row on Form 3. This length is multiplied by 0.10 and the credit for that structure is calculated.

Bankfull Bench Creation (0.15 credit per foot per bank)
This activity involves the creation of a bankfull bench along one or both of the stream banks. This activity may result in less than the proper entrenchment ratio but does result in a stable channel. The compensation plan should state, and the plan sheets should clearly demarcate, the length (in linear feet) of stream channel where bankfull benches are proposed. This length is recorded in the appropriate bank row on Form 3. This length is multiplied by 0.15 and the credit for that length of bench is calculated.

Lay Back Bank (0.1 credit per foot per bank)
This activity involves the manual manipulation of the bank slope but does not create a bankfull bench or floodplain. The compensation plan should state, and the plan sheets should clearly demarcate, the length (in linear feet) of stream channel where laying back the banks is proposed. This length is recorded in the appropriate bank row on Form 3. This length is multiplied by 0.1 and the credit for that length of bank is calculated.

Bioremediation Techniques (0.1 credit per foot per bank)
This activity primarily relates to the use of coir logs or similar materials for bank stabilization. Techniques and materials in this category include, but are not limited to, live fascines, branch packing, brush mattresses, coir logs, and natural fiber rolls. More than one of these materials or techniques may be warranted over the same stream length. In this case, no additional credit will be applied for that length. In other words, the compensation plan should include all bioremediation techniques required over a particular length. Techniques and materials other than those listed will be considered on a case-by-case basis for approval by the agencies.

The compensation plan should state, and the plan sheets should clearly demarcate, the length (in linear feet) of stream channel where bioremediation techniques are proposed. This length is recorded in the appropriate bank row on Form 3. This length is multiplied by 0.1 and the credit for that length of bank is calculated.

Streambank Planting (0.09 credit per foot per bank)
This activity includes the installation of plants other than seed along the immediate stream bank area. This is primarily done for streambank stabilization. This activity includes live stakes, dormant post/stakes, branch layering, and the installation of plants. The length of the bank over which this activity occurs is entered into the Form 3. If it occurs on both banks, it is entered in both rows.

The compensation plan should state, and the plan sheets should clearly demarcate, the length (in linear feet) of stream channel where streambank plantings are proposed. This length is recorded in the appropriate bank row on Form 3. This length is multiplied by 0.09 and the credit for that length of bank is calculated.

EQUATION 4:

Structure Credit = Length affected*Credit

Left Bank Credit =SUM (Length*Credit)

Right Bank Credit = SUM (Length*Credit)

Enhancement Credit = Structure Credit + Left Bank Credit + Right Bank Credit

Enhancement Restrictions:

1. **Activities cannot be credited as both Restoration and Enhancement activities.**
2. **A structure cannot be credited as both an Instream Structure and a Habitat Structure.**
3. **Mechanical bank work cannot be credited as both Bankfull Bench and Laying Back the Banks.**
4. **Bioremediation Techniques do not include Erosion Control matting.**

5.2.1 Enhancement Photographs

(see USM Photo File)

5.3 Riparian Areas

This compensation activity includes improvements to riparian zones and includes their preservation in perpetuity. This activity includes: Buffer Re-Establishment, Heavy Buffer Planting, Light Buffer Planting, and Preservation Only.

The credit is determined by calculating the area within the first 100' buffer in which a given riparian activity is proposed. For each bank, the Percent Area for each activity is multiplied by the credit given to that area. No area can be counted twice. The sum of these products for each bank results in the credit for that bank. The right bank and left bank credits are then averaged to obtain an average per-foot credit for the work being done on the reach. This average credit is then multiplied by the total length of the stream reach to obtain the total riparian credit for that particular reach. See Example 2 below, for further explanation.

The same process is used to determine the percent area within the outer 100' buffer using the outer 100 feet credit values. Credit is reduced since this buffer area has less influence on stream stability, water quality, and instream habitat.

Buffer Re-Establishment (0.4 inner 100 feet/0.2 outer 100 feet)
Credit for this activity is given when invasive plant species are eradicated and the buffer area is returned to native species, monitored to ensure invasive species eradication and the success of the native species. Invasive species are those listed as highly or moderately invasive on the Department of Conservation and Recreation *Invasive Alien Plant Species of Virginia* List.

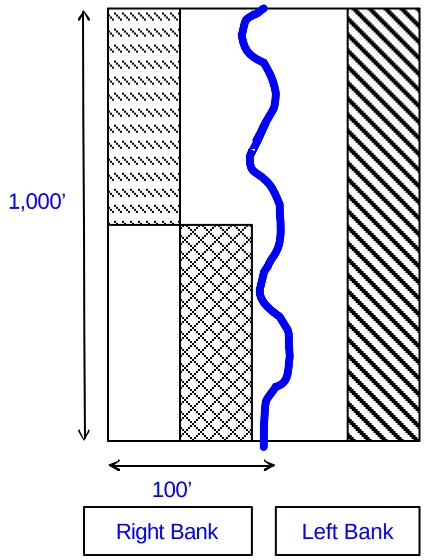
Heavy Buffer Planting (0.38 inner 100 feet/0.19 outer 100 feet)
Credit for this activity is given when the buffer area requires extensive planting (example: 400 stems per acre or more) and may include balled and burlapped specimens and/or containerized specimens.

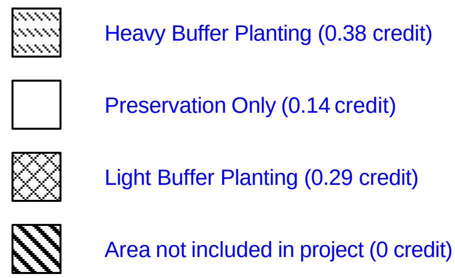
Light Buffer Planting (0.29 inner 100 feet/0.15 outer 100 feet)
Credit for this activity is given when the buffer area requires only light or supplemental planting. This activity would involve planting at less than ideal densities (example: less than 400 stems per acre), either because vegetation is already present, a seed source is present, or the project does not otherwise warrant it.

Preservation Only (No Work Proposed)
Credit for this activity is given when no work to a riparian buffer area is proposed but that area will be placed under perpetual protection through the implementation of appropriate legal mechanisms. Credit is given based on the quality of the stream preserved. Additional credit is given for the preservation of High Quality streams (streams with an **RCI** from 1.25 to 1.5). Low Quality streams are those with an RCI from 1.0 to 1.24. Preservation is rarely allowed for streams that score below an **RCI** of 1.0. When preservation of the buffer is conducted on streams where stream restoration/enhancement activities are proposed, the credit for High Quality streams is applied since the compensation proposal will result in an improvement. For the inner 100 feet, High Quality streams receive 0.14 credit per percent area and Low Quality streams receive 0.07 credit per percent area. For the outer 100 feet, all streams receive 0.07 credit per percent area.

Riparian Areas Restrictions:

1. **Buffer proposals for less than 25 feet in width or greater than 200 feet in width, on either side of the stream, must be approved by the Agencies on a case-by-case basis.**
2. **When trees are removed in order to perform restoration or enhancement activities, the areas to be replanted cannot be credited toward heavy or light buffer planting. These areas will be credited as Preservation Only.**
3. **No area of buffer can be credited under more than one Riparian Buffer category.**
4. **Credit is reduced by 0.03 for each of the three vegetative layers excluded from any particular riparian area. For example, if a riparian buffer is preserved but maintained as shrub and herbaceous vegetation without trees, the preservation credit of 0.14 is reduced by 0.03 for the missing tree layer.**





For this example, a proposed project consists of the preservation of 50’ buffer on one side of the stream and 100’ buffer on the other. Within the 100’ buffer, the outer 50’ (over 500’ of stream length) will be restored with Heavy Buffer Planting and inner 50’ will be restored with Light Buffer Planting (over 500’ of stream length).

For this example, the Evaluator considers the area of each activity within the 100’ buffer. On both sides of the stream an area of 100,000 square feet (sf) is available for consideration (100’ wide X 1,000’ long).

An area of 25,000 sf on the Right Bank is being restored with Heavy Buffer Planting (50’ wide X 500’ long). 25,000 sf is 25% of 100,000 sf. Therefore, 25 is entered into Right Bank Percent Area row of the CC form and 0.38 is entered into the credit row below the corresponding Percent Area (25%). [25 X 0.38 X 0.01 = 0.095]

An area of 25,000 sf on the Right Bank is being restored with Light Buffer Planting (50’ wide X 500’ long). 25,000 sf is 25% of 100,000 sf. Therefore, 25 is entered into Right Bank Percent Area row of the CC form and 0.29 is entered into the credit row below the corresponding Percent Area (25%). [25 X 0.29 X 0.01 = 0.0725

An area of 50,000 sf on the Right Bank is only being preserved (50’ wide X 500’ long X .14). 50,000 sf is 50% of 100,000 sf. Therefore, 50 is entered into Right Bank Percent Area row of the CC form and 0.14 is entered into the credit row below the corresponding Percent Area (50%). [50 X 0.14 X 0.01 = 0.07]

An area of 50,000 sf on the Left Bank is only being preserved (50’ wide X 500’ long). 50,000 sf is 50% of 100,000 sf. Therefore, 50 is entered into Left Bank Percent Area row of the CC form and 0.14 is entered into the credit row below the corresponding Percent Area (50%).
[50X 0.14 X 0.01 = 0.07]

An area of 50,000 sf on the Left Bank (50’ wide X 500’ long) is not part of the proposed project (0 credit earned). 50,000 sf is 50% of 100,000 sf. Therefore, 50 is entered into Percent Area row of the CC form and 0 is entered into the credit row below the corresponding Percent Area (50%).
[500 X 0.0 X 0.01 = 0.00]

This project alone (not considering any restoration, enhancement, or adjustment factors) provides 153.75 credits of Compensation Credit.

RB % Area	25	25	50	RB Credit		Reach Length
Credit	0.38	0.29	0.14	0.24		1,000
					CREDIT	Buffer Credit
LB % Area	50	50		LB Credit	0.16	160
Credit	0.14	0.0		0.07		

Example 2: Riparian Areas Crediting Example

5.3.1 Riparian Areas Photographs

(see USM Photo File)

5.4 Adjustment Factors

Adjustment Factors **(A_F)** are used to account for exceptional or site specific circumstances associated with the compensation site. These circumstances may provide ecological benefits that exceed the minimal requirements of the method presented in this Manual. The Adjustment Factors are applied only when ecological and/or water quality benefits are achieved.

Each **A_F** activity is credited within a prescribed range. The range is to account for variation in activities and conditions that warrant **A_F** credit. Examples are given for each of the ranges. The agency representative shall make this determination on a case-by-case basis and use best professional judgment.

Rare, Threatened, and Endangered Species or Communities
Increased **Compensation Credit (CC)** is warranted for sites that show a significant improvement in restoring, enhancing, or preserving communities or individuals of rare or threatened and endangered species (T&E). It is necessary to consider the influences of activities upstream of the compensation site before applying this **A_F**. If upstream activities would prevent significant improvement from occurring, this **A_F** may not be warranted. The agency representative should coordinate with State and Federal agencies such as Virginia Department of Conservation and Recreation (DCR), Virginia Department of Game and Inland Fisheries (DGIF), or U.S. Fish and Wildlife Service (FWS) prior to applying this **A_F.**

The range of credit provided by this activity is 0.1 – 0.3. The following factors are considered in determining the credit: 1) the indicator status of the species, 2) the amount the proposed activity will aid or protect that species, 3) whether an activity will protect habitat or known locations of a species, 4) the connection to other wildlife corridors, and 5) the number of species protected. **This A_F does not apply to projects where compensation of T&E species is required as a result of consultation with state and federal resource agencies.**

Livestock Exclusion
Increased compensation credit is warranted for sites that exclude livestock because it has significant water quality and streambank stability benefits. Livestock exclusion is a process of placing fencing around a stream and adjacent riparian buffer so that livestock access is limited. Livestock must be excluded for a site to be accepted as compensation. Infrequent livestock crossings or watering holes may be permitted, if necessary.

Sites where livestock have been recently placed for the purposes of obtaining additional credit will not be considered for this **A_F**. This Af does not apply to sites where livestock are excluded due to land development.

The range of credit provided by this activity is 0.1 – 0.3. The following factors are considered when determining the credit: 1) the number of livestock excluded, and 2) the water quality and streambank stability improvements.

Watershed Preservation
Increased **CC** may be warranted if the compensation site incorporates additional legal mechanisms that prohibit any increase in runoff rates in the watershed above pre-development rates, and the site is designed to accommodate the existing rates. These legal mechanisms may be in the form of preserving the entire watershed as is, or instituting future runoff restrictions within the watershed. This factor does not apply to sites designed to accommodate future increases in runoff rates that do not incorporate these additional legal mechanisms. This factor

also does not apply if such restrictions are already in place or when they are otherwise required by another agency or entity.

The range of credit provided by this activity is 0.1 – 0.3. The following factors are considered when determining the credit: 1) the nature of the restriction, 2) the level of preservation or protection provided, and 3) the benefit to the stream system.

6.0 Evaluating Compensation Credit

The sum of all of the credits provided by all of the Compensation Activities and Adjustment Factors within the reach equals the Total Compensation Credit (Total **CC**) provided by the reach. This is calculated using the following equation:

EQUATION 5

Total CC=SUM (Restoration Credit + Enhancement Credit + Riparian Buffer Credit + Adjustment Factor Credit)

If more than one form is completed, then the results from each form are recorded on the Compensation Summary Form (Form 4), included in Appendix B, which is used to summarize each individual stretch of stream and to calculate **Compensation Credits (CC)**.

Appendix A

Stream Assessment Forms

Form 1: Stream Assessment Form

(see USM Forms File)

Form 2: Stream Assessment Summary Form

(see USM Forms File)

Appendix B

Compensation Crediting Forms

Form 3: Compensation Crediting Form

(see USM Forms File)

Form 4: Compensation Summary Form

(see USM Forms File)

Appendix C

Definitions

Channel Dimension- The cross-sectional profile of a channel.

Channel Pattern - The sinuosity or meander geometry of a channel.

Channel Profile – The longitudinal slope of a channel.

Embeddness - is measurement of the degree to which larger particles are covered with finer particles.

Enhancement - physical alterations to the channel that do not constitute Restoration but that directly augment channel stability, water quality, and stream ecology in accordance with a reference condition where appropriate.

Ephemeral Streams - streams that have flowing water only during and for a short duration after, precipitation events in a typical year. Ephemeral streambeds are located above the groundwater table year-round. Groundwater is not a source of water for the stream. Runoff from rainfall is the primary source of water for these streams.

High Gradient Streams – is defined by EPA as streams with moderate-high gradient landscapes; substrates primarily composed of coarse sediments [gravel (2mm) or larger] or frequent coarse particulate aggregations; riffle/run prevalent.

Intermittent Streams - streams that have flowing water during certain times of the year, when groundwater provides water for stream flow. During dry periods, intermittent streams may not have flowing water. Runoff from rainfall is a supplemental source of water for stream flow.

Low Gradient Streams - is defined by EPA as streams with low-moderate gradient landscapes; substrates of fine sediment particles or infrequent aggregations of coarse sediment particles [gravel (2mm) or larger]; glide/pool prevalent.

Macroinvertebrates - are small stream dwelling animals that do not have vertebrae and are visible with the naked eye.

Natural Channel Design - proper dimension, pattern, and profile for a given stream type. (See definitions for channel dimension, channel pattern, and channel profile).

Priority 1 Restoration - is defined as stream channel restoration that involves the re-establishment of a channel on the original floodplain, using either a relic channel or construction of a new channel. The new channel is designed and constructed with the proper dimension, pattern, and profile characteristics for a stable stream. The existing, incised channel is either backfilled or made into discontinuous oxbow lakes level with the new floodplain elevation.

Priority 2 Restoration - is defined as stream channel restoration that involves re-establishment of a new floodplain at the existing level or higher but not at the original level. The new channel is designed and constructed with the proper dimension, pattern, and profile characteristics for a stable stream.

Priority 3 Restoration - is defined as stream channel restoration to a channel without an active floodplain but with a floodprone area. However, the restoration of the channel must involve establishing proper dimension, pattern, and profile. Some sites may present difficulties in reestablishing a sinuous pattern when they are laterally contained or have limitations in available belt width. This is often caused by utilities, infrastructure, and other floodplain encroachments. Such physical constraints often favor the creation of a step/pool bed morphology with less sinuosity (associated with Priority 3) over a riffle/pool bed morphology with greater sinuosity (associated with Priorities 1 & 2). It is necessary to consider the available belt width and the slope of the proposed stream when designing the appropriate stream type that is suitable for that situation. Information should be provided showing that the appropriate dimension, pattern, and profile are being restored for the proposed stream type in that particular situation.

Stream Preservation - The protection of ecologically important aquatic resources in perpetuity through the implementation of appropriate legal and physical mechanisms. Preservation will include protection of riparian areas adjacent to stream channels or other aquatic resources as necessary to ensure protection and/or enhancement of the aquatic ecosystem.

Stream Relocation - Movement of a stream from one location to another, usually by filling the old channel and redirecting the stream to a separate location.

Stream Restoration - Converting an unstable, altered, or degraded stream corridor, including adjacent riparian zone (buffers) and flood-prone areas, to its natural stable condition considering recent and future watershed conditions. This process should be based on a reference condition/reach for the valley type and includes restoring the appropriate geomorphic dimension (cross-section), pattern (sinuosity), and profile (channel slopes), as well as reestablishing the biological and chemical integrity, including transport of the water and sediment produced by the stream's watershed in order to achieve dynamic equilibrium.

\

Appendix D

Useful Internet Links/References

I. Corps-DEQ Guidance

Corps-DEQ guidance "Off-site Mitigation Location Guidelines": Coming soon

Corps-DEQ guidance "Abbreviated Corps-DEQ Mitigation Recommendations" (June 2004):
http://www.nao.usace.army.mil/technical services/Regulatory branch/Guidance/Abbreviated_Corps-DEQ_Mit_7-04.pdf

Corps-DEQ deed restriction boilerplate language (updated June 2003 and in Microsoft word):
http://www.nao.usace.army.mil/technical services/Regulatory branch/Guidance/DECLARATION_OF_RESTRICTIONS.doc

II. Stream Restoration References

Stream Restoration: A Natural Channel Design Handbook (North Carolina Stream Restoration Institute):
http://www.bae.ncsu.edu/programs/extension/wqg/sri/stream_rest_guidebook/guidebook

Wildland Hydrology (Dave Rosgen's official website): http://www.wildlandhydrology.com/

Virginia Department of Conservation and Recreation's The Virginia Stream Restoration and Stabilization Best Management Practices Guide: http://www.dcr.virginia.gov/sw/index.htm

U.S. Fish and Wildlife Service Stream Restoration Publications:
http://www.fws.gov/chesapeakebay/streampub.htm

U.S. Department of Agriculture Stream Corridor Restoration: Principles, Processes, and Practices http://www.nrcs.usda.gov/technical/stream_restoration/

USGS document Development and Analysis of Regional Curves for Streams in the Non-Urban Valley and Ridge Physiographic Province, Maryland, Virginia, and West Virginia
http://pubs.usgs.gov/sir/2005/5076/

Regional curves for North Carolina
http://www.bae.ncsu.edu/programs/extension/wqg/sri/regional.htm

III. References for Invasive Plant Species

Virginia Department of Conservation and Recreation's (DCR) List of Invasive Plants:
www.dcr.state.va.us/dnh/pdflist.htm

United States Department of Agriculture's List of Invasive Plant Species: http://plants.usda.gov/

A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

Prepared by Pamela C. Dodds, Ph.D., Licensed Professional Geologist
Prepared for The Wilderness Society - January 24, 2023

REFERENCE 6

February 21, 2023

Science Documentation

Revised Universal Soil Loss Equation Version 2

(RUSLE2)

(for the model with release date of May 20, 2008)

USDA-Agricultural Research Service

Washington, D.C.

August 2013

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Acknowledgements

RUSLE2 was developed cooperatively by the USDA-Agricultural Research Service (ARS), the USDA-Natural Resources Conservation Service (NRCS), and the Biosystems Engineering and Environmental Science Department of the University of Tennessee. Each project participant maintains a RUSLE2 Internet site directed toward their specific interests. Consult these sites for a list of the employees of these organizations who contributed to the development of RUSLE2. Contributors from several other organizations also participated in the development of RUSLE2.

The USDA-ARS was responsible for providing the erosion science on which RUSLE2 is based including the mathematical equations used in RUSLE2, core data values used to calibrate RUSLE2, scientific documentation, and a user's reference guide for RUSLE2.

The USDA-NRCS was the principal client for RUSLE2. The NRCS provided information to ensure that RUSLE2 could be easily used in their local field (district) offices. The NRCS also developed an extensive RUSLE2 operational (working) database, primarily for cropland. The NRCS has developed RUSLE2 templates and user guides specifically for their purposes.

The University of Tennessee participated in the development of the mathematical equations used in RUSLE2, developed the computer science used in RUSLE2, and developed the RUSLE2 computer program. They also developed user guides and other RUSLE2 information for their clients.

The interests and needs of a wide variety of other users were considered during RUSLE2's development. RUSLE2 was developed to be land-use independent to give RUSLE2 the widest applicability range possible and to accommodate the needs of these users.

This RUSLE2 Science Documentation was reviewed by USDA-Natural Resources Conservation Service technical specialists from several disciplines; Kenneth G. Renard (retired), USDA-Agricultural Research Service, Tucson, Arizona; and Seth Dabney, USDA-Agricultural Research Service, Oxford, Mississippi.

Preface

The Revised Universal Soil Loss Equation, Version 2 (RUSLE2) is used to guide conservation and erosion control planning at the local field office level. RUSLE2 estimates average annual rill and interrill erosion based on site-specific conditions. In a typical application, the planner identifies several potential erosion control alternatives for the site and estimates erosion for each alternative. The planner then chooses the alternative that provides adequate erosion control and best meets other requirements.

RUSLE2 is computer-based technology that involves a computer program, mathematical equations, and a large database. The RUSLE2 user describes a specific site by making selections from the database. RUSLE2 uses this information in its mathematical equations to compute erosion estimates for alternative erosion control practices for the site.

RUSLE2 can be used to estimate rill and interrill erosion where mineral soil is exposed to the erosive forces of impacting raindrops and water drops falling from vegetation and surface runoff produced by Hortonian overland flow. RUSLE2 is land use independent and can be applied wherever these conditions exist. RUSLE2 can be used on cropland, pastureland, rangeland, constructions site, reclaimed mine land, landfills, mine tailings, mechanically disturbed and burned forestlands, military training sites, and similar lands.

This document describes the RUSLE2 science, which is primarily embodied in the mathematical equations used in RUSLE2. The RUSLE2 User's Reference Guide, a companion document, describes how RUSLE2 works, how to interpret values computed by RUSLE2, how to select and enter values into the RUSLE2 database, and how to judge the adequacy of RUSLE2. Additional information is available on the RUSLE2 Internet site maintained by the USDA-Agricultural Research Service: http://www.ars.usda.gov/Research/docs.htm?docid=6010. Additional information is also available on RUSLE2 Internet sites maintained by the USDA-Natural Resources Conservation Service and the University of Tennessee.

Each chapter in this document stands alone with its own list of symbols given at the end of the chapter. Symbols are defined on their occurrence. Refer to the list of symbols at the end of each chapter because symbol usage differs between chapters.

RUSLE2 uses mathematical equations from several disciplines. In most cases, the symbols that are common in a given discipline are used in this document, which results in the same symbol being used for multiple variables, even within the same chapter. Using the typical symbol for a given variable was considered to be more useful than having a unique symbol for each variable.

Also, topics overlap between chapters. The topics within and between chapters are organized according to the mathematical structure of RUSLE2 rather than along a user oriented structure, which is followed in the RUSLE2 User Reference Guide. Consequently, the mathematical representation of key variables such as residue may be discussed in several places in this document. Cross references to other sections where this variable is discussed are included for the major variables.

Disclaimer

The purpose of RUSLE2 is to guide and assist erosion-control planning. Erosion-control planners should consider information generated by RUSLE2 to be only one set of information used to make an erosion-control decision. RUSLE2 has been verified and validated, and every reasonable effort has been made to ensure that RUSLE2 works as described in RUSLE2 documentation available from the USDA-Agricultural Research Service. However, RUSLE2 users should be aware that errors may exist in RUSLE2 and exercise due caution in using RUSLE2.

Similarly, this RUSLE2 Science Documentation has been reviewed by erosion scientists and RUSLE2 users. These reviewers' comments have been faithfully considered in the revision of this document.

Every reasonable effort has been made to ensure that this document is accurate. The USDA-Agricultural Research Service alone is responsible for this document's accuracy and how faithfully the RUSLE2 computer program represents the information in this document.

Glossary of Terms

Term	Description
10 yr EI	Storm EI with a 10-year return period
10 yr-24 hr EI	Storm EI for the 10 yr-24 hr precipitation amount
10 yr-24 hr precipitation	24 hour precipitation amount having a 10 year return period
Antecedent soil moisture subfactor	See cover-management subfactors
Average annual, monthly, period, and daily erosion	RUSLE2 computes average daily erosion for each day of the year, which represents the average erosion that would be observed if erosion was measured on that day for a sufficiently long period. Average period, monthly, and annual erosion are sums of the average daily values
Average erosion	Average erosion is the sediment load at a given location on the overland flow path divided by the distance from the origin of overland flow path to the location
b value	Coefficient in equation for effect of ground cover on erosion, values vary daily with rill-interrill erosion ratio and residue type
Buffer strips	Dense vegetation strips uniformly spaced along overland flow path; can cause much deposition
Burial ratio	Portion of existing surface (flat) cover mass that is buried by a soil disturbing operation (dry mass basis-not area covered basis)
Calibration	Procedure of fitting an equation to data to determine numerical values for equation’s coefficients
Canopy cover	Cover above soil surface; does not contact runoff; usually vegetation
Canopy shape	Standard shapes used to assist selection of fall height values
Canopy subfactor	See cover-management subfactors
Climate description	Input values for variables used to represent climate, stored under a location name in the climate component of RUSLE2 database

Concentrated flow area	Area on landscape where channel flow occurs; ends overland flow path
Conservation planning soil loss	A conservation planning erosion value that gives partial credit to deposition as soil saved, credit is function of location on overland flow path where deposition occurs
Contouring	Support erosion control practice involving ridges-furrows that reduces erosion by redirecting runoff around hillslope
Contouring failure	Contouring effectiveness is lost where runoff shear stress exceeds a critical value
Contouring description	Row grade used to describe contouring; stored in contouring component of RUSLE2 database; ridge height in *operation* description used in cover-*management* description also key input
Core database	RUSLE2 database that includes values for base conditions used to validate RUSLE2; input values for a new condition must be consistent with values in core database for similar conditions
Cover-*management* description	Values for variables that describe cover-management, includes dates, *operation* descriptions, *vegetation* descriptions, vegetation production levels (yields), external *residue* descriptions and amount applied, cover-*management* descriptions named and saved in the management component of RUSLE2 database
Cover-management subfactors	Cover-management subfactor values used to compute detachment (sediment production) by multiplying subfactor values; subfactor values vary through time as cover-management conditions vary temporally
Canopy	Represents how canopy affects erosion; function of canopy cover and fall height, canopy varies through time
Ground cover	Represents how ground cover affects erosion; function of portion of soil surface covered
Surface roughness	Represents how soil surface roughness affects erosion; function of roughness index
Soil biomass	Represents how live and dead roots in upper 10 inches and buried residue in upper 3 inches and less affect erosion
Soil consolidation	Represents how a mechanical disturbance affects erosion;, erosion decreases over time after last disturbance as the soil consolidates (soil consolidation as used in RUSLE2 represents soil particles rebonding during soil wetting and drying; rebonding process is not

	to occur by mechanical compaction)
Ridging	Represents how ridges increase detachment (sediment production)
Ponding	Represents how a water layer on soil surface reduces erosion
Antecedent soil moisture	Represents how previous vegetation affects erosion by reducing soil moisture; used only in Req zone
Critical slope length	Location where contouring fails on a uniform overland flow path
Cultural practice	Erosion control practice such as no-till cropping where cover-management variables are used to reduce erosion
Curve number	An index used in NRCS curve number method to compute runoff; RUSLE2 computes curve number values as a function of hydrologic soil group and cover-management conditions
Database	RUSLE2 database stores both input and output information in named descriptions
Dead biomass	Represents live above ground and root biomass converted to dead biomass by *kill vegetation* process in an *operation* description; dead biomass decomposes
Dead root biomass	A *kill vegetation* process in an *operation* description converts live root biomass to dead root biomass; dead roots decompose at the same rate as surface and buried residue
Decomposition	Loss of dead biomass as a function of material properties, precipitation, and temperature; decomposition rate for all plant parts and buried and surface biomass is equal; decomposition rate for standing residue is significantly decreased because of no soil contact
Deposition	Process that transfers sediment from sediment load transported by runoff to soil surface; net deposition causes sediment load to decrease with distance along overland flow path; depends on sediment characteristics and degree that sediment load exceeds sediment transport capacity; enriches sediment load in fines; computed as a function of sediment particle class fall velocity, runoff rate, and difference between sediment load and transport capacity
Deposition portion	Portion of overland flow path where net deposition occurs
Detachment	Separates soil particles from soil mass by raindrops, waterdrops falling from vegetation, and surface runoff; net detachment causes

	sediment load to increase along overland flow path; detachment is non-selective with respect to sediment characteristics; computed as function of erosivity, soil erodibility, distance along overland flow path, steepness of overland flow path, cover-management condition, and contouring
Disaggregation	Mathematical procedure used to convert monthly precipitation and temperature values to daily values assuming that daily values vary linearly; daily precipitation values sum to equal monthly values, average daily monthly temperature values equals average monthly temperature value
Diversion/terrace/ sediment basin	A set of support practices that intercept overland flow to end overland flow path length.
Diversions	Intercepts overland flow and directs it around hillslope in channelized flow, grade is sufficiently steep that deposition does not occur but not so steep that erosion occurs
EI_{30}	Storm (rainfall) erosivity; product of storm energy and maximum 30 minute intensity; storm energy closely related to rain storm amount and partly to rainfall intensity
Enrichment	Deposition is selective, removing the coarse and dense particles and leaving the sediment load with increased portion of fine and less dense particles
Enrichment ratio	Ratio of specific surface area of sediment after deposition to specific surface area of soil subject to erosion
Eroding portion	Portion of overland flow path where net detachment (erosion) occurs
Erosivity	Index of average annual rainfall erosivity at a location; closely related to rainfall amount and intensity; monthly erosivity is average sum of individual storm values in month, annual erosivity is average sum of values in year; storm rainfall amount must be ½ inch or more to be included in sum
Erosivity density	Ratio of monthly erosivity to monthly precipitation amount
External residue	Material, usually biomass, added to soil surface or placed in the soil; affects erosion as surface residue and buried residue produced by vegetation
Fabric (silt) fence	Fabric about 18 inches wide placed against upright posts on the contour; porous barrier that ponds runoff and causes deposition;

	widely used on construction sites
Fall height (effective)	Effective fall height is the effective height from which waterdrops fall from canopy; depends on canopy shape, canopy density gradient from bottom to top of canopy, and top and bottom canopy heights
Filter strip	A single strip of dense vegetation at the end of an overland flow path; can induce high amounts of deposition
Final roughness	Soil surface roughness after roughness has decayed to unit-plot conditions; primarily represents roughness provided by soil resistant clods
Flattening ratio	Describe how much standing residue that an operation flattens; ratio of standing residue before operation to standing residue after operation; values depend on operation and residue dry mass basis.
Flow interceptors	Topographic features (ridge or channel) on an overflow path that collects overland flow and directs the runoff around hillslope; ends overland flow path; diversions, terraces, and sediment basins are flow interceptors
Gradient terraces	Terraces on a uniform grade (steepness)
Ground cover	Represents the portion of the soil surface covered by material in direct contact with soil; includes plant litter, crop residue, rocks, algae, mulch, and other material that reduces both raindrop impact and surface flow erosivity
Ground cover subfactor	See cover-management subfactors
Growth chart	The collection of values that describe the temporal vegetation variables of live root biomass in upper 4 inches, canopy cover, effective fall height, and live ground cover; values are in a *vegetation* description in the vegetation component of the RUSLE2 database
Hortonian overland flow	Overland flow generated by rainfall intensity being greater than infiltration rate; although flow may be concentrated in micro-channels (rills), runoff is uniformly distributed around hillslope
Hydraulic (roughness) resistance	Degree that ground cover, surface roughness, and vegetation retardance slow runoff; daily values vary as cover-management conditions change
Hydraulic element	RUSLE2 hydraulic elements are a channel and a small

	impoundment
Hydraulic element flow path description	Describes the flow path through a sequence of hydraulic elements; named and saved in hydraulic element flow path component of RUSLE2 database
Hydraulic element system description	Describes a set of hydraulic element paths that are uniformly spaced along the overland flow path described without the hydraulic element system being present, named and saved in the hydraulic element system component of the RUSLE2 database
Hydrologic soil group	Index of runoff potential for a soil profile at a given geographic location, at a particular position on the landscape, and the presence or absence of subsurface drainage
Impoundment	A flow interceptor; impounds runoff; results in sediment deposition; represents impoundments typical of impoundment terraces on cropland and sediment basins on construction sites
Impoundment parallel terrace	Parallel terraces; impoundments occur where terraces cross concentrated flow areas; impoundments drains through risers into underground pipe
Incorporated biomass	Biomass incorporated (buried) in the soil by a *soil disturbing* operation; also biomass added to the soil by decomposition of surface biomass; amount added by decomposition of surface material is function of soil consolidation subfactor
Inherent organic matter	Soil organic matter content in unit-plot condition
Inherent soil erodibility	Soil erodibility determined by inherent soil properties, measured under unit-plot conditions (see soil erodibility)
Initial conditions	Cover-management conditions at the beginning of a no-rotation cover-*management* description
Initial input roughness	Roughness index value assigned to *soil disturbing* operation for the base condition of a silt loam soil having a high biomass on and in the soil; actual initial roughness value used in computations is a function of soil texture, soil biomass, existing roughness at time of soil disturbance, and tillage intensity
Injected biomass	Biomass placed in the soil using an *add other residue/cover* process in a *soil disturbing operation* description; biomass placed in lower half of disturbance depth (see operation processes)
Interrill erosion	Erosion caused by water drop impact; not function of distance along overland flow path unless soil, steepness, and cover-

	management conditions vary, interrill areas are the spaces between rills; very thin flow occurs on interrill areas
Irrigation	Water artificially added to the soil to enhance seed germination and vegetation production
Land use independent	RUSLE2 applies to all situations where Hortonian overland flow occurs and where raindrop impact and surface runoff cause rill and interrill erosion of exposed mineral soil; the same RUSLE2 equations are used to compute erosion regardless of land use
Live above ground biomass	Live above ground biomass provided by vegetation (dry matter basis); converted to standing residue (dead biomass) by a *kill vegetation* process in an *operation* description.
Live ground (surface) cover	Parts of live above ground biomass that touches the soil surface to reduce erosion.
Live root biomass	RUSLE2 distributes input values for live root biomass in upper four inches over a constant rooting depth of 10 inches for all vegetation types and plant growth stages; a *kill vegetation* process in an *operation* description converts live root biomass to dead root biomass. Primarily refers to fine roots that are annually produced, RUSLE2 uses live and dead root biomass in the upper 10 inches to compute a value for the soil biomass subfactor
Local deposition	Deposition that occurs very near, within a few inches, the point of detachment in surface roughness depressions and in furrows between ridges; given full credit for soil saved
Long term roughness	Roughness that naturally develops over time; specified as input in cover-*management* description; depends on vegetation characteristics (e.g., bunch versus sod forming grasses, root pattern near soil surface) and local erosion and deposition, especially by wind erosion; RUSLE2 computes roughness over time; fully developed by *time to soil consolidation*
Long term vegetation	Permanent vegetation like that on pasture, range, reclaimed mined land, and landfills; vegetation description can include temporal values starting on seeding date through maturity, any arbitrary date, or only for the annual cycle of vegetation at maturity
Management alignment offset	Used to sequence cover-management descriptions along an overland flow path to create alternating strips
Mass-cover relationship	Equation used to compute portion of soil surface covered by a

	particular residue mass (dry basis)
Mass-yield relationship	Equation used to compute standing biomass (dry basis) as a function of vegetation production (yield) level
Maximum 30 minute intensity	Average rainfall intensity over the continuous 30 minutes that contains the greatest amount in a rain storm
Non-erodible cover	Cover such as plastic, standing water, snow, and other material that completely eliminates erosion; material can be porous and disappear over time
Non-uniform overland flow path	Soil, steepness, and/or cover-management vary along an overland flow path; path is divided into segments where input selections are made for each segment
NRCS curve number method	Mathematical procedure used in RUSLE2 to compute runoff; a daily runoff value is computed using the 10 yr-24 hr precipitation amount and temporally curve number values that vary as cover-management varies
NWWR	Northwest Wheat and Range Region, a region in the Northwestern US covering eastern Washington and Oregon, northern Idaho (see Req zone)
Operation	An operation changes soil, vegetation, or residue; typically used to represent common farm and construction activities such as plowing, blading, vehicular or animal traffic, and mowing; also used to represent burning and natural processes such as killing frost and germination of volunteer vegetation.
Operation disturbance depth	Surface residue buried by a *soil disturbing* operation is a function of operation disturbance depth
Operation description	Information used to describe an operation, named and stored in the operations component of the RUSLE2 database
Operation processes	An operation is described by a sequence of processes; used to describe how an operation changes cover-managements conditions that affect erosion
No effect	Has no effect on computations; commonly used to reference dates in a cover-management description and to cause RUSLE2 to display information for a particular set of dates
Begin growth	Tells RUSLE2 when to begin using data from a particular *vegetation* description

Kill vegetation	Converts live above ground biomass to standing residue and to convert live root biomass to dead root biomass
Flatten standing residue	Converts a portion of the standing residue to surface residue
Disturb (soil) surface	Mechanically disturbs soil; required to bury surface residue; resurfaces buried residue; required to create roughness and ridges; required to place material (external residue) directly into the soil
Add other cover	Adds material (external residue) to the soil surface and/or places it in the soil
Remove live above ground biomass	Removes a portion of the live above ground biomass; leaves a portion of the affected biomass as surface (flat) residue and standing residue
Remove residue/cover	Removes a portion of standing and surface (flat) residue
Add nonerodible cover	Adds nonerodible cover such as plastic, water depth, snow, or other material that allows no erosion for portion of soil surface covered, cover disappears over time; cover can be porous; cover has no residual effect; not used to represent erosion control blankets and similar material
Remove nonerodible cover	Removes portion of nonerodible cover
Operation speed	Surface residue buried by a soil disturbing operation is a function of operation speed
Overland flow path	Path taken by overland flow on a smooth soil surface from its point of origin to the concentrated flow area that ends the overland flow path; runoff is perpendicular to hillslope contours
Overland flow path (profile) description	Includes values for steepness, names for *soil* and cover-*management* descriptions for segments along an overland flow path; a uniform overland flow path (profile) is where steepness, soil, or cover-management does not vary with distance along overland flow path; a convex profile is where steepness increases with distance; a concave profile is where steepness decreases with distance; a complex profile is a combination of convex, concave, and/or uniform sub-profiles or where soil and/or cover-management vary along the overland flow path

Overland flow path length	Distance along the overland flow path from the origin of overland flow to the concentrated flow area (channel) that intercepts runoff to terminate overland flow;, does not end where deposition begins (see USLE slope length and steepness)
Overland flow path segments	Overland flow path is divided into segments to represent spatial variability along an overland flow path; conditions are considered uniform within each segment
Overland flow path steepness	Steepness along the overland flow path, not hillslope steepness (see USLE slope steepness)
Permeability index	Index for the runoff potential of the soil under the unit-plot condition; used in RUSLE2's soil erodibility nomographs, similar to inverse of hydrologic soil group
Plan description	Collection of RUSLE2 *profile* descriptions used to computed weighted averages for a complex area based on the portion of the area that each profile represents; named and saved in plan component of RUSLE2 database
Ponding subfactor	See cover-management subfactors
Porous barriers	Runoff flows through a porous barrier; does not affect overland flow path; typically slows runoff to cause deposition; examples are stiff grass hedges, fabric (silt) fences, gravel dams, and straw bales
Precipitation amount	Includes all forms of precipitation; RUSLE2 disaggregates input monthly values into daily values to compute decomposition and temporal soil erodibility
Production (yield) level	A measure of annual vegetation live above ground biomass production; user defines yield measure and preferred units on any moisture content basis; input value used to adjust values in a vegetation description at a base yield; maximum canopy cover in base vegetation description must be less than 100 percent
Profile description	Information used to describe profile (overland flow path); includes names for location, topography, soil, cover-management, and support practices used to make a particular RUSLE2 computation, named and stored in profile component of RUSLE2 database
Profile shape	See overland flow path description
Rainfall (storm) energy	Computed as sum of products of unit rainfall energy and rainfall amount in storm intervals where rainfall intensity is assumed uniform; storm energy is closely related to rain storm amount

Rainfall intensity	Rainfall rate express as depth (volume of rainfall/per unit area) per unit time
Remote deposition	Deposition that occurs a significant distance (tens of feet) from the point where the sediment was detached; examples include deposition by dense vegetation strips, terraces, impoundments, and toe of concave overland flow paths; only partial credit given to remote deposition as soil saved; credit depends on location of deposition along overland flow path; very little credit given for deposition near end of overland flow path
Req	Equivalent erosivity for the winter months in the Req zone; used to partially represent Req effect
Req effect	Refers to Req equivalent erosivity; erosion per unit rainfall erosivity in the winter period in the Req zone is much greater than in summer period; winter effect is much greater than in other regions because of a greatly increased soil erodibility; effect partially results from an elevated soil water content, increased runoff, and soil thawing
Req zone	Region where erosion is elevated in the winter months because of the Req effect; region primarily in eastern WA and OR, portions of ID, CA, UT, CO, and limited area in other western US states
Residue	Has multiple meanings in RUSLE2; generally refers to dead biomass, such as crop residue, created when vegetation is killed; plant litter from senescence; and applied mulch material (external residue) such as straw, wood fiber, rock, and erosion control blankets used on construction sites; material is generally assumed to be biomass that decomposes; also used to represent applied material like rock that does not decompose
Residue description	Values used to describe residue, named and stored in the residue component of the RUSLE2 database
Residue type	Refers to fragility and geometric residue characteristics; affects residue amount buried and resurfaced by an operation; affects degree that residue conforms to surface roughness; affects erosion control on steep slopes like those on construction sites
Resurfacing ratio	Portion (dry mass basin) of the buried residue in the soil disturbance depth that a soil disturbing operation brings to the soil surface; function of residue and operation properties
Retardance	Degree that vegetation (live above ground biomass) and standing residue slows runoff; varies with canopy cover; function of

	production (yield) level; part of *vegetation* description
Ridge height	Height of ridges created by a *soil disturbing* operation; major variable along with row grade that determines contouring effectiveness; decays as a function of precipitation amount and interrill erosion
Ridge subfactor	See cover-management subfactors
Rill erosion	Caused by overland flow runoff; increases with distance along the overland flow path
Rill to interrill erosion ratio	Function of slope steepness, rill to interrill soil erodibility, and how cover-management conditions affect rill erosion different from interrill erosion
Rock cover	Rock cover entered in the *soil* description; represents naturally occurring rock on soil surface; operations do not affect this rock cover; rock cover created by an operation that *adds other cover* (rock residue) is treated as external residue; soil disturbing operations bury and resurface rock added as external residue
Root biomass	See dead and live root biomass
Root sloughing	Annual decrease in root biomass, RUSLE2 adds the decrease in live root biomass to dead residue biomass pool
Rotation	Refers to whether a list of operation descriptions in a cover-*management* description are repeated in a cycle; length of cycle is rotation duration; list of operation descriptions are repeated in RUSLE2 until computed average annual erosion value stabilizes; eliminates need to specify initial conditions; *operation* descriptions in a no-rotation cover-*management* descriptions are sequentially processed in a single pass, first *operation* descriptions in cover-*management* description establish initial conditions
Rotation duration	Time (length of cycle) before the list of *operation* descriptions in a rotation type cover-*management* description repeats; time period over which RUSLE2 makes its computation in a no-rotation cover-*management* description
Rotational strip cropping	A rotation type cover-management description that involves periods of dense vegetation that are sequenced along the overland flow path to create strips of alternating dense vegetation that cause deposition
Row grade	Grade along furrows separated by ridges; usually expressed as

	relative row grade, which is the ratio of grade along the furrows to steepness of the overland flow path
Runoff	RUSLE2 computes runoff using NRCS curve number method and the 10 yr-24 hour precipitation amount; used to compute contouring effect, contouring failure (critical slope length), and deposition by porous barriers, flow interceptors, and concave overland flow path profiles
Sediment basin	Small impoundment typical of those used on cropland and construction sites; discharge is usually through a perforated riser that completely drains basin in about 24 hours
Sediment characteristics	Deposition is computed as a function of sediment characteristics, which are particle class diameter and density and the distribution of sediment among particle classes
Sediment particle classes	RUSLE2 uses sediment particle classes of primary clay, silt, and sand and small and large aggregate classes, diameter of aggregate classes and the distribution of sediment among particle classes at point of detachment is function of soil texture; RUSLE2 computes how deposition changes the distribution of sediment particle classes
Sediment load	Mass of sediment transported by runoff per unit hillslope width
Sediment transport capacity	Runoff's capacity for transporting sediment; depends on runoff rate, overland flow path steepness, and hydraulic roughness; deposition occurs when sediment load is greater than runoff's transport capacity
Sediment yield	Sediment load at the end of the flow path represented in a RUSLE2 computation; flow path ends at overland flow path unless hydraulic elements (channel or impoundment) are present; sediment yield for site only if RUSLE2 flow path ends at site boundary
Segments	The overland flow path divided into segments based on topography, soil, and cover-management to represent spatial variation
Senescence	Decrease in vegetation canopy cover; senescence adds biomass to surface (flat) residue unless RUSLE2 is instructed that a decrease in canopy cover, such as leaves drooping, does not add to surface residue
Shear stress	Total runoff shear stress is divided into two parts of that acting on the soil (grain resistance) and that acting on surface residue, surface

	roughness, live vegetation, and standing residue (form resistance); shear stress acting on the soil is used to compute sediment transport capacity; total shear stress is used to compute contouring failure; also function of runoff rate and steepness of overland flow path
Short term roughness	Roughness created by a soil disturbing operation, decays over time as a function of precipitation amount and interrill erosion
Slope length exponent	Exponent in equation used to compute rill-interrill erosion as a function of distance along overland flow path, function of rill to interrill erosion ratio.
Soil biomass subfactor	See cover-management subfactors
Soil consolidation effect	Represents how wetting/drying and other processes cause soil erodibility to decrease over time following a mechanical soil disturbance; increase in soil bulk density (mechanical compaction) not the major cause of reduced soil erodibility; affects runoff, accumulation of biomass in upper 2 inch soil layer, and soil biomass effectiveness
Soil consolidation subfactor	See cover-management subfactors
Soil description	Describes inherent soil properties that affect erosion, runoff, and sediment characteristics at point of detachment on unit plot conditions, named and saved in the soil component of the RUSLE2 database
Soil disturbance width	Portion of the soil surface disturbed; weighted effects of disturbance computed as a function of erosion on disturbed and undisturbed area to determine an effective time since last disturbance, effective surface roughness, and effective ground cover
Soil disturbing operation	*Operation* description that contains *disturb soil* process
Soil erodibility	RUSLE2 considers two soil erodibility effects, one based on inherent soil properties and one based on cover-management; inherent soil erodibility effect represented by K factor value empirically determined from erosion on unit plot; part related to cover-management is represented in cover-management subfactors
Soil erodibility nomograph	Mathematical procedure used to compute a K factor value, i.e., inherent soil erodibility
Soil loss	Proper definition is the sediment yield from a uniform overland

	flow path divided by the overland flow path length; loosely used as the net removal of sediment from an overland flow path segment
Soil loss from eroding portion	Net removal of sediment from the eroding portion of the overland flow path
Soil loss tolerance (T)	Erosion control criteria, objective is that "soil loss" be less than soil loss tolerance T value, special considerations must be given to non-uniform overland flow paths to avoid significantly flawed conservation and erosion control plans
Soil mechanical disturbance	Mechanical soil disturbance resets soil consolidation effects; *disturb soil* process must be included in an *operation* description to create surface roughness and ridges and to place biomass into the soil
Soil saved	Portion of deposited sediment that is credited as soil saved; computed erosion is reduced by soil saved to determine a conservation planning soil loss value; credit depends on location of deposition along overland flow path
Soil structure	Refers to the arrangement of soil particles in soil mass; used to compute soil erodibility (K) factor values
Soil texture	Refers to the distribution of primary particles of sand, silt, and clay in soil mass subject to erosion
Standing residue	Created when live vegetation is *killed*, decomposes at a reduced rate; falls over at a rate proportional to decomposition of surface residue
Strip/barrier *description*	Support practice, describes porous barriers, named and stored in the strip/barrier component of RUSLE2 database
Subfactor method	See cover-management subfactors
Subsurface drainage description	Support practice that lowers water table to reduce soil water content, runoff, and reduces erosion; RUSLE2 uses difference between hydrologic soil groups for drained and undrained conditions to compute erosion as affected by subsurface drainage, named and save in subsurface drainage component of RUSLE2 database
Support practices	Erosion control practice used in addition to cultural erosion control practice, hence a support practice; includes contouring, filter and buffer strips, rotational strip cropping, silt (fabric) fences, stiff grass hedges, diversions/terraces, gravel dams, and sediment basins

Surface (flat) residue	Material in direct contact with the soil surface; main source is plant litter, crop residue, and applied mulch (external residue).
Surface roughness	Random soil surface roughness; combination of soil peaks and depressions that pond runoff; created by a *soil disturbing* operation, decays as a function of precipitation amount and interrill erosion
Surface roughness index	A measure of soil surface roughness; standard deviation of surface elevations measured on a 1 inch grid about mean elevation; effect of ridges and land steepness removed from measurements
Surface roughness subfactor	See cover-management subfactors
Temperature	Input as average monthly temperature; disaggregated into daily values, used to compute biomass decomposition and temporal soil erodibility
Template	Determines the computer screen configuration of RUSLE2 and inputs and outputs; determines the complexity of field situations that can be described with RUSLE2
Terraces	Flow interceptors (channels) on a sufficiently flat grade to cause significant deposition
Three layer profile schematic	Some RUSLE2 templates include an overland flow path schematic having individual layers to represent cover-management, soil, and topography; used to graphically divide the overland flow path into segments to represent complex conditions
Tillage intensity	Degree that existing soil surface roughness affects roughness left by a soil disturbing operation
Tillage type	Identifies where a soil disturbing operation initially places buried residue in soil, also refers to how operation redistributes buried residue and dead roots
Time to soil consolidation	Time required for 95 percent of the soil consolidation effect to be regained following a soil disturbing operation
Topography	Refers to steepness along the overland flow path and the length of the overland flow path
Uniform slope	Refers to an overland flow path where soil, steepness, and cover-management along the overland flow path do not vary along flow path

Unit rainfall energy	Energy content of rainfall per unit of rainfall; function of rainfall intensity
Unit plot	Base condition used to determine soil erodibility; reference for effects of overland flow path steepness and length; cover-management, and support practices; continuous tilled fallow (no vegetation; tilled up and downhill, maintained in seedbed conditions; topographic, cover-management, support practice factor values equal 1 for unit-plot condition
USLE slope length and steepness	USLE slope length is distance to a concentrated flow (e.g., terrace or natural waterway) or to the location where deposition occurs; USLE soil loss is sediment yield from this length divided by length (mass/area); USLE steepness is steepness of the slope length, uniform steepness often assumed
Validation	Process of ensuring that RUSLE2 serves its intended purpose as a guide to conservation and erosion control planning.
Vegetation description	Information used by RUSLE2 to represent the effect of vegetation on erosion; includes temporal values in growth chart, flow retardance, and biomass-yield information; named and stored in the vegetation component of the RUSLE2 database
Verification	Process of ensuring RUSLE2 correctly solves the mathematical procedures in RUSLE2
Worksheet description	A form in RUSLE2 program; used to compare conservation and erosion control practices for a given site; used to compare erosion computer for profile descriptions; named and saved in the worksheet component of the RUSLE2 database

Rusle 2 Science Documentation

1. ABOUT RUSLE2

1.1. Introduction

The Revised Universal Soil Loss Equation, Version 2 (RUSLE2) is a computer program that estimates rill and interrill erosion by solving a set of mathematical equations (Toy et al., 2002). RUSLE2 makes estimates based on site specific conditions, which allows erosion control practices to be tailored to each specific site. The RUSLE2 user describes the site by making selections from the RUSLE2 database. RUSLE2 uses this information to compute its erosion estimates. The purpose of RUSLE2 is to serve as a guide to conservation and erosion control planning. RUSLE2 is land use independent and applies to all conditions where rill and interrill erosion occurs when mineral soil is exposed to the erosive forces of impacting raindrops and water drops falling from vegetation and runoff produced by Hortonian overland flow. RUSLE2 computes erosion and deposition along a single overland flow path. RUSLE2 also computes deposition in channels and small impoundments that end overland flow paths.

RUSLE2 has three major components. One component is the science component that includes the mathematical equations that RUSLE2 uses to compute erosion and deposition. Inputs to the equations are user selected to represent the four major factors that affect erosion at a specific site. Those factors are climate (determined by location), inherent soil properties including soil erodibility, topography, and land use.

The second major RUSLE2 component is the RUSLE2 database. The RUSLE2 user makes selections from the database to describe site-specific conditions. The database contains information that describes climate (weather) at various locations, soils, cover-management systems, vegetations, residues, operations, porous strips and barriers, flow interceptors including diversions and terrace channels and small impoundments, subsurface drainage systems, irrigation systems, overland flow paths, worksheets, and plan views (collections of overland flow paths). A single overland flow path is the basic RUSLE2 computational unit. Erosion can be compared in a worksheet for multiple erosion control alternatives for a single overland flow path or multiple overland flow paths. A plan view is used to compute erosion on overland flow areas in spatially complex landscapes.

The third major RUSLE2 component is the computer program. The program includes a powerful computational engine that organizes and solves the mathematical equations, database maintenance tools, and an interface (computer screen) that accepts user inputs and displays computed values.

The USDA-Agricultural Research Service had overall lead responsibility for developing RUSLE2 and lead responsibility for developing the science (i.e., mathematical equations used in RUSLE2). The University of Tennessee had lead responsibility for developing the RUSLE2 computer program including its interface and computational engine. The USDA-Natural Resources Conservation Service had lead responsibility for developing user requirements as the principal RUSLE2 client and the RUSLE2 database for cropland. Other organizations developed database information, user guides, and instructional material for RUSLE2. For example, the University of Denver developed database information and other materials for application of RUSLE2 to construction sites, reclaimed mined land, landfills, and other highly disturbed lands.

This document describes the RUSLE2 science, which is primarily embodied in the mathematical equations used in RUSLE2 to compute erosion and deposition estimates.

1.2. Major requirements

The RUSLE2 erosion prediction technology was designed to meet several requirements, many of which affected RUSLE2's science and the equations. These requirements included:

1) Purpose of RUSLE2 is to serve as a guide to conservation and soil erosion control planning at the local field office level.

2) Be easy to use.

3) Be robust so that computed erosion values are not overly sensitive to small changes in variables where input values involve considerable uncertainty. Helps ensure good estimates when extrapolated beyond range of data used to derive RUSLE2.

4) Input values are physically meaningful to typical RUSLE2 users and directly measurable where possible.

5) Not require resources beyond those available at the field office level, especially for the USDA-Natural Resources Conservation Service that is the primary RUSLE2 user.

6) Produce useful information for conservation and erosion control planning that is consistent with the resources (i.e., expertise, time, effort, and other costs) required to implement and use RUSLE2.

7) Lead to desired conservation and erosion control planning decisions as expected based on available erosion research data, accepted erosion science, field experience, and professional judgment.

8) Apply to Hortonian overland flow where rill and interrill erosion is caused by mineral soil being exposed to the erosive forces of surface runoff and impacting waterdrops from rainfall and rainwater falling from vegetation.

9) Be land-use independent by using relationships based on the fundamental variables that affect erosion.

10) Produce accurate erosion estimates comparable to measured research values and estimated by the Universal Soil Loss Equation (USLE).

11) Be an evolution of the USLE and RUSLE1.

12) Be thoroughly and carefully reviewed and evaluated to ensure that RUSLE2 performs acceptably.

13) Recommendations on how to best apply RUSLE2 would be a part of the RUSLE2 development and documentation.

1.3. Major guiding principles used to develop RUSLE2 science

The following principles guided the development of the RUSLE2 science according to the requirements listed in **Section 1.2**.

1) The USLE is accepted in term of its conceptual basis, equation structure, empirical derivation, and computed values by both the scientific and user communities.

2) The USLE is valid (i.e., serves its intended purpose) for conservation and soil erosion control planning.

3) RUSLE2 development will start from the USLE structure and extend that structure and empirical derivation.

4) RUSLE2 will represent main effects that can be considered in the conservation and erosion control planning. These main effects are those established by empirical data and fundamental erosion science.

5) Erosion data available for empirically deriving RUSLE2 equations are very limited. The data set is small in relation to the many variables and their many complex interactions that affect erosion. The dataset is not a statistically robust data set because of non-uniform coverage of important variables. The data contain much unexplained variability that can not be resolved.

6) Equations will be chosen to best represent established main effects rather than using regression procedures to fit equations to data to provide the best overall statistical fit. Equations will be chosen based on main effects conclusively established by empirical data, fundamental erosion science, practical experience, professional judgment, and overall good judgment (common sense).

7) First establish mathematical relationships empirically using experimental data and then use process-based equations based on fundamental erosion science to extend the RUSLE2 beyond the available research data.

8) Start from a mean, typical, or accepted value consistent with the USLE unit-plot concept and use normalized variables to compute values that deviate about the

value for a base condition to capture main effects. Equations and limits will be selected to produce a robust erosion prediction technology.

9) Minimize use of geographic zones and variable classes to avoid step changes (discontinuities) between zones and classes.

10) Achieve land-use independence by having a single set of equations that vary as a continuous function of the major variables that affect erosion across all land uses.

11) Make judgments in the context of reasonableness and appropriateness for conservation and erosion planning and implementation. Do the results make good overall sense? If one had perfect knowledge, what would be the planning decision? RUSLE2 is a tool for conservation and erosion control planning, not a scientific product designed to produce new scientific knowledge and understanding.

2. BASIC MATHEMATICAL STRUCTURE

RUSLE2 computes values for the three fundamental erosion processes of detachment (sediment production), transport, and deposition.[1] The empirical equation form of the USLE is used to compute detachment while process-based equations are used to compute sediment transport and deposition. These equations, which are written for a point in time and a location on an overland flow path, are integrated in both time and distance to produce average annual and spatial estimates for segments along the overland flow path and for the entire overland flow path.

2.1. Detachment (Sediment Production) Equation

The USLE in its original form is:

$$A = RKLSCP \qquad [2.1]$$

where: A = average annual erosion rate (mass/area·year) for the slope length λ, R = erosivity factor (erosivity unit/area·year), K = soil erodibility factor (mass/ erosivity unit), L = slope length factor (dimensionless), S = slope steepness factor (dimensionless), C = cover-management factor (dimensionless), and P = support practice factor (dimensionless).[2] The USLE, equation 2.1, has two parts, the part that computes unit-plot erosion and the part that adjusts unit plot-erosion to represent actual field conditions. The part that computes unit-plot erosion is:

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[1] Refer to the RUSLE2 User's Reference Guide for detailed explanations of RUSLE2 terms. Also, see **Glossary of Terms** section in this document.

[2] See List of symbols at end of this chapter.

$$A_u = RK \qquad [2.2]$$

where: A_u = average annual erosion (mass/area·year) for the unit plot (mass/area·year).[3] The terms LSCP are normalized with respect to the unit plot and, therefore, have a value of 1 for unit plot conditions.[4] In effect, the USLE computes erosion for unit plot conditions with the product RK and then uses the terms LSCP to adjust the unit plot erosion to account for differences between unit plot conditions and actual field conditions.

Equation 2.2 is a temporal integration of the basic USLE equation that computes unit-plot erosion for individual storms as:

$$a_{us} = (EI_{30})K \qquad [2.3]$$

where: a_{us} = the unit-plot erosion (mass/area) from the storm that has the rainfall erosivity EI_{30} (force·length/area)(length/time), E = rain storm energy (force·length/area), and I_{30} = average intensity (length/time) over the continuous 30 minutes with the most rainfall in the storm. The linear relationship between unit plot erosion and storm erosivity EI_{30} means that the erosivity factor R can be computed for a locations as:

$$R = \sum_{j=1}^{M_r} \sum_{m=1}^{M_{s(j)}} (EI_{30})_m \Big/ M_r \qquad [2.4]$$

where: EI_{30} = storm erosivity for storm events greater than 0.5 inches (12 mm), $M_{s(j)}$ = the number of storms in the *jth* year, M_r = number of years in the record being used to compute erosivity.[5]

The linear relationship between erosion on the unit plot and erosivity mathematically means that average daily erosion can be computed as:[6]

$$a_u = rK \qquad [2.5]$$

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[3] The unit plot is 72.6 ft (22.1 m) long on a 9 percent slope, maintained in continuous fallow, tilled up and down hill to a seedbed condition periodically to control weeds and break crusts that form on the soil surface.

[4] The terms A_u, R, and K have dimensions and units. The terms LSCP are ratios of erosion from a given field condition to erosion for the unit-plot condition, and these terms are, therefore, dimensionless and have no units.

[5] See RUSLE2 User's Reference Guide for a detailed description of the computation of RUSLE2 erosivity values.

[6] Daily erosion computed by RUSLE2 is a long-term average erosion for that day.

where: a_u = daily erosion from the unit plot on the *ith* day and r = the average daily erosivity on the *ith* day. Average daily erosivity values are determined by the disaggregation of average monthly erosivity input values into daily values (see **Section 3.1**).

Although the terms LSCP vary with time as field conditions change, the cover-management factor C is the only one of these USLE terms that is mathematically integrated with time. An average annual representative value is selected for the other terms. The mathematical equation used in the USLE to compute erosion for a crop stage period is:

$$a_k = KLS\,\mathrm{P}r_k\, c_k \qquad [2.6]$$

where: a, r, and c = the erosion, erosivity, and cover-management (soil loss ratio) factors, respectively, for the *kth* crop stage.[7] The erosivity for the *kth* crop stage is given by:

$$r_k = f_k R \qquad [2.7]$$

where: f_k = the portion of the average annual erosivity that occurs during the *kth* crop stage.[8] Therefore, the average annual cover management C factor in the USLE is computed as:

$$C = \left(\sum_{k=1}^{M_k} f_k c_k \right) \Big/ N_c \qquad [2.8]$$

where: M_k = the number of crop stages over the period of N_c years involved in the computation, such as years in a crop rotation or years after disturbance of a construction site, used to compute erosion.

The mathematics of the USLE equation structure, therefore, allows RUSLE2 to compute an average daily erosion as:

$$a = rklScp_p p_c p_d \qquad [2.9]$$

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[7] A crop stage period is a time interval over which a constant soil loss ratio can be assumed. The soil loss ratio is the ratio of erosion with a given cover-management condition to the unit plot erosion for the same period, with all other conditions being the same between the two cover-management conditions.

[8] Erosivity varies during the year. The empirical curve that describes this temporal distribution is referred to as the EI distribution.

where: r = daily erosivity (erosivity unit/area·day), k = daily soil erodibility factor (mass/erosivity unit), l = daily slope length factor dimensionless, c= daily cover-management (soil loss ratio) factor (dimensionless), p_p = daily ponding subfactor (dimensionless), p_c = daily contouring subfactor (dimensionless), and p_d = daily subsurface drainage subfactor (dimensionless).[9] The average daily erosion computed by equation 2.9 is the average erosion (mass/area) for the slope length λ. All terms in equation 2.9 use average daily values except for the slope steepness factor that is assumed to be constant in RUSLE2 for all conditions except for variations in slope steepness.[10]

2.1.1. Equation for rill and interrill detachment combined

Equation 2.9 is converted to an equation that computes rill and interrill erosion combined at a point so that RUSLE2 can be applied to non-uniform overland flow paths where soil, steepness, and cover-management vary along the overland flow path. This equation is (Foster and Wischmeier, 1974):

$$D = (m+1)rk(x/\lambda_u)^m Scp_p p_c p_d \qquad [2.10]$$

where: D = average daily net detachment by both rill and interrill erosion (mass/area) at a point at the distance x from the origin of the overland flow path, λ_u = the unit plot length (72.6 ft, 22.1 m), and m = daily slope length exponent. The value for each term, except erosivity r, is the value for the term at the location x on the overland flow path.

2.1.2. Equation for interrill erosion

Interrill erosion is assumed to occur even when RUSLE2 computes deposition (see **Sections 2.3.1, 2.3.6, and 2.3.8**). The RUSLE2 equation for interrill erosion is:

$$D_i = 0.5rkS_i cp_r p_c p_d \qquad [2.11]$$

where: D_i = daily interrill erosion (mass/area·day), and S_i = the slope steepness factor for interrill erosion. Equation 2.11 for interrill erosion is similar to equation 2.10 for rill and interrill erosion combined except that equation 2.11 has no distance (x) term, has a slope steepness factor specifically for interrill erosion, and has a 0.5 factor. The reason for not having a distance term is that detachment on interrill areas is caused by impacting

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[9] RUSLE2 describes the effect of other support practices besides contouring on erosion. Those effects are described using process-based equations that compute deposition rather than a P factor value as in the USLE.

[10] Lower case symbols are used in equation 2.9 to distinguish between the daily factor values used in RUSLE2 and the average annual factor values used in the USLE. An upper case symbol is used for the slope steepness factor because a constant value is used in RUSLE2 that is equivalent to the USLE slope steepness factor value.

raindrops and waterdrops falling from vegetation. Detachment on interrill areas is assumed to be uniform along the overland flow path provided soil, steepness, or cover-management does not change along the overland flow path (Foster and Meyer, 1975; Foster et al., 1977a; Toy et al., 2002).

The slope steepness factor for interrill erosion differs from the slope steepness for rill erosion because the detachment forces produced by impacting waterdrops differ from the detachment forces produced by flow in rill areas. The interrill erosion slope steepness factor in equation 2.11 was empirically derived from experimental data (Lattanzi et al., 1974; Foster, 1982; McGregor et al., 1990). The slope steepness factor in the equation 2.10 represents the effect of slope steepness on rill and interrill erosion combined. The 0.5 factor in equation 2.11 results from the assumption that interrill erosion and rill erosion are equal for unit plot conditions (Foster and Meyer, 1975; Foster et al., 1977b; McCool et al., 1989).

2.1.3. Ratio of rill to interrill erosion

The slope length exponent m in equation 2.10 is a function of the ratio of rill to interrill erosion. RUSLE2 computes the slope length exponent m as (Foster et al., 1977b; McCool et al., 1989):

$$m = \beta/(1+\beta) \qquad [2.12]$$

where: β = ratio of rill to interrill erosion. The typical slope length exponent in the USLE is 0.5, which is the value computed by equation 2.12 when rill and interrill erosion are equal. The slope length exponent m computed by equation 2.12 varies about 0.5 as the ratio of rill erosion to interrill erosion varies about 1. The base condition for rill erosion equaling interrill erosion is for unit plot conditions.

The ratio of rill to interrill erosion is computed from:[11]

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[11] Equations 2.11 and 2.13 illustrate an important design principle in RUSLE2. The terms that represent interrill erosion in equation 2.13 differ from those in equation 2.11 used to compute absolute interrill erosion, which seems inconsistent. The design philosophy in RUSLE2 is that RUSLE2 starts from accepted empirical values, which is 0.5 for the slope length exponent for unit plot conditions. Empirical values are used to the extent that they can be determined from experimental data, especially to represent main effects. The best possible empirical value is determined from the experimental data, and then the accepted empirical value is adjusted using process-based equations. The adjustment is up or down about the accepted empirical value, which is almost always a ratio in RUSLE2 because the LSCP variables are non-dimensional ratios. This approach of adjusting up or down about an accepted empirical ratio value rather than computing absolute values gives RUSLE2 increased robustness and avoids RUSLE2 giving seriously erroneous values when it is extrapolated. The ratio of rill to interrill ratio can be computed more accurately than can an absolute value for interrill erosion. The advantage of equation 2.11 is that it computes values that are close to erosion values computed by the USLE, which is a more conservative and robust approach than computing an absolute value of interrill erosion using variables from equation 2.13.

$$\beta = \left(\frac{K_r}{K_i}\right)\left(\frac{c_{pr}}{c_{pi}}\right)\left(\frac{\exp(-b_r f_g)}{\exp(-0.025 f_g)}\right)\left(\frac{s/0.0896}{3s^{0.8}+0.56}\right) \qquad [2.13]$$

The ratio K_r/K_i = the inherent rill to interrill soil erodibility ratio (see **Section 4.3**), which is computed as a function of soil texture to reflect that some soils are inherently more susceptible to rill erosion than to interrill erosion than are other soils. The term c_{pr}/c_{pi} = the rill to interrill erosion ratio for prior land use soil erodibility (see **Section 6.2.2**), which reflects how soil consolidation and soil biomass affect rill erosion differently from how it affects interrill erosion. The ratio $\exp(-b_r f_g)/\exp(-0.025 f_g)$ reflects how ground cover affects rill erosion more than it affects interrill erosion, where b_r and 0.025 = coefficients (percent^{-1}) that express the relative effectiveness of ground cover for reducing rill erosion and interrill erosion, respectively (see **Section 6.2**), and f_g = ground cover expressed as a percent (see **Section 6.2.2**).

The term $(s/0.0896)/(3s^{0.8}+0.56)$ [where s = steepness of overland flow path (sine of slope angle)] reflects how steepness affects rill erosion differently than it does interrill erosion (Foster, 1982). This term assumes that rill erosion varies linearly with steepness.

The assumption in equation 2.12 that rill erosion varies with a slope length exponent of 1 (McCool et al., 1989) is consistent with the maximum slope length exponent of 1 observed in the experimental plot data used to derive the USLE [AH537 (Wischmeier and Smith, 1978)]. The maximum exponent of 1 is also consistent with the variation of erosion with discharge on steep slopes (Meyer et al., 1972) but is less than a value of 0.75 reported in other field research (Govers, 1991; McCool et al., 1989) where rill erosion is the dominant erosion process.

The slope length exponent base value is 0.5. Equation 2.12 increases or decreases this value as rill erosion increases or decreases relative to interrill erosion. The terms in equation 2.13 represent the main variables that affect rill erosion relative to interrill erosion.

Given that rill erosion varies with a slope length exponent of 1, the rill erosion term in equation 2.13 should have included a slope length term. The reason that a slope length term is not in equation 2.13 is because of mathematical limitations in devolving the USLE equation structure into rill and interrill erosion terms. If a slope length term had been included in equation 2.13, RUSLE2 could not have met the requirement that erosion computed for the entire overland flow path length be independent of how many overland flow path segments are used in the computations when other conditions are uniform along the overland flow path (see **Section 5.Appendix 1**).

2.2. Spatial and Temporal Integration

RUSLE2 requires both a spatial and temporal integration. The spatial integration is made by solving the governing equations along the overland flow path each day. Temporal integration is made by summing daily values to obtain totals for the computation duration.[12] The average annual erosion is the sum of the daily values divided by the number of years (duration) in the computation.

If RUSLE2 were applied to only spatially uniform overland flow paths, equation 2.9 could be analytically solved for each day and the values summed to compute total erosion for a **rotation duration**. However, the solution is complex when soil, steepness, and cover-management vary along the overland flow path (i.e., spatially non-uniform overland flow paths), especially when deposition occurs.[13] RUSLE2 performs a spatial integration each day to compute daily spatially-distributed erosion, deposition, and sediment load values along the overland flow path. The spatial integration process in RUSLE2 is referred to as **sediment routing**, a common term used in hydraulic analyses.

2.3. Sediment Routing (Spatial Integration)

2.3.1. Continuity equation

The RUSLE2 governing equation that is spatially integrated is the steady state continuity (conservation of mass equation) given by (Foster, 1982):

$$dg / dx = D_i + D_{rorp} \qquad [2.14]$$

where: g = sediment load (mass/unit overland flow width·time), x = distance along the overland flow path from its origin, and D_{rorp} = either rill erosion rate (D_r) (mass/area· time) or deposition (D_p) (mass/area· time) by runoff in rill areas.

Equation 2.14 is solved numerically because it can not be analytically solved except for the special case of a uniform overland flow path where neither soil, steepness, nor cover-management vary along the overland flow path. RUSLE2 applies in the general case where any or all of these variables change along the overland flow path. The numerical solution requires that the overland flow path be divided into segments as illustrated in Figure 2.1 where the soil, steepness, and cover-management conditions are uniform over each segment. The numerical form of equation 2.14 for this computation is:

$$g_i = D_i\left(x_{(i)} - x_{(i-1)}\right) + \int_{x_{(i-1)}}^{x_{(I)}} D_{rorp}\, dx + g_{(i-1)} \qquad [2.15]$$

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[12] Computation duration is the rotation duration (cycle length) for a **rotation** type cover-management description. The computation duration is the length of time specified for the duration of a no-rotation type cover-management description.

[13] RUSLE2 is much more powerful than the USLE because the USLE can not be applied to spatially non-uniform conditions that cause deposition (Foster and Wischmeier, 1974).

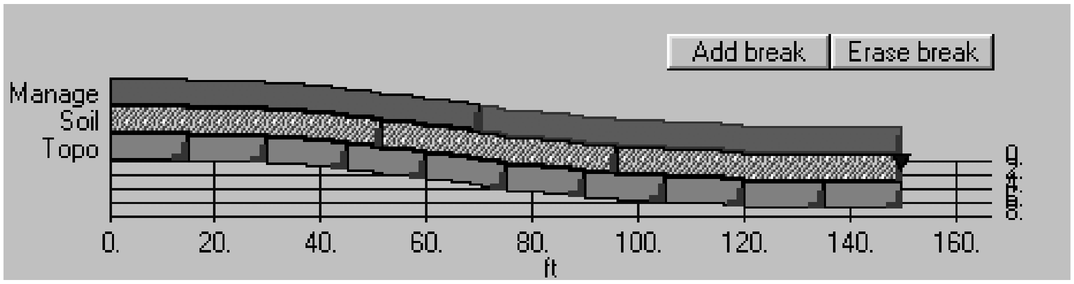

Figure 2.1. Schematic of the three layers that represent an overland flow path (a RUSLE2 hillslope(overland flow path) profile).

The lower and upper ends of the segment are delineated by $x_{(i)}$ and $x_{(i-1)}$, respectively, and the segment length is the difference $x_{(i)} - x_{(i-1)}$. Equation 2.12 is applied sequentially along the overland flow path starting at x = 0, which is the origin of the overland flow path. The incoming sediment load $g_{(i-1)}$ to the first segment at x = 0 is zero because no runoff enters at the origin of the overland flow path. The sediment load, g_{i-1}, entering the *ith* segment is known from the computation for the upslope *(i-1)th* segment. The sediment load g_i is the sediment load leaving the *ith* segment.

Rill and interrill erosion combined are computed with equation 2.10 rather computing interrill erosion and rill erosion separately as implied in equation 2.15. Equation 2.10 is solved analytically over the segment by assuming that soil, steepness, and cover-management are uniform over the segment. If deposition occurs, interrill erosion D_i is computed with equation 2.11 and the integral for deposition D_p is solved numerically (see **Section 2.3.6**).

The RUSLE2 assumption of uniformity within a segment causes step changes in input variables and certain computed variables where segments adjoin. Each soil, steepness, and cover-management variable is constant over a segment, but these variables make step changes at the common point between two segments. For example, the steepness values for two segments are not averaged to obtain a single steepness value at the intersection of two segments. Consequently, computed detachment and deposition values are discontinuous (i.e., step change) across segment intersections where soil, steepness, or cover-management changes between segments. However, runoff rate and sediment load are continuous at adjoining segment points. These step changes require sufficiently short segments to represent variables that vary continuously along the overland flow path. An example is a concave overland flow path (profile) where steepness continuously decreases from its upper end to lower end. A preliminary sensitivity analysis can be conducted to determine appropriate segment lengths for developing an erosion control plan for a specific site.

RUSLE2 could have been constructed to accommodate both step and continuous changes with distance. However, the benefits of representing both continuous and step changes were judged insufficient to merit the increased complexity in the equations, inputs, and programming for most RUSLE2 applications in erosion control planning. Step changes seem to occur more frequently than continuous changes in variables along an overland flow path in most field situations. RUSLE2 represents these step changes, such as those associated with buffer strips and intersection of land slopes on construction sites.

2.3.2. Transport capacity-detachment limiting concept

RUSLE2 uses the transport capacity-detachment limiting concept to compute rill detachment or deposition (Foster et al., 1981a). The assumption is that rill erosion occurs where runoff transport capacity exceeds sediment load. Rill erosion is assumed not to be affected by the degree that sediment load fills runoff's sediment transport capacity, except where rill erosion would overfill transport capacity if rill erosion were to occur at its capacity rate. In this situation, rill erosion occurs at the rate that just fills transport capacity.[14]

A very important RUSLE2 assumption is that detachment and deposition by flow in rill areas at a location on an overland flow path can not occur simultaneously. Another important assumption is that both rill and interrill erosion are non-selective (Foster et al., 1985b). When rill and interrill detachment occur, the detached sediment contains all of the sediment classes having a distribution and size based solely on soil texture (see **Section 4.7**). That is, neither rill nor interrill detachment processes can "reach into the soil" and selectively remove sediment from particular sediment classes and not remove sediment from other particle classes. The basis of this assumption is that most soils are cohesive. Detachment is a process that separates soil particles from the soil mass by breaking cohesive bonds within the soil. This separation process produces sediment in all sediment classes because not all bonds in the soil are uniformly broken, much like striking a piece of concrete with a hammer produces a mixture of particles.[15]

Another important RUSLE2 assumption is that interrill erosion and deposition in rill areas occur simultaneously. When flow causes rill erosion, small incised channels are eroded. When deposition by runoff in rill areas occurs, the deposition is spread across the slope so that deposition covers the entire local area unless ridges are present (Toy et al., 2002). Therefore, a case can be made that no interrill erosion occurs on depositional areas, especially where deposition rates are high and flow is deep to protect the underlying soil surface from raindrop impact. However, even in these cases, deposition and water depths are quite spatially non-uniform, resulting in local areas that are not

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[14] The concept of the interaction between rill erosion, sediment load, and transport capacity is valid, especially in ideal conditions and has advantages for RUSLE2 (Foster and Meyer, 1975; Foster, 1982). However, rill erosion in most field conditions is highly variable along rills where very intense local erosion occurs (e.g., at headcuts) and intervening areas of very low rill erosion. Because the hydraulic equations used in RUSLE2 do not represent this high degree of spatial non-uniformity, RUSLE2 can not adequately capture this important interaction.

[15] Soils can contain gravel that runoff does not transport. Conceptually, those particles are not assumed in RUSLE2 to be a part of the cohesive soil mass. The reason that gravel particles are not transported is that the runoff does not have sufficient transport capacity to move these particles. The effect of gravel and rock fragments on erosion is taken into account in RUSLE2 (see **Section 4.6**).

protected by deposited sediment or deep water. Also, many soil disturbing operations, such as tillage, leave surface roughness and ridges where soil protrudes above the flow and is directly exposed to interrill erosion. The RUSLE2 assumption is that interrill erosion and deposition by rill flow occurs simultaneously has the important benefit of allowing RUSLE2 to compute local deposition in soil surface roughness, furrows between ridges, and similar local roughness features.[16]

2.3.3. Basic deposition equation

RUSLE2 computes deposition when sediment load exceeds transport capacity using (Foster et al., 1981a; Foster, 1982):

$$D_p = (\alpha_d V_f / q)(T_c - g) \qquad [2.16]$$

where: D_p = deposition rate (mass/area·time), α_d = a deposition coefficient determined by calibration, V_f = fall velocity of the sediment in still water (length/time), q = overland flow (runoff) rate (volume/overland flow width·time) where flow depth is assumed to be uniform across the slope, T_c = transport capacity (mass/overland flow width·time). Equation 2.16 is solved for each sediment class (see **Section 4.7**). The distribution of the total transport capacity among the sediment classes is assumed to equal the distribution of the total sediment load among the classes. Equation 2.16 gives RUSLE2 its capability for computing deposition's selectivity where coarse, dense sediment is deposited more readily than fine, less dense sediment. The orders of magnitude variation in sediment fall velocity among the sediment classes is the major factor in computing selective deposition.

2.3.4. Sediment transport capacity equation

The RUSLE2 equation for sediment transport capacity of runoff in the rill areas is (Foster and Meyer, 1972; Foster and Meyer, 1975; Nearing et al., 1989, Finkner et al., 1989):

$$T_c = K_T \zeta q s \qquad [2.17]$$

where: the coefficient K_T coefficient for sediment transportability (mass/volume) and the ζ = coefficient for effect of hydraulic resistance on sediment transport capacity (dimensionless).

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[16] Equation 2.11, which computes interrill erosion, actually computes sediment load delivered to rill flow rather than detachment on interrill areas. An improved approach is to use separate equations to compute detachment, deposition, and sediment transport on interrill areas, but that approach was judged to be too complex for RUSLE2. The RUSLE2 limitation regarding interrill erosion is that RUSLE2 does not compute sufficient enrichment of fines in the sediment although interrill erosion is appropriately computed. However, this limitation can be overcome by using the procedure described by Foster (1982) that can be used to compute distribution of sediment by sediment class delivered from interrill areas as a function of soil surface roughness.

A RUSLE2 assumption is that all sediment regardless of its composition is equally transportable, and therefore, a single value for sediment transportability is used in RUSLE2 (see **Section 4.7**). This assumption is questionable because the transportability of coarse sediment is much less than for fine sediment. Sediment transport capacity equations are available that could be used to vary sediment transportability as a function of sediment characteristics, but these equations were judged not to be sufficiently robust for RUSLE2 (Foster and Meyer, 1972; Alonso et al., 1981). For example, slight changes in fine sediment properties significantly affect overland flow's sediment transport capacity computed with sediment transport equations. Slight spatial variations in overland flow hydraulics that can not be described in RUSLE2 also dramatically affect overland flow's sediment transport capacity. Using a complex sediment transport equation is not warranted when RUSLE2 does not capture important details in describing flow hydraulics. Furthermore, the effect of sediment transportability is partially captured by RUSLE2's soil erodibility factor (see **Section 4.1**).[17]

A value for the transportability coefficient K_T was obtained by fitting RUSLE2 to experimental data where deposition occurred on a concave profile overland flow path (Foster et al., 1980c). Sediment transport capacity equals sediment load at the location where deposition begins. Values for K_T were adjusted until computed sediment transport capacity matched the measured sediment load at the location where deposition began in the field study. The K_T value was validated by computing deposition along on the same overland flow path used to determine the K_T value the point where deposition started. The K_T value was also validated by computing deposition for other laboratory and field experimental data (Foster et al., 1980; Neibling and Foster, 1982; Lu et al., 1988). Deposition was computed with RUSLE2 for a wide range of field conditions and those values were inspected for reasonableness and consistency with field observations (see the **RUSLE2 User's Reference Guide**).

The RUSLE2 calibrated value for K_T is 250,000 (lbs_m/ft^3). This value is based on the following set of units. T_c: $lbs_m/(sec \cdot ft\ width)$, ζ: dimensionless, q: $ft^3/(sec \cdot ft\ width)$, s: dimensionless.

The coefficient ζ represents the effect of hydraulic resistance on runoff's sediment transport capacity. This coefficient, which is the ratio of transport capacity with a hydraulic rough surface to transport capacity for a hydraulic smooth surface, varies from essentially 0 for a very hydraulic rough surface to 1 for a hydraulically smooth surface. Hydraulic resistance (roughness) is provided by soil surface roughness, ground cover (material in direct contact with the soil surface), and vegetation retardance. Flow over a soil surface applies a total shear stress. Part of the shear stress is applied to form

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[17] RUSLE2 is a hybrid empirical/process-based model. Many of the variables and equations used in RUSLE2 are not nice and crisp where elemental properties and processes are described. For example, the RUSLE2 soil erodibility factor represents both detachability and transportability. RUSLE2 has been validated to ensure that it acceptably computes erosion over the vast majority of situations where RUSLE2 is applied. See the RUSLE2 User's Reference Guide for a discussion of RUSLE2's validation.

roughness (soil surface roughness, ground cover, and vegetation retardance) and the other part is applied to grain roughness (the individual soil particles and aggregates at the soil-flow interface). The shear stress exerted on grain roughness is assumed to be responsible for sediment transport (Foster et al., 1981a; Foster, 1982). The grain roughness shear stress decreases as form roughness increases, and consequently values for ζ decrease as form roughness increase (see **Section 3.4.1**). RUSLE2 computes a change in ζ, and thus sediment transport capacity, as cover-management conditions change.

2.3.5. Runoff

RUSLE2 uses flow rate values for runoff to compute sediment transport capacity (see **Section 2.3.4**), contouring effectiveness (see **Section 7.1**), and contouring failure (see **Section 3.4.3**). Discharge rate at a location along an overland flow path is computed with:

$$q = q_{(i-1)} + \sigma\left(x - x_{(i-1)}\right) \quad [2.18]$$

where: q = discharge rate at the location x between the segment ends x_{i-1} and x_i, q_{i-1} = discharge rate at x_{i-1}, and σ = excess rainfall rate (rainfall rate minus infiltration rate) on the *ith* segment. Excess rainfall rate is computed using the NRCS runoff curve number method that computes runoff depth (see **Section 3.3.1.1**). The RUSLE2 assumption is that excess rainfall rate equals runoff depth divided by one hour. The difference between the two is accounted for in calibration coefficients including the K_T value for sediment transport capacity in equation 2.17. The RUSLE2 principle is to capture runoff's main effects sufficiently well for erosion control planning. RUSLE2 computes excess rainfall rate as a function of hydrologic soil group, surface roughness, ground cover, soil biomass, and soil consolidation to represent cover-management's effect on runoff.

In most cases, runoff rate q increases within each segment, where the rate of increase depends on infiltration within the segment. RUSLE2 computes a decreasing runoff rate within a segment if infiltration rate in the segment is sufficiently high (see **Sections 2.3.8.3.3 and 3.3.1.1**).

2.3.6. Numerical solution of deposition equation

The deposition equation (equation 2.16) combined with the continuity equation (equation 2.14) must be integrated to compute deposition over a segment of an overland flow path. RUSLE2 solves these equations numerically because an analytical solution was not found. Equations 2.15 and 2.16 along with an equation for transport capacity were written in discrete form for each sediment class as:

$$\frac{D_{pk(1)} + D_{pk(2)}}{2} = \frac{\alpha_d V_{fk}}{[(q_{(1)} + q_{(2)})/2]}\left(\frac{T_{ck(1)} + T_{ck(2)}}{2} - \frac{g_{k(1)} + g_{k(2)}}{2}\right) \quad [2.19]$$

$$g_{k(2)} = g_{k(1)} + D_{ik}\Delta x + \left(\frac{D_{pk(1)} + D_{pk(2)}}{2}\right)\Delta x \quad [2.20]$$

and

$$T_{ck} = (g_k / g)T_c \quad [2.21]$$

where: D_{ik} = interrill erosion for the *kth* sediment class, D_{pk} = deposition rate of the *kth* sediment class, α_d = a deposition coefficient, V_{fk} = fall velocity for the *kth* sediment class, T_{ck} = transport capacity for the *kth* sediment class, T_c = the total sediment transport capacity for all sediment classes, g_k = sediment load for the *kth* sediment class, g = total sediment load, and Δx = the length of the distance step used in the numerical integration. The subscript (1) refers to the upstream end of the distance step and the subscript (2) refers to the downstream end of the distance step.

These equations are combined and solved for the deposition rate D_2, which is the only unknown, at the lower end of the distance step. The solution is by trial and error because a value for sediment transport capacity for a sediment class is not known until a value for the total sediment load is computed. The total sediment load can not be computed until sediment load is computed for each sediment class. The trial-and-error solution starts with the sediment load distribution computed in the previous distance step. This distribution is updated with each trial-and-error iteration until the total sediment load becomes stable.

An alternative approach and perhaps simpler approach is to numerically solve equations 2.15 as:

$$g_{k(2)} = D_{ik}\Delta x + \left(\frac{D_{pk(1)} + D_{pk(2)}}{2}\right)\Delta x + g_{k(1)} \quad [2.22]$$

Substitution for D_2 using equation 2.14 in equation 2.22 gives:

$$g_{k(2)} = D_{ik}\Delta x + \left(\frac{D_{pk(1)} + (\alpha_d V_{fk} / q_2)(T_{ck(2)} - g_{k(2)})}{2}\right)\Delta x + g_{k(1)} \quad [2.23]$$

Equation 2.23 is solved for the sediment load $g_{k(2)}$, the only unknown in equation 2.23, at the end of the distance step. A trial-and-error solution is also required for this procedure as well because transport capacity for a single sediment class computed with equation 2.21 depends on the total sediment load.

Regardless of the numerical procedure, the boundary condition must the determined for each segment (see **Section 2.3.8.2)**. This boundary condition is the deposition rate of each sediment class determined at the upper end of the *ith* segment to start the step by step solution of the equations. The deposition rate at the lower end of the *(i-1)th* segment can not be used as the boundary condition for the upper end of the *ith* segment because deposition values are not continuous at common points of segments. Deposition rates change stepwise at these points even though discharge rate and sediment load are continuous at these points. Steepness makes a step change at common segment points.

The deposition rate at the upstream end of the *ith* segment is computed from:

$$D_{puk(i)} = \left(\alpha_d V_{fk} / q_{(i-1)}\right)\left(T_{cuk(i)} - g_{k(i-1)}\right) \qquad [2.24]$$

where: equation 2.24 is solved for each sediment class using sediment transport capacity computed for each class using equation 2.21. The sediment load $g_{k(i-1)}$ is the sediment load at the end of the upslope *(i-1)th* segment, which is the same as the sediment load at the upper end of the *ith* segment because sediment load is continuous along the overland flow path.

A value of 3 was determined by calibration for the deposition coefficient. Values for α_d were adjusted until the computed sediment distribution matched observed distributions for situations where deposition occurred (Foster et al., 1980c). This calibration coefficient is partly needed to adjust for runoff depth rather than excess rainfall rate being used to compute runoff rate.

The numerical procedure used to compute deposition must be carefully chosen so that computed values are not affected by arbitrary division of a segment. Segments by definition are uniform in soil, steepness, and cover-management. Dividing a portion of the overland flow path where conditions do not change into segments as illustrated in Figure 2.2 should not affect the detachment and erosion computations. Also, the computations for a segment must not be affected by downslope conditions, including overland flow path length beyond the segment.

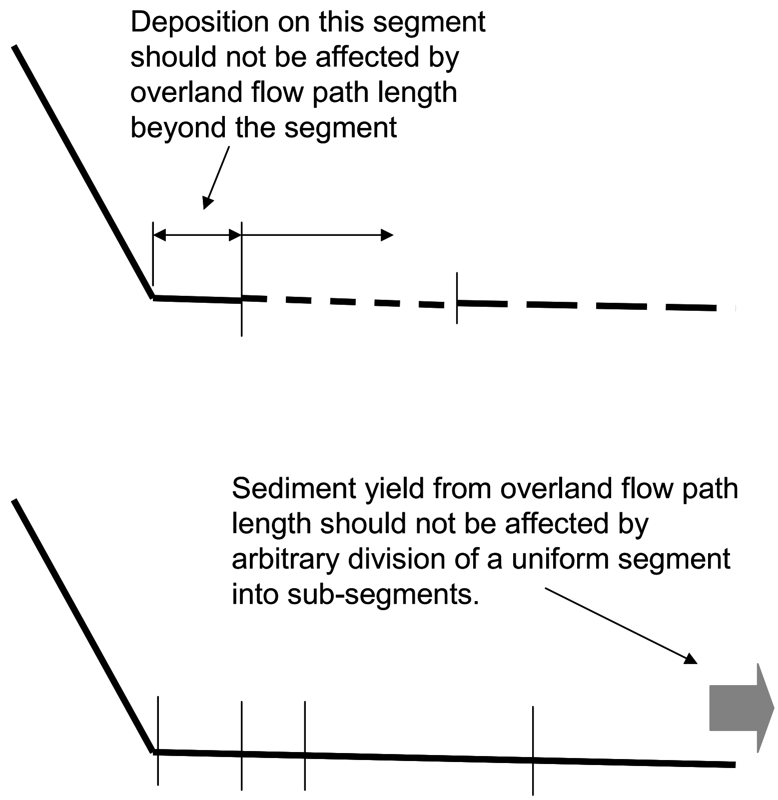

Figure 2.2. Situations where overland flow path lengths and segment divisions should have no effect on computed deposition.

The RUSLE2 procedure avoids these problems by dividing the entire overland flow path into a particular number of segments. The number of sub-segments used in RUSLE2 for an overland flow path length is 200. The sub-segments are only used in the segments having deposition. Thus, the density of sub-segments within a particular segment is the same for all segments. The number of sub-segments within a segment x_{i-1} to x_i is:

$$n_i = [(x_i - x_{i-1})/\lambda_o]n_o \qquad [2.25]$$

where: n_i = an integer number of sub-segments within the *ith* segment, λ_o = the overland flow path length, and n_o = 200, the number of sub-segments for the entire overland flow path length. The length of the sub-segment Δx used in the numerical solution of the deposition equations is:

$$\Delta x = \left(x_{(i)} - x_{(i-1)}\right)/n_i \qquad [2.26]$$

These equations ensure that the end sub-segments within a particular segment begin and end on the segment ends.

A sensitivity analysis was conducted to determine how the sediment delivery ratio (sediment yield/sediment production) for an overland flow path like the ones in Figure

2.2 varied as a function of n_o, the number of sub-segment for the entire overland flow path length. The variation in sediment delivery ratio was about 5 percent as the number of sub-segments for the overland flow path length varied from 100 to 10,000. The value of 200 was chosen, which gives acceptable accuracy while minimizing computer run time.

2.3.7. Concept of a representative storm

Runoff is a key RUSLE2 variable used to compute erosion reduction by support practices including contouring, porous barriers, and flow interceptors and deposition on concave overland flow paths. The intent for using RUSLE2 as a guide to erosion control planning is that RUSLE2 compute the relative erosion control effectiveness of support practices by location. For example, support practices like contouring are less effective in the southern US than in the northern US because of differences in storm severity (Foster et al., 1997). RUSLE2 is calibrated to compute the effectiveness of support practices at the base Columbia, Missouri location. RUSLE2 compute the deviation in support practice effectiveness by the degree that climatic conditions at a specific location vary from those at the base Columbia, Missouri location. This approach gives RUSLE2 increased robustness.

RUSLE2 uses the 10 year (return period-frequency), 24 hour (storm duration) P_{10y24h} precipitation amount to capture the climatic variation by location to compute erosion control by support practices.[18] This precipitation variable is used as an index of storm severity. A more erosive storm than an average annual storm is used as a storm severity index because support practice effectiveness, especially for contouring, depends on storm severity (Foster et al., 1997). For example, contouring can greatly reduce erosion for small storms but fail completely for large storms.

The effect of support practices and concave overland flow path profile shape on erosion and deposition depends much more on runoff than the combination of raindrop impact and runoff. RUSLE2 uses a representative storm in process-based equations to compute runoff that in turn is used to compute deposition. The daily erosion and deposition values computed with this representative storm are scaled to match the daily detachment values computed with equation 2.10 (**see Section 2.3.9**). The same representative storm is used in the process-based equations for each day, but the computed daily runoff values vary as cover-management conditions change daily. The representative storm is used as an index for storm severity at a location. The intent is not to compute actual runoff on each day but to compute runoff values that show the how relative effectiveness of support practices and concave overland flow path profiles changes daily for the index storm. The index storm captures main-effect differences between locations. RUSLE2 computes comparable P-factor type effects for each day rather than using a single temporally constant P factor value like the USLE and RUSLE1.

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[18] The 10 year-24 hour precipitation procedure used in RUSLE2 is a replacement for the 10 year EI procedure used in RUSLE1.

RUSLE2 also computes an erosivity value for the P_{10y24h} index storm in addition to runoff. The storm erosivity r_{10y24h} for the 10 year-24 precipitation amount P_{10y24h} is computed from:

$$r_{10y24h} = 2\gamma_m P_{10y24h} \quad [2.27]$$

where: γ_m = the maximum monthly erosivity density at the location. Monthly erosivity density is the ratio of average monthly erosivity to average monthly precipitation amount (see **Section 3.2.1.4.1**).

2.3.8. Solving the sediment routing equations segment by segment

The sediment routing equations are solved using the value for the 10 year-24 hour precipitation amount P_{10y24h} used as an index storm. Although the same storm is used each day, computed sediment load changes daily as cover-management conditions temporally change. Daily sediment load values computed using the representative index storm are scaled to compute daily sediment load values appropriate for the daily erosivity values (see **Section 2.3.9**).

2.3.8.1. Inconsistency between slope effect in detachment and sediment transport capacity equations

Inconsistencies occur between the empirical detachment equation (equation 2.10) and the process-based sediment transport capacity equation (equation 2.17) because of differences in the steepness terms in the equations. The steepness effect in equation 2.10 for detachment is a two piece linear equation (see **Section 5.6**), whereas the steepness effect in equation 2.17 for sediment transport capacity is a single linear term. Equations 2.10 and 2.17 are calibrated to be close at the unit-plot nine percent steepness. However, the steepness effect in equation 2.10 can exceed the steepness effect in equation 2.17 at both flat and steep slopes depending on values for the other terms in the equations. Although equation 2.10 is generally assumed to represent detachment limiting conditions in RUSLE2, this empirical equation reflects a mixture of both detachment and transport capacity limiting at low steepness. The assumption used to deal with this and other similar inconsistencies that occur between the empirical USLE formulation and the process-based equations is that RUSLE2 gives the empirical USLE erosion estimate for uniform overland flow paths.[19]

The inconsistencies between these two steepness effects could not be reconciled for non-uniform overland flow paths at low steepness, but RUSLE2 was very carefully evaluated to ensure that the inconsistencies have little effect in conservation planning.

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[19] These inconsistencies could be eliminated by developing RUSLE2 so that it uses all process-based equations rather than combining the empirical USLE equation with process-based equations. However, the RUSLE2 hybrid approach combines the best of the empirical USLE approach with the best of the process-based approach (see **Section 1.2 and 1.3**).

2.3.8.2. Boundary values

Boundary values must be determined for each segment to solve the sediment routing equations. The equations are solved sequentially starting with the first segment at the origin of the overland flow path and then moving downslope segment by segment. The computed values for runoff and sediment load at the end of the last segment become boundary values for the next segment. The major boundary values for the first segment at x = 0 is that no inflow of either runoff or sediment occurs (i.e., $q_0 = 0$ and $g_0 = 0$).

2.3.8.3. Special boundary conditions cases

Five special cases were used to organize the sediment routing computations and to set boundary values.

2.3.8.3.1. Case 1: First segment

The first segment is a special case because of the no-inflow boundary condition and because the sediment load leaving this segment must equal the sediment load computed by the USLE (i.e., equation 2.10), (assuming the RUSLE2 factor values are used in the USLE). The first segment directly matches the USLE uniform slope assumptions.

Many RUSLE2 conservation and erosion control planning applications involve a uniform overland flow path. In these situations, RUSLE2 uses a single uniform overland flow path segment and only the equations for the Case 1: First Segment special case in its sediment routing computations.

An important logic check for the first segment is to determine if local deposition is computed within the segment. RUSLE2 computes no deposition if the rate of increase in sediment transport capacity with distance dT_c/dx is greater than the interrill erosion rate D_i within the first segment. The rate of increase in transport capacity in the first segment is computed as:

$$dT_c / dx = K_T \zeta \sigma s \qquad [2.28]$$

Excess rainfall rate σ is computed using the 10 year-24 hour representative storm P_{10y24h} and the interrill erosion rate D_i is computed with equation 2.11 using the representative (index) storm erosivity r_{10y24h} (see **Section 3.2.4**).

2.3.8.3.1.1. $dT_c/dx > D_i$ - No local deposition

RUSLE2 computes no local deposition in the first segment when the rate of increase in sediment transport capacity with distance dT_c/dx is greater than the interrill erosion rate D_i. No local deposition occurs because runoff's sediment transport capacity is sufficient to transport the sediment load produced by interrill erosion. The interrill erosion rate $D_{i10y24h}$ in the first segment is computed using the erosivity r_{10y24y} value computed with equation 2.27 for the P_{10y24h} representative storm. In that case, the sediment load leaving the segment is given by equation 2.15 after rill and interrill erosion are combined into a single term as:[20]

$$g = r_{10y24h} kScp_p p_c p_d x_{(1)}^{m_i+1} / \lambda_u^{m_i} \quad [2.29]$$

where: g = the total sediment load for all sediment classes and $x_{(1)}$ = distance to downstream of the first segment.[21] The sediment load g_k of each sediment class at the end of the first segment is given by:

$$g_k = \psi_k g \quad [2.30]$$

where: ψ_k = sediment mass in the *kth* sediment class (fraction). This special case is detachment limiting. Therefore, the distribution of sediment classes in the sediment load at the end of segment 1 for Case 1 where $dT_c/dx > D_i$ equals the distribution of the sediment classes at the point of detachment (see **Section 4.7.5**). The enrichment ratio is one (1) for this case because no deposition is computed (see **Section 4.7.6**).

2.3.8.3.1.2. $dT_c/dx < D_i$ - Local deposition occurs

When the interrill erosion rate D_i within the first segment exceeds the rate of increase in transport capacity with distance dT_c/dx, local deposition is computed. Even though local deposition is computed, equation 2.29 is used to compute sediment load at the end of the first segment to ensure that RUSLE2 gives the USLE result for the first segment. However, local deposition enriches the sediment in fines. RUSLE2 computes quasi-deposition and -sediment load values to estimate the distribution of the sediment classes for the sediment leaving the first segment. The sole purpose of this computation is to obtain the sediment distribution; this computation does not affect the value computed for sediment load at the end of the first segment, which is computed with equation 2.29.

Equations 2.14, 2.16, 2.17, and 2.18 were solved in closed form to compute the quasi-deposition and -sediment load values in segment 1 (Renard and Foster, 1983). The equation used to compute deposition is:

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[20] The units for sediment load depend on the units used for erosivity r, soil erodibility k, distance x, and length λ_u. For example, in the US customary units system for the USLE, the typical units for sediment load g would be $(tons_m/acre \cdot day) \cdot ft$. These set of units are multiplied by $(2000\ lbs_m/ton)/(43560\ ft^2/acre)$ to obtain a consistent set of units of lbs for mass and ft for length. In RUSLE2, erosion values are computed for each day using a daily erosivity value (see **Sections 2.1 and 3.1**), which is the reason for the day unit in sediment load. The sediment amount values have mass units. In the US customary USLE units, lbs-mass and lbs-force are equal. In the SI system, kg is the recommended unit for sediment mass, although the output would likely be displayed in metric tonnes. See AH703 (Renard et al., 1997) for additional discussion of USLE/RUSLE units.

[21] Equation 2.29 is the USLE equation form when the slope length λ is substituted for x_i and the equation is divided by slope length λ to compute average erosion for the slope length.

$$D_{qk} = [(a_d V_{fk} / \sigma)/(1 + a_d V_{fk} / \sigma)][(dT_c / dx - D_i)\psi_k] \qquad [2.31]$$

$$g_{qk} = \psi_k T_c - qD_{qk} /(a_d V_{fk}) \qquad [2.32]$$

$$q = \sigma x_{(1)} \qquad [2.33]$$

$$T_c = K_T \zeta q s \qquad [2.34]$$

where: D_{qk} and g_{qk} are the quasi-deposition and -sediment load variables used specifically to compute the distribution of the sediment load among the sediment classes for the first segment when local deposition occurs and $x_{(1)}$ = the distance to the end of the first segment. The subscript k refers to sediment class. Equations 2.31-2.34 are solved for each sediment class. The fraction of the sediment load in each sediment class for the sediment load at the end of the first segment is computed as:

$$\omega_k = g_{qk} / \sum_{k=1}^{5} g_{pk} \qquad [2.35]$$

where: ω_k = the portion of the total sediment load leaving the first segment that is composed of sediment in the *kth* sediment class and 5 is the number of sediment classes used in RUSLE2. The sediment load in each sediment class at the end of the first segment is computed as:

$$g_k = \omega_k g \qquad [2.36]$$

The enrichment ratio for the sediment at the end of the first segment is greater than 1 based on the portion of the interrill erosion that RUSLE2 computes as deposited in the first segment. Enrichment ratio is based on specific surface area of the sediment (see **Section 4.7.6**).

2.3.8.3.2. Case 2: Detachment over entire segment

Two boundary conditions must be met for detachment to be computed over an entire segment. The incoming sediment load at the upper end of the segment must be less than transport capacity at the upper end of the segment. The mathematical condition for this check is that $g_{i-1} < T_{cu(i)}$ where $T_{cu(i)}$ = transport capacity at the upstream end of the *ith* segment. This transport capacity is computed using the runoff discharge rate q_{i-1}, the slope steepness s_i, and sediment transport capacity coefficient ζ_i for the ith segment. Therefore, transport capacity at the upstream end of the *ith* segment $T_{cu(i)}$ does not equal the transport capacity $T_{cl(i-1)}$ at the downstream end of the *(i-1)th* segment if steepness and/or cover-management changes between the segments.

The second condition is that the potential sediment load at the end of the segment computed as the sum of the incoming sediment load plus the sediment produced by interrill erosion within the segment is less than the transport capacity at the lower end of the segment. This potential sediment load is computed as:

$$g_{p(i)} = g_{(i-1)} + D_{i(i)}\left(x_{(i)} - x_{(i-1)}\right) \quad [2.37]$$

where: g_p = potential sediment load. The boundary condition is that this potential sediment load be less than transport capacity at the downstream end of the segment, i.e., $g_{p(i)} < T_{cl(i)}$.

2.3.8.3.2.1. Sediment load when rill erosion occurs at capacity rate

A subsequent check must also be made to determine if rill erosion can occur at its capacity over the segment. A second potential sediment load is computed as:

$$g_{p(i)} = g_{(i-1)} + r_{10y24h}k_{(i)}S_{(i)}c_{(i)}p_{p(i)}p_{c(i)}p_{d(i)}\left(x_{(i)}^{m_i+1} - x_{(i-1)}^{m_i+1}\right)/\lambda_u^{m_i} \quad [2.38]$$

where rill erosion is assumed to occur at its capacity rate. If this potential sediment load is less than sediment transport capacity at the lower end of the segment, rill erosion is assumed to occur at its capacity rate and the sediment load leaving the segment is given by equation 2.38.

The distribution of the sediment load among the sediment classes is computed by:

$$g_{k(i)} = g_{k(i-1)} + \psi_k\left(g_{(i)} - g_{(i-1)}\right) \quad [2.39]$$

which results from detachment being non-selective.[22] That is, the distribution of the sediment added within the sediment load, $g_{(i)} - g_{(i-1)}$, is assumed to be the same as sediment at the point of detachment.

2.3.8.3.2.2. Sediment load when rill erosion at less than capacity rate

If potential load computed by equation 2.39 exceeds the transport capacity at the downstream end of the segment, rill erosion is limited to the rate that will just fill transport capacity, which means that sediment load at the end of the segment is given by:

$$g_{(i)} = T_{Cl(i)} \quad [2.40]$$

Even though rill erosion is not computed at its capacity rate, some rill erosion is computed, and, therefore, no local deposition is computed. The distribution of the sediment load at the end of the segment is given by equation 2.39.

[22] Sediment characteristics at the point of detachment change as soil texture changes by segment. RUSLE2 starts at the first segment with the five sediment classes for that segment based on soil texture. RUSLE2 adds sediment classes to represent soil texture changes in the segments along the overland flow path.

2.3.8.3.3. Case 3: Detachment on upper portion of segment, deposition on lower portion of segment

An example where detachment occurs on the upper portion of a segment and deposition occurs on the lower portion of the segment is illustrated in Figure 2.3. Infiltration rate on the *ith* (second) segment is greater than the rainfall rate, which causes the runoff rate to decrease within the segment. Sediment load increases within the segment while sediment transport capacity decreases within the *ith* segment. Deposition begins at the point where sediment load equals transport capacity.

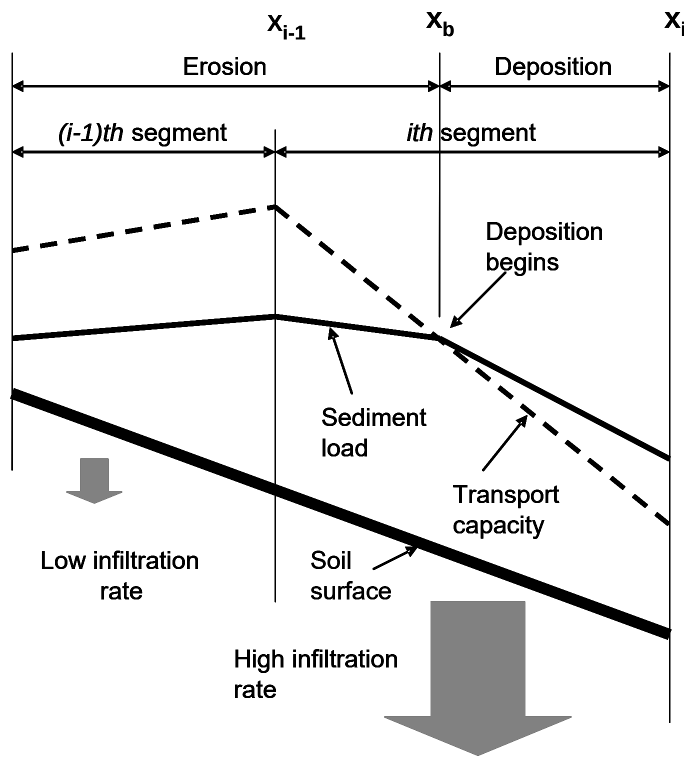

Figure 2.3. Illustration where detachment ends and deposition begins within the ith segment

Two conditions must be met for this case. The first condition is that the incoming sediment load is less than sediment transport capacity at the upstream end of the segment, i.e., $g_{(i-1)} < T_{cu(i)}$. The second condition is that the potential sediment load at the lower end of the segment computed with equation 2.37 is greater than the transport capacity at the downstream end of the segment.

When this condition is met, deposition begins at the location where the sediment load equals transport capacity. The sediment load where deposition begins is given by:

$$g_b = g_{(i-1)} + D_{i(i)}\left(x_b - x_{(i-1)}\right) \qquad [2.41]$$

where: g_b = sediment load at the location x_b = where deposition begins. The sediment transport capacity T_{cb} where deposition begins is given:

$$T_{cb} = K_T \zeta_{(i)} s_{(i)} \left[q_{(i-1)} + \sigma_i \left(x_b - x_{(i-1)} \right) \right] \qquad [2.42]$$

where: σ = the excess rainfall rate (rainfall rate minus infiltration rate).[23] Equations 2.41 and 2.42 are combined and solved to determine a value for the location x_b where deposition begins.

The sediment load by sediment class at the location where deposition begins is given by:

$$g_{bk} = g_{k(i-1)} + \psi_k \left(g_b - g_{(i-1)} \right) \qquad [2.43]$$

Deposition is computed on the portion of the segment from x_b to x_i using equations 2.19-2.21. The main boundary values are that deposition rate is zero and sediment load equals sediment transport capacity at $x = x_b$. These equations compute values for total sediment load and sediment load for each sediment class at the lower end of the segment.

2.3.8.3.4. Case 4: Deposition over entire segment

Figure 2.4 illustrates deposition occurring over an entire segment. In this case, the width of the vegetation strip is so narrow that sediment transport capacity does not increase within the strip to where it exceeds sediment load. The first boundary condition for this case is that the incoming sediment load is greater than sediment transport capacity at the upper end of the segment. The second condition is that the interrill erosion rate D_i within the segment is greater than the increase in sediment transport capacity with distance dT_c/dx within the segment. This boundary condition is the same as the incoming sediment load plus sediment production by interrill erosion within the segment being greater than sediment transport capacity at the lower end of the segment.

Equation 2.24 is used to compute the deposition rate at the upper end of the segment, which is a boundary value along with the incoming discharge rate $q_{(i-1)}$ and sediment load $g_{(i-1)}$ from the immediate upslope segment. These boundary values are used in equations 2.19-2.21 to compute deposition within the segment and values for total sediment load and sediment load by sediment class at the lower end of the segment.

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[23] Excess rainfall rate is negative for situations where RUSLE2 computes a decreasing runoff rate within a segment (see **Section 3.3.1.1**).

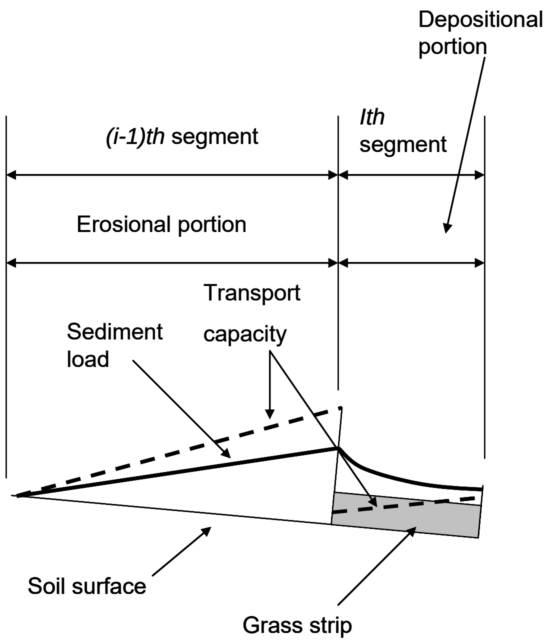

Figure 2.4. Narrow grass where deposition occurs over entire segment

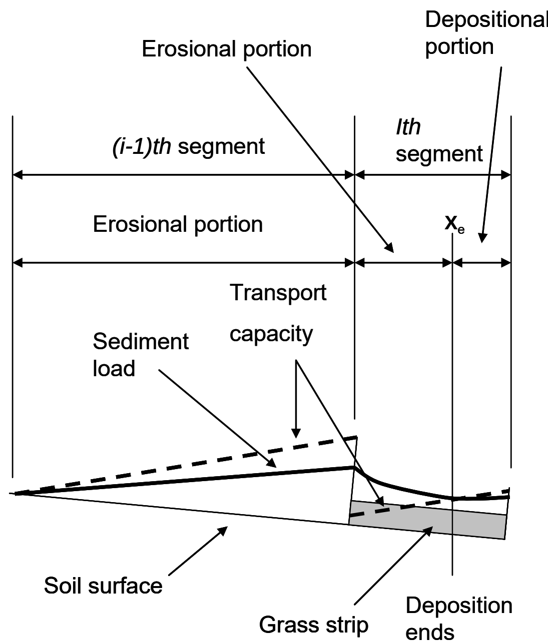

Figure 2.5. Grass strip sufficiently wide that deposition ends within segment and erosion occurs on lower portion of segment

2.3.8.3.5. Case 5: Deposition over upper part of segment, detachment over lower part of segment

Figure 2.5 illustrates deposition ending within a segment. Another example of deposition ending within a segment is illustrated in Figure 2.2 provided the segment is sufficiently long. As discussed in **Section 5.3**, RUSLE2 assumes that segments are discontinuous, even when used to represent a smooth, continuous concave overland flow path profile. The result is that RUSLE2 computes deposition on the upper portion of the segment and detachment on the lower portion of the segment if the segment is sufficiently long. This result is opposite from that for a smooth, continuously decreasing slope steepness where detachment occurs on the upper portion of the segment and deposition occurs on the lower portion of the segment where deposition begins. The error from not properly computing the location of the deposition is minimized by choosing short segment lengths to represent smooth, continuous overland flow path profiles.

The first boundary condition is that incoming sediment load is greater than the transport capacity at the upper end of the segment. The second boundary condition is that the incoming sediment load plus the sediment produced by interrill erosion within the segment is less than the transport capacity at the lower end of the segment. This boundary condition is the same as the boundary condition that the rate of increase in transport capacity with distance dT_c/dx is greater than the interrill erosion rate D_i within the segment. These boundary conditions are required but are not sufficient to determine that deposition ends within the segment if the segment length is short. The location x_e where deposition ends within the segments is determined by solving equations 2.19-2.21 and 2.24. Deposition ends at the location where computed deposition rate becomes zero. These equations compute the total sediment load g_e and the sediment load of each sediment class $g_{e(k)}$ at the location that deposition ends.

Detachment occurs on the lower portion of the segment. The potential sediment load at the end of the segment is computed from:

$$g_{p(i)} = g_e + r_{10y24h} k_{(i)} S_{(i)} c_{(i)} p_{p(i)} p_{c(i)} p_{d(i)} \left(x_i^{m_i+1} - x_e^{m_i+1} \right) / \lambda_u^{m_i} \quad [2.44]$$

This potential sediment load is checked against sediment transport capacity at the lower end of the segment. If the sediment transport capacity at the lower end of the segment exceeds this sediment load, then the sediment load leaving the segment is the potential sediment load computed by equation 2.44, i.e, $g_{(i)} = g_{p(i)}$. However, if the potential sediment load computed with equation 2.44 exceeds the transport capacity at the end of the segment, then rill erosion is limited to the rate that will just fill sediment transport capacity. In that case, the sediment load at the end of the segment equals sediment transport capacity at the lower end of the segment, i.e., $g_{(i)} = T_{cl(i)}$.

The sediment load for each sediment class at the end of the segment is given by:

$$g_{k(i)} = g_{ek} + \psi_k \left(g_{(i)} - g_e \right) \quad [2.45]$$

2.3.9. Scaling values computed with representative storm to create daily values

The daily sediment load values computed using the sediment routing equations and the representative storm P_{10y24h} must be scaled to compute daily sediment load values appropriate for the daily erosivity values. This scaling factor is computed as the ratio of sediment load computed at the end of each segment with the sediment routing equations and the sediment load at the lower end of each segment that would be produced if detachment occurs at detachment capacity for the representative storm. That sediment load g_{detcap} is computed as:

$$g_{\det cap(i)} = r_{10y24h} k_{(i)} S_{(i)} c_{(i)} p_{p(i)} p_{c(i)} p_{d(i)} \left(x_{(i)}^{m_i+1} - x_{(i-1)}^{m_i+1} \right) / \lambda_u^{m_i} \quad [2.46]$$

The scaling factor δ_i for each *ith* segment is computed as:

$$\delta_{(i)} = g_{(i)} / g_{\det cap(i)} \quad [2.47]$$

A sediment load based on detachment capacity comparable to $g_{detcap(i)}$ is computed using daily values for erosivity and the other factors as:

$$g_{daily \det cap(i)} = r k_{(i)} S_{(i)} c_{(i)} p_{p(i)} p_{c(i)} p_{d(i)} \left(x_{(i)}^{m_i+1} - x_{(i-1)}^{m_i+1} \right) / \lambda_u^{m_i} \quad [2.48]$$

where: $g_{dailydetcap(i)}$ = daily sediment load at end of *ith* segment that would be produced if full detachment occurred in each segment, r = the daily erosivity value determined from the disaggregation of the monthly erosivity values (see **Section 3.1**), and all of the other values in equation 2.48 are the same daily values used in the sediment routing equations.

The daily sediment load value is computed as the product of this daily detachment sediment load and the sediment load scaling factor as:

$$g_{daily(i)} = \delta_{(i)} g_{daily\,det\,cap(i)} \qquad [2.49]$$

where: $g_{daily(i)}$ = average daily sediment load at the end of the *ith* segment. The average daily net erosion rate $D_{daily(i)}$for the *ith* segment is computed as:

$$D_{daily(i)} = \left(g_{daily(i)} - g_{daily(i-1)}\right) / \left(x_{(i)} - x_{(i-1)}\right) \qquad [2.50]$$

2.3.10. Computing average annual erosion values for conservation and erosion control planning[24]

RUSLE2 computes average annual values for four variables used in conservation and erosion control planning. These variables are: (1) average annual erosion rate for the entire overland flow path (sediment yield from the overland flow path), (2) average annual detachment rate for the entire overland flow path, (3) average annual erosion rate for the eroding portion of the overland flow path, and (4) an average annual conservation planning soil loss for the overland flow path that gives partial credit to deposition as soil saved.

2.3.10.1. Average annual erosion rate for entire overland flow path (sediment yield)

The average annual erosion rate for the entire overland flow path is the ratio of the average annual sediment amount leaving the overland flow path divided by the overland flow path length. The sediment load at the end of the last segment on the overland flow path is also known as sediment yield or sediment delivery from the overland flow path.

The average annual sediment load at the end of the overland flow path is given by:

$$G_{\lambda} = \left(\sum_{j=1}^{J_d} g_{daily\lambda(j)} \right) \Big/ M_d \qquad [2.51]$$

where: G_{λ} = the average annual sediment load (i.e., sediment yield, sediment delivery) at the end of the overland flow path, $gdaily\lambda_{(j)}$ = the daily sediment load at the end of the overland flow path on the *jth* day, M_d = the number of years in the computation period

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[24] See the RUSLE2 User's Reference Guide for detailed information on these variables and how they are used in conservation and erosion control planning.

(duration entered in cover-management description, see **Section 2.2**), and J_d = the total number of days in the computation period (i.e., $J_d = 365 \cdot M_d$). The subscript n refers to each day in the computation period and the subscript I is the index value of the last segment used to describe the overland flow path.

The average annual erosion rate (sediment yield, sediment delivery) for the overland flow path is given by:

$$A_{sedyld} = G_{\lambda} / \lambda_o \qquad [2.52]$$

where: A_{sedyld} = the average annual erosion rate for the overland flow path length, λ_o.

2.3.10.2. Average annual detachment rate (sediment production) for entire overland flow path

The average annual detachment rate for the entire overland flow path represents a measure of total sediment production on the overland flow path. This variable is a measure of local erosion and sediment that has been moved away from its local point of origin. RUSLE2 computes detachment on each segment in its sediment routing computations and a sediment load value based on detachment. That sediment load is given by:

$$g_{\det(i)} = g_{\det(i-1)} + D_{i(i)}\left(x_{(i)} - x_{(i-1)}\right) + \Delta g_{r(i)} \qquad [2.53]$$

where: g_{det} = the sediment load produced by detachment at the lower end of the *ith* segment and ΔG_r = the sediment amount produced by rill erosion within the segment. Interrill erosion D_i is assumed to occur over an entire segment regardless of whether deposition occurs. If deposition does not occur, rill detachment occurs. Rill detachment in each segment is computed as described for each of the special cases in **Section 2.3.8.3**.

The average annual sediment load produced by detachment at the end of the overland flow path is given by:

$$G_{\det\lambda} = \left(\sum_{j=1}^{J} g_{\det\lambda(j)}\right) \Big/ M_d \qquad [2.54]$$

where: $G_{det\lambda}$ = the average annual sediment load at the end of the overland flow path. The average annual detachment rate for the entire overland flow path is given by:

$$A_{\det} = G_{\det\lambda} / \lambda_o \qquad [2.55]$$

where: A_{det} = the average annual detachment rate for the entire overland flow path.

2.3.10.3. Average annual erosion rate for eroding portions of the overland flow path

The average annual sediment load is computed for each segment as:

$$G_{(i)} = \left(\sum_{j=1}^{J_d} g_{daily(i,j)} \right) \Big/ M_d \qquad [2.56]$$

The average annual erosion rate for each segment is given by:

$$D_{aseg(i)} = \left(G_{(i)} - G_{(i-1)}\right)/(x_{(i)} - x_{(i-1)})/\left(x_{(i)} - x_{(i-1)}\right) \qquad [2.57]$$

where: $D_{aseg(i)}$ = the average annual erosion rate for the *ith* segment. Positive values for $D_{aseg(i)}$ values indicate net erosion and negative values indicate deposition. The eroding portions of the overland flow path are the segments where $D_{aseg(i)}$ is positive. The value for average annual erosion rate for the eroding portions of the overland flow path is computed as:

$$A_{erod} = \left[\left(G_{(l1)} - G_{(u1)}\right) + \left(G_{(l2)} - G_{(u2)}\right) + \left(G_{(l3)} - G_{(u3)}\right) + \ldots\right] / \qquad [2.58]$$

$$\left[\left(x_{(l1)} - x_{(u1)}\right) + \left(x_{(l2)} - x_{(u2)}\right) + \left(x_{(l3)} - x_{(u3)}\right) + \ldots\right]$$

where: A_{erod} = average annual erosion rate for the eroding portions of the overland flow path, the subscript l refers to the downstream end of an eroding portion of the overland flow path, the subscript u refers to the upstream end of an eroding portion of the overland flow path, and the subscript 1, 2, 3, and ... refers to individual eroding portions of an overland flow path.

2.3.10.4. Conservation planning soil loss

The conservation planning soil loss variable gives partial credit for remote deposition as soil saved. The credit that is given to remote deposition along an overland flow path as soil saved is computed as (Foster et al., 1997):[25]

$$b_{d(i)} = 1 - \left(x_{du(i)} / \lambda_o\right)^{1.5} \qquad [2.59]$$

where: $b_{d(i)}$ = the fraction of the deposition in the *ith* segment that is credited as soil saved (i.e., deposition benefit) and $x_{du(i)}$ = the location of the upper edge of deposition in the

[25] Remote deposition is the deposition of sediment some distance from the location on the overland flow path that the sediment is detached. Examples of remote deposition are deposition upslope of dense vegetation strips, on the toe of concave overland flow path profiles, and in terrace channels. Local deposition is deposition very near the point of detachment such as deposition in the depressions created by random roughness and in the furrows between ridges on a low grade. Local deposition is given full credit as soil saved, which is implicit in the empirical equation structure for computing detachment. Local deposition associated with random roughness is explicitly computed only for the first segment in an overland flow path description. Deposition computed for segments other than the first segment for overland flow paths involving multiple segments is considered to be remote deposition and is given partial credit as soil saved according to equation 2.59.

segment in which the deposition occurs. A significantly reduced benefit is computed when the deposition occurs close to the overland flow path end, which is the location x = λ. The credited deposition in a segment is computed as:[26]

$$\Delta g_{pb(i)} = \Delta gp_{a(i)} b_{d(i)} \quad [2.60]$$

where: $\Delta g_{pb(i)}$ = daily deposited sediment credited as soil saved (mass/width) and $\Delta g_{pa(i)}$ = the daily computed total deposition for the segment before any credit is taken (mass/width). The daily conservation planning sediment load along the overland flow path is computed as:

$$g_{cp(i)} = g_{cp(i-1)} + \Delta g_{pb(i)} + \Delta g_{i(i)} + \Delta g_{r(i)} \quad [2.61]$$

where: g_{cp} = daily conservation planning sediment load along the overland flow path, $\Delta g_{i(i)}$ = total interrill detachment within the segment (mass/width) and $\Delta g_{r(i)}$ = total rill detachment within the segment (mass/width). Interrill erosion D_i is assumed to occur over an entire segment regardless of whether deposition occurs. If deposition does not occur, rill detachment occurs. Rill detachment in each segment is computed as described for each of the special cases in **Section 2.3.8.3**.

The average annual conservation planning sediment load at the end of the overland flow path or at the end of terrace channels for the computation period is given by:

$$G_{cp\lambda} = \left(\sum_{j=1}^{J_d} g_{cp\lambda(j)} \right) \Big/ M_d \quad [2.62]$$

where: $G_{cp\lambda}$ = the average annual sediment load for conservation planning.

The conservation planning soil loss is given by:

$$A_{cp} = G_{cp\lambda} / \lambda_o \quad [2.63]$$

where: A_{cp} = the average annual conservation planning soil loss.

Deposition occurs in terrace channels that are on a sufficiently low grade. The credit for soil saved computed for this deposition is computed with (Foster and Highfill, 1983; Foster et al., 1997):

$$a_{cpt} = a_{ty} \exp[-0.011(\lambda_t - 100)] \quad \lambda_t > 100 \quad [2.64]$$

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[26] These computations are made using the scaled values that match the daily erosivity values.

$$a_{cpt} = 0.45 a_{ty} \quad \lambda_t \le 100 \qquad [2.65]$$

where: a_{cpt} = the daily conservation planning sediment yield [average erosion for area (mass/area)] when deposition occurs in terrace channels, a_{yt} = daily sediment yield [average erosion for area (mass/area)] from terrace channels, and λ_t = terrace spacing (feet). The average annual conservation planning soil loss for conservation planning is:

$$A_{cp} = \left(\sum_{j=1}^{J_d} a_{cp(j)} \right) \Big/ M_d \qquad [2.66]$$

2.3.10.5. Comments on conservation and erosion control planning variables

The values for all four of these conservation and erosion control planning variables are equal for a uniform overland flow path. If a dense vegetation strip is located at the end of the overland flow path, the value for average erosion rate for the entire overland flow path (sediment yield) will be much lower than the other values because of deposition caused by the grass strip and its backwater. The highest value of the four will be the average erosion rate for the eroding portion of the overland flow path. In this example, this part of the overland flow path is from its origin to the location where deposition begins at the upper edge of the backwater created by the vegetation strip. The value for the average detachment rate for the entire overland flow path will be less than the average erosion rate for the eroding portion of the overland flow path because of the greatly reduced detachment in the backwater and in the vegetation strip itself. The conservation planning soil loss will be less than the detachment value but greater than the sediment yield value because of the partial credit taken for deposition as soil saved. In this example, the conservation planning soil loss value will be closer to the detachment value than to the sediment yield value. Not much credit (benefit) is given to the deposition because it occurs near the end of the overland flow path (see the RUSLE2 User's Reference Guide).

2.4. List of symbols

a = daily erosion (mass/area·day)

a_{cpt} = daily conservation planning soil loss for terraces (mass/area·day)

a_{yt} = daily average sediment yield expressed for terrace interval expressed as average erosion for area (mass/area·day)

a_k = erosion in *kth* crop stage (mass/area)

a_u = unit plot daily erosion (mass/area·day)

a_{us} = unit plot erosion for a single storm (mass/area)

A = average annual erosion (mass/area·year)

A_{cp} = average annual conservation planning soil loss (mass/area·year)

A_{det} = average annual detachment rate for the entire overland flow path (mass/time·year)

A_{erod} = average annual erosion for the eroding portions of the overland flow path (mass/area·year)

A_{sedyld} = average annual erosion rate for the overland flow path length (mass/area·year)

A_u = unit plot average annual erosion (mass/area·year)

b_d = deposition in a segment credited as soil saved (i.e., deposition benefit) (fraction)

b_r = **b** value, coefficient for ground surface) cover effectiveness for rill erosion ($percent^{-1}$)

c = daily cover-management factor (soil loss ratio) (dimensionless)

c_k = cover-management factor (soil loss ratio) for *kth* crop stage (dimensionless)

c_{pr}/c_{pi} = rill to interrill prior land use soil erodibility ratio

C = average annual cover-management factor (dimensionless)

D = daily detachment by rill and interrill erosion combined (mass/area·day)

D_{aseg} = average annual erosion for a segment (mass/area·day)

D_i = daily detachment by interrill erosion (mass/area·day)

D_i = interrill erosion rate (mass/area·time)

$D_{daily =}$ average daily net erosion for a segment (mass/area·day]

D_p = deposition rate in rill areas (mass/area· time)

D_{pk} = deposition rate for the *kth* sediment class (mass/area·time)

D_{puk} = deposition rate at the upstream end of a segment for the *kth* sediment class (mass/area·day)

D_{qk} = quasi-deposition rate in first segment for *kth* sediment (mass/area· time)

D_r = rill erosion rate(mass/unit area· time)

D_{rorp} = either rill erosion (D_r) or deposition (D_p) in rill areas (mass/area·time)

$\exp(-b_r f_g)/\exp(-0.025 f_g)$ = rill erosion surface cover effect to interrill erosion surface cover effect ratio

E = rain storm energy (force·length/area)

EI_{30} = rain storm erosivity (force·length/area)·(length/time)

f_g = ground (surface) cover (percent)

f_k = portion of average annual erosivity that occurs during *kth* crop stage (fraction)

g = sediment load (mass/unit overland flow width· time)

g_b = sediment load at the location where deposition begins within segment (mass/width· time)

g_{bk} = sediment load for the *kth* sediment class at the location where deposition begins within segment (mass/width· time)

g_{cp} = daily conservation planning sediment load (mass/width·day)

$g_{cp\lambda}$ = daily conservation planning sediment load at end of overland flow path (mass/width·day)

g_{daily} = daily sediment load (mass/width· day)

$g_{daily\lambda}$ = daily sediment load at end of overland flow path (mass/width· day)

$g_{dailydetcap}$ = daily sediment load that would be produced if detachment occurred at detachment capacity (mass/width· day)

g_{det} = daily sediment load produced by detachment (mass/width· day)

g_{detcap} = daily sediment load that would result from detachment at capacity rate (mass/width· day)

g_{ek} = sediment load where deposition ends for *kth* sediment class (mass/width· time)

g_k = sediment load for *kth* sediment class (mass/width· time)

g_0 = 0, sediment load at x = 0 (mass/width· time)

g_p = potential sediment load at end of segment (mass/width· time)

g_{qk} = quasi-sediment load for *kth* sediment class rate for first segment (mass/width·time)

$G_{cp\lambda}$ = average annual conservation planning sediment load at end of overland flow path (mass/width·year)

$G_{det\lambda}$= average annual sediment load produced by detachment at end of overland flow path (mass/width·year)

G_λ = average annual sediment load (i.e., sediment yield, sediment delivery) at end of overland flow path (mass/width·year)

I_{30} = average intensity over the continuous 30 minutes with most rainfall in storm (distance/time)

J_d = number of days in computation period (J_d =365M_d)

k = daily soil erodibility factor (mass/erosivity unit)

K = average annual soil erodibility factor (mass/erosivity unit)

K_r/K_i = inherent rill to interrill soil erodibility ratio

K_T = sediment transportability coefficient (mass/volume)

l = daily slope length factor (dimensionless)

L = average annual slope length factor (dimensionless)

m = daily slope length exponent (dimensionless)

M_c = number of year in computation for cover-management computation

M_d = number of years in the computation period

M_k = number of crop stages in computation period

M_r = number of years in the record being used to compute erosivity

$M_{s(j)}$ = the number of storms in the *jth* year

n_i = number of sub-segments within the *ith* segment (integer)

n_o = 200, number of sub-segments for the entire overland flow path length, used to solve numerical deposition equation

p_c = daily contouring subfactor dimensionless)

p_d = daily subsurface drainage subfactor (dimensionless)

p_p = daily ponding subfactor (dimensionless)

P = average annual support practice factor (dimensionless)

P_{10y24h} = 10 year(return period)-24 hour (storm duration) precipitation amount (length)

q = overland flow (runoff) rate (volume/width·time)

q_0 = 0, discharge rate at x = 0 (mass/width·time)

r = daily erosivity (erosivity unit/area·day)

r_k = erosivity during *kth* crop stage (erosivity unit/area)

r_{10y24h} = storm erosivity associated with 10 year-24 hour precipitation amount P_{10y24h} (erosivity unit)

R = average annual erosivity factor (erosivity unit/area·year)

$(s/0.0896)/(3s^{0.8}+0.56)$ = steepness effect for rill erosion to interrill erosion ratio

s = overland flow path steepness (sine of slope angle)

S = average annual slope steepness factor (dimensionless)

S_i = slope steepness factor for interrill erosion

T_c = sediment transport capacity in rill areas (mass/overland flow width·time)

T_{ck} = transport capacity for *kth* sediment class (mass/width·time)

T_{clk} = sediment transport capacity at the downstream (lower) end of segment (mass/width·time)

T_{cuk} = sediment transport capacity at the upstream (upper) end segment (mass/width·time)

T_{cb} = sediment load where deposition begins (mass/width·time)

V_f = sediment fall velocity (length/time)

V_{fk} = sediment fall velocity for *kth* sediment class (length/time)

x = distance from origin of overland flow path (length)

x_b = location where deposition begins (length)

x_e = location where deposition ends (length)

x_{ud} = location of upper edge of deposition in a segment in which deposition occurs (length)

α_d = deposition coefficient (dimensionless)

β = daily ratio of rill to interrill erosion for unit plot length

δ = scaling factor used to compute daily sediment load

Δg_i = daily sediment load produced by interrill erosion in a segment (mass/width·day)

Δg_{pa} = daily sediment load deposited in a segment before any credit is taken for deposition benefit (mass/width·day)

Δg_{pb} = daily sediment load deposited in a segment credited as soil saved (mass/width·day)

Δg_r = daily sediment load produced by rill erosion in a segment (mass/width·day)

Δx = length of the distance step used in the numerical integration to compute deposition (length)

γ_m = the maximum monthly erosivity density at the location (erosivity unit/length)

ζ = coefficient for effect of hydraulic resistance on sediment transport capacity

K = the number of crop stages

λ = slope length (length)

λ_o = overland flow path length (length)

λ_u = unit plot length (length)

σ = excess rainfall length rate (rainfall rate - infiltration rate) (length/time)

ψ_k = sediment mass in *kth* sediment class (fraction)

indices

i = segment along overland flow path

j = year

k = crop stage

k = sediment class

m = storm

1 and 2 = subscript 1 for upstream (upper) end of distance step and subscript 2 for downstream (lower) end of distance step in numerical integration of deposition equation

3. CLIMATE (WEATHER), RUNOFF, AND HYDRAULICS

The major weather variables used by RUSLE2 are monthly erosivity, precipitation, and temperature and the 10 year (return period)-24 hour (storm duration) precipitation amount. Erosivity values are an index of erosive rainfall at a location for causing rill and interrill erosion. Erosivity is a major variable in the equations used to compute detachment (e.g., see Section **2.1**). Precipitation and temperature influence the loss of biomass on and in the soil and how that loss varies among locations (e.g., see **Section 10.4.1**). Precipitation and temperature also affect the temporal distribution of soil erodibility and how that distribution varies by location (see **Section 4.5**). The 10 year-24 hour precipitation amount is a representative (index) storm that is used to compute the effect of ponding on erosivity, deposition on concave overland flow path profiles, deposition by dense vegetation strips, deposition in terrace channels, and the effectiveness of contouring (e.g., see **Section 7.1**). These computations are made using runoff and flow hydraulics based equations.

3.1. Disaggregation of monthly values into daily values

RUSLE2 uses daily values for erosivity, precipitation, and temperature to compute daily erosion (see **Section 2.1**). The RUSLE2 disaggregation procedure converts (disaggregates) the input monthly erosivity, precipitation, and temperature into daily values.

3.1.1. Basic disaggregation procedure

The same basic disaggregation procedure is used for monthly temperature, precipitation, and erosivity. The procedure assumes that daily values vary linearly within each month according to a two-piece linear equation. A requirement is that the average of the daily values in a month equals the input monthly value.

The daily value at the beginning of a month is assumed to equal the mean of the monthly values for the current and immediately preceding month and the daily value at the end of the month equals the mean of the monthly values for the current and next month as illustrated in Figure 3.1. That is:

$$Y_b = (M_{(j)} + M_{(j-1)})/2 \qquad [3.1]$$

and

$$Y_e = (M_{(j+1)} + M_{(j)})/2 \qquad [3.2]$$

where: M = the average monthly value of the variable being disaggregated, Y_b = the daily value at the beginning of the *jth* month, Y_e = the daily value at the end of the month, and the index j refers to the month.

Figure 3.1 illustrates an example of increasing monthly values. The same equations apply to both increasing and decreasing values. A second set of equations apply for local maximums and local minimums illustrated in Figure 3.2.

3.1.1.1. Increasing or decreasing monthly values

The third major value is the time t_c where the two linear lines in Figure 3.1 equal the average monthly value M_j. The value for t_c is determined so that the total area under the two linear lines equals the average monthly value M_j. The area under the two lines is given by:

$$M_{(j)} = t_c (Y_b + M_{(j)})/2 + (1 - t_c)(M_{(j)} + Y_e)/2 \qquad [3.3]$$

A value for t_c is determined by rearranging equation 3.3 as:

$$t_c = [M_{(j)} - (Y_e + M_{(j)})/2]/[(Y_b + M_{(j)})/2 - (Y_e + M_{(j)})/2] \qquad [3.4]$$

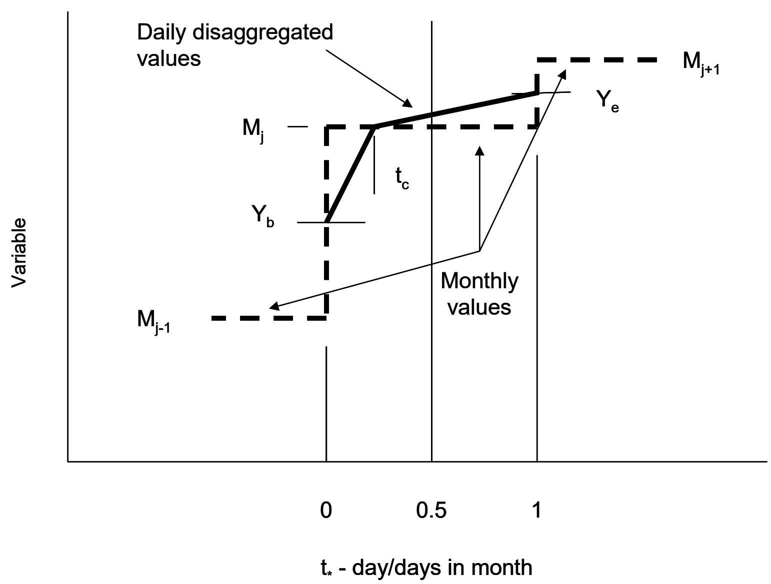

Figure 3.1. Illustration of two linear equations used to disaggregate monthly values into daily values for increasing or decreasing monthly values.

The equation used to compute daily values for times less than t_c is given by:

$$y_d = (d / D_{(j)})[(M_{(j)} - Y_b)/t_c] + Y_b \qquad [3.5]$$

where: y_d = the daily value on day d of the month and D_j = the number of days in the month. The equation to compute daily values for times greater than t_c is given by:

$$y_d = (1 - d / D_{(j)})[(M_{(j)} - Y_e)/(1 - t_c)] + Y_e \qquad [3.6]$$

3.1.1.2. Local maxima and minima

Figure 3.2 illustrates a local maximum. The equations apply both to local maximums and minimums.

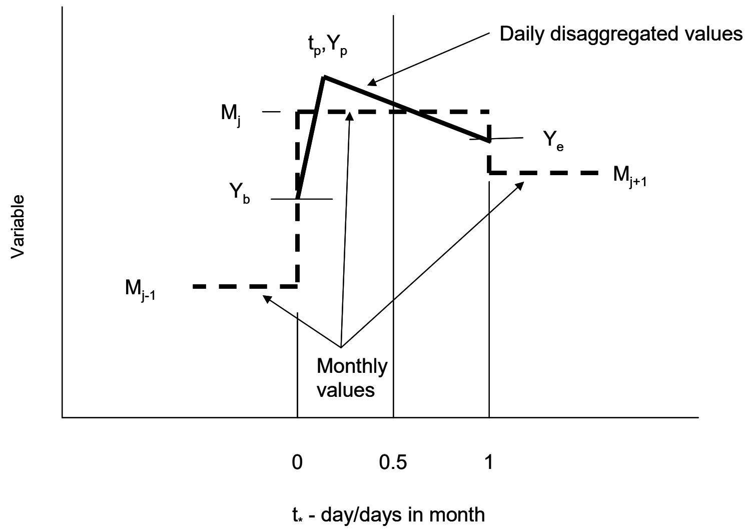

Figure 3.2. Illustration of two linear equations used to disaggregate monthly values for a local maxima or minima.

The daily value at the beginning and end of the month are computed using equations 3.1 and 3.2. The total area under the two lines must equal the average monthly value as:

$$M_{(j)} = (Y_b + Y_p)t_p / 2 + (Y_p + Y_e)(1 - t_p)/2 \qquad [3.7]$$

where: Y_p = the maximum value during the month that occurs at time t_p. Equation 3.7 is rearranged so that a value for the maximum value Y_p can be computed from:

$$Y_p = 2M_{(j)} + t_p(Y_e - Y_b) - Y_e \qquad [3.8]$$

The equation for the time of the peak t_p is given by:

$$t_p = 1 - (M_{(j)} - Y_b)/(2M_{(j)} - Y_b - Y_e) \qquad [3.9]$$

The equation for daily values for times less than the time of the peak is given by:

$$y_d = (d / D_{(j)})(Y_p - Y_b)/t_p + Y_b \qquad [3.10]$$

and the equation for times after the time to peak is given by:

$$y_d = [(Y_p - Y_e)/(1 - t_p)](1 - d / D_{(j)}) + Y_e \qquad [3.11]$$

3.1.2. Disaggregation procedure for temperature and erodibility

The disaggregation procedure is applied directly as described in **Section 3.1.1** for temperature. Figure 3.3 illustrates disaggregation of monthly temperature values into daily values for Columbia, Missouri. Notice that the date of the minimum daily temperature occurs in the third week of January as expected.

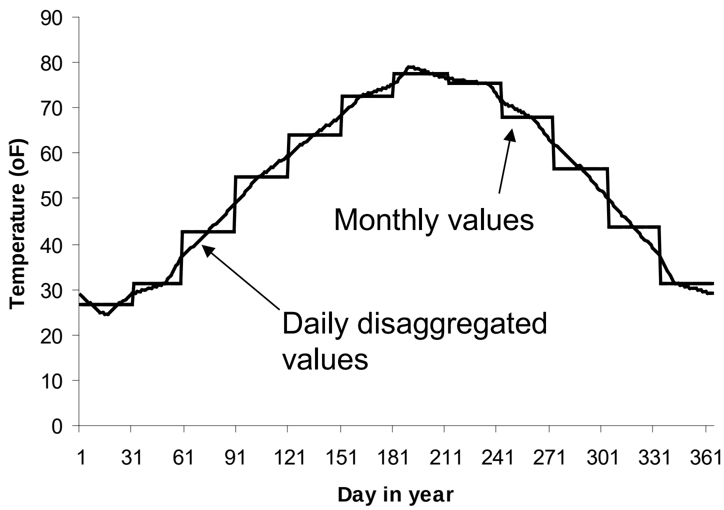

Figure 3.3. Daily temperature values obtained by disaggregating monthly temperature values at Columbia, Missouri.

3.1.3. Disaggregation procedure for precipitation and erosivity

When the disaggregation procedure is applied to monthly precipitation and erosivity, the average monthly value is divided by number of days in the month to obtain a mean daily value for the month. The disaggregation procedure is applied to the mean daily value in each month. Daily precipitation and erosivity values must be checked for negative values in very low rainfall areas like Yuma, Arizona. Daily precipitation and erosivity values are set to zero when negative values are computed. Setting these values to zero results in the sum of the disaggregated daily values being slightly greater than the monthly values in the months when the negative values occur. This adjustment has an insignificant effect on computed erosion values. Figure 3.4 shows daily disaggregated precipitation values for Columbia, Missouri.

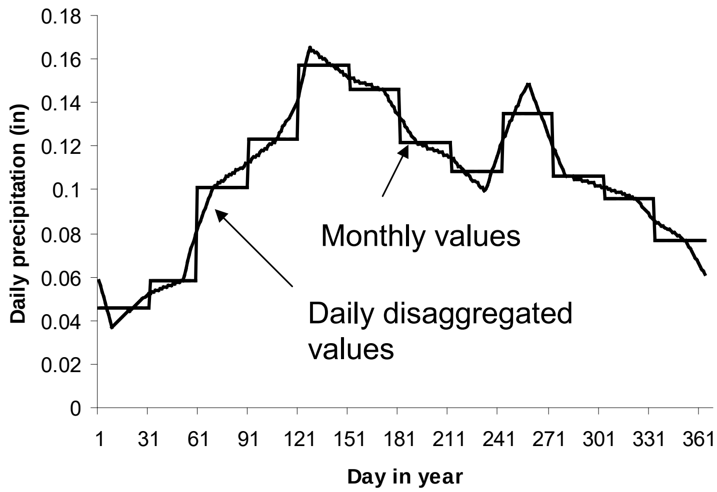

Figure 3.4. Daily precipitation values obtained from disaggregating monthly precipitation values at Columbia, Missouri.

3.2. Climate (weather) variables

The four basic RUSLE2 weather variables are monthly erosivity, precipitation, and temperature and the 10 year-24 hour precipitation amount. Selection of values for these variables is described in the RUSLE2 User's Reference Guide. This section describes underlying concepts, principles, and equations for processing weather data to develop input values consistent with RUSLE2 procedures and RUSLE2's purpose as a guide to conservation and erosion control planning.

3.2.1. Erosivity

RUSLE2 disaggregates average monthly erosivity values to obtain daily erosivity values used to compute daily erosion (see **Section 3.1**). Monthly erosivity values can be input directly into RUSLE2 in three ways, the recommended procedure for the Continental US is to input average monthly values for erosivity density.[27] Erosivity density, which is the ratio of monthly erosivity to monthly precipitation, is multiplied by monthly precipitation to obtain monthly erosivity values. The first step in developing average monthly erosivity density values is to compute erosivity values for individual storms using measured weather data.

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[27] RUSLE2 can uses monthly erosivity values (1) computed by multiplying monthly erosivity density and precipitation values (see **Section 3.2.1.4.1**), (2) input directly, or (3) determined from input values for annual erosivity and the biweekly temporal distribution of erosivity.

3.2.1.1. Storm erosivity

Erosivity, the product of a storm's energy and its maximum 30 minute intensity, for an individual storm is computed as (Wischmeier and Smith,1978):

$$r_s = EI_{30} \qquad [3.12]$$

where: r_s = storm erosivity, E = storm energy, and I_{30} = maximum 30-minute intensity. Maximum 30 minute intensity is the average intensity over the continuous 30 minutes in the storm with the most rainfall. Storm energy is computed using (Renard et al., 1997):

$$E = \sum_{k-1}^{m} e_k \Delta V_k \qquad [3.13]$$

where: e = unit energy (energy content per unit area per unit rainfall depth) in the *kth* period, and ΔV = the amount (depth) of rainfall in the *kth* period, k = index for periods during the rainstorm where rainfall intensity is considered uniform, and m = the number of periods in the rainstorm. Unit energy is computed from (Brown and Foster, 1987; McGergor et al., 1995; Renard et al., 1997):

$$e_k = 0.29[1 - 0.72\exp(-0.082 i_k)] \qquad [3.14]$$

where: e_k = the unit energy [MJ/(mm·ha)] for the *kth* period and i_k = rainfall intensity (mm/h) for the *kth* period.[28]

Data for storms less than 0.5 inch (12 mm), non-rainfall precipitation events, and extreme storm erosivity events with a return period greater than 50 years are excluded in the RUSLE2computation of storm erosivity.

3.2.1.2. Determining average annual erosivity values from measured precipitation data

Data from 15-minute precipitation gages that provide rainfall intensity values are required to compute storm erosivity values using equations 3.12-3.14. Modern data from 1960 through 1989 (1960-1999 in several cases) were analyzed to determine rainstorm erosivity and precipitation values at approximately 3700 15-minute precipitation gage locations across the Continental US (Hollinger et al., 2002). Erosivity values computed for the qualifying storms (i.e., rain events where amount was 0.5 inch or greater) were summed over the record length and divided by the years of record to determine an average annual erosivity value for each 15-minute precipitation station.

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[28] See Foster et al. (1981) and AH703 (Renard et al., 1997) for a discussion of RUSLE2 units and how to convert between customary US units and SI units.

The plan was to develop an average annual erosivity contour map based on values computed from measured data at as many 15-minute precipitation gage locations as possible. Initial maps had many “bull’s eyes” and irregular spatial trends rather than smooth trends required for RUSLE2 application as a guide for conservation planning. Data analysis showed that short and differing record lengths among locations greatly contributed to undesired spatial variability. The analysis also showed that the record length should be at least 18 years for directly computing average annual erosivity from measured 15-minute precipitation gage data. Even then the spatial variability among precipitation gage locations was sometimes too great.

3.2.1.3. Need for consistency in conservation and erosion control planning

Consistency in computed erosion estimates (hence, consistency in erosivity values) between locations within geographic regions and between regions is just as important as the absolute erosion estimates computed with RUSLE2. Land users impacted by erosion prediction perceive inconsistency and variability in erosion estimates for no apparent reason to be unfair, especially when the results negatively affect them. The probability distribution (return periods) of storms in a measured precipitation record used to compute erosivity values should be the consistent among locations. To illustrate, the average annual erosivity values at Wink, Texas and Pecos, Texas, towns in West Texas, computed from measured 15-minute precipitation data differed by a factor of two for no obvious reason. Inspection of the data showed that a 600-year return period storm caused the much larger average annual erosivity at one location.

The benefits or costs incurred by land users impacted by RUSLE2 should not be determined by the “luck of the draw” based on where they happen to be located. Furthermore, extreme events, such as a 100-, 200-, and 600-year storms, in the last 30 years are a very poor indicator of events likely to occur in the next 30 years. An average annual record that excludes extreme events is the best predictor of the immediate future for conservation planning where the objective is to protect the on-site soil resource from excessive degradation by erosion. However, other erosion prediction applications such as protecting highly sensitive water bodies and designing sediment storage in reservoirs may well require a different consideration of extreme events and a different set of input erosivity values than those developed for RUSLE2. Most erosion control practices are not designed or expected to withstand extreme events because in most cases failure does not cause catastrophic damages and the practices can be reinstalled without great costs.

Therefore, all storms with a return greater than 50 years were deleted from the measured data used in the RUSLE2 analysis to develop erosivity values.

3.2.1.4. Erosivity density approach to developing erosivity values

3.2.1.4.1. Erosivity density analysis

The RUSLE2 erosivity density approach for determining monthly erosivity values was developed in consideration of RUSLE2’s consistency requirements for conservation planning and to maximize the information that could be extracted from the measured 15-minute precipitation data. RUSLE2 multiplies input values for average monthly erosivity density by input values for average monthly precipitation to compute monthly erosivity values as:

$$R_{m(j)} = \alpha_{(j)} P_{md(j)} \quad [3.15]$$

where: R_m = average monthly erosivity, α = average monthly erosivity density, and P_{md} = average monthly precipitation determined from daily precipitation gage data, all for the *jth* month. Erosivity density refers to the erosivity content per unit precipitation. Erosivity density for a month is computed from measured 15-minute precipitation data as:

$$\alpha = \frac{\sum_{i=1}^{n} E_{(i)} I_{30(i)}}{\sum P_{15}} \quad [3.16]$$

where: all values were determined from 15-minute precipitation gage data including precipitation amount P_{15} from all storms and storm energy E is computed using equations 3.13 and 3.14, i = the index for storm in a month and n = total number of storms greater than 12 mm but smaller than a 50-yr event in a given month. Unit energy e_k for each *kth* period is computed from the average intensity for each 15-minute period in the storm (i.e., $i_k = \Delta V_k/15$ minutes and V_k = the rainfall amount in the *kth* 15-minute period). The I_{30} values used in equation 3.16 using 15-minute precipitation data were multiplied by a 1.04 factor to account for the fact that maximum intensity values from the 15-minute precipitation data are slightly lower than those computed with breakpoint rainfall (Hollinger et al., 2002). Breakpoint rainfall data are data divided into non-uniform periods where constant rainfall intensity can be assumed for each period. Breakpoint data are preferred rather than 15-minute precipitation data for computing storm erosivity.[29]

Approximations can be made in Equation 3.16 to aid the interpretation of erosivity density. Unit energy e does not vary greatly with intensity such that storm energy can be approximated with $\hat{e}P_{15}$ where $\hat{e}$ = effective unit energy for a month (Foster et al., 1982d). By assuming a representative $\bar{I}_{30}$ for the month, erosivity density is approximated by:

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[29] The storm data including computed storm erosivity values were provided by the Illinois State Water Survey. The analysis of erosivity data was a joint effort between the Illinois State Water Survey, the USDA-ARS and NRCS, and the University of Tennessee.

$$\alpha \approx \frac{\bar{I}_{30}\hat{e}\sum_{i=1}^{n} P_{15(i)}}{\sum_{i=1}^{n} P_{15(i)}} \qquad [3.17]$$

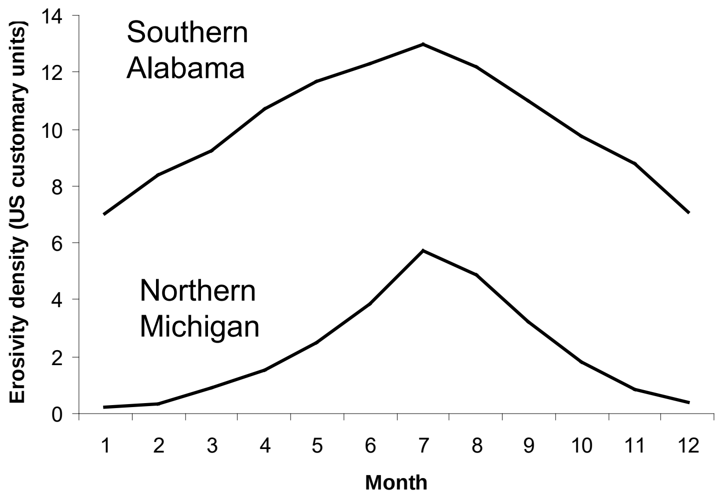

Figure 3.5. Erosivity density values for two locations.

where: $\bar{I}_{30}$ = the representative maximum 30-minute intensity for the month. Equation 3.17 in turn reduces to:

$$\alpha \approx \hat{e}\bar{I}_{30} \qquad [3.18]$$

Equation 3.18 shows that erosivity density varies directly with 30-minute rainfall intensity.

Erosivity density varies by location as illustrated in Figure 3.5 that shows that erosivity is higher in Southern Alabama than in Northern Michigan. In both locations, erosivity density is higher in the summer months than in the winter months, which according to equation 3.18, is caused by rainfall intensity varying with season. Rainfall intensity is greater in the summer than in the winter, resulting in erosivity being greater in the summer than in the winter for a given amount of rainfall. Also, most of the precipitation in Northern Michigan in the winter is snow and, therefore, is not included in the rainfall erosivity index.[30]

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[30] The storm precipitation and erosivity values used in this analysis were provided by the Illinois State Water Survey and the USA-Natural Resources Conservation Service Water and Climate Center. These

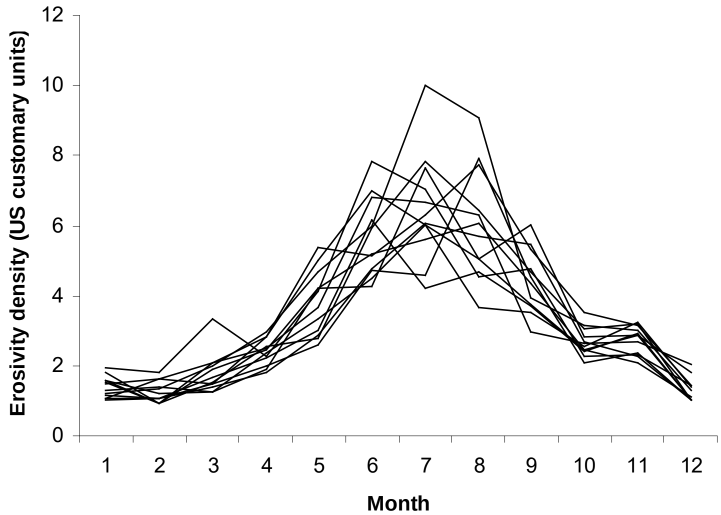

Figure 3.6. Spatial and temporal variability in erosivity density for locations in Southwestern Indiana.

Spatial and temporal variation in the erosivity density values computed from the 15-minute precipitation data was a major problem. Erosivity density values computed directly from the 15-minute precipitation data, as illustrated in Figure 3.6 for 15-minute gage locations in the southwest quadrant of Indiana, do not provide the smooth temporal and spatial trends required for RUSLE2 as a conservation and erosion control planning tool. Spatially averaging the erosivity density values by quadrant in Indiana smoothed the erosivity density values, both temporally and spatially, across Indiana as illustrated in Figure 3.7.

Geographic information systems (GIS) techniques, including kriging, were used to spatially average the erosivity density values computed from 15-minute precipitation data measured at the various gage locations. The procedure is similar to a spatial, moving average fitting technique and produced results similar to that illustrated in Figure 3.7.[31] Before kriging was applied, the monthly erosivity density values computed from the measured data in a relatively small region, such as a quadrant of Indiana, were inspected and analyzed for outliers. Monthly erosivity density values that departed from the mean in this local region by more than two times the standard deviation were considered outliers. Rather than excluding the entire dataset for a location (i.e., deleting the location from the entire data set), the outlier data point was adjusted to be consistent with other

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values are computed from measured weather data collected by the National Weather Service. See (Hollinger et al., 2002) for additional information.

[31] The GIS and kriging analysis was conducted by the Department of Biosystems Engineering and Environmental Science, University of Tennessee, Knoxville.

monthly erosivity density values at the location. Adjusting individual monthly data points kept the number of locations in the dataset as large as possible. In most cases, the same outliers at a location identified by the statistical test could also be identified by inspection. Outliers were monthly erosivity density value outside the smooth trend obtained by averaging the data points in the local region as was done in Figure 3.7. This process of identifying and adjusting outliers typically involved two or three iterations.

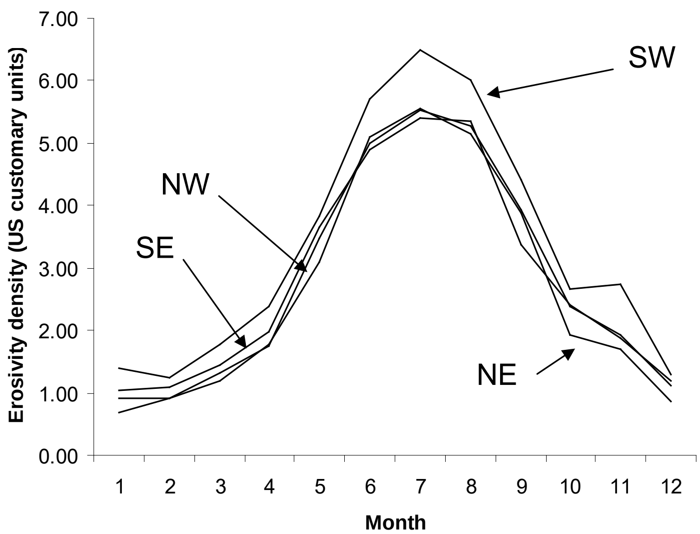

Figure 3.7. Erosivity density values spatially averaged for the four quadrants in Indiana.

A compromise was made in the number of nearest neighbors used in the kriging analysis. Using the 10 nearest neighbors worked well in the eastern US, but it did not work well along the eastern side of the Cascade Mountains in Washington and Oregon where erosivity density values decrease very rapidly with distance in this area. This rapid decrease necessitated using five rather than 10 nearest neighbors. This problem was also related to a very low density of 15-minute precipitation stations in the region. Using the five nearest neighbors also worked better than 10 nearest neighbors along coastlines and borders between Canada and Mexico where no precipitation data were available.

This procedure produced erosivity density values that varied smoothly over the Continental US, including mountainous regions. The hypothesis that erosivity density was not affected by mountainous terrain was tested in two ways. The first test involved fitting a linear equation to erosivity density values as a function of elevation at the 15-minute precipitation gage locations in a local region. The region had to relatively small, such as a quadrant of Utah, to avoid cross and spurious correlations. For example, the linear equation could not be fitted to erosivity density values for the entire state of Montana. When erosivity density values for all of Montana were included in the analysis, erosivity density values appeared to be a function of elevation, but that correlation was spurious. Elevation decreases from west to east across Montana while erosivity density increases across Montana. The increase in erosivity density across

Montana was not caused by elevation but by a west to east broad geographic increase in erosivity density.

Measured precipitation data from the 15-minute precipitation gages were available to compute erosivity density values for elevations up to about 10,000 ft. Statistical analysis for eleven local regions in mountainous areas throughout the western US and two local regions in the eastern US were conducted to determine if the hypothesis that erosivity density varied with elevation could be rejected. The analysis involved fitting a linear equation to the erosivity density values as a function of elevation. The data for three regions are shown in Figure 3.8-3.10. The result of the analysis was that the hypothesis that erosivity density values are independent of elevation could not be rejected. This test was not especially robust because of data variability. Elevation clearly affects erosivity density in the winter months because an increasing fraction of the precipitation occurs as snow at higher elevations. However, the assumption of no effect of elevation on erosivity density values in the summer months is considered acceptable.

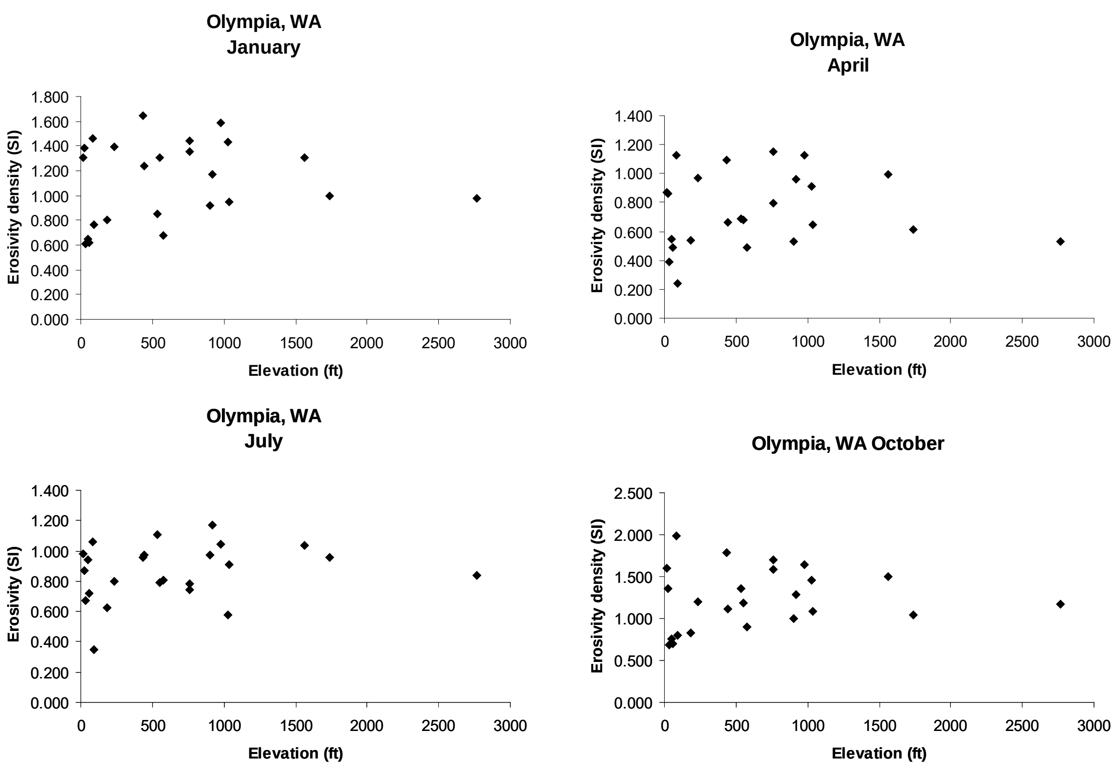

Figure 3.8. Variation of erosivity density with elevation in the Olympia, Washington region.

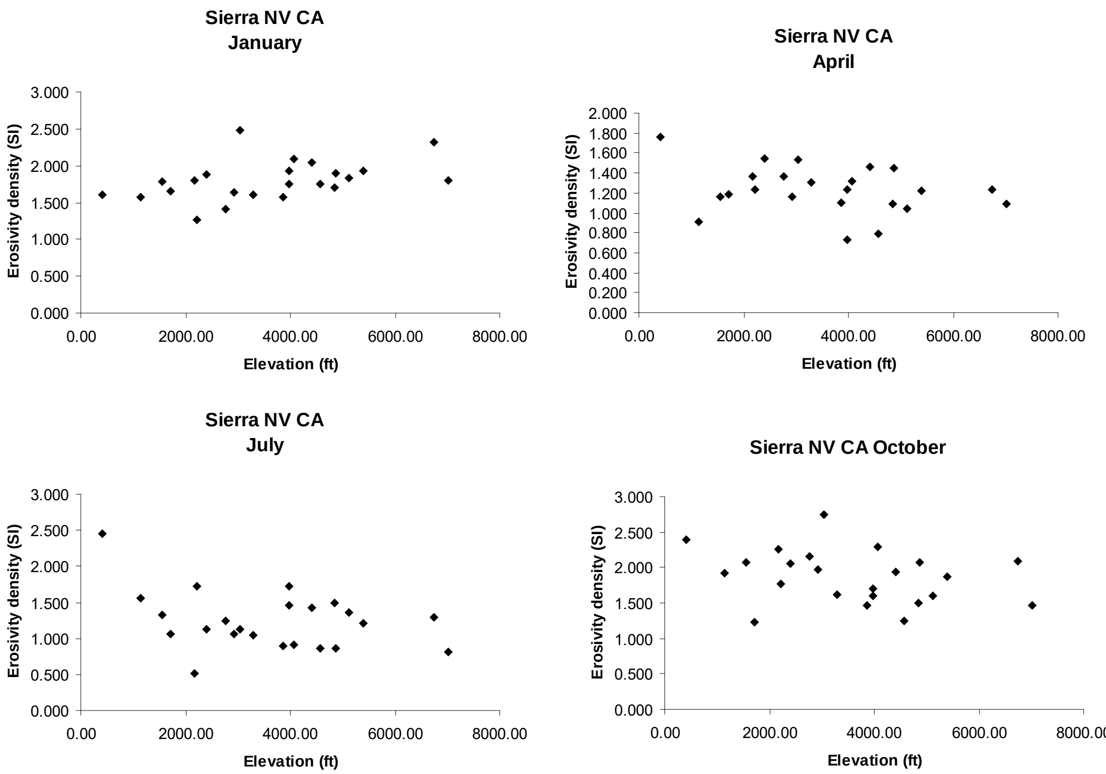

Figure 3.9. Variation of erosivity density with elevation in Sierra NV-CA region.

Another test of the hypothesis that erosivity density values are independent of elevation was to inspect a map, shown in Figure 3.11, of average 30 minute intensity for all storms in the data set (Hollinger et al., 2002). Even though these data were extensively smoothed as a part of the contouring process, the map shows no effect of mountainous terrain in the Western US on maximum 30-minute intensity. Equation 3.18 shows that erosivity density is approximately proportional to maximum 30-minute rainfall intensity. Therefore, if 30-minute intensity is independent of elevation in mountainous regions, as indicated in Figure 3.11, then erosivity density is independent of elevation. This result means that the effect of mountainous terrain on erosivity can be fully captured in how terrain affects monthly precipitation. While these tests are not especially robust, the erosivity density approach is a major improvement over previously available erosivity values in AH703 (Renard et al., 1997) for the Western US.

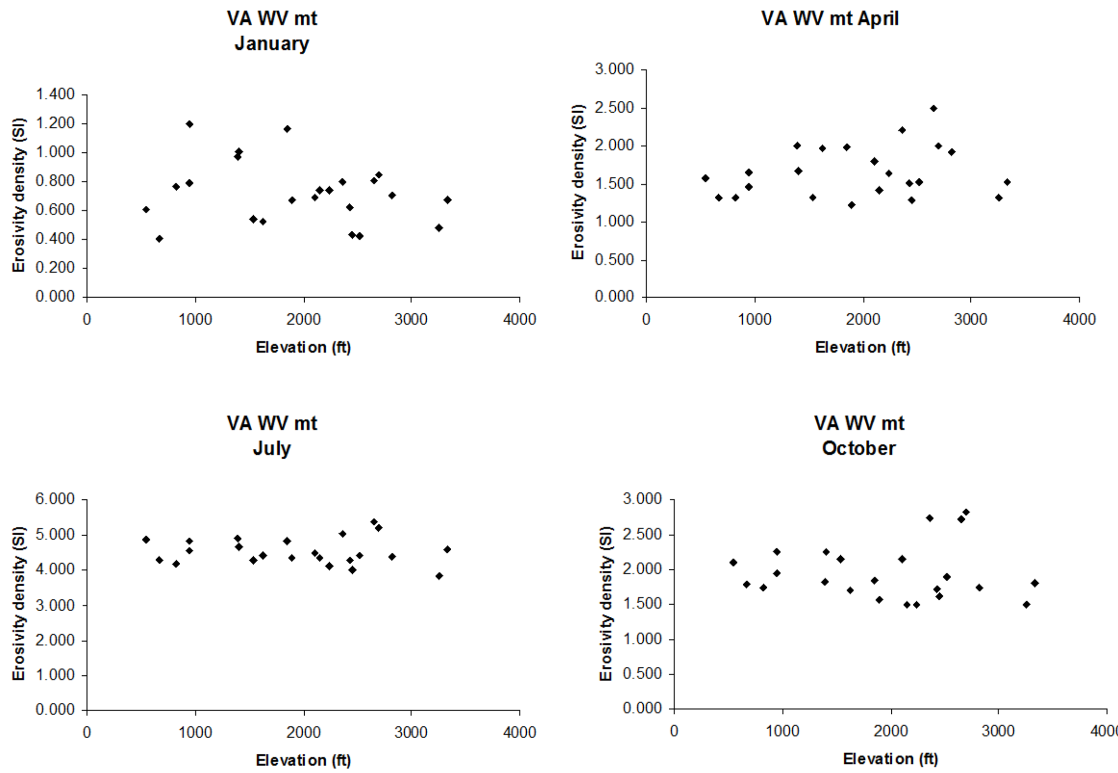

Figure 3.10. Variation of erosivity density with elevation in the West Virginia and Virginia mountainous region.

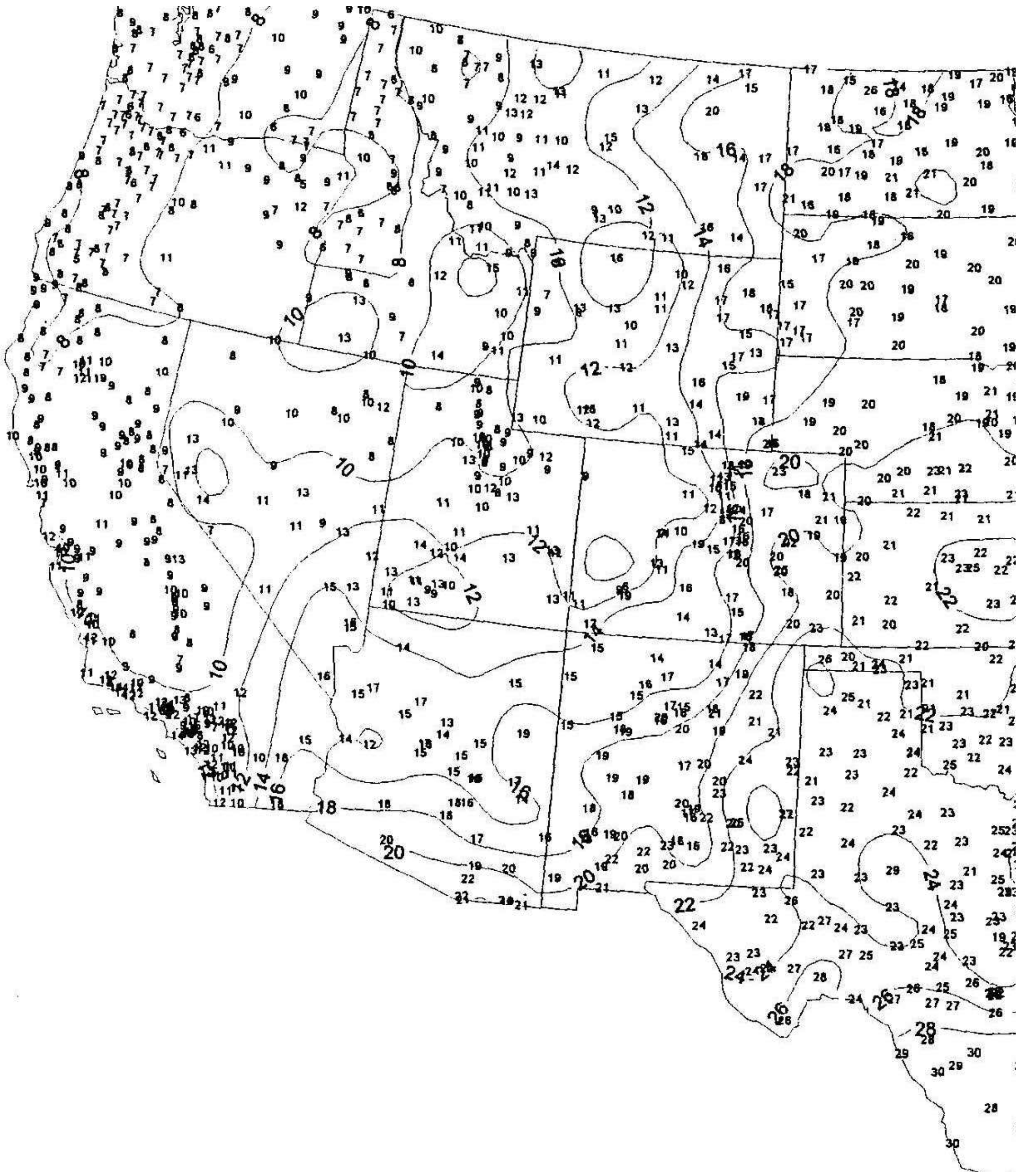

Figure 3.11. Average maximum 30 minute intensity computed for all storms. Source: Illinois State Water Survey (Hollinger et al., 2002).

3.2.1.4.2. Advantages of erosivity density approach

The erosivity density approach has major advantages. It produces consistent, smoothly varying erosivity density values across the US as desired for conservation and erosion control planning. The erosivity density approach uses data from daily precipitation gage stations, which are far more numerous than the 15-minute precipitation stations, to fill in erosivity values between the 15-minute precipitation gage locations where erosivity was computed from measured precipitation data. The erosivity maps for the Eastern US in AH282 (Wischmeier and Smith, 1965) and AH537 (Wischmeier and Smith, 1978) were based on approximately 2000 data points (see AH282). However, storm erosivity was computed from detailed intensity precipitation data comparable to the 15-mintue precipitation data at only 181 locations. An equation involving 2 year-6 hour precipitation amount and other variables was fitted to average annual erosivity values computed from the measured detailed precipitation data at the 181 locations (AH282, AH537). This equation was then used to estimate average annual erosivity values at the approximately 2000 locations used to draw the AH282 and AH537 erosivity maps for the Eastern US. The erosivity density approach using monthly precipitation measured by daily precipitation gages to compute erosivity at any particular location serves this function in RUSLE2.

The USLE and RUSLE1 use EI distribution zones in the US to describe the spatial variations in the temporal distribution of erosivity during the year. The temporal distribution of erosivity is assumed to be constant within a zone. Differences in temporal erosivity distributions between zones resulted in major differences in erosion estimates across certain zone boundaries. For example, Little Rock, Arkansas is very close to a EI zone boundary. The USLE and RUSLE1 compute a 25 percent change in erosion across the EI zone boundary at this location for a conventionally tilled corn cropping system. The impact of this step change is that a client should not be expected to change management practices unless estimated erosion changes by at least 25 percent. RUSLE2's estimated erosion values vary smoothly across the US because RUSLE2 does not use such zones. See RUSLE2 User's Reference Guide for a discussion on how aggregating input weather data by counties affects estimated erosion across county boundaries.

Precipitation data measured by daily precipitation gages are much more stable and reliable and have much less missing data than precipitation data measured with the 15-mintue precipitation gages. That is, the quality of the 15-minute precipitation data is less than the quality of the daily precipitation data. The erosivity density approach computes a ratio in contrast to the standard approach that computes an absolute sum. The data requirements for computing a ratio of monthly erosivity to monthly precipitation amount are less demanding than for computing an absolute erosivity sum. An absolute sum is greatly affected by missing data, unless the missing data are so small that the missing values have little effect on the sum. In contrast, missing data have no effect on the ratio if the missing data are not biased. Although the missing 15-minute precipitation data were surely biased, problems caused by missing data and errors in reconstructing missing data are much less in the ratio erosivity density approach than in the absolute standard approach.

The erosivity density approach also reconciles differences in precipitation amounts measured by the daily and 15-minute precipitation gages. The Illinois State Water Survey provided precipitation data for 14 locations in West Texas and Eastern New Mexico where daily and 15-minutes precipitation gages were located sufficiently close so that annual precipitation measured by the two gages types could be compared. Overall, the annual precipitation measured by the 15-minute gages was 85 percent of that measured by the daily gages. The annual precipitation measured by the 15-minute gages was less than that measured by the daily gages for all 14 locations. The ratio of the precipitation amounts for the two gage types ranged from 0.76 to 0.94. This disparity between gage types affects erosivity density values much less than it does absolute erosivity values. The erosivity density approach computes monthly erosivity values, determined from 15-minute precipitation gage data that are consistent with the monthly precipitation values, determined from daily precipitation gage data, used in RUSLE2.

A shorter record length and a record with more missing data can be used to compute erosivity density values than can be used to directly compute erosivity values with the standard method. Record length, including both number of years and number of storms, is especially critical in the Western US where spatial density of 15-minute precipitation gages is low, spatial and temporal variability is great, and records are often short with missing data. Twenty years was the minimum data record length considered to be acceptable for computing erosivity values for the Eastern US. That record length was actually too short using the standard procedure, but it was a compromise to include as many stations as possible. A data record length of 15 years was judged to be satisfactory for computing erosivity density values in the Eastern US. This conclusion was based on analysis of precipitation data collected by the USDA-Agricultural Research Service in Northern Mississippi in a research environment where data quality was very carefully maintained (McGregor et al. 1995). As Table 3.1 shows, a record length of 10 years was acceptable for these data using the erosivity density approach. Most important, the analysis showed that a shorter length of record could be used in the erosivity density approach than in the standard approach.

Table 3.1. Percent error in estimating monthly R from measured preciptiation data. Ratio refers to erosivity density approach. Abs refers to standard approach that computes absolute values.

record length (yrs)	jan		feb		mar		apr		may		jun	
	ratio	abs	ratio	abs	ratio	abs	ratio	abs	ratio	abs	ratio	abs
11	-21	-32	1	25	-5	3	-9	11	1	32	-10	-6
12	-21	-32	1	16	-4	-4	-5	6	-4	24	-8	-12
13	-12	-25	1	14	-8	-3	-5	2	-8	15	-8	-8
14	-9	-22	1	9	-1	0	-8	-3	-3	10	-7	-4
15	-2	-18	0	2	0	1	-6	0	0	4	-12	-2
16	-2	-11	3	3	2	0	-8	-3	-2	6	2	8
17	-7	-7	3	5	-3	-2	0	-1	-2	0	0	2
18	0	0	0	0	0	0	0	0	0	0	0	0

record length yrs	jul		aug		sep		oct		nov		dec		ann		aver	
	ratio	abs	ratio	abs	ratio	abs	ratio	abs	ratio	abs	ratio	abs	ratio	abs	ratio	abs
11	-4	17	10	19	7	-10	11	17	11	31	16	18	3	13	1	11
12	-5	8	4	27	4	-14	9	12	10	25	16	14	2	7	0	6
13	-6	10	4	18	0	-13	1	13	9	26	11	12	-1	6	-2	5
14	-8	9	1	13	-1	-16	5	9	6	22	10	5	0	3	-1	3
15	3	8	-3	5	-5	-9	6	16	5	19	7	5	1	3	-1	3
16	0	5	2	5	-3	13	3	11	3	11	3	4	2	5	1	4
17	0	0	0	-1	-3	6	2	4	1	5	0	-1	0	1	-1	1
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The length of record in years and number of storms in the record are more important in the Western US than in the Eastern US. Figure 3.12 shows the effect of record length for a precipitation gage located in Beaver County, Utah. The example in Figure 3.12 is not very robust, but it represents typical conditions for the 15-minute precipitation data in the Western US where the data record was short, the data was highly variable and contained relatively few storms, and number of the 15-minute gage locations was sparse. The erosivity density approach much more effectively uses the limited data in the Western US than does the standard procedure.

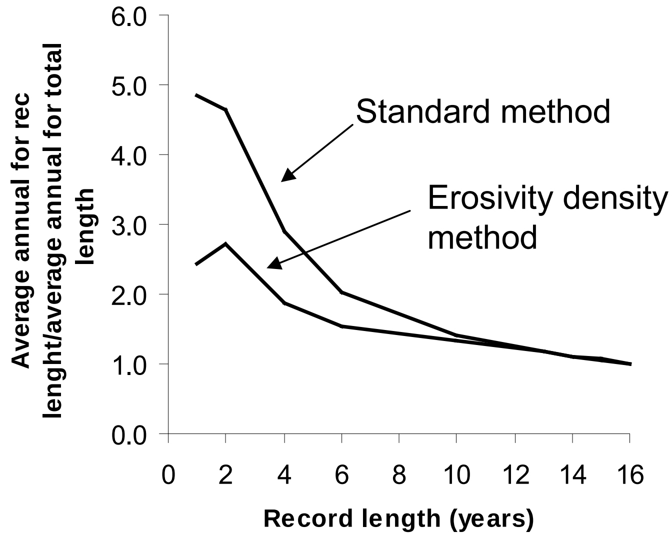

Figure 3.12. Effect of record length on variation of average annual values for erosivity and erosivity density for Beaver County, Utah.

Data for a gage location were not automatically discarded because of a short record length in the Western US in order to include as many stations as possible. The overall curve of monthly erosivity density by month computed by averaging erosivity density values in a local region was examined (e.g., see Figures 3.6 and 3.7), and the data for the location were left in the analysis if the trend at the location matched the local regional trend. When the trends in a dataset at a location did not match the overall trend, the record length at the location was almost always short.

3.2.1.4.3. Comments on erosivity density approach

Precipitation amount is a very poor indicator of erosivity (Wischmeier, 1958; Foster et al., 1982). Measures of both rainfall intensity and amount are required in erosivity measures and indices. Monthly erosivity values computed using the erosivity density method have the immediate appearance of being solely a function of monthly precipitation amount. The erosivity density value for each month depends strongly on intensity as shown by equation 3.18. The erosivity density method also seems to conflict with the empirical result that storm erosivity is a nonlinear function of storm amount (Richardson et al., 1983). The empirical erosivity density values account for this nonlinearity. Nonlinear mathematical relationships can be linearized by dividing the solution space into sufficiently small intervals so that linear equations can be assumed within each interval. The erosivity density approach is a linearized procedure that captures the effect of both intensity and nonlinearity between storm erosivity and storm amount.

Care must be taken in developing and applying the erosivity approach in other situations, especially when it is used where only very limited precipitation data are available. The erosivity density method can be quite useful in these situations, but sufficient data must be available and analysis must be conducted to determine the variation of erosivity density values over the region where the method is being applied. Assuming constant erosivity density values over too large of a region can produce very erroneous results.

3.2.1.4.4. Alternative procedures for estimating erosivity involving precipitation amount

Lack of adequate precipitation data to derive RUSLE2 erosivity values is a major limitation in applying RUSLE2 in many countries. Erosivity values are estimated from storm, monthly, and annual precipitation amounts. Rainfall intensity is a critical element in erosivity indices and any estimation procedure must account for how intensity varies over space and time in relation to precipitation amount. The effect of intensity on erosivity varies by location and by month as Figure 3.5 and equation 3.18 indicate.

A procedure to estimate storm or daily erosivity from storm or daily precipitation, respectively, uses the equation (Richardson et al., 1983):

$$r_s = a_p P_s^b \qquad [3.19]$$

where: r_s = storm or daily erosivity, P_s = storm or daily precipitation amount, and a and b are coefficients that vary by location and month. Values for a_p and b are determined by empirically fitting equation 3.19 to observed data. The procedure requires sufficient data and analysis to determine values for a_p and b over space and by month or season. The Illinois State Water Survey (ISWS) attempted to apply this procedure to US data but concluded they had insufficient data to properly compute a and b values (Hollinger et al., 2002). Another problem was that they used a logarithmic transformation and linear regression in fitting equation 3.19 to the data rather than a nonlinear fitting procedure. The logarithmic transformation-linear regression procedure returns the mean of the logarithms of the observed values rather than the mean of the absolute observed values. Erosivity values that would be used in RUSLE2 produced by the ISWS procedure had a systematic error by being too low by about 10 percent. Use of equation 3.19 can work if the proper precautions are followed and sufficient data are available to determine values for a_p and b in equation 3.19 over space and time by month or season.

Another procedure is to compute storm erosivity using a design storm that has a particular intensity distribution (Cooley, 1980; Brown and Foster, 1987). The requirement for this procedure is that design storm intensity distributions vary over space and time. A few design storms are available that vary intensity distributions over space in the US, but no design storms seem to be available that vary intensity distributions by month or season.

A modified Fournier index is widely used to estimate erosivity where precipitation data are very limited. A value for the modified Fournier index is computed from (Renard and Freimund, 1994):

$$F = \frac{\sum_{j=1}^{12} P_{m(j)}^2}{\sum_{j=1}^{12} P_{m(j)}} \qquad [3.20]$$

where: F = the modified Fournier index, P_m = average monthly precipitation, and j = index for each month. The usual procedure is to fit a linear equation involving average annual erosivity as a function of the modified Fournier index (Fournier, 1960). Values of the modified Fournier index were computed at the US locations listed in Table 3.2. Average annual erosivity values at these locations are plotted as a function of the modified Fournier index in Figure 3.13.

Table 3.2. Locations where modified Fournier index computed
Minneapolis, MN
Des Monies, IA
Columbia, MO
Oklahoma City. OK
Bryan, TX
Oxford, MS
Mobile, AL
Atlanta, GA
Norfolk, VA
Boston, MA
Scotfsbluff, NE
Houston, TX
Gulfport, MS
Miami, FL
Montgomery, AL
Denver, CO
Bismark, SD
Tombstone, AZ
Lincoln, NE
Lafayette, IN
San Francisco, CA
Bakesfield, CA
Jackson, MI
Pittsburg, PA

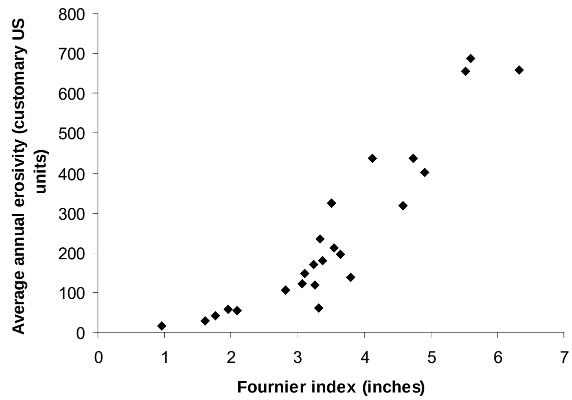

Figure 3.13. Relation of average erosivity to modified Fournier index for several US locations.

These results show that the relation between average annual erosivity and the modified Fournier index is nonlinear rather than linear. Renard and Freimund (1994) also found that the relationship of average annual erosivity to the modified Fournier index was nonlinear where erosivity varied with the index raised to the 1.85 power for US data that are comparable to data represented in Figure 3.13. That equation is given by:

$$R = a_F F^{1.85} \qquad [3.21]$$

where: R = average annual erosivity. When this equation form is fitted to the data represented by Table 3.2, the exponent is 2.24. The difference in these exponent values is caused by differences in datasets and fitting procedures.

Another concern with the modified Fournier index is whether the square of monthly precipitation in equation 3.20 is the appropriate value for the exponent. A modified Fournier index with a generalized value for the exponent would be computed as:

$$F_r = \frac{\sum_{j=1}^{12} P_{m(j)}^{z}}{\sum_{j=1}^{12} P_{m(j)}} \qquad [3.22]$$

$$R = a_r F_r \qquad [3.23]$$

where: F_r = the modified Fournier index where a value for the exponent z is determined by fitting equations 3.22 and 3.23 to observed data. In this formulation, the relationship between average annual erosivity and the generalized modified Fournier index is linear as shown in equation 3.23. The value for the exponent b most likely varies with the dataset. A value of 3.02 was obtained when equations 3.22 and 3.23 were fitted to the data represented in Table 3.2. Figure 3.14 shows a comparison between the values computed by equations 3.20 and 3.21 and equations 3.22 and 3.23. The values computed by equation 3.21 are slightly better than the values computed with equations 3.22 and 3.23. Using equations 3.20 and 3.21 or equations 3.22 and 3.23 is an improvement over fitting a linear equation to the standard modified Fournier index with the square exponent.

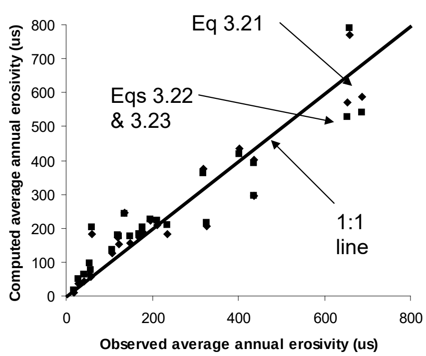

Figure 3.14 Comparison of alternate ways of using a modified Fournier index to estimate average annual erosivity.

The best approach for fitting either equations 3.20 or 3.21 or equations 3.22 and 3.23 is to divide the data into subsets by geographic region where the relationship between precipitation amount and intensity is constant over the region. A separate equation is fitted to the sub-dataset for each region. If the regions are too large, the variation in the relationship of intensity to precipitation amount over geographic space will be too large. Otherwise, the error in estimated erosivity will be very large. For example, the range in average annual erosivity in Figure 3.13 is from about 50 to 325 (US units) for a modified Fournier index value of about 3.5 inches. Obviously this great difference in erosivity for a particular value of the modified Fournier index results in very large errors in estimated erosion.

The implicit assumption in the modified Fournier procedure is that the monthly precipitation distribution coincides with the monthly intensity distribution. That is, the monthly precipitation distribution must coincide with the monthly erosivity density distribution. These distributions coincide well at Minneapolis, Minnesota but not at Oxford, Mississippi. The effect of the coincidence of the distributions on the monthly erosivity distribution is illustrated in Figure 3.15. The monthly erosivity distribution computed from the Fournier index, assuming a square power as in equation 3.20, compares reasonably well with the observed distribution at Minneapolis but compares very poorly at Oxford. Therefore, if the Fournier index is used to estimate monthly erosivity for the USLE, RUSLE1, or RUSLE2, the monthly erosivity density distribution must correspond closely to the monthly precipitation distribution.

Another procedure to estimate erosivity from monthly or annual precipitation amounts is to empirically fit equations involving these variables to observed data (Renard and Freimund, 1994). These procedures work satisfactorily only if the spatial and temporal variations in the relationship between precipitation amount and intensity are taken into account. For example, average annual erosivity ranged from 88 (US units) to 470 (US units) for an average annual precipitation of 39 inches in the data analyzed by Renard and Freimund (1994). This variation in average annual erosivity for a particular average annual precipitation is much too great to be useful in erosion prediction used for

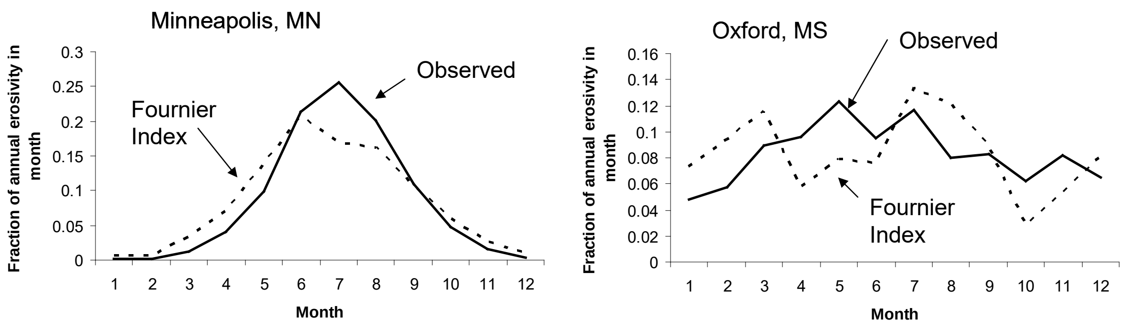

Figure 3.15. Comparison of monthly erosivity distributions computed with the modified Fournier index with observed monthly erosivity distributions.

conservation and erosion control planning. The data should be divided into subsets according to the relation of intensity to precipitation amount.

Any method used to estimate erosivity from precipitation amount MUST take into account how the relationship between precipitation and intensity varies over space and time.

3.2.2. Precipitation

RUSLE2 uses average monthly precipitation values as input values for precipitation. RUSLE2 uses the disaggregation procedure described in **Section 3.1** to disaggregate average monthly precipitation values into daily values. A consistent and sufficient record length should be used to determine average monthly precipitation values from measured data. A 22-year record length was used to develop erosivity values for the USLE (Wischmeier and Smith, 1958, 1965, 1978) because climate was thought to vary in a 22-year cycle. The modern accepted record length seems to be 30 years for hydrologic modeling. The National Weather Service has assembled 30-year data records for the locations where daily precipitation was measured. These data have been reviewed to correct erroneous and missing data. In addition, the USDA-NRCS, National Weather Service, and other agencies used the PRISM (Daly et al., 1997) computer program that extrapolates the measured data at each weather station to compute monthly precipitation values across the US on a 4 km grid. This mathematical procedure adjusts measured values for the effect of elevation, proximity to a coastline, and other variables that spatially affect precipitation. RUSLE2 users should contact their USDA-NRCS state office for precipitation data to use in RUSLE2.

The data available from the NRCS, referred to as the PRISM data, were analyzed to ensure that the probability distribution of the data is uniform for all locations. For example, extreme summer precipitation events can be highly localized. The PRISM data should be reviewed to ensure that the return periods for the precipitation input data are uniform among locations where RUSLE2 is being applied so that a land user is not unfairly affected by the happenstance of extreme precipitation occurring at their location and not at other locations (See RUSLE2 User's Reference Guide). In general, events having a return period greater than 50 years should be excluded when using RUSLE2 for conservation and erosion control planning.

3.2.3. Temperature

RUSLE2 uses average monthly values for input temperature values. RUSLE2 uses the disaggregation procedure described in **Section 3.1** to compute average daily temperature values from average monthly input values. The time period used to obtain monthly precipitation values should be the same as that used to obtain average monthly temperature values so that precipitation and temperature input values will be consistent. The most recent 30 years is an acceptable period over which to obtain average monthly temperature values. However, the data should be reviewed to ensure that the data record does not contain unusually extreme events that would have extraordinary effect on RUSLE2's computations. Extreme events in the observed temperature data do not seem be as severe as in the precipitation record.

The best source of temperature values for use in RUSLE2 is from the USDA-NRCS. Their data have been produced with the PRISM program that takes into account how elevation and other variables affect temperature. Like precipitation, the USDA-NRCS PRISM temperature values are available on a 4 km grid across the US.

3.2.4. 10 year-24 hour precipitation

RUSLE2 uses the precipitation amount for a 24-hour event that has a 10-year return period as a representative storm to compute the effect of ponding on rainfall erosivity, runoff's sediment transport capacity, and the location along an overland flow path length that contouring fails (e.g., see **Section 3.4.3**). The fundamental structure of RUSLE2 computes daily erosion for unit plot conditions (see **Section 2.1**), which in turn is multiplied by non-dimensional ratios to account for effects of topography, cover-management, and support practices. A single storm is used to compute values for these non-dimensional ratios that involve ponding and runoff. The RUSLE2 intent is to capture main effects related to runoff as they vary with location, soil, and cover-management. RUSLE2 starts with accepted USLE values and uses runoff computations to adjust the ratio values up or down as runoff departs from a base condition. An advantage of this approach is ratio values vary less temporally than erosivity, which allows a single precipitation event to be used to compute runoff. Most of the temporal variation is captured by the temporal varying erosivity. Other temporal differences are captured by computing daily runoff for the representative storm as cover-management variables change temporally. The 10 year-24 hour precipitation was chosen to make the runoff computations because most of the rill-interrill erosion at a site is caused by moderate to large rainfall events (Wischmeier and Smith, 1958, 1978).

The 10-year EI storm was used for the same purpose in RUSLE1 [Foster et al., 1997; AH703 (Renard et al., 1997)]. The procedure in RUSLE1 computed a precipitation amount for the 10 year-EI storm using an empirical equation. This equations was derived by fitting storm erosivity values as a function of storm precipitation amount (Richardson et al., 1983). The RUSLE1 procedure worked satisfactory for the eastern US but not for the Western US, especially in the Northwest Wheat and Range Region (NWRR) that includes the eastern portions of Washington and Oregon and northern portion of Idaho. Winter precipitation causes most of the erosion in the NWRR. This precipitation occurs at a very low intensity, which has low unit energy whereas most of the erosion in the Eastern US is caused by summer precipitation at high unit energy. Directly using the 10 year-24 hour precipitation values more accurately computes runoff for RUSLE2 purposes than computing runoff from a precipitation value computed from an erosivity-precipitation equation empirically derived from eastern US data as was done in RUSLE1.

An erosivity value is needed for the 10 year-24 hour precipitation amount. This erosivity value should reflect the 10 year-24 hour precipitation amount and unit energy at the location. The equation used in RUSLE2 to compute the erosivity for the 10 year-24 hour precipitation amount is:

$$EI_{10y24h} = 2\alpha_m P_{10y24h} \qquad [3.24]$$

where: EI_{10y24h} = the storm erosivity associated with the 10 year-24 hour precipitation amount, α_m = the maximum monthly erosivity density at the location, and P_{10y24h} = the 10 year-24 hour precipitation amount. The 2 coefficient in equation 3.24 was obtained by calibrating equation 3.24 to observed values for the 10-year EI from modern precipitation data in the Eastern US (Hollinger et al., 2002).

Equation 3.24 is consistent with the procedure used to compute monthly erosivity using monthly precipitation amount and monthly erosivity density (see **Section 3.2.1.4.1**). The implicit assumption is that the 10 year-24 hour precipitation event occurs in the month having the maximum erosivity density. A procedure that uses the erosivity density from the month with the maximum precipitation was evaluated. That procedure gave inconsistent results because of spatial variability in the month with the maximum precipitation. The month having the maximum precipitation varies greatly within a relatively small region, which in turn results in relatively large variations in the monthly erosivity density values used in equation 3.24.

The main role of using the 10 year-24 hour precipitation event in RUSLE2 and the 10 year EI in RUSLE1 was to compute the variation in the effectiveness of support practices, especially contouring and strip cropping, across the US. The 10-year EI map published in AH703 (Renard et al., 1997) shows numerous narrow ridges and valleys for the 10-year EI contours. Those narrow ridges and valleys were judged to represent unexplained variability in the measured data used to compute 10-year EI values rather than trends in precipitation important in support practice effectiveness. The smooth trends in the widely accepted maps of the 10 year-24 hour precipitation for the Eastern

US were judged to much more accurately represent precipitation trends important in support practice effectiveness.

3.2.5. Req

In the Northwest Wheat and Range Region (NWRR), erosion per unit erosivity is much greater during the winter months than during the summer months and much greater than for the Eastern US. A unique set of conditions in the NWRR related to highly saturated thawing soil produces a highly erodible soil condition (McCool et al. 1995). The approach used in RUSLE2 computes erosion using standard soil erodibility values (see **Section 4.1**) and adjusted erosivity, i.e., Req for the effective (equivalent) average annual erosivity. Also, a special monthly erosivity distribution is used to distribute the annual Req erosivity over each month.

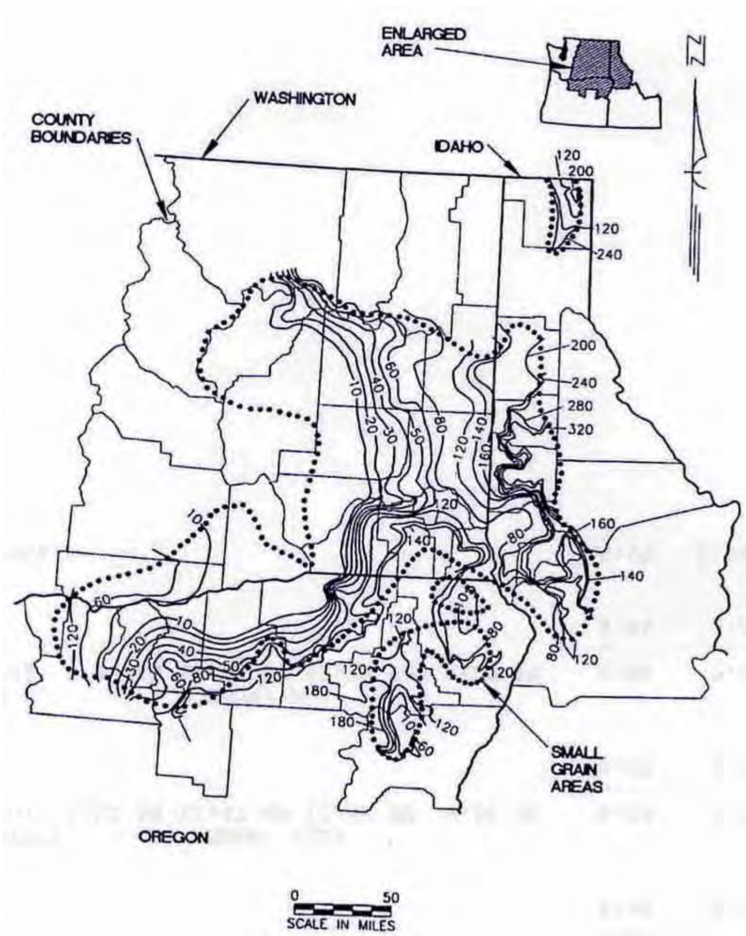

Figure 3.16. Area in Oregon, Washington, and Oregon where RUSLE2 Req procedure works best. Ignore contour lines.

The principal source of data for determining Req has been from research erosion plots operated by the USDA-ARS at Pullman, WA and Pendleton, OR. The procedure is to measure erosion on plots having the unit plot cover-management condition (see **Section 2.1** and **Footnote 3**) and to adjust measured erosion values for the effect of length and steepness to account for differences between the actual plots and unit plots. The adjusted average annual erosion value is divided by the standard soil erodibility value to produce an Req value. The distribution of measured erosion on unit-plot conditions by month is used to obtain an Req erosivity distribution.

The RUSLE2 Req procedure works well for the region shown in Figure 3.16, which is mainly northeastern Oregon, eastern Washington and northern Idaho. The Req effect occurs in other parts of the Western US, but the Req relationships for these regions have not been well determined. RUSLE2 compute Req as a function of average annual precipitation based on conditions across eastern Washington. Whether that relationship applies in other regions where the precipitation and temperature differs from that in eastern Washington is a concern. Certainly the monthly distribution for Req differs in other regions where the monthly distribution of precipitation differs from that in eastern Washington. The Req distribution for eastern Washington should not be used at other locations without making adjustments for differences in monthly precipitation and temperature distributions.

Another consideration is that winter temperatures are so low at some locations that soil freezing significantly decreases erosion, which is represented by a decreased soil erodibility value during that period. Also, snow covers the soil at high elevations to prevent winter erosion. Another factor is erosion by snowmelt in late winter and early spring, but RUSLE2 is not designed to estimate erosion by snowmelt. Erosion research at Morris, Minnesota showed that only about seven percent of the erosion occurred by snowmelt (Knisel, 1980). Thawing and recently thawed soil can be highly erodible in late winter and early spring in all locations, including the eastern US. Even though soil erodibility can be greatly increased for a short time, less than three weeks, not much erosion occur if little erosivity occurs during this period, which is the case in Minnesota. A similar effect occurs in the Mid-South region. This effect is partially captured in the temporal soil erodibility equation for the mid-south US and similar regions (see **Section 4.5**).

The Req effect is described in detail in the **RUSLE2 User's Reference Guide**. Additional information can be obtained by contacting D.K. McCool, USDA-ARS, Pullman, WA, and by reviewing his scientific publications.

3.3. Runoff

RUSLE2 uses the 10 year-24 hour index (representative) storm to compute runoff depth, which is subsequently used as an index to compute deposition, erosion control effectiveness of support practices, and effect of water depth (ponding) on erosion (see **Sections 2.3.3, 7 and 3.4.5**). This procedure captures runoff's main effects but not every detail. For example, RUSLE2 uses this approach to estimate how contouring effectiveness differs between the Northern and Southern US.

Both runoff amount and rate are important for computing erosion. RUSLE2's equations for runoff hydraulics (see **Section 3.4**) are based on runoff rate. RUSLE2 computes a daily sediment load to erosivity ratio, which RUSLE2 multiplies by daily erosivity to estimate daily erosion, deposition, and sediment load (see **Section 2.3.9**). The RUSLE2 assumption is that excess rainfall rate (depth/time) equals runoff depth divided by one hour. Rainfall depth is the major determinant of excess rainfall rate. The 10 year-24 hour precipitation amount is used each day to compute daily runoff depth as cover-management conditions temporally vary. The resulting runoff values are indices of how runoff varies by location as a function of soil and cover-management.

3.3.1. Computation of runoff

RUSLE2 uses the NRCS curve number method to compute runoff depth as a function of precipitation amount and curve number (Haan et al., 1994). Curve number values vary with cover-management, hydrologic soil group, and antecedent soil moisture. A moderate antecedent soil moisture condition is used in RUSLE2.

3.3.1.1. NRCS curve number method

The NRCS curve number equation computes runoff depth as:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad [3.25]$$

where: Q = runoff depth, P = precipitation depth, and S = a variable computed with:

$$S = 1000 / N - 10 \qquad [3.26]$$

where: N = curve number and inches are the units for P, Q, and S.

A requirement for equation 3.25 is that precipitation depth P is greater than 0.2S. Equation 3.25 was modified so that RUSLE2 computes decreasing runoff rate with distance along the overland flow path where a segment has a much higher infiltration rate than do upslope segments. The modified equation computes the additional precipitation amount that would be needed to just produce runoff for the precipitation depth P as:

$$P_a = P - 0.2\left[\left(\frac{1000}{N}\right) - 10\right] \qquad [3.27]$$

where: P_a = the additional precipitation (inches) needed to produce runoff.

Excess rainfall rate σ (inches/hour) in equation 2.18 is set equal to Q (inches) in equation 3.25 or to P_a (inches) in equation 3.27 if P < 0.2S (see **Section 2.3.5**). The negative excess rainfall rate causes RUSLE2 to compute a decreasing discharge rate along the overland flow path.

3.3.1.2. Curve number as function of cover-management variables

RUSLE2 uses equations that are functions of cover-management variables to compute curve number N values. Curve number values vary daily as cover-management variables including ground cover, soil surface roughness, soil biomass, and soil consolidation, change daily (see **Section 6**).

Equations were derived for RUSLE2 that compute curve number values as a function of cover-management variables and hydrologic soil group. First, curve number values was assigned to each hydrologic soil group for a wide range of cover-management conditions based on standard NRCS procedures for non-Req conditions and measured runoff from USDA-ARS research plots at Pullman, Washington for Req conditions. These curve number values are comparable to those used in RUSLE1. The equations used to compute RUSLE2 curve numbers were empirically derived using equation forms chosen to represent the trend of curve number values as a function of key cover-management variables. Coefficient values for these equations were obtained by fitting the equations to the assigned curve number values.

3.3.1.2.1. Standard conditions – no Req, no non-erodibile cover, no irrigation, no adjustment made for subsurface drainage

Curve number N represents the effect of cover-management on runoff and the inherent potential of the soil for producing runoff. Hydrologic soil group is the variable used in RUSLE2 to represent the inherent runoff potential of the soil. Cover-management affects runoff in several ways. For example, improved soil management, which is represented in RUSLE2 by increased soil biomass, decreases runoff. Mechanical soil disturbance like tillage reduces runoff on soils having no biomass in comparison to the soils not disturbed for several years. Soil biomass and soil consolidation interact to affect runoff. Soil consolidation increases runoff when soil biomass is very low, typical of construction sites not recently mechanically disturbed. Conversely, soil consolidation decreases runoff when soil biomass is very high, typical of undisturbed, high production pasture. Increased soil surface roughness and ground cover decrease runoff depending on soil biomass levels. Curve numbers and how they are affected by cover-management are also a function of soil properties as represented by hydrologic soil group. For example, cover-management decreases runoff more on soils having a high infiltration potential, hydrologic soil group A, than on soils having a low infiltration potential, hydrologic soil group D.

RUSLE2 curve number equations were calibrated to curve number values commonly used by NRCS (Haan et al., 1994). Indices in these empirical equations reflect how cover-management is known to affect infiltration and runoff.

The main RUSLE2 equation used to compute curve number values is:

$$N = [N_{u100} - s_u(1 - s_c)] f_B \exp(b_D B_s) \qquad [3.28]$$

where: N = curve number used in equations 3.25, 3.26, and 3.27 to compute runoff, N_{u100} = a curve number value that represents the effect of ground cover and soil roughness on curve number on a soil recently mechanically disturbed (i.e., $s_c = 1$), s_u = the change in curve number per unit change in the soil consolidation subfactor (see **Section 6.6**), f_B = a fraction, which along with the term $\exp(b_D B_s)$, describes the main effect of soil biomass and its interaction with soil consolidation on curve number, b_D = a coefficient that is a function of the soil consolidation subfactor s_c, and B_s = soil biomass. Soil biomass B_s is the sum of buried residue averaged over the residue accounting depth (see **Section 6.2**) and the live and dead root biomass averaged over the upper 10 inch soil depth (see **Section 6.2.1**). Units for B_s are biomass on a dry basis/(land area·unit soil depth). The accounting depth for buried residue decreases from 3 inches to 1 inch as the soil consolidation subfactor s_c decreases from 1 to 0.45 (see Section **6.6**).

The curve number N_{u100} is determined by starting with a base curve number for a recently mechanically tilled soil. This curve number is decreased for increases in both ground cover and adjusted soil surface roughness r_a greater than 0.24 inch, which is the base roughness value assumed for unit plot conditions (see **Section 2.1** and **Footnote 3**). Curve number values increase when adjusted roughness is less than 0.24 inch, which represents a condition where runoff is greater than from the unit plot condition. The adjusted soil surface roughness is used in equation 6.26 to compute a soil surface roughness subfactor value (see **Section 6.3**).

The equations used to compute N_{u100}, which do not consider any effect of soil biomass or soil consolidation on curve number, are given by:

Table 3.3. Curve number and coefficient values used in standard RUSLE2 curve number equations (not Req)

Hydrologic soil group	N_{s100}	N_{uB}	N_{lB}	N_{u45}	N_{lb45}	b_B (in ac/lbs$_m$)	a_{cu}	a_{cl}	a_{ru}	a_{rl}	a_{45}
A	87.0	87.0	53.0	94.0	70.0	0.00219	-12.0	-6.5	-12.0	6.5	-0.12
B	92.0	92.0	68.0	98.0	82.0	0.00174	-12.0	-6.5	-12.0	6.5	-0.12
C	93.0	93.0	75.0	98.6	84.6	0.00200	-7.0	-5.0	-7.0	5.0	-0.07
D	94.0	94.0	79.0	98.7	88.4	0.00153	-5.0	-3.0	-5.0	4.0	-0.05

$$N_{u100} = N_{s100} + a_{cu}(f_g/100) + a_{ru}\{1 - \exp[-1.7(r_a - 0.24)]\} \quad [3.29]$$

$$N_{u100} = N_{s100} + a_{cl}(f_g/100) + a_{rl}[(0.24 - r_a)/0.24] \quad r_a \le 0.24 \text{ in} \quad [3.30]$$

where: N_{u100} = a curve number for a recently mechanically disturbed soil (i.e., s_c = 1) with no soil biomass, N_{s100} = a starting curve number value for unit plot conditions that are recently mechanically disturbed, adjusted soil surface roughness r_a = 0.24 in, and no soil biomass, a_{cu} = a coefficient for the effect of ground cover when surface roughness is greater than 0.24 inches, a_{cl} = a coefficient for the effect of ground cover when surface roughness is less than 0.24 inches, f_g = ground cover (percent), a_{ru} = a coefficient for the effect of soil surface roughness when roughness is greater than 0.24 inches, a_{rl} = a coefficient for the effect of adjusted soil surface roughness when the adjusted soil surface roughness is less than 0.24 inches, and r_a = adjusted soil surface roughness index (inches) (see **Section 6.3**). Values for starting curve number N_{s100} and the coefficients a_{cl}, a_{clu}, a_{rl}, and a_{ru}, which vary with hydrologic soil group, are given in Table 3.3.

The main effect of soil consolidation is represented in the terms involving s_u, which is the rate of change in the curve number per unit change in the soil consolidation subfactor s_c. The equation for s_u is given by:

$$s_u = (N_{u100} - N_{u45})/0.55 \quad [3.31]$$

where: N_{u45} = the curve number for a fully consolidated soil with no ground (surface) cover or soil biomass and soil surface roughness = 0.24 inches, 0.55 = the range in the soil consolidation subfactor s_c from 1 for a recently mechanically disturbed soil to 0.45 for a fully consolidated soil. Values for the curve number N_{u45}, given in Table 3.3, are for a fully consolidated soil with no ground cover and soil biomass.

The fraction f_B represents the main effect of soil biomass on curve number. A value for f_B is computed with:

$$f_B = [(N_{uB} - N_{lB})\exp(-b_B B_s) + N_{lB}] / N_{uB} \qquad [3.32]$$

where: N_{uB} = the curve number value when no biomass is present in the soil and the soil has been recently mechanically disturbed, N_{lB} = the curve number for a very high soil biomass (i.e., when $\exp(-b_B B_s)$ is near zero) and the soil has been recently mechanically disturbed, and b_B = a decay coefficient that represents how the curve number decreases exponentially as a function of soil biomass. Curve number values for N_{uB} and N_{lB} are given in Table 3.3. The effect of soil biomass on curve number is assumed to be greater in soils having a low runoff potential, i.e., hydrologic soil group A, than soils having high runoff potential, i.e., hydrologic soil group D. Values for the decay coefficient b_B, are also given in Table 3.3.

The term $\exp(b_D B_s)$ in equation 3.28 represents how the interaction between soil biomass and soil consolidation affect curve number values. A value for the coefficient b_D is computed from:

$$b_D = \ln(N_l / N_u)/1750 \qquad [3.33]$$

where: N_l and N_u = lower and upper curve numbers, respectively, that represent the difference in curve numbers for a soil with no soil biomass and one with a high soil biomass of 1750 $lbs_m/(\text{acre}\cdot\text{in})$ value. The value for N_u is computed from:

$$N_u = N_{u100} - s_u(1 - s_c) \qquad [3.34]$$

A value for the lower curve number that is comparable to the upper curve number N_u is computed as:

$$N_l = N_{u100} - s_l(1 - s_c) \qquad [3.35]$$

where: s_l is computed from:

$$s_l = (N_{l100} - N_{l45})/0.55 \qquad [3.36]$$

The curve number N_{l45} is adjusted for ground cover is computed as:

$$N_{l45} = N_{lb45}(1 + a_{45} f_g / 100) \qquad [3.37]$$

where: a_{45} = a coefficient having values given in Table 3.3. Soil surface roughness is assumed not to affect curve number for a fully consolidated soil with high soil biomass.

Values for the index curve number N_{lb45} used to calculate curve numbers for fully consolidated soil at high soil biomass with no ground cover are also given in Table 3.3.

Table 3.4. RUSLE2 (R2) curve numbers computed for Columbia, Missouri compared with curve numbers used in RUSLE1 (R1) for A, B, C, and D hydrologic soil groups

Cover-management condition		A		B		C		D	
R1 class	Description	R1	R2	R1	R2	R1	R2	R1	R2
C1	Established meadow, very dense cover with high soil biomass	30	45	58	64	71	71	78	78
C2	Mixed grass-legume hay, moderate cover, and moderate to high soil biomass	46	61	66	75	78	80	83	85
C3	Heavy cover (75-95%) or very rough with moderate biomass	54	46	69	62	79	70	84	77
C4	Moderate cover (40-65%) or rough with moderate soil biomass	55	54	72	66	81	75	85	81
C5	Light cover (10-30%), moderate roughness, and low to moderate soil biomass	56	61	75	70	83	76	87	82
C6	Essentilly no cover (5%), minimal roughness and low to moderate soil biomass	64	67	78	78	85	82	89	84
C7	Very little soil biomass and smooth	77	84	86	90	91	91	94	93
	Cut soil, no soil biomass without mulch		94		98		99		99
	Cut soil, no soil biomass with 4000 lbs/ac straw mulch		94 - 63		98 - 77		98 - 82		99 - 87
	Fill soil, graded smooth with no mulch		87 - 88		92 - 93		93 - 94		94 - 95
	Fill soil, graded smooth with 4000 lbs/ac straw mulch		81 - 85		86 - 90		89 - 92		91 - 94

Notes:

The curve numbers from RUSLE2 were taken at planting time because theRUSLE1 curve numbers are most applicable for that period.

The range in RUSLE2 curve numbers for the construction site conditions are for the 12 month period

A-hydrologic soil group (lowest runott potential) to D-hydrologic soil group (highest runoff potential)

RUSLE2 computed curve number values as shown in Table 3.4 along with the curve number values used in RUSLE1. RUSLE2 adequately captures the trends in curve numbers for land use that varies from construction sites to dense grass. RUSLE2 computes higher curve number values for the A-hydrologic soil group soils (low runoff potential) than those used in RUSLE1. However, the higher curve numbers are considered more appropriate for RUSLE2 applications. RUSLE2 also computes curve number values that are consistent with those reported for a wide range of land uses (Haan et al. 1994).

3.3.1.2.2. Req conditions, no irrigation, no adjustment made for subsurface drainage

The procedure described in Section 3.3.1.2.1 is also used to compute runoff for Req conditions, but different runoff curve number and coefficient values are used. A major effect in the Req zone is that infiltration is very low during the winter unless residue cover, soil biomass, and soil surface roughness is very high. The soil becomes highly saturated resulting in a very high portion of the precipitation becoming runoff during the winter period. High residue cover, soil biomass, and surface roughness seem to keep open macro-pores for significantly increased infiltration. The values given in Table 3.5 are used during by RUSLE2 for the winter Req period to compute runoff while the values given in Table 3.3 can be used for the summer months.

Table 3.5. Curve number and coefficient values used in RUSLE2 curve number equations for Req conditions

Hydrologic soil group	N_{s100}	N_{uB}	N_{lB}	N_{u45}	N_{lb45}	b_B (in ac/lbs$_m$)	a_{cu}	a_{cl}	a_{ru}	a_{rl}	a_{45}
A	92.0	92.0	22.0	94.0	70.0	0.00024	-12.0	-6.5	-25	2.0	-0.12
B	97.0	97.0	58.0	98.0	82.0	0.00020	-12.0	-6.5	-25	2.0	-0.12
C	98.0	98.0	73.0	98.6	84.6	0.00025	-7.0	-5.0	-15	2.0	-0.07
D	98.0	98.0	78.0	98.7	88.4	0.00020	-5.0	-3.0	-10	2.0	-0.05

3.3.1.2.3. Effect of non-erodible cover on runoff

RUSLE2 assumes no detachment for the portion of the soil surface covered by non-erodible cover. However, RUSLE2 assumes that non-erodible cover can be permeable. A RUSLE2 input value used to describe non-erodible cover is the fraction of the non-erodible cover that is fully permeable so that infiltration is controlled by the underlying soil. All of the precipitation is assumed to become runoff for the remaining portion of the non-erodible cover. The overall effective curve number for this condition is computed by RUSLE2 as:

$$N = N_b(1 - f_\mu) + f_\mu[N_b f_\rho + 100(1 - f_\rho)] \qquad [3.38]$$

where: N = overall, effective curve number used in equation 3.25 or 3.27 to compute runoff, f_μ = fraction of the soil surface covered by non-erodible cover, f_ρ = fraction of the non-erodible cover that is permeable, N_b = the curve number for the portion of the soil not covered by the non-erodible cover, and 100 = the curve number for the non-permeable portion of the non-erodible cover. A 100 curve number means that all of the precipitation becomes runoff.

3.3.1.2.4. Effect of subsurface drainage on runoff

The RUSLE2 procedure for adjusting for subsurface drainage is to select a hydrologic soil group that describes runoff potential for the undrained condition and one that describes runoff potential for the drained condition (see **Sections 7.4** and the RUSLE2 User's Reference Guide). RUSLE2 uses the hydrologic soil group assigned to the drained and undrained soil conditions to compute runoff using the values in either Table 3.3 or 3.4.

A RUSLE2 input for subsurface drainage is the portion of the area represented by the overland flow path that is subsurface drained. RUSLE2 uses this input to compute an effective curve number value for the entire overland flow path. The effective curve number is computed with:

$$N = N_d f_d + N_{ud}(1 - f_d) \quad [3.39]$$

where: N = effective curve number used in equation 3.25 or 3.27 to compute runoff, N_d = curve number for the drained condition, N_{ud} = the curve number for the undrained condition, and f_d = the fraction of the area represented by an overland flow path that is drained.

3.3.1.2.5. Effect of irrigation on runoff

RUSLE2 computes the effect of irrigation on erosion when rainfall occurs. RUSLE2 does not compute erosion caused by the applied water. RUSLE2 computes increased erosion on irrigated areas because increased soil moisture increases soil erodibility and residue decomposition and decreases soil surface roughness. However, RUSLE2 does not compute increased runoff caused by irrigation.

3.4. Hydraulics

RUSLE2 uses shear stress as the hydraulic variable to compute sediment transport capacity and locations where contouring fails. Runoff's total shear stress is applied to surface soil particles, ground cover, soil surface roughness elements, and stems of live and standing dead vegetation. Total shear stress is computed with (Chow, 1959):

$$\tau_t = \gamma y s \quad [3.40]$$

where: τ_t = total shear stress (force/unit area), γ = weight density of water (force/volume), y = flow depth (length), and s = overland flow path steepness (sine of slope angle). Flow depth is computed with the Manning equation as (Chow, 1959):

$$y = \left(\frac{q n_t}{1.49 s^{1/2}} \right)^{3/5} \quad [3.41]$$

where: q = discharge rate, n_t = total Manning's n (index for hydraulic roughness-resistance), and the 1.49 is used when US customary units [q - ft3/(sec·ft width), y – ft] are used.

3.4.1. Concept of grain and form roughness

The total shear stress can be divided into two parts (Graf, 1971), the part referred to as grain roughness shear stress that acts on surface soil particles and the part referred to as form roughness shear stress that acts on ground cover, stems of live and dead standing vegetation, and soil surface roughness elements. Grain roughness shear stress is assumed to be responsible for sediment transport while form roughness shear stress is assumed to be responsible for contouring failure (Foster, 1982; Foster et al., 1982b).

3.4.2. Grain roughness shear stress for computing sediment transport capacity

RUSLE2 uses Equation 2.17 to compute sediment transport capacity. That equation is based on the assumption that sediment transport capacity can be computed as:

$$T_c = K_T \tau_g^{3/2} \quad [3.42]$$

where: T_c = sediment transport capacity (mass/width·time), and τ_g = grain roughness shear stress(force/aea). By using the concept that flow depth can be divided into parts associated with grain and form roughness, equations 3.41 and 3.42 can be combined with a Manning's n for grain roughness to give equation 2.17 where the coefficient ζ is given by (Foster et al., 1982b):

$$\zeta = 0.0008 n_t^{-1.5} \quad [3.43]$$

where: the coefficient ζ has absorbed γ and the Manning's n_g value for grain roughness, which is assumed to be 0.01.[32] Total Manning's n_t is computed by RUSLE2 as a function of soil surface roughness, ground cover, live vegetation biomass, and standing residue biomass (see **Section 3.4.6**).

3.4.3. Form roughness shear stress for computing contouring failure

3.4.3.1. Main equations

RUSLE2 computes form roughness shear stress as a function of discharge rate as:

$$\tau_f = a_f q^{0.85714} s / n_t^{1.2857} \quad [3.44]$$

[32] This equation is based on US customary units of ft^3/sec per ft width for discharge rate (q), ft for flow depth (y), and lbs_f/ft^2 for shear stress (τ).

where: τ_f = grain roughness shear stress and a_f =a coefficient that includes γ in equation 3.40, 1.49 in equation 3.41, and other empirical coefficients. RUSLE2 assumes contouring failure where form roughness shear stress computed with equation 3.44 exceeds a critical shear stress. A value for critical shear stress for contouring failure was determined by calibrating equation 3.44 to critical slope length values given in AH537 (Wischmeier and Smith, 1978). The resulting critical shear stress for contour failure is 3619 value when US customary units are used in the equations. The value for a_f in equation 3.44 is absorbed in the critical shear stress value along with conversion factors that would be used to convert excess rainfall rate to ft/sec rather than using inches/hour. Form roughness shear stress for contouring failure is computed with:

$$\tau_f = q_i^{0.85714} s / n_t^{1.2857} \qquad [3.45]$$

where: the discharge rate q_i is computed using excess rainfall rate (σ_i) in inches/hour rather than ft/sec as $q_i = x\sigma_i$ and x = distance (feet) along overland flow path.[33]

The critical slope length values beyond which contouring failure is assumed were based on judgment of soil conservation technical specialists and were not determined by research. These values were developed at a 1956 workshop (Wischmeier and Smith, 1978) and therefore represented observations from research studies and field observations from the early 1930's to the mid 1950's The base condition used in calibrating the critical shear stress for contouring failure represents those conditions rather than modern conditions. The assumed base condition is conventionally tilled, low yield (50 bu/ac), continuous corn at Columbia, Missouri. The operations assumed for this cropping system include a moldboard plow in the spring for primary tillage, two secondary tillage operations to prepare the seedbed, row planter to seed the crop, row cultivator to control weeds, and harvest. Table 3.6 shows a comparison between the values computed with RUSLE2 and those given in AH537 (Wischmeier and Smith, 1978). The values compare well except at very flat steepness where RUSLE2 computed values are much longer than those given in AH537. The values computed by RUSLE2 are considered acceptable.

Table 3.6. Critical slope lengths

	Critical slope length (ft)	
Slope steepness (%)	AH537	RUSLE2
1.5	400	>1000
4.0	300	384
7.0	200	200
10.5	120	125
14.5	80	86
18.5	60	66
23.0	50	51

RUSLE2 sets the contouring subfactor value to 1 for those portions of the overland flow path where form roughness shear stress exceeds the critical shear stress for contouring failure (see **Section 7.1**). No adjustments are made in the cover-management subfactors used to compute detachment in equation 2.10. RUSLE2 also computes the location

[33] Mixed units are given in these equations for consistency with the equations used in the RUSLE2 computer program to facilitate a comparison of computer code with this documentation.

where runoff shear stress acting on form roughness equals the critical shear stress for contour failure. That equation is:

$$q_c = 13900 n_t^{1.5} / s^{1.1667} \qquad [3.46]$$

where: q_c = the discharge rate (where excess rainfall rate in equation 2.18 is in units of in/hr) at which contouring fails. The location of this discharge rate can be determined from equation 2.18.

RUSLE2 computes where contouring fails along overland flow paths as a function of location (i.e., as reflected by the $P_{10y\text{-}24h}$ precipitation amount), runoff, soil infiltration potential, overland flow path steepness, and cover-management conditions. For example, RUSLE2 computed critical slope length values are a function of crop yield. Increased crop yield increases critical slope length. The increased biomass improves soil properties that increase infiltration and reduce runoff, increases soil surface roughness, and increases ground cover provided by crop residue. The critical slope length increases from 103 to 151 ft for an increase in corn yield from 50 to 115 bu/ac in a grain corn-silage corn-alfalfa hay-alfalfa hay-alfalfa hay crop rotation for an overland flow path on a silt loam soil at 20 percent steepness at LaCrosse, Wisconsin. Tillage systems that leave increased surface soil roughness and surface crop residue cover also increase RUSLE2 computed critical slope length as illustrated in Table 3.7.

Table 3.7. RUSLE2 computed critical slope lengths for three tillage systems for continuous 50 bu/ac corn.

	RUSLE2 computed critical slope length (ft)		
Slope steepness (%)	Conv till	Mulch till	No-till
1.5	>1000	>1000	>1000
4.0	384	594	837
7.0	200	310	436
10.5	125	194	273
14.5	86	134	188
18.5	66	101	143
23.0	51	79	112

RUSLE2 does not compute contouring failure as a function of how soil properties affect the soil's critical shear stress for contouring failure. This capability is desirable, but sufficient empirical data are not available to develop the required critical shear stress values as a function of soil properties. Contouring failure in RUSLE2 is assumed not to be a function of ridge height or grade along the ridges-furrows. Clearly contouring failure is a function of ridge height because ridge height affects storage of runoff water and the likelihood of ridge breakover especially in low areas. However, accurately describing flow hydraulics and water storage on a specific field site is very difficult because of imperceptible variations of row grade and ridge heights along the ridges-furrows. Although RUSLE2 has these shortcomings, it was developed to guide conservation planning, and in that context, RUSLE2 is a major improvement over the USLE and RUSLE1.

3.4.3.2. Form roughness shear stress below segment having a high hydraulic roughness

RUSLE2 assumes a gradual rather than a step decrease in total hydraulic roughness where total hydraulic roughness decreases from one overland flow path segment to the next segment. Consequently, the form roughness shear stress increases gradually rather than abruptly between segments. An example is runoff exiting from dense vegetation onto a relatively smooth, bare soil surface. The dense vegetation spreads the runoff so that the flow has a laterally uniform depth as it exits the vegetation. Form roughness shear stress is assumed to be less when flow depth is laterally uniform than when concentrated in rills. A distance is required below the dense vegetation for the runoff to become concentrated in rills with increased form roughness shear stress.

This concept is implemented in RUSLE2 by assuming that the effective total hydraulic roughness decreases exponentially below a segment having a high total hydraulic roughness. The equation for the total Manning's n_t in the transitional region is:

$$n_{et} = n_{tl} + (n_{tu} - n_{tl})\exp[-0.065(x - x_u)] \qquad [3.47]$$

where: n_{et} = Manning's n_t in the transitional zone, n_{tl} = the total Manning's n_t in the lower segment, Manning's n_{tu} = the Manning n_t in the upper segment, x = distance along the overland flow path (ft), and x_u = the distance to the upper end of the lower segment (ft). Figure 3.17 shows the RUSLE2 computed decrease in Manning's n_t below a hay strip in a typical strip cropping system used in LaCrosse, Wisconsin and evaluated in research studies (Hays and Attoe, 1957; Hays et al., 1949). Also, erosion from other strip cropping systems was also studied at other locations (Borst et al., 1945; Hill et al.,. 1944; Hood and Bartholomew, 1956; Smith et al. 1945). RUSLE2 gives similar results for these systems discussed in AH703 (Renard et al., 1997; Foster et al., 1997).

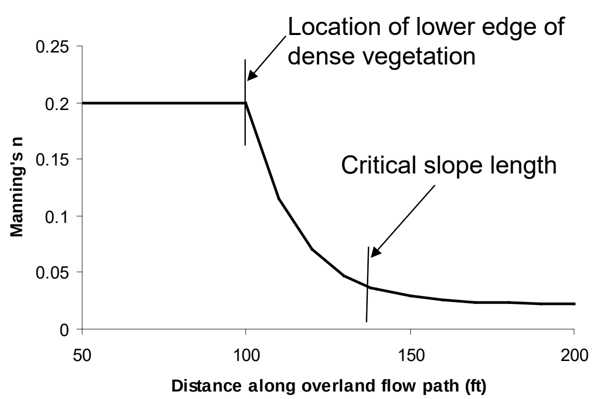

Figure 3.17. Decrease in Manning's n_t along overland flow path below a segment having a high Manning's n_t.

The reduction in form roughness shear stress by runoff spreading reduces the portion of an overland flow path where form roughness shear stress can exceed critical shear stress for contouring failure. The result is that contour strip cropping increases computed critical slope length (i.e., the location where contouring fails). The assumption that contour strip cropping increases critical slope length has long been accepted and used in conservation planning [e.g., see AH282 (Wischmeier and Smith, 1965) and AH537 (Wischmeier and Smith, 1978)]. In AH537, the critical slope length (referred as slope length limits in AH537) is doubled for contour strip cropping without regard to cover-management condition such as type, quality, and density of vegetation on each overland flow path segment. However, the AH537 contouring factor values for contour strip cropping do vary with cover-management condition.

Data from research in Wisconsin (Hays and Attoe,1957; Hays et al., 1949) were the best available in the 1950's to guide development of critical slope length concepts and values by erosion scientist and soil conservation specialists for use in the USLE (AH282, AH537). The RUSLE1 developers judged that critical slope length with strip cropping was 1.5 times the critical slope length without strip cropping [AH703 (Renard et al., 1997)]. A major RUSLE2 improvement is that RUSLE2 computes how location (i.e., $P_{10y\text{-}24h}$ precipitation), runoff, overland flow path steepness, cover-management conditions, number of strips, and relative placement of strips along an overland flow path affect critical slope length. The RUSLE2 procedure is far more comprehensive that previous USLE and RUSLE1 procedures.

The 0.065 ft^{-1} value in equation 3.47 was selected to give critical slope length values considered appropriate for the LaCrosse, Wisconsin experimental contour strip cropping (Hays et al., 1949). For example, RUSLE2 computes a critical slope length of 103 ft on a 20 percent steep overland flow path for the crop rotation used in the contour stripping studies without the crops being arranged in strips. That is, cover-management along the overland flow path is uniform at any particular time although cover-management temporally changes during the crop rotation. The crop rotation is a year of grain corn and a year of silage corn conventionally tilled with a moldboard plow, and three years of alfalfa hay fall seeded immediately after the silage corn is harvested. The assumed corn yield is 50 bu/acre, a typical yield in the 1930's and 1940's. The RUSLE2 computed critical slope length is 191 ft when the crops are arranged in a four strip contour strip cropping system.

The RUSLE2 computed critical slope length is a function of number of strips along the overland flow path. For example, the RUSLE2 computed critical slope length is 153 ft for the LaCrosse, Wisconsin crop rotation placed in two rather than four strips. Strip width is 50 ft for the four-strip system on a 200 ft overland flow path length while it is 100 ft for the two-strip system. As Figure 3.17 shows, about 38 ft is required for total effective hydraulic roughness computed with equation 3.47 to decrease to where form roughness shear stress exceeds the critical shear stress for contouring failure. Strip width should be no wider than 38 ft, according to Figure 3.17 for these conditions, to prevent form roughness shear stress from exceeding the critical shear stress for contour failure. The 100 ft strip width in the two-strip contouring strip cropping system greatly exceeds 38 ft. In contrast, the 50 ft wide strip in the four-strip contour strip cropping system is sufficiently narrow that the form roughness shear stress only exceeds critical shear stress for contouring failure over the last 9 ft of the overland flow path length.

3.4.3.3. Determining location where contouring failure occurs

RUSLE2 uses rules to determine where the form roughness shear stress exceeds critical shear stress for contouring failure within an overland flow path segment.

3.4.3.3.1. Discharge rate increases within segment

If discharge rate increases within a segment and form roughness shear stress at both the upper and lower ends of the segment is less than the critical shear stress for contouring failure, contouring failure does not occur within the segment. If form roughness shear stress exceeds the critical shear stress for contouring failure at both the upper and lower ends of the segment, contouring failure occurs over the entire segment. However, if form roughness shear stress at the upper end of the segment is less than the critical shear stress for contouring failure, and form roughness shear stress at the lower end of the segment exceeds critical shear stress for contouring failure, contouring failure occurs over the lower portion of the segment beginning at the location where form roughness shear stress equals the critical shear stress for contouring failure. This location is computed with equations 2.18 and 3.46.

3.4.3.3.2. Discharge rate decreases within segment

If discharge rate decreases within a segment and form roughness shear stress at both the upper and lower ends of the segment is less than the critical shear stress for contouring failure, contouring failure does not occur within the segment.

If form roughness shear stress at the upper end of the segment is less than the critical shear stress for contouring failure but exceeds critical shear stress for contouring failure at the lower end of the segment, contouring failure occurs over the lower portion of the segment beginning at the location where form roughness shear stress equals the critical shear stress for contouring failure. This location is computed with equations 2.18 and 3.46.

If form roughness shear exceeds the critical shear stress for contouring failure at both the upper and lower ends of the segment, the possibility exists for contouring failure on upper and lower portions of the segment without contouring failure in the middle portion of the segment. RUSLE2 determines where the form roughness shear stress is a maximum within the segment and if that shear stress is greater than the critical shear stress for contouring failure, then contouring failure occurs over the entire segment. If the minimum form roughness shear stress within the segment is less than the critical shear stress for contouring failure, then form roughness shear stress equals the critical shear stress at two locations within the segment. These locations are determined with equations 2.18 and 3.46.

If form roughness shear stress is less than the critical shear stress for contouring failure at both the upper and lower ends of the segment, the possibility exists that form roughness shear stress increases to a value greater than the critical shear stress for contouring failure within the segment and then decreases to below this critical shear stress above the lower end of the segment. Contouring failure occurs on a middle portion within the segment. This check can be made by computing the maximum form roughness shear stress within the segment, and if it exceeds the critical shear stress for contouring failure, this condition exists. The portion where contouring fails lies in the middle of the segment between the two locations where form roughness shear stress equals the critical shear stress for contouring failure, which are determined from equations 2.18 and 3.46.

3.4.3.4. Runoff rate used to compute contouring failure

To compute contouring failure, RUSLE2 computes a daily runoff rate that varies with both cover-management and the probability of an intense storm occurring when contouring is susceptible to failure. The daily precipitation amount used to compute contouring failure is assumed to vary linearly with the temporal daily erosivity distribution (see **Sections 3.1 and 3.2.1**) with the maximum daily precipitation occurring on same day that the maximum daily erosivity occurs. This daily precipitation amount is computed as:

$$P_{cf} = (f_{Rd} / f_{Rmx})P_{10y24h} \qquad [3.48]$$

where: P_{cf} = the daily precipitation amount used to compute contouring failure, f_{Rdj} = the fraction of the annual erosivity that occurs on the *jth* day, and f_{Rmx} = the fraction of the annual erosivity that occurs on the day when maximum daily erosivity occurs.[34] **The time varying precipitation computed with equation 3.48 is only used to compute contouring failure. It is not used anywhere else in RUSLE2.**

3.4.4. Backwater

Backwater occurs at locations on an overland path where total hydraulic roughness makes a step increase, such as at the upper edge of a dense vegetation strip. This backwater is especially important because most of the deposition caused by dense vegetation strips occurs in the backwater (Dabney et al., 1995; Flanagan et al., 1989; Foster et al., 1980a; Hayes et al., 1984; McGregor et al., 1999). Ignoring backwater length would cause RUSLE2 to greatly underestimate deposition when computing deposition caused by narrow, dense vegetation strips.

The Manning equation is used in RUSLE2 to compute flow depth at the upper edge of segments where Manning's n_t makes a step increases. An effective backwater length is computed from this flow depth assuming that the backwater is level. The combined equation for computing backwater length is:

$$\Delta x_b = 3.44[n_t q_u /(1.49 s_{lh}^{0.5})]^{0.6} / s_{uh} \qquad [3.49]$$

where: Δx_b = the backwater length (ft), q_u = discharge rate (ft^2/s) at the upper edge of the segment having the high total Manning's n_t, s_{lh} = the steepness of the segment having the high Manning's n (**sine** of the slope angle), and s_{uh} = steepness of the immediately upslope segment (the **tangent** of the slope angle). The 3.44 value in equation 3.49 was determined by calibration. The coefficient was adjusted until RUSLE2 computed the observed sediment yield from plots having a dense 1.5 ft wide dense stiff grass hedge below conventionally tilled cotton on a 5 percent steepness at Holly Springs, Mississippi (McGregor et al., 1999). The RUSLE2 computed backwater length was compared to

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[34] In an early version of RUSLE2, contouring failure was computed with the single precipitation P10y,24h precipitation amount. Runoff rate varies temporally only as cover-management variables varied temporally. Although RUSLE2 was calibrated to give the correct critical slope length, the timing of contouring failure was out of phase with precipitation during the year. Use of Equation 3.48 gave the correct timing for contouring failure.

measured backwater values and locations of deposited sediment above the stiff grass hedge. Although the upper edge of deposition moves upslope as deposited sediment accumulates (Dabney et al., 1995), this dynamic effect is not considered in RUSLE2. The RUSLE2 computed backwater length is an index that captures the effects of location through the 10 year-24 hour precipitation amount, runoff, hydraulic roughness, and overland flow path steepness. The maximum computed backwater length is limited to 15 ft to prevent RUSLE2 from computing excessively long backwater lengths on relatively flat overland flow paths. Also, RUSLE2 assumes a 3 ft minimum for special cases like fabric filter fence on construction sites (see **Section 7.2**). RUSLE2 adds the computed backwater length to the lower edge of the segment having the high total Manning's n_t and decreases the length of the immediate downslope segment by the same amount except for the segment at the end of the overland-flow path.

3.4.5. Ponding

Water deeper than about 3 mm reduces raindrop impact erosivity (Mutchler, 1970; Mutchler and Murphree, 1985; Mutchler and Young. 1975). The judgment of soil conservation specialists is that water depth reduces erosion on flat overland flow paths in high erosivity locations, such as the lower Mississippi Delta [AH703 (Renard et al., 1997)]. Erosivity (R) values along the Gulf Coast Region were reduced to consider this effect in the USLE (e.g., compare erosivity values between AH282 (Wischmeier and Smith, 1965) and AH537 (Wischmeier and Smith, 1978). RUSLE1 uses a ponding subfactor that reduces effective erosivity based on flow depth if ridges are not present. Water depth (ponding) was assumed to have no effect on erosivity in RUSLE1 when high ridges are present. However, in RUSLE2, the ponding effect is assumed to reduce erosivity regardless of the presence or absence of ridges.

The 10 year-24 hour precipitation amount is used to compute a runoff amount using equation 3.25. A normalized flow depth is computed using the Manning equation as:

$$y_n = (v_r / 3.03)^{0.6} (0.01 / s)^{0.3} \qquad [3.50]$$

where: y_n = the normalized flow depth, v_r = the runoff amount (inches), computed with P10y24h precipitation amount, 3.03 = a reference runoff depth (inches) selected to represent runoff and 0.01 = a reference overland flow path steepness to represent slopes typical of cotton production in the Mississippi Delta where the water depth effect is most highly important. This ponding effect has been studied by Mutchler et al. (1982), Mutchler and McGregor (1983), Mutchler and Murphree (1985), and McCool et al. (1987). This normalized flow depth is then used to compute a ponding subfactor value using:

$$p_r = \exp[-0.49(y_n - 1)] \text{ if } p_r < 0.4, p_r = 0.4 \text{ if } p_r > 1, p_r = 1 \qquad [3.51]$$

where: p_r = the ponding subfactor for the effect of water depth on raindrop impact erosivity. The minimum value for the ponding subfactor is 0.4. The 0.49 value in equation 3.51 was chosen by calibration to represent the judgment of erosion scientists and soil conservationists regarding the ponding effect [AH537 (Wischmeier and Smith, 1978), AH703 (Renard et al., 1997)]. Example values for the average annual ponding factor are given in Table 3.8 where daily ponding values have been weighted by the temporal erosivity distribution (see **Sections 3.1** and **3.2.1**).

Table 3.8. Example values for the ponding subfactor

Location, 0.5% steepness	Value	Steepness (%), at Jackson, MS	Value
New Orleans, LA	0.58	0.001	0.45
Baton Rouge, LA	0.63	0.005	0.73
Jackson, MS	0.73	0.01	0.85
Memphis, TN	0.82	0.02	0.96
Columbia, MO	0.86	0.04	1.00

3.4.6. Manning's n_t as a function of cover-management and row grade

RUSLE2 computes total Manning's n_t values as a function of soil surface roughness, ground cover, live vegetation, and standing residue using:

$$n_t = 0.11[1 - \exp(-0.6 r_n)] + [0.075(f_g/100)/\exp(0.35 r_n)] + n_v + n_s \text{ if } n_t < 0.01, n_t = 0.01 \quad [3.52]$$

$$r_n = r_a \text{ if } r_n > 5, r_n = 5 \text{ inches} \quad [3.53]$$

where: n_t = total Manning's n_t, r_n = r_a = adjusted roughness index value (inches) used to compute roughness subfactor values (see **Section 6.3**), f_g = net ground (surface) cover (percent) (see **Section 6.2**), n_v = Manning's n contributed by live vegetation (see **Section 9.2.6**), and n_s = the Manning's n contributed by standing residue (see **Section 10.4.3**). Equation 3.52 was derived from multiple data sets where overland flow velocity was measured for a wide variety of conditions. Manning's n values derived from these measurements have been compiled and used in numerous models including CREAMS, RUSLE1, and scientific articles (Foster et al., 1980b; Foster, 1982; Foster et al., 1982a; Foster et al., 1997; Gilley and Finkner, 1991; Gilley and Kottwitz, 1994; Gilley and Kottwitz, 1995).

Equation 3.52 represents form and form roughness combined rather than representing them as two separate terms. The condition on n_t in equation 3.52 is to prevent total Manning's n_t from being less than the grain roughness Manning's n_g of 0.01.

The ground (surface) cover and soil surface roughness combination term in equation 3.52 reduces the effect of ground cover on hydraulic roughness as soil surface roughness increases. Ground cover in depressions is inundated by ponded water and deposited sediment so that ground cover has reduced effect on runoff hydraulics as soil surface roughness increases.

The condition that adjusted roughness not be greater than 5 inches is primarily because no research data were available at high roughness values to derive equation 3.52. Actually the high soil surface roughness condition has little effect on computed Manning's n_t values. For example, the first term in equation 3.52 is 0.105 for r_a = 5 inches and 0.11 for r_a = 10 or more inches.

Net ground cover is (1 – the fraction of soil surface not covered by ground cover). Net ground cover takes into account surface residue overlapping rock cover and live ground cover overlapping both surface residue and rock cover.

The maximum Manning's n value for vegetation in rows perpendicular to the overland flow path (i.e., on the contour) is computed with:

$$n_{vmxc} = 0.017154 R_v + 3.82 \times 10^{-5} R_v^5 \qquad [3.54]$$

where: n_{mvxc} = the Manning's n for live vegetation in rows on the contour at maximum canopy cover and R_v = vegetation retardance at maximum canopy cover for vegetation in rows on the contour, which is a measure of how much vegetation and porous barriers like fabric fences slow runoff. Input retardance values are chosen to represent the combined hydraulic roughness of the vegetation in rows and bare soil between the rows for vegetation at its maximum growth in the RUSLE2 vegetation description.[35] Using these input retardance values listed in Table 3.9, RUSLE2 computes a retardance value based on vegetation production (yield) level (see **Section 9.3.1**). The Manning's n_{mvc} represents the effect of stems and any vegetation component, besides live ground cover, that slows runoff. Live ground cover values in the RUSLE2 vegetation description are used to represent the effect of leaves and similar plants components touching the soil surface and slowing runoff.

Table 3.9. Retardance classes used in RUSLE2

Class	Retardance index
no retardance (wide plant spacing in strip-row)	0
low retardance (corn)	1
moderate low (soybeans, cotton)	2
moderate (dense wheat)	3
moderate high (legume hay before mowing)	4
high (legume-grass hay before mowing)	5
very high (dense sod)	6
extreme (stiff grass hedge, silt fence)	7

Table 3.10. Factor values used to multiply Manning's vegetation n on contour to obtain Manning's n value for orientation parallel to overland flow path

Row width	Factor
Vegetation on ridges	0.063
Wide row	0.125
Moderate row spacing	0.250
Narrow row spacing	0.500
Very narrow row spacing	0.750
No rows (broadcast)	1.000

The hydraulic roughness for vegetation rows oriented parallel to the overland flow path (up and down hill) differs from the hydraulic roughness for the vegetation's rows on the contour. RUSLE2 computes a value for the Manning's n_{mvud} for vegetation in rows parallel to the overland flow path by multiplying the contour vegetation Manning's n_{vmxc}

[35] Assignment of retardance values considers the geometrical arrangement of the vegetation rows. For example, retardance for small grain represents the net retardance for multiple grain rows whereas the retardance for a narrow stiff grass hedge considers only a single row of the vegetation. In the case of the stiff grass hedge, the overland flow path is divided into segments to represent the bare soil separately from the vegetation in a situation where backwater created by the dense vegetation has an important effect on deposition.

by a factor based on the user entered row width. Values for this factor are given in Table 3.10. The **No rows (broadcast)** input means that the vegetation is randomly spaced in both directions so that no row orientation exists. Manning's n is the same in all directions. The **Vegetation on ridges** represents vegetation rows so widely spaced or the vegetation being on ridges so that the vegetation stems have no effect on hydraulic roughness.

Depending on row grade (steepness along the vegetation rows), vegetation Manning's n varies between the Manning's n for vegetation rows on the contour and the Manning's n for the vegetation rows oriented up and down hill. The RUSLE2 equation used to compute vegetation Manning's n for intermediate row orientations is:

$$n_{vrg} = n_{vud} + (n_{vc} - n_{vud})[1-(s_r / s_{ud})^{1/2}] \qquad [3.55]$$

where: n_{vrg} = vegetation Manning's n for the row grade s_r, n_{vc} = vegetation Manning's n for rows on the contour (perpendicular to the overland flow path), n_{vud} = vegetation Manning's n for rows parallel to overland flow path (i.e., up and down slope), s_r = row grade (tangent of slope angle), and s_{ud} = overland flow path steepness (tangent of slope angle).

RUSLE2 assumes that vegetation Manning's n varies temporally as the vegetation's effective fall height varies (see **Section 6.1**). The equation used to compute vegetation Manning's n values through time is:

$$n_v = n_{vmx}(h_f / h_{fmx})^{0.3} \qquad [3.56]$$

where: n_{vm} = the vegetation Manning's n at maximum growth in the vegetation description, h_f = the daily effective fall height for a particular vegetation description and h_{fmx} = the maximum daily effective fall height for the vegetation description (see **Section 9**).

When live vegetation is killed in RUSLE2, it becomes standing residue that continues to provide hydraulic roughness. The hydraulic roughness caused by standing residue is assumed to vary through time as:

$$n_s = n_{sk}(B_{td} / B_{tk}) \qquad [3.57]$$

where: n_s = Manning's n for standing residue on day d, n_{sk} = Manning's n for the standing residue on the day that the live vegetation is killed, B_{td} = standing residue biomass (dry matter basis) on day d, and B_{tk} = the live vegetation biomass (dry matter basis) on the day that the vegetation is killed (see **Section 9.2.5**).

3.5. List of symbols

a_{cl} = a coefficient used to compute curve number values as a function of ground (surface) cover when surface roughness is less than 0.24 inches

a_{cu} = a coefficient used to compute curve number values as a function of ground (surface) cover when surface roughness is greater than 0.24 inches

a_f = coefficient used to compute form roughness shear stress

a_F = coefficient used to compute average annual erosivity from Fournier index

a_p = coefficient in equation that computes storm or daily erosivity from storm or daily precipitation

a_r = coefficient used to average annual erosivity from RUSLE2 modified Fournier index

a_{rl} = a coefficient used to compute curve number values as a function of soil surface roughness when soil surface roughness is less than 0.24 inches

a_{ru} = a coefficient used to compute curve number values as a function of soil surface roughness when soil surface roughness is greater than 0.24 inches

a_{45} = coefficient used to compute curve number values for fully consolidated soils as a function of ground (surface) cover

b= exponent in equation that computes storm or daily erosivity from storm or daily precipitation

b_B = a decay coefficient used how the curve number values decreases exponentially as a function of soil biomass

b_D = a decay coefficient used to compute how curve number values are affected by the interaction of the soil consolidation factor and soil biomass

B_s = soil biomass per unit depth (dry mass/area·soil depth)

B_{tk} = live above ground biomass on day that vegetation is killed (mass/area)

B_{td} = live above ground biomass on day d (mass/area)

D = number of days in the month

e = unit storm energy (energy content per unit area per unit rainfall depth) [force-distance/(area·length)]

$\hat{e}$ = effective unit storm energy directly (force-length)/(area·length)

E = storm energy (force-distance/area)

EI_{10y24h} = the storm erosivity associated with the 10 year-24 hour precipitation amount (erosivity units)

EI_{30} = storm erosivity (erosivity units)

f_B = a fraction that represents the main effect of soil biomass on curve number values

f_d = fraction of area represented by an overland flow path that is subsurface drained

f_g = net ground (surface) cover (percent)

f_{Rd} = fraction of the annual erosivity that occurs on *jth* day

f_{Rmx} = fraction of the annual erosivity that occurs on day when maximum daily erosivity occurs

f_μ = portion of the soil surface covered by non-erodible cover (fraction)

f_ρ = portion of the non-erodible cover that is permeable (fraction)

F = the modified Fournier index

F_r = the RUSLE2 modified Fournier index

h_f = daily effective fall height for a particular vegetation description (length)

h_{fmx} = maximum daily effective fall height for the vegetation description (length)

i = rainfall intensity for a period during rainstorm (length/time)

I_{30} = maximum 30-minute intensity for a rain strom (length/time)

$\bar{I}_{30}$ = representative maximum 30 minute intensity for rain storms occurring in amonth (length/time)

m = number of periods in a storm used to compute storm energy

M = monthly value of climate variable being disaggregated

n = number of rainstorms in a month

n_{et} = Manning's n_t in the transitional zone below a high hydraulic resistance segment

n_g = grain roughness Manning's n

n_k = Manning's n for standing residue on day that live vegetation is killed

n_s = Manning's n contributed by standing residue

n_{sk} = Manning's n contributed by standing residue on the day that live vegetation is killed

n_t = total Manning's n

n_{tl} = total Manning's n_t in segment downslope of high hydraulic resistance segment

n_{tu} = Manning n_t in upslope high hydraulic resistance segment

n_v = Manning's n contributed by live vegetation

n_{vc} = vegetation Manning's n for rows (strips) on the contour (perpendicular to the overland flow path)

n_{vmx} = vegetation Manning's n at maximum growth in the vegetation description

n_{vmxc} = Manning's n for live vegetation in rows (strips) on the contour at maximum canopy cover

n_{vrg} = vegetation Manning's n for row grade s_r

n_{vud} = vegetation for Manning's n for rows up and down slope (parallel to overland flow path)

N = curve number in NRCS curve number method used to compute runoff

N_b = curve number for the portion of the soil not covered by the non-erodible cover

N_d = curve number for the drained condition

N_l = lower curve numbers that represents difference in curve numbers for a soil with no soil biomass and one with a high soil biomass of 1750 lbs_m/(acre·in) value

N_{lb45} = index curve number for fully consolidated soil at high soil biomass with no ground cover

N_{lB} = the curve number for a very high soil biomass and the soil has been recently mechanically disturbed

N_{l45} = N_{lB} curve number adjusted for ground cover

N_{s100} = a starting curve number value for unit plot conditions

N_u = upper curve numbers that represents difference in curve numbers for a soil with no soil biomass and one with a high soil biomass of 1750 lbs_m/(acre·in) value

N_{uB} = curve number value when no biomass is present in the soil and the soil has been recently mechanically disturbed

N_{ud} = curve number for the undrained condition

N_{u45} = the curve number for a fully consolidated soil with no ground (surface) cover or soil biomass and soil surface roughness = 0.24 inches

N_{u100} = curve number value that represents the effect of ground cover and soil roughness on curve number on a soil recently mechanically disturbed with no soil biomass

p_r = daily ponding subfactor

P = precipitation depth (length)

P_a = additional precipitation required so that zero runoff would be computed when infiltration is greater than precipitation (length)

P_{cf} = daily precipitation amount used to compute contouring failure (length)

P_{md} = average monthly precipitation from daily precipitation gage data (length)

P_m = average monthly precipitation (length)

P_s = storm or daily precipitation amount (length)

P_{10y24h} = the 10 year-24 hour precipitation amount (length)

P_{15} = storm precipitation amount determined from 15-minute precipitation gage data (length)

q = discharge rate (volume/width·time)

q_c = discharge rate (where excess rainfall rate is in units of in/hr) at which contouring fails (volume/width·time)

q_i = discharge rate $q_i = x\sigma_i$ computed using excess rainfall rate in inches/hour rather than ft/sec

q_u = discharge rate at upper edge of segment having high hydraulic resistance (volume/width·time)

Q = runoff depth computed with NRCS curve number method (length)

r_a = adjusted soil surface roughness index (length)

r_n = adjusted soil surface roughness index used to compute Manning n for soil surface roughness (length)

r_s = storm erosivity (erosivity units)

R = average annual erosivity (erosivity units)

R_m = average monthly erosivity (erosivity units)

R_v= vegetation retardance at maximum canopy cover for vegetation in rows (strips) on contour, which is a measure of how much vegetation and porous barriers like fabric fences slow runoff

s = overland flow path steepness (sine of slope angle)

s_c = soil consolidation subfactor

s_l = change in lower curve numbers per unit change in soil consolidation subfactor

s_{lh} = steepness of segment having high hydraulic resistance (**sine** of slope angle)

s_r = row grade (**tangent** of slope anagle)

s_u = change in upper curve number per unit change in the soil consolidation

s_{ud} = steepness of overland flow path (**tangent** of soil angle)

s_{uh} = steepness of segment immediately upslope of high hydraulic resistance segment (**tangent** of slope angle)

S = a variable in NRCS curve number equation used to compute runoff

t_c = time during month that disaggregated value equals monthly value

t_p = time during month of peak or minimum of climate variable being disaggregated

T_c = sediment transport capacity (mass/width·time)

x = distance along overland flow path (length)

x_u = the distance to the upper end of segment immediately downslope of high hydraulic resistance segment (length)

y = flow depth (length)

y_d = daily value of climate variable being disaggregated

v_r = runoff amount used to compute ponding subfactor (length)

y_n = normalized flow depth used to compute ponding subfactor

Y_b = daily value of climate variable being disaggregated at beginning of month

Y_e = daily value at end of month

Y_p = maximum value of climate variable being disaggregated when peak or minimum occurs within month

z = exponent in RUSLE2 modified Fournier index

α = average monthly erosivity density (erosivity units/length)

α_m = maximum monthly erosivity density

Δx_b = backwater length upslope of a segment having a high hydualic resistance (length)

ΔV = rainfall depth during a period in a rainstorm (length)

γ = weight density of water (force/volume)

σ_i = excess rainfall rate in inches/hour (length/time)

τ_f = form roughness shear stress (force/area)

τ_g = grain roughness shear stress (force/area)

τ_t = total shear stress (force/area)

ζ = coefficient that has absorbed γ and the Manning's n_g for grain roughness

Indices

i – storm

j - month

k – period during a rainstorm

4. SOIL

4.1. Erodibility

The major RUSLE2 soil variable is the soil erodibility factor. A value for the soil erodibility factor for soils that have their soil horizons in place and have not been disturbed other than for cultivation can be selected from the USDA-NRCS soil survey database. However, soil erodibility values are not available for all soils, especially highly disturbed soils where the original soil layers have been mixed. RUSLE2 includes two sets of equations referred to as the standard soil erodibility nomograph and the RUSLE2 modified soil erodibility nomograph. These nomographs can be used to estimate soil erodibility factor values for most situations (See RUSLE2 User's Reference Guide), especially where the original soil profile has been disturbed.

The RUSLE2 soil erodibility factor is a measure of soil erodibility under unit plot conditions. These conditions empirically measure soil erodibility where cover-management effects are removed so that the measured erosion represents how inherent soil properties and local climate affect soil erodibility as defined in RUSLE2. The RUSLE2 soil erodibility factor is not an inherent soil property like soil texture. It is defined in terms of the RUSLE2 erosivity variable and, therefore, should not be used in other erosion prediction technologies that use a different erosivity factor than the RUSLE2 erosivity factor. Conversely, soil erodibility factor values from other erosion models that use an erosivity factor that differs from the RUSLE2 erosivity factor can not be used in RUSLE2.

The RUSLE2 soil erodibility factor, which is the same as the USLE and RUSLE1 soil erodibility factor (Wischmeier and Smith, 1965 and 1978; Römkens et al,, 1997), is a measure of erosion per unit erosivity EI for unit plot conditions. The RUSLE2 soil erodibility factor is a function of local climate in addition to soil properties because erosion per unit erosivity is greater where runoff is increased per unit erosivity. For example, if the same soil properties were to occur in two locations, the RUSLE2 soil erodibility factor would be increased in locations where frequent, high, intense rainfall occurs that produces increased runoff per unit precipitation. Unfortunately, the soil erodibility nomograph commonly used to estimate soil erodibility factor values, including those in RUSLE2, is not a function of climate variables. However, the RUSLE2 temproal soil erodibility equation described below takes location into account.

4.1.1. Standard soil erodibility nomograph

The standard soil erodibility nomograph (Wischmeier et al., 1971) was derived from erosion data produced by applying simulated rainfall to about 55 agricultural soils, primarily in Indiana (Wischmeier. and Mannering, 1969). Although these soils represented a range of inherent soil properties, the standard nomograph best fits medium textured soils.

The equation for the standard soil erodibility nomograph is:[36]

$$K = (k_t k_o + k_s + k_p)/100 \qquad [4.1]$$

where: K = soil erodibility factor, k_t = texture subfactor, k_o = organic matter subfactor, k_s = soil structure subfactor, and k_p =soil profile permeability subfactor.

4.1.1.1. Texture subfactor

The soil texture subfactor equation is (Wischmeier et al., 1971):

$$k_{tb} = 2.1[(P_{sl} + P_{vfs})(100 - P_{cl})]^{1.14}/10000 \qquad [4.2]$$

$$k_t = k_{tb} \qquad \text{if } P_{sl} + P_{vfs} \le 68\% \qquad [4.3]$$

where: P_{sl} = percent silt, P_{vfs} = percent very fine sand based on the total soil primary particles and not just the portion of the sand content, and P_{cl} = percent clay. Although equation 4.2 was derived using regression analysis, Wischmeier et al. (1971) used judgment to graphically draw the k_t relationship for P_{sl} + P_{vfs} percentage above 68 percent. The RUSLE2 equations fitted to the Wischmeier et al. (1971) graphical curves are:

$$k_{t68} = 2.1[68(100 - P_{cl})]^{1.14}/10000 \qquad [4.4]$$

$$k_t = k_{tb} - [0.67(k_{tb} - k_{t68})^{0.82}] \qquad \text{if } P_{sl} + P_{vfs} > 68\% \qquad [4.5]$$

where: k_{t68} = base soil texture subfactor in soil erodibility nomograph when $P_{sl} + P_{vfs} > 68\%$.

4.1.1.2. Organic matter subfactor

The equation for the soil erodibility nomograph organic matter subfactor is:

$$k_o = (12 - O_m) \qquad [4.6]$$

where: O_m = percent inherent soil organic matter. Inherent organic matter is the organic matter content of the soil in unit plot conditions. The experimental plots used to develop the soil erodibility nomograph were not in unit plot condition (Wischmeier and

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[36] Units for K and associated variables are US customary units

Mannering, 1969). Above ground biomass was removed but the plots were not maintained in a tilled fallow condition for more than a few months. Soil organic matter had not reached inherent soil organic matter levels for unit plot conditions, which resulted in measured soil organic matter being higher than it would have been in unit plot conditions. However, measured erosion values were adjusted to remove land use residual effects from previous cover-management conditions (see **Section 6**), but organic matter content values were not adjusted to unit plot conditions.

The organic matter relationship in the soil erodibility nomograph ***can not be used*** to evaluate how biomass additions and organic farming practices affect rill and interrill erosion. Those effects are considered in RUSLE2's cover-management relationships (see **Section 6**). Furthermore, the experimental conditions used to derive the soil erodibility nomograph were very dissimilar to organic matter conditions associated with organic farming or application of manure, biological waste, or other biological soil amendments.

4.1.1.3. Soil structure subfactor

The soil erodibility nomograph soil structure subfactor refers to how the arrangements of soil primary particles in aggregates and the arrangement of aggregates in the soil affect erosion under unit plot conditions. Four structural classes are used in the nomograph. These classes are 1-very fine granular, 2-fine granular, 3-medium or coarse granular, and 4-blocky, platy, or massive. These classes are defined in the USDA-NRCS soil survey manual. The classes used to derive the soil erodibility nomograph were those in use in the mid-1960's when the experiments were conducted. The definitions for those classes should be used to assign RUSLE2 values for soil structure.

The equation for the soil erodibility nomograph soil structure subfactor is:

$$k_s = 3.25(S_s - 2) \qquad \text{if } (k_t k_o + k_s) \geq 7 \qquad [4.7]$$

$$k_t k_o + k_s = 7 \qquad \text{if } (k_t k_o + k_s) < 7 \qquad [4.8]$$

where: S_s = the soil structure class. The graphical soil structure relationship in the soil erodibility nomograph has a slight "knee" close the origin of the subfactor (Wischmeier et al., 1971), which is represented with equation 4.8.

4.1.1.4. Soil profile permeability subfactor

The soil permeability subfactor is a measure of the potential of the soil profile in unit-plot conditions for generating runoff. Six permeability classes that range from 1-rapid (very low runoff potential) to 6-very slow (very high runoff potential) are used to rate the soil profile for infiltrating precipitation and reducing runoff. The USDA-NRCS soil survey definitions for soil profile permeability used in the mid-1960's should be used to assign a soil permeability class in applying the soil erodibility nomograph. ***The assigned permeability class must not be based on a permeability measurement of the surface soil layer.*** The permeability rating should take into account the presence of restricting layers such as rock, claypan, or fragipan. Also, the rating should consider landscape position.

For example, the permeability rating for a sandy soil underlain by a restricting layer might be moderate for the soil at the top of a hillslope but be very slow if the soil is at the bottom of the hillslope. The input permeability rating should consider the presence of rock fragments. ***The permeability rating should not reflect current or past cover-management on runoff; it is a rating for the soil in unit plot condition*** (see **Sections 4.6 and 7.4** and RUSLE2 User's Reference Guide). The RUSLE2 temporal soil erodibility equation described in **Section 4.5** takes into account how the permeability rating varies as climate varies among locations.

The equation for the permeability subfactor is given by:

$$k_p = 2.5(P_r - 3) \qquad [4.9]$$

where: P_r = the soil profile permeability class.

4.1.2. RUSLE2 modified soil erodibility nomograph

Soil erodibility factor values computed with the standard soil erodibility nomograph do not show the expected range or trend for very high sand soils and very high clay soils typical of highly disturbed lands, such as reclaimed mined land and construction sites. This problem seemed most associated with the soil structure subfactor. Soil erodibility is expected to decrease as soil structure changes from very fine granular to blocky, platy, or massive because of the role of clay as a bonding agent and its effect on soil structure.

The unexpected trend in the soil structure subfactor most likely resulted from the empirical derivation of the standard soil erodibility nomograph from a relatively small database where the soils were predominantly medium texture (Wischmeier and Mannering, 1969; Wischmeier et al., 1971). Consequently, the data points were not uniformly distributed among the major variables that affect soil erodibility. Furthermore, all of the nomograph variables are correlated with each other, which can result in empirical equations derived from a small database not reflecting proper trends for how major variables affect soil erodibility. For example, soil structure is related to soil texture. The soil structure subfactor in the standard soil erodibility nomograph may well represent an interactive effect rather than a main effect in the particular dataset used to derive the standard soil erodibility nomograph.

After reviewing measured erosion data from high clay soils typical of construction sites (Römkens et al., 1975; Römkens et al., 1977; Roth et al., 1974), the judgment was made to modify the soil structure subfactor in the standard nomograph. The modification results in the RUSLE2 modified nomograph computing soil erodibility values that decrease as soil structure goes from fine granular to blocky, platy, and massive and decrease as soil structure goes from fine granular to coarse granular. Soil erodibility factor values computed with the RUSLE2 modified soil erodibility nomograph are smaller than those computed with the standard nomograph for high clay and high sand soils.

4.1.2.1. Soil structure subfactor

The soil structure subfactor equation used in the RUSLE2 modified soil erodibility nomograph is:

$$k_s = 3.25(2 - S_s) \qquad [4.10]$$

The difference between this equation and the comparable equation, equation 4.7, in the standard soil erodibility nomograph is the algebraic sign on the variables in the second term in equations 4.7 and 4.10. A nice feature of both the standard and the RUSLE2 modified nomographs is that they use equations referenced to a midpoint. The equations compute values about the midpoint well established by the experimental data. The midpoint for the soil structure subfactor is the fine granular structure. Both soil erodibility nomographs give the same soil erodibility factor values for the fine granular soil structure, but the two nomographs give different trends for departures from this midpoint soil structure.

4.1.2.2. Other subfactors in RUSLE2 modified soil erodibility nomograph

All other subfactors in the RUSLE2 modified soil erodibility nomograph are the same as those used in the standard nomograph.

4.1.3. Special soil erodibility cases

Special cases, described in the RUSLE2 User's Reference Guide, exist where neither RUSLE2 soil erodibility nomograph applies. Equations are available in AH703 (Renard et al., 1997) and elsewhere (El-Swaify and Dangler, 1976; Mutchler et al., 1976; Young and Mutchler. 1977; Roth et al., 1974) to estimate soil erodibility for some of these special conditions. However, these equations were not included in RUSLE2 even though some of them were included in RUSLE1 [AH703 (Renard et al., 1997)]. The equations were judged to give poor results or to use variables that were not properly defined or could not be easily measured for input in typical RUSLE2 applications. Soil erodibility values can be user determined outside of RUSLE2 and entered in RUSLE2.

4.2. Very fine sand

Soil texture is the single most important variable in estimating soil erodibility. In many cases, the standard soil texture such as clay loam, silt loam, or sandy loam based on the USDA classification may be known or can be estimated. However, as Wischmeier et al. (1971) found, this standard classification does not work as well as including the very fine sand fraction with the silt fraction. Unfortunately, the sand, silt, and clay content may be known for a soil, but information on the very fine sand fraction may not be available. A mechanical analysis of the soil is required to determine the very fine sand fraction. The following RUSLE2 equation was developed to estimate the very fine sand fraction from sand, silt, and clay content:

$$P_{vfs} = (0.74 - 0.62 P_{sd}/100) P_{sd} \qquad [4.11]$$

where: P_{vfs} and P_{sd} are in percent. Regression analysis was used to fit equation 4.11 to the USDA-NRCS soil survey data for Lancaster County, Nebraska.

4.3. Rill to interrill soil erodibility

RUSLE2 computes a ratio of rill to interrill erosion used to compute a slope length exponent in equation 2.10 (e.g., see **Section 2.1.3**) and a **b** value in the subfactor equation for the ground cover effect on erosion (see **Section 6.2**). The RUSLE2 equation used to compute a value for the rill to interrill soil erodibility ratio is:

$$K_r / K_i = (P_{sd}/100)[(1-\exp(-0.05P_{sd})] + 2.7(P_{sl}/100)^{2.5}[1-\exp(-0.05P_{sl})] \quad [4.12]$$

$$+0.35(P_{cl}/100)[1-\exp(-0.05P_{cl})]$$

where: K_r/K_i = the rill to interrill soil erodibility ratio and all soil texture values are in percent. Rill to interrill soil erodibility ratio values computed with equation 4.12 are shown in Table 4.1 at the central point of the textural classes.

Table 4.1. Rill to interrill soil erodibility ratio as a function of soil texture

Soil textural class	Rill to interrill soil erodibility ratio
Clay	0.36
Clay loam	0.50
Loam	0.65
Loamy sand	0.82
Sand	0.89
Sandy clay	0.61
Sandy clay loam	0.65
Sandy loam	0.7
Silt	1.91
Silt loam	1.04
Silty clay	0.53
Silty clay loam	0.73

Equation 4.12, like many RUSLE2 equations, is based on computing variations about a mid or central point that is well established by experimental data. As shown in Table 4.1, equation 4.12 gives a value of 1 for the reference silt loam soil. Equation 4.12 computes values that vary about one as soil texture deviates from silt loam. Although soil erodibility data from the Water Erosion Prediction Project (WEPP) were reviewed as the basis for deriving equation 4.12 (Elliot et al., 1989; Laflen et al., 1991a), the equation was derived based on judgment.

For example, increased clay content is assumed to reduce rill erosion much more rapidly than it reduces interrill erosion. Conversely, soils very high in silt are assumed to have increased rill erosion relative to interrill erosion. Increased rill erosion relative to interrill erosion is expected because of reduced clay content that reduces soil cohesiveness, which increases rill erosion more than interrill erosion. In addition, soils high in silt produce increased runoff, which increases rill erosion more than interrill erosion.

Soils high in sand are more susceptible to rill erosion than interrill because of low clay content and reduced cohesiveness. However, offsetting the increase in rill erosion susceptibility is decreased runoff, which would reduce rill erosion more than interrill erosion because rill erosion is directly related to runoff. Overall, the rill to interrill soil erodibility ratio is assumed to be reduced for soils high in sand but not as much as for soils high in clay.

Equation 4.12 quantifies concepts and advice that users were expected to consider in RUSLE1 for selecting LS and ground cover effect relationships [(AH703 (Renard et al., 1997)]. Equation 4.12 is considered to be a significant improvement over RUSLE1 procedures.

4.4. Geographic soil erodibility variability

Even when soil properties are identical, RUSLE2 soil erodibility factor values should vary with location because of climatic differences among locations. For example, erosion is greater per unit rainfall erosivity in locations such as the southern US, where frequent, high, and intense rainfall occurs, than in the northern Great Plains. Average annual soil erodibility factor values also vary with the temporal distribution of erosive precipitation because of the interaction between the temporal variation of erosive precipitation and the temporal variation of soil erodibility values [(AH703 (Renard et al., 1997)]. The temporal variation of erosive precipitation varies among locations

The RUSLE2 standard and modified soil erodibility nomographs do not take these factors into consideration. The data used to derive the standard soil erodibility nomographs were produced by uniform intensity simulated rainfall applied in a sequence of three events. The first simulated storm was 60 minutes of rainfall at 2.5 in/hr on dry soil conditions. The second storm was 30 minutes of rainfall at 2.5 in/hr approximately 24 hour later. The third storm was also 30 minutes long at 2.5 in/hr that occurred approximately 15 minutes after the second storm. When Wischmeier et al. (1971) developed the standard soil erodibility nomograph, they weighted measured erosion values produced by each simulated storm to compute an average annual soil erodibility factor value. This sequence of storms reflects a greater likelihood of a storm on dry conditions than on wet conditions.

This weighting procedure was assumed to apply at all locations, which is probably satisfactory for conservation planning on cropland in the eastern US. However, major questions arise about applying the soil erodibility nomograph to the western US where the precipitation patterns and rainfall amounts and intensities differ significantly from that used to derive the soil erodibility nomograph.

Although questions can be raised about the applicability of the soil erodibility nomograph for these and other reasons, the RUSLE2 assumption is that the nomographs provide soil erodibility values suitable for conservation and erosion control planning. Some of the nomograph issues are not significant with respect to conservation planning when uncertainty in the RUSLE2 soil erosion estimates are considered (See Section 17, RUSLE2 User's Reference Guide) because other factors have a much greater effect on rill-interrill erosion than does the soil erodibility factor.

The temporal soil erodibility equation described in **Section 4.5** takes into account soil erodibility factor values vary with location as temperature and precipitation var with location. Also, the effect of rainfall amount, intensity, and temporal climate patterns are considered in RUSLE2 equations for estimating rill-interrill erosion from rainfall on irrigated lands (see **Section 7.5**).

4.5. Temporal soil erodibility factor values

Along with factors for slope length, cover-management, and supporting practices, the RUSLE2 soil erodibility factor varies temporally (Mutchler and Carter, 1983). Erosion is significantly increased if peak soil erodibility occurs, for example, when cover-management conditions are most susceptible to erosion. An equation is needed to compute daily soil erodibility so that daily erosion can be computed to improve the mathematical accuracy of the RUSLE2 (see **Section 2.1**).

Soil erodibility is high for thawing soil and for the immediate period after the soil has thawed because the soil's susceptibility to detachment is increased (Van Klaveren and McCool, 1998.). Also, soil erodibility is high when soil moisture is high, which increases runoff per unit rainfall and hence erosion per unit erosivity. Erosion on the unit plot per unit erosivity is soil erodibility in RUSLE2. Runoff per unit rainfall is increased on the unit plot, and hence rill erosion is increased, when rainfall is frequent and soil evaporation is low. Soil erodibility may also be related to biological activity in the soil, which is a function of soil moisture and temperature (Vigil and Sparks, 2004).[37]

Although the reasons for soil erodibility varying temporally are partially known, adequate equations for temporal soil erodibility are lacking. The pattern for temporally varying soil erodibility seems well defined for plots at Morris, Minnesota and Holly Springs, Mississippi but not at other locations (Mutchler and Carter, 1983). A complication in making soil erodibility measurements is the coincidence of plot maintenance with highly erosive rains. The unit plots used to experimentally determine soil erodibility factor values are periodically tilled to break the soil crust and to control weeds. Erosion per unit erosivity, hence RUSLE2's soil erodibility factor, can be very high if a highly erosive rain occurs immediately after plot tillage.

The RUSLE1 temporal soil erodibility equations were reexamined and found to work poorly at most of the 11 locations where temporal soil erodibility data are available. Also, the equations performed very poorly in Minnesota and northern Iowa where computed temporal soil erodibility factor values varied too much with slight differences in weather between adjacent counties. Furthermore, the empirically derived RUSLE1 temporal soil erodibility equations are not applicable in the Western US. Consequently, a new temporal soil erodibility equation was derived for RUSLE2 using data collected at the locations listed in Table 4.2. The record length for these data is about 10 years.

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[37] The RUSLE2 soil erodibility factor is solely related to unit plot conditions. Soil erodibility is also influenced by cover-management conditions but those effects, such as related to soil moisture and runoff, are considered in cover-management variables (see **Section 6**).

Table 4.2. Locations where unit plot conditions were used to determine monthly soil erodibility factor values

Location
Tifton, GA
Watkinsville, GA
Holly Springs, MS
Bethany, MO
Independence, IA
Beaconsfield, IA
Castana, IA
Clarinda, IA
Morris, MN
LaCrosse, WI
Presque Isle, ME

Temporal soil erodibility values grouped by geographic area are shown in Figure 4.1. A similar pattern in the temporal erodibility values by location was expected for each geographic area, especially for the four Iowa locations. The patterns are similar for the two northern Midwestern US and Northern Maine locations where almost no rill-interrill erosion occurs during the winter. The patterns are mostly similar for the two Georgia locations but differ significantly from the pattern at Holly Springs, Mississippi. The difference in patterns, especially among the Iowa locations, indicates that other variables besides weather, such as timing of plot maintenance with erosive rains, affect temporal soil erodibility.

With the exception of the southern locations, the data do not capture the increased soil erodibility in late winter and early spring during and immediately after soil thawing. The very few data available for these conditions are not usable because of very large variability. In many cases, measurements were not made during late winter and early spring because measuring equipment was difficult to operate during cold weather. Also, increased soil erodibility during the thawing and recently thawed period seems to be related to a unique set of conditions that do not occur every year.

Regardless of these limitations, a temporal soil erodibility equation seemed advisable for

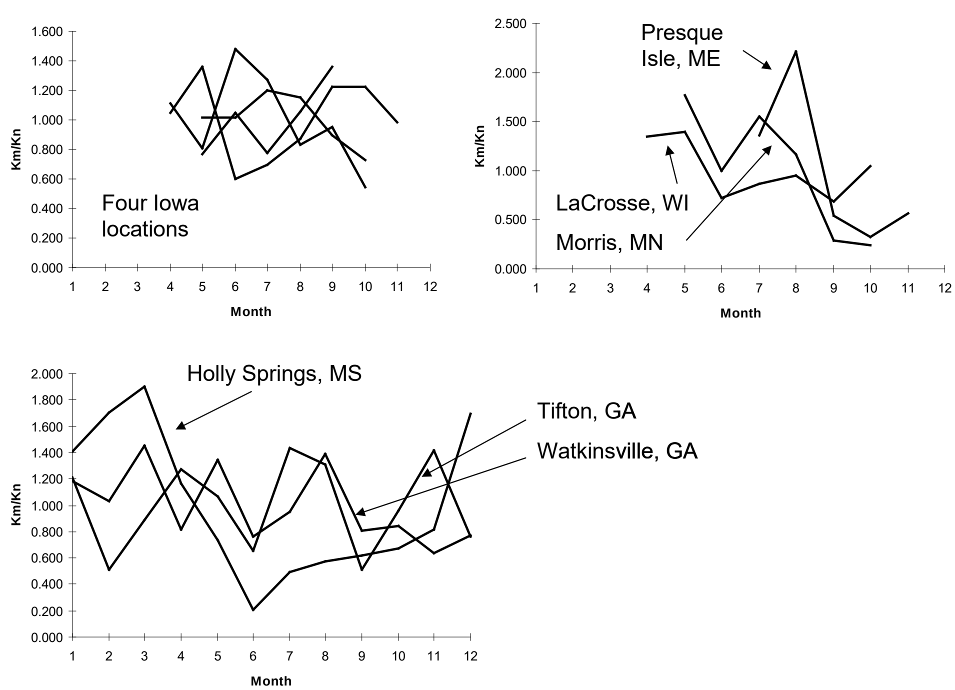

Figure 4.1. Monthly variation in soil erodibility at several locations.

RUSLE2. An equation for RUSLE2was empirically derived from these data.

4.5.1. Basic assumptions

The RUSLE2 assumption is that the soil erodibility value entered in RUSLE2, whether user entered or computed with either of the RUSLE2 soil erodibility nomographs, represents average soil erodibility for a summer period. The RUSLE2 summer period is defined for temporal soil erodibility purposes as the period when average daily temperature exceeds 40 ^{o}F. Analysis of soil erodibility data at Pullman, WA indicates that a better definition is the time between when average daily temperature reaches 45 ^{o}F early in the year to when it decreases to 35 ^{o}F late in the year.

The major assumption used to derive the RUSLE2 temporal soil erodibility equation is that monthly precipitation and temperature can be used as indices to estimate the temporal variability in soil erodibility during the RUSLE2 summer period.

4.5.2. Temporal soil erodibility for the summer period referenced to summer conditions at location

Average values for the ratio of monthly soil erodibility to average soil erodibility for the RUSLE2 summer period were computed for the data collected at the locations listed in Table 4.2. Average soil erodibility for the RUSLE2 summer period was computed as the total erosion for the period of record divided by total erosivity, excluding storms less than 0.5 inches (see **Section 3.2.1**). The period of record at all locations closely corresponded to the RUSLE2 summer definition because the plots were not operated during the winter as can be seen in Figure 4.1. However, the plots were operated throughout the year in the southern US locations and the total data for the year were used to compute an average erodibility value for the southern locations.

The resulting equation from fitting the data is:

$$K_j / K_n = 0.591 + 0.732(P_j / P_s) - 0.324(T_j / T_s) \quad [4.13]$$

where: K_j = average daily soil erodibility factor value for the *jth* day, K_n = soil erodibility value from the RUSLE2 soil erodibility nomographs or user entered into RUSLE2, T_j = average daily temperature for the *jth* day (^{o}F), T_s = the average temperature for the RUSLE2 summer period defined above, P_j = the average daily precipitation, and P_s = the average precipitation for the RUSLE2 summer period. This equation follows the expected trends of increased soil erodibility when precipitation is high and decreased soil erodibility when temperature is high. Equation 4.13 does not describe increased soil erodibility during or immediately after soil thawing.

The fit of equation 4.13 to the observed data at three locations is shown in Figure 4.2, which also represents the fit at the other locations. Equation 4.13 is a major improvement over the RUSLE1 equations as can be seen by inspection and by comparing the sum of squares of differences between observed and computed values. However, the fit of

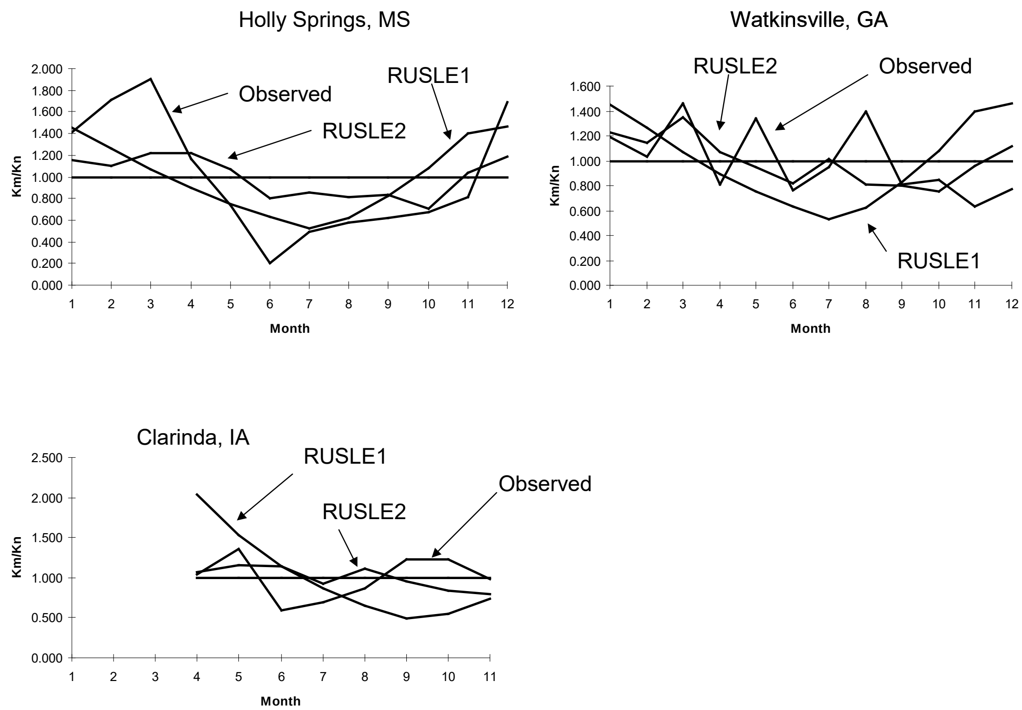

Figure 4.2. Fit of RUSLE2 temporal erodibility equation (equation 4.13), RUSLE1 equation, and constant value to observed data.

equation 4.13 is only slightly better than assuming a time invariant soil erodibility factor value for the summer period.

Computed values from equation 4.13 are shown in Figure 4.3 for Tombstone, Arizona and compared to values computed with the RUSLE1 equations and observed values. Very clearly, equation 4.13 performs much better than the RUSLE1 equations, which illustrates why a time invariant soil erodibility factor value should be assumed when applying RUSLE1 to the western US. The observed values shown in Figure 4.3 were obtained by applying rainfall each month with a rainfall simulator.[38] The observed values are not

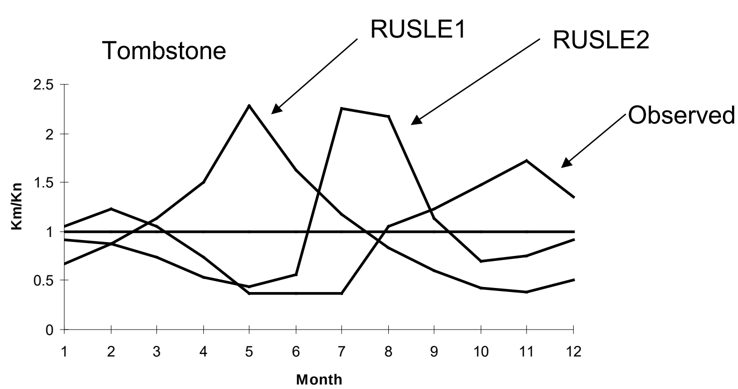

Figure 4.3. Fit of temporal erodibility equations to data from simulated rainfall on rangeland plots at Tombstone, Arizona.

JSDA-Agricultural Research
Service, Tucson, Arizona.

directly comparable to soil erodibility values produced by natural precipitation because of temporal differences between natural precipitation and the uniform precipitation of the simulated rainfall. Nevertheless, the fit of equation 4.13 to the observed Tombstone, Arizona data is comparable to the fit of equation 4.13 to soil erodibility values produced by natural rainfall in the eastern US.

Therefore, the recommendation is that the RUSLE2 temporal soil erodibility equation be used for all locations in the US except for Req periods (see **Section 3.2.5** and RUSLE2 User's Reference Guide).

4.5.3. Temporal soil erodibility for the summer period referenced to summer conditions at Columbia, Missouri

Equation 4.13 does acceptably well in capturing the relative temporal variations in soil erodibility at a location. Equation 4.13 is an improvement over using a constant soil erodibility factor at a location.

However, equation 4.13 gives exceptionally high soil erodibility values that do not seem reasonable in many western US locations. For example, equation 4.13 computes summer soil erodibility values at Tombstone, Arizona that are twice the average erodibility for summer period (i.e, the period that average daily temperature exceed 100 ^oF). The soil erodibility nomograph gives the same average erodibility for both Columbia, Missouri and Tombstone when soil properties are the same at the two locations.. However, the absolute July soil erodibility at Tombstone should not be higher than the absolute July soil erodibility at Columbia.

The root cause of the problem is that the soil erodibility nomograph is not a function of climate at a location. This deficiency does not cause major problems in the Eastern US, but it does cause great problems in the Western US.

To fix this problem, the P_s and T_s variables in equation 4.13 were changed from location values to values at Columbia, MO. The temporal soil erodibility equation referenced to Columbia, Missouri is:

$$K_j / K_n = 0.591 + 0.732(P_j / 0.123) - 0.324(T_j / 62.8) \qquad [4.14]$$

$$If\,(K_j / K_n) > 2.0 \text{ then } (K_j / K_n) = 2.0$$

$$If\,(K_j / K_n) < 0.4 \text{ then } (K_j / K_n) = 0.4$$

where: P_j = daily precipitation (inches), 0.123 (inches) = the daily average reference precipitation at Columbia, Missouri, T_j = the daily temperature (^oF), and 62.8 (^oF) = the daily average reference temperature at Columbia, Missouri. The j subscript is for the *jth* day. The reference precipitation and temperature value for Columbia, Missouri are for the time period that the average daily temperature is above 40 ^oF.

Either the standard or RUSLE2 soil erodibility nomographs can be used to determine a value for the nominal soil erodibility factor K_n, or another soil erodibility value can be used if values computed by the RUSLE2 soil erodibility nomographs are not applicable. The upper limit of 2 and the lower limit of 0.4 for the ratio K_j/K_n provides robustness by preventing extreme precipitation and temperature from excessively affecting daily soil erodibility factor values.

4.5.4. Temporal soil erodibility for the winter period

Equation 4.14 is used to compute temporal RUSLE2 soil erodibility factor values in the winter period as well as the summer period, except when average daily temperature is less than 30 ^oF. The RUSLE2 temporal soil erodibility equation for average daily temperature less than 30 ^oF is:

$$K_{(j)} / K_n = (K_{s(j)} / K_n) \exp[-0.2(30 - T_{(j)})] \qquad [4.15]$$

where: $K_{s(j)}$ = the soil erodibility factor value computed with equation 4.14 on the *jth* day, T_j = the average daily temperature on the *jth* day (^oF), and 30 = the average daily temperature below which soil erodibility is reduced because of soil freezing (^oF). The *exp* term in equation 4.15 computes a K_j/Kn value less than 0.05 when average daily temperature is less than 15 ^oF. The exponential decay term in equation 4.15 takes into account the fact that temperature in some years on a given day will not be less than freezing even though average daily temperature is below freezing. Also, the temperature used in equation 4.15 is air temperature rather than soil temperature.

Equation 4.15 does not compute increased erosion during and immediately after soil thawing.

4.5.5. Temporal soil erodibility for winter and summer periods combined

Figure 4.4 shows temporal soil erodibility factor values computed for the entire year at selected locations. Note the difference in the mean soil erodibility factor value among the locatins for the same base soil erodibility factor value.

4.5.6. Temporal soil erodibility for the Req regions

Winter erosion processes differ greatly from summer erosion processes in the Northwest Wheat and Range Region (NWRR) and other areas in the Western US (McCool et al., 1995). Soil erodibility is very high during the winter in these regions, resulting in very high erosion. This winter effect is accounted for in RUSLE2 by assuming an equivalent erosivity known as Req. Equation 4.14 can be used to estimate temporal erodibility for the summer period defined as the time between the day when average daily temperature reaches 45 ^oF early in the year and decreases to 35 ^oF late in the year. Equation 4.15 does not apply where Req effects are assumed to occur (see **Section 3.2.5** and RUSLE2 User's Reference Guide).

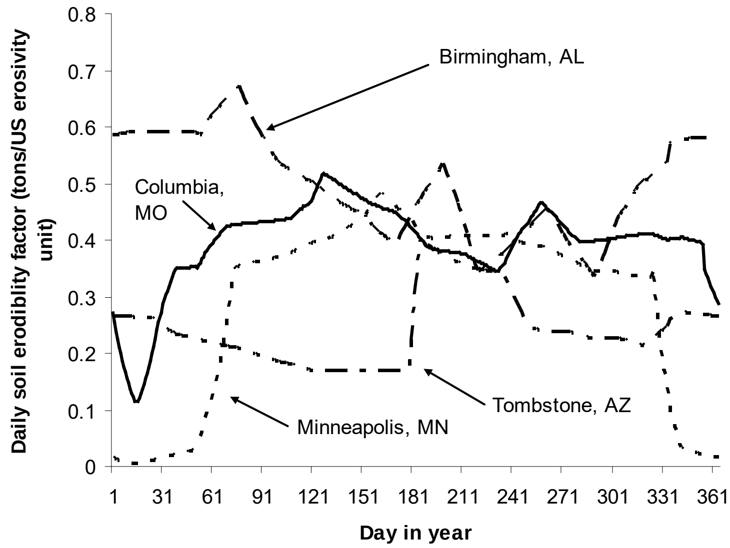

Figure 4.4. RUSLE2 computed temporal soil erodibility factor values for the same base soil erodibility factor value. The temporal soil erodibility factor equations are referenced to Columbia, Missouri.

4.6. Effect of rock on soil erodibility

Rock on and in the soil affects rill-interrill erosion. RUSLE2 treats rock on the soil surface as ground cover (see **Section 6.2**). Rock in the soil is assumed to affect runoff and this effect on erosion is represented by choosing a soil erodibility factor value based on how rock in the soil profile is assumed to affect runoff under unit plot conditions. **User entered soil erodibility values should reflect how rock in the soil profile affects erosion but not account for any effect of rock on the soil surface.**

The permeability class input should reflect how rock in the soil profile affects runoff when a RUSLE2 soil erodibility nomograph is used to compute a soil erodibility factor value. Although RUSLE2 includes the RUSLE1 soil erodibility nomograph equations used to estimate how rock in the soil profile affect soil erodibility (Römkens et al., 1997), these equations should not be used in RUSLE2, especially for construction sites and reclaimed surface mine lands. Toy and Foster (1998) describes how to adjust input values to the RUSLE2 modified soil erodibility nomograph to estimate the effect of large rock fragments in the soil on soil erodibility. 20-40=+1; 40-60=+2; 60-80=+3; >80=+4; max permeability is class=6 (very slow).

A value for soil surface cover provided by rock that is a natural part of the soil can be entered in RUSLE2's soil input. RUSLE2 assumes that this rock cover is not affected by mechanical soil disturbing operations. Rock cover can also be represented in RUSLE2 as an operation that adds surface cover, but RUSLE2 handles this rock cover differently from how it handles rock cover entered in the soil input. Rock cover represented as surface cover added by an operation is affected by soil disturbing operations and

RUSLE2 treats this rock as an organic material. Special inputs are required when rock cover is represented in this way (see **Section 10.1** and RUSLE2 User's Reference Guide).

The USDA-NRCS soil survey database includes soil erodibility factor values that have been adjusted for rock cover on the soil surface. **NRCS soil erodibility factors values adjusted for rock surface cover must not be used in RUSLE2.** The ground cover subfactor relationship used by NRCS to adjust for rock surface cover differs from the comparable RUSLE2 relationship (see **Section 6.2.1**). The surface cover relationship used by the NRCS is the USLE mulch cover subfactor [AH537 (Wischmeier and Smith, 1978)], which has an approximate 0.026 **b** value whereas the approximate RUSLE2 **b** value is 0.035. The error in estimated erosion from this difference for a 20 percent rock cover is 20 percent.

Also, RUSLE2 uses a net ground cover that takes into account surface residue and live ground cover overlapping rock surface cover. This overlap is not taken into account when NRCS soil erodibility factor values adjusted for rock surface cover are used, which can result in serious errors because the ground (mulch) cover relationships are highly non-linear (see RUSLE2 User's Reference Guide). The error in estimated erosion from neglecting the overlap for a 50 percent residue cover and a 20 percent rock cover is 30 percent even when if the proper **b** value had been used in the NRCS adjustment.

4.7. Sediment characteristics

RUSLE2 computes deposition and enrichment ratio as a function of sediment characteristics (see **Sections 2.3.3** and **4.7.6**). Diameter, specific gravity, distribution among sediment particle classes, and composition of sediment particle classes are the RUSLE2 variables used to describe sediment characteristics. RUSLE2 uses only soil texture and inherent soil organic matter content to compute values for sediment characteristics at the point of detachment although soil management affects these sediment characteristics. Sufficient information was not available to develop equations for the effect of soil management on sediment characteristics at the point of detachment.

The RUSLE2 equations used to compute sediment characteristics at the point of detachment are described by (Foster et al., 1985b). The RUSLE2 intent in representing sediment characteristics is to capture main effects rather than precisely representing all variables that affect sediment characteristics at the point of detachment. Also, more detail, such as more than the five sediment particle classes used in RUSLE2 equations is desired for computing deposition. However, the desired information is not readily available for most RUSLE2 applications as a conservation planning tool in local field offices. The RUSLE2 approach is far better than assuming that sediment characteristics at the point of detachment are the same as the characteristics of dispersed samples of the soil subject to detachment. A critically important point is that sediment is eroded as a mixture of aggregates and primarily particles. Assuming that sediment is composed entirely of primary particles produces serious errors when computing deposition. RUSLE2 computes how deposition changes sediment characteristics so that the characteristics of sediment leaving an overland flow path, terrace/diversion channels, and small impoundments can be quite different from the characteristics of the soil being eroded, especially where RUSLE2 computes a high degree of deposition.

4.7.1. Definition of sediment particle classes

Five sediment particle classes are used to represent the sediment produced by detachment for each soil along an overland flow path. The five classes are primary clay, primary silt, small aggregate, large aggregate, and primary sand. Sediment from cohesive soils is eroded as a mixture of primary particles (small mineral particles that the soil can be divided into) and aggregates (conglomerates of primary particles) (Foster et al., 1985b). Also, the sediment distribution for many cohesive soils is bimodal, having a peak in the silt-size range and a peak in the sand-size range (Meyer et al., 1980). The two aggregate sediment particle classes represent these two peaks in the sediment distribution. The three primary sediment particle classes represent primary particles in the sediment while the two aggregate classes represent aggregates in the sediment.

4.7.2. Density of sediment particle classes

Densities, expressed as specific gravity, of the sediment particle classes are given in Table 4.3. The slightly reduced density for the primary clay class relative to the primary silt and sand classes is because of the platy nature of clay particles. The difference is of no consequence in RUSLE2. The significantly reduced densities of the aggregate classes from the primary particle classes reflect how aggregates are conglomerates of primary particles with internal open spaces in them that are partially or fully filled with water. Sediment particle density is especially important for sediment sizes larger than 0.1 mm because density seems to affect deposition by overland flow as much as size (Lu et al., 1988; Neibling and Foster, 1982). A smaller density is assigned to the large aggregate class than to the small aggregate class because density decreases as aggregate size increases (Foster et al., 1985b).

Table 4.3. Densities of sediment particle classes

Particle class	Density (specific gravity)
Primary clay	2.60
Primary silt	2.65
Small aggregate	1.80
Large aggregate	1.60
Primary sand	2.65

4.7.3. Diameters of sediment particle classes

The diameters of the sediment particle classes are given in Table 4.4. The diameter of each primary particle class is fixed. However, the diameter for each aggregate sediment particle class varies with soil clay content, which reflects the role of clay as a bonding agent.

Table 4.4. Diameter of sediment particle classes.

Particle class	Diameter		Condition where equation applies
	Symbol	Size (mm)	
Primary clay	d_{cl}	0.002	
Primary silt	d_{sl}	0.010	
Small aggregate	d_{sa}	0.030	$P_{cl} < 25$
	d_{sa}	$0.2(P_{cl}/100 - 0.25) + 0.03$	$25 \le P_{cl} \le 60$
	d_{sa}	0.100	$P_{cl} > 60$
Large aggregate	d_{la}	0.300	$P_{cl} \le 15$
	d_{la}	$2P_{cl}/100$	$P_{cl} > 15$
Primary sand	d_{sd}	0.200	

The diameter of each aggregate class is a function of soil clay content for certain ranges of clay content. RUSLE2 adds aggregate sediment particle classes as necessary along the overland flow path where soil clay differs by segment to represent unique particle classes having different diameters. The same primary sediment particle classes are used for all soils along an overland flow path because the diameters used for these classes do not vary with soil.

4.7.4. Distribution of sediment mass among particle classes at point of detachment

As shown in Table 4.5, the distribution of sediment mass among the sediment particle classes at the point of detachment depends mainly on the soil's clay content. Seventy four percent of the clay in the sediment at the point of detachment is in the aggregate sediment particle classes while only 26 percent is in the primary clay sediment particle class.

Table 4.5. Distribution of sediment mass among particle classes at the poi				
Particle class	Fraction			
	Symbol		Condition	Comment
Primary clay	F_{cl}	$0.26P_{cl}/100$		
Primary silt	F_{sl}	$P_{sl}/100 - F_{sa}$		
Small aggregate	F_{sa}	$1.8P_{cl}/100$	$P_{cl} < 25$	
	F_{sa}	$0.45 - 0.6(P_{cl}/100 - 0.25)$	$25 \le P_{cl} \le 50$	If $F_{sl} < 0$, $F_{sl} = 0.0001$ and
	F_{sa}	$0.6P_{cl}/100$	$P_{cl} > 50$	$F_{sa} = P_{sl}/100 - F_{sl}$
Large aggregate	F_{la}	$1 - F_{cl} - F_{sl} - F_{sa} - F_{sd}$		If $F_{la} < 0$, each fraction is multiplied by the same fraction to give F_{la} = 0.0001
Primary sand	F_{sd}	$(P_{sd}/100)(1 - P_{cl}/100)^5$		
Note:				
If the clay content of the large aggregate class is less than $0.5P_{cl}$, the value for F_{sa} must be reduced to meet this condition.				

Soil clay content determines the fraction of the sediment mass that is in the small aggregate sediment particle class at the point of detachment. The fraction of the sediment in the primary silt class at the point of detachment is the soil's silt content less the silt fraction computed to be in the small aggregate class. The fraction of sediment mass in the small aggregate class at the point of detachment can not be larger than the silt content in the soil.

Both clay and sand content in the soil determine the fraction of the sediment mass that is in the primary sand sediment particle class at the point of detachment. The role of soil clay content in determining this fraction increases rapidly as soil clay content increases. The fraction of sediment mass in the large aggregate sediment particle class at the point of detachment is computed as 1 minus the sum of the fractions of the other four sediment particle classes. The fractions for the other four classes are adjusted when the fraction of the large aggregate sediment particle class is computed as being less than zero.

4.7.5. Composition of each sediment particle class

Detachment in RUSLE2 is assumed to be non-selective. Consequently, the sediment's primary particle composition at the point of detachment is the same as the composition of the surface soil subject to detachment.

4.7.5.1. Primary clay sediment particle class

The primary sediment particle is composed of primary clay and the organic matter associated with the clay.[39] The RUSLE2 assumption is that the ratio of organic matter to clay on a mass basis is the same for all sediment particle classes where clay is present. That ratio is given by:

$$r_{om,cl} = P_{om} / P_{cl} \qquad [4.16]$$

where: $r_{om,cl}$ = the fraction (mass) of the primary clay sediment particle class that is composed of organic matter and P_{om} = 100 times the ratio of mass of organic matter in the soil to the mass of soil mineral particles.

4.7.5.2. Primary silt sediment particle class

The primary silt sediment particle class is composed solely of silt. This particle class contains no organic matter because the class contains no clay.

4.7.5.3. Small aggregate sediment particle class

The small aggregate sediment particle class is composed of clay, silt, and organic matter. This particle class contains no sand by definition. The size of the small aggregate particle class is too small to contain any sand except very fine sand. However, the RUSLE2 assumption is that this particle class does not contain even very fine sand. The distribution of the clay and silt is assumed to equal the proportion of clay and silt in the soil subject to detachment. That is,

$$f_{cl,sa} = P_{cl} /(P_{cl} + P_{sl}) \qquad [4.17]$$

where: $f_{cl.sa}$ = the fraction (mass) of the small aggregate that is composed of clay. The fraction of the small aggregate that is composed of silt is given by:

$$f_{sl,sa} = P_{sl} /(P_{cl} + P_{sl}) \qquad [4.18]$$

where: $f_{sl,sa}$ = the fraction (mass) of the small aggregate that is composed of silt. The fraction of the small aggregate that is composed of organic matter is given by:

$$f_{om,sa} = r_{om,cl} f_{cl,sa} \qquad [4.19]$$

where: $f_{om,sa}$ = fraction (mass) of the small aggregate sediment class composed of organic matter.

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[39] The terms clay, silt, and sand sometimes refer to particle sizes. However, as used herein, clay, silt, and sand refer to mineral particles in the clay, silt, and sand sizes. The fractions of the primary particles sum to 1. Organic matter is not considered in determining fraction of the particles classes.

4.7.5.4. Large aggregate sediment particle class

The large aggregate sediment particle class is assumed to be composed of clay, silt, sand, and organic matter. The total of each constituent among the sediment particles classes must equal the constituent's amount in the soil. The mass of a constituent, except organic matter, in the large aggregate is computed as the total minus the sum of that constituent in the other sediment particle classes That is:

$$f_{cl,la} = (P_{cl}/100 - F_{cl} - f_{cl,sa}F_{sa})/F_{la} \quad [4.20]$$

$$f_{sl,la} = (P_{si}/100 - F_{si} - f_{sl,sa}F_{sa})/F_{la} \quad [4.21]$$

$$f_{sd,la} = (P_{sd}/100 - F_{sa})/F_{la} \quad [4.22]$$

Equations 4.20-4.22 directly result from the RUSLE2 assumption that detachment is a non-selective process, which requires that the distribution of the constituents in the sediment at the point of detachment be the same as that in the soil subject to detachment. A check is made of the clay content in the large aggregate sediment particle class. Because clay and the organic matter associated with it are assumed to be bonding agents for the two aggregate classes, clay must be sufficient in the large aggregate class to give those particles stability. To meet this requirement, the RUSLE2 assumption is that the clay content in the large aggregate class must be at least half of the soil's clay content. If the clay content in the large aggregate particle class computed with equation 4.20 is less than half the soil's clay content, the fraction F_{sa} of the small aggregate sediment particle class is reduced to meet this requirement.

The fraction of the organic matter in the large aggregate sediment particle class is given by:

$$f_{om,la} = f_{cl,la}r_{om,cl} \quad [4.23]$$

4.7.5.5. Primary sand sediment particle class

The primary sand class is solely composed of sand. It contains no organic matter because it contains no clay.

4.7.6. Specific surface area

Table 4.6. Specific surface area of soil/sediment constituents.

Constituent	Specific surface area (m^2/g)
Clay	20
Silt	4
Sand	0.05
Organic matter	1000

Each constituent of clay, silt, sand, and organic matter is assigned a specific surface area so that RUSLE2 can compute an enrichment ratio based on specific area of the soil subject to detachment and the computed sediment yield from the overland flow path, terrace/diversion channel, or small impoundment, represented in a RUSLE2 computation. Specific surface area is the total surface area of the soil or sediment per unit mass. The specific surface areas used in RUSLE2 are given in Table 4.6, which were used in the CREAMS model (Foster et al.1980a, 1980b; Foster et al., 1981a). As Table 4.6 shows, most of the surface area is associated with organic matter and clay with almost no specific surface area associated with sand. Because organic matter is directly associated with the clay, the specific surface of both the soil and the sediment is directly related to clay content in each.

Specific surface area of the soil subject to detachment and the sediment leaving the RUSLE2 flow path is used to compute an enrichment ratio as:

$$E_r = S_{sed} / S_{soil} \quad [4.24]$$

where: E_r = enrichment ratio, S_{sed} = the specific surface area of the sediment and S_{soil} = the specific surface area of the soil. The enrichment ratio is a measure of the degree that RUSLE2 computes that deposition enriches the sediment in fine particles, especially clay. Deposition is a selective process that first deposits particles that are coarse and dense, which have a low specific surface area, leaving the sediment enriched in fine particles that have a high specific surface area. The enrichment ratio increases as deposition increases. A sediment delivery ratio can be computed as the ratio of sediment yield at the end of the RUSLE2 flow path divided by the total amount of sediment produced by detachment. Enrichment ratio increases as the sediment delivery ratio decreases. A low sediment delivery ratio represents a high degree of deposition. Enrichment ratio is a relative term and not an absolute term. A high enrichment ratio means that the specific area of the sediment is greater than that of the soil that produced the sediment, but the specific surface area of the sediment may still be low if the soil being eroded has a high sand content and a low inherent organic matter content.

Table 4.7. RUSLE2 computed enrichment ratios for a filter strip

Soil textural class	Enrichment ratio
Clay	1.95
Clay loam	2.23
Loam	2.65
Loamy sand	7.56
Sand	11.50
Sandy clay	2.13
Sandy clay loam	3.07
Sandy loam	3.47
Silt	0.94
Silt loam	1.58
Silty clay	1.19
Silty clay loam	1.44

The enrichment ratio computed by RUSLE2 is strongly affected by soil texture as shown in Table 4.7. Interestingly, the highest enrichment ratio is for a sand soil while the lowest enrichment ratio is for a high silt soil. Enrichment ratio values are moderate for high clay soils. These results are directly related to the sediment being a mixture of aggregates and primary particles, the role of clay as a bonding agent in determining size of the large the aggregates, and the distribution of sediment between the small aggregate and large aggregate sediment particle classes. An important point to remember when interpreting and using the RUSLE2 computed enrichment ratio values is that about 74 percent of the clay is in the small and large aggregate particle classes at the point of detachment. RUSLE2 computes that a moderate sized large aggregate class is deposited at a rate comparable to the primary sand sediment particle class. Because much of the clay is assumed to be in the large aggregate class, a significant amount of clay is deposited when the large aggregate class is deposited.

The enrichment ratio values computed by RUSLE2 are very different from those that would be computed if the sediment at the point of detachment was assumed to be composed entirely of primary particles. High sand soils have very low clay contents such that the portion of the sediment in the aggregates classes at the point of detachment is low. The aggregate classes, which contain most of the clay, have small diameters for high sand soils and are, therefore, less readily deposited. Consequently, the enrichment ratio for sediment from high sand soils is generally high as illustrated in Table 4.7. In contrast, the diameters of both the small and large aggregate classes, which contain most of the clay, are very large for the high clay soils. These aggregates classes are more readily deposited than the aggregate classes produced by high sand soils. The result is that a higher fraction of the clay in a high sand soil remains in the sediment after deposition than for a high clay soil.

Essentially no enrichment occurs with the high silt soil because of the very low clay content and a very high portion of the sediment at the point of detachment being in the primary silt class that is not readily deposited. Most of the clay is in the aggregate classes that are more readily deposited than the primary silt class where most the sediment is concentrated at the point of detachment.

Although specific surface area of clay varies significantly with clay mineralogy, RUSLE2 does not consider that effect. Also, RUSLE2 uses the inherent soil organic matter content under unit plot conditions in these computations. Soil organic matter content as influence by cover-management is a more appropriate measured than inherent soil organic matter content.

The enrichment ratio values computed by RUSLE2 represent an index. The enrichment ratio value indicates the concentration of sediment associated chemicals in the sediment relative to their concentration in the soil. Calibration should be used to empirically relate the concentration of chemicals on sediment to the RUSLE2 enrichment ratio values because the values computed by RUSLE2 are lower than expected (Knisel et al., 1980).

4.8. Time to soil consolidation

Soil consolidation refers to the soil becoming resistant to erosion over time after a mechanical soil disturbance and not to a mechanical increase in bulk density of the soil (see **Section 6.6**). RUSLE2 computes time to soil consolidation as function of annual precipitation using:

$$t_c = 20 \quad P_a < 10 \qquad [4.25]$$

$$t_c = 26.5 - 0.65 P_a + 0.5 \quad 10 \le P_a \le 30 \qquad [4.26]$$

$$t_c = 7 \quad 30 < P_a \qquad [4.27]$$

where: t_c = the time to soil consolidation (years) and P_a = annual precipitation (inches). The equation that computes values for the soil consolidation subfactor uses the ratio of time since last mechanical soil disturbance to time to soil consolidation and computes subfactor values that asymptotically approach the 0.45 final value (see **Section 6.6.2**). The time to soil consolidation is defined as the time for 95 percent of the reduction in the soil consolidation subfactor to occur. The time to soil consolidation occurs when the soil consolidation factor equals 0.4775, which is 95 percent of the decrease from 1 for the soil consolidation subfactor immediately after a mechanical soil disturbance to the final 0.45 value.

After a mechanical soil disturbance, the soil becomes resistant to detachment by the soil experiencing wetting and drying cycles in the presence of soil moisture and bonding agents including clay and organic matter (Foster et al., 1985b). Mechanical compaction of the soil is assumed to have little effect on this increase in erosion resistance in RUSLE2. The seven year time to soil consolidation is based on analysis of fallow plot data from Zanesville, Ohio (Borst et al., 1945), which are the only sufficient data available to empirically determine time to soil consolidation. This seven year period is assumed to apply to all areas where annual precipitation is greater than 30 inches. The increase of time to soil consolidation based on average annual precipitation is an approximate way to capture the idea that soil consolidation occurs more slowly in the western US than in the eastern US because of reduced rainfall amount and reduced number of rainfall events. Equations 4.25 and 4.26 are based on judgment.

4.9. List of symbols

b = coefficient used to compute ground cover subfactor values

d_{cl} = diameter of primary clay sediment class (mm)

d_{la}= diameter of large aggregate sediment class (mm)

d_{sa}= diameter of small aggregate sediment class (mm)

d_{sd} = diameter of primary sand sediment class (mm)

d_{sl} = diameter of primary silt sediment class (mm)

E_r = enrichment ratio

$f_{cl.la}$ = mass portion of large aggregate sediment class composed of clay (fraction)

$f_{cl.sa}$ = mass portion of small aggregate sediment class composed of clay (fraction)

$f_{om,la}$ = mass portion of large aggregate sediment class composed of organic matter (fraction)

$f_{om,sa}$ = mass portion of the small aggregate sediment class composed of organic matter (fraction)

$f_{sd,la}$ = mass portion of large aggregate sediment class composed of sand (fraction)

$f_{sl,la}$ = mass portion of large aggregate sediment class composed of silt (fraction)

$f_{sl,sa}$ = mass portion of small aggregate sediment class composed of silt (fraction)

F_{cl} = mass portion of sediment at point of detachment composed of primary clay sediment class (fraction)

F_{la} = mass portion of sediment at point of detachment composed of large aggregate sediment class (fraction)

F_{sa} = mass portion of sediment at point of detachment composed of small aggregate sediment class (fraction)

F_{sd} = mass portion of sediment at point of detachment composed of primary sand sediment class (fraction)

F_{sl} = mass portion of sediment at point of detachment composed of primary silt sediment class (fraction)

k_o = organic matter subfactor in soil erodibility nomograph

k_p =soil profile permeability subfactor in soil erodibility nomograph

k_s = soil structure subfactor in soil erodibility nomograph

k_t = texture subfactor in soil erodibility nomograph

k_{tb} = base soil texture subfactor in soil erodibility nomograph for all soil textures

k_{t68} = base soil texture subfactor in soil erodibility nomograph when $P_{sl} + P_{vfs} > 68\%$.

K = soil erodibility factor[40]

K_j = average daily soil erodibility factor value for the *jth* day

K_n = soil erodibility value from RUSLE2 soil erodibility nomographs or user entered for summer periods

K_r/K_i = rill to interrill soil erodibility ratio

$K_{s(j)}$ = soil erodibility factor computed with equation 4.14

O_m = inherent soil organic matter (percent)

P_a = annual precipitation (inches)

P_{cl} = portion of soil mass composed of clay based on total soil primary particles (percent)

P_j = average daily precipitation (inches)

P_{om} = 100 times ratio of mass of organic matter in soil to mass of soil mineral particles

P_r = soil profile permeability class used in soil erodibility nomograph

P_s = average precipitation for the RUSLE2 summer period (inches)

P_{sd} = portion of soil mass composed of sand based on total soil primary particles (percent)

P_{sl} = portion of soil mass composed of silt based on total soil primary particles (percent)

P_{vfs} = portion of soil mass composed of very fine sand based on total soil primary particles, not the portion of sand content (percent)

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[40] US customary units used for K and associated variables

$r_{om,cl}$ = mass portion of the primary clay sediment class composed of organic matter (fraction)

S_s = soil structure class used in soil erodibility nomograph

S_{sed} = specific surface area of sediment

S_{soil} = specific surface area of soil subject to erosion

t_c = time to soil consolidation (years)

T_j = average daily temperature for the *jth* day (^oF)

T_s = average temperature for the RUSLE2 summer period (^oF)

Indices

j - day

5. TOPOGRAPHY

This section describes mathematical consequences of RUSLE2's equation structure rather than providing additional equations except for the steepness factor and adjusting soil loss tolerance values for position along the overland flow path.

Equations that describe how topography affects rill-interrill erosion where the overland flow streamlines are parallel are described in **Section 2**. Those equations provide RUSLE2's fundamental, underlying mathematical structure. Those equations accommodate spatial variability in soil, steepness, cover-management, and support practices along the overland flow path. Those equations compute whether detachment or deposition occurs along the overland flow path. RUSLE2 computes its erosion and sediment load values using a numerical solution of the governing RUSLE2 equations written as a function of distance along the overland flow path. The numerical solution is a spatial integration of the governing equations. Furthermore, RUSLE2 performs a temporal integration of the governing equations, where the slope length exponent m in equation 2.10, along with soil erodibility and cover-management relationships change daily.

5.1. Converging-diverging streamlines on overland flow areas

The RUSLE2 assumption is that overland flow streamlines are parallel. Consequently, RUSLE2 does not estimate how converging or diverging overland flow affects rill-interrill erosion. An analysis based on a simple process-based erosion model showed that rill-interrill erosion with converging overland flow is about 7/6 times that where the streamlines are parallel (Toy and Foster, 2000). The same analysis showed that rill-interrill erosion with diverging overland flow is about 5/6 times that where the streamlines are parallel.

5.2. Topographic equations for overland flow having parallel streamlines on uniform overland flow paths

RUSLE1 requires users to select a slope length exponent value, m in equation 2.10, based on land use classes [AH703, (Renard et al., 1997); Toy and Foster, 1998]. The RUSLE1 slope length exponent is time invariant and thus does not change as cover-management conditions change temporally. Overland flow path steepness is the only variable considered in adjusting the slope length exponent in the USLE [AH537 (Wischmeier and Smith, 1978)].

A RUSLE2 major improvement is that it computes slope length exponent values as a function of overland flow path steepness, soil, and cover-management conditions. Consequently, the RUSLE2 slope length exponent varies as cover-management conditions vary temporally. RUSLE2 automatically computes slope length exponent values from basic input data rather than the user selecting a value as required by RUSLE1.

The slope length exponent should vary with position along the overland flow path according to erosion theory (Foster and Meyer, 1975). However, equation 2.10 is based on the assumption that the slope length exponent is a not a function of position x. The slope length exponent not varying with position greatly simplifies RUSLE2 mathematics and numerical procedures (see **Section 2.3**) and gives RUSLE2 increased robustness for overland flow paths longer than 150 ft (see **Section 5-Appendix I**).

If equation 2.10 is used to compute erosion for a slope length exponent that varies with position, RUSLE2 computes erroneous erosion values for a uniform overland flow path divided into segments, even if conditions are the same for all segments. Computed erosion should be independent of the number and length of segments used to represent a uniform overland flow path.

Some of the sediment produced by interrill erosion is deposited in "rill" areas when overland flow path steepness is low and interrill erosion is sufficiently high. RUSLE2 computes no rill erosion when it computes deposition. RUSLE2 computes this local deposition[41] when interrill erosion rate is greater than the increase in transport capacity with distance along the overland flow path (i.e., $D_i > dT_c/dx$ where D_i = interrill erosion rate, T_c = runoff's sediment transport capacity, and x = distance). Interrill erosion is computed with equation 2.11, dT_c/dx is computed using equation 2.17, and deposition and net erosion is computed using equation 2.16 and its companion equations. RUSLE2-computed net erosion does not vary with distance along the overland flow path as expected (Renard and Foster, 1983; Meyer and Harmon, 1985).

Erosion values computed with equations 2.16 and 2.17 differ from values computed by the empirical USLE, which is equation 2.10. This inconsistency, which should not occur, results from RUSLE2 combining the empirical USLE equation with a process-based sediment transport capacity equation. These equations do not work well together for this condition. A choice must be made as to whether the USLE based erosion value or the process-based erosion value will be the RUSLE2-computed value.

A RUSLE2 development principle is that RUSLE2 compute erosion values agree with USLE computed values (see **Section 1**). The conflict between equation 2.16 and the USLE equation forms, therefore, is resolved by having RUSLE2 produce the same results as the USLE. However, RUSLE2 uses equation 2.16 to compute how local deposition change sediment characteristics.

This procedure works well for local deposition on a uniform overland flow path not subdivided into segments. Subdivision without changing any of the segment variable values should not affect computed erosion and sediment values. Subdivision does not

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[41] Local deposition is where sediment is deposited almost adjacent to the point of detachment such as in soil surface roughness depressions and in furrows between ridges. Remote deposition is where sediment is deposited a significant distance from the point detachment such as at the upper edge of dense vegetation strips and on the toe of concave-shaped overland flow path profiles.

affect computed erosion values but does affect computed enrichment ratio values when RUSLE2 computes local deposition. The RUSLE2-computed enrichment ratio value is correctly computed when a uniform overland flow path is not subdivided.

RUSLE2 was constructed so that its remote deposition computations are independent of segment subdivision. An example of remote deposition is the deposition that occurs at the upper end of a 0.5 percent segment downslope from a one percent steep segment. RUSLE2 also computes local deposition on the 1 percent steep segment if interrill erosion is sufficiently great.

RUSLE2 makes these computations correctly if the upper one percent segment is not subdivided. However, if that segment is subdivided, it will compute erroneous enrichment ratio values, especially if the subdivision is near the upper end of the segment. The erosion values are affected only very slightly by subdivision of the upslope segment.

The error in the enrichment ratio values caused by subdividing the overland flow path is a RUSLE2 flaw. This flaw can not be eliminated because of differences in equation structure between the USLE and the process-based sediment transport capacity equation used in RUSLE2. The enrichment ratio error could have been prevented by developing RUSLE2 entirely from process-based equations. However, RUSLE2's power of giving the well-accepted, empirically derived USLE values would have been lost. RUSLE2 was derived, developed, and evaluated to ensure that inconsistencies, which can not be totally eliminated, are acceptable for the purpose of conservation and erosion control planning. Fortunately, most RUSLE2 conservation planning applications assume a uniform overland flow path without subdivision.

5.3. Topographic equations for overland flow having parallel streamlines on non-uniform overland flow paths

RUSLE2 uses the equations described in **Section 2** to compute erosion and sediment load on non-uniform overland flow paths. The overland flow path is divided into segments where soil, steepness, or cover-management change along the overland flow path. The governing equations are numerically solved along the overland flow path starting at the upper end of the overland flow path where overland flow originates (see **Section 2.3**).

Each soil, steepness, and cover-management variable that changes between segments is treated as a step rather than a continuous change (see **Section 2.3.1**). Assuming step changes is appropriate for most cover-management changes, whereas continuous change is appropriate for changes in soil and steepness for overland flow paths on most natural landscapes.

Steepness at the intersection of two segments could be treated as the average of the steepness of the two segments, which is appropriate for describing an overland flow path where steepness changes continuously along the overland flow path, such as a concave overland flow path profile. However, a continuous change in steepness is not appropriate for constructed slopes where steepness makes a step change. Examples include the intersection a landfill's top with a sideslope and the intersection of a hillslope cut with a flat area. RUSLE2 assumes a step change in steepness to accommodate step changes in steepness common to constructed slopes. The effect of step changes in representing gradual soil and steepness changes along an overland flow path is minimized by dividing the overland flow path into several segments (see the RUSLE2 User's Reference Guide).

A concern in applying RUSLE2 to non-uniform overland flow paths is dealing with changes in infiltration caused by soil and cover-management changes along the overland flow path. RUSLE2 considers how changes in infiltration along an overland flow path affect contouring failure, sediment transport capacity, and deposition. RUSLE2 does not consider how changes in infiltration along an overland flow path affect detachment on a downslope segment. While interrill erosion on a particular segment is only affected by infiltration rate on that segment, rill erosion on a segment is affected by both the runoff generated on that segment and by the runoff that arrives from the upslope area of the overland flow path. This effect can be partially represented by adjusting the upslope overland flow path length to reflect runoff coming into a downslope segment.

Nevertheless, a conflict exists in RUSLE2 between the way that overland flow path distance is treated for computing runoff and the way that overland flow path distance is treated for computing detachment. An example situation is runoff from an upslope pasture draining onto a cultivated field where infiltration on the pasture area is much higher than on the cultivated area. If the actual overland flow length is entered, RUSLE2 computes detachment values that are too high on the cultivated area because runoff reaching the cultivated area will be much less than is implicitly assumed in RUSLE2. If an effective overland flow path length is entered to correctly compute detachment on the cultivated area, RUSLE2 computes runoff rates that are too low on the cultivated area and incorrectly computes detachment on the pasture area. See the RUSLE2 User's Reference Guide for recommendations for selecting overland flow path lengths where infiltration varies greatly along an overland flow path.

The resolution to this problem is to have derived RUSLE2 using process-based erosion equations. Given that most RUSLE2 conservation planning applications involve uniform overland flow paths or overland flow paths where infiltration does not vary greatly along the path, RUSLE2 is considered to produce satisfactory results for most conservation planning applications.

5.4. Applying RUSLE2 to complex topography with converging and diverging overland flow

The RUSLE2 User's Reference Guide describes the proper procedure for applying RUSLE2 to complex topography. The effect of converging and diverging overland flow on RUSLE2 computed erosion is discussed in **Section 5.1**.

The USLE and RUSLE1 are used in GIS applications to compute erosion on topographically complex areas where overland flow converges and diverges. In these applications, overland flow path distance is considered equivalent to upslope drainage area (Desmet and Govers, 1996). This assumption is questionable as discussed in **Sections 5.2** and **5.Appendix I**. The slope length exponent should be a function of upslope drainage area. If the slope length exponent is used as a function of upslope drainage area, the proper numerical procedure must be used. The irregular slope procedure derived by Foster and Wischmeier (1974) assumes that the slope length exponent does not vary with position along the overland flow path. If the slope length exponent is varied with the Foster and Wischmeier irregular slope procedure, erroneous erosion values will be computed (see **Sections 5.3** and **5.Appendix I**).

RUSLE2 is much more complex than the USLE or RUSLE1 regarding the rill to interrill erosion ratio used to compute slope length exponent values. RUSLE2 may be used in GIS applications to represent complex topography where distance along an overland flow path is assumed to be comparable to upslope drainage area. Such applications should be made ***only*** **where infiltration rate varies little spatially and where convergence or divergence of overland flow is minimal.**

A much better approach than using the RUSLE2 equations is to derive separate rill erosion, interrill erosion, and deposition equations using RUSLE2 assumptions, concepts, and equations. In this approach, a discharge rate can be properly computed from upslope drainage area. The discharge rate can be used to compute rill erosion, sediment transport capacity, deposition, and contouring failure. Interrill erosion is computed independent of upslope drainage area.

A common error in using the USLE and RUSLE1 in GIS applications is that excessively long overland flow path lengths are assumed. Inadequate resolution in topographic data, results in excessively long overland flow paths and poor representation of steepness along the overland flow path (Toy and Foster, 2000). The maximum overland flow path length allowed in RUSLE2 is 1,000 ft (see RUSLE2 User's Reference Guide). In fact, overland flow is collected in concentrated flow areas within 200 ft on most farm fields (Foster, 1985).

When using GIS applications to compute erosion, deposition, and sediment yield, separate relationships should be used to compute sediment production and sediment transport capacity needed to compute deposition. Desmet and Govers (1996) illustrate this procedure.

5.5. Slope length exponent

5.5.1. Slope length exponent for standard (non-Req) conditions

The slope length exponent is the exponent m in equations 2.10 and 5.1. The RUSLE2 slope length exponent is a function of the rill to interrill erosion ratio just is it was in RUSLE1 [Foster and Meyer, 1975; McCool et al., 1989; AH703 (Renard et al., 1997)]. However, in contrast to RUSLE1 where the slope length exponent is time invariant, the RUSLE2 slope length exponent varies daily as cover-management conditions change. A value for the RUSLE2 slope length exponent for standard, non-Req conditions is computed daily using equations 2.12 and 2.13 (see **Section 5.2**).

5.5.2. Slope length exponent for Req conditions

The erosion processes that occur during the winter Req conditions (see **Section 3.2.5** and RUSLE2 User's Reference Guide) differ from those that occur with standard rill-interrill erosion. Most of the erosion during Req conditions is by surface runoff. The empirically derived RUSLE2 soil length exponent for Req conditions is m = 0.5 (McCool et al., 1989, 2002); [AH703, (Renard et al., 1997)]. The slope length exponent for Req conditions is time invariant and does not vary with the rill to interrill erosion ratio.

The slope length exponent (equations 2.12 and 2.13) for standard, non-Req rill-interrill erosion can be used for the non-Req period (summer period) at Req locations. Standard rill-interrill erosion can be assumed for the summer months at Req locations. This summer period defined for RUSLE2 as the time between the day when average daily temperature becomes greater than 45 ^oF early in the year to the day average daily temperature falls to 35 ^oF late in the year (see **Section 4.5.1**).

5.6. Steepness effect on rill-interrill erosion

5.6.1. Steepness factors for standard (non-Req) conditions

An interrill erosion steepness factor is used in equation 2.11 and 6.13 to compute interrill erosion and to compute the rill to interrill erosion ratio in several equations (e.g., equations 2.13). A steepness relation for rill erosion is needed to compute rill erosion (e.g., equation 6.13) and the rill to interrill ratio in several equations including equations 2.13. Also, a steepness factor equation is needed to compute rill-interrill erosion combined in equation 2.10.

The same equation used for interrill erosion in RUSLE1 is also used in RUSLE2 [Foster, 1982; AH703 (Renard et al., 1997)]:

$$S_i = 3s_i^{0.8} + 0.56 \qquad [5.1]$$

where: S_i = the interrill erosion steepness factor, s_i = steepness of the interrill area (sine of slope angle). Equation 5.1 is referenced to the unit-plot steepness so that the equation gives a value of 1 for nine percent steepness. The interrill steepness is the same as the overland flow path steepness in RUSLE2. However, the overland flow path steepness and the interrill steepness are not always the same as the land steepness. An example is when RUSLE2 is used to compute erosion on ridge side slopes, where the interrill and overland flow path steepness equals the steepness of the ridge side slopes (see RUSLE2 User's Reference Guide).

A simple rill erosion equation is assumed to compute the rill to interrill erosion ratio (Foster and Meyer, 1975). The steepness factor for rill erosion is:

$$S_r = s_r / 0.0896 \quad [5.2]$$

where: S_r = the rill erosion steepness factor and s_r = steepness of the rill area (sine of slope angle). This steepness factor is normalized to the nine steepness of the unit plot. The steepness of the rill area is the same as the overland flow path steepness, which can differ from the land steepness.

A third steepness factor is used to compute rill-interrill erosion in equation 2.10. The relationship of rill-interrill erosion for a wide range of studies is shown in Figure 5.1 (McCool et al., 1987). These erosion data were normalized to the erosion for 20 percent steepness rather than to the unit plot nine percent steepness.

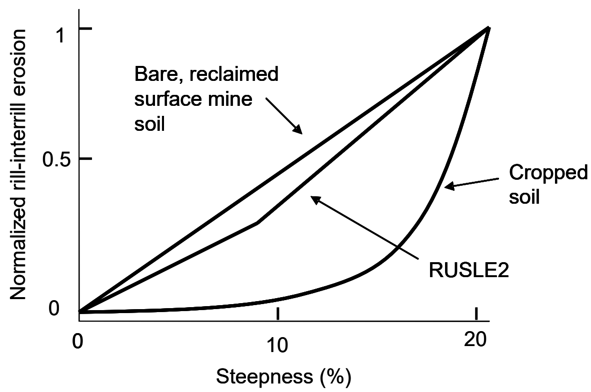

Figure 5.1. Effect of slope steepness on rill-interrill erosion.

The steepness factor for rill-interrill differed greatly among cover-management conditions. At one extreme is where erosion varied linearly for a bare reclaimed, surface mine soil. Steepness had little effect on runoff in this case. At the other extreme is erosion for a cropped soil where the relationship between erosion and steepness is very non-linear. In this case, runoff increased as steepness increased. Most of the erosion for the cropped soil at low steepness is caused by interrill erosion with little or no rill erosion. Once the overland flow path steepness exceeds a critical steepness, rill erosion begins, which results in rill-interrill erosion increasing rapidly. Runoff's shear stress must exceed a critical shear stress for rill erosion to begin, much like contouring failure. The resulting rill erosion equation would have rill erosion being proportional to the difference between shear stress applied to the soil and a critical shear stress related to soil conditions (Meyer et al., 1975b; Foster, 1982; Graf, 1971; Foster et al., 1980a).

The relation of rill-interrill erosion to overland flow path steepness should be a function of the rill to interrill erosion ratio and a critical shear stress at which rill erosion begins. However, in contrast to the temporally varying slope length effect, RUSLE2 uses an invariant slope steepness factor. Although erosion theory indicates reasons why the steepness factor should vary, the experimental plot data were not sufficient to develop a RUSLE2 steepness factor as a function of the rill to interrill erosion ratio, critical shear stress, or other variables. Consequently, RUSLE2 uses the invariant steepness relationship illustrated by the middle curve in Figure 5.1. The equation for that curve is given by [McCool et al., 1987; AH703 (Renard et al., 1997)]:

$$S = 10.8s + 0.03 \quad s_p < 9\% \quad [5.3]$$

$$S = 16.8s - 0.50 \quad s_p \geq 9\% \qquad [5.4]$$

where: S = steepness factor in equation 2.10, s = overland flow path steepness (sine of slope angle) and s_p = overland flow path steepness (100 times tangent of slope angle). Equations 5.3 and 5.4 give a value of 1 referenced to the unit plot 9 percent steepness rather than the 20 percent steepness in Figure 5.1.

5.6.2. Steepness factor for Req conditions

A special steepness factor relationship is used for Req winter conditions because erosion processes for the Req condition differ significantly from the standard rill-interrill erosion conditions. Most of the erosion is caused by surface runoff during the Req conditions. The empirically derived steepness factor for Req conditions is given by [McCool et al., 1987; McCool et al., 1997; AH703 (Renard et al., 1997)]:

$$S = 10.8s + 0.03 \quad s_p < 9\% \qquad [5.5]$$

$$S = (s / 0.0896)^{0.6} \quad s_p \geq 9\% \qquad [5.6]$$

where: 0.0896 = the sine of the angle for 9 percent unit plot steepness. Equations 5.4 and 5.6 are also referenced to the unit plot steepness.

Equations 5.3 and 5.4 can be used for the summer period at locations where the Req winter effects occur.

5.7. Topographic relationships for short overland flow paths (x ≤ 15 ft)

Equation 2.10 does not apply for short overland flow path distances because these equations compute a zero erosion rate for a zero overland flow path length. Erosion rate should equal the interrill erosion rate at the origin of overland flow (x = 0). Experimental interrill erosion studies show that overland flow path length must be about 15 feet before rill erosion begins to occur (Meyer and Harmon, 1989), a distance that is also consistent with field observations, including rainfall simulator studies of the variables that affect rill-interrill erosion (Meyer et al., 1975ab). Therefore, equation 2.10 is assumed not to apply to short overland flow path distances less than 15 ft.

5.7.1. Overland flow steepness < 9 percent

The overland flow path distance x is set to 15 ft when the actual overland flow path distance is less than 15 ft to represent the concept that interrill erosion is independent of distance. The preferred steepness factor for interrill erosion is equation 5.1, but his equation conflicts with the empirically derived rill-interrill erosion S factor given by equation 5.3 for steepness less than 9 percent. Therefore, the rill-interrill erosion steepness factor, equation 5.3, is used for all overland flow distances less than 15 ft if the overland flow path steepness is less than 9 percent. The variables used for $(x/\lambda_u)^m S$ in equation 2.10 are $(15/72.6)^m S_i$ where S_i is the rill-interrill steepness factor computed from equation 5.3, 15 = 15 ft, the overland flow path length assumed for all overland flow path lengths less than 15 ft, and 72.6 = 72.6 ft, the unit plot length.

5.7.2. Overland flow path steepness ≥ 9 percent

5.7.2.1. Overland flow path length ≤ 3 ft

The inconsistency between the interrill steepness factor, equation 5.1, and the rill-interrill steepness, equation 5.4, does not occur when overland flow path steepness exceeds 9 percent. If the overland flow path length is less than or equal to 3 ft, the rill-interrill steepness factor in equation 2.10 equals the interrill steepness factor, equation 5.1. The overland flow path distance is set to 15 ft regardless of actual overland flow path distance. The variables used for $(x/\lambda_u)^m S$ in equation 2.10 are $(15/72.6)^m S_i$ where S_i is the interrill steepness factor computed from equation 5.1, 15 = 15 ft, the overland flow path length assumed for all overland flow path lengths less than 15 ft, and 72.6 = 72.6 ft, the unit plot length.

5.7.2.2. Overland flow path 3 ft < x ≤ 15 ft

A logarithmic interpolation is used to transition between the interrill steepness factor, equation 5.1, at a 3 ft overland flow distance to the rill-interrill steepness factor, equation 5.4, at a 15 ft overland flow distance. This interpolation is computed as:

$$\alpha_3 = (3/72.6)^m S_i \qquad [5.7]$$

$$\alpha_{15} = (15/72.6)^m S \qquad [5.8]$$

where: α_3 and α_{15} = the combined distance and steepness factor for 3 ft and 15 ft overland flow path lengths, respectively, at the given steepness, 15 = 15 ft, the assumed overland flow path distance for all actual overland flow path distances less than 15 ft. The interrill steepness factor S_i, equation 5.1, is used to compute and S = the rill-interrill steepness factor, equation 5.3, is used to compute the steepness effect at a 15 ft overland flow distance. A logarithmic interpolation is made between α_3 in equation 5.7 and α_{15} in equation 5.8 as:

$$\ln(\alpha_x) = [\ln(\alpha_{15}) - \ln(\alpha_3)][(\ln(x) - \ln(15)]/[\ln(15) - \ln(3)] + \ln(\alpha_3) \qquad [5.9]$$

$$\alpha_x = \exp[\ln(\alpha_x)] \qquad [5.10]$$

where: α_x = the combined length and steepness factor at the overland flow distances between 3 and 15 ft and an overland flow path steepness greater than 9 percent. This distance and steepness factor value is used in equation 2.10 for the variables $(x/\lambda_u)^m S$.

5.8. Effect of position along overland flow path on soil loss tolerance (T) factor

The powerful conservation planning approach of comparing an estimated erosion rate to an allowable erosion rate developed in the mid 1940's (Mannering, 1981; McCormack and Young, 1981; Toy et al., 2002). Erosion control practices resulting in an estimated erosion rate that is less than the allowable erosion rate are considered to provide adequate erosion control for the site. Soil loss tolerance (T) values assigned to soil mapping units in the USDA-NRCS Soil Survey are widely used for allowable erosion rate on croplands.[42] Other values for the erosion control criteria are used when RUSLE2 is applied to other lands including construction sites and rangelands. For example, very low soil loss tolerance values are used for very fragile soils that are easily damaged by erosion. Soil loss tolerance values larger than those used for cropland are often used for construction sites for the disturbance and reclamation periods. However, cropland soil loss tolerance values are used for the after-reclamation period where maintenance of the soil for long-term vegetation production is the primary erosion control concern.

Erosion is not considered excessive if the estimated erosion rate is less than the T value. The procedure implicitly assumes a uniform overland flow path, which is common practice in most erosion prediction applications and in research used to determine soil loss tolerance (T) values. The average erosion rate for the entire overland flow path, rather than maximum erosion rate, is compared to the soil loss tolerance (T) value.

The erosion rate computed with RUSLE2 varies along even a uniform overland flow path from an interrill erosion rate at the origin of overland flow ($x = 0$) to ($m+1$) times the average erosion rate for the entire overland flow path length at the end of the path ($x = \lambda$). Therefore, erosion rate over the approximate lower one half of uniform overland flow paths exceeds T when the average erosion rate for the overland flow path equals T. That is, the conservation planning criteria does not require that maximum erosion rate along an overland flow path be less than soil loss tolerance; only that average erosion rate for a uniform overland flow path be less than soil loss tolerance [AH703 (Renard et al., 1997); Toy et al., 2002].

Comparing average erosion rate for the overland flow path to soil loss tolerance is not appropriate for overland flow paths on non-uniform shape profiles, especially convex profiles. To make these comparisons, RUSLE2 computes an adjusted soil loss tolerance value that is compared against the RUSLE2 estimated erosion rate for each segment along a non-uniform overland flow path (see the RUSLE2 User's Reference Guide). The comparison with the adjusted T value puts conservation planning on the same basis for non-uniform overland flow paths as for a uniform overland flow path. The adjusted soil

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[42] Soil loss tolerance (T) values have a specific definition in the NRCS Soil Survey and NRCS RUSLE2 applications. However, T in general RUSLE2 applications refers to the erosion control criteria used in a specific RUSLE2 application. This value can be quite different from the assigned NRCS T value depending on the application. See the RUSLE2 User's Reference Guide.

loss tolerance values are the T factor values for the soil on *jth* segment times a factor value computed with [(AH703 (Renard et al., 1997)]:

$$F_j = (x_j^{m_i+1} - x_{j-1}^{m_i+1})/[(x_j - x_{j-1})\lambda^{m_i}] \qquad [5.11]$$

where: F_j = the factor that is used to multiply the soil loss tolerance (T) value to obtain a soil loss tolerance value adjusted based on the position of the *jth* segment along the overland flow path, x_j = distance to the lower end of the *jth* segment, m_j = slope length exponent for the *jth* segment, and λ = the entire length of the overland flow path. The ratio of computed erosion rate to the adjusted soil loss tolerance value is the same for all segments along a uniform overland flow path.

5.9. Conservation planning soil loss

RUSLE2 computes a conservation planning soil loss where deposition is given partial credit based on the location where the deposition occurs along the overland flow path. This type of deposition, which is referred to as remote deposition, occurs on concave overland flow path profiles and at the upper edge of dense vegetations strips. The use of conservation planning soil loss in conservation planning is discussed in the RUSLE2 User's Reference Guide, and the equations used to compute a value for conservation planning soil loss are given in **Section 2.3.10.4**.

Partial credit for deposition as soil saved also is taken with terraces. The deposition credit decreases as terrace spacing increases beyond 90 ft. However, the credit for deposition remains constant for terrace spacing closer than 90 ft.

High ridges spaced about 3 ft apart on a uniform, nearly flat grade act like small terraces. RUSLE2 can be applied to the ridge side slopes just like RUSLE2 is applied to the inter-terrace interval. The furrows between the ridges act like terrace channels. The deposition in the furrows should be treated as local deposition rather than remote deposition. The conservation planning soil loss that RUSLE2 computes for this case incorrectly assumes that this deposition is remote deposition. The user should ignore the conservation planning soil loss and use sediment yield as the conservation planning soil loss.

5.10. List of symbol

a = coefficient that is product of terms that do not vary with x in $D = ax^m$

a_e = product of terms that do not vary with x in $D = a_e x_e^m$ when x_e is the overland flow distance adjusted in proportion to upslope drainage area for converging runoff surface

a_p = product of terms that do not vary with x in equation $D = a_p x^m$ when runoff streamlines are parallel

a_T = product of terms that do not vary with x in sediment transport capacity equation $T_c = a_T q$

A = average combined rill-interrill erosion rate for the slope length λ (mass/area·time)

D = combined rill-interrill erosion (detachment) rate at location x along an overland flow path (mass/area·time)

D_i = interrill erosion rate (mass/area·time)

D_r = rill erosion rate (mass/area·time)

D_{rc} = capacity rill erosion rate (mass/area·time)

F = factor used to multiply soil loss tolerance (T) to obtain adjusted soil loss tolerance value based on position of segment along overland flow path

g = sediment load (mass/width·time)

g_λ = sediment load at end of overland flow path

k_c = product of terms that do not vary with x in equation $A = k_c\lambda^m$

k_r = product of terms that do not vary with x in rill erosion equation $D_r = k_r x$

m = slope length exponent

q = discharge rate (volume/width·time)

q_c = discharge rate at which runoff shear stress applied to soil equals the soil's critical shear stress

s = overland flow path steepness (sine of slope angle)

s_i = interrill area steepness (sine of slope angle)

s_p = overland flow path steepness (100 times tangent of slope angle)

s_r = rill area steepness (sine of slope angle)

S = combined rill-interrill erosion steepness factor

S_i = interrill erosion steepness factor

S_r = rill erosion steepness factor

T = soil loss tolerance (mass/area·time)

T_c = runoff's sediment transport capacity (mass/width·time)

$T_{c\lambda}$ = runoff's sediment transport capacity at end of overland flow path (mass/width·time)

W = width of runoff surface at location x (length)

x = distance along overland flow path (length)

x_e = distance along overland flow path that is proportional to upslope drainage area for converging runoff surface (length)

α_x = combined length and steepness factor at overland flow distances between 3 and 15 ft and overland flow path steepness greater than 9 percent

α_3 = combined distance and steepness factor for 3 ft overland flow path length at a particular steepness

α_{15} = combined distance and steepness factor for 15 ft overland flow path length at a particular steepness

Δ = change in a variable

β = ratio of rill erosion sediment load to interrill erosion sediment load

λ = overland flow path length

λ_u = unit plot overland flow path length (72.6 ft, 22.1 m)

ρ = term in equation $\beta = \rho x$

σ = excess rainfall rate (length/time)

Indices

j – segment

5.Appendix 1. Slope length exponent that varies with position

5.Appendix 1.1. Derivation of equations

The RUSLE2 slope length exponent m does not vary with position along the overland flow path. The topographic equations for the slope length exponent m varying with position along the overland flow path are much more complex than the equations used in RUSLE2. The additional complexities and reduced robustness did not warrant their use in RUSLE2 for routine erosion-control planning in local field offices. However, a variable slope length exponent m that varies with position along the overland flow path is very important for applying RUSLE2 to landscapes where surface runoff converges or diverges. Representation of flow convergence/divergence must be considered when RUSLE2 equations are used in GIS models applied to three dimensional landscapes.

In the 1940's when erosion prediction was first developed as an erosion-control planning tool, the following simple empirical equation became widely accepted for describing how erosion varies with overland flow path length for uniform slopes (Zingg, 1940).[43]

$$A = k_c \lambda^m \qquad \text{[V.1]}$$

where: A = average erosion rate (mass/area·time) for the slope length λ, k_c = a term that combines the other terms used to compute A that are not a function of λ, and m = the slope length exponent. Equation V.1 is a derived equation. The equation that actually represents the measured field data is:

$$g_\lambda = k_c \lambda^{m+1} \qquad \text{[V.2]}$$

where: g_λ = the sediment load (mass/width·time) at the end of the slope length λ, which was the measured sediment discharge from the plots used to measure erosion. The term A in equation V.1 was determined by dividing equation V.2 by the slope length λ. Soil loss A was the variable needed in erosion-control planning.

Equation V.2, not equation V.1, is the starting point for developing RUSLE2 (and the USLE and RUSLE1) equations that represent spatial variability along overland flow paths (Foster and Wischmeier, 1974). The equation for detachment at any point along a uniform overland flow path can be derived by differentiating equation V-2 as:

$$D = dg / dx \qquad \text{[V.3]}$$

where: D = detachment rate (mass/area·time) at the location x along an overland flow path. The derivation of a detachment equation is simple where the slope length exponent m is not a function of position x along the overland flow path. By inspection, equation

[43] Uniform means that steepness does not vary with x and the surface runoff streamlines are parallel.

V.2 is recognized to compute sediment load g (mass/width·time) at any position x along a uniform slope as well as sediment load at the end of the overland flow path. If m does not vary with position, the detachment equation is:

$$D = (m+1)k_c x^m \qquad \text{[V.4]}$$

Equation V.4 is equation 2.10 with terms except x and m combined in k_c. **Thus, equation 2.10 is based on the assumption that m does not vary with x**. Consequently, the rill to interrill erosion ratio term in equation 2.13 does not contain a distance (x or λ) term. Equation V.4 does not correctly compute detachment if m is varied by segment. If that computation is attempted, sediment load values at the end of the overland flow path for a uniform overland flow path become a function of how many segments and their lengths that are used to divide the overland flow path even if conditions do not vary between segments. **Therefore, if the slope length exponent m is to vary with position x, a new detachment equation must be derived to replace equation 2.10**.[44]

The slope length exponent m was observed to vary from about 0 to 1 for measured ersion data (McCool et al., 1989). Other than m increasing with slope steepness up to five percent steepness, possible reasons for m varying did not seem to be understood when the USLE was developed (Wischmeier and Smith, 1975; Foster and Meyer, 1975).

As early as the mid 1940's, detachment on overland flow areas was recognized to be caused by raindrop impact and surface runoff (Ellison, 1947). Detachment by flow varied much more along the overland flow path than detachment by raindrop impact. These terms are written as (Meyer and Wischmeier, 1969; Foster and Meyer, 1975):

$$D = D_r + D_i \qquad \text{[V.5]}$$

where: D_r = rill erosion (mass/area·time), D_i = interrill erosion (mass/area·time), and D = the total of rill and interrill erosion (mass/area·time) at the location x. Interrill erosion is assumed not to vary along a uniform overland flow path, while rill erosion is assumed to vary with (Foster and Meyer, 1975):

$$D_r = k_r x \qquad \text{[V.6]}$$

where: k_r = a product of terms that do not vary with x. The combined equation for rill-interrill erosion is therefore:

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[44] RUSLE2 did not have the slope length exponent m as a function of x to avoid extrapolation too far beyond the experimental data. Only two sets of plots used to derive RUSLE2 had overland flow path lengths greater than 150 ft. Not having the slope length exponent vary with position x significantly increases RUSLE2's robustness, which is important for an erosion control planning tool.

$$D = k_r x + D_i \qquad [V.7]$$

Equation V.4 was chosen as the basic RUSLE2 detachment equation because a wide array of empirically derived and **accepted** factor values are available for that form (see **Section 1**). Equation V.7 was used to extrapolate equation V.4 to conditions beyond that represented in the USLE plot data.

The RUSLE2 approach was to start with equation V.4 and mold it to equation V.7 as much as possible. However, the difference in equation form between equations V.4 and V.7 causes conflict within RUSLE2. Rules were established to deal with those conflicts (see **Section 2.3.8.3**).

The m value for equation V.7 increases from 0 at x = 0 to 1 as either x or k_r becomes large or D_i becomes small (McCool et al., 1989). Mathematical analysis of equation V.7 shows that the slope length exponent m varies from 0 to 1 and is a function of the rill to interrill erosion ratio as (Foster and Meyer, 1975):

$$m = \beta / (\beta + 1) \qquad [V.8]$$

where: β = the ratio of rill sediment load to interrill erosion sediment load, which is equation 2.12. The equation for β from equation V.7 is:

$$\beta = \frac{(k_r x / 2)}{D_i} \qquad [V.9]$$

which is equation 2.13 with an x term in the numerator.

Equation V.9 can be simplified to:

$$\beta = \rho x \qquad [V.10]$$

where: $\rho = k_r/2D_i$. Substitution of equation V.10 into equation V.8 gives:

$$m = \rho x / (\rho x + 1) \qquad [V.11]$$

Substitution of equation V.11 into equation V.2 gives:

$$g = k_c x^{[\rho x / (\rho x + 1)] + 1} \qquad [V.12]$$

The equation form for sediment load when the slope length exponent m varies with position x differs significantly from equation V.2, which is the RUSLE2 form. An equation for D can be derived by differentiating equation V.12 with respect to x. The resulting equation is much more complicated than equation V.4 used in RUSLE2. However, equation V.12 can be solved numerically to determine values for average detachment for a segment to route sediment downslope as described in **Section 2.3**. However, equation V.12 was not used in RUSLE2 because of concerns about its robustness.

Equation V.12 is based on the assumption that equation V.6 describes rill erosion. Equation V.6 could be written as:

$$D_r = k_r q \qquad [V.13]$$

where: q = discharge rate (volume/width·time), q = σx where σ = excess rainfall rate (length/time) that is assumed to be constant along the overland flow path, and k_r = a collection of terms that do not vary with x.

A case can be made for two other rill erosion equation forms. One form is (Meyer et al., 1975):

$$D_r = k_r(q - q_c) \qquad if\,(q \le q_c) D_r = 0 \qquad [V.14]$$

where: q_c = the discharge rate where runoff shear stress applied to soil exceeds the soil's critical shear stress and rill erosion begins and k_r = the collection of terms that do no vary with x.

A case can also be made for (Foster and Meyer, 1975):

$$D_r = D_{rc}(1 - g/T_c) \qquad [V.15]$$

where: D_{rc} = detachment capacity (mass/area·time) computed with equation V.6 or V.14 and T_c = runoff's sediment transport capacity (mass/width·time). Transport capacity is computed with:

$$T_c = a_T q \qquad [V.16]$$

where: the term a_T is the product of terms that do not vary with position x. Equation V.15 reduces rill erosion as transport capacity becomes filled with sediment on long overland flow paths or where sediment production rate by rill or interrill erosion is very high.

As Figure V.1 shows, the ax^m form (equation 2.10) fits well the equation form D_i+k_rx except for short overland flow paths. This deficiency is corrected as described in Section 5.7. However, neither of these two equation forms fits V.14 or V.15, an equation form that involves a critical shear stress term for estimating rill erosion.

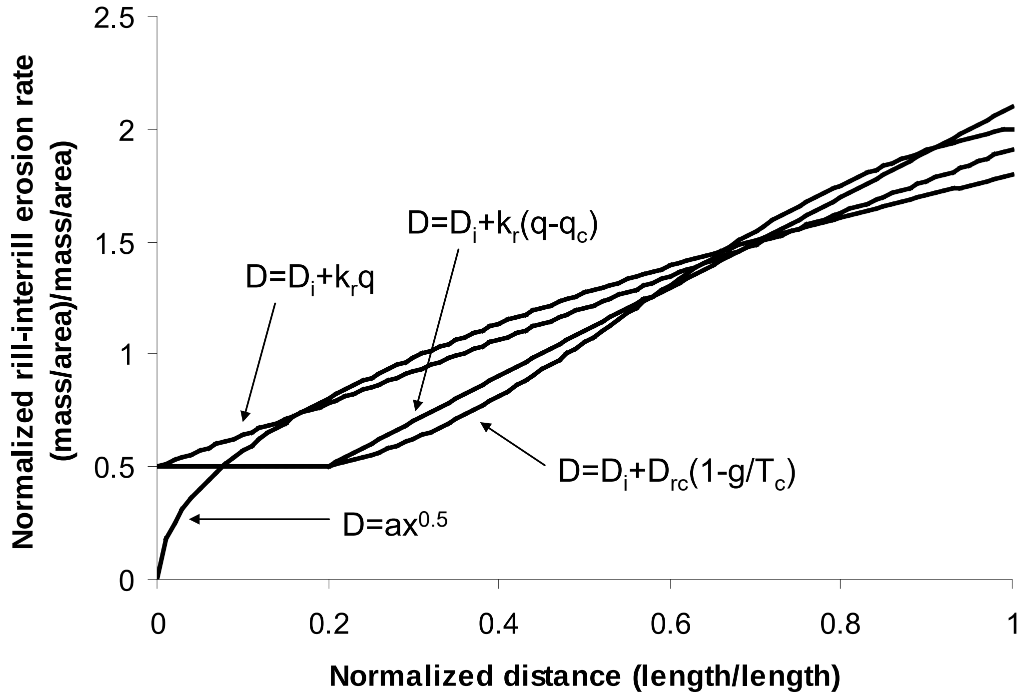

Figure V.1. Variation of detachment along an overland flow path for various rill erosion equation forms.

These advanced rill erosion equation forms greatly complicate RUSLE2 mathematics and further reduce RUSLE2's robustness of. A questionable gain in accuracy while losing robustness is not a wise choice for RUSLE2 as an erosion control planning tool. Choices were made in RUSLE2 that favor robustness for erosion control planning. RUSLE2 may not be as accurate as it could be but it is less likely to give poor results because of uncertainties when extrapolated.

5.Appendix 1.2. Implications for use of RUSLE2 in GIS models

A sediment transport capacity equation should be included with RUSLE2 detachment equations when RUSLE2 is used in a GIS model that computes that computes the spatial variability in erosion and deposition over the landscape. Equation 2.10 is used to compute sediment production (detachment) and equation 2.17 and other equations are used to compute deposition. A sediment transport capacity is required to compute deposition, and a deposition equation like equation 2.16 should be used also. The RUSLE2 sediment production equation (i.e., equation 2.10) does not and can not be used to compute deposition that occurs on the toe of many natural hillslopes.

Also, the RUSLE2 detachment equation 2.10 should be modified to compute how erosion varies with either converging or diverging surface runoff. Applying equation 2.10

without varying the slope length exponent m can result in significant error, even when the overland flow path length is varied in proportion to upslope drainage area.

5.Appendix 1.2.1. Computing detachment and sediment transport capacity

RUSLE2 computes sediment transport capacity per unit width as a function of discharge rate per unit width. An equivalent overland flow path length can be used to represent a converging or diverging landscape to compute discharge rate per unit width and sediment transport capacity per unit width. However, RUSLE2 does not compute the proper sediment production (detachment) values because equation 2.10 does not contain a runoff term. The equivalent overland flow path length that works for computing sediment transport capacity is not the equivalent length required to compute detachment. Furthermore, even though the overland flow path length is adjusted, the slope length exponent m also should be varied with position along the overland flow path to properly represent convergence/divergence in computing detachment with equation 2.10.

5.Appendix 1.2.2. Equations for RUSLE2 in a GIS model

A simple erosion model can be used to evaluate the behavior of RUSLE2 equations in a GIS model. The watershed for a single rill on a hillslope where the streamlines are parallel is a rectangle of width W and length λ. The watershed for a single rill on a converging surface is pie (wedge) shaped. The width at the upper end is 2W and 0 at the lower end. Figure V.2 shows a plot of computed erosion along the overland flow path where streamlines are parallel and where streamlines converge. Erosion was computed with the equation form D_i+k_rq using discharge rate computed by multiplying the excess rainfall rate by the upslope area divided by the watershed width at x. This equation form is assumed to give the desired values, and thus the other equation forms are compared against this one.

The x in the ax^m equation form in Figure V.2 is proportional to upslope drainage area. As Figure V.2 shows, the ax^m approximation does well where streamlines are parallel except for short overland flow paths. In contrast, the ax^m approximation does not work well where the streamlines converge.

When discharge is assumed to be a broad sheet flow across the individual rill watersheds, discharge rate rapidly increases and approach infinity as x approaches λ, the overland flow path length. A corresponding increase in rill erosion is computed. An infinite discharge rate per unit width at $x = \lambda$ computes an infinite rill erosion rate. Such high erosion rates near the end of converging surfaces are not observed in the field. Consequently, the broad sheet flow assumption should not be used without carefully constructed limits on converging surfaces. This problem does not exist on diverging surfaces.

A better approach than assuming broad sheet flow across the entire rill watershed is to assume that surface runoff is concentrated in defined rills. The overland flow path ends where the interrill path length becomes zero, which is where the rill edges meet. Discharge rate (volume; not volume per unit width) does not go to infinity, which means that rill erosion rate does not go to infinity (Toy and Foster, 2000).

The other equation form evaluated in Figure V.2 is equation V.12 where the slope length exponent varies with distance along the overland flow path. This equation was solved numerically to compute detachment along the overland flow path. In these computations, the slope length exponent m was varied with discharge rate rather actual distance to reflect the increase in rill erosion as the surface runoff converges. This approach, while improved, is less than satisfactory.

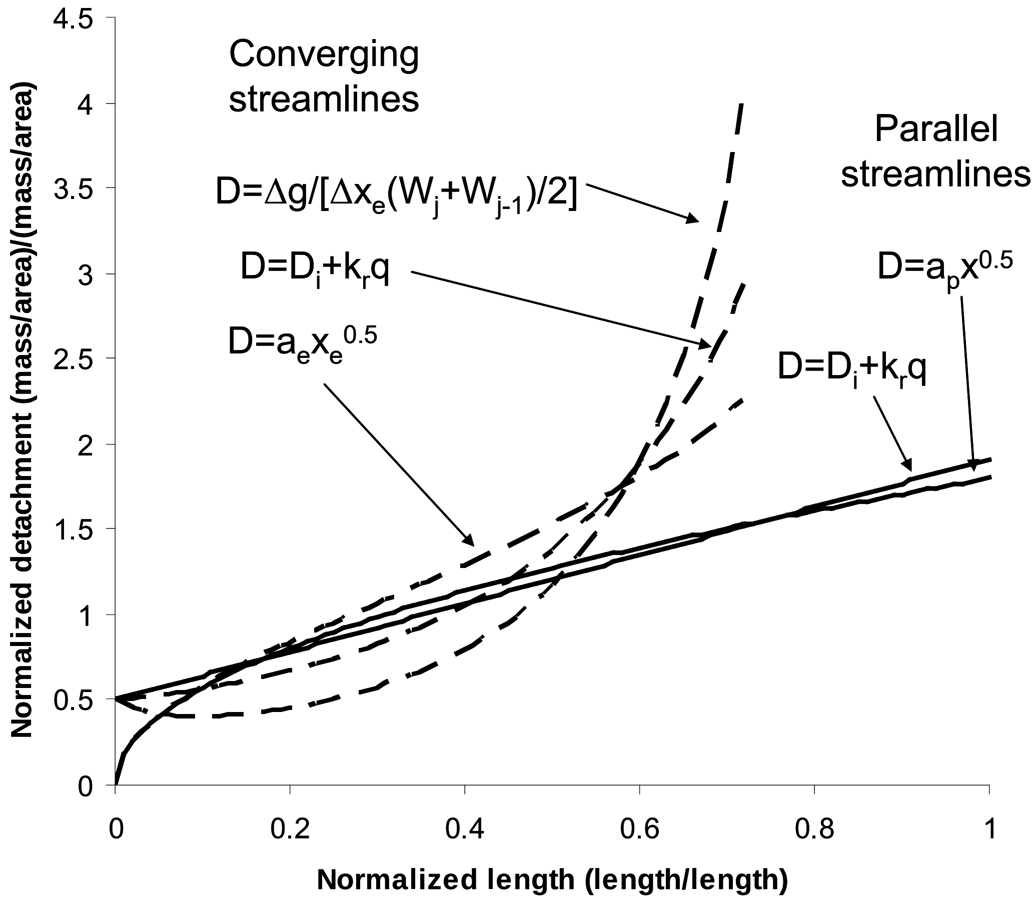

Figure V.2. Erosion along the overland flow paths for parallel and for a converging streamlines.

None of the approximations compare well to the preferred erosion equation that has separate terms for rill and interrill erosion. The best approach in applying RUSLE2 in a GIS model is to devolve the equation 2.10 into separate terms for rill and interrill erosion. Discharge rate can be computed and used directly in both the detachment and sediment transport equations without having to make the overland flow path length proportional to upslope drainage area. This approach would significantly simplify RUSLE2 and would remove the inconsistencies between equation forms.

6. COVER-MANAGEMENT

Equation 2.10 includes the term c used to compute the main effect of cover-management on detachment. The c factor is the product of subfactors as:[45]

$$c = c_c g_c s_r r_h s_b s_c s_m \quad [6.1]$$

where: c = daily cover-management factor, c_c = daily canopy subfactor, g_c = daily ground (surface) cover subfactor, daily s_r =soil surface roughness subfactor, r_h = daily ridge height subfactor, s_b = daily soil biomass subfactor, s_c = daily soil consolidation subfactor, and s_m = daily antecedent soil moisture subfactor used when RUSLE2 is applied in Req zones (see RUSLE2 User's Reference Guide). A daily cover-management c factor value is computed using daily values for each of the subfactors in equation 6.1.[46]

6.1. Canopy subfactor

Canopy is live and dead vegetative cover above the soil surface that intercepts raindrops but does not contact the surface runoff. The portion of the above ground plant biomass touching the soil surface is treated as live ground cover. The canopy subfactor equation is (Wischmeier, 1975; Yoder et al. 1997):

$$c_c = 1 - f_{ec} \exp(-0.1 h_f) \quad [6.2]$$

where: f_{ec} = daily effective canopy cover (fraction) and h_f = daily effective fall height (ft). Equation 6.2 is based on how canopy cover affects the impact energy of waterdrops falling from canopy that has intercepted rainfall. The impact energy of a waterdrop striking the soil surface is:

$$e_d = m_d V^2 / 2 \quad [6.3]$$

where: e_d = impact energy of the waterdrop, m_d = waterdrop mass, and V_d = the waterdrop impact velocity.

Canopy cover affects waterdrop impact energy in several ways. Canopy cover increases the size of waterdrops falling from the canopy. Waterdrops falling from canopy have

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[45] The RUSLE2 subfactor procedure is an extension of the RUSLE1 procedure [AH703 (Renard et al., 1997)]. The RUSLE2 procedure has several scientific improvements and added capability, and it uses of a daily time step rather than the RUSLE1 half-month time step. The RUSLE1 and RUSLE2 subfactor procedures are patterned after ones developed and used by Wischmeier (1975); (Wischmeier, 1978); Dissmeyer and Foster (1981); Mutchler et al. (1982); and Laflen et al. (1985).

[46] This section describes the subfactor relationships. Other sections describe how RUSLE2 computes values for variables used by the subfactor equations.

about a 3 mm drop diameter compared to 1.5 mm for median drop diameter of raindrops (Wischmeier, 1975). Therefore, canopy must be sufficiently close to the ground surface for waterdrops falling from canopy to have reduced impact velocity to offset the increased mass of waterdrops falling from canopy in comparison to raindrops. Because of the increased drop size, the impact energy of water drops falling from tall canopies, (e.g., 30 ft high) exceeds the impact energy of raindrops (Chapman, 1948). Equation 6.2 is based on an assumed 3 mm diameter for waterdrops falling from canopy and empirical fall velocities of waterdrops based on effective fall height h_f (Gunn and Kinzer. 1949).

Equation 6.2 should be interpreted as empirically representing the main effects of canopy cover on detachment with a particular equation form rather than describing how a physical variable, impact energy, affects detachment. Equation 6.2 does not directly represent all of the ways that canopy affects detachment. For example, some of the intercepted rainfall becomes stem flow and reaches the soil surface without falling from the canopy. Also, some of the intercepted rainfall evaporates from the vegetation, never to reach the soil surface by drop impact or stemflow. Also, RUSLE2 does not consider how wind driven rainfall in conjunction with vegetation affects erosion.[47]

Input effective fall height values are chosen based on judgment of how canopy of a particular plant type affects erosion (see RUSLE2 User's Reference Guide). The reference fall height, illustrated in Figure 6.1, is one third of the distance from the bottom of the canopy to the top of a canopy for a cylindrical shaped canopy where the vegetative surface area is uniformly distributed along the vertical axis of the canopy.

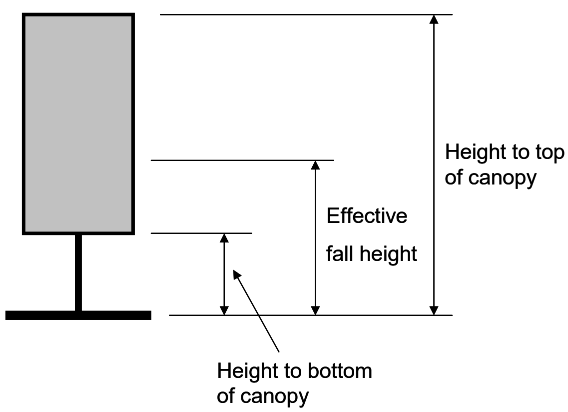

Figure 6.1. Effective fall height for a cylindrical shaped, uniform gradient canopy.

RUSLE2 also includes an equation that can be used to compute effective fall height. The equation is a function of canopy shape, vertical gradient of vegetative surface area, and heights to the bottom and top of the canopy. The effective fall height equation is:

$$h_f = h_b + a_s a_g (h_t - h_b) \qquad [6.4]$$

where: h_b = the height to the bottom of the canopy, h_t = the height to the top of the canopy, and a_s = a coefficient that is a function of canopy shape, and a_g = a coefficient

[47] An improved approach would be to divide equation 6.2 into two parts, one part related to interrill erosion and one part related to rill erosion.

Table 6.1. Values for the coefficient a_s used to estimate effective fall height as a function of canopy

Canopy shape	Value
Inverted trianagle	0.5
Rectangle	0.33
Diamond	0.29
Round	0.29
Triangle	0.25

Table 6.2. Values for coefficient a_g used to estimate fall height as a function of concentration of surface area within canopy.

Location of surface surface area concentration	Value
Top	1.33
Toward top	1.17
Uniform	1.00
Toward bottom	0.88
Bottom	0.75

related to the height within the canopy where vegetative surface area is concentrated. Values for the coefficient a_s and a_g are given in Tables 6.1 and 6.2, respectively.

Some vegetation communities involve multiple plant types that produce over and under stories. RUSLE2 uses only a single set of variables to represent the net effect of canopy on erosion. RUSLE2 does not mathematically combine sets of values for over and under stories nor does RUSLE2 separately compute how each canopy type affects erosion. RUSLE2 uses a single set of values in equation 6.2 to compute the net canopy effect for the vegetation that exists on any given day.

In addition to varying with plant community type, effective fall height varies with production (yield) level and with time as vegetation emerges, grows, matures, and experiences senescence. The RUSLE2 computes effective fall height as a function of production (yield) level and time (see **Sections 9.1** and **9.3.3.3)**.

Canopy cover directly above ground cover is assumed not to affect erosion. The equation used to compute daily effective canopy cover f_{ec} is:

$$f_{ec} = f_c(1 - f_g) \qquad [6.5]$$

where: f_c = daily canopy cover (fraction) and f_g = daily net ground cover, which takes into account the overlap of different types of ground (surface) cover (see **Section 10.2.4**). Net ground cover equals 1 – fraction of the soil surface exposed to direct waterdrop impact from either rainfall or waterdrops falling from canopy.

Furthermore, the RUSLE2 assumption is that canopy cover affects erosion the same way as does ground cover when effective fall height becomes zero. Therefore, the value for the canopy subfactor c_c can not be less than the ground cover subfactor g_c when ground cover equals the effective canopy cover value f_{ec}.

6.2. Ground cover subfactor

Ground cover is provided by material directly in contact with the soil surface. Ground cover affects both waterdrop impact, which in turn affects interrill erosion, and surface runoff, which in turn affects rill erosion. The RUSLE2 equation for the ground cover subfactor is given by (Foster and Meyer, 1975; Laflen et al., 1985; Yoder et al., 1997):

$$g_c = \exp[-bf_g(0.24/R_a)^{0.08}] \qquad [6.6]$$

where: **b** = a coefficient (percent^{-1}) that describes the relative effectiveness of the ground (surface) cover for reducing erosion, f_g = net ground cover (percent), R_a = adjusted roughness used to compute the soil surface roughness subfactor (inches) (see **Section 6.3**), and 0.24 is the assumed adjusted soil surface roughness value (inches) for unit plot conditions. Research has shown that a single variable, portion of the soil surface covered by material directly in contact with the soil surface, describes how all types of ground (surface) cover affects rill-interrill erosion. Analysis based on fundamental erosion mechanics shows that large diameter, long pieces of material, such as intact corn stalks, perpendicular to the overland flow path should affect rill-interrill erosion per unit of soil surface covered more than small diameter, flat pieces (Brenneman and Laflen, 1982). A special concern is how rock fragments on the soil surface affects rill-interrill erosion (see **Section 4.6**). However, when data from various types and rates of surface cover are combined, portion of the soil surface covered seems adequate as a single ground cover variable to use in the ground cover subfactor, equation 6.6 (Box, 1981; Dickey et al., 1983; Dickey et al., 1985; Laflen and Colvin, 1981; Meyer et al., 1972; Simanton et al., 1984; Meyer et al., 1970; Swanson et al., 1965; 1970; Mannering and Meyer, 1963; Meyer and Mannering, 1967).

Net ground cover used in equation 6.6 takes into account the overlap of ground cover materials. For example, applied materials, such as mulch and erosion control blankets, and plant residue are assumed to lie on top of rock cover entered in the RUSLE2 soil input. Live ground cover is assumed to lie on top of applied material and plant residue. Thus, net ground cover (percent) is 100 – bare ground (percent).

The soil surface roughness term in equation 6.6 computes a reduced effect of ground cover on rough soil surfaces. The RUSLE2 assumption is that ground cover in soil depressions is covered by water and deposited sediment, and therefore has no effect on erosion.

The RUSLE2 ground cover subfactor computed with equation 6.6 only partially captures the effect of ground (surface) cover material on rill-interrill erosion. A RUSLE2 ground cover subfactor value is primarily the ratio of rill-interrill erosion at a given point in time with ground (surface) cover to rill-interrill erosion from the same soil in unit plot conditions. The effect most represented by the RUSLE2 ground cover subfactor is how the physical presence of surface cover material affects the erosive forces applied to the soil by impacting raindrops and waterdrops falling from canopy and surface runoff. Other subfactors, such as soil surface roughness and soil biomass, are affected by ground (surface) cover materials (see **Sections 6.3 and 6.5**).

Many of the **b** values reported in the literature were determined by plotting erosion solely a function of ground cover. The RUSLE2 **b** values used in equation 6.6 are not the same as the literature **b** values. The RUSLE2 **b** values are smaller than the literature values because the literature **b** values include other effects not included in equation 6.6. Erosion values were computed with RUSLE1 for a range of corn yields for mulch-till and no-till cropping systems to illustrate this difference. The net **b** value for equation 6.6 without the surface roughness terms fitted to erosion values plotted as a function as cover immediately after planting was 0.058. In comparison, the **b** values used in equation 6.6

as used in RUSLE1 were 0.031 for the mulch till systems and 0.04 for the no-till systems. The conclusion of this preliminary analysis using RUSLE1, which uses a similar but simpler cover-management subfactor method, is that **b** values used in the RUSLE2 subfactor method can not be compared to widely reported literature values. Also, terms in addition to ground cover are needed in the RUSLE2 subfactor procedure to adequate how cover-management affects erosion, even for the same cover-management practice.

6.2.1. b value (ground cover effectiveness index)

6.2.1.1. Literature b values

Research shows that **b** values derived from measured erosion data range from approximately 0.025 to greater than 0.1 (Box, 1981; Colvin and Gilley. 1987; Dickey et al., 1983; Gilley et al., 1986; Laflen et al., 1980; Laflen and Colvin, 1981; Mannering and Meyer, 1963; Meyer and Mannering, 1967; Meyer et al., 1970; Meyer et al., 1972; Simanton et al., 1984). The reason for a variation in **b** is obvious in some cases. For example, Mannering and Meyer (1963) and Meyer and Mannering (1967) conducted two similar studies involving wheat straw applied to recently tilled soil. In one case, infiltration increased significantly as mulch rate increased, which in turn gave a larger **b** value than was the case where mulch rate did not affect infiltration. In some cases, large **b** values resulted when other effects of a tillage system including soil surface roughness and residue incorporation were lumped with the ground cover effect.

6.2.1.2. Rill-interrill effect on b values

Another reason for a range of **b** values is related to the erosion mechanics of rill and interrill erosion. A given amount of ground cover reduces rill erosion more than interrill erosion as illustrated in Figure 6.2 (Foster and Meyer, 1975). The term in equation 2.13 that represents the effect of ground cover on the rill to interrill erosion ratio is:

$$\frac{g_{cr}}{g_{ci}} = \left[\frac{\exp(-b_r f_g)}{\exp(-0.025 f_g)} \right] \qquad [6.7]$$

where: g_{cr} = the surface cover subfactor for rill erosion, g_{ci} = the surface cover subfactor for interrill erosion, b_r = the coefficient for how ground cover affects rill erosion and 0.025 = the value for the coefficient for how ground cover affects interrill erosion.[48] Consequently, RUSLE2 **b** values range between the **b** value (0.025) for interrill erosion and the **b** value (b_r) for rill erosion. The **b** value of 0.025 used in RUSLE2 for interrill

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[48] Although not used in RUSLE2 an improved approach would be to assume that the **exp** expression for ground cover effect on interrill erosion should end where it becomes tangent to the linear line in Figure 6.2, where values follow the linear line to zero for a completely covered surface.

erosion was derived from the Lattanzi et al. (1974) and McGregor et al. (1988) data (Foster, 1982).

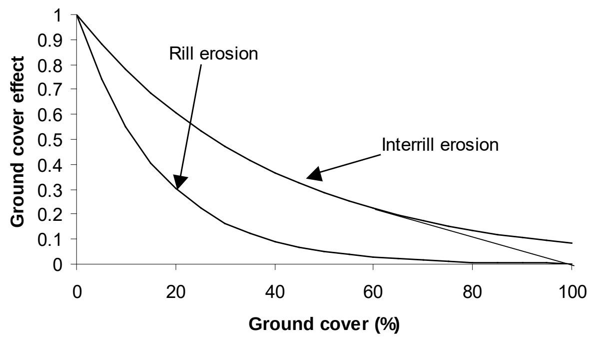

Figure 6.2. Effect of ground cover on rill and interrill erosion

The **b** value for rill erosion is the upper limit for the range of **b** values computed by RUSLE2. A 0.05 b_r value was chosen for soil conditions where ground (surface) cover does not affect infiltration, and the largest values used for b_r by RUSLE2 is 0.06 for situations where increased ground (surface) has a major effect on infiltration. RUSLE2's upper limit on **b** values is less than values reported in the literature, partly because RUSLE2 accounts for other subfactor effects that researchers included in a ground-cover type effect. Also, the reduced upper limit for **b** values was chosen so that RUSLE2 would be conservative in its computations of how much mulch, crop residue, and other ground cover materials reduce erosion for conservation planning purposes.

The coefficient b_r is assumed to increase in RUSLE2 from 0.05 to a maximum of 0.06 as ground cover increases, buried residue in the soil accounting depth increases, and the soil consolidation subfactor decreases. Mechanical soil disturbance is assumed to disrupt macro-pores and large aggregates, which increases runoff and increases erosion for a given ground cover. Conversely, biomass accumulates in a shallow, undisturbed soil surface layer with time after a mechanical soil disturbance increases infiltration, which in turn reduces runoff and rill erosion. The equation for the rill erosion ground cover effectiveness coefficient is given by:

$$b_r = 0.05 + 0.01 c_a \quad [6.8]$$

where: c_a = coefficient for the combined effect of buried residue and soil consolidation on ground (surface) cover effectiveness in relation to rill erosion. The equation for c_a is:

$$c_a = 3.52 \times 10^{-6} B_{rs}^2 (1 - s_c) \text{ if } c_a > 1 : c_a = 1 \quad [6.9]$$

where: B_{rs} = buried residue mass (dry basis) density [$lbs_m/(ac \cdot in)$] in the accounting soil depth d_{rs}. The value for the coefficient c_a varies between 0 and 1. A value of zero is computed when the soil has been recently mechanically disturbed, which sets b_r to a value of 0.05 and a value of 1 for the combination of high buried residue and low soil consolidation subfactor. If a value greater than 1 is computed for c_a, the value is set to 1.

The equation for the soil accounting depth for the effect of buried residue on erosion is given by:

$$d_{rs} = 1 + 2(s_c - 0.45)/0.55 \quad [6.10]$$

where: d_{rs} = the soil depth (inches) over which the density of buried residue mass is computed, 1 = the minimum accounting depth (inches) when the soil is fully consolidated (i.e., s_c = 0.45), 2 = the range (inches) over which the accounting depth varies as a function of the soil consolidation subfactor s_c (see **Section 6.6**), and 0.55 = the range of the soil consolidation subfactor. The maximum accounting depth is 3 inches when the soil has just been mechanically disturbed (i.e., s_c =1).

Values computed by equation 6.10 are rounded to the nearest 1 inch. RUSLE2 divides the soil depth into 1-inch intervals and accounts for soil biomass within these 1-inch intervals. RUSLE2 does not subdivide soil depth intervals further in making its buried residue density computations.

6.2.1.3. RUSLE2 b value equations

RUSLE2 uses a series of equations to compute a **b** value for equation 6.6 based on the fundamental concept that **b** values are a function of the rill to interrill erosion ratio. The starting point for developing these equations is the simple equation that computes erosion when ground cover is present as:

$$D_c = D_b \exp(-bf_g) \quad [6.11]$$

where: D_c = rill-interrill erosion when ground (surface) cover is present and D_b = rill and interrill erosion when ground cover is not present (bare soil). Therefore, a **b** value is computed by rearranging equation 6.11:

$$b = -\ln(D_c / D_b) / f_g \quad [6.12]$$

The equation for rill-interrill erosion D_c when ground cover is present is:

$$D_c = D_{ib}(3s^{0.8} + 0.56)\exp(-0.025 f_g) + D_{rb}(s/0.0896)\exp(-b_r f_g) \quad [6.13]$$

where: D_{rb} and D_{ib} = rill and interrill erosion, respectively, when ground cover in not present (bare soil). A value for rill erosion for bare soil is computed from:

$$D_{rb} = [\alpha/(\alpha + 1)] \quad [6.14]$$

where: the term α in equation 6.14 represents a rill to interrill erosion ratio for bare soil. Equation 6.14 is the same as β in equation 2.13 without the ground cover effect. The term $(3s^{0.8} + 0.56)$ adjusts for the effect of overland flow path steepness on interrill erosion and the term s/0.0896 adjusts for the effect of overland flow path steepness on rill erosion.[49] Rill and interrill erosion D_{rb} and D_{ib} are normalized so that they sum to 1 for a base, reference condition. Consequently, interrill erosion D_{ib} is computed from:

$$D_{ib} = 1 - D_{rb} \quad [6.15]$$

The term D_b in equations 6.11 and 6.12 is computed as:

$$D_b = D_{ib}(3s^{0.8} + 0.56) + D_{rb}(s / 0.0896) \quad [6.16]$$

The next step is to compute a value for the rill to interrill erosion ratio for bare soil as:

$$\alpha = (K_r / K_i) a_2 a_4 \quad [6.17]$$

where: the rill to interrill soil erodibility ratio (K_r/K_i) is computed using equation 4.12 and the coefficients a_2 and a_4 describe how soil consolidation, soil biomass, and conformance of the ground cover to the soil surface affect the rill to interrill erosion ratio for the purpose of computing a **b** value.

The coefficient a_2 is given by:

$$a_2 = a_1 + a_b \text{ if } a_2 > 8 : a_2 = 8 \quad [6.18]$$

where: the coefficient a_1 is given by:

$$a_1 = 1 - \{0.9[(1 - s_c) / 0.55][1 - \exp(-0.0022 B_{rt})]\} \quad [6.19]$$

where: B_{rt} = mass (dry basis) density (lbs_m/acre·inch) of the total of the live and dead roots in the soil accounting depth (10 inches) for roots. The a_1 coefficient represents how the rill to interrill erosion ratio changes as the soil becomes consolidated and as live and dead root biomass in the soil increases. This coefficient reflects how soil consolidation and root biomass affect rill erosion differently than it does interrill erosion.

The coefficient $a_{b,}$ which represents how soil consolidation and buried residue affects the rill to interrill erosion ratio, is given by:

$$a_b = 1.76x10^{-5} B_{rs}^2 (1 - s_c) \quad [6.20]$$

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[49] No adjustment is made for overland flow path length because of mathematical limitations in devolving the USLE equation structure into rill and interrill terms while meeting the requirement that erosion computed for the entire overland flow path be independent of how many overland flow path segments are used in the computations when other conditions are uniform along the overland flow path.

The a_b coefficient computes the effect of buried residue on the b value increasing as soil consolidation increases, such as for no-till crop, pasture, range, and similar lands that are not mechanically disturbed and B_{rs} = buried residue mass density in the soil accounting depth for buried residue.

Research shows that straw mulch cover is less effective at reducing rill-interrill erosion on steep overland flow paths characteristic of construction sites where mulch is applied to a smooth cut or graded soil in comparison to mulch applied to steep cropland soils [Meyer and Ports, 1976; AH537 (Wischmeier and Smith, 1978), Meyer et al., 1970; 1971; 1972].

RUSLE2 computes this effect assuming that the lost of ground (surface) effectiveness is determined by how well the mulch material conforms to the soil surface and stays in place. The coefficient a_4 describes how conformance of ground cover to the soil surfaces affects the rill to interrill erosion ratio. Poor conformance of ground cover to the soil surface affects rill erosion more than it does interrill erosion. The equation for a_4 is:

$$a_4 = a_3 + (1 - a_3)[1 - \exp(-0.0055 B_{rt})] \qquad [6.21]$$

where: the equation for a_3 is given by:

$$a_3 = \exp[-\psi(\lambda / s^{1/2})^{0.6} s] \qquad [6.22]$$

where: λ = the overland flow path length and ψ = a coefficient that describes conformance of ground cover to the soil surface.

Three classes of ground (surface) cover conformance that vary with material properties are used in RUSLE2 (see RUSLE2 User's Reference Guide). The values used for the conformance coefficient ψ are 0.0 for material like gravel that very closely conforms to the soil surface, 0.15 for materials that conform to the soil surface much like typical pieces of soybean stems and wheat straw after having passed through a combine, and 0.3 for corn stalks and woody debris that do not conform well to the soil surface.

Equations 6.21 and 6.22 compute reduced effectiveness of mulch, erosion control blankets, and similar materials applied on construction sites where overland flow paths are steep and long and no roots or plant stems are present. Both live and dead roots provide plant stems that help hold ground cover in place so that runoff does not dislodge and move mulch downslope or undercut erosion control blankets (Foster et al., 1982a). The tendency for mulch failure and rill erosion under erosion control blankets increases when these materials bridge soil surface roughness elements.

6.2.2. Slope length exponent m

Equations 2.12 and 2.13 are the equations used to compute the slope length exponent **m**. Values for the prior land use residual effect term in equation 2.13 are computed with:

$$c_{pr} / c_{pi} = 0.45 + 1.55(s_c s_b)^2 \qquad [6.23]$$

Equation 6.23 is based on the assumption that soil consolidation and soil biomass have a greater relative effect on rill erosion than on interrill erosion. The term for effective ground cover in equation 2.13 is computed from:

$$f_{ge} = f_g(0.4 + 0.6\delta) \qquad [6.24]$$

where: the cover adjustment term δ is given by:

$$\delta = (b_r - 0.05)/0.01 \qquad [6.25]$$

Equations 6.24 and 6.25 reflects how ground cover has a greater effect on rill erosion than on interrill erosion when the soil has not been mechanically disturbed recently and soil biomass is high in the soil surface layer (e.g., no-till type crop, pasture, range, and similar undisturbed lands).

6.2.3. Non-uniform ground cover

The user can divide the overland flow path into segments to partially represent spatial variability of ground cover. However, RUSLE2 assumes that ground cover is spatially uniform within a segment. When a soil disturbing operation occurs that disturbs only a portion of the soil surface, RUSLE2 computes detachment on both the undisturbed and disturbed portions, and it then determines the overall detachment based on the relative areas of the undisturbed and disturbed portions. An effective ground cover that gives the overall detachment is then back calculated using equation 6.6. The effective surface residue mass associated with that ground cover is determined (see **Section 10.2**). The ratio between this effective mass and the actual mass is maintained as surface residue is lost by decomposition.

6.2.4. b and m values for Req conditions

Most of the erosion during the winter Req period in Req areas is caused by rill erosion. Constant values of 0.50 and 0.046 are used for the slope length exponent **m** and the ground cover effectiveness index **b** for these conditions. These values are based on analysis of experimental research data (McCool et al., 2002).

6.2.5. Comments on b and m equations

The equations used to describe how ground cover affects erosion are empirically based on the RUSLE2 developers' judgment of how various factors affect the ratio of rill to interrill erosion. These empirical equations replace user inputs of selecting LS tables and **b** values [AH703 (Renard et al., 1997)] or land use classes (Toy and Foster, 2000). Although the equations were not fitted to experimental research data, the equations qualitatively represent both laboratory and field research findings.

These equations for **b** and **m** values, along with other cover-management equations, give RUSLE2 its **land use independence**. RUSLE2 uses fundamental variables common to all land uses to compute how cover-management affects rill-interrill erosion.

6.3. Soil surface roughness subfactor

6.3.1. How surface roughness created by mechanical soil disturbance affects erosion

The soil surface roughness subfactor represents how random soil surface roughness created by mechanical soil disturbance affects rill-interrill erosion. Soil surface roughness includes depressions where local deposition occurs and soil peaks of large, stable soil aggregates that are resistant to detachment depending on soil biomass content. Infiltration is increased, which reduces runoff and rill erosion. Also, soil surface roughness slows surface runoff, which reduces its erosivity.

The RUSLE2 equation for the soil surface roughness subfactor is:

$$s_r = \exp[-0.66(R_a - 0.24)] \quad [6.26]$$

where: R_a = daily adjusted roughness value (inches) and 0.24 inches (6 mm) = the adjusted roughness value assigned to unit plot conditions. Equation 6.26 was derived from research measurements of roughness and erosion (Cogo et al., 1984).

The reference condition where the soil roughness subfactor s_r equals 1 is the unit plot condition during and after intense rainfall. The reference unit plot soil surface roughness of 0.24 (6 mm) is produced by a harrow or similar soil finishing tool after disking or similar tools used to prepare seedbeds. Most soil surface conditions are rougher than the unit plot conditions, which give s_r values less than 1. However, some soil surfaces are smoother than the unit plot. Equation 6.26 gives s_r values up to 1.17 for soil surface roughness smoother than 0.24 inches, the roughness value assumed for unit-plot conditions. Mechanical soil disturbing operation such as roto-tilling that finely pulverizes soil, cutting and filling with a blade, and rolling a finely pulverized soil surface produces a surface that is smoother than the unit plot soil surface.

6.3.2. Random roughness as affected by soil biomass

Biomass production (yield) level affects the soil surface roughness subfactor. The effect of biomass production level on the roughness subfactor, as seen in experimental soil loss ratio values [AH537 (Wischmeier and Smith, 1978)] is illustrated in Table 6.3. The roughness subfactor values in Table 6.3 were computed by dividing the soil loss ratio for the fallow crop stage period by the soil loss ratio for the seedbed period.[50] The only essential difference in soil conditions between these two short periods is soil surface roughness.

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[50] Crop stages are periods where soil loss ratio values are considered constant in the USLE [AH537 (Wischmeier and Smith, 1978)]. The fallow period is for the time between when the soil is first tilled with a primary tillage tool such as a moldboard plow and when the soil is first tilled afterwards with a secondary tillage tool to prepare a seedbed. The seedbed period is the time between the first secondary tillage following primary tillage to when canopy cover of the planted crop reaches 10 percent.

Table 6.3. Effect of corn production level and soil biomass on soil surface roughness subfactor s_r				
		Soil loss ratio		
Yield (bu/acre)	Management	Fallow	Seedbed	Roughness subfactor
112	Grain	0.31	0.55	0.56
87	Grain	0.36	0.60	0.60
67	Grain	0.43	0.64	0.67
49	Grain	0.51	0.68	0.75
112	Silage	0.66	0.74	0.89
87	Silage	0.67	0.75	0.89
67	Silage	0.68	0.76	0.89
49	Silage	0.69	0.77	0.90

Experimental roughness subfactor values increased as production (yield) level decreased as shown in Table 6.3. Similarly, experimental roughness subfactor values [AH537 (Wischmeier and Smith, 1978)], as shown in Table 6.4, were significantly reduced when a corn grain crop followed an established meadow (sod), which has a very high soil biomass. Roughness subfactor values increased as hay yield decreased and increased in the second year of corn following sod. Residual soil biomass was less in the second year after the sod than in the first year immediately after the meadow. Also, roughness subfactor values were higher when corn followed small grain than when it followed sod. The small grain provided less soil biomass than did the sod.

Table 6.4 Effect of sod on soil surface roughness subfactor s_r for moldboard plow period		
Hay yield (tons/acre)	Year after sod	Roughness subfactor
4	1	0.35
2.5	1	0.38
1.5	1	0.39
4	2	0.49
2.5	2	0.50
1.5	2	0.50

Roughness subfactor values are interpreted as being a function of soil biomass level caused by different yield levels, soil biomass level determined by whether crop residue is removed such as with silage or left with grain harvest, and the difference in biomass level caused by type of preceding crop such as hay, small grain, or row crop grain. Recommendations for the USLE [AH537 (Wischmeier and Smith, 1978)] are that non-sod forming meadows such as sweet clover or lespedeza have less effect on rill-interrill erosion than does sod forming vegetation, which is explained by the difference in soil biomass production between these vegetation types.

RUSLE2 computes initial soil roughness after a mechanical soil disturbance as a function of the soil biomass in the soil disturbance depth using:

$$R_{ib} = 0.24 + (R_{it} - 0.24)\{0.8[1 - \exp(-0.0015B_{td})] + 0.2\} \qquad [6.27]$$

where: R_{ib} = the initial roughness adjusted for the soil texture and biomass effect, R_{it} (inches) = the initial roughness after the input roughness value is adjusted for soil texture and B_{td} = the total mass (dry basis) [lbs_m/(acre·inch)] of buried residue and live and dead roots averaged over the soil disturbance depth after the operation. The 0.24-inch value is the roughness value assumed for unit plot conditions. The 0.2 value reflects the portion of the roughness value that is not affected by soil biomass.

6.3.3. Adjusting roughness input values for soil texture

Input roughness entered in the RUSLE2 database for a soil disturbing operation is adjusted for soil texture before equation 6.27 is used to adjust for the soil biomass effect on roughness. The equation that adjusts input roughness values for soil texture is:

$$R_{it} = R_{in}[0.16(P_{sl}/100)^{0.25} + 1.47(P_{cl}/100)^{0.27}] \qquad [6.28]$$

where: R_{in} = the input roughness value entered for a soil disturbing operation in the RUSLE2 database, P_{sl} = percent silt in the soil, and P_{cl} = percent clay in the soil. The roughness values R_{it} adjusted for soil texture are the same as roughness input R_{in} values for the reference silt loam soil texture. Roughness values computed by equation 6.28 are greater than the roughness input values for soils high in clay and less than roughness input values for soils high in sand. Equation 6.28 was developed based on judgment and field observations of how soil surface roughness varies with soil texture when mechanically disturbed.

6.3.4. Assigning input roughness values for operations

Input values entered in the RUSLE2 database for soil surface roughness created by a mechanical soil disturbing operation are assigned according to the soil surface roughness that the operation creates for a base, reference condition. This condition is a smooth, silt loam soil (clay = 15%, silt = 65%) having a very high soil biomass (dry basis) density of greater than 1000 lbs_m/(acre·inch) in the soil disturbance depth, which includes both buried residue and dead roots. These soil biomass levels occur where crop yield exceeds 200 bu/acre corn, 70 bu/acre wheat, and 4 tons/acre hay or pasture land (see RUSLE2 User's Reference Guide).

The roughness index used in RUSLE2 for input values assigned to soil disturbing operations in the RUSLE2 database is the standard deviation soil surface elevations measured on a 1-inch grid. The elevations are relative to a plane that removes elevation differences caused by land steepness and ridges.

6.3.5. Effect of existing roughness at time of soil disturbance (tillage intensity effect)

Roughness left by a soil disturbing operation is a function of the operation itself and existing roughness at the time of the operation. The RUSLE2 assumption is that existing roughness has no effect if the roughness, adjusted for soil texture and biomass, left by a soil disturbing operation is greater than the existing soil roughness at the time of the operation. However, the RUSLE2 assumption is that the roughness left by a soil disturbing operation is a function of existing roughness if the adjusted roughness created by an operation is less than existing roughness. In this case, the resulting roughness is a function of the initial adjusted roughness, existing roughness, and tillage intensity of the soil disturbing operation. Tillage intensity is a measure of the aggressiveness of the soil disturbing operation for obliterating existing roughness. The equation for how existing roughness and tillage intensity affect soil roughness is:

$$R_{aa} = (1-\xi)(R_{ae} - R_{ib}) + R_{ib} \qquad [6.29]$$

where: R_{aa} = the adjusted roughness immediately after a soil disturbing, ξ = tillage intensity for the operation, R_{ae} = existing adjusted roughness immediately before the operation, and R_{ib} = the input roughness for the soil disturbing operation after adjustment for soil biomass and soil texture, which is computed with equation 6.27.

A tillage intensity of 1 means that the soil disturbing operation is so aggressive that existing roughness has no effect on the roughness left by the operation. Examples of these operations include moldboard plows and roto-tillers. Conversely, a tillage intensity of 0 means roughness after the soil disturbing operation is the same as existing roughness before the operation. Harrows that have a tillage intensity of 0.4 are examples of operations where existing roughness has a significant effect on roughness left after a soil disturbing operation.

6.3.6. Roughness decay

Roughness diminishes (decays) after a mechanical soil disturbance because of soil slumping (i.e., settlement and subsidence) caused by the presence of moisture, interrill erosion wearing away roughness peaks, and local deposition in roughness depressions. The RUSLE2 equation used to represent this effect is given by [AH703 (Renard et al., 1997)]:

$$f_r = \exp[-0.07(P_d + I) - 0.006 r_d c_c g_{ci})] \qquad [6.30]$$

where: f_r = the fraction of the current roughness greater than 0.24 inch that remains, P_d = the daily precipitation amount (inches), I = daily amount (inches) of water added by irrigation, r_d = the daily erosivity (US customary units), and g_{ci} = the interrill ground cover factor. The term in equation 6.30 associated with precipitation amount represents roughness loss by settlement and subsidence and the term associated with erosivity represents roughness loss by interrill erosion. The RUSLE2 assumption is that half of the roughness loss is by settlement and the other half is by interrill erosion. Roughness loss by local deposition is not explicitly represented. Roughness decay is not computed as a function of soil properties including texture and soil biomass. The adjustment made to initial roughness by equations 6.27 and 6.28 is assumed to adequately represent the effect of soil texture and soil biomass on roughness at any time.

The interrill ground cover factor is given by:

$$g_{ci} = \exp(-0.025 f_g) \qquad [6.31]$$

where: f_g = the net ground cover (percent). Daily adjusted roughness used in equation 6.26 is computed as:

$$R_a = 0.24 + f_r (R_{ap} - 0.24) \qquad [6.32]$$

where: R_{ap} = adjusted roughness on the previous day. The RUSLE2 assumption is that roughness is not decayed when the input initial roughness in the RUSLE2 database for a soil disturbing operation is less than the unit plot roughness of 0.24 inch.

6.3.7. Base roughness value

The 0.24-inch value in equations 6.27 and 6.32 represents a base roughness value for unit plot conditions. The assumption is that soil clods persist so that the unit-plot surface never becomes perfectly smooth. The unit plot final roughness value is not varied as a function of soil texture because that effect is empirically accounted for in the RUSLE2 soil erodibility factor. However, RUSLE2 allows the user to enter a “final” roughness value for an operation that is greater than 0.24 inch to represent conditions where roughness decays to a final value greater than 0.24 inch. If an input final roughness value greater than 0.24 inch is entered in the RUSLE2 database for a soil disturbing operation, RUSLE2 uses that value instead of the 0.24 value in equations 6.27 and 6.32. RUSLE2 does not allow roughness to decay to a value less than 0.24 inch, even if the input final roughness is less than 0.24 inches. The input initial and final roughness values can be used force RUSLE2 to use a particular roughness in its computations (see RUSLE2 User’s Reference Guide).

6.3.8. Long term roughness development

A natural soil roughness develops over time after the last mechanical soil disturbance. The final natural roughness is a function of soil properties, vegetation characteristics, and local erosion and deposition. RUSLE2 assumes that the time required for this long-term roughness to develop equals the time to soil consolidation (see **Section 4.8**). The RUSLE2 equation used to compute long term roughness is given by:

$$R_l = 0.24 + (R_{alf} - 0.24)/\{1 + \exp[(0.5 - t_d / t_c)/0.1]\} \qquad [6.33]$$

where: R_l = daily long term roughness, R_{alf} = the adjusted final long term roughness value, t_d = number of days since the last mechanical soil disturbance, and t_c = the time to soil consolidation (days). A value for R_{alf} is computed using equations 6.27and 6.28 using the input long-term natural roughness values entered in the RUSLE2 database. The biomass value used in equation 6.27 is based on total soil biomass including buried residue and dead and live roots in the upper 4 inches of the soil. The value input for final long-term roughness for a given cover-management description is relative to the reference condition for short term roughness associated with mechanical soil disturbance (see **Section 6.3.4** and RUSLE2 User’s Reference Guide). RUSLE2 adjusts this input value for soil texture and soil biomass just as it does roughness created by mechanical disturbance. The assumption is that vegetation must be present for long term surface roughness to develop and be effective. Equation 6.33 is illustrated in Figure 6.3 where the time to soil consolidation is 7 years.

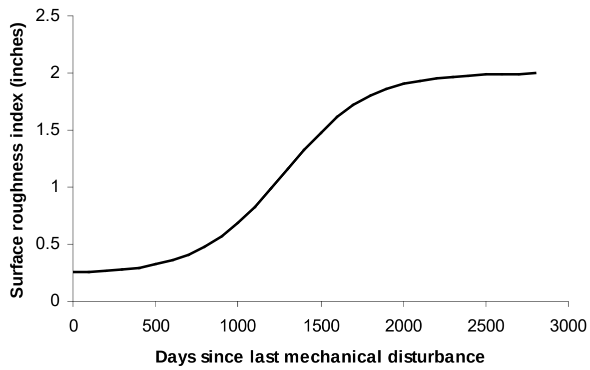

Figure 6.3. Development of long term roughness as a function of time since last mechanical soil disturbance.

RUSLE2 tracks both short term roughness resulting from mechanical soil disturbance and long term roughness development. RUSLE2 uses the maximum of the two roughness values in equation 6.26 to compute a soil surface roughness subfactor value.

6.3.9. Accounting for spatial variability in roughness

RUSLE2 can take soil surface roughness spatial variability partially into account by dividing the overland flow path into segments. However, roughness is assumed to be uniform within a segment. Some mechanical soil disturbing operations disturb the soil in strips. For these operations, RUSLE2 computes soil surface roughness subfactor values for both the undisturbed and disturbed areas and the overall soil surface roughness subfactor value based on the portion of the soil surface that the operation disturbs. RUSLE2 then back-calculates an effective roughness using equation 6.26 that gives the effective roughness subfactor value. This single effective roughness value is assigned to the segment and decayed over time using equation 6.30.

6.3.10. Comments on roughness subfactor

RUSLE2 captures the main effects of roughness on rill-interrill erosion. The intent is not to explicitly model soil roughness to produce roughness values comparable to field measured values except for input values determine from the reference condition (see **Section 6.3.4**). For example, internal RUSLE2 computed roughness values are less than those measured in the field on construction sites where soil clay content is high. The roughness effect on erosion is more than the geometric effect of soil surface roughness slowing runoff, ponding water, and depositing sediment. It also includes an infiltration effect that is less related to soil surface roughness than are the other erosion processes. The adequacy of the soil roughness relationships in RUSLE2 should be judged on the basis of how well RUSLE2 computes rill-interrill erosion as affected by soil disturbing operations that create soil surface roughness.

6.4. Ridge height subfactor

6.4.1. Effect of ridges on rill-interrill erosion

Ridges affect erosion primarily in two ways. When the ridges are oriented parallel to the overland flow path, ridges increase rill-interrill erosion because of increased interrill erosion on the ridge sideslopes. This effect is represented by the ridge height subfactor. When ridges are nearly perpendicular to the overland flow path, ridges alter the runoff flow path by partially redirecting runoff around the hillslope or by ponding runoff behind the ridges if the ridges are perfectly on the contour. This effect of ridges is considered in the contouring subfactor (see **Section 7.1**).

Increased ridge height increases ridge sideslope (interrill) steepness, which in turn increases interrill erosion steepness (Lattanzi et al., 1974). RUSLE2 uses only ridge height to compute ridge height subfactor values although both ridge height and spacing determine interrill steepness. Accurately identifying ridge spacing or number of ridges per unit overland flow path width is difficult whereas ridge height can be easily visualized and measured.

6.4.2. Reference condition for ridge height subfactor

The reference condition for the ridge height subfactor, as with all cover-management subfactors, is the unit plot condition. Unit plots are prepared to a seedbed condition (see **Section 2.1** and **Footnote 3**) using tools like spike tooth harrow that leave small ridges up and down slope. The RUSLE2 ridge subfactor must be 1 for the unit plot condition. Unit plot conditions are not static because the unit plots are periodically tilled to break soil crusts and to control weeds. A ridge subfactor value of 1 for unit plot conditions represents an average over time because of periodic ridge formation and decay.

The ridge subfactor equations are also derived for the reference condition of the ridges being parallel to the overland flow path (i.e., up and down slope).

6.4.3. Ridge height subfactor for low steepness

The RUSLE2 ridge height subfactor is constant for overland flow path steepness less than six percent as determined from experimental data and the judgment of scientists who experimentally measured the effect of ridges on rill-interrill erosion from almost flat slopes (<1%) to land steepness as great as 5 percent (Young and Mutchler, 1969; Mutchler and Murphree, 1985; McGregor et al., 1999).[51] The RUSLE2 ridge height subfactor equations derived from experimental data are:

$$r_{h6} = 0.9(1 + 0.0582H^{1.84}) \quad H \le 3 \text{ inches} \qquad [6.34]$$

$$r_{h6} = 2.136[1 - \exp(-0.484H)] - 0.336 \quad H > 3 \text{ inches} \qquad [6.35]$$

where: r_{h6} = daily ridge height subfactor when the overland flow path steepness is less than or equal to 6 percent and H = daily ridge height (inches). The significance of the 0.9 in equation 6.34 is that the minimum ridge height subfactor is 0.9 for a flat soil surface and the maximum ridge height subfactor from equation 6.35 is 1.8, which is consistent

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[51] C.K. Mutchler and K.C. MCGregor. 1999. Effect of ridge height on erosion on low slopes. Personal communication. Scientists (retired) at the USDA-National Sedimentation Laboratory, Oxford, Mississippi.

with the values given in AH537 (Wischmeier and Smith, 1978) for applying the USLE to cotton production on high ridges [Mutchler et al., 1982; Mutchler and Murphree, 1985, AH537 (Wischmeier and Smith, 1978)]. Also, equation 6.34 gives a subfactor value of 1 for a ridge height of 1.42 inch, which represents unit plot conditions except for the difference between six percent steepness and the unit plot nine percent steepness.

6.4.4. Adjustment for effect of overland flow path steepness

Interrill steepness is affected by land steepness. Interrill steepness is much greater than land steepness on flat slopes than on steep slopes. For example, local interrill steepness with high ridges (about 8 inches high when formed) like those used in cotton production in the Mississippi Delta is about 20 percent (Meyer and Harmon, 1985; Mutchler and Murphree, 1985), which is the interrill steepness when the land is flat (about 0.5%). As land steepness increases, local interrill steepness increases but much more slowly than does land steepness. Local interrill steepness of the ridge sideslope almost equals land steepness on steep slopes. For example, the same ridges that give a 20 percent steep ridge sideslope on a 6 percent land steepness give a 54 percent interrill steepness on a land steepness of 50 percent. The ridge height subfactor, therefore, approaches 1 for steep overland flow paths.

A simple rill-interrill erosion model was used to develop equations for the ridge height subfactor for overland flow path steepness greater than six percent. That simple equation is:

$$D_t = 0.5[(s/0.0896) + (3s_i^{0.8} + 0.56)] \qquad [6.36]$$

where: the 0.5 represents the assumption that rill and interrill erosion are equal for unit plot conditions (Foster and Meyer, 1975; Foster et al., 1977a, 1977b; Foster, 1982), the term s/0.0896 represents the effect of steepness on rill erosion, and the term $(3s_i^{0.8} + 0.56)$ represents the effect of steepness on interrill erosion. Steepness s_i of the interrill area is greater than the steepness s of the rill area because ridge height increases interrill steepness (i.e., the ridge sideslope steepness).

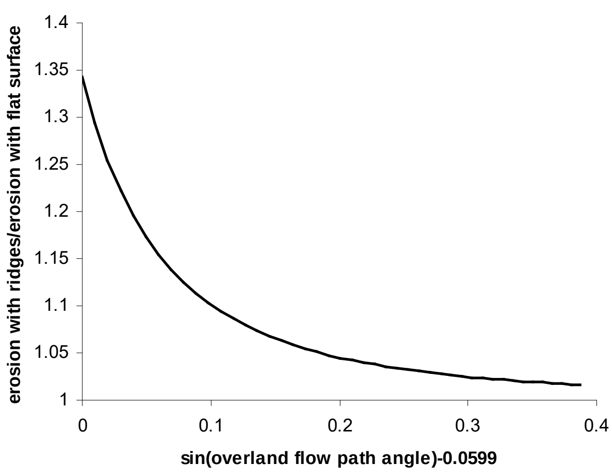

Figure 6.4. Effect of overland flow path steepness on the ratio of erosion with a 20% ridge sideslope to erosion from a flat surface.

Equation 6.36 was solved for overland flow path steepness between and 6 and 50 percent for a range of ridge side slope steepness and for a flat (i.e., non-ridged soil surface). Erosion computed for a given ridge sideslope steepness for a particular flow path steepness was divided by erosion for a flat soil surface at that same overland flow path steepness. An example of those values is shown in Figure 6.4 for a ridge sideslope of 20 percent. The RUSLE2 equations used to represent this effect are:

$$r_h = r_{h6} \quad s_p < 6\% \qquad [6.37]$$

$$r_h = 1 + (r_{h6} - 1)\exp[-a_h(s - 0.05989)] \quad s_p \geq 6\% \qquad [6.38]$$

where: s_p = overland flow path steepness (100 times tangent of slope angle) and a_h is computed from:

$$a_h = 16.02 - 0.927H \quad H \leq 10 \text{ inches} \qquad [6.39]$$

$$a_h = 6.75 \quad H > 10 \text{ inches} \qquad [6.40]$$

where: ridge height H has units of inches.

6.4.5. Effect of row grade on ridge height subfactor

The ridge height subfactor equations given above apply to the reference condition of the ridges being parallel to the overland flow path (i.e., up and down slope). As relative row grade (i.e., ratio of grade along the ridges to overland flow path steepness) decreases from 1 (up and down slope) to 0 (on contour), the ridge subfactor value should become 1. The effect of ridge height on rill-interrill erosion is represented in the contouring subfactor when the ridges are on the contour (see **Section 7.1**). However, this requirement can not be met because of RUSLE2's mathematical structure. Instead, the ridge subfactor value is 0.9 when ridges are perfectly on the contour, which is the ridge height subfactor value for a flat soil surface.

The equations that compute ridge height subfactor values as a function of ridge orientation (i.e., relative row grade) are:

$$r_h = 0.9 - (0.9 - r_{h,u\&d})g_r^2 \quad r_{h,u\&d} \leq 1 \qquad [6.41]$$

$$r_h = 0.9 + (r_{h,u\&d} - 0.9)g_r^2 \quad r_{h,u\&d} > 1 \qquad [6.42]$$

where: $r_{h,u\&d}$ = the ridge height subfactor value when ridge orientation is parallel to the overland flow path, which are computed equations 6.37 and 6.38 and g_r = relative row grade (grade along the ridges/overland flow path steepness).

6.4.6. Ridge height decay

Ridge height decays because of settlement and interrill erosion. Settlement occurs quickly after the ridges are formed when water is presence. The RUSLE2 assumption is that forty percent of the initial ridge height is lost by settlement while the remaining sixty percent is lost by interrill erosion based on analysis of experimental data (Lyles and.

Tatarko. 1987).[52] Thus, the initial ridge height left by a soil disturbing operation is divided into two parts as:

$$H = H_s + H_e \quad [6.43]$$

where: H_s = daily ridge height component associated with settlement and H_e = daily ridge height component associated with interrill erosion. The initial value for H_s is 0.4 times the ridge height left by the soil disturbing operation, while the initial value for H_e is 0.6 times the ridge height left by the soil disturbing operation. The daily settlement component ridge height is computed as:

$$H_s = H_{sp} \exp = [-0.2343(P_d + I)] \quad [6.44]$$

where: H_{sp} = the daily ridge height associated with settlement from the previous day. The daily interrill erosion ridge height is computed as:

$$H_e = H_{ep} - a_e r_d c_c g_{ci} \quad [6.45]$$

where: H_{ep} = ridge height associated with interrill erosion for the previous day and the coefficient a_e is computed as:

$$a_e = 0.033 - 0.002 H_i \quad H_i \le 10 \text{ inches} \quad [6.46]$$

$$a_e = 0.013 \quad H_i > 10 \text{ inches} \quad [6.47]$$

where: the units for a_e are inches/(US customary EI unit) and H_i = initial ridge height left by the soil disturbing operation (inches). The reason for the coefficient a_e is a function of ridge height is the RUSLE2 assumption that high ridges have a wide base so that the overall loss of ridges having a wide base occurs more slowly than does the loss of ridges with a narrow base. The minimum allowable ridge height is zero. These equations and their coefficients were derived from research data (Lyles and Tatarko, 1987) and from field observations in cotton fields in the Mississippi Delta.[53]

6.4.7. Effect of existing ridge height, soil, and cover-management on ridge height when new ridges are formed

The RUSLE2 assumption is that existing ridges have no effect on the ridges created by a soil disturbing operation. Also, the RUSLE2 assumption is that initial ridge height.

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[52] K.C. McGregor. 1999. Field observations of ridge height decay in the Mississippi Delta. Personal communtation. Scientist (retired), USDA-National Sedimentation Laboratory, Oxford, Mississippi.

[53] McGregor, K.C. 1999. Loss of ridge heights in the spring in the Mississippi Delta. Personal communication. Scientist (retired), USDA-National Sedimentation Laboratory, Oxford, Mississippi.

Ridge height at formation is determined entirely by the soil disturbing operation. The effect of existing ridges and soil and cover-management conditions on ridge height can be taken into account in RUSLE2 by creating multiple soil disturbing operation decriptions having a range of ridge height values. The user then selects a particular operation description for RUSLE2 input that gives the desired ridge height for the given situation.

6.4.8. Comments on ridge height subfactor

The intent in RUSLE2 is to capture the main effect of ridge height on rill-interrill erosion as ridge height interacts with land steepness and to capture the main effect of variables that cause ridge height to decay. The intent is not to explicitly model ridge height. The adequacy of the RUSLE2 ridge height subfactor equations should be judged on the basis of how well RUSLE2 computes rill-interrill erosion as a function of soil disturbing operations that create ridges.

RUSLE2 not giving 1 for the ridge subfactor when ridges are perfectly on the contour is a limitation of RUSLE2's empirical mathematical structure not being consistent with process-based equations. RUSLE2 was constructed so that these problems do not significantly affect RUSLE2's utility as a conservation and erosion control planning tool.

6.5. Soil biomass subfactor

6.5.1. Soil biomass effect

The RUSLE2 soil biomass subfactor estimates how soil biomass affects rill-interrill erosion [Mannering et al., 1968; Foster et al., 1985c; McGregor et al., 1990; Brown et al., 1989; Toy et al., 2002; Van Liew and Saxton, 1983, AH537 (Wischmeier and Smith, 1978)]. Soil biomass represented by RUSLE2 includes buried residue, live roots, and dead roots.

Live roots produce exudates that reduce soil erodibility. Also, live root biomass is a measure of plant transpiration, which reduces soil moisture that in turn increases infiltration and decreases runoff. Dead roots add organic matter to the soil that increases infiltration and decrease soil erodibility. Both live and dead roots mechanically hold the soil in place, hold soil in "clumps" when the soil is mechanically disturbed, and reduce waterdrop impact and runoff erosivity if the roots are exposed.

Buried residue is biomass that has been mechanically incorporated into the soil. RUSLE2 also "incorporates" up to 25 percent of the daily decomposition of surface residue into the soil to represent the accumulation of high organic matter at the soil surface for no-till and other conditions where little or no soil disturbance occurs (Kay and VanderBygaart, 2002; Shelton and Bradley, 1987). Incorporated biomass, such as crop residue, manure, or bio-solids in sewage waste, provides organic compounds that increase infiltration and decrease soil erodibility [Browning et al., 1948; Copley et al., 1944; Hays et al., 1949; AH537 (Wischmeier and Smith, 1978)]. Also, pieces of organic material, such as incorporated crop residue, can be sufficiently large to mechanically reduce rill erosion (Brown et al., 1989).

6.5.2. Soil biomass subfactor equation

The equation for the RUSLE2 soil biomass subfactor is:

$$s_b = 0.951\exp(-0.0026B_{rt} - 0.0006B_{rs} / s_c^{0.5}) \quad s_b \le 0.9035 \qquad [6.48]$$

$$s_b = \exp[-1.9785(0.0026B_{rt} + 0.0006B_{rs} / s_c^{0.5})] \quad s_b > 0.9035 \qquad [6.49]$$

Equation.6.49 is used for very low soil biomass where the soil biomass subfactor s_b is greater than 0.9035. Equation 6.48 does not give the required value of 1 for unit plot conditions that has no soil biomass (i.e., B_{rt} and $B_{rs} = 0$). The common point of s_b = 0.9035 results from the product of 0.951 in equation 6.48 and 0.95, the upper value for which the exp(…) term in equation 6.48 is assumed to apply.

The coefficient values in equation 6.48 were obtained by fitting the equation to soil biomass subfactor values estimated from research-based soil loss ratio values. The values points for no-till and mulch (reduced) till were obtained from the literature.[54] The other values selected from AH537 (Wischmeier and Smith, 1978). These values are given in Table 6.5, and the fit of equation 6.48 to the observed values is shown in Figure 6.5. The data points (soil loss ratio values) shown in Table 6.5 were selected across the range of soil biomass represented by Table 5, AH537. Equation 6.48 fits the observed values well except for the 112 bu/acre corn following 1.5 tons/acre meadow.

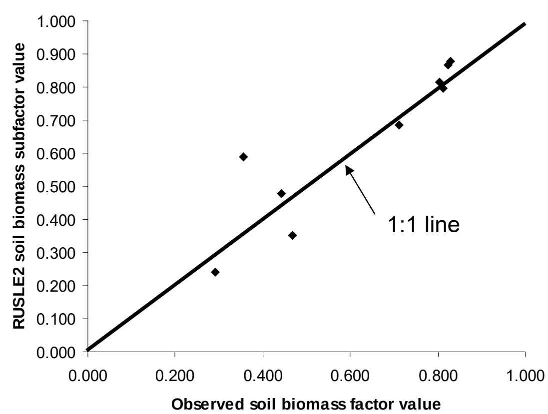

Figure 6.5. Comparison of RUSLE2 soil biomass values to observed values

Observed soil biomass subfactor values were estimated from the soil loss ratio values given in Table 6.5. Soil biomass subfactor values were computed from soil loss ratio values by rearranging equation 6.1 to solve for the soil biomass subfactor and substituting RUSLE2 estimated values for the other subfactors. Soil loss ratio values were substituted for cover-management factor c in equation 6.1.

Using soil loss ratios in Table 5, AH537 for the seedbed crop stage period for conventional, clean tillage,

[54] More than 100 articles were reviewed to evaluate the effect of no-till and mulch till cropping on rill-interrill erosion. Those articles are listed in the **Additional References Section**.

which is most like the unit plot condition, minimizes the error in estimated subfactor values used in equation 6.1 to estimate soil biomass subfactor values. The major subfactor affecting soil loss ratio values for the seedbed crop stage for conventional, clean tillage is soil biomass although some ground (surface residue) cover is present and soil surface roughness is rougher than for unit-plot conditions.

Soil loss ratio values given in Table 5, AH537 are assumed to apply to the reference silt loam soil at Columbia, Missouri. RUSLE2 was used to compute subfactor values for ground cover (surface residue) and surface roughness for all conditions listed in Table 6.5 and soil consolidation for the no-till data condition. The canopy subfactor value was 1 for all conditions and the soil consolidation subfactor was 1 except for no-till. RUSLE2 was used to compute soil biomass values using values in the RUSLE2 **core database** (see RUSLE2 User's Reference Guide).

Table 6.5. Soil biomass subfactor values used to derive RUSLE2 subfactor equation

Cover-management (yield)	Data source	Seedbed soil loss ratio	Soil biomass factor Obs	Soil biomass factor RUSLE2
conv corn 112 bu/ac	AH537	0.55	0.71	0.69
conv corn 50 bu/ac	AH537	0.68	0.80	0.82
conv corn sillage 112 bu/ac	AH537	0.74	0.81	0.79
conv corn sillage 50 bu/ac	AH537	0.77	0.83	0.88
conv corn 112 bu/ac soybeans 25 bu/ac	AH537	0.72	0.82	0.87
conv corn 112 bu/ac after meadow 4 tons/acre	AH537	0.18	0.29	0.24
conv corn 112 bu/ac after meadow 1.5 tons/acre	AH537	0.29	0.35	0.59
no till corn 112 bu/ac	literature	0.028	0.47	0.35
mulch till corn 112 bu/ac	literature	0.24	0.44	0.48

The soil consolidation term s_c in equation 6.48 gives increased credit for buried residue to represent no-till cropping and other undisturbed soil conditions. For example, a given amount of buried residue at the soil surface decreased rill-interrill erosion more with no-till than with clean tillage. Increased soil macro-pores and aggregation develop in the upper few inches of soil under no-till cropping and other undisturbed soil conditions (Kay and VanderBygaart, 2002). Frequent, routine tillage and other mechanical soil disturbance prevent these conditions from developing. Mechanical soil disturbance disrupts these favorable soil conditions for reducing rill-interrill erosion, and time is required for these soil conditions to become reestablished. The term $1/s_c^{0.5}$ in equation 6.48 and 6.49is used as an index for the development of these favorable soil properties.

Values for the accounting depths d_{rs}, described in **Section 6.2** for buried residue, and d_{rt} for roots were determined during the fitting of equation 6.48 and 6.49. The best fit was obtained with a buried residue accounting depth of three inches for conventional, clean tillage, which is represented by $s_c = 1$. The accounting depth is reduced to 1 inch as the soil consolidation subfactor value decreases from 1 for a soil recently mechanically disturbed to 0.45 for a fully consolidated soil (see equation 6.10). The accounting depth for buried residue reflects the soil depth over which buried residue has its major effect on infiltration, soil erodibility, and runoff erosivity.

The accounting depth determined for roots was 10 inches. This depth contains the bulk of roots for most vegetation, especially major agricultural crops like corn, soybeans, and wheat. The apparent depth over which roots affect erosion is greater than that for buried residue because live roots affect infiltration by extracting soil water. The 10-inch accounting depth for roots is also influenced by the common depth of 10 inches for modern moldboard plows, which invert the soil. Moldboard plow bring roots near the bottom of the plow depth to near the soil surface. Moldboard plows also move surface residue and buried residue near the soil surface to near the bottom of the plow depth, where the buried residue has little effect on rill-interrill erosion. Although the case can be made that live roots and dead roots should be treated differently in RUSLE2 because of moisture extraction, the effect of live roots and dead roots per unit mass are considered to be the same for both live and dead roots.

See **Sections 8.2** and **9.2.1** for additional comments.

6.5.3. Soil biomass subfactor equation for Req conditions

When RUSLE2 is applied to Req conditions (see **Section 3.2.5** and the RUSLE2 User's Reference Guide), soil biomass values are multiplied by 1.65 to give increased erosion reduction per unit biomass. Most of the rill-interrill erosion for Req conditions is rill erosion, and soil biomass has a greater relative effect on rill erosion than on interrill erosion (Van Liew and Saxton,1983; Brown et al., 1989; McGregor et al., 1990). The 1.65 value was determined by fitting RUSLE2 to data collected at Pullman, Washington (McCool et al., 2002).

6.5.4. Applicability of soil biomass subfactor equation for biomass additions

The data used to derive equations 6.48 and 6.49 were for cropped conditions where the biomass source was vegetation grown on-site. RUSLE2 must also represent the effect of incorporation of applied biomass from other sources including animal manure, compost, bio-solids in sewage and similar waste, and forest litter. The applicability of RUSLE2 for these conditions was evaluated by computing and comparing rill-interrill RUSLE2 erosion estimates with measured erosion in research studies. Tables 6.6 and 6.7 show estimated and observed erosion values for surface application of manure and its incorporation into the soil using primary tillage at Clarinda, Iowa and La Crosse, Wisconsin (Browning et al, 1948; Hays et al., 1949). Table 6.8 shows erosion values for various biomass types applied and incorporated in the soil for cotton grown at Statesville, North Carolina (Copley et al., 1944). RUSLE2 is judged to adequately estimate how surface applied and soil incorporated biomass affects rill-interrill erosion.

Table 6.6. Effect of manure additions on erosion at Clarinda, Iowa

			Ratio of erosion with manure to erosion without manure	
Cover	Yield (bu/ac)	Manure application (tons/acre wet basis)	Obs	RUSLE2
Corn	22	0	1.00	1.00
Corn	30	8	0.42	0.39
Corn	36	16	0.21	0.20
Fallow		0	-	-
Fallow		8	0.79	0.42
Fallow		16	0.63	0.24

Table 6.7. Effect of manure additions on erosion at La Crosse, Wisconsin

			Ratio of erosion with manure to erosion without manure	
Cover	Yield (bu/ac)	Manure application (tons/acre wet basis)	Obs	RUSLE2
Corn	30	0	1.00	1.00
Corn, manure spring applied	30	8	0.82	0.42
Corn, manure fall applied	30	8	0.80	0.42
Fallow		0	1.00	1.00
Fallow, manure spring applied		5	0.85	0.75

Several factors complicate this analysis. One factor is data variability. Incorporated animal manure decreased erosion much more at Clarinda, Iowa than at La Crosse, Wisconsin. RUSLE2 seems to seriously over estimate the effect of manure applied to fallow conditions at both Clarinda and La Crosse. A comparison of observed erosion with manure applied to corn with erosion for manure applied to fallow soil at Clarinda indicates a much greater effect of the corn biomass than is supported by data in Table 5, AH537 (Wischmeier and Smith, 1978). Another problem with the experimental data is that manure applied to the corn at La Crosse did not reduce erosion as much as expected based on the results for the fallow soil. Such unexplained variability in erosion data is common.

Another complicating factor is how well the biomass was incorporated into the soil by the 6-inch deep manual spading operation used on the research plots to replicate moldboard plowing. The RUSLE2 inputs were based on the assumption that the spading incorporated the biomass more like a chisel plow than like a moldboard plow. Assuming that the incorporation was like a moldboard plow rather than a chisel plow results in RUSLE2 estimating that the ratio of erosion with incorporated biomass to erosion without incorporated biomass increases from 0.42 to 0.48 for applying 8 tons/acre of manure at Clarinda, Iowa. Consequently, the uncertainty in how the spading operation incorporated the biomass does not seem to account for the large difference between the RUSLE2 values and the measured values for fallow conditions.

Table 6.8. Effect of biomass additions on erosion with cotton at Statesville, North Carolina

Yield (lbs/acre seed cotton)	Biomass type	Biomass application (tons/acre wet basis)	Ratio of erosion with biomass to erosion without manure	
			Obs	RUSLE2
800	-	none	1.00	1.00
1800	Animal manure	8	0.19	0.27
1800	Compost	12	0.39	0.21
1800	Compost	18	0.13	0.16
1800	Compost	60	0.03	0.04
1800	Wood litter	24	0.09	0.13
1800	Pine needles	24	0.10	0.13

Another complicating factor is that the reported application rates were on a wet basis rather than a dry basis required as input to RUSLE2. The dry biomass was assumed to be 25 percent of the wet basis application rates for all biomass types. The erosion ratios for fallow conditions at La Crosse assuming a 6 inch deep moldboard plowing are 0.65, 0.48, and 0.29 for the dry biomass inputs of 2000, 4000, and 8000 lbs/acre, respectively. Errors in estimating the dry biomass can have a significant effect on the RUSLE2 estimate erosion.

RUSLE2 assumes that the effect of all types of buried residue on rill-interrill erosion is described solely by biomass amount on a dry basis. Mechanical characteristic, such as diameter and length of individual pieces, of buried residue are assumed not to affect rill-interrill erosion in RUSLE2. This assumption is supported by the experimental and RUSLE2 results for the Statesville, North Carolina data.

The experimental results given in Tables 6.6 - 6.8 do not indicate the effect of biomass addition on rill-interrill erosion with modern farming practices. The depth of incorporation in these studies, which were conducted primarily in the late 1930's, was six inches while common modern moldboard plows incorporate material to 10 inches deep. Changing incorporation depth affects the RUSLE2 estimated ratio of erosion with incorporated biomass to erosion without biomass incorporation. Increasing incorporation depth from 10 to 6 inches increases the erosion ratio from 0.42 assuming a chisel plow type incorporation in the soil (0.48 assuming a moldboard plow incorporation) to 0.82 assuming incorporation with a modern moldboard plow for the 8 tons/acre manure spring application to corn at La Crosse, Wisconsin. The reason for the major difference is the effect of machine operation depth on the fraction of the biomass that is incorporated (see **Section 8.2.4.2**) and the biomass density in the surface 3-inch soil depth.

6.5.5. Soil biomass subfactor for pasture, range, and similar undisturbed lands

The equations for the soil biomass subfactor, equations 6.48 and 6.49, are considered to apply to all land use conditions (i.e., that is RUSLE2 is land-use independent). Range, pasture, and other undisturbed lands are highly variable in both time and space. Accurately measuring root biomass is extremely difficult, if not impossible for undisturbed lands because of temporal and spatial variability. Reliable measurements of root biomass and buried residue are not available to either directly validate equations 6.48 and 6.49 or derive alternative equations for these lands.[55] Therefore, erosion data from research plots under simulated rainfall were used to derive effective root biomass values for rangeland plant communities rather than use measured root biomass values. [56]

The common approach for applying the USLE [AH537 (Wischmeier and Smith, 1978)] and RUSLE1 [AH703 (Renard et al., 1997)] to undisturbed lands is to input values that represent average annual conditions to make a single erosion computation using subfactors similar to those in equation 6.1 to for the year rather than to compute daily erosion. This approach can also be used in RUSLE2, although a better approach is to use time varying inputs to represent temporal effects on rill-interrill erosion (see RUSLE2 User's Reference Guide). The lack of both measured soil biomass data and research that establishes how soil biomass and its characteristics affect rill-interrill erosion required derivation of effective root biomass ratio values, which is defined as the ratio of effective root biomass to average annual above ground biomass production on a dry basis. Values for this ratio vary by plant community and were determined directly from experimental soil erosion research data (See RUSLE2 User's Reference Guide; Simanton et al., 1991). This derivation empirically accounts for differences between cropland and undisturbed land conditions and overcomes the impossibility of measuring root biomass on undisturbed lands.

First, a **c** factor value was computed for each site from measured erosion data by rearranging equation 2.1 as:

$$c_p = A_p / [R_p K_n (\lambda_p / \lambda_u)^m S_p] \qquad [6.50]$$

where: c_p = the c factor value for the measured erosion data obtained from applying simulated rainfall to field plots 12 ft wide by 35 ft long, A_p = measured erosion, R_p = the erosivity for the simulated rainfall, K_n = the soil erodibility value determined by applying the standard soil erodibility nomograph (see **Sections 4.1.1** and **4.1.2**) using soil property values measured at each site, λ_p = the plot length, λ_u = unit plot length, and S_p = the slope steepness factor computed from the measured plot steepness. Next an observed soil biomass subfactor value s_c was computed for each experimental site by rearranging

[55] An extensive review of measured root biomass for rangeland plant communities was conducted during the development of RUSLE1. The variability in these values, as indicated in Table 5-4, [AH703 (Renard et al., 1997) , is far too great to use these values as either input to RUSLE2 or to develop a soil biomass subfactor, especially a temporally varying one, for these conditions.

[56] Data from the WEPP study (Simanton et al., 1991) were used in the analysis to compute effective root biomass values. Data from the USDA Range Study Team study Spaeth et al., 2003) were considered for use in the development of RUSLE2. However, the data were not used because of inconsistencies in the data, which were not resolved by the researchers who collected the data (see the RUSLE2 User's Reference Guide).

equation 6.1, substituting c_p values for c and values for the subfactors, and solving for the soil biomass subfactor s_b value.

An effective root biomass value was computed by rearranging equation 6.48 and assuming no buried residue effect (i.e., assuming $B_{rs} = 0$). RUSLE2 does not consider a buried residue effect when using a single average annual input for root biomass. This RUSLE2 application method also requires using RUSLE2 inputs that add surface residue that does not decompose (see RUSLE2 User's Reference Guide). The value for the effective root biomass was divided by the average annual dry matter above ground biomass production to compute a value for effective root biomass ratio for the site. These values were averaged where the same plant community occurred at multiple sites. RUSLE2 multiplies the input value for above ground annual production by the effective root biomass ratio to obtain a value for effective root biomass B_{rt} that is used in equation 6.48 or 6.49 to compute a value for the soil biomass subfactor. Derivation of RUSLE2 effective root biomass values was the same as that used to derive comparable values for RUSLE1 [Yoder et al., 1997; AH703 (Renard et al., 1997)], except that RUSLE2 equations and procedures were used for equations 6.1, 6.48, and 6.50.

The RUSLE2 User's Reference Guide discusses how time varying inputs can be used in RUSLE2 to represent changes in time during the establishment of permanent cover on mechnanically disturbed lands such as construction sites, reclaimed mined lands, rangelands, military training grounds, and logged and burned forest lands. This Guide also describes how time varying inputs can be used in RUSLE2 to represent long-term vegetation that has reached maturity on undisturbed land. Using time varying inputs for canopy and root biomass allows RUSLE2 to compute a litter cover produced by senescence, soil biomass produced by dead (soughed) roots, and soil biomass produced by buried residue that are a function of plant community, production level, and location (Reeder et al., 2001).

RUSLE2 was fitted directly to the measured erosion data for rangelands to determine the soil biomass effect for these lands. However, RUSLE2 erosion estimates for undisturbed lands, especially rangelands, are much more uncertain than erosion estimates for cropland. This increased uncertainty exists for all erosion prediction technologies and is not unique to RUSLE2. Reasons for this uncertainty and its magnitude are discussed in detail in the RUSLE2 User's Reference Guide.

6.5.6. Sources of soil biomass in RUSLE2

The sources of soil biomass in RUSLE2 are biomass applied to the soil surface or directly injected into the soil, above ground biomass from vegetation grown on site, and roots from vegetation grown on-site. The amount of applied biomass is a direct input to RUSLE2 (see **Section 10**). The amounts of above ground and root biomass for vegetation grown on-site are directly related to RUSLE2 inputs (see **Section 9**). Once live above ground biomass becomes dead biomass (i.e., residue) by senescence or killed by an operation such as mowing, it disappears by decomposition discussed in **Section 10.3.** Similarly, once live roots become dead roots either by the plants being killed or by root sloughing, this biomass disappears by decomposition. Operations, including soil disturbing operations, move biomass between the various biomass pools and redistribute biomass within the soil (see **Section 8**). The RUSLE2 User's Reference Guide describes the RUSLE2 biomass pools in detail and how these pools are manipulated in RUSLE2.

6.5.7. Transfer of surface residue to soil biomass by decomposition in RUSLE2

The organic matter content of the approximate 2-inch soil depth for no-till cropped soil is about twice that for conventional, clean-till cropping (Kay and VanderBygaart, 2002; Shelton and Bradley, 1987). A RUSLE2 assumption is that biomass occurs in the soil only by roots grown in the soil or a mechanical soil disturbing operation incorporating biomass. To accommodate the accumulation of high organic matter level in a shallow soil surface layer where little or no mechanical soil disturbance occurs, such as for no till croplands and undisturbed lands, RUSLE2 assumes that a portion of the daily surface residue decomposition is added to the top 2-inch soil layer. Once in this soil layer, this biomass is treated as any other buried residue that is subject to decomposition and has the same effect on rill-interrill erosion as any other buried residue.

This empirical procedure is used as a mechanism for increasing soil biomass in the upper soil layer when the soil is minimally disturbed. The equation used to compute this buried residue addition is:

$$f_b = 0.25[(1/s_c) - 1] \qquad [6.51]$$

where: f_b = the fraction of the daily biomass decomposed from surface residue that is added to the buried residue biomass in the upper 2-inch soil layer. The 0.25 value was determined during the fitting of equation 6.48 to observed data. The 0.25 variable was adjusted so that RUSLE2 computes a soil biomass in the top 2-inch soil layer for the no-till data point that is approximately twice the soil biomass for conventional, clean tillage. The structure of equation 6.51 was chosen so that the rate of change in the effect of soil consolidation is least immediately after a mechanical soil disturbance (i.e., $s_c = 1$). The rate of increase in f_b increases as the soil approaches full soil consolidation (i.e., s_c = 0.45).

The soil consolidation s_c subfactor term in equation 6.51 and the time to soil consolidation (see **Section 4.8**) determine the time required after a conversion from conventional, clean tillage to no tillage for soil biomass to come to a new equilibrium. Seven years is used for the time to soil consolidation in the eastern US, which is too short for all of the soil biomass changes to occur (Kay and VanderBygaart, 2002). However, seven years for time to soil consolidation is sufficient for RUSLE2 to represent particulate organic matter, and seven years seems sufficiently long for most major land use changes that affect rill-interrill erosion in the context of conservation planning. The time to soil consolidation is also used to compute change in soil erodibility when no biomass is present. Consequently, thus the RUSLE2 time to soil consolidation variable is a compromise for describing multiple effects.

Equation 6.51 computes no transfer of biomass from the surface residue to the buried residue when the soil has been recently mechanically disturbed, which is indicated by s_c =

1, which gives $f_b = 0$ from equation 6.51. If the soil is totally undisturbed where $c_s = 0.45$, $f_b = 0.31$, which means that for each day, approximately 30 percent of the surface residue that is lost by decomposition on that day is added to the buried residue in the upper 2-inch soil depth. In no-till corn cropping where the only soil disturbing operation is a planter that disturbs 15 percent of the soil surface, the c_s ranges from 0.54 to 0.61 during the year. The approximate annual average is 0.58, which gives a value of 0.18 from equation 6.51. That is, approximately 18 percent of the daily surface residue decomposition is added to the upper 2-inch soil depth for typical no-till corn cropping in comparison to almost 30 percent being added for a completely undisturbed soil condition (e.g., a pasture or rangeland).

6.5.8. Spatial variability in the soil biomass subfactor

Soil biomass and the soil biomass subfactor are assumed to be spatially uniform within a segment along the overland flow path, even when the soil is disturbed in strips. Non-uniformity in soil biomass along the overland flow path can be represented by dividing the overland flow path into segments.

6.5.9. Comments on soil biomass subfactor

The purpose of the soil biomass subfactor is to capture the main effect of live and dead roots and buried residue on rill-interrill erosion. The RUSLE2 soil biomass relationships are not meant to be a model of soil biomass that stands alone from how it used in RUSLE2 to estimate rill-interrill erosion for conservation and erosion control planning. The soil biomass subfactor does not capture all interactions, such as how the effect of soil biomass on erosion is affected by soil texture.

The importance of the soil biomass subfactor is often overlooked in evaluating how cover-management practices affect rill-interrill erosion. For example, large amounts of biomass added to the soil can greatly reduce rill-interrill erosion as indicated in Table 6.8. Similarly, large amounts of live and dead root biomass also greatly reduce erosion.

RUSLE2 only uses biomass amount as the variable to capture how soil biomass affects erosion. For example, RUSLE2 makes no distinction between how small and larges roots affect erosion. However, preference in selecting root biomass input values is given to fine roots instead of coarse roots (see RUSLE2 User's Reference Guide). Not much of the mass of coarse roots is entered for root biomass because coarse roots are assumed to have relatively little effect on erosion. Fine roots are assumed to have much greater effect on erosion per unit biomass than do coarse roots. Fine roots have greater surface area per unit mass than coarse roots and often are very close to the soil surface where they have a greater effect on runoff and erosion than coarse roots. Fine roots are readily sloughed and become a part of the soil organic matter pool.

Research to directly determine the effect of buried residue on rill-interrill erosion has been limited and incomplete (Van Liew and Saxton, 1983; Brown et al., 1989; McGregor et al., 1990; Box, Jr. and Bui, 1993). Research to measure soil buried residue and its characteristics as they affect rill-interrill erosion is difficult and is very incomplete.

However, research, such as that summarized in AH537 (Wischmeier and Smith, 1978), conclusively shows that root biomass reduces erosion. No studies have shown how root characteristics affect rill-interrill erosion.

Getting good results from RUSLE2 requires that instructions in the RUSLE2 User's Reference Guide for selecting input values be carefully followed. RUSLE2's soil biomass subfactor equation and other subfactor equations were calibrated using the data in the RUSLE2 **core database**. When those values and the procedures described in the RUSLE2 User's Reference Guide are followed, RUSLE2 users can expect good results from RUSLE2 for conservation and erosion control planning. If one disagrees with the soil biomass values used by RUSLE2, one can not simply change RUSLE2 input values because of RUSLE2 having been calibrated using values from the RUSLE2 **core database**. If soil biomass values are changed, the soil biomass subfactor equation must be re-derived because the RUSLE2 equation was derived using RUSLE2 computed soil biomass values.

The importance of this point can not be over emphasized.

6.6. Soil consolidation subfactor

6.6.1. Soil consolidation effect

The RUSLE2 assumption is that mechanical soil disturbance by tillage, construction activities, and other soil loosening operations significantly increases soil susceptibility to erosion. Rill-interrill erosion immediately after a mechanical soil disturbance is assumed to be about twice that when the soil has not been disturbed for an extended period. The effect is much greater for rill erosion than for interrill erosion (Foster, 1982; Foster et al., 1982c).

The term soil consolidation does not accurately connote the process by which soil becomes less susceptible to erosion over time. The reduction in soil erodibility over time represented by the soil consolidation subfactor is related to internal cohesive soil bonding increasing over time rather than to a mechanical increase in soil bulk density. Cohesive bonding increases as the soil experiences wetting and drying cycles in the presence of organic matter and chemical bonding agents in the soil (Foster et al., 1985c; Toy et al., 2002). The important role of soil moisture is the reason for the time to soil consolidation being a function of average annual precipitation between 10 and 30 inches (see **Section 4.8**).

The soil consolidation effect is based on a comparison of erosion from a soil in the unit plot condition to erosion of the same soil that has not been mechanically disturbed for some time after being left in unit-plot condition by the last mechanical soil disturbance. Soil disturbance also affects the ground cover, soil surface roughness, and soil biomass subfactors in addition to the soil consolidation subfactor. The soil consolidation subfactor represents solely the effects of soil loosening on erosion relative to time since the last mechanical soil disturbance that left unit plot conditions. The soil consolidation subfactor variable is also used to compute values for the soil biomass subfactor, rill to interrill erosion ratio, and runoff curve number. Therefore, the effect of soil loosening computed by RUSLE2 can be significantly greater than the effect represented by the soil consolidation subfactor.

6.6.2. Soil consolidation subfactor equation

The equation for the RUSLE2 soil consolidation subfactor is:

$$s_c = 0.45 + \exp\{-3.314[0.1804 + (t_d / t_c)^{1.439}]\} \qquad [6.52]$$

where: t_d = days since last mechanical soil disturbance and t_c = the time to soil consolidation The 0.45 value in equation 6.52 represents the minimum soil consolidation subfactor value that occurs for time exceeding the time to soil consolidation.[57] The soil consolidation subfactor value is 1 for $t_d = 0$, which is immediately after a mechanical soil disturbance. A plot of equation 6.52 is shown in Figure 6.6 for two times to soil consolidation.

Equation 6.52 was derived from experimental erosion data collected from natural runoff plots at Zanesville, Ohio (Borst et al., 1945). Erosion was measured for a few years from a plot periodically tilled to maintain unit plot conditions. Tillage was stopped and erosion measurements were continued for several years after tillage stopped. Measured annual erosion values were adjusted based on the annual erosivity to account for weather differences between years. Observed soil consolidation subfactor values were computed by dividing the adjusted annual erosion values after tillage stopped by adjusted average annual erosion before tillage stopped.

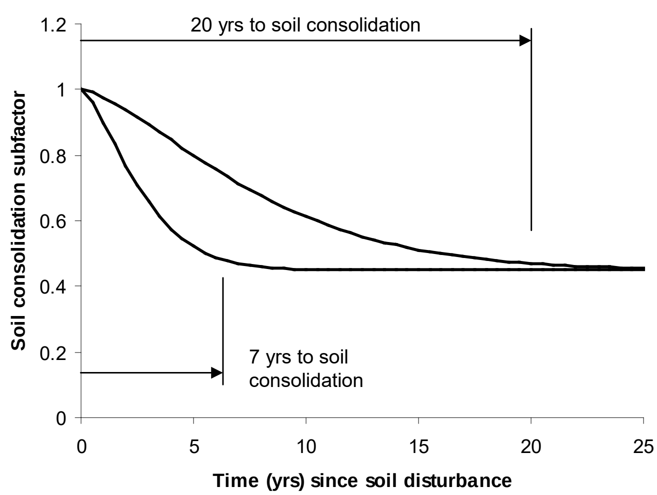

Figure 6.6. Variation of the soil consolidation subfactor as a function of time after last mechanical soil disturbance.

Experimental erosion studies on mine spoil and reconstructed shoed that compaction can increase rill-interrill erosivity by as much as 40 percent (Barfield et al.,

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[57] Equation 6.52 approaches 0.45 asymptotically. The time to soil consolidation is defined as the time when 95 percent of the decrease in the soil consolidation subfactor has occurred (see **Section 4.8**).

1988). About half of this effect can be captured in RUSLE2 by inputting a 0 soil surface roughness value for the soil disturbing operation used to describe the compaction. The 0 input value for soil surface roughness represents a smooth soil surface that is assumed to result from the compaction. This value is increased to represent the roughness effect left by a compactor such as a sheep's foot roller that leaves some soil surface roughness.

6.6.3. Spatial variability effect on soil consolidation subfactor

RUSLE2 accommodates spatial variability along the overland flow path when the overland flow path is divided into segments. RUSLE2 also represents the effect of operations that disturb only a portion of the soil surface (e.g., strip tillage) based on the fraction of the soil surface that the operation disturbs. An effective value for the soil consolidation subfactor is computed as the weighted average of $s_c = 1$ for the portion disturbed and the s_c value for the undisturbed portion at the time of the mechanical soil disturbance. An effective time since soil disturbance is calculated by rearranging equation 6.52 and solving for the time t_d that gives the effective s_c value (see **Section 8.3.1**). The time since last soil disturbance is reset to this effective time, and time accounting for soil consolidation begins again from the effective time value.

6.6.4. Comments on soil consolidation subfactor

The RUSLE2 soil consolidation subfactor only captures the soil loosening effect on rill-interrill erosion in the broadest terms. The soil consolidation subfactor is the most poorly defined of all the RUSLE2 cover-management subfactors. Very little empirical and not much fundamental research has been conducted to determine how the soil consolidation effect varies with climate, soil texture, and other factors. The RUSLE2 soil consolidation subfactor is determined from a single set of data collected at a single location on a single soil texture. The effect is greater for rill erosion than for interrill erosion (Foster et al., 1982c). However, the soil consolidation effect on rill erosion can be quite variable. In one study, rill erosion of a silt loam soil decreased by about 75 percent over about a year's time (Dissmeyer and Foster, 1981). In another study, sediment eroded from ridges and deposited in furrows became quite resistant to erosion in just four weeks (Foster et al., 1982c).

The soil consolidation effect surely must be a function of soil texture. For example, the range in the soil consolidation subfactor for soils high in sand is assumed to be less than for silt loam soils. Also, the time to soil consolidation is assumed to be a function of soil texture. However, available research information is not sufficient to include these effects in the RUSLE2 soil consolidation subfactor.

The RUSLE2 assumption is that mechanical soil compaction (i.e., mechanical increases in soil bulk density) does not affect rill-interrill erosion. Soil compaction has two offsetting effects. One is to decrease infiltration, which increases runoff and hence rill-interrill erosion. The other effect is to decrease erosion by decreasing the detachability of soil particles by raindrop and runoff forces. The assumption of no effect of soil compaction on erosion is false for a high clay soil being mechanically compacted at optimum soil moisture. Soil compaction of a high clay soil can greatly reduce rill erosion

(Graf, 1971). Available research information was not sufficient to include a RUSLE2 relationship that computes erosion as a function of soil bulk density. An input value less tha 0.24 inches for soil surface roughness can be used to represent increase in erosion caused by compaction. Also, the soil erodibility factor value can be reduced to represent decreased erosion caused by compaction of high clay soils.

RUSLE2 does represent the effect on rill-interrill erosion of subsoiling, scarifying, and similar mechanical soil disturbances designed to break up soil to increase infiltration, which in turn decreases runoff and erosion. RUSLE2 represents this effect though the soil surface roughness subfactor (see the RUSLE2 User's Reference Guide).

The RUSLE2 soil erodibility factor does not represent the effect of soil compaction. Soil compaction is a cover-management effect. Changing a soil erodibility input value to represent soil compaction is for convenience only in RUSLE2 because no other input method is available to represent the effect of compaction. RUSLE2 soil erodibility are based on the tilled unit plot condition.

6.7. Antecedent soil moisture subfactor

The antecedent soil moisture subfactor is used only when RUSLE2 is applied to Req conditions (see **Section 3.2.5**).

6.7.1. Antecedent soil moisture effect

Rill-interrill erosion under Req conditions is highly sensitive to soil moisture [AH703 (Renard et al., 1997); Van Klaveren and McCool,1998]. High soil moisture significantly increases erosion during the winter Req period. Freezing and thawing cycles in the presence of very high soil moisture and other processes dramatically increase soil erodibility during the winter months at Req locations [see RUSLE2 User's Reference Guide, AH703 (Renard et al., 1997); Van Klaveren and McCool,1998). Highly saturated soil in the tilled surface layer plays a major role in Req processes that do not occur to nearly the same degree or regularity in non-Req locations.

6.7.2. Antecedent soil moisture subfactor equations

The RUSLE2 antecedent soil moisture subfactor equations are a refinement of those in RUSLE1 [Yoder et al., 1997; AH703 (Renard et al., 1997); McCool et al., 2002]. The year is divided into periods of soil moisture replenishment (October 1 – March 31), stable at maximum soil moisture (April 1 – April 30), depletion (May 1 – July 31), and stable at minimum soil moisture (August 1 – September 30).

6.7.2.1. Replenishment (October 1 – March 31)

The average daily soil moisture replenishment rate is computed as:

$$R_m = 0.5/182 \quad P_a \le 10 \text{ inches} \qquad [6.53]$$

$$R_m = [0.5 + 0.062(P_a - 10)]/182 \quad 10 < P_a \le 18 \text{ inches} \qquad [6.54]$$

$$R_m = 1/182 \quad P_a > 18 \text{ inches} \qquad [6.55]$$

where: R_m = an index (dimensionless) for daily moisture replenishment rate, P_a = average annual precipitation (inches), and 182 = number of days over which replenishment occurs.

$$s_m = s_{mp} + R_m \quad if\,(s_m > 1): s_m = 1 \qquad [6.56]$$

where s_m = daily antecedent soil moisture subfactor and s_{mp} = the soil moisture subfactor on the previous day.

6.7.2.2. Depletion (May 1 – July 31)

The daily soil moisture depletion rate is computed as:

$$D_m = \phi_m / 91 \qquad [6.57]$$

where: D_m = an index (dimensionless) for daily moisture depletion rate, ϕ_m = the total soil moisture depletion as a function of vegetation, and 91 is the number of days over which depletion is assumed to occur. Example values for ϕ_m are given in Table 6.9.

$$s_m = s_{mp} - D_m \quad if\,(s_m < 0): s_m = 0 \qquad [6.58]$$

6.7.2.3. Minimum and maximum periods (April 1 – April 30) and (August 1 – September 30)

The soil moisture subfactor is assumed not to change during the minimum period between the depletion and replenishment periods and the maximum period between the replenishment and depletion periods. That is:

$$s_m = s_{mp} \qquad [6.59]$$

6.7.2.4. Initial s_m value

Table 6.9. Soil moisture depletion index for vegetation grown in Req location

Vegetation	Depletion index
Winter wheat and other deep rooted crops	1.00
Spring wheat and barley	0.75
Spring peas and lentils	0.67
Shallow rooted crops	0.50
Summer fallow	0.00
Vegetation that has been killed	0.00

The initial default value for the antecedent soil moisture subfactor s_m is 1. The initial condition is not important when cover-management practice are rotations (i.e., the set of operations is repeated in cycles). RUSLE2 runs until dynamically stable conditions are reached. However, when the cover-management practice is not a rotation, the initial operations in the cover-management description are used to set the desired initial condition (see RUSLE2 User's Reference Guide). Specific values can not be entered in the RUSLE2 computer program to set initial values of RUSLE2 variables.

6.7.2.5. Applicability of RUSLE2 antecedent soil moisture subfactor equations

The RUSLE2 antecedent soil moisture subfactor equations (equations 6.53 - 6.59) strictly apply only to the portion of the Req zone from central Washington across northern Idaho and in northeastern Oregon illustrated in Figure 3.16 (also, see RUSLE2 User's Reference Guide). Although Req conditions occur in other locations, equations 6.53 – 6.59 do not apply to those locations because of differences in precipitation patterns. These equations were empirically derived from data collected at Pullman, Washington. Differences in monthly precipitation distributions between Pullman Washington and Salt Lake City, Utah are illustrated in Figure 6.7. Equation 6.53 – 6.55 do take into account differences in annual precipitation between locations but not differences in monthly precipitation and vegetation extraction patterns. Replenishment and depletion rates are expected to differ among locations as monthly precipitation distributions vary.

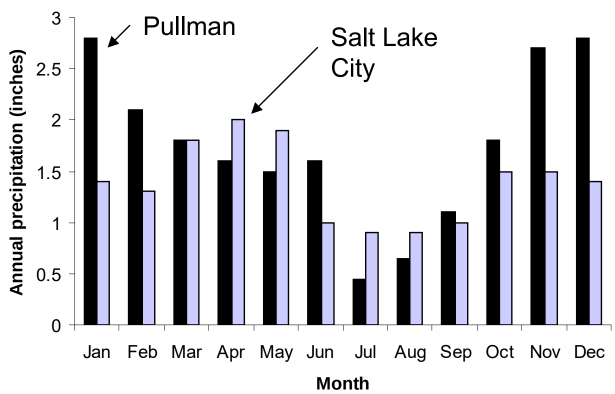

Figure 6.7. Distribution of monthly precipitation at Pullman, Washington (P_a = 20.9 inches) and Salt Lake City, Utah (P_a = 16.9 inches)

6.7.3. Comments on antecedent soil moisture subfactor

The antecedent soil moisture subfactor is a very important variable at Req locations. For example, changing the moisture depletion variable ϕ_m from 1, its standard value, to 0 for no moisture depletion, increased estimated erosion from 8.9 to 14 tons/acre per year for a typical conventional, clean-till continuous wheat crop at Pullman, Washington. Given that the antecedent soil moisture subfactor has a major effect on rill-interrill erosion emphasizes the need for improved equations for this subfactor as a function of monthly precipitation distribution.

The RUSLE2 antecedent soil moisture subfactor should be used only for Req locations. The antecedent soil moisture subfactor equations were empirically derived from data collected at Pullman, Washington where climatic conditions are very different from those in other US regions. Antecedent soil moisture affects rill-interrill erosion in all locations. Those effects are empirically described by the canopy and soil biomass subfactors and by the precipitation and temperature variables used to compute temporal soil erodibility factor values (see **Section 4.5**). Using the antecedent soil moisture subfactor in non-Req location causes serious errors in RUSLE2 estimated erosion.

6.8. Validation of cover-management factor values

RUSLE2 should represent the effect of cover-management on rill-interrill erosion better than it does for any other major factor. Rill-interrill erosion varies more as cover-management varies over its likely range than it does for the likely range of any other factor. Cover-management type erosion control practices are used more widely than any other type of erosion control practice. RUSLE2 must accurately estimate how cover-management affects erosion to avoid excessive expense of installing more erosion control than necessary. Likewise, RUSLE2 must accurately estimate how cover-management affects erosion to ensure adequate erosion control and prevention of excessive damages. The RUSLE2 User's Reference Guide extensively discusses the validity of RUSLE2 for estimating how cover-management affects rill-interrill erosion.

Tables 6.10 – 6.12 illustrate how well the RUSLE2 cover-management subfactors compute soil loss ratios in relation to summarized experimental data taken from AH537 (Wischmeier and Smith, 1978) and other sources. As these tables show, RUSLE2 estimates very well the variation in soil loss ratios as a function of crop stage periods and as a function of the major cover-management variables that affect rill-interrill erosion.

In addition, an extensive set of literature was reviewed and analyzed in validating RUSLE2 for conservation tillage especially no till (see **Section 12.23**).

Table 6.10. Soil loss ratios for conventional clean tilled continuous 112 bu/ac from AH537 and RUSLE2 computed values.

Crop stage (defined in AH537)	AH537 soil loss ratio	RUSLE2 computed soil loss ratio
Fallow	0.31	0.28
Seedbed	0.55	0.54
1 - 10% < canopy cover < 50%	0.48	0.52
2 - 50% < canopy cover < 75%	0.38	0.3
3 - 75% < canopy cover to maturity	0.23	0.18
4 after harvest (stalks spread)	0.06	0.06

Table 6.11. Soil loss ratio values for conventional clean till flat planted continuous 750 lbs/acre cotton at Holly Springs, Mississippi.

Crop stage (defined in AH537)	AH537 soil loss ratio	RUSLE2 computed soil loss ratio
Fallow	0.39	0.54
Seedbed	0.64	0.74
1- 10% canopy cover < 35%	0.59	0.74
2 - 35% < canopy cover < 60%	0.46	0.49
3 - 60% canopy cover to maturity	0.32	0.23
Defoliation to Dec 31	0.26	0.24
Jan 1 to Feb. tillage	0.32	0.32

Table 6.12. Soil loss ratio values for conventional clean till ridge (hipped) continuous planted 750 lbs/acre cotton at Holly Springs, Mississippi.

Crop stage (defined in AH537)	AH537 soil loss ratio	RUSLE2 computed soil loss ratio
1st hip, no prior tillage	0.84	0.88
Split ridges with a “do-all”	0.54	0.52
Hip after 2 prior tillages	1.08	1.01
Split ridges with a “do all”	0.62	0.58
Hip after 3 or more tillages	1.1	1.12
Split ridges with a “do all”	0.64	0.64
Seedbed	0.64	0.64
1 - 10% canopy cover < 35%	0.59	0.64
2 - 35% < canopy cover < 60%	0.46	0.45
3- 60% canopy cover to maturity	0.32	0.21
Defoliation to Dec 31	0.22	0.23
Jan 1 to Feb. tillage	0.32	0.27

6.9. List of symbols

a_b = coefficient related to buried residue and soil consolidation used to compute a_2

a_e = coefficient used to compute loss of ridge height by interrill erosion (inch/customary US erosivity unit)

a_g = coefficient related to height within the canopy where vegetative surface area is concentrated, used to compute effective fall height

a_h = coefficient used to compute ridge subfactor values

a_s = coefficient that is a function of canopy shape, used to compute effective fall height

a_1 = coefficient related to soil biomass and soil consolidation used to compute a_2

a_2 = coefficient, along with a_4, for how soil consolidation, soil biomass, and conformance of ground cover to the soil surface affect rill to interrill erosion ratio

a_3 = coefficient related overland flow path length and steepness and conformance of ground cover to soil used to compute a_4

a_4 = coefficient, along with a_2, for how soil consolidation, soil biomass, and conformance of ground cover to the soil surface affect rill to interrill erosion ratio

A_p = measured erosion from simulated rainfall applied to plots used to determine c_p factor values (mass/area)

b = coefficient for how ground (surface) cover affects rill-interrill erosion (percent^{-1})

b_r = coefficient for how ground cover affects rill erosion (percent^{-1})

B_{rs} = buried residue mass (dry basis) density in soil accounting depth for buried residue (mass/area·length)

B_{rt} = live and dead root mass (dry basis) density in soil accounting depth for roots (mass/area·length)

B_{td} = total mass (dry basis) density of buried residue and live and dead roots averaged over soil disturbance depth after the operation (lbs_m/acre·inch)

c = daily cover-management factor

c_a = coefficient for combined effect of buried residue and soil consolidation on ground cover effectiveness in relation to rill erosion

c_c = daily canopy subfactor

c_p = c factor value for measured erosion data obtained from applying simulated rainfall to field plots

c_{pr}/c_{pi} = rill to interrill prior land use soil erodibility ratio

d_{rs} = accounting soil depth for buried residue (inches)

D_b = rill-interrill erosion when ground cover is not present (bare soil) (mass/area)

D_c = rill-interrill erosion when ground cover is present (mass/area)

D_{ib} = interrill erosion when ground cover is not present (bare soil) (mass/area)

D_m = index for daily moisture depletion rate

D_{rb} = rill erosion when ground cover in not present (bare soil) (mass/area)

D_t = normalized rill-interrill erosion

e_d = waterdrop impact energy (force-distance)

f_b = fraction of the daily biomass decomposed from surface residue added to buried residue biomass in upper 2-inch soil layer

f_c = daily canopy cover (fraction)

f_{ec} = daily effective canopy cover (fraction)

f_g = ground (surface) cover (fraction or percent when used to compute g_c)

f_{ge} = effective ground cover used to compute values for slope exponent m (percent)

f_{gn} = net ground cover, portion of soil surface covered

f_r = fraction of today's soil surface roughness greater than 0.24 inch that remains after today's loss of roughness

g_c = daily ground (surface) cover subfactor

g_{ci} = interrill erosin ground (surface)cover subfactor

g_{cr} = rill erosion ground (surface)cover subfactor

g_r = relative row grade (grade along the ridges/overland flow path steepness)

h_b = height to canopy bottom (length)

h_f = daily effective fall height (feet)

h_t = height to canopy top (length)

H = daily ridge height (inches)

H_e = ridge height component associated with interrill erosion (inches)

H_{ep} = previous day ridge height component associated with interrill erosion (inches)

H_s = ridge height component associated with settlement (inches)

H_{sp} = previous day ridge height component associated with settlement (inches)

I = daily amount of water added by irrigation (inches)

K_n = soil erodibility value determined from standard soil erodibility nomograph using soil property values measured at each site (mass/erosivity unit)

K_r/K_i = rill to interrill soil erodibility ratio

m = slope length exponent

m_d = waterdrop mass

P_a = average precipitation (inches)

P_{cl} = mass portion of soil composed of clay (percent)

P_d = daily precipitation (inches)

P_{sl} = mass portion of soil composed of silt (percent)

r_d = daily erosivity (erosivity units)

r_h = daily ridge height subfactor

$r_{h,u\&d}$ = ridge height subfactor value when ridge orientation is parallel to overland flow path

r_{h6} = daily ridge height subfactor when overland flow path steepness is less than or equal to 6 percent

R_a = daily adjusted sil surface roughness roughness used to compute soil surface roughness subfactor values (inches)

R_{aa} = adjusted soil surface roughness immediately after soil disturbing operation (inches)

R_{ae} = existing adjusted soil surface roughness before a soil discturbing operation (inches)

R_{alf} = adjusted final long term soil surface roughness value after input value for long term roughness adjusted for soil texture and soil biomass (inches)

R_{ap} = adjusted soil surface roughness on previous day (inches)

R_{ib} = initial soil surface roughness after input roughness adjusted for soil texture and biomass (inches)

R_{in} = input soil surface roughness value for reference condition for soil disturbing operation (inches)

R_{it} = initial soil surface roughness after input roughness value adjusted for soil texture (inches)

R_l = daily adjusted long long term soil surface roughness (inches)

Req = equivalent erosivity related to greatly increased soil erodibility during winter months in Nrthwestern US

R_m = index for daily moisture replenishment rate

R_p = erosivity for simulated rainfall applied to plots used to determine c_p factor values (erosivity units)

s = overland flow path steepness (sine of slope angle)

s_b = daily soil biomass subfactor

s_c = daily soil consolidation subfactor

s_i = interrill area steepness (sine of slope angle)

s_m = daily antecedent soil moisture subfactor used in Req zone

s_p = overland flow path steepness (100 times tanget of slope angle)

s_r = daily soil surface roughness subfactor

S_p = slope steepness factor computed from steepness of plots used with simulated rainfall to determine c_p factor values

t_c = time to soil consolidation (days)

t_d = time since the last mechanical soil disturbance (days)

V = waterdrop impact velocity (length/time)

α = rill to interrill erosion ratio for bare soil

δ = cover adjustment term used to compute slope length exponent

ξ = tillage intensity

λ = overland flow path length (length)

λ_p = length of plots used with simulated rainfall to determine c_p factor values

λ_u = unit plot length (72.6, 22.1 m)

ϕ_m = the total soil moisture depletion as a function of vegetation

ψ = coefficient related to conformance ground (surface) cover to soil surface

7. SUPPORT PRACTICES

7.1. Contouring (ridging)

7.1.1. Description of contouring (ridging)

Contouring is an erosion control practice where ridges are placed on the contour around the hillslope perpendicular to the overland flow path. Runoff flows uniformly over the ridges along their length when the ridges are perfectly on the contour and the ridge top is level. Ponded water in the furrows between the ridges reduces detachment and causes a major portion of the sediment eroded from the ridges to be deposited in the furrows.

These ideal conditions seldom occur in the field. Breakovers occur in low ridge areas and where the soil is susceptible to rill erosion. Erosion reduction with contouring is reduced when breakovers occur. However, erosion reduction occurs even with breakovers if furrow (row) grade is sufficiently flat to cause deposition in the furrows or to cause reduced rill erosion in relation to the rill-interrill erosion that occurs when the ridges are parallel to the overland flow path. Runoff travels long distances in the furrows between high ridges to concentrated flow areas where ephemeral gully erosion occurs. RUSLE2 does not explicitly estimate ephemeral gully erosion (see RUSLE2 User's Reference Guide), although ephemeral gully erosion occurred in the small watersheds used to derive the RUSLE2 contour subfactor relationships. Thus, ephemeral gully erosion is partially included in RUSLE2 erosion estimates for contoured conditions.

The effect of ridging (contouring) on rill-interrill erosion must be considered even when ridging is not used explicitly as an erosion control practice. For example, tillage direction in an agricultural field is often parallel to a field boundary, which results in ridges at an angle to the overland flow path. Rill-interrill erosion varies between the extremes of being minimal when the ridges are perfectly on the contour and maximum when the ridges are parallel to the overland flow path.

The base, reference unit plot condition is that ridges-furrows are parallel to the overland flow path. Thus, the RUSLE2 contouring subfactor represents the effect of ridge-furrow orientation with respect to the overland flow path on rill-interrill erosion.

7.1.2. Contouring (ridging) effect

Figure 7.1 is a graph of experimental data that shows how contouring affects rill-interrill erosion on plots that ranged in width from12 to 150 ft and small watersheds that were about 5 acres in area (Foster et al., 1997; see other references in **Section 7.1** and **Section 12.2.1**).

Each type of measurement area has shortcomings. A shortcoming of watersheds is that measured sediment from watersheds includes sediment produced by ephemeral gully erosion, which is not estimated by RUSLE2. A shortcoming of plots narrower than about

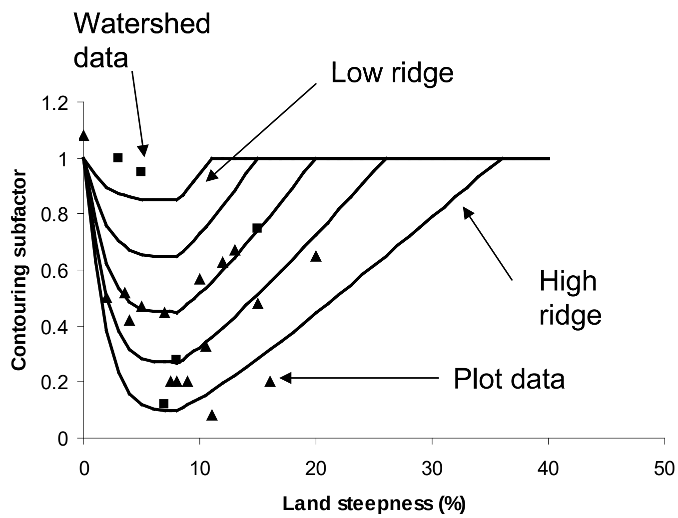

Figure 7.1. Experimental data from plots and small watershed (~ 5 acres) for effect of contouring (ridging) on rill-interrill erosion and fitted lines for effect of ridge height on contouring.

20 ft is that runoff rates are too low at the ridge breakovers. Several plot widths exceeded 20 ft with some as wide as 150 ft, which are sufficiently wide to represent field contouring. Although, neither plot nor watershed data are entirely satisfactory, data from both plots and watersheds were combined to derive RUSLE2 contouring subfactor equations.

The well accepted general contouring subfactor relationship is an upward concave curve that starts at 1 for a zero steepness, decreases to a minimum as land steepness increases to an approximate 8 percent steepness and then increases to 1 at an upper steepness beyond which contouring is assumed not to reduce erosion [AH537 (Wischmeier and Smith, 1978)]. Contouring has no effect at zero land steepness because no flow direction is defined. Contouring has no effect beyond a maximum steepness that is a function of ridge height because the land is so steep that no water can be stored by the ridges.

The range in the data illustrated in Figure 7.1 for the effect of contouring on rill-interrill erosion is assumed to be caused primarily by a ridge height variation. Experimental data show that contouring's erosion reduction increases as ridge height increases (Moldenhauer and Wischmeier, 1960). Increased ridge height increases storage of runoff, decreases interrill detachment, and increases deposition in the furrows, which is the basis for the curves in Figure 7.1 being a function of ridge height. Also, dense plant stems in narrow rows on the contour have the same effect on rill-interrill erosion as ridges on the contour (Daniel et al., 1943; Van Doren et al., 1950). Experimental data show that contouring is less effective for large intense runoff events than for small ones (Moldenhauer and Wischmeier, 1960). In some cases, erosion on watersheds was greater with contouring than with tillage up and down hill as illustrated in Figure 7.1 (Hill et al., 1944). These examples of increased erosion are associated with concentrated flow erosion where ridge-breakovers occurred. Thus, the effective of contouring on rill-interrill erosion depends on storm, soil, and cover-management characteristics that affect runoff.

A long accepted principle by soil conservationists is that contouring fails if the overland flow path length exceeds a critical length that is a function of land steepness [(AH282 (Wischmeier and Smith, 1965); AH537 (Wischmeier and Smith, 1978)]. That critical length is assumed in RUSLE2 to be a function of the shear stress applied to the soil by runoff, which in turn is a function of storm characteristics, inherent potential of the soil for generating runoff, and how cover-management affects runoff and the shear stress that runoff applies to the soil.

The RUSLE2 contouring subfactor equations are very similar to the comparable RUSLE1 equations [Foster et al, 1997, AH703 (Renard et al., 1997)] except for the RUSLE2 equations being a function of daily ridge height, runoff, and cover-management conditions.

7.1.3. Contouring (ridging) subfactor equations

The RUSLE2 contouring equations were developed to give accepted values for a base, reference condition of conventional, clean tilled 50 bu/ac corn grown on a silt loam hydrologic C soil group soil located at Columbia, Missouri.[58] This management practice was common when the contouring data were collected from the mid 1930's to the mid 1950's for much of the data represented in Figure 7.1.

The RUSLE2 equations vary contouring subfactor values about base, reference values as climate, soil, and cover-management conditions depart from the base, reference condition. The RUSLE2 equations were structured to meet required boundary conditions and were calibrated to experimental data to give similar contouring subfactor values used by the USLE and computed by RUSLE1 for base, reference conditions. In contrast to the RUSLE1 equations that used a representative ridge height and cover-management condition to represent the cover-management practice to compute an average annual contouring subfactor value (Foster et al, 1997), the RUSLE2 equations compute daily contouring subfactor values as climate, cover-management, runoff, and ridge height vary daily.

7.1.3.1. Base equations

The data shown in Figure 7.1 were collected from several locations in the eastern US. However, the data were insufficient for directly deriving explicit equations and coefficient values that consider all of the major variables related to contouring's effect on rill-interrill erosion. The data in Figure 7.1 were assumed to represent the overall effect of contouring for the base, reference condition described in **Section 7.1.3**.

The first step in deriving the RUSLE2 contouring equations was to develop a set of equations that represent the base, reference condition. Those equations, which follow similar RUSLE1 equations, are given by:

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[58] These farming conditions differ from current farming practices. Also, these farming practices are not typical of rangelands, surface mine reclamation, construction sites, and other conditions where ridging (contouring) is used to control rill-interrill erosion. RUSLE2 includes procedures to account for these differences.

$$p_b = a_c(s_m - s_c)^4 + p_{bm} \quad s_c < s_m \qquad [7.1]$$

$$p_b = c_c(s_c - s_m)^{1.5} + p_{bm} \quad s_m \le s_c < s_{be} \qquad [7.2]$$

$$p_b = 1 \qquad s_{be} \le s_c \qquad [7.3]$$

where: p_b = base contouring subfactor value, s_c = a scaled land steepness (sine of slope angle), s_m = the land steepness (sine of slope angle) at which $p_b = p_{bm}$, the minimum base contouring value and s_{be} = the steepness (sine of slope angle) at which the contouring subfactor reaches 1. Values for the coefficients a_c and c_c are computed from:

$$a_c = (1 - p_{bm}) / s_m^4 \qquad [7.4]$$

$$c_c = (1 - p_{bm}) / (s_{be} - s_m)^{1.5} \qquad [7.5]$$

These equations satisfy the boundary conditions that $p_b = 1$ at $s_c = 0$, $p_b = p_m$ at $s_c = s_m$, $p_b = 1$ at $s_c = s_{be}$, and the slope of equations 7.1 and 7.2 is zero at $s_c = s_m$.

7.1.3.2. Ridge height adjustments

The minimum contouring subfactor value p_{bm}, which occurs at $s = s_m$, is assumed to be a function of ridge height as (Moldenhauer and Wischmeier, 1960):

$$p_{bm} = 0.05 + 0.95\exp(-0.5512 H_e) \quad if\,(H_e > 8) : H_e = 8 \text{ inches} \qquad [7.6]$$

where: H_e = daily effective total ridge height (inches), which is the sum of the daily soil ridge height H (see **Sections 6.4.6 and 8.3.5**) and the daily effective vegetation ridge height H_{vr} (see **Section 9.2.7**). The steepness s_{bm} at which the base contouring subfactor is minimum (i.e., $p_b = p_{bm}$) is also assumed to be a function of effective ridge height as:

$$s_{bm} = 4[1 - \exp(-0.7903 H_e)] + 4 \quad if\,(H_e > 8) : H_e = 8 \text{ inches} \qquad [7.7]$$

The steepness s_{be} at which the contouring subfactor p_b becomes 1 as steepness increases is assumed to be a function of effective ridge height as:

$$s_{be} = \sin\{\tan^{-1}[(9 + 53.09 H_e / 8)/100]\} \; if\,(H_e > 8) : H_e = 8 \text{ inches} \qquad [7.8]$$

where: s_{be} = the steepness (sine of slope angle) that the contouring subfactor becomes 1. Maximum effective ridge height for equations 7.6, 7.7, and 7.8 is limited to 8 inches.[59]

[59] The uncertainty of contouring's erosion control effectiveness at any specific site is greater than for all other erosion control practices. Also, data for the effect of ridge height and other factors on the erosion control effectiveness of contouring are very limited for a wide range of conditions. Contouring using high ridges can be highly effective, especially in low rainfall areas, but result in very high erosion for rarely

7.1.3.3. Runoff adjustments

The minimum contouring subfactor values p_{rm} at s_m are assumed to vary directly with the ratio of runoff with the given climate, soil, and cover-management condition to the runoff for the base, reference condition as:

$$p_{rm} = p_{bm}(d_r / 4.16) \qquad [7.9]$$

where: p_{rm} = the minimum contouring subfactor value adjusted for runoff, d_r = runoff depth (inches) for the 10 year-24 hour precipitation amount P_{10y24h} at the given location, soil, and cover-management condition on the day that a contouring factor value is computed, and 4.16 (inches) = runoff computed with the 10 year-24 hour storm for the base, reference condition (see **Section 2.3.7**).

The steepness at which the contouring subfactor becomes 1 for a given condition is assumed to be related to the shear stress that the runoff applies to the soil. It is computed from:

$$s_{re} = s_{be} / (d_r / 4.16)^{0.8571} \qquad [7.10]$$

where: s_{re} = the runoff adjusted steepness (sine of slope angle) above which the contouring subfactor equals 1.

7.1.3.4. Steepness scaling

A scaled steepness s_c is used to compute a base contouring p_b subfactor value using equation 7.1, 7.2, or 7.3. The equation for the scaled steepness at low steepness is given by:

$$s_c = s \quad s \le s_m \qquad [7.11]$$

where: s = the steepness (sine of slope angle) of the overland flow path. The scaled steepness for $s > s_m$ is given by:

$$s_c = s_{bm} + \frac{(s - s_{bm})(s_{be} - s_{bm})}{s_{re} - s_{bm}} \quad s > s_m \qquad [7.12]$$

The reason that steepness used to compute a p_b value must be scaled is that the upper steepness where the contouring subfactor becomes equal to 1 varies as conditions vary from the base, reference condition.

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occurring intense storms. The 8 inch limit in these equations was chosen based on professional judgment and experience (see **Section 7.1.5**). See the RUSLE2 User's Reference Guide for guidance on using RUSLE2 to evaluate the erosion control effectiveness of contouring (ridging).

7.1.3.5. Contouring subfactor scaling

The contouring subfactor value must also be scaled because the contouring factor value at s_m for the given condition differs from the contouring subfactor value for the base, reference conditions. The contouring subfactor value for level furrow (row) is computed from the scaling equation as:

$$p_{c0} = 1 - \frac{(1-p_b)(1-p_{rm})}{1-p_{bm}} \quad if\,(p_{c0} > 1): p_{c0} = 1 \qquad [7.13]$$

where: p_{c0} = the contouring subfactor for a zero row grade (grade along furrows separating the ridges).

7.1.3.6. Contouring subfactor limits

Contouring subfactor values computed by equation 7.13 must be within certain limits. The upper limit is that contouring subfactor values can not be greater than 1. The other limit is a lower limit assumed to be acceptable for conservation and erosion control planning. RUSLE2 must account for the possibility of an extreme storm occurring even when annual erosivity and the P_{10y24h} precipitation amounts are low. The lower limit for contouring subfactor values is computed from:

$$p_{c0,\min} = 0.05 + 0.95\exp(-h_e) \qquad [7.14]$$

$$if\,(p_{c0} > p_{c0,\min}): p_{c0} = p_{c0,\min} \qquad [7.15]$$

where: $p_{c0,min}$ = minimum contouring subfactor value for a given ridge height.

7.1.3.7. Adjusting for row grade

The RUSLE2 assumption, which is the same as the RUSLE1 assumption, is that contouring rapidly loses its effectiveness as row grade increases (Foster et al., 1997).

$$p_c = p_{c0} + (1-p_{c0})(s_f / s_p)^{1/2} \qquad [7.16]$$

where: p_c = the daily contouring subfactor and s_f = grade along the furrows separating the ridges (row grade) (100·tangent of slope angle). The variable s_f/s_p is designated as the relative row grade and sp =land steepness (100·tangent of slope angle). Measured erosion on 150 ft wide plots on a 5 percent land steepness showed that the contouring subfactor values vary with row grade (McGregor et al., 1969). The observed contouring subfactor values were 0.10 and 0.39 for the ridges perfectly on the contour and ridges on a 0.3 percent row grade, respectively. Given the observed p_{c0} = 0.10 contouring subfactor value for ridges perfectly on the contour (i.e., row grade = 0), the computed contouring subfactor value from equation 7.16 is 0.32, which is slightly less than the 0.39 observed value.

7.1.4. Contouring failure

The RUSLE2 assumption is that contouring fails when the shear stress applied to the soil by runoff exceeds a critical shear stress. The contouring subfactor is set to 1 for those portions of the overland flow path where contouring failure is computed. The equations used in these computations are described in **Section 3.4.3**.

Once contouring failure occurs at a location on an overland flow path, the daily contouring subfactor remains at 1 until the next soil disturbing operation. The RUSLE2 assumption is that contouring failure results from runoff breaking through the ridges, and thus the contouring effect can be regained only after ridges are re-established to fill the breakthrough areas. The RUSLE2 procedure is that only a soil disturbing operation creates ridges that repair the ridge breakthroughs that represent contouring failure (see RUSLE2 User's Reference Guide).

7.1.5. Comments on contouring subfactor

RUSLE2 allows row grade to be input as absolute row grade or as relative row grade. In most applications, relative row grade should be used as the input for consistency with the concepts behind equation 7.16 for the effect of row grade on the contouring subfactor. Using relative row grade implicitly results in the quality of contouring being treated equally regardless of land steepness (see RUSLE2 User's Reference Guide).

RUSLE2 accurately represents the general trends of how major variables affect contouring's reduction on rill-interrill erosion. However, local conditions that can not be easily measured or visualized, especially before a storm event, greatly affect contouring's effectiveness. For example, slight and imperceptible variations in ridge height and furrow grade along the ridges greatly affect the number and locations of breakovers. Therefore, while RUSLE2 accurately represents the overall effect of contouring on rill-interrill erosion, the uncertainty in how contouring affects rill-interrill erosion on a specific site is greater than for any other major RUSLE2 variable (see RUSLE2 User's Reference Guide).

7.2. Porous barriers

7.2.1. Description of porous barriers

A porous barrier is a portion of the overland flow path that has a significantly higher hydraulic resistance than the overland flow path immediately upslope of the barrier. The RUSLE2 assumption is that runoff passes through porous barriers. That is, porous barriers do not end the overland flow path. Porous barriers include strips of dense vegetation used in rotational strip cropping; grass buffers, filter strips, and stiff grass hedges; a strip of dense vegetation left undisturbed along a channel on construction and logging sites; and fabric fences and gravel bag dams used on construction sites (see RUSLE2 User's Reference Guide).

7.2.2. Processes associated with porous barriers

The significantly increased hydraulic resistance of the porous barrier slows and ponds runoff in backwater at the upper edge of the barrier. Runoff's sediment transport capacity is greatly reduced in both the backwater and within the porous barrier. Deposition occurs if the sediment transport capacity is reduced to less than the sediment load coming into the backwater and barrier. Most of the deposition caused by porous barriers actually occurs in the backwater. The upper edge of deposited sediment and backwater advance upslope as deposition occurs in the backwater, which increases transport capacity within the backwater. Eventually the backwater becomes filled with sediment and most of the incoming sediment load is then transported into the barrier itself. However, RUSLE2 does not account for sediment accumulation within the backwater and change in sediment transport capacity as sediment accumulates in the backwater.

Runoff is assumed to pass through porous barriers. Infiltration rate within the barrier can be much higher than that on the overland flow path immediately upslope of the barrier, which reduces runoff downslope of the barriers. The high hydraulic resistance in a porous barrier can eliminate rill erosion and spread runoff within the barrier so that runoff exits the barrier as a thin uniform depth flow along the lower edge of the barrier. Spreading of the runoff reduces its erosivity immediately downslope of a porous barrier.

7.2.3. RUSLE2 equations used to describe porous barriers

The RUSLE2 equations used to compute deposition caused by porous barriers and the sediment load leaving porous barriers are described in **Sections 2.3 and 3.4**. This section describes key features of these equations.

RUSLE2 uses the same cover-management values to compute detachment within the backwater as it uses to compute detachment within the porous barrier. The RUSLE2 assumption is that detachment downslope of a porous barrier is not affected by the barrier except as the barrier affects contouring failure. RUSLE2 does not compute how increased infiltration on an overland flow path segment affects detachment on downslope segments because of reduced runoff. That is, RUSLE2 computes the same detachment, except for contouring failure, immediately downslope of a porous barrier regardless of the presence or absence of the barrier.

The conceptual basis for this assumption is that spreading the overland flow by the porous barrier reduces runoff erosivity. However, the very low sediment concentration in the runoff leaving the barrier increases runoff erosivity. Flow has greater erosivity when it has a very low sediment load in contrast to when the runoff's sediment transport capacity is nearly filled with sediment (Foster and Meyer, 1975; Foster, 1982). The RUSLE2 assumption is that these two effects on runoff erosivity offset each other.

The assumption that downslope detachment is unaffected by high infiltration on an upslope segment is obviously invalid where a porous barrier is sufficiently wide and has a sufficiently high infiltration rate to significantly reduce the runoff that leaves the barrier.

The RUSLE2 User's Reference Guide describes how to choose RUSLE2 inputs to partially represent conditions where high infiltration and reduced runoff affects downslope detachment.

RUSLE2 computes reduced runoff from segments, including those with porous barriers, having high infiltration rates. RUSLE2 computes reduced sediment yield from these segments if transport capacity is less than sediment load within the segment because of reduced runoff. Also, reduced runoff from high infiltration segments affects downslope sediment transport capacity and deposition computations. For example, computed deposition and sediment load on a concave shaped overland flow profile is affected by high infiltration and reduced runoff for an upslope segment.

RUSLE2 computes how reduced runoff caused by high infiltration within a porous barrier and runoff spreading by the barrier affects shear stress applied by runoff to the soil immediately downslope from the barrier. Contouring failure is assumed to occur if this shear stress exceeds a critical shear stress (see **Section 3.4.3**). RUSLE2 computes reduced erosion below a porous barrier where RUSLE2 computes no contouring failure below the barrier but computes contouring failure without the barrier.

Hydraulic resistance is a major variable that affects the amount of deposition caused by a porous barrier. A Manning's n value, RUSLE2's measure of hydraulic resistance, is computed as a function of retardance (see **Section 3.4.6**), which varies temporally as vegetation changes through time. All porous barriers are represented in RUSLE2 as strips of vegetation, even when the barriers are non-vegetative including fabric fences, gravel bags, and similar behaving barriers. Non-vegetative porous barriers slow runoff as do vegetative porous barriers.

Eight retardance classes are used to describe porous barriers based on the degree that a barrier slows runoff (see **Section 3.4.6** and RUSLE2 User's Reference Guide). The eighth retardance class is a special case used to describe barriers such as stiff grass hedges and silt fences that provide maximum retardance. The minimum backwater length that RUSLE2 uses for this retardance class is 3 ft, whereas no minimum backwater length is used for the other retardance classes (see **Section 3.4.4**). The maximum backwater length allowed by RUSLE2 is 15 ft for all retardance classes.

7.2.4. Effect of row grade

Runoff must pass through porous barriers for them to reduce sediment load. A ridge of soil at the upper side of porous barriers left by tillage or deposited sediment or debris collected on a fabric fence causes runoff to flow along the upper edge of the barrier and never enter the barrier if the grade along the upper edge of the barrier is too steep. The barrier acts as a flow interceptor (see **Section 7.3**) that ends the overland flow path.

Inputs used to describe porous barriers can be entered in two ways. One way is to select porous barriers from a list of supporting practices. When this input method is used, RUSLE2 requires that the relative row grade for the barrier be less than 10 percent. RUSLE2 assumes that trapping efficiency is independent of row grade for relative row grade less than 10 percent. The RUSLE2 assumption with this input method is that runoff does not enter the barrier but runs along the upper edge of the barrier if the relative row grade along the upper edge of the barrier exceeds 10 percent. In that case, the barriers operate as a flow interceptor barrier.

The other way to input information to describe porous barriers in RUSLE2 is to divide the overland flow path into segments and enter information for each segment, including those segments used to represent the porous barriers. When this input method is used, RUSLE2 assumes that runoff enters the porous barrier regardless of the relative row grade along the upper edge of the porous barrier (see RUSLE2 User's Reference Guide).

7.2.5. Spatial variability

When the RUSLE2 input method of selecting a support practice is used to represent porous barriers, RUSLE2 assumes that multiple barriers are spaced uniformly along the overland flow path length. Also, the conditions are assumed to be the same for each barrier. When the input method of dividing the overland flow path into segments is used, each segment can be described individually and barriers can be spaced non-uniformly. Conditions are assumed to be uniform within a segment.

7.2.6. Validation of RUSLE2 computed values

7.2.6.1. Strip cropping

RUSLE2 computed values for the effect of strip cropping and narrow stiff grass hedges on sediment yield from an overland flow path were compared with measured data reported in the literature (Foster et al., 1997, see references this section). Because strip cropping data are highly variable, many more years of data and/or experimental plots and small watersheds are required to accurately evaluate strip cropping than for any other soil conservation practice. Sediment yield from strip cropping is closely related to the storm events that occur when the erodible strips are at the end of the overland flow path. Data must be recorded over a sufficiently long duration for representative storms to occur on the erodible strips in all positions along the overland flow path. Sediment yield is much less when an extreme event occurs when an erodible strip is near the upper end of the overland flow path than at the lower end of the overland flow path. Data from such a storm would indicate that strip cropping is much more effective than it actually is. Very little of the available strip cropping data are for an adequate duration. Also, much of the strip cropping data are inconsistent. In one study, erosion with a small grain in a rotation in a strip cropping system was much less than when in the same crop rotation was not in strip cropping.

Priority was given to ensuring that RUSLE2 fits strip cropping data from Wisconsin (Hays et al., 1949; Hays and Attoe,1957) and to values given in AH282 and AH537 (Wischmeier and Smith, 1965, 1978) for a base, reference condition. Strip cropping has been used extensively and highly successfully since the 1930's in the La Crosse, Wisconsin region. The support practice factor values given in AH282 and AH537 have been well accepted in conservation planning by USDA-NRCS personnel for this region. Also, the Wisconsin data seem to be of higher quality than most of the other available data. Wischmeier and Smith (1965, 1978) and technical and scientific personnel from the USDA-Agricultural Research Service and Soil Conservation Service reviewed these same data and developed recommendations included in AH282 and 537. These values are established and accepted based on many years of field applications of the USLE.

The values in AH282 and AH537 are that strip cropping reduces sediment yield from the end of an overland flow path by 50 percent "For 4-year rotation of row crop, small grain with meadow (mixture of legume and grass hay), and 2 years of meadow. A second row crop can replace the small grain if meadow is established in it [AH537 (Wischmeier and Smith, 1978)]." The comparable RUSLE2 computed value is 0.43 for the base, reference condition of a 150 ft long, six percent steep overland flow path on a silt loam soil at Columbia, Missouri for crops and yields comparable to those represented in the data on which the AH282 and 537 values are based. The comparable measured values from research in Wisconsin are 0.42 and 0.55 (Hays et al, 1949; Hays and Attoe, 1957).

The AH282/537 values for the ratio of sediment yield with strip cropping to sediment yield without strip cropping is 0.75 "For 4-year rotation of 2 years row crop, winter grain with meadow seeding, and 1-year meadow." The RUSLE2 computed value is 0.54.

The AH282/537 values for the ratio of sediment yield with strip cropping to sediment yield without strip cropping is 1 "For alternate strips of row crop and small grain." RUSLE2 also computes a value of 1 for this condition.

7.2.6.2. Stiff grass hedges

RUSLE2 computed value of 0.25 for fraction of the incoming sediment load from a conventional, clean tilled cotton that is trapped by a stiff grass hedge at Holly Springs, MS is very close to the measured value of 0.25 (McGregor et al., 1999). RUSLE2 computes a value of 0.20 for no-till cotton upslope of the stiff grass hedge while the measured value was 0.43. The study was run for three years. The hedges were much better established and uniform in the third year of the experiment than in the first year. The fraction of the incoming sediment load that was trapped by the hedges in the third year was 0.29 and 0.33 for the conventional and no-till managements, respectively, which are close to the RUSLE2 computed values.

7.2.7. Comments on porous barriers

The RUSLE2 intent for computing how porous barriers affect erosion is for the purpose of conservation and erosion control planning where the main effects of the major variables are captured. The equations are based on well accepted hydraulic principles. The performance of porous barriers is highly dependent on how well the barriers are installed and maintained. For example, fabric fences are widely used on construction sites to control sediment leaving the site. However, very poor sediment control occurs in far too many cases because of substandard installation and/or maintenance. The actual sediment trapping of fabric in a typical field situation is much less than the sediment trapping measured in laboratory studies.

A comparable situation exists with vegetative strips that are poorly established and/or maintained. For example, non-uniform grass stands within a strip or damage caused by tillage, construction activities, or other soil disturbing operations can significantly reduce sediment trapping efficiency.

RUSLE2 does not represent the variations that result from poor installation and maintenance. RUSLE2 represents the performance of porous barriers that are installed and maintained according to specifications and inspections.

The RUSLE2 equations and input values were chosen to represent barriers that perform well in the field but less than would be measured in carefully controlled laboratory hydraulic studies.

7.3. Interceptor barriers

7.3.1. Characteristics of interceptor barriers

Interceptor barriers are topographic features that end the overland flow path. Examples of interceptor barriers represented by RUSLE2 include terraces, diversions, and small impoundments. Terraces are defined as channels on a sufficiently flat grade to cause deposition while diversions are channels are on a sufficiently steep grade that deposition does not occur in them but are not on such a steep grade that erosion occurs in them. Impoundments are water bodies where flow velocities are almost negligible. RUSLE2 represents typical impoundments comparable to those used with impoundment terraces in farm fields [e.g., parallel tile outlet (PTO) terraces] and small sediment basins used on construction sites.

Interceptor barriers reduce erosion by cutting overland flow path length and causing deposition. RUSLE2 also computes how deposition by interceptor barriers affects sediment characteristics. RUSLE2 does not compute ephemeral gully erosion that occurs in concentrated flow areas (channels) (Foster, 1985).

7.3.2. Channels (Terraces/diversions)

7.3.2.1. Deposition and sediment load equations

Deposition occurs in a channel when the incoming sediment load exceeds sediment transport capacity of flow in the channel (Foster, 1982; Foster et al., 1980a). Deposition rate is computed in RUSLE2 using (Renard and Foster, 1983):

$$D_{p(k)} = f_{(k)}\left(\frac{\phi_{(k)}}{1+\phi_{(k)}}\right)\left(\frac{dT_c}{dx} - g_o\right) \quad dT_c / dx < g_o \qquad [7.17]$$

$$D_{p(k)} = 0 \quad dT_c / dx \geq g_o \qquad [7.18]$$

$$\phi_{(k)} = 400000 V_{f(k)} / q_o \qquad [7.19]$$

where: $D_{p(k)}$ = deposition rate for the *kth* particle class [mass/(unit channel length·time)], $f_{(k)}$ = fraction, based on mass, of the total incoming sediment load g_0 (mass/unit channel length·time) from the overland flow area made up of the *kth* particle class, T_c = sediment transport capacity of the flow in the channel (mass/time), x = distance along the channel $V_{f(k)}$ = the fall velocity (ft/sec) of the *kth* sediment particle class, and q_o = the discharge rate at the end of the overland flow path (ft^3/sec per ft channel length). Equation 7.17 is derived from equation 2.16 and the assumptions of uniform channel grade, uniform sediment input from the overland flow area along the channel length, incoming sediment load for each particle class exceeds the sediment transport capacity in the channel for that particle class, and channel sediment transport capacity for each particle is proportional to the distribution (mass basis) of the incoming sediment load.

The change in sediment load with distance along the channel is computed using:

$$dT_c / dx = 450 s_{ch}^{1.16} q_0 \qquad [7.20]$$

where: T_c = transport capacity (lbs_m/sec), s_{ch} = grade (steepness) of the channel (sine of channel slope angle), and x = distance along the channel (ft). Equation 7.20 was derived from the assumptions that transport capacity is directly proportional to the 3/2 power of shear stress applied to the channel boundary by the flow and that Manning's equation is used to compute hydraulic radius for flow in the channel (Foster and Meyer, 1975; Foster, 1982; Foster et al., 1980). The channel's hydraulic roughness is assumed to be that of deposited sediment that covers soil surface roughness, surface residue, and standing vegetation. The effect of standing live or dead vegetation on deposition in channels is not considered in RUSLE2 because most of the deposition is assumed to occur when little vegetation is present, such as at seedbed time when crops are planted. The 450 coefficient value in equation 7.20 was determined by calibrating RUSLE2 to compute values similar to those given by the RUSLE1 sediment delivery ratio equation, which was empirically derived from field data [AH703(Renard, 1997); Foster et al., 1997; Foster and Ferreira, 1981; Foster and Highfill, 1983).

Equation 7.17 and its companion equations compute a uniform deposition rate along the channel. The sediment leaving the channel is computed with:

$$g_{ch(k)} = g_{o(k)} - D_{p(k)} \qquad [7.21]$$

where: $g_{ch(k)}$ = the sediment load (mass/unit channel length·time) leaving the end of the channel for the *kth* particle class. The sediment load leaving the channel expressed as the ratio of sediment load at the end of the channel to unit drainage area for the channel is computed with:

$$A_{ch(k)} = g_{ch(k)} / \lambda_o \qquad [7.22]$$

where: $A_{ch(k)}$ = the sediment load for the *kth* particle class leaving the end of the channel expressed as mass/time per unit drainage area and λ_o = the length of the overland flow path that discharges into the channel. The sediment delivery ratio for the channel for the *kth* particle class is given by:

$$\omega_{(k)} = 1 - D_{p(k)} / g_{o(k)} \qquad [7.23]$$

where: $\omega_{ch(k)}$ = sediment delivery ratio for a channel for the *kth* sediment particle class. Total sediment load is computed by summing the sediment load values for the five RUSLE2 particle classes (see **Section 4.7**).

7.3.2.2. Comments on channels

When flow interceptors are represented in RUSLE2 as a support practice, the spacing between flow interceptors is the same for all flow interceptors represented by the support practice. However, non-uniform spacing among flow interceptors can be represented by manually entering appropriate spacing values. Similarly, the grade is assumed the same for all channels when flow interceptors are represented as a support practice. However, separate grade values for each channel can be entered in RUSLE2.

RUSLE2 requires that a representative channel grade be chosen for channels on a non-uniform grade. This limitation can be of consequence for parallel terraces where grade varies along the channel. In most of these situations, channel grade is flattest at the upper channel end with grade increasing along the channel. RUSLE2's estimates for deposition for these conditions are less accurate than for uniform grade channels. A grade flatter than the average channel grade for its length is the appropriate input grade.

RUSLE2 does not represent channels where sediment inflow varies along the channel length. Not many field situations occur where this limitation is of consequence.

The RUSLE2 equations used to compute deposition in channels are based on commonly used equations for channel hydraulics. However, RUSLE2 is a conservation and erosion control planning tool, not a hydraulic design tool. Appropriate hydraulic equations should be used to design the channels represented in RUSLE2. Channels are usually designed to accommodate runoff rate from a particular design storm under particular soil and cover conditions whereas most conservation and erosion control planning is based on average annual erosion rates for the range of cover-management conditions expected over the time period being represented in the RUSLE2 computation. See the RUSLE2 User's Reference Guide for information on the types of channels represented by RUSLE2.

7.3.3. Impoundments

7.3.3.1. Sediment delivery ratio equation

The RUSLE2 assumption is that sediment transport capacity in impoundments is essentially zero. Impoundments are treated as a fixed length settling basin in RUSLE2. The RUSLE2 equation for computing sediment deliver ratio for an impoundment is:

$$\omega_{(k)} = \exp(-c_i V_{f(k)}) \quad [7.24]$$

where: $\omega_{i(k)}$ = the sediment delivery ratio for an impoundment for the *kth* sediment particle class. Sediment delivery ratio is the ratio of sediment mass leaving the sediment basin to incoming sediment mass.

A 10000 $(ft/sec)^{-1}$ value for the coefficient c_i for a base reference silt loam soil was determined by fitting equation 7.24 to experimental data for impoundments used in parallel tile outlet terraces (Laflen et al., 1972). The average trapping efficiency of those impoundments was 94 percent. Literature reporting measured trapping efficiency of sediment basins on construction sites was reviewed during the development of RUSLE1.06 (Toy and Foster, 2000; Bonta and Hamon, 1980, Fennessey and Jarret, 1997; USEPA, 1976 a, 1976b). The trapping efficiency of these basins is comparable to that for impoundment terraces when the sediment basins are well designed, constructed, and maintained and perform at maximum efficiency. Also, no deposition is assumed to occur between the point that the sediment is detached and where the sediment reaches the impoundment. If deposition occurs along the overland flow path upstream of the impoundment, trapping efficiency will be less than computed by RUSLE2 (see **Section 7.3.3.2**).

Many sediment basins on construction sites do not perform at maximum efficiency because of poor design, the basins being partly filled with sediment, and water/sediment chemistry that keeps fine sediments highly dispersed.

The RUSLE2 user can select a base sediment delivery ratio for the reference silt loam soil texture to accommodate trapping efficiency variations by specific site. The c_i coefficient values used in RUSLE2 for a range of sediment delivery ratios are given in Table 7.1.

Table 7.1. Values for the coefficient c_i used to compute sediment delivery ratio for deposition of sediment from reference silt loam soil in impoundments.

Sediment trapping ratio (%)	c_i $(ft/sec)^{-1}$
6.4	10000 (1)
10	5900
15	3500
20	2300
25	1700

Note (1): Coefficient value determined by fitting RUSLE2 equation to experimental data for impoundment terraces

7.3.3.2. Effect of incoming sediment characteristics

RUSLE2 computes trapping efficiency for impoundments solely as a function of incoming sediment characteristics. RUSLE2 does not consider basin geometry or flow withdrawn characteristics in these computations. However, RUSLE2 computes sediment delivery ratios as a function of texture of the soil that produces the sediment, upslope deposition amount, and the feature that produces the upslope deposition as shown in Table 7.2 because these variables affect sediment characteristics. As a point of reference, the RUSLE2 computed sediment characteristics leaving the uniform overland flow path represented in Table 7.2 are the same as the sediment characteristics at the point of detachment because

RUSLE2 computed no local deposition for this particular overland flow path.

Table 7.2. RUSLE2 computed sediment delivery ratio for sediment basin in various flow sequence.

	Flow path			
Soil texture	uniform overland flow path into basin	steep flow segment onto low steepness segment into basin	uniform flow path into grass strip into basin	uniform overland flow path into basin into basin
silt loam	0.064	0.469	0.317	0.678
silt	0.068	0.157	0.101	0.216
silty clay	0.119	0.612	0.581	0.825
clay	0.105	0.741	0.905	0.902
loamy sand	0.014	0.125	0.531	0.890
sand	0.009	0.127	0.333	0.900

The primary particle distribution of the soil producing the sediment does not accurately indicate the RUSLE2 computed sediment delivery ratio for impoundments. Sediment is eroded as a mixture of primary particles and aggregates (see **Section 4.7**). The size and density distributions of the sediment do not parallel the distribution of primary particles in the soil. Clay is assumed in RUSLE2 to be a bonding agent that influences aggregate sizes and densities and the mass distribution between the particle classes, especially the small and large aggregates. Consequently, sediment eroded from high clay soils has a large portion of the sediment in aggregates of increased size. Conversely, soils very high in silt produce poorly aggregated sediment that is almost entirely in small-sized primary silt particles that are not rapidly deposited. Soils high in sand produce poorly aggregated sediment that is almost entirely in sand-sized primarily particles that are readily deposited. Consequently, the sediment delivery ratio computed for sediment eroded from high clay soils is not proportionally higher than that for silt loam soils when no upslope or local deposition occurs. **Expecting RUSLE2 computed sediment delivery ratio values for an impoundment to be directly related to the primary particle distribution of either the soil or sediment is a very serious error.**

As illustrated in Table 7.2, RUSLE2 computed sediment delivery ratio values for impoundments also vary with the type of upslope feature that causes deposition. Even though the sediment delivery ratios for the overland flow path with a low steepness segment, a grass strip, and a sediment basin are comparable, the characteristics of the sediment leaving each of these flow paths and entering a sediment basin are quite different because of differences in upslope erosion and deposition processes. RUSLE2 computes a relatively high interrill erosion rate for the overland flow path that has the low steepness segment in comparison to the one with a dense grass strip at the end of the overland flow path. Interrill erosion is very low in the grass strip, which adds very little sediment to the sediment load in the grass strip in contrast to interrill erosion adding sediment to the sediment load on the low steepness segment. The sediment leaving the grass strip is finer than the sediment leaving the low steepness segment. Consequently, the RUSLE2 computed sediment delivery ratio values for impoundments are generally larger for the grass strip overland flow path than for the low steepness segment overland flow path. Sediment delivery ratios for sediment eroded from high silt soils are not affected as much as for the other soil textures because sediment eroded from the high silt soils is poorly aggregated and has a very narrow size range in a relative small size range.

Sediment delivery ratio values are high for a basin downstream of another sediment basin. That is, much less sediment trapping occurs in the second basin than in the first basin, except for the sediment eroded from the high silt soils. The upstream sediment basin removes almost all of the sediment that is easily deposited.

7.3.3.3. Design

RUSLE2 should not be used to design sediment basins unless regulations explicitly state that RUSLE2 can be used. The RUSLE2 values computed for impoundments are for the purpose of conservation and erosion control planning. The accuracy of RUSLE2's computations for sediment trapping by small impoundments is comparable to that for other erosion and sediment control practices. The specific hydraulic and sediment trapping performance of impoundments depends on many complex, interactive variables. Accepted design procedures should be used to design impoundments (e.g., see Haan et al., 1994).

7.3.3.4. Comments

RUSLE2 results for sediment trapping by impoundments must be interpreted very carefully. The flow path up to the sediment basin must be properly represented. For example, RUSLE2 seriously under-computes sediment delivery by an impoundment if a uniform steepness overland flow path is assumed when in fact the overland flow path has a segment at the lower end of the overland flow path that causes a high degree of deposition. Likewise, when RUSLE2 computed values are compared to research and field measurements, the RUSLE2 inputs must be very carefully selected to accurately represent measurement conditions. The characteristics of the sediment entering the experimental basin must match those assumed in RUSLE2. For example, as Table 7.2 shows, if upstream deposition is not considered, the sediment delivery values computed by RUSLE2 will be much less than is measured.

Another consideration is that RUSLE2 does not represent basin geometry, degree that the basin is filled, and other factors. The assumption in RUSLE2 is that the basin is well designed and maintained. Standards and specifications for design, construction, and maintenance of impoundments should be a principal tool used to ensure expected results.

7.3.4. Hydraulic flow paths

Simple channels and impoundments can be combined into simple hydraulic flow paths. RUSLE2 can represent an overland flow area discharging into a channel from a single side and the channel in turn discharging into an impoundment or a series of impoundments. Non-uniform conditions along the channel can not be represented. RUSLE2 can not represent a channel on a particular grade discharging into a channel on a different grade. That is, RUSLE2 can not represent channels in series nor can RUSLE2 represent an impoundment discharging into a channel. However, RUSLE2 can represent overland areas discharging into a channel from both sides. Also, RUSLE2 can represent an overland flow area discharging directly into an impoundment without involving a channel. (See the RUSLE2 User's Reference Guide)

7.3.5. Benefit of deposition caused by porous barriers and flow interceptors

7.3.5.1. Concepts

Deposited sediment trapped on the hillslope by porous barriers and by flow interceptors including channels/impoundments (e.g., terraces) is assumed to be a soil conservation benefit. Landscape quality is degraded less when sediment is retained by deposition on the hillslope.

Partial credit is taken for deposition on the hillslope as soil saved based on the location of the deposition along the overland flow path (see Section **2.3.10.4)**. The credit taken for deposition caused by flow interceptors is less than the credit taken for porous barriers because most flow interceptors are much more permanent and the deposition more localized than with porous barriers. Porous barriers such as grass strips are assumed to be periodically removed and reestablished in new locations. An increased portion of the hillslope benefits from deposition with these barriers than occurs with flow interceptor such as impoundment-type terraces. Full credit for deposition as soil saved is taken for rotational strip cropping (see Section **2.3.10.4**).

Partial credit is given to deposition as soil saved with flow interceptors (e.g., channels/impoundments in farm fields) because the deposition is localized although the deposited sediment is spread over a significant-sized area on either side of channels/impoundments in farm fields. The absolute size of this area is the same regardless of channel/impoundment spacing. Consequently, the fraction of the total field area over which the sediment is spread becomes less as channel/impoundment spacing increases.

Deposition near the end of the original overland flow path before porous/interceptor barriers were placed is assumed to be less valuable for maintaining landscape quality than sediment deposited near the upper end of the overland flow path. This concept is consistent with that used to compute the benefit of deposition on the overland flow area (see **Section 2.3.10.4**).

Deposition is a selective process that enriches the deposited sediment in coarse particles. Even though coarse sediment is deposited first, clay and silt primary particles are deposited because sediment is assumed to be a mixture of primary particles and aggregates so that fine primary particles are deposited along with sand particles (see **Section 4.7.5**). The assumption that deposition on overland flow areas is predominantly sand is erroneous. Thus, deposition is assumed to be beneficial because deposited sediment includes clay and silt particles even though the deposited sediment is partially enriched in sand.

7.3.5.2. Equations for benefit of deposition caused by flow interceptors

The RUSLE2 equation for the benefit of deposition by a flow interceptor is:

$$b_{s(i)} = 0.45\exp[-0.011(\delta_{s(i)} - 100)] \quad \delta_{s(i)} \geq 100 \text{ ft} \qquad [7.25]$$

$$b_{s(i)} = 0.45 \quad \delta_{s(i)} < 100\,\text{ft} \qquad [7.26]$$

where: $b_{s(i)}$ = the fraction of the deposition that is credited as soil saved for the *ith* flow interceptor and δ_s = flow interceptor spacing (ft). The credit $b_{p(i)}$ for deposition as affected by the *ith* flow interceptor location along the original overland flow path is computed with:

$$b_{p(i)} = 1 - (\lambda_{s(i)} / \lambda_o)^{1.5} \qquad [7.27]$$

where: $\lambda_{s(i)}$ = distance from the origin of overland flow for the original overland flow path to the *ith* flow interceptor and λ_o = the overland flow path length without flow interceptors. The conservation planning sediment load (see **Section 2.3.10.4**) for each channel is computed from:

$$g_{cp(i)} = g_{o(i)}[1 - (b_{s(i)} + 0.2b_{p(i)})(1 - \omega_{(i)})] \qquad [7.28]$$

where: $g_{cp(i)}$ = the conservation planning sediment load per unit channel length for the *ith* channel, the $g_{o(i)}$ = the sediment load for conservation planning from the overland flow area immediately above the *jth* channel, and ω = sediment delivery ratio. The conservation planning soil loss in term of mass per unit area for the area represented by the overland flow path without channels is:

$$A_{cp} = \left(\sum_{i=1}^{J} g_{cp(i)} \right) \Big/ \lambda_o \qquad [7.29]$$

where: A_{cp} = the conservation planning soil loss (mass/area) for the area represented by λ_o and i = the index for each flow interceptor along the original overland flow path, and J = number of flow interceptors.

7.4. Subsurface drainage

The effect of subfactor drainage on detachment is represented by the subsurface drainage subfactor p_d in equation 2.10.[60] In general, research has shown that subsurface drainage reduces rill-interrill erosion by approximately 40 percent (Bengston and Sabbage, 1988; Formanek et al., 1987; Schwab and Fouss, 1967; Schwab, 1976; Skaggs et al., 1982). The reduction is caused by reduced runoff and an increased vegetation production (yield) level. The input value for production (yield) level in vegetation descriptions should reflect production level under subsurface drained conditions. RUSLE2 does not adjust production (yield) level as a function of environmental inputs.

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[60] The effect of subsurface drainage on runoff is discussed in **Section 3.3.1.2.4**.

The runoff effect on erosion with subsurface drainage is assumed to be same as the soil erodibility factor being a function of a soil's runoff potential. Therefore, equation 4.9, the permeability subfactor equation used to compute soil erodibility factor values, is used to compute how subsurface drainage affects detachment. The subsurface drainage subfactor is computed as:

$$p_d = K_d / K_u \quad if\,(p_d < 0.2): p_d = 0.2 \qquad [7.30]$$

where: K_d and K_u = soil erodibility factors (US customary units) for the drained and undrained conditions, respectively (see **Section 4.1**). A minimum value of 0.2 is set for the subsurface drainage subfactor. A base soil erodibility factor value without the permeability subfactor is computed as:

$$K_b = K_u - 0.025(P_{ru} - 3) \qquad [7.31]$$

where: K_b = a base soil erodibility factor value (US customary units) computed without the permeability subfactor and P_{ru} = the soil profile permeability class for the undrained condition. The soil erodibility factor with subsurface drainage is computed with:

$$K_d = K_b + 0.025(P_{rd} - 3) \qquad [7.32]$$

where: P_{rd} = the soil profile permeability class for the drained condition.

Hydrologic soil group (see **Section 3.3.1 and** RUSLE2 User's Reference Guide) used in NRCS soil survey descriptions is used as the RUSLE2 input to describe how subsurface drainage affects soil profile permeability class. The RUSLE2 relationship between hydrologic soil group and the soil profile permeability class is given in Table 7.3.

Table 7.3. Relation between hydroligc soil groups and permeabiltiy classes.

Hydrologic soil group	Permeability class
A	1
B	2.67
C	4.33
D	6

RUSLE2 computed subsurface drainage subfactor values are shown in Table 7.4. As expected, subsurface drainage reduces the subsurface drainage subfactor the greatest when subsurface drainage causes the greatest change in hydrologic soil group from D to A in contrast to a change from D to C. The erosion reduction is also related to the soil erodibility (K factor) value. The subsurface drainage subfactor reduction is greatest when soil erodibility factor values are low. This effect results from the additive equation form used to compute soil erodibility factor values (See **Section 4.1.1**). Location has only a slight effect on the RUSLE2 subsurface drainage subfactor and probably should be greater than is computed by RUSLE2. However, the values computed by RUSLE2 are considered adequate for conservation and erosion control planning. Other erosion estimation procedures can be used when increased accuracy is desired (Skaggs et al., 1982).

Table 7.4. Subsurface drainage subfactor values as affected by soil erodibility factor value (US customary units) for undrained soil condition and for a change in hydrologic soil group by hydrologic soil group.

	subsurface drainage subfactor p_d			
	K = 0.20	K = 0.20	K = 0.30	K = 0.55
Location	D to A	D to C	D to A	D to A
Ft Wayne, IN	0.38	0.83	0.58	0.77
Raleigh, NC	0.38	0.78	0.57	0.76
Jackson, MS	0.38	0.75	0.60	0.77

7.5. Irrigation

RUSLE2 computes how irrigation affects rill-interrill erosion caused by precipitation, but RUSLE2 does not compute erosion caused by water drop impact and surface runoff directly produced by the applied irrigation water. The increase soil moisture from irrigation affects rill-interrill erosion by precipitation during the irrigation period because of increased soil erodibility, increased biomass decomposition, decreased soil surface roughness and ridge height, and increased vegetation production (yield). The effect of irrigation on production (yield) level is accounted for by inputting yield values appropriate for production under irrigated conditions. RUSLE2 does not adjust production (yield) level as a function of environmental inputs.

7.5.1. Effect on soil erodibility

The effect of increased soil moisture on soil erodibility during the irrigation period is computed using equation 4.14 that computes temporal (daily) values for the soil erodibility factor. This equation is modified by adding the daily amount of water added by irrigation to the daily precitation amount as:

$$K_{(j)}/K_n = 0.591 + 0.732[(P_{(j)} + I_{(j)})/0.123] - 0.324(T_{(j)}/62.8) \qquad [7.33]$$

$$If\,(K_{(j)}/K_n) > 2.0 \quad \text{then} \quad (K_{(j)}/K_n) = 2.0$$

$$If\,(K_{(j)}/K_n) < 0.4 \quad \text{then} \quad (K_{(j)}/K_n) = 0.4$$

where: $K_{(j)}$= the soil erodibility factor on the *jth* day, K_n = the soil erodibility factor value computed with a RUSLE2 soil erodibility nomograph for the frost free period defined as the period that average daily temperature $T_{(j)}$ is above 40 ^oF, 62.8 = the average temperature during the frost free period (^oF), $P_{(j)}$ = daily precipitation (inches), $I_{(j)}$ = average daily water added by irrigation (inches), and 0.123 = average daily precipitation during the frost free period (inches).

The average daily water added by irrigation on the *jth* day is computed from:

$$I_{(j)} = V_{w(j)} - P_{(j)} \quad if\,(I_{(j)} < 0) : I_{(j)} = 0 \qquad [7.34]$$

where: $V_{w(j)}$ = consumption use (inches) by the vegetation on the *jth* day (Schwab et al., 1966). Plant consumption use values are input for the vegetation descriptions that represent irrigated conditions.

7.5.2. Effect on soil surface roughness, ridge height, and decomposition

The daily amount of water added by irrigation is added to the daily precipitation amount to compute the effect of irrigation on soil surface roughness (see **Section 6.3.6** and equation 6.30), ridge height (see **Section 6.4.6** and equation 6.43), and decomposition (see **Section 10.3.1** and equation 10.5).

7.5.3. Effect on vegetation

Individual vegetation descriptions must be created to describe vegetation under irrigated conditions. These descriptions include values for consumptive water use that are a function of the soil properties and location and location where the RSULE2 computation is being made. Figure 7.2 illustrative consumptive use values for a particular corn crop grown at Lincoln, Nebraska.

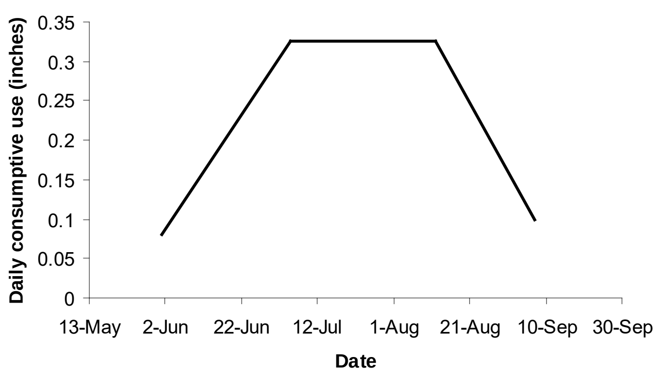

Figure 7.2. Daily consumptive water use for a 120 day corn crop grown at Lincoln, Nebraska.

The input yield for the vegetation description is the yield expected for the consumptive use water values entered because RUSLE2 does not compute how environmental conditions affect yield. RUSLE2 adjusts consumptive use values in its yield adjustment procedures directly in proportion to live above ground biomass (see **Section 9.3**).

7.6. List of symbols

a_c = coefficient used to compute values for base contouring subfactor values

$A_{ch(k)}$ = sediment load for *kth* particle class leaving end of the channel (mass/ unit drainage area·time)

A_{cp} = conservation planning soil loss for the area having channels (mass/area)

$b_{p(i)}$ = deposition credit as affected by the *ith* flow interceptor location along the original overland flow path

$b_{s(i)}$ = fraction of the deposition that is credited as soil saved for the *ith* flow interceptor

c_c = coefficient used to compute values for base contouring subfactor values

c_i = coefficient used to sediment delivery ratio in an impoundment for base reference silt loam soil

d_r = runoff depth for P_{10y24h} storm (inches)

$D_{p(k)}$ = deposition rate for *kth* sediment class (mass/unit channel length·time)

$f_{(k)}$ = mass fraction of the incoming sediment load g_0 from the overland flow area made up of *kth* sediment class

$g_{ch(k)}$ = sediment load leaving end of the channel for *kth* particle class (mass/unit channel length·time)

$g_{cp(i)}$ = conservation planning sediment load for the *jth* channel (mass/unit channel length)

g_o =total incoming sediment load from overland flow area (mass/unit channel length·time)

$g_{o(k)}$ = incoming sediment load from overland flow area (mass/unit channel length·time)

$g_{o(i)}$ = sediment load for conservation planning from overland area immediately above the *jth* channel (mass/unit channel length·time)

H = daily soil ridge height (inches)

H_e = daily effective total ridge height, which is sum of soil ridge height and effective vegetation ridge height (inches)

H_{vr} = daily effective vegetation ridge height (inches)

I_j = average water added by irrigation on *jth* day (length)

J = number of flow interceptors along an overland flow path

K_b = base soil erodibility factor value computed without the permeability subfactor (US customary units)

K_d = soil erodibility factor for drained condition (US customary units)

K_j = soil erodibility factor on the *jth* day (US customary units)

K_n = soil erodibility factor computed with a RUSLE2 soil erodibility nomograph for frost free period (US customary units)

K_u = soil erodibility factor for undrained condition (US customary units)

p_b = base contouring subfactor value

p_{bm} = minimum base contouring subfactor value

p_c = the daily contouring subfactor

p_{c0} = contouring subfactor for a zero row grade

$p_{c0,min}$ = minimum contouring subfactor value for a given ridge height

p_d = subsurface drainage subfactor

p_{rm} = minimum contouring subfactor value adjusted for runoff

P_j = daily precipitation (length)

P_{rd} = the soil profile permeability class for the drained condition

P_{ru} = the soil profile permeability class for the undrained condition

P_{10y24h} = 10 year-24 hour precipitation amount (length)

q_o = discharge rate at end of the overland flow path (volume/ unit channel length·time)

s = overland flow path steepness (sine of slope angle)

s_{be} = land steepness at which the contouring subfactor reaches 1 (sine of slope angle)

s_{bm} = land steepness at which contouring subfactor value is minimum (sine of slope angle)

s_c = scaled land steepness (sine of slope angle)

s_{ch} = grade of the channel (sine of channel angle with horizontal)

s_f = grade along the furrows separating the ridges (row grade) (100 time tangent of slope angle)

s_f/s_p = relative row grade

s_m = land steepness at which $p_b = p_{bm}$ (sine of slope angle)

s_p = land steepness (100 time tangent of slope angle)

s_{re} = runoff adjusted land steepness above which contouring subfactor equals 1 (sine of slope angle)

T_c = total sediment transport capacity for all sediment classes of the flow in the channel (mass/time)

$V_{w(j)}$ = daily consumption watercuse by vegetation (length)

$V_{f(k)}$ = fall velocity of *kth* sediment class (length/time)

x = distance along the channel (length)

$\delta_{s(i)}$ = *ith* flow interceptor spacing (feet)

λ_o = overland flow path length without flow interceptors (length)

$\lambda_{s(i)}$ = distance from origin of overland flow for the original overland flow path to the *ith* flow interceptor (length)

$\phi_{(k)}$ = a deposition coefficient for the *kth* sediment class ($length^{-1}$)

$\omega_{(k)}$ = sediment delivery ratio for *kth* sediment class

$\omega_{(i)}$ = total sediment delivery ratio for the *ith* flow interceptor

Indices

i – flow interceptor

j - day

k – sediment class

8. OPERATIONS

A RUSLE2 operation is an event that changes vegetation, residue, or soil conditions. RUSLE2 uses a set of rules and 10 processes to represent how operations affect rill and interrill erosion (see the RUSLE2 User's Reference Guide). RUSLE2 computes erosion based on user supplied descriptions of the variables that affect rill-interrill erosion. For example, RUSLE2 does not use simulation modeling to compute how environmental conditions affect vegetation. This section discusses the RUSLE2 equations used to describe how operations affect vegetation, residue, and soil variables.

8.1. Effect on vegetation

RUSLE2 uses **begin growth**, **kill vegetation**, and **remove live vegetation processes** to describe how operations affect vegetation variables.

8.1.1. Begin growth

The **begin growth** process tells RUSLE2 to stop using data in the current vegetation description and start using data from another vegetation description. The change occurs on the date of the operation that uses the **begin growth** process (See RUSLE2 User's Reference Guide).

RUSLE2 uses only a single vegetation description on any particular date. RUSLE2 does not combine data from multiple vegetation descriptions to represent a composite of vegetations having different properties. For example, a single vegetation description is used to describe a rangeland plant community that involves multiple plant types such as shrubs that provide an over-story and grasses that provide an under-story under the shrubs with open space between the individual shrub-grass clumps.

8.1.2. Kill vegetation

The **kill vegetation** process transfers the biomass (dry mass basis) of live vegetation to the dead standing residue pool and transfers live root biomass to the dead root biomass pool in the soil. Both the standing residue and dead root biomass pools disappear by daily decomposition.

8.1.3. Remove live vegetation

The purpose of the **remove live vegetation** process is to determine the amount of residue left by a field operation like a hay harvest that removes live biomass and leaves both standing and surface residue. The standing and surface residue biomass left by a remove live vegetation process is computed as:

$$\Delta B_{tr} = f_{tl}(f_{lr} B_{al}) \qquad [8.1]$$

$$\Delta B_{sr} = f_{sl}(f_{lr} B_{al}) \qquad [8.2]$$

where: ΔB_{tr} = the biomass left as standing residue that is added to the existing standing biomass pool, $f_{lr}B_{al}$ = the live biomass that is affected by the operation, f_{tl} = the fraction of the affected biomass that is left as standing residue, f_{lr} = the fraction of the above ground live biomass that is affected by the operation, B_{al} = existing live vegetation biomass, ΔB_{sr} = the biomass left as surface residue that is added to the existing surface residue biomass pool, and f_{sl} = the fraction of the affected biomass that is left as surface residue. These residue biomass values are added to the existing biomass values in the respective residue pools.

The amount of live aboveground biomass left after a remove live biomass process is computed from:

$$B_{al} = (1 - f_{lr})B_{alp} \qquad [8.3]$$

where: Bal = the mass (dry basis) of the above bround live biomass that is left after the operation and Balp = the mass (dry basis) of the above bround live biomass that exists immediately before the operation.

8.2. Effect on residue/dead roots

RUSLE2 tracks the three residue pools of standing residue, surface residue, and buried residue. Operations that include a **flatten standing residue** process transfer biomass from the standing residue pool to the surface residue pool. Operations that include a **disturb soil** process bury transfer surface residue to the buried residue pool and transfers buried residue to the surface residue pool. RUSLE2 rules are that standing residue can not be buried without first being flattened and live above ground biomass can not be flattened or buried without first being killed (i.e., transferred from the live above ground biomass pool to the standing residue pool).

8.2.1. Flatten standing residue

The **flatten standing residue** process transfers biomass from the standing residue pool to the surface residue pool using:

$$\Delta B_{tr} = f_f B_{tr} \qquad [8.4]$$

where: f_f = the fraction of the existing standing residue that is flattened (i.e., added to the surface biomass pool).[61] The standing residue biomass pool after the operation is computed as:

[61] Flattening, burial, and resurfacing ratios are based on mass, not portion of the soil surface covered (see RUSLE2 User's Reference Guide).

$$B_{tr} = B_{trp}(1 - f_f) \quad [8.5]$$

where: B_{tr} = mass (dry basis) of the standing residue immediately after the operation and B_{trp} = the mass (dry basis) that existed immediately before the operation.

8.2.2. Burial of surface residue

Burial of surface residue is the transfer of biomass from the surface residue pool to the buried residue pool. The amount of surface residue that is buried is computed by:

$$\Delta B_{sr} = f_b B_{sr} \quad [8.6]$$

where: ΔB_{sr} = the mass of the surface residue that is transferred to the buried residue pool and f_b = the fraction of the surface residue that is buried.

The surface residue mass is computed by (Wagner and Nelson, 1995):

$$B_{sr} = (B_{trp} f_f + B_{srp})(1 - f_b) + B_{brp} f_u \quad [8.7]$$

where: B_{sr} = the surface residue mass (dry basis) immediately after the operation, B_{srp} = the surface mass immediately before the operation, f_u = the fraction of the buried residue mass that is resurfaced and B_{brp} is the amount of buried biomass in the soil disturbance depth immediately before the operation. Note that the surface residue mass in equation 8.7 is the sum of the existing surface residue mass plus the mass added by flattening of standing residue and the mass of buried residue that is resurfaced.

8.2.3. Resurfacing of buried residue

The mass of buried residue that is resurfaced by the operation is computed from:

$$\Delta B_u = f_u B_{br} \quad [8.8]$$

where: ΔB_u = residue that is resurfaced from soil disturbance depth, f_u = the resurfacing ratio, and B_{br} = the mass of buried residue in the soil disturbance depth. RUSLE2 does not consider the resurfacing of dead roots.

8.2.4. Determining values for the flattening, burial, and resurfacing ratios

8.2.4.1. Base reference values

A single data point can be used to determine a value for the flattening ratio. However, equation 8.7 involves the two unknowns of burial and resurfacing ratios, which requires at least two data points to determine values for these two ratios. The proper data for determining values for these ratios is where the same operation is repeated multiple times, preferably at least four times. Only two data sets were found that meet this requirement (Brown et al., 1992; Wagner and Nelson, 1995) and even then the (Brown et al., 1992) data set did not include standing residue. Most data previously used to determine burial ratio values are not usable because they are from situations where a particular operation was used a single time.

Base reference values for the flattening ratio were determined by fitting equation 8.5 to observed data reported by (Wagner and Nelson, 1995). Values for the burial and resurfacing ratios were determined by fitting equation 8.7 to observed data reported by (Brown et al., 1992; Wagner and Nelson, 1995). Surface residue biomass values were estimated for the (Brown et al., 1992) data from measured surface residue cover values using equation 10.1 that estimates surface cover as a function of surface biomass (see **Section 10.2**).

The minimization function that was minimized to fit equations 8.5 and 8.7 to measured data to determine flattening, burial, and resurfacing ratio values is:

$$\delta = \left\{ \sum_{n=1}^{N} \left[\ln(y_{e(n)} - \ln(y_{o(n)}) \right]^2 \right\} \Big/ N \qquad [8.9]$$

where: δ = the function that is minimized, $y_{e(n)}$ = estimated value for the *nth* data point, $y_{o(n)}$ = observed value for the *nth* data point, and N = number of observations. A minimization function using logarithms rather than absolute values gives a more uniform relative error among the observations in comparison to a minimization function that uses absolute values. A minimization function using absolutes values gives flattening, burial, and resurfacing ratio values that are biased to the large surface biomass values. Equations 8.5 and 8.7 were fitted by the soil disturbing implement types represented in the observed data. The flattening, burial, and resurfacing ratio values obtained by fitting equations 8.5 and 8.7 were used to guide assign values in the RUSLE2 core database (see the RUSLE2 User's Reference Guide).

8.2.4.2. Effect of soil disturbance depth on residue burial

The input value for burial ratio is for a reference depth, which is assumed to the manufacturer recommended or normal operating depth for the implement, machine, tool, or other residue burial process.

The effect of operation depth (i.e., soil disturbance depth) on the residue burial ratio is computed using:

$$\alpha_d = [1-(1-y_d/y_m)^{2.7}]/[1-(1-y_{rc}/y_m)^{2.7}] \qquad [8.10]$$

where: α_d = an adjustment factor for depth, y_{rc} = reference soil disturbance depth, y_d = the soil disturbance depth of the operation, and y_m = the maximum soil disturbance depth for the operation. The fit of equation 8.10 to observed data is shown in Figure 8.1 (Hanna et al., 1995; Hill and Stott, 2000; Johnson, 1988).[62]

8.2.4.3. Effect of speed on surface residue burial

The effect of operation speed on residue burial ratio values is computed using:

$$\alpha_s = [0.6 + 0.4(v_s / v_m)^{1/2}]/[0.6 + 0.4(v_r / v_m)^{1/2}] \qquad [8.11]$$

where: α_s = an adjustment factor for speed, v_r = reference speed, v_s = operation speed, and v_m = maximum operation speed. The fit of equation 8.11 to observed data is shown in Figure 8.2 (Hanna et al., 1995; Hill and Stott, 2000; Johnson, 1988).

8.2.4.4. Combined effect of soil disturbance depth and speed on surface residue burial

The burial ratio for the effect of both depth and speed is computed from:

$$f_b = \alpha_d \alpha_s f_{br} \qquad [8.12]$$

where: f_{br} = the burial ratio for the given residue type for the reference soil disturbance depth y_{rc} and reference operation speed v_r.

8.2.5. Distribution of buried residue and dead roots by soil disturbing operations

Soil disturbing operations resurface buried residue but not dead roots, redistribute existing buried residue in the soil, redistribute dead roots in the soil, and bury surface residue. RUSLE2 makes these computations in three steps. The first step computes inversion of the burial material. The second step computes the redistribution of existing buried residue and dead roots and resurfacing of buried residue from the upper soil layer(s). The third step computes the mass distribution by soil layer of the material buried by the

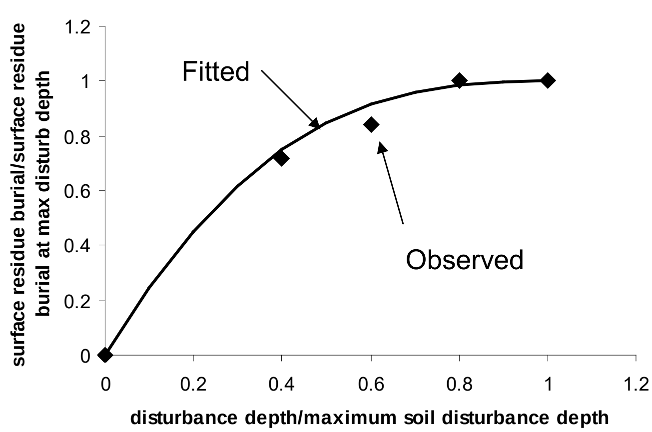

Figure 8.1. Effect of soil disturbance depth on surface residue burial.

[62] R.L. Raper, USDA-Agricultural Research Service, researched the literature and assembled the data used to derive the equations for effect of soil disturbance depth and operation speed on residue burial and equations for distribution of buried material by soil layer.

operation.

8.2.5.1. Types of soil disturbance operations

Types types of soil disturbing operations are used in RUSLE2 to describe how these operations distribute bury residue and dead roots in the soil. These types are: inversion, mixing with some inversion, and mixing. The *inversion* type represents machines like moldboard plows and soil disturbances (e.g., hand tillage with a spading fork) that primarily bury and mix material in the soil by inverting the disturbed soil layer. The *mixing with some inversion* type represents machines like field cultivators, chisel plows, tandem disks, and scarifiers and soil disturbances that bury material in the soil primarily by mixing with some inversion. The *mixing* type represents machines like rotary powered machines (e.g., rototillers); shank machines used to inject manure, fertilizers, and other materials into the soil; and soil disturbances that incorporate material by mixing with essentially no inversion. The mixing type also represents materials pressed into the soil by cattle trampling, sheep's foot compactors, and similar operations. Burial of residue by compression does not involve soil disturbance.

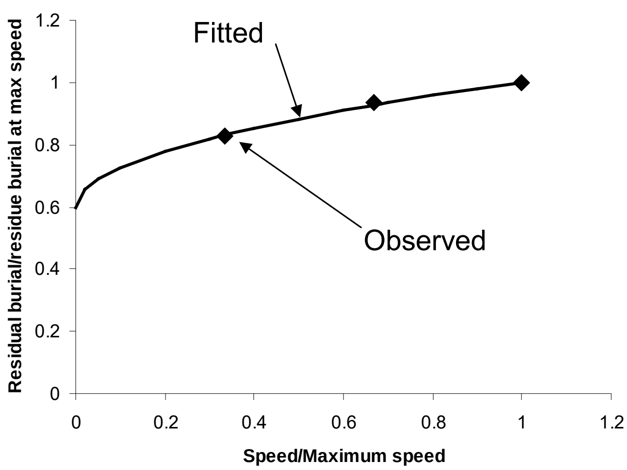

Figure 8.2. Effect of speed on surface residue burial.

8.2.5.2. Equations for redistribution of buried residue and dead roots

A sifting concept is used in RUSLE2 to compute redistribution of buried material by soil disturbing operations. RUSLE2 computes separately the redistribution of buried residue and dead roots. Conceptually, soil disturbance "sifts" each soil layer so that some of the buried material (i.e., buried residue or roots) is retained in each layer and the remainder moves downward to the next soil layer.[63]

RUSLE2 assumes that no material moves upward except by inversion-type soil disturbances. The first step is to compute inversion of the buried material for inversion type soil disturbing operations. This computation assigns the existing buried material

[63] The RUSLE2 equations used to redistribute buried residue and dead roots are based on empirical data reported in the literature cited in **Section 12.2.4.**

mass in the bottom soil layer to the top soil layer, the existing material in the top layer to the bottom layer, the existing material in the next to bottom soil layer is assigned to the soil layer next to top layer, and so forth. For example, the buried material mass in the top soil layer after inversion is set equal to the material mass in the bottom soil layer before inversion and the mass in the bottom layer after inversion is set equal to the mass in the top soil layer before inversion.

The next step for all soil disturbing operations is to "sift" the soil layers to compute the buried material that leaves each soil layer using:

$$\Delta B_{(i)} = (1 - \phi_{k(i)})(B_{p(i)} + \Delta B_{(i-1)} - R_{(i)}) \qquad [8.13]$$

where: $\Delta B_{(i)}$ = the buried material (dry mass/area) that moves from the *ith* soil layer to the *(i+1)th* layer, $\Delta B_{(i-1)}$ = the buried material (dry mass/area) that moves from the *(i-1)th* soil layer to the *)th* layer ϕ_k = the mass fraction of the buried material in the *ith* layer that is retained for the *kth* type soil disturbance operation, $B_{p(i)}$ = existing buried material (mass/area) in the *ith* soil layer, $R_{(i)}$ = the buried residue (dry mass/area) that is resurfaced for the *ith* layer. The soil disturbance depth is divided into 10 layers to make these computations where i = index for the soil layers (i = 1 for surface soil layer). The computations start with the top layer and proceed downward. The inflow to the top layer is set to zero in this step. The amount of material that enters the top layer by burial is added in the third step described below.

The fine roots tightly bound to soil particles dead roots are assumed to have the greatest effect on erosion. Therefore, the RUSLE2 assumption is that dead roots are not resurfaced.[64]

Values for R in equation 8.13 are zero when equation 8.13 is used to compute the redistribution of dead roots. The total mass of buried residue that is resurfaced is computed using equation 8.8. The value for R in the top soil layer (i.e., R_1) in equation 8.13 is set to the value computed by 8.8. If the value computed by equation 8.8 exceeds the buried residue mass in layer 1, the value for the mass removed is set equal to the buried residue in layer 1 before sifting. The remainder of the buried residue mass needed to provide the mass computed by equation 8.8 is removed from layer 2. If the buried residue mass in layer 2 is insufficient, the entire buried residue before sifting is removed from layer 2. The check moves to subsequent layers until the total resurfaced residue mass computed by equation 8.8 is satisfied.

[64] The fact that soil disturbing operations surface dead roots is recognized. However, the fraction of dead roots in the soil that is resurfaced is considered to be much smaller than the fraction of buried residue that is resurfaced.

Table 8.1. Retention coefficient Φ values for redistributing buried material among soil layers

	Type soil disturbance operation		
Layer	Inversion w/mixing	Mixing w/inversion	Mixing
1 (top)	0.40	0.32	0.50
2	0.40	0.39	0.56
3	0.40	0.47	0.61
4	0.40	0.54	0.67
5	0.40	0.62	0.72
6	0.40	0.69	0.78
7	0.40	0.77	0.83
8	0.40	0.84	0.89
9	0.50	0.92	0.94
10	1.00	1.00	1.00

Values for the retention coefficient ϕ are given in Table 8.1. The value of 1 for the *10th* layer denotes that no buried material passes through the bottom layer in the soil disturbance depth. Retention values for the mixing-type soil disturbing operations are assumed to increase linearly from the value for the top layer to 1 for the bottom layer. This increase with depth means that buried material is more likely to move downward in the upper part of the disturbed soil layer than in the lower part. The increased retention coefficient values with depth indicate greater retention because of less stirring and mixing in the bottom of the soil disturbed layer. In contrast, stirring, mixing, and retention are assumed to be nearly uniform with depth for inversion-type soil disturbing operations as shown in Table 8.1.

The retention ϕ values in Table 8.1 were determined by fitting equation 8.13 to measured data where the same operation was repeated multiple times. These data conclusively show that buried material redistributed by multiple events of mixing with some inversion and mixing types soil disturbing operations forms a bulge that moves downward in the soil rather than producing a uniform distribution (see RUSLE2 User's Reference Guide). In contrast, the distribution of buried material becomes nearly uniform with multiple events of an inversion-type soil disturbing operation. Retention values were independent of characteristics of the buried material.

The third step is to distribute surface residue by soil layer when it is buried by a soil disturbing operation. That mass is added to the buried residue mass after sifting as computed with equation 8.13 for redistribution and resurfacing of existing buried residue. The equation used to compute the distribution of surface residue when it is buried in the soil by mixing-type soil disturbing operations is:

$$M = (y / y_d)^b \quad [8.14]$$

where: M = cumulative normalized mass (cumulative mass above depth in soil/total mass buried in soil depth disturbed by operation) of buried residue with depth (i.e., M = 0 at y = 0 and M =1 at y = y_d), y = depth in soil, y_d = soil disturbance depth for a specific soil disturbing operation, and b = 0.5 for *mixing with some inversion* type soil disturbing operations and b = 0.3 for *mixing* type soil disturbing operations.

The comparable equations for inversion-type soil disturbing operations are:

$$M = 0.28\{\exp[1.83(y / y_d) - 1]\} \quad y / y_d \le 0.6 \quad [8.15]$$

$$M = 1 - 0.441\{[1 - (y / y_d)] / 0.4\}^{1.4} \quad y / y_d > 0.6 \quad [8.16]$$

Equations 8.14 - 8.16 were derived from observed data where surface material was buried by a single occurrence of an operation when no buried residue existed in the soil. The distributions of buried residue computed by equations 8.14 – 8.16 are shown in Figure 8.3.

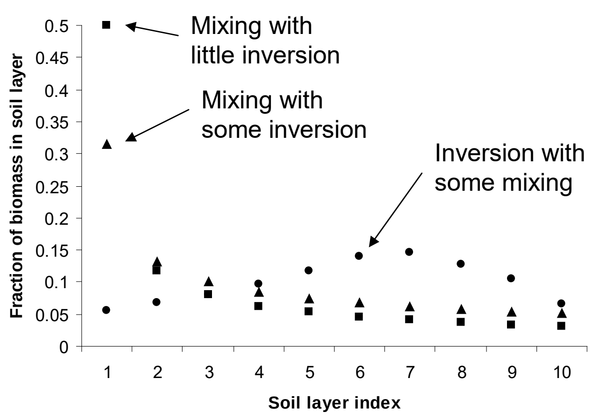

Figure 8.3. Distribution of residue by soil layer when initially buried by a soil disturbing operation.

In summary, RUSLE2 computes buried residue mass in each soil layer after an operation by (1) computing inversion of buried residue biomass if the operation is an inversion-type operation, (2) using equation 8.13 to compute redistribution of existing buried residue mass caused by stirring and mixing (i.e., sifting), and (3) using equations 8.14 – 8.16 to distribute the surface biomass among soil layers that is buried by the operation, which is added to the buried residue mass computed in step 2. The steps for computing redistribution of dead roots is to (1) add the dead roots produced by the kill live vegetation process to the existing dead roots in each soil layer if the operation includes a kill vegetation process, (2) invert the dead roots by soil layer if the operation is an inversion type operation, and (3) compute the sifting of dead roots using equations 8.13.

8.2.6. Add other cover

The **add other cover** process is used to apply material to the soil surface and/or place (inject) material into the soil.

8.2.6.1. Add cover to soil surface

The **add other cover** process has the inputs of the residue, amount (dry mass basis) added as well as the portion added to the soil surface and the portion placed (injected) in the soil. The mass of the material added to the soil surface is added to the surface residue pool.

8.2.6.2. Injection of material (residue) into the soil by a soil disturbing operation

The **add other cover** process along with a **disturb soil** process are used together to inject material into the soil. This material is assumed to be added in the lower half of the disturbed soil depth in a parabolic distribution. The equations for cumulative mass with depth for material injected into the soil are:

$$M = 6\left[\frac{(2y/y_d - 1)^2}{2} - \frac{(2y/y_d - 1)^3}{3}\right] \quad y/y_d \geq 0.5 \qquad [8.17]$$

$$M = 0 \quad y/y_d < 0.5 \ [8.18] \qquad [8.18]$$

where: m = cumulative normalized mass (cumulative mass above depth in soil/total mass), y = depth in soil, and y_d = soil disturbance depth. The mass placed in the soil is added to the buried residue pool.

8.2.7. Remove residue cover

The **remove residue cover** process is used to describe removal of standing and surface residue. Inputs for this process include the portions of the standing and surface residue masses that are removed. The masses of standing and surface residue are reduced by these portions. Another input is whether the residue removal applies to all residues involved in the RUSLE2 computation or only the last residue added to the soil surface in the computation. An example is where corn and wheat grain crops are grown in sequence. The harvest of each crop leaves residue. The straw is baled (removed) but the corn residue is left in the field. The input to remove the last residue is selected in this situation. Another example is burning where all residues is selected.

8.2.8. Add/remove non-erodible cover

8.2.8.1. Description of add/remove non-erodible cover processes

The **add non-erodible** cover process sets detachment to zero for the portion of the soil surface covered with non-erodible cover. That is:

$$c = c_{\omega}(1 - f_{\mu}) \qquad [8.19]$$

where: c = the c in equations 2.10 and 6.1 used to compute detachment, c_{ω} = the c term in equation 2.10 without the non-erodible cover effect, and f_{μ} = the portion of the soil surface covered by non-erodible cover. Equation 8.19 in effect adds a non-erodible cover subfactor to equation 6.1.

Non-erodible cover also affects runoff. The equations used to adjust cover number values used to compute runoff when non-erodible cover is present are given in **Section 3.3.1.2.3**.

The **remove non-erodible cover** process removes non-erodible cover. The input value is the portion of the existing non-erodible cover that is removed by the operation. A 100 percent input value removes all of the existing non-erodible cover. A 40 percent input value removes 40 percent of the existing non-erodible cover. For example, assume that the existing non-erodible cover is 72 percent on the day of an operation that removes 40 percent of the non-erodible cover. The remaining non-erodible cover is 43 percent [72·(100-40)/100] after the operation.

8.2.8.2. Loss of non-erodible cover over time

RUSLE2 assumes that non-erodible cover disappears over time because of photo-chemical and other processes. The equation for the loss of non-erodible cover is given by:

$$f_\mu = f_0 \exp(-\alpha_\mu \Delta t_\mu) \qquad [8.20]$$

where: f_0 = the fraction of the soil surface covered by non-erodible cover immediately after an operation affects non-erodible cover (i.e., added or removed) and Δt_μ = the days since the non-erodible cover was affected. The coefficient α_μ = a coefficient (days^{-1}) that describes the rate of loss of non-erodible cover. Equation 8.20 is not written as a function of environmental conditions. To consider the effect of environmental conditions on this cover loss, users select α_μ values that reflect both material properties and local environmental conditions. Consequently, α_μ values can differ among locations for the same material based on variation of environmental conditions between locations.

8.3. Effect on soil

The **disturb soil** process is used to describe how operations affect the soil. An operation that includes a disturb soil process is referred to as a soil disturbing operation. Soil disturbing operations loosen the soil, buries surface residue, resurfaces buried residue, redistributes buried residue and dead roots, affects soil roughness, and affects ridges. Some operations such as planting disturb only a portion of the soil surface.

8.3.1. Loosen soil

The effect of an operation loosening the soil is described by the soil consolidation subfactor. The equation for the soil consolidation subfactor is given in **Section 6.6.2**.

For those operations that do not disturb the entire soil surface area, RUSLE2 computes a net soil consolidation subfactor as:

$$s_{cn} = f_d + (1 - f_d) s_{cu} \qquad [8.21]$$

where: $s_{c,n}$ = the net soil consolidation subfactor for the overall soil surface, f_d = the fraction of the soil surface that is disturbed, $s_{c,u}$ = the soil consolidation subfactor for the portion of the soil surface not disturbed by the operation, and 1 = the consolidation subfactor value for the soil surface portion that is disturbed.

An effective soil consolidation time t_{de} since last soil disturbance is computed by solving equation 6.52 for the time that gives the value for the net soil consolidation subfactor value computed with equation 8.21. The time used in equation 6.52 to compute the soil consolidation subfactor starts from this effective soil consolidation time.

8.3.2. Burying and resurfacing residue

Soil disturbing operations bury surface residue and resurface buried residue. The RUSLE2 assumption is that surface residue can only be buried by disturbing the soil. The equations used to compute residue mass buried and resurfaced by soil disturbing operations are given in **Section 8.2**. Important variables used in these computations are the fraction of the surface residue mass that the operation buries and the faction of the buried residue mass in the soil disturbance depth that is resurfaced. **The burial and resurfacing ratios apply to the entire soil surface and not just to the portion of the soil surface that is disturbed** (see the RUSLE2 User's Reference Guide).

Some soil disturbing operations that disturb only a portion of the soil surface. The RUSLE2 procedure that determines an effective surface residue biomass for the entire surface is described in **Section 6.2.3**.

8.3.3. Redistribution of buried residue and dead roots

Soil disturbing operations redistribute existing buried residue and dead roots on the date of the operations. The equations used in these computations are given in **Section 8.2.5**.

The RUSLE2 assumption is that soil disturbance is required to place material in the soil (e.g., manure and fertilizer injection). The equations used to compute the distribution of material placed in the soil by an **add other cover** process are given in **Section 8.2.6.1**.

8.3.4. Soil surface roughness

A soil disturbing operation affects soil surface roughness. An operation can either smooth the soil surface (i.e., reduce soil surface roughness) or roughen the soil (i.e., increase soil surface roughness). Roughness decays over time because of subsidence (settlement), interrill erosion, and local deposition.

The RUSLE2 assumption is that soil surface roughness can only be created by a soil disturbing operation. Consequently, operations with a disturb soil process must be used to represent soil surface roughness creation.

8.3.4.1. Inputs for soil surface roughness in an operation description

Three inputs are used in a **disturb soil** process to describe soil surface roughness. One input is initial roughness, which is the roughness created by the operation when performed on a smooth surface under the base, reference condition of high biomass and silt loam soil (see **Section 6.3.1** and **6.3.6** and RUSLE2 User's Reference Guide). Equations given in **Sections 6.3.2, 6.3.3,** and **6.3.5** are used to adjust this initial roughness value for soil texture, biomass, and existing soil surface roughness to represent site specific conditions where RUSLE2 is being applied.

RUSLE2 computes soil surface roughness decay over time as a function of precipitation and interrill erosion using equations given in **Section 6.3.6**. RUSLE2 computes roughness decay to the final roughness value input for the particular operation. The final roughness value is usually set to 0.24 inches and not adjusted for soil texture or soil biomass. This final roughness value represents persistent, highly stable soil clods that remain even after extensive erosivity applied to the reference silt loam soil in unit plot conditions. The roughness subfactor value is 1 for unit plot conditions (see **Section 6.3.1**). Final roughness on unit plots varies by soil texture, but that effect on rill-interrill erosion is captured in the soil erodibility factor (see **Section 4.1**).

In special cases such as construction sites where a high clay soil is scarified, a final roughness value greater than 0.24 inches can be entered to represent an increased roughness effect (see the RUSLE2 User's Reference Guide). A final roughness value less than 0.24 inches is entered for operations, such as for fine seedbeds typical of vegetable production or smooth surfaces left by a blading operation on a construction site, that create roughness smoother than that for unit-plot conditions (see **Section 2.1**). When the final roughness value is less than 0.24 inches, the initial roughness input value should be the same as the final roughness input value. RUSLE2 computes no roughness decay when the final roughness input is less than 0.24 inches.

8.3.4.2. Partial soil disturbance

In contrast to the assumption made for burying and resurfacing residue, the RUSLE2 assumption is that the input roughness values only apply to the portion of the soil surface disturbed. A net soil surface roughness value is computed as:

$$s_{rn} = f_d s_{rd} + (1 - f_d) s_{ru} \qquad [8.22]$$

where: s_{rn} = the net soil surface roughness subfactor immediately after a soil disturbing operation that occurs on day t, s_{rd} = the soil surface roughness subfactor for the disturbed portion of the soil surface immediately after the operation on day t, and s_{ru} = the soil surface roughness subfactor for the undisturbed portion of the soil surface on day of the operation. The starting value in equation 6.26 for the roughness subfactor immediately after the operation that is decayed is the s_{rn} value computed with equation 8.22.

RUSLE2 assumes that an operation that disturbs only a portion of the soil surface disturbs some of the undisturbed soil. Consequently, multiple occurrences of an operation that disturbs only a portion of the soil surface ultimately disturb most of the soil surface. That is, RUSLE2 can not represent an operation that disturbs the same area with each occurrence of the operation.

8.3.4.3. Tillage intensity (effect of existing roughness)

The RUSLE2 assumption is that the roughness left by a soil disturbing operation can depend on existing roughness. The input for this effect is a **tillage intensity** value assigned to the disturb soil process (see RUSLE2 User's Reference Guide). Tillage intensity refers to the degree that a soil disturbing operation obliterates existing roughness (i.e., conversely the degree that existing roughness affects roughness left by the soil disturbing operation). A tillage intensity value of 1 means that the soil disturbing operation is so aggressive that existing roughness has no effect on roughness left by the operation. For example, the tillage intensity value of 1 is used to describe moldboard plows and rototillers. A tillage intensity of 0 means that the operation does not affect existing roughness. Harrows used as secondary tillage to create a seedbed are assigned 0.4 for tillage intensity to reflect that existing roughness has a significant effect on the roughness left by harrows. For example, the soil surface roughness after a harrow is greater when it follows a moldboard plow than when it follows a tandem disk used for secondary tillage. The tillage intensity effect is computed using:

$$R_a = (R_{ae} - R_{ao})(1-\xi) + R_{ao} \quad R_{ao} \le R_{ae} \qquad [8.23]$$

$$R_a = R_{ao} \quad R_{ao} > R_{ae} \qquad [8.24]$$

where: R_a = adjusted roughness after a soil disturbing operation, R_{ae} = existing adjusted roughness immediately before the operation, ξ = tillage intensity, and R_{ao} = the adjusted roughness left by the operation when applied to a smooth surface. Roughness values used in equations 8.23 and 8.24 have been adjusted for soil texture and biomass effects using the procedures described in **Section 6.3**.

8.3.5. Ridges

The RUSLE2 assumption is that only soil disturbing operations create ridges. Consequently, operations with a disturb soil process must be used to represent ridge creation.

The ridge input for the **disturb soil** process is initial ridge height. In contrast to soil surface roughness, the input ridge height is not adjusted for soil texture, soil biomass, existing ridges, or portion of the soil surface disturbed. For example, the ridge height left by a planter run on top of existing ridges depends on the existing ridge height. This effect is represented in RUSLE2 by having a set of planter descriptions in the RUSLE2 database for a range of ridge heights. A particular planter entry is selected from this input set based on the operations that precede the planter operation (see the RUSLE2 User's Reference Guide).

8.4. List of symbols

b = exponent in equation for distribution of buried residue left by an operation

$B_{(i)}$ = buried material in *ith* soil layer (mass/area)

B_{al} = live vegetation biomass (mass/area)

B_{br} = buried biomass in soil disturbance depth (mass/area)

B_{sr} = surface residue (mass/area)

B_{tr} = stading residue biomass (mass/area)

c = daily cover-management factor value in equation 2.10 with non-erodible cover effect

c_{ω} = daily cover-management factor in equation 2.10 without non-erodible cover effect

f_b = portion of surface residue that is buried (fraction)

f_{br} = burial ratio for given residue type for reference soil disturbance depth and speed

f_d = portion of the soil surface that is disturbed (fraction)

f_f = portion of existing standing residue biomass that is flattened a flatten standing residue process operation (fraction)

f_{lr} = portion of above ground live biomass that is affected by a **remove live vegetation** process operation (fraction)

f_n = faction of soil surfaced by non-erodible cover

f_{sl} = portion of affected biomass that is left as surface residue by a **remove live vegetation** process operation (fraction)

f_{tl} = portion of affected biomass that is left as standing residue by a **remove live vegetation** process operation (fraction)

f_u = portion of the buried residue biomass in soil disturbance depth that is resurfaced that is resurfaced (fraction)

f_0 = portion of soil surface covered by non-erodible cover immediately after an operation affects non-erodible cover (i.e., added or removed) (fraction)

f_{μ} = portion of soil surface covered by non-erodible cover (fraction)

M = cumulative buried residue normalized with depth (cumulative mass above depth in soil/total mass buried in soil disturbance depth) bured by a **soil disturb** process operation

N = number of data points

$R_{(i)}$ = buried residue niomass that is resurfaced from a soil layer (mass/area)

R_a = roughness after a soil disturbing operation (length)

R_{ae} = existing roughness immediately before the operation (length)

R_{ao} = the roughness left by the operation when applied to a smooth surface (length)

s_{cn} = net soil consolidation subfactor

s_{cu} = soil consolidation subfactor for the portion of soil surface not disturbed by operation

s_{rn} = net soil surface roughness subfactor immediately after a soil disturbing operation that occurs on day t

s_{rd} = soil surface roughness subfactor for disturbed portion of the soil surface immediately after the operation

s_{ru} = soil surface roughness subfactor for undisturbed portion of the soil surface on day t

v_m = maximum operation speed (length/time)

v_r = reference speed (length/time)

v_s = operation speed (length/time)

y = depth in soil (length)

y_d = soil disturbance depth of operation (length)

y_{en} = estimated value for the *nth* data point

y_m = the maximum soil disturbance depth for operation (length)

y_{on} = observed value for the *nth* data point

y_{rc} = reference soil disturbance depth (length)

α_d = adjustment factor for depth

α_s = adjustment factor for speed

α_μ = coefficient that describes rate of loss of non-erodible cover ($days^{-1}$)

δ = function that is minimized

$\Delta B_{(i)}$ = buried material that moves from *ith* soil layer to *(i+1)th* layer (mass/area)

$\Delta B_{(i-1)}$ = buried material that moves from (*i-1)th* soil layer to *i)th* layer (mass/area)

ΔB_{sr} = standing residue added to surface residue biomass pool by a **remove live vegetation** operation process or surface residue biomass transferred to the buried residue pool by a **soil disturb** process operation (mass/area)

ΔB_{tr} = live above ground biomass added to standing biomass pool added by a **remove live vegetation** process operation or biomass lost from standing residue bimass and added to surface bimass by a **flatten standing residue** process in an operation (mass/area)

$\Delta B_{u(i)}$ = residue biomass that is resurfaced from soil disturbance depth by a **soil disturb** process operation (mass/area)

Δt_{μ} = time since non-erodible cover was affected (days)

ξ = tillage intensity

$\phi_{k(i)}$ = portion of buried material in the *ith* layer that is retainedby a *kth* type soil disturbance operation (fraction)

Indices

i – soil layer

j – day

k - type of soil disturbance operation

n – data point

9. VEGETATION

The input variables used to describe vegetation are biomass (dry basis) at maximum canopy cover and the temporal variables of root biomass (dry basis) in the upper 4-inch (100 mm) soil depth, canopy cover, effective fall height, and live ground cover. These variables are used to compute values for the temporal variables of the live root biomass by soil layer, dead root biomass produced by root sloughing, live above ground biomass, biomass produced by senescence that falls to the soil surface, and retardance. All of these variables are used to compute values for the cover-management subfactors (see **Section 6**), curve numbers used to compute runoff (see **Section 3.3.1.2**), and hydraulic resistance (see **Section 3.4.6**). The RUSLE2 User's Reference Guide describes selection of input values for variables used to describe vegetation.

9.1. Input of temporal variables

Input values for the temporal vegetation variables are often manually constructed and entered in RUSLE2 using values in the RUSLE2 core database as a guide (see RUSLE2 User's Reference Guide). This procedure works satisfactorily for simple vegetation descriptions for annual agricultural and horticultural crops and annual descriptions for mature perennial plant communities. However, creating and entering values for vegetation descriptions for long term vegetation from seeding to maturity is cumbersome and time consuming. RUSLE2 includes a long term vegetation tool that can be used to create long term vegetation descriptions (see RUSLE2 User's Reference Guide).

Temporal variables used to describe vegetation are assumed to vary linearly between the times in the data points entered for these variables. The time between data points should be sufficiently small to accurately represent non-linear variations.

9.2. Computed temporal vegetation variables

9.2.1. Live root biomass by soil layer

RUSLE2 uses input values for live root biomass in the upper 4-inch soil depth to compute daily live root biomass values in individual soil layers.

The literature was reviewed to obtain measured data for root biomass and its distribution in the soil at plant maturity for the major agricultural crops of corn, soybeans, cotton, and wheat; several vegetable crops; and several pasture/range plant communities (see **Section 12.2.5**). The RUSLE2 equations for the distribution of live root biomass in the soil were derived from these data, especially the data by Long (1959). These equations are:

$$M_r = y[24.24y\exp(-5.50y) + 0.778] \quad y \le 0.533333 \qquad [9.1]$$

$$M_r = 0.783391 + 0.147688(y - 0.533333) \quad 0.533333 < y \le 2 \qquad [9.2]$$

$$M_r = 0 \quad 2 < y \qquad [9.3]$$

where: M_r = cumulative root biomass (dry basis) above the depth y, y = Y/15, Y = depth (inches) in soil (Y = 0 at soil surface), and 15 = a reference depth (inches) used to normalize the depth variable y. A plot of these equations by 1 inch layer is shown in Figure 9.1.

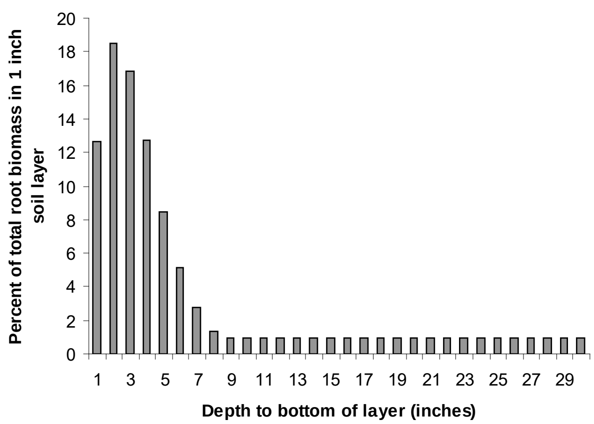

Figure 9.1. Fraction of total root biomass in 1 inch soil layers.

No data were found for measured root biomass in 1-inch soil layers. Accurately measuring roots is very difficult in soil layers as thin as 1-inch, especially near the soil surface. Preference was given to data where root biomass was measured in soil layers sufficiently thick to obtain accurate measurements, which is one of the reasons why the input value for root biomass is based on the upper 4-inch soil layer. This depth also contains the bulk of the roots that significantly affect rill-interrill erosion as discussed below.

The shape of the curve in Figure 9.1 within the upper 4-inch soil layer is based on judgment. A power equation gave the best fit to the observed data, but it was not used because a power equation form gives maximum root biomass density at the soil surface. The judgment is that root mass in the upper 1-inch layer is less than that at a slightly deeper soil depth. Soil moisture at the soil surface is reduced because of evaporation when soil surface (residue) cover is minimal, which in turn results in reduced root biomass near the soil surface. Increased surface residue reduces evaporation, which increases soil moisture at the soil surface. The form of equation 9.1, which represents reduced root biomass near the soil surface, was judged more appropriate overall for RUSLE2 than the power equation form. The shape of the curve in the upper 4-inch soil depth is of minimal consequence because RUSLE2 uses the average root biomass density in the upper 10-inch soil depth to compute runoff curve values, b values for effect of ground (surface) cover, slope length exponent, soil surface roughness, and soil biomass subfactor values (see **Sections 3.3.1.2, 6.2.1, 6.2.2, 6.3, and 6.5**).

A major result from the literature review and data analysis was that rooting depth for the roots judged to have the greatest effect on rill-interrill erosion do not vary greatly among agricultural crops and pasture/range plant communities. However, the rooting depths for most vegetable crops were about one half of that for agricultural crops. A rooting depth of 30 inches was assumed in RUSLE2 for all plant communities, including vegetable crops. Other RUSLE2 assumptions based on data analysis were that 85 percent of live root biomass was above the 15-inch depth, the live root biomass distribution by depth was the same for all plant communities, and rooting depth does not temporally vary.

The adequacy of these RUSLE2 assumptions must be judged in terms of RUSLE2's stated purpose of being an easily used guide for erosion control planning. Do RUSLE2's erosion estimates adequately represent the effect of temporal variability in root biomass for purposes of erosion control planning? Such an evaluation described in the RUSLE2 User's Reference Guide shows that RUSLE2 meets that criterion. Capturing the main effects of root biomass rather than all of the details is adequate for RUSLE2 purposes.

RUSLE2 uses average live root biomass density in the upper 10 inch soil depth to compute values for the soil biomass subfactor (see **Section 6.5.2**). The RUSLE2 live root distribution described by equations 9.1 and 9.2 compute that 61 percent of the total live root biomass is in the upper 4-inch soil depth and 80 percent is in the upper 10-inch soil depth. The constant rooting depth assumption does not result in large errors for estimating the soil biomass subfactor because the input variable is the root biomass in the upper 4-inch soil depth that contains more than half of the total root biomass.[65] Temporal live root biomass values given in the RUSLE2 Core Database (see the RUSLE2 User's Guide) were scaled from measured values at plant maturity. RUSLE2 accurately computes expected erosion estimates for times before the vegetation reaches maturity for major agricultural crops (see RUSLE2 User's Reference Guide), which strongly indicates that these assumptions are adequate for RUSLE2 purposes.

These assumptions are in accordance with the RUSLE2 objective to provide a system where the major vegetation variables affecting rill-interrill erosion can be easily described and measured and values for variables used to describe vegetation can be easily entered in RUSLE2. The objective is to sufficiently represent vegetation for RUSLE2 to estimate the effects of vegetation for conservation and erosion control planning. The adequacy of RUSLE2 for conservation and erosion control planning is the criteria for judging these RUSLE2 relationships. **The RUSLE2 User's Reference Guide guidelines must be followed to ensure accurate RUSLE2 erosion estimates.**

9.2.2. Live root biomass becoming dead root biomass

RUSLE2 uses a single vegetation description on any particular day (see **Section 8.1.1**). An operation that includes a **kill vegetation** process transfers the entire live root biomass in each soil layer to the dead root biomass in the corresponding soil layer. RUSLE2 does not allow killing a portion of the live root biomass. That effect can be accomplished by using an operation that includes a **begin growth** process that instructs RUSLE2 to begin using values for a new vegetation description. RUSLE2 assumes that the difference between the live root biomass on the last day that a vegetation description is used and the live root biomass on day zero in the new vegetation description represents dead root biomass that is added to the existing root biomass. RUSLE2 assumes that a decrease in

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[65] A possible RUSLE2 improvement would be to temporally vary rooting depth according to plant community. Similarly, the root distribution should also be varied with plant community and plant growth stage. These improvements were judged to excessively complicate RUSLE2.

root biomass from one day to the next represents root sloughing (Reeder et al., 2001). Each daily decrease in live root biomass is added that day to the dead root biomass.

9.2.3. Live above ground biomass

RUSLE2 vegetation descriptions are divided into new growth, senescence, and regrowth periods, illustrated in Figure 9.2, to compute temporal values for live above ground biomass as a function of canopy cover.[66]

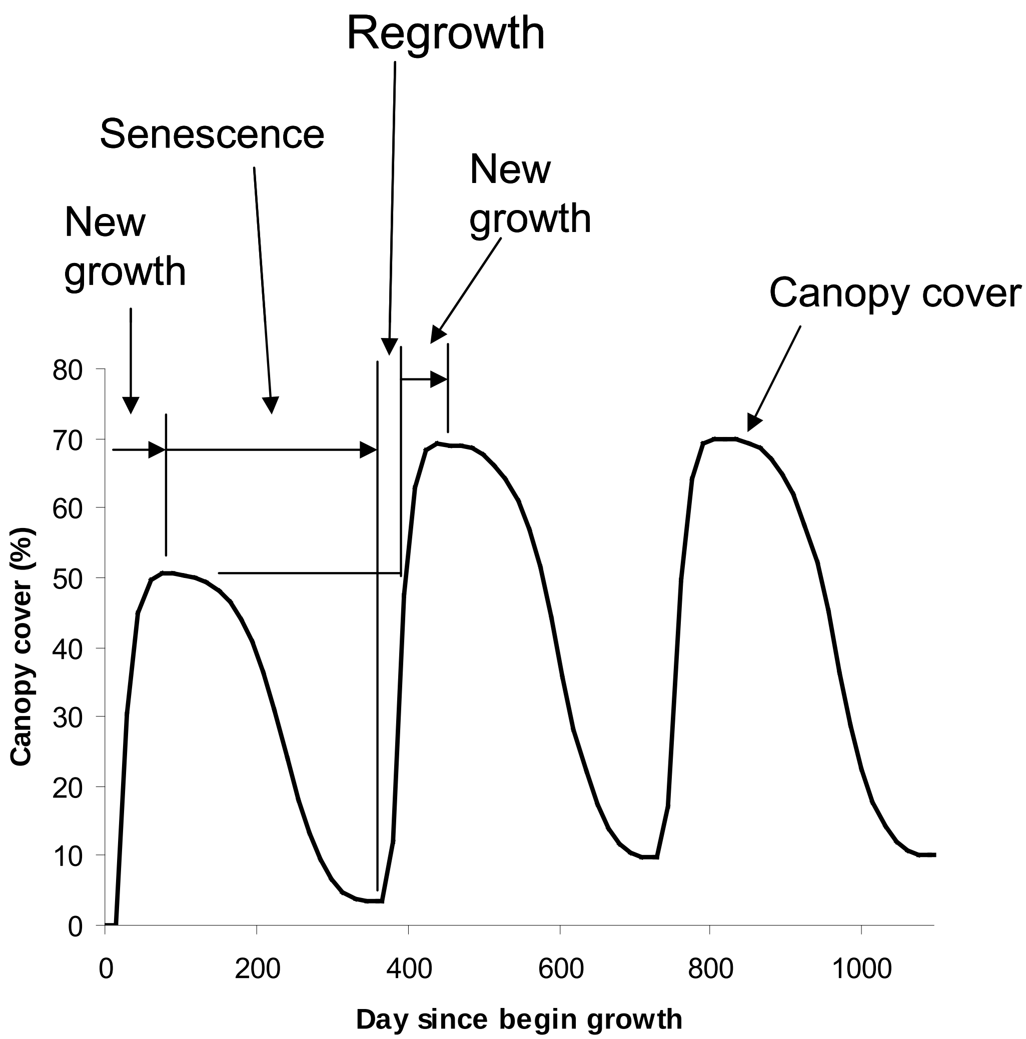

Figure 9.2. Vegetation growth periods used to compute live above ground biomass as a function of canopy cover.

9.2.3.1. New growth period

A **new growth** period is the time during which particular canopy cover values are first reached in a vegetation description. For example, the canopy cover from the seeding date to the first canopy cover maxima is a new growth period as illustrated in Figure 9.2. A second new growth period occurs in the second year over the time that canopy cover increases from the value of the first local canopy cover maxima in the first year to the local canopy cover maxima in the second year, also illustrated in Figure 9.2. A similar third new growth period, not illustrated, occurs in the third year. A composite of plant materials including leaves and stems is assumed to be produced during new growth periods.

The local canopy cover maxima that occurs in the third year for the vegetation description illustrated in Figure 9.2 is also the absolute canopy cover maxima for the vegetation description. The local canopy cover minima that occurs immediately after the absolute local canopy cover maxima is defined in RUSLE2 as the local absolute canopy cover minima for the vegetation description, even though other local canopy cover minima are less than this canopy cover. Values for the absolute canopy maxim and minima and the corresponding live above ground biomass values for these canopy values are user RUSLE2 inputs.

Live above ground biomass is computed from canopy cover during a new growth period using:

$$B_l = B_{lamx}(C/C_{amx})^{1.5} \qquad [9.4]$$

where: B_l = daily live above ground biomass during a new growth period, B_{lamx} = the live above ground biomass at absolute maximum canopy cover for a vegetation description, C = daily canopy cover, and C_{amx} = canopy cover at absolute maximum canopy cover for a vegetation description.

9.2.3.2. Senescence period

A **senescence** period is the time over which canopy cover decreases in a vegetation description from a local canopy cover maxima to a local canopy cover minima as illustrated in Figure 9.2. The equation used to compute live above ground biomass for a senescence period is:

$$B_l = B_{lmn(k)} + (B_{lmx(k)} - B_{lmn(k)})[(C - C_{mn(k)})/(C_{mx(k)} - C_{mn(k)})]^{1.5} \qquad [9.5]$$

where: $B_{lmn(k)}$ = live above ground biomass at the *kth* local canopy cover minima, $B_{lmx(k)}$ = live above ground biomass at the *kth* local canopy cover maxima, $C_{mn(k)}$ = canopy cover at the *kth* local minima, and $C_{mx(k)}$ = canopy cover at the *kth* local maxima. The index k refers to canopy cover maxima-canopy cover minima combinations where canopy cover minima occur after the corresponding canopy cover maxima.

The live above ground biomass and canopy cover at local canopy cover minima must be on the curve given by:

$$B_{lmn(k)} = B_{lamn}(C_{mn(k)} / C_{mn(1)})^{1.5} \qquad [9.6]$$

where: B_{lamn} = the absolute minimum live above ground biomass which occurs at $C_{mn(1)}$ = the first minimum canopy cover defined in **Section 9.2.3.1.** Values for live above ground biomass and canopy cover at local maxima must fall along the curve defined by equation 9.4.

The live above ground biomass-canopy cover curves for the new growth and the senescence periods are illustrated in Figure 9.3 for the first year of the vegetation description represented in Figure 9.2. The live above ground biomass for a given canopy cover during the senescence period is greater than that during the new growth period. Canopy cover loss during the senescence period is primarily by leaves falling to the soil surface. The biomass per unit canopy cover is much less for leaves than for the material, primarily stems, left standing during senescence. Each daily decrease in live above ground biomass is assumed to be biomass that falls and reaches the soil surface. This daily above ground biomass loss is added to the daily surface residue pool.

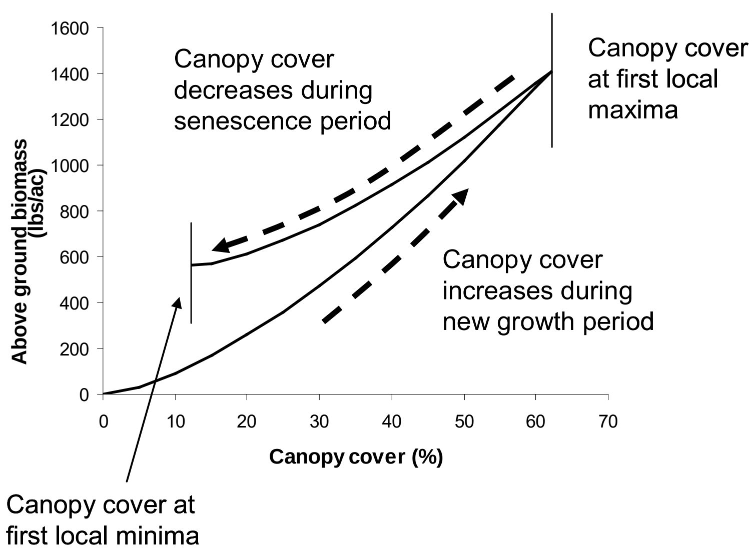

Figure 9.3. Live above ground biomass-canopy cover relationships for new growth and senescence periods during first year.

Equations 9.4 and 9.5 compute a decrease in live above ground biomass for a decrease in canopy cover. However, a decrease in live above ground biomass can occur with some plant communities with canopy cover remaining at 100 percent. An exponential equation form was evaluated to describe these plant communities. However, an exponential type equation was not used in RUSLE2 because such an equation can not be easily calibrated using the desired RUSLE2 inputs. Also, the exponential equation form did not give desired values for low canopy cover values.

Multiple vegetation descriptions are used in a RUSLE2 cover-management description to describe significant changes in live above ground biomass during periods when canopy cover changes very little. The inputs for these vegetation descriptions are selected so that

RUSLE2 computes a significant change in live above ground biomass for very little change in canopy cover such as from 99.9 percent to 99.5 percent. Such small changes in canopy cover have essentially no effect on canopy subfactor values (see **Section 6.1**). Additional vegetation descriptions are used for times during the cover-management description that canopy cover changes rapidly.

9.2.3.3. Regrowth period

The **regrowth** period starts from the canopy cover and live above ground biomass at the last local minima that was reached in the RUSLE2 computations as illustrated in Figure 9.2. Equation 9.5 is used to compute live above ground biomass values for the regrowth period as the live above ground biomass-canopy cover relationship retraces the senescence curve as illustrated in Figure 9.4. Most of the live biomass added during this period is assumed to be leaves and other material that has low biomass for the canopy cover that it provides. The regrowth period ends when canopy cover becomes equal to the canopy cover value of the last local maxima. A new growth period begins at this

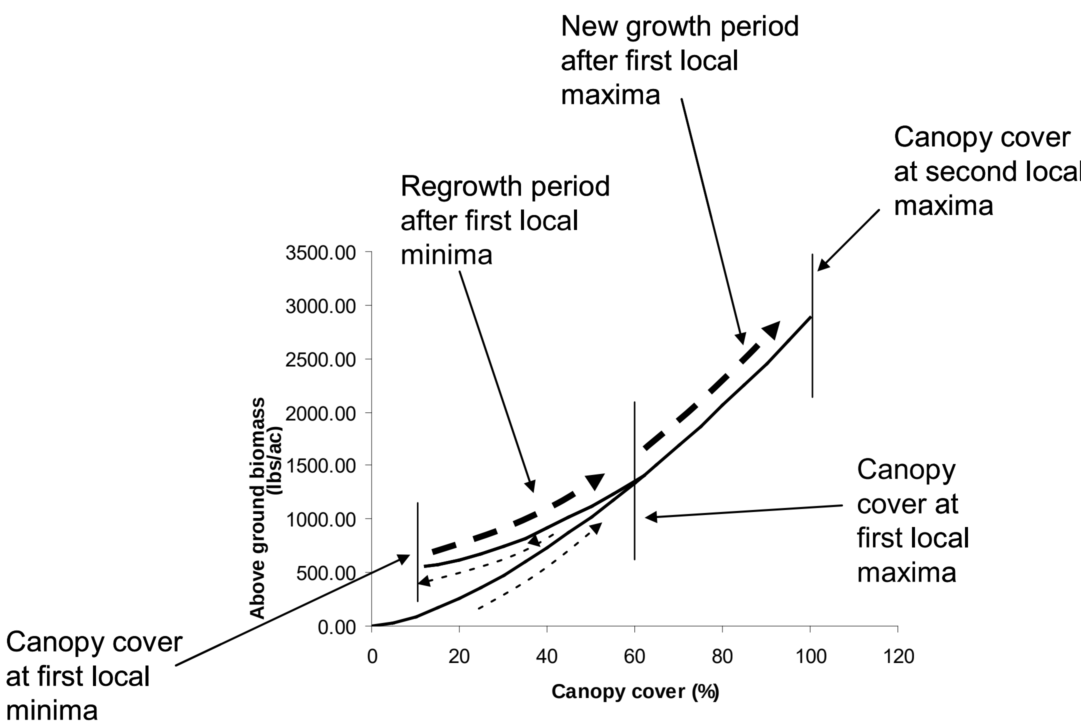

Figure 9.4. Live above ground biomass-canopy cover relationships for regrowth and new growth periods during second year.

point and continues until canopy cover becomes equal to the canopy cover of the next local maxima as illustrated in Figures 9.2 and 9.4. Equation 9.4 is used to compute values for live above ground biomass from canopy cover values during this new growth period. Once the next local maximum is reached, the next senescence period begins where equation 9.5 is used to compute live above ground biomass values.

Computations for this sequence of vegetation periods are repeated until the end of the RUSLE2 computation period.

9.2.3.4. Special cases

9.2.3.4.1. Annual plant communities that experience senescence

Most agricultural crops are annual and are described with either a single new growth period or by a single new growth period and a senescence period. Soybeans and cotton are examples of crops that experience senescence.

9.2.3.4.2. Annual plant communities that experience a decrease in canopy cover without a corresponding decrease in live above ground biomass

RUSLE2 also represents vegetation (e.g., corn and wheat) where canopy cover decreases by leaves drooping instead of falling to the soil surface. In this special case, the live above ground biomass does not decrease as canopy cover decreases. However, RUSLE2 can not represent perennial (long term) vegetation (i.e., multiple sequences of new growth-senescence-regrowth periods in the vegetation description) that has these characteristics.

9.2.4. Litter fall by other processes than senescence

9.2.4.1. Simultaneous birth and death of live above ground biomass

Litter is produced during the increase in growth period before canopy cover begins to decrease by senescence (Dubeux et al., 2005; Thomas and Asakawa, 1993). The litter produced during this period adds substantially to the surface residue produced by litter fall during senescence.

The amount of litter fall during the increase in growth period and into the first part of the senescence period is computed using:

$$L_f = c_f(B_l - B_{lmn(k)}) \quad if(B_l < B_{lmn(k)}): L_f = 0 \qquad [9.7]$$

where: L_f = day litter fall rate (mass/area·day) during the birth-death period and c_f = coefficient for birth-death litter fall (day^{-1}). A single value of 0.01 day^{-1} probably can be used almost all vegetation types (Dubeux et al. 2005; Thomas and Asakawa, 1993). However, this conclusion needs further research.

Litter fall is computed using equation 9.7 into the senescence period until the rate of litter falls computed by the difference in above ground biomass in a day exceeds the litter fall rate computed by equation 9.7.

9.2.4.2. Litter fall caused by mechanical traffic

Mechanical traffic by humans, animals, and vehicles can transfer biomass from the canopy to the soil surface that adds to surface residue. That biomass transfer is estimated by:

$$L_m = c_m(B_l - B_{lmn(k)}) \;\; if\,(B_l < B_{lmn(k)}) : L_f = 0 \qquad [9.8]$$

where: L_m = litter fall rate (mass/area·day) caused by mechanical traffic and c_m = a litter fall coefficient (day^{-1}) for the litter fall caused by mechanical traffic. The input value for c_m is based on the user's judgment.

9.2.4.3. Adjustment in above ground biomass for litter fall

RUSLE2 does not adjust live above ground biomass for litter fall. The user entered input values for canopy cover are assumed to represent the canopy that exists in the field regardless of what affects canopy cover. RUSLE2 converts those values to biomass, which like the canopy cover values are the live above ground biomass that exists regardless of how it came to be. RUSLE2's litter fall computations describe the disposition of live above ground biomass.

9.2.5. Operations that affect live vegetation

Operations that include **begin growth**, **kill vegetation**, **remove live biomass, and Process: Perennial biomass & current standing res removal** processes affect live above ground biomass. A **begin growth** process instructs RUSLE2 to begin using values from a new vegetation description. RUSLE2 assumes no relationship between live above ground biomass for the two vegetation descriptions although a relationship is assumed for live root biomass (see **Section 9.2.2**). The RUSLE2 assumption is that a decrease in live root biomass between the last day that a vegetation description is used to compute daily erosion and the live root biomass on day zero in the new vegetation description is biomass added to the existing dead root biomass pool. In contrast, no such connections are assumed for live above ground biomass. The RUSLE2 user explicitly use operations, such as **remove live biomass**, to describe the fate of live above ground biomass between vegetation descriptions when a begin growth process is executed. Within the period represented by a vegetation description, the RUSLE2 assumption is that a decrease in canopy cover represents a senescence period and the decrease in live above ground biomass during a senescence period is daily added to the surface residue biomass pool.

Consequently, RUSLE2 assumes that a new growth vegetation period begins on day zero for a new vegetation description when a begin growth process is executed. This assumption applies to transplanted crops and to vegetation that regrows after hay harvest or mowing where canopy and live above ground biomass are greater than zero on day zero in the vegetation description. Similarly, an operation that includes the **remove live biomass** process can leave live above ground biomass after the operation. RUSLE2 assumes that a new growth period begins immediately after the remove live biomass process is executed. The increase in live above ground biomass is assumed to be a composite of above ground plant components, including stems and leaves, during a new growth vegetation period in contrast to the increase in live above ground biomass being primarily leaves during the regrowth period that follows a senescence period.

A **kill vegetation** process transfers the entire live above ground biomass that exists on the day that the process is executed to the standing residue pool. The relation between standing residue biomass and canopy cover is given in **Section 9.2.3**.

9.2.6. Temporal standing live vegetation Manning's n

Standing vegetation contributes to total hydraulic resistance (see **Section 3.4**). The temporal contribution of standing live vegetation, not including live ground cover, to Manning's n is computed using:

$$n_v = n_{vmx}(h_f / h_{fmx})$$

where: n_v = daily Manning's n contributed by live standing vegetation not including live ground cover, n_{vmx} = maximum Manning's n contributed by live standing vegetation, not including live ground cover, during the period represented by the vegetation description, h_f = daily effective fall height, h_{fmx} = maximum effective fall height during the vegetation description, and i = subscript for day. Manning's n contributed by standing live vegetation is most affected by stems. Of the temporal input or computed variables used in a RUSLE2 vegetation description, Manning's n for standing live vegetation was assumed to be best related to effective fall height. The Manning's n contributed by live ground (surface) cover is consider in the relation of Manning's n to net ground (surface) cover (see **Section 3.4.6**)

Table 9.1. Coefficient a_H values used to multiply maximum effective vegetation ridge height on contour to obtain effective vegetation ridge height for effect of row spacing

Row width	Coefficient a_H
Vegetation on ridges	0.25
Wide row (≥ 30 inches)	0.50
Moderate row spacing (15 to 20 inches)	0.75
Narrow row spacing (7 to 10 inches)	1.00
Very narrow row spacing (≤5 inches)	0.50
No rows (broadcast)	0.00

Maximum Manning's n for live standing vegetation for a vegetation description is computed from the user input vegetation retardance at maximum canopy cover. Vegetation retardance is a function of vegetation stem density and orientation of vegetation strips (rows) to the overland flow path (see **Section 3.4.6**). The live vegetation Manning's n when vegetation strips (rows) are on the contour (i.e., perpendicular to the overland flow path) is computed using equation 3.54. A Manning's n value for live standing vegetation for vegetation in rows up and downhill (i.e., parallel to the overland flow path) is computed using values in Table 3.10. The live standing vegetation Manning's n for the actual orientation of vegetation rows to the overland flow path (i.e., row grade) is computed using equation 3.55.

9.2.7. Temporal effective vegetation ridge height

Densely spaced stems of vegetation rows on the contour affect rill-interrill erosion much like soil ridges (see **Section 7.1.3**). An effective live vegetation ridge height is added to the soil ridge height to obtain an effective total ridge height used to compute values for the contouring subfactor in equation 7.6. The effect of live standing vegetation rows on erosion depends on row spacing. If row spacing is zero (i.e., the vegetation is not in rows and the plant stems are randomly spaced over the entire soil surface), orientation of vegetation rows to the overland flow path and row spacing has no meaning or effect on the contouring subfactor. The erosion reduction (i.e., contouring effect) for effective live standing vegetation ridge height increases as vegetation row spacing increases to a maximum at the narrow row width of approximately 8 inches). Erosion reduction by effective vegetation ridge height decreases as row spacing widens beyond the narrow row spacing. This effect is represented by the coefficient α_h values given in Table 9.1.

The maximum effective live standing vegetation ridge height for contour vegetation strips (rows) for a vegetation description is computed using:

$$H_{vmx} = 0.5 a_H R_v \quad if\,(R_v > 7) : R_v = 7 \qquad [9.10]$$

where: H_{vmx} = maximum effective live standing vegetation ridge height (inches) for the vegetation description when vegetation strips (rows) are on the contour, a_H = the coefficient that adjusts for row spacing (inches), and R_v = the retardance class at maximum canopy cover in the vegetation description (see **Section 9.3.1**).

Daily effective live standing vegetation ridge height H_v is computed using:

$$H_v = H_{vmx}(h_f / h_{fmx})^{0.3} \qquad [9.11]$$

Like Manning's n for live standing vegetation, of the temporal vegetation variables, effective live vegetation ridge height is assumed to be most related to effective fall height.

9.3. Adjust input values for vegetation production (yield) level

Input values in RUSLE2 vegetation descriptions are functions of vegetation production (yield) level, and each RUSLE2 vegetation description applies to a particular production (yield) level. RUSLE2 computes values in a vegetation description for a new production (yield) level by adjusting values in a base vegetation description. The maximum canopy cover in the base vegetation description must be less than 100 percent for RUSLE2 to make the proper mathematical computations. RUSLE2 can use a base vegetation description that has a maximum canopy cover of 100 percent to adjust for production (yield) levels greater than the production (yield) level for the base vegetation description, but RUSLE2 can not use a base vegetation description with a 100 percent maximum canopy cover to adjust to a lower production (yield) level.

Biomass values used in RUSLE2 computations are on a dry basis, but input values for vegetation production (yield) level are on a user defined basis. The user inputs information that RUSLE2 uses to convert production (yield) level value on the user defined basis to the dry basis needed for RUSLE2's computations (see RUSLE2 User's Reference Guide).

Multiple RUSLE2 vegetation descriptions can be used to compute erosion for a particular plant community over the period represented in the RUSLE2 computation (i.e., rotation duration). For example, vegetation descriptions are used to describe a multiple year alfalfa hay production system. The first vegetation description describes the alfalfa crop from seeding to first hay harvest, the second vegetation description describes regrowth after each hay harvest in the first harvest year, the third vegetation description describes senescence and regrowth after senescence to the first hay harvest in the second harvest year, and so on. Input values such for live above ground biomass at maximum canopy apply to that particular vegetation description and not to the vegetation as a whole over the RUSLE2 computation period, such as the example alfalfa crop.

9.3.1. Live above ground biomass at maximum canopy cover

A major vegetation input is live above ground biomass at maximum canopy cover for a particular vegetation description. When multiple vegetation descriptions are used to represent a particular vegetation, the live above ground biomass entered for each vegetation description is for the maximum canopy cover in that particular vegetation description.

The RUSLE2 assumption is that live above ground biomass at maximum canopy varies linearly as a function of production (yield) level. That is:

$$B_{lamx} = a_y + b_y Y_d \qquad [9.12]$$

where: B_{lamx} = live above ground biomass (dry basis, mass/area) at maximum canopy cover for the vegetation description and Y_d = production (yield) level (dry basis, mass/area). The user provides inputs that RUSLE2 uses to convert production (yield) level in user units to biomass on a dry basis. These equations have the form:

$$Y_d = b_u Y_u \qquad [9.13]$$

where: Y_u = production level (yield) in user defined units and b_u = a conversion factor that RUSLE2 computes from user inputs. The values for the coefficients a_y and b_y in equation 9.12 are computed from user inputs for two live above ground biomass at maximum canopy cover-production (yield level) data points (see RUSLE2 User's Reference Guide).

9.3.2. Retardance at maximum canopy cover

Retardance for live vegetation at maximum canopy cover is computed from:

$$R_v = c_R + d_R Y_u \qquad [9.14]$$

where: R_v = retardance at maximum canopy cover for a vegetation description and Y_u = production (yield) level in user defined units for the vegetation description. The user enters two input data points for retardance-production (yield) level that RUSLE2 uses to determine values for the coefficients c_R and d_R in equation 9.14. RUSLE2 uses eight retardance classes that vary with the degree that vegetation grown in strips (rows) on the contour slows runoff (see Table 3.9). Equation 9.14 computes continuous values that are used in equation 3.54 to compute Manning's n values.

Vegetation descriptions are used to describe both live vegetation and porous barriers (fabric fences, gravel bag dams, and similar mechanical devices used on construction sites to trap and retain sediment on site) (see **Section 7.2** and RUSLE2 User's Reference Guide). The yield input for the vegetation description selected to describe these devices is used to represent the degree that the installed device retards runoff. The eighth retardance class is reserved for conditions that provide extremely high retardance such as stiff grass hedges, fabric (silt) fences and gravel bag dams. RUSLE2 computes backwater length caused by vegetation strips and flow retarding devices as a function of Manning's n, which are computed from the retardance class for the vegetation description (see **Section 3.4.4**). RUSLE2 assigns a minimum backwater length of 3 ft for the extremely high retardance class but uses the backwater length computed for the other retardance classes. RUSLE2 assumes a maximum backwater length of 15 ft for all vegetation/mechanical retarding strips.

9.3.3. Temporal input vegetation variables

Simple equations based on values computed by the EPIC model (Williams et al., 1989) are used in RUSLE2 to compute values for the temporal variables of root biomass, canopy cover, effective fall height, live ground cover, and consumptive water use.

9.3.3.1. Root biomass

Live root biomass values are assumed to vary linearly with live above ground biomass at maximum canopy cover. Live root biomass values for a new vegetation are computed as a function of production level (yield) using:

$$B_{rn(j)} = B_{rb(j)}(B_{lamxn} / B_{lamxb}) \qquad [9.15]$$

where: $B_{rn(j)}$ = root biomass value in the new vegetation description for the *jth* data point, $B_{rb(j)}$ = root biomass value for the *jth* data point in the base vegetation description, and B_{lamxb} = absolute maximum live above ground biomass in the base vegetation description. A value for the live above ground biomass at absolute maximum canopy B_{lamxn} in the new vegetation description is computed using equation 9.12 and the production (yield) level value for the new vegetation description.

9.3.3.2. Canopy cover

The equation used to adjust canopy cover values for production (yield) level is:

$$C_{n(j)} = C_{b(j)}(B_{lamxn} / B_{lamxb})^{0.5} \qquad [9.16]$$

where: $C_{n(j)}$ = canopy cover for *jth* data point the new vegetation description and $C_{b(j)}$ = the corresponding canopy cover value for the *jth* data point in the base vegetation description.

9.3.3.3. Effective fall height

The equation used to adjust effective fall height values for production (yield) level is:

$$h_{fn(j)} = h_{fb(j)} (B_{lamxn} / B_{lamxb})^{0.2} \qquad [9.17]$$

where: $h_{fn(j)}$ = effective fall value for the *jth* data point in the new vegetation description and $h_{fb(j)}$ = corresponding effective fall height value for the *jth* data point in the base vegetation description.

9.3.3.4. Live ground cover

The equation used to adjust live ground cover values as a function of production (yield) level is:

$$f_{\lg cn(j)} = f_{\lg cb(j)} (B_{lamxn} / B_{lamxb})^{0.5} \qquad [9.18]$$

where: $f_{lgcn(j)}$ = live ground cover value for the *jth* data point in the new vegetation description (percent) and $f_{lgcb(j)}$ = corresponding live ground cover value for the *jth* data point in the base vegetation description (percent).

9.3.3.5. Consumptive water use

Consumptive water use is used to compute how irrigation affects rill-interrill erosion by precipitation (see **Section 7.5**). Consumption water use is a function of production (yield) level. The equation used to adjust consumptive water use values as a function of production (yield) level is:

$$V_{wn(j)} = V_{wb(j)} (B_{lamxn} / B_{lamxb}) \qquad [9.19]$$

where: $V_{wn(j)}$ = consumptive water use value for the *jth* data point in the new vegetation description and $V_{wb(j)}$ = corresponding values for consumptive water use value for the *jth* data point in the base vegetation description.

9.4. List of symbols

a_y = coefficient used to compute live above ground biomass at absolute maximum canopy cover for a vegetation description

a_H = coefficient used to computed effective vegetation ridge height from vegetation retardance (inches)

b_u = coefficient used to convert user defined yield units to dry mass

b_y = coefficient used to compute live above ground biomass at absolute maximum canopy cover for a vegetation description

B_l = daily live above ground biomass (dry basis) during a new growth period (mass/area)

B_{lamn} = live above ground biomass (dry basis) at first minimum canopy cover $C_{mn(1)}$ for a vegetation description (mass/area)

B_{lamx} = absolute maximum live above ground biomass (dry basis) at absolute maximum canopy cover for a vegetation description (mass/area)

$B_{lmn(k)}$ = live above ground biomass (dry basis) at *kth* local canopy cover minina in a vegetation description (mass/area)

$B_{lmx(k)}$ = live above ground biomass (dry basis) at *kth* local canopy cover maxima in a vegetation description (mass/area)

B_{lamxb} = live above ground biomass at absolute maximum canopy cover in base vegetation description (mass/area)

B_{lamxn} = live above ground biomass at absolute maximum canopy cover in new vegetation description (mass/area)

$B_{rb(j)}$ = root biomass value for the *jth* data point in the base vegetation description (mass/area in upper 4-inch depth)

$B_{rn(j)}$ = root biomass value for the *jth* data point in the new vegetation description (mass/area in upper 4-inch depth)

$B_{t,mn}$ = live above ground biomass (dry basis) at a local canopy cover minima (mass/area)

$B_{t,mx}$ = live above ground biomass (dry basis) at a local canopy cover maxima (mass/area)

c_f = coefficient for birth-death litter fall (day^{-1})

c_m = cooefficient fr litter fall caused by mechanical traffic (day^{-1})

c_R = coefficient used to compute retardance from user input yield

C = daily canopy cover (fraction)

C_{amx} = canopy cover at absolute maximum canopy cover for a vegetation description (fraction)

$C_{mn(k)}$ = canopy cover at the *kth* local canopy minima (fraction)

$C_{mx(k)}$ = canopy cover at the *kth* local canopy maxima (fraction)

$C_{b(j)}$ = canopy cover value for *jth* data point in base vegetation description (fraction)

$C_{n(j)}$ = canopy cover for *jth* data point in new vegetation description (fraction)

d_R = coefficient used to compute retardance from user input yield

$f_{lgcb(j)}$ = live ground cover value for *jth* data point in base vegetation description (percent)

$f_{lgcn(j)}$ = live ground cover value for *jth* data point in new vegetation description (pecent)

h_f = daily effective fall height (length)

$h_{fb(j)}$ = effective fall height value for the *jth* data point in the base vegetation description (length)

$h_{fn(j)}$ = effective fall value for *jth* data point in new vegetation description (length)

h_{fmx} = maximum effective fall height for a vegetation description (length)

H_v = daily effective live standing vegetation ridge height (inches)

H_{vmx} = maximum effective live standing vegetation ridge height for a vegetation description

L_f = daily litter fall during birth-death period (mass/area·day)

L_m = daily litter fall caused by mechanical traffic (mass/area·day)

M_r = cumulative root biomass (dry basis) above the depth y (mass/area)

n_v = daily Manning’s n contributed by live standing vegetation not including live ground cover

n_{vmx} = maximum Manning’s n contributed by live standing vegetation not including live ground cover for a vegetation description

R_v = vegetation retardance class at maximum canopy cover for a vegetation description

$V_{wb(j)}$ = corresponding values for consumptive water use value for *jth* data point in base vegetation description (inches)

$V_{wn(j)}$ = consumptive water use value for *jth* data point in the new vegetation description (inches)

y = normalized depth in soil from soil surface Y/15 inches

Y = depth in soil from soil surface (inches)

Y_d = production (yield) level (dry basis) (mass/area)

Y_u = production level (yield) in user defined units

15 = reference depth in inches for determining root mass distribution in soil

Indices

j – data point

k - refers to canopy cover maxima-canopy cover minima combination where canopy cover minima occur after a canopy cover maxima

10. RESIDUE AND DEAD ROOTS

10.1. Description of residue and dead roots

Residue and dead roots are materials lost by decomposition. RUSLE2 includes standing, surface, and buried residue pools that account for material produced when live above ground biomass is converted to standing residue (**Sections 6.1, 6.2, 6.5, and 9.2.5**). RUSLE2 accounts for the movement of residue mass between these pools by harvest, tillage, ripping, and other operations that affect vegetation, residue, and soil (see **Section 8.2**). The RUSLE2 surface residue pool also includes material such as mulch, manure, and erosion control blankets applied to the soil surface (see **Section 6.2**). The RUSLE2 buried residue pool includes material such as manure and bio-solids in sewage sludge that are injected or incorporated into the soil (see **Sections 6.3 and 6.5**).

Mass in the RUSLE2 dead root residue pool results from live root biomass associated with a vegetation description being transferred to the dead root biomass pool (see **Sections 6.5.6 and 9.2.2**).

The general RUSLE2 assumption is that residue and dead roots are organic materials that decompose. RUSLE2 also describes the effects of non-organic material such as erosion control blankets and rock placed on the soil surface or incorporated into the soil. However, special inputs are used to represent non-organic material (see **Section 10.2.5**).

Crop residue and plant litter are composed of diverse components including stems, leaves, seed pods, and chaff. Similarly, dead roots vary from very fine to coarse roots. A single residue description is used to represent a composite of these components for a particular vegetation description

10.2. Relation of portion of soil surface covered to surface residue mass

10.2.1. Size criteria for counting residue

To be counted as ground cover, soil surface material must remain in place, not be moved downslope by surface runoff during a rainstorm, and not be moved away by wind. The minimum size required to be counted as ground cover for RUSLE2 purposes must meet this criteria. **No single size should be used for all ground cover material in all situations**. For example, small pieces of residue will stay in place at the upper end of an overland flow path that would be moved at the lower end of a long overland flow path. Similarly, residue will be stable on a very flat overland flow path that would be moved on a steep overland flow path. Small residue pieces can be stable among a gradation of residue sizes but be unstable when the residue is uniformly composed of the small pieces. Small residue pieces that are stable at high residue surface covers may be unstable at low residue surface covers.

Equations that compute the hydraulic stability of mulch and crop residue were considered for RUSLE2 but were rejected because the equations were judged not to be sufficiently robust for RUSLE2 purposes (Foster et al., 1982a, 1982b).

Rock fragments on the soil surface require special consideration. The same stability considerations for other surface residue also apply to counting surface rock fragments as surface cover. Another factor is whether the rock fragments are a part of the soil matrix or simply "loose" rock on the soil surface that acts like surface cover. An approximate guideline is that rock fragments must be larger than 5 mm on coarse textured soils in arid and semi-arid regions where runoff is low and larger than 10 mm in other regions to be counted as ground cover.

10.2.2. Equation for computing residue cover from residue mass

RUSLE2 tracks surface residue (material in direct contact with the soil surface) on a dry mass basis (mass/area). However, the portion of the soil surface covered is the major variable used in equation 6.6 to compute how ground cover (surface residue) affects rill-interrill erosion. The RUSLE2 equation that computes portion of the soil surface covered by surface residue is:

$$f_g = 1 - \exp(-\alpha B_s) \qquad [10.1]$$

where: f_g = fraction of the soil surface covered by residue when no other residue type is present and B_s = surface residue mass (dry mass/area). RUSLE2 computes a value for the coefficient α using equation 10.1 rearranged and user entered values for the residue mass that provides 30, 60, or 90 percent soil cover.

A typical example of surface residue mass-cover data is illustrated in Figure 10.1. A common feature of these data is their high variability, which in turn greatly affects the variability in computed erosion estimates. For example, cover ranges from 0.70 to 1.0 percent in Figure 10.1 at a mass of 150 g/m^2. This range in cover gives ground cover subfactor values for g_c in equation 6.6 (**b** = 0.04 percent^{-1}and R_a = 0.24 inches) that range from 0.018 to 0.061. The portion of the soil surface covered ranges from 0.55 to 0.85 percent for a residue mass of 50 g/m^2, which gives values of 0.033 to 0.11 for g_c. In both cases, erosion

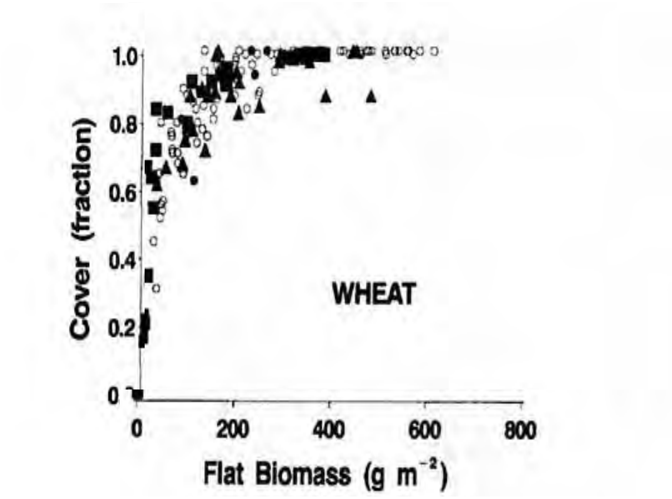

Figure 10.1. Measured data for relationship of residue cover to surface residue mass. (Source: Steiner et al., 2000).

can differ by a factor of 3 for a given surface residue mass. Therefore, even if RUSLE2 could estimate surface residue mass perfectly, RUSLE2's estimated portion of the soil surface covered, and its corresponding estimated erosion, could be significantly in error when compared to an individual measurement of soil surface cover.

Given this variability, the best that RUSLE2 can represent is differences in major residue types. Expecting RUSLE2 to accurately estimate percent residue cover at a particular location on a landscape at a particular point in time is unreasonable.

Data reported in the literature for residue cover as a function of residue mass vary greatly from study to study and even within a particular study as illustrated in Figure 10.1. The values used in the RUSLE2 Core Database were chosen as representative values for conservation and erosion control planning, realizing that numerous studies give values that differ from the RUSLE2 values. For example, surface cover ranged from about 65 percent to 100% for a flat wheat residue mass of about 1500 lbs/acre (168 g/m^2) in the Steiner et al. (2000) study, which is significantly greater than the 58 percent that the RUSLE2 Core Database values compute for the same residue mass. The RUSLE2 Core Database values for wheat straw are based on AH537 (Wischmeier and Smith, 1978) values, which were primarily derived from data reported by Mannering and Meyer (1963), Meyer and Mannering (1967) and Meyer et al. (1970).

The variation among some plant varieties is so great than different mass-cover relationships should be used for major variety types. For example, Stott (1995) noted that α values for corn varied from about 0.00023 to 0.00045 $(lbs/acre)^{-1}$ for corn residue based on her measurements and data reported in the literature. Stott recommended that the 0.00023 acre/lbs value (60 percent cover at 4000 lbs/acre flat corn residue mass) be used for corn grown after the mid 1980's and that the RUSLE2 Core Database value of 0.00038 $(lbs/acre)^{-1}$ (60 percent cover at 2400 lbs/acre corn residue mass) be used for corn grown before the mid 1980's. RUSLE2 satisfactorily estimates flat residue cover at planting for a wide range of soil and conservation tillage methods as Table 10.1 shows, with the recognition that the corn in these studies was grown before the mid 1980's.

Another example is that soybean varieties grown in the Midwest US differ from those grown in the Mid-South US. The RUSLE2 Core Database mass-cover value for soybeans varieties grown in the Midwestern US is that 600 lbs/acre of soybean residue gives 30 percent soil surface cover [AH703 (Renard et al., 1997)] while the mass-cover value for the variety of soybeans grown in the Mid-South US is that 1460 lbs/acre of soybean residue gives 30 percent soil surface cover (Mutchler and Greer, 1984).[67]

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[67] K.C. McGregor. 1994. Mass-cover data for soybeans grown at Holly Springs, Mississippi. Personal communication. Scientist (retired) at the USDA-National Sedimentation Laboratory, Oxford, Mississippi.

Table 10.1. Measured and RUSLE2 estimated residue cover (percent) immediately after planting (Source: RUSLE2 User's Reference Guide)

Crop	Tillage system	Observed cover	Estimated cover	Reference
corn	spring disk	15	21	1
corn	fall chisel, spring disk	13	12	1
corn	spring disk, spring disk	27	18	2
corn	spring chisel, spring disk	22	11	2
corn	spring disk	15	21	2
corn	fall chisel, spring disk	13	12	2
soybeans	spring disk, spring disk	27	18	2
soybeans	spring chisel, spring disk	22	11	2
corn	spring disk	8	20	2
corn	spring disk, spring disk	5	7	2
corn	spring chisel, spring disk	7	3	2
corn	field cultivator	24	20	2
soybeans	spring disk, spring disk	11	8	2
soybeans	spring disk	15	22	2
soybeans	spring chisel, spring disk	11	4	2
corn	fall chisel, spring disk	33	26	3
corn	spring chisel, spring disk	19	19	4
corn	spring disk, spring disk	30	27	4
corn	fall chisel, spring disk, spring field cultivator	9	14	5
soybeans	fall chisel, spring field cultivator, spring field cultivator	9	5	5
corn	fall chisel, spring disk, spring field cultivator	16	14	6
soybeans	fall chisel, spring field cultivator, spring field cultivator	3	5	6
soybeans	spring disk, spring disk	9	7	7
soybeans	spring disk, spring disk	9	7	8
soybeans	spring disk	13	18	8

Table 10.1 (continued). Measured and RUSLE2 estimated residue cover (percent) immediately after planting			
References:			
1. Siemens and Oschwald (1976)			
2. Dickey et al. (1985)			
3. Lindstrom and Onstad (1984)			
4. Laflen et al. (1978)			
5. McIsacc et al. (1990)			
6. McIsaac et al. (1991)			
7. Shelton et al, (1986)			
8. Jasa et al. (1986)			

The RUSLE2 Core Database values for surface residue mass-cover relationships should be used for routine RUSLE2 applications. When RUSLE2 users wish to use values for residue mass-cover other than those in the RUSLE2 Core Database, users should review and analyze data from multiple sources because of the great variability in these data within a study as illustrated in Figure 10.1 and between studies. RUSLE2 was calibrated to measured erosion values using the values in the RUSLE2 Core Database. That is, RUSLE2 was calibrated to give expected erosion values. **Unexpected serious error in RUSLE2 computed erosion estimates can occur when input residues values are improperly changed from those in the RUSLE2 Core Database (see the RUSLE2 User's Reference Guide). If a change is made in residue input values, RUSLE2 computed erosion values with the new input values should be compared against erosion measured with the residue represented in the new input values.**

10.2.3. Reasons for variability in the surface residue mass-residue cover relationship

A major reason for the variability in the residue mass-residue cover relationship is that crop residue, plant litter, and similar materials are composed of multiple plant components (e.g., leaves, stems, seed pods, and chaff) and pieces that vary in composition, geometry, size, mass, and surface area covered per unit dry mass. RUSLE2 uses a single residue description to represent residue as a composite of multiple components. Consequently, α in equation 10.1 is a function of the relative mass of each residue component in the composite and varies temporally as the relative mass of each residue component varies temporally. For example, the α value for corn and soybean residue immediately after harvest differs significantly from the α value several months later because leaves cover more area than do stems per unit mass and leaves decompose much more rapidly than do the stems. In contrast to corn and soybeans, field measured data at Bushland, Texas showed that α values for barley, oats, spring wheat, and winter wheat did not vary from 24 to 400 days after harvest (Steiner et al., 2000). However, data variability, as in all studies of residue mass-residue cover, may have masked temporal changes in the residue mass-residue cover relationship.

The RUSLE2 assumption is that residue properties such as α in equation 10.1 are time invariant for the period represented by a residue description in a RUSLE2 computation. Consequently, equation 10.1 is a compromise and the values in the RUSLE2 Core Database used to compute α were chosen to compute erosion values appropriate for conservation and erosion control planning (see RUSLE2 User's Reference Guide). The input values that RUSLE2 uses to compute α values should be carefully selected to ensure that equation 10.1 gives the best erosion estimates for the time periods that have the greatest effect on average annual erosion. User entered values for a new residue description being added to a RUSLE2 database should be consistent with values in the RUSLE2 Core Database. Procedures described in the RUSLE2 User's Reference Guide must be followed.

In some cases, temporal changes in residue properties can be represented in RUSLE2 by using multiple residue descriptions during the RUSLE2 computation period. Using multiple residue descriptions requires using an operation that includes a **remove residue/cover process** to remove the existing material and another operation that includes an **add other cover process** that adds the removed material back to the soil surface using a new residue description. The computer mechanics of using RUSLE2 in this way are not convenient for routine conservation and erosion control planning. However, the procedure is mentioned to illustrate RUSLE2's capability for computing the effects of temporal variations of residue properties. Technical specialists for agencies using RUSLE2 in routine conservation planning can use this technique to evaluate the uncertainty in RUSLE2 erosion estimates resulting from the assumption that residue properties do not vary temporally (see RUSLE2 User's Reference Guide).

10.2.4. Overlap of residue

The user assigns a single residue description to each vegetation description and to each operation description in a cover-management description that adds material to the soil surface (see RUSLE2 User's Reference Guide). For example, a corn-soybeans crop rotation involves two residue descriptions, one for corn and one for soybeans. The mass for each residue description is tracked separately. A daily ground cover value is computed with equation 10.1 for each residue description. A net ground cover value is used in equation 6.6 to compute a value for the ground cover subfactor, not the sum of the ground cover values computed with equation 10.1 for each residue description when multiple residue descriptions are involved. RUSLE2 takes into account the overlap of residue applications to compute net ground cover. The RUSLE2 assumption is that the portion of material that overlaps underlying material has no effect on rill-interrill erosion. The computation of net ground cover is illustrated for crop residue or mulch applied to a soil surface with existing rock cover. The net ground cover for these two residue descriptions (e.g., crop residue or mulch and rock) is computed as:

$$f_{gn} = f_{gr} + f_{gm}(1 - f_{gr}) \qquad [10.2]$$

where: f_{gn} = net ground cover (fraction), f_{gr} = ground cover (fraction) computed with equation 10.1 provided by the rock surface residue cover assuming no other material is present, and f_{gm} = ground cover (fraction) computed with equation 10.1 for crop residue or mulch assuming no other material is present. Equations 10.1 and 10.2 are used repeatedly to account for each residue description used in a particular RUSLE2 computation to compute a net ground cover value. The overall net ground cover value is used in equations 6.6, 6.7, and related equations to compute the effect of surface residue cover on rill and interrill erosion. A ground cover subfactor g_c is not computed for each residue description.

10.2.5. Inputs for non-organic residue

In some cases, a material is applied to the soil surface that significantly affects erosion but has less effect on erosion when incorporated into the soil than routine plant residue. The mass values entered in the residue description for cover-mass data points can be scaled to be so small that the mass values used for the material when incorporated in the soil are so small that they have no effect on soil biomass subfactor values (see **Section 6.5**). Input values for mass of these materials applied to the soil must be accordingly scaled. The objective in these RUSLE2 applications is that RUSLE2 uses desired ground cover values to compute ground cover subfactor values using equation 6.6 but uses such small residue mass values that soil biomass factor values computed with equation 6.48 are hardly affected if the material is incorporated into the soil (see RUSLE2 User's Reference Guide).

The importance of using recommended RUSLE2 inputs and following RUSLE2 procedures described in the RUSLE2 User's Reference Guide can not be over-emphasized, especially when making comparisons with the USLE, RUSLE1, and much of the historical data used to develop those models as well as RUSLE2. However, crop characteristics and yield, especially for corn, has changed greatly from the 20 bu/ac corn yield common in the 1930's data used to determine the AH282 and 537 soil loss ratio values, which were used to calibrate RUSLE2, to modern 200 bu/ac high production corn yields. The values in the RUSLE2 Core Database are considered adequate for evaluating modern crops and cropping practices, especially when RUSLE2 erosion computed values are being compared with values computed with the USLE or RUSLE1.

Consideration should be given to changing input values to represent modern crops and cropping practices in certain RUSLE2 applications. In doing so, the procedures described in the RUSLE2 User's Reference Guide should be carefully followed, and input values must be based on multiple data sources, not a single source. RUSLE2 was calibrated to compute expected erosion rates as a function of the principal variables affecting erosion. Therefore, RUSLE2's computation of what appears to be an erroneous cover value does not necessarily mean that RUSLE2's computed erosion values are erroneous.

Improper inputs without consideration of RUSLE2's calibration can result in very serious errors in RUSLE2 computed erosion values.

10.3. Decomposition of residue and dead roots

10.3.1. Description of equations

Both residue and dead roots are assumed to be lost over time as a result of decomposition and other processes related to precipitation and temperature. The basic RUSLE1 decomposition equations are used in RUSLE2 [AH703 (Renard et al., 1997); Yoder et al., 1997; Stott et al., 1990; Stott et al., 1995], which are a simplification of the decomposition equations used in the erosion prediction model WEPP (Laflen et al., 1991b; Flanagan and Nearing, 1995).[68] The main decomposition equation is:

$$B = B_p \exp(-\beta D) \quad [10.3]$$

where: B = the mass in a particular residue/dead root pool after decomposition B_p= the mass in the pool on the previous day, and D = the number of days in the period over

[68] Also, see references listed in the **Decomposition Subsection** of the **References Section**.

which decomposition is being computed, which is a single day in RUSLE2 (i.e., D = 1 day). A daily value for the coefficient β is computed from:

$$\beta = \phi[\min(W_f, T_f)] \qquad [10.4]$$

where: ϕ = a decomposition coefficient (day^{-1}) that is a function of biomass type, W_f = a moisture function, and T_f = a temperature function. Equation 10.4 is based on the assumption that decomposition on a particular day is limited by either moisture or temperature on that date.

Moisture must be present for decomposition to occur. Daily precipitation is used in RUSLE2 as an indicator of moisture available for decomposition. RUSLE2 does not compute moisture in residue/dead root pieces or in the soil that contacts residue/dead roots. Decomposition rate decreases if moisture decreases below the moisture content for optimum decomposition. RUSLE2 does not take into account reduced decomposition at excessively high moisture contents. Daily values for the moisture function W_f are computed from:

$$W_f = (P+I)/P_b \quad if[(P+I)/P_b > 1]: W_f = 1 \qquad [10.5]$$

where: P = daily precipitation (inches), I = daily amount (inches) of water added by irrigation, and P_b = base daily precipitation (inches) at which optimum decomposition occurs. A value of 0.173 inch (4.4 mm) was determined by fitting the RUSLE2 decomposition equations to the field data identified in Table 10.2.

Decomposition also varies with temperature. Decomposition decreases as temperature decreases below 32 ^oC, the optimum temperature at which decomposition rate is maximum. Similarly, decomposition decreases as temperature increases above 32 ^oC. Daily values for the temperature function are computed from:

$$T_f = \frac{2(T+A)^2(T_o+A)^2 - (T+A)^4}{(T_o+A)^4} \quad if(T < -10): T_f = 0 \qquad [10.6]$$

where: T = daily air temperature (^oC), T_o = the optimum temperature (^oC) for decomposition (32 ^oC), and A = 8 ^oC. The value for A was set so that when air temperature becomes less than – 10 ^oC, the temperature function is set to zero.[69] The reason that the temperature function does not become zero at a higher temperature, such as near 0 ^oC, is that temperature varies between a minimum and maximum during the day and average temperature on a given day varies about the long-term average temperature for that day. Air temperature rather than soil temperature is used in the temperature

[69] An adjustment should have been made to equation 10.6 to flatten the top of the curve around the 32 ^oC temperature for maximum decomposition to account for within day and year-to-year variation in temperature about the average daily temperature used in RUSLE2. See Schomberg et al. (2002).

function because soil temperature data are not readily available for use in RUSLE2. Like precipitation, air temperature is an indicator variable rather than the actual temperature that the decomposing material experiences. Values for the RUSLE2 decomposition coefficient ϕ differ from values for decomposition coefficient in similar equations used in other erosion prediction models such as WEPP (Stott et al., 1995), WEPS (Steiner et al., 1995), and RWEQ (Schomberg and Steiner, 1997).

The RUSLE2 composition coefficient ϕ can be expressed in terms of residue half life, which is defined as the time required for half of the residue mass to decompose at optimum temperature and moisture (i.e., $W_f = 1$ and $T_f = 1$). The relation of residue half life $D_{1/2}$ to the decomposition coefficient ϕ is given by:

$$D_{1/2} = -\ln(0.5)/\phi \qquad [10.7]$$

where: $D_{1/2}$ = residue half life (days) and ln(0.5) = 0.693.

The same decomposition coefficient ϕ values and moisture (W_f) and temperature (T_f) functions are used in RUSLE2 for buried and surface residue and dead roots (see **Section 10.3.3** for discussion of the reasons for this decision). Also, RUSLE2 decomposition coefficient ϕ values and the W_f and T_f functions are assumed not to vary with depth in the soil, soil texture, soil management, or residue mass. The same W_f and T_f functions are used to estimate decomposition of standing residue, but the RUSLE2 decomposition coefficient ϕ value for standing residue is 0.3 of that for surface and buried residue because moisture available for decomposition of standing residue is assumed to be much less than moisture available for decomposition of surface and buried residue (Douglas et al., 1980; Ghidey and Alberts, 1993; Steiner et al., 1994) (see **Section 10.3.3** for discussion of the reasons for this decision).

10.3.2. Calibration of equations

Values for the daily base precipitation P_b in equation 10.5 and values for the decomposition coefficient ϕ were determined by fitting the decomposition equations to measured data. Resulting P_b and ϕ values are given in Table 10.2.

The decomposition equations were fitted to the field data using daily average precipitation and temperature values disaggregated (see **Section 3.1**) from long term average monthly precipitation and temperature rather than actual precipitation and temperature values. Using long term-averages in these computations had a smoothing effect. Also, RUSLE2 uses average daily precipitation regardless of whether precipitation actually occurs, and thus values determined for P_b and ϕ are a function of RUSLE2's mathematical structure. Furthermore, the RUSLE2 purpose is to

Table 10.2. Values for P_b and Φ determined by fitting decomposition equations to measured data

Location	Crop	Daily precipition above which W_f = 1 P_b (mm)	Decompo sition coefficient Φ (day^{-1})	Placement	Refere nce
Columbia, MO	corn	4.4 assumed	0.016	buried, in bags	(1)
Columbia, MO	corn	4.4 assumed	0.010	surface, in bags	(1)
Columbia, MO	corn	4.4 assumed	0.010	buried, in bags	(2)
W. Lafayette, IN	corn, conventio nal till	4.4 assumed	0.016	surface, determined from surface samples removed from plots, not in bags	(3)
W. Lafayette, IN	corn, no-till	4.4 assumed	0.016	same	(3)
Treynor, IA	corn, till plant	4.4 assumed	0.011	same	(4)
Bushland, Tx	corn	4.4 assumed	0.006	surface, in bags	(5)
Columbia, MO	soybeans	3.6	0.029	buried, in bags	(2)
W. Lafayette, IN	soybeans	4.4 assumed	0.025	surface, determined from surface samples removed from plots, not in bags	(3)
W. Lafayette, IN	soybeans	4.4 assumed	0.025	same	(3)
Griffin, GA	soybeans	4.4 assumed	0.025	same	(5)
Holly Springs, MS	soybeans	10.0	0.015	estimated from measured portion of soil surface covered and mass-cover equations	(6)
Holly Springs, MS	soybeans	2.7	0.013	same	(6)

Table 10.2. Values for P_b and Φ determined by fitting decomposition equations to measured data (continued)

Location	Crop	Daily precipition above which W_f = 1 P_b (mm)	Decomposition coefficient Φ (day^{-1})	Placement	Reference
W. Lafayette, IN	wheat	4.2	0.0064	surface, determined from surface samples removed from plots, not in bags	(7)
W. Lafayette, IN	wheat	4.4	0.008	same	(7)
Bushland, TX	wheat	3.7	0.0081	same	(7)
Bushland, TX	wheat	4.4	0.008	same	(7)
Griffin, GA	wheat	4.4 assumed	0.008	same	(5)
Twin Falls, ID	wheat	1.8	0.012	buried, in bags	(8)
Twin Falls, ID	wheat	4.4 assumed	0.021	same	(8)
Pullman, WA	wheat	0.5	0.0099	surface, determined from surface samples removed from plots, not in bags	(7)
Pullman, WA	wheat	0.5	0.0098	same	(7)
Pullman, WA	wheat	0.5	0.0097	same	(7)
Pullman, WA	wheat	4.4 assumed	0.019	same	(7)
Pullman, WA	wheat	4.4 assumed	0.019	same	(7)
Pullman, WA	wheat	4.4 assumed	0.019	same	(7)
Holly Springs, MS	cotton	4.4 assumed	0.015	estimated from measured portion of soil surface covered and mass-cover equations	(9)
Holly Springs, MS	cotton	10.0	0.029	same	(10)
Holly Springs, MS	cotton	3.0	0.010	same	(10)
Holly Springs, MS	cotton	2.7	0.026	same	(10)
Holly Springs, MS	cotton	6.3	0.011	same	(10)
Holly Springs, MS	cotton	5.4	0.017	same	(10)
Holly Springs, MS	cotton	6.6	0.03	same	(10)
Holly Springs, MS	cotton	5.0	0.012	same	(10)

Table 10.2. Values for P_b and Φ determined by fitting decomposition equations to measured data (continued)

Location	Crop	Daily precipition above which W_f = 1 P_b (mm)	Decompo sition coefficient Φ (day^{-1})	Placement	Refere nce
Bushland, TX	grain sorghum	4.4 mm assumed	0.007	surface, in bags	(11)
Griffin, GA	alfalfa	4.4 mm assumed	0.015	surface, determined from surface samples removed from plots, not in bags	(5)
Melfort, SK	alfalfa	4.4 mm assumed	0.015	same	(12)
Akron, CO	blue stem hay	4.4 mm assumed	0.015	surface, in bags	(13)
Akron, CO	blue stem hay	4.4 mm assumed	0.015	buried, in bags	(13)
SW Australia	Eucalypt litter	4.4 mm assumed	0.002	surface, determined from samples	(14)

References:
(1) Parker (1962)
(2) Broder and Wagner (1988)
(3) Stott (1995)
(4) Alberts and Schrader (1980)
(5) Schomberg and Steiner (1997)
(6) Mutchler and Greer (1984)
(7) Stott et al. (1990)
(8) Smith and Peckenpaugh (1986)
(9) Mutchler et al. (1985)
(10) Mutchler, personal communiction
(11) Schomberg et al. (1994)
(12) Schomberg et al. (1996)
(13) Hunt (1977)
(14) Birk and Simpson (1980)

capture the main differences in decomposition between locations rather than to precisely compute decomposition as a function of soil and cover-management. Furthermore, empirical data available to calibrate RUSLE2's decomposition equations were not sufficient to empirically determine coefficient values that are functions of soil and cover-management.

The RUSLE2 decomposition equations should be calibrated with several years of data at a location for a particular residue type and placement so that the data represent the expected range of climatic conditions at that site over a 10 to 30 year period. Unfortunately, most residue decomposition studies involve only a single year. Even when only single years of data were available, the RUSLE2 average daily precipitation and temperature values were used to calibrate the RUSLE2 decomposition equations.

Data sets were assembled from as many locations for each residue type as were available. Field residue mass-area and decomposition data are highly variable. Multiple sets of data for the same residue type were used as much as possible. The RUSLE2 decomposition equations were fitted to averages of these data by residue type and location.

Calibration of the RUSLE2 decomposition equations involved fitting them to field data to determine values for the base precipitation P_b and the decomposition coefficient ϕ. The first step in the fitting was to allow both P_b and ϕ to vary. The results for some of those fittings are shown in Table 10.2 for the P_b entries other than "4.4 assumed." A consideration was whether both P_b and ϕ varied by residue type and location. Based on an inspection of the fitted P_b and ϕ values, the conclusion was that a constant value of 4.4 mm (0.173 inches) could be used for P_b for the entire US except in the Palouse region (Req region, see **Section 3.2.5**) in the Northwestern US.

The use of a constant $P_b = 4.4$ mm value also was evaluated qualitatively by making computations for numerous locations across the US for several residue types. The 4.4 mm value worked well everywhere except for the Req region where a 0.5 mm value worked better. As Table 10.2 shows for the Pullman, WA location, use of the 0.5 mm P_b value gave ϕ values of 0.01 day^{-1} for wheat residue that are comparable to 0.008 day^{-1} values determined in other parts of the country. The reason for the low P_b values in the Req region is that the soil is highly saturated during the winter months when almost all of the erosion occurs and moisture does not limit decomposition even though daily precipitation is not high. If the 4.4 mm P_b value is used in the Req region, the ϕ value for wheat is 0.017 day^{-1} rather than the 0.008 day^{-1} for other parts of the US (see **Section 10.3.3.9**).

Table 10.3. Recommended values for the decomposition coefficient Φ in RUSLE2 with A = 8 °C and P_b = 4.4 mm (0.173 inches) based on fitting decomposition equations to measured data.

Crop	Decomposition Coefficient Φ (day^{-1})
Alfalfa	0.015
Blue stem hay	0.012
Corn	0.016
Cotton	0.015
Sorghum	0.016
Soybeans (Midwest US)	0.025
Soybeans (Mid South US)	0.015
Wheat in Eastern US (soft white wheat)	0.008
Wheat in Northwest Wheat and Range Region (NWRR) (hard red wheat)	0.017

Note: If P_b = 0.5 mm, then Φ = 0.01 day^{-1} for NWRR wheat

Once the P_b value was set at 4.4 mm, the calibration was repeated where values of ϕ were determined by fitting the decomposition equations to the field data. Table 10.2 entries for the "4.4 assumed" value for P_b are where the decomposition equations were fitted to the data with the P_b value fixed at 4.4 mm. The fitted values for ϕ were inspected and the ϕ values chosen for the RUSLE Core Database are shown in Table 10.3. Figure 10.2 shows how well RUSLE2 decomposition equations fit field data using the 4.4 mm P_b value and Table 10.2 ϕ values for surface residue. Decomposition of buried residue is discussed in **Section 10.3.3.3**.

The ϕ value for the Eucalypt litter was determined using a different calibration approach from the one used to determine the ϕ values shown in Table 10.2.

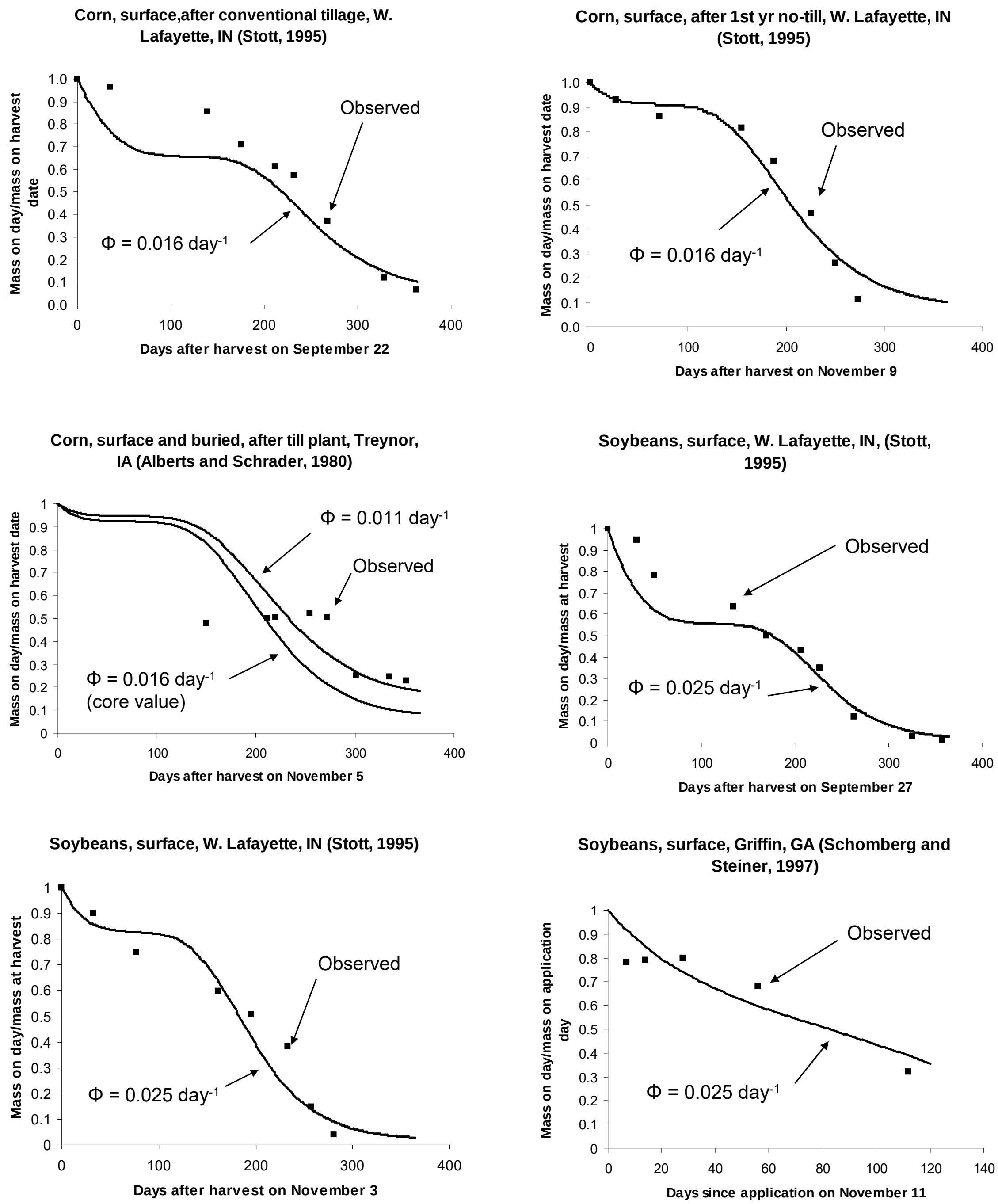

Figure 10.2. Comparison of RUSLE2 decomposition estimates using RUSLE2 Core Database values in comparison with field data.

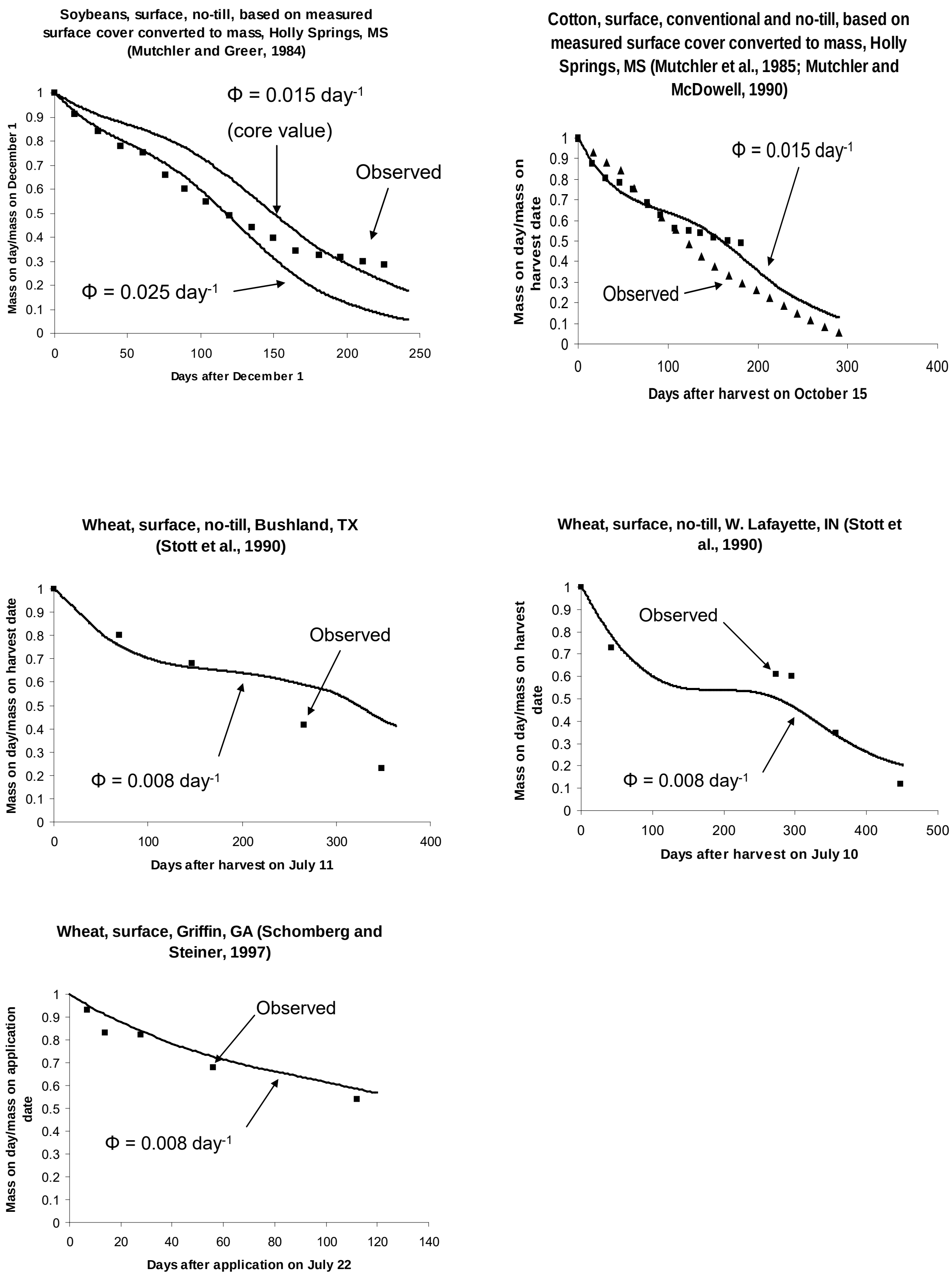

Figure 10.2. Comparison of RUSLE2 decomposition estimates using RUSLE2 Core Database values in comparison with field data. (continued)

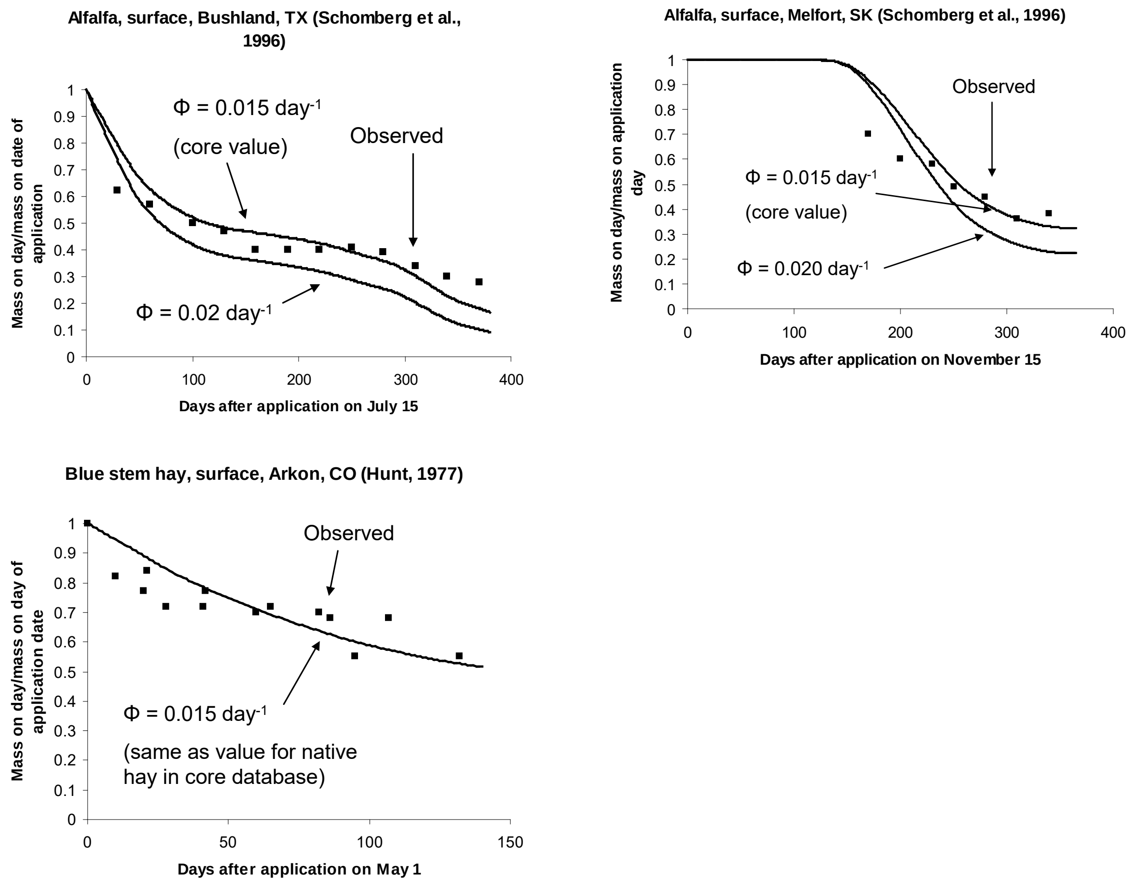

Figure 10.2. Comparison of RUSLE2 decomposition estimates using RUSLE2 Core Database values in comparison with field data. (continued)

Rather than fitting the RUSLE2 decomposition equations to the loss of residue mass over time, a ϕ value was determined for the Eucalypt litter by fitting RUSLE2 decomposition equations to an increasing residue mass over time until the mass reached a stable maximum. The Eucalypt litter data shown in Figure 10.3 are for surface residue (litter) accumulation following a forest fire in the Southwestern Australian Eucalypt forest (Birk and Simpson, 1980). This application illustrates RUSLE2's capability for computing both the accumulation of a surface litter layer where the biomass input is produced by aboveground senescence and the accumulation of a similar below ground biomass pool produced by root growth and death (root senescence, turnover).

An inspection of Figure 10.2 shows that RUSLE2 captures well the effect of location and material type on residue decomposition over time. A constant P_b value over almost all of the US works surprisingly well. Also, assuming the same ϕ value for a residue type works well for locations where climate differs greatly. For example, compare the results for alfalfa at both Griffin, Georgia and Melfort, Saskatchewan.

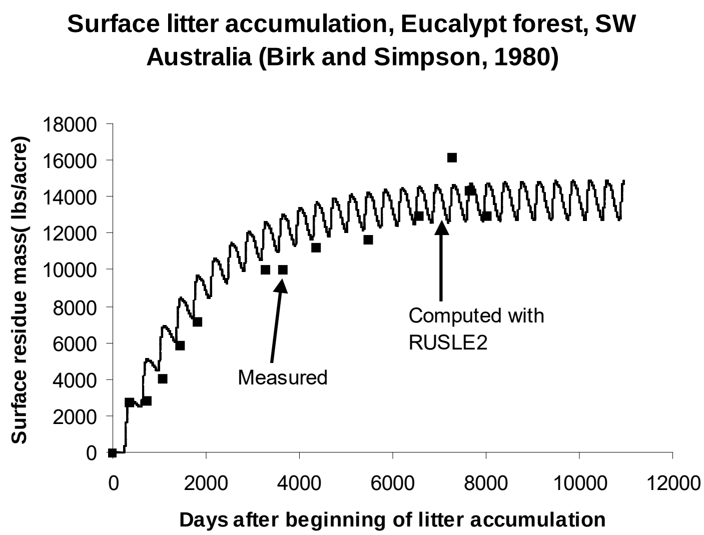

Figure 10.3. Computing the accumulation of a litter layer for an Eucalypt forest in Southwestern Australia.

An expectation is that RUSLE2 database developers can use values in the RUSLE2 Core Database to guide assignment of decomposition coefficient ϕ values for other residue types based on a comparison of residue characteristics. This procedure works but it requires more thought that initially expected. For example, a ϕ value of 0.02 day^{-1} was originally assigned for alfalfa before the ϕ value of 0.015 day^{-1} illustrated in Figure 10.2 was obtained by fitting measured field data. A ϕ value of 0.012 day^{-1} was assigned for native hay before the same ϕ value was determined by fitting measured data for the blue stem hay illustrated in Figure 10.2. The procedure of using values in the RUSLE2 Core Database as a guide in selecting decomposition coefficient values for other residue types will give reasonable RUSLE2 results for erosion control planning provided a careful comparison is made between residue types. The role of stems seems to be a major factor to consider in selecting ϕ values.

10.3.3. Basis for RUSLE2 decomposition decisions

RUSLE2's computation of residue loss is based on decomposition principles even though residue loss occurs by other processes besides decomposition. RUSLE2 is calibrated to field data representative of actual conditions as much as possible. RUSLE2 computations of residue and soil biomass loss are consistent with RUSLE2's purpose to be a **guide** to erosion control planning. Many decisions involved judgment during the formulation and calibration of RUSLE2's residue loss (decomposition) equations. This section describes the basis for those decisions.

10.3.3.1. User expectations

RUSLE2 computes residue decomposition and portion of the soil surface covered essentially using RUSLE1 procedures. Based on the RUSLE1 experience, some users will scrutinize RUSLE2's computed values for ground (surface, flat) residue cover more closely than RUSLE2's computed erosion values. RUSLE2 users are well aware of the importance of ground cover for controlling erosion. RUSLE2 users can not visually estimate erosion rates but they can visually measure ground (surface) cover. If RUSLE2's computed ground cover values do not meet their expectations, they assume that RUSLE2's erosion computations must also be wrong, which is often a false assumption.

Surface residue cover is a major variable used in judging the adequacy of cropland erosion control measures. USDA-Natural Resources Conservation Service (NRCS) standards and specifications for certain conservation practices require a minimum surface residue cover at planting (e.g., 30 percent). The RUSLE2 decomposition procedures were carefully constructed to ensure that RUSLE2 computes appropriate surface residue cover values for conservation planning, as demonstrated by the values shown in Table 10.1. The RUSLE2 decomposition procedures were designed specifically for RUSLE2's use as a conservation planning tool, not for residue management and certainly not to advance residue decomposition science and modeling. The RUSLE2 intent is to capture main differences in loss of residue/dead roots between material types and locations in the context of estimating average annual erosion rates for comparison against a criteria such as the USDA-NRCS soil loss tolerance (T) values (Toy et al., 2002).

While RUSLE2 users can easily measure residue cover, which they can compare with RUSLE2 computed values, they must exercise great caution in their measurements and evaluations of RUSLE2's adequacy for computing residue cover and corresponding erosion estimates. Residue mass-cover data are highly variable as illustrated in Figure 10.1. The cotton data in Table 10.2 illustrates the variability in decomposition data among multiple data sets collected under near identical conditions for the same residue type. Making a few field measurements is not the proper way to evaluate RUSLE2's computed residue cover values. The RUSLE2 User's Reference Guide provides information on how to adjust RUSLE2 inputs to obtain particular RUSLE2 computed residue cover values.

10.3.3.2. Residue sampling method

RUSLE2's computation of residue loss is based on dry mass, which requires field measurements of residue mass over time are needed to calibrate RUSLE2. The mesh bag and the "grab" sample are the two techniques used most often to determine surface residue mass in decomposition experiments. The mesh bag method involves inserting residue in a mesh bag and placing the bag on the soil surface or in the soil. The grab sample method involves removing amd unconfined residue from a sample area. Each method has significant drawbacks (Dabney, 2005).

The residue loss measured by the mesh bag method is a function of mesh size (Dabney, 2005). The mesh bag method tends to underestimate residue loss. The residue loss determined using the common 1 mm mesh bags has to be multiplied by a factor that ranges from 1 to greater than 2 to represent the loss of unconfined residue.

Conversely, the grab sample method tends to overestimate residue loss and has its own shortcomings including the difficulty of removing soil particles attached to the residue. Another difficulty is retrieving the entire residue from the sample area because fragile residue pieces can be broken and not recovered.

The difference in measured residue loss by sampling methods is very significant as illustrated in Figure 10.4. Using the RUSLE2 Core Database values, RUSLE2 computes that a 150 bu/acre corn crop produces 8200 lb/acre of residue. The corn residue mass remaining after 12 months at Bushland, Texas measured by the bag method would be 4100 lbs/acre (Schomberg et al., 1995, 1997) (see Figure 10.4). The percent soil surface cover provided by this residue mass is 79 percent and the ground cover subfactor value computed with equation 6.6 is 0.042.

The RUSLE2 decomposition equations were fitted to corn residue loss at W. Lafayette, Indiana measured using the grab sample method (Stott, 1995). The RUSLE2 computed value for residue mass remaining after 12 months using climate data for Bushland, Texas is 1480 lbs/acre. The percent soil surface cover provided by this residue mass is 43 percent and the ground cover subfactor value is 0.18, which is four times the value based on mesh bag measurements. Consequently, RUSLE2 computes greatly different erosion estimates depending on which set of data is used to calibrate RUSLE2's residue loss (decomposition) equations.

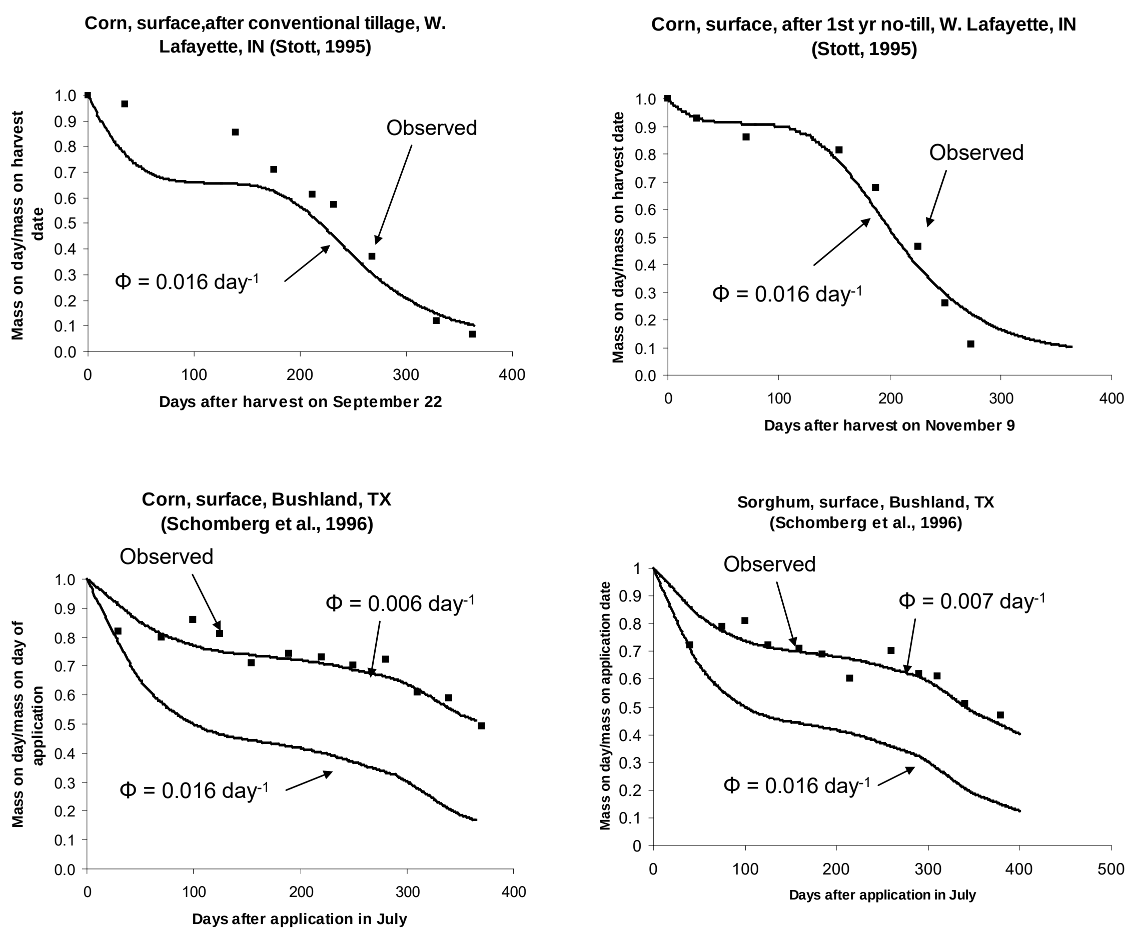

Figure 10.4. Comparison of observed and RUSLE2 computed decomposition of corn residue at W. Lafayette, Indiana and corn and sorghum residue at Bushland, Texas.

The difference in the measured Bushland, Texas data for corn and the RUSLE2 computed values based on a calibration to corn data measured at W. Lafayette, Indiana is not attributable to the RUSLE decomposition equations not performing equally well at the two locations. When wheat straw decomposition was measured by grab sampling from the soil surface (Stott et al., 1990; Stott, 1995; Stenier et al., 1999), measured decomposition at Bushland, Texas was consistent with data collected at W. Lafayette, Indiana and the RUSLE2 decomposition equations performed equally well at both locations (see Figure 10.2).

The difference in measured residue loss between the mesh bag and the grab sampling method is too large too ignore, which required a choice of one sampling method over the other. The grab sampling method was chosen for the development of RUSLE2. The conditions represented by this method, including the loss of residue by wind and other processes besides decomposition, better represent actual field conditions than does the mesh bag method. The differences between the two sampling methods seemed to be greatest for corn and wheat and much less for soybeans and forage crops. Decomposition coefficient ϕ values were determined for corn and wheat from the grab sample method while decomposition coefficient values were determined for forage crops from the mesh bag method.

Surface residue cover data were used to determine decomposition coefficient ϕ values for cotton and soybeans at Holly Springs, Mississippi. These data are field measured values for ground cover, which are the values most important in computing the effect of surface residue on rill-interrill erosion. These field data were considered to be superior to residue loss data measured with the mesh bag method.

The RUSLE2 decomposition coefficient ϕ value determined for corn is assumed to apply to grain sorghum based on the similarity in decomposition of corn and sorghum residue measured at Bushland, Texas by the mesh bag method. While the absolute decomposition values determined by the mesh bag method are not considered acceptable for RUSLE2 use, the mesh bag method is useful for determining relative differences in decomposition among residue types.

Other experimental procedures besides use of the mesh bag can affect decomposition results. The Ghidey and Alberts (1993) dataset includes decomposition values for roots and buried, surface, and above surface residue. Their data differ significantly from data considered best for RUSLE2 as illustrated in Figure 10.5. Oven drying the residue at 65 ^{o}C for 24 hours before placing the residue in the field may have contributed to the differences illustrated in Figure 10.5 in addition to mesh bags being used to measure residue loss.

10.3.3.3. Residue placement

RUSLE2 considers three placements of residue: (1) standing above ground, (2) soil surface, and (3) buried in the soil.

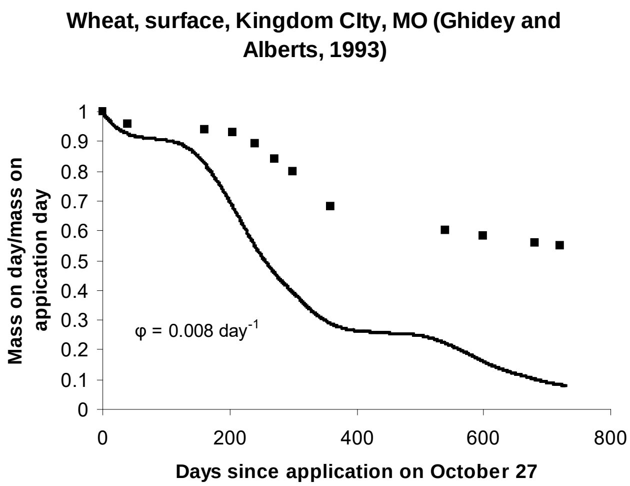

Figure 10.5. Difference in decomposition between that measured by Ghidey and Alberts (1993) and other data considered better for RUSLE2.

The RUSLE2 decomposition coefficient ϕ value used for above ground biomass is 0.3 times the ϕ value used for surface and buried residue. The decomposition coefficient ϕ value for above ground residue should be about 0.75 times the surface/buried residue ϕ value based on data collected by Douglas et al. (1980) and Ghidey and Alberts (1993). However, these data are questionable because the bundled residue samples used in these experimental studies do not represent individual pieces of standing stubble residue. Standing residue would retain much less moisture than the bundled residue samples. The 0.3 value performed satisfactorily in RUSLE2's computation of loss of standing residue (see **Section 10.4.1**)

The RUSLE2 assumption is that buried residue is lost at the same rate that soil surface residue is lost, although the common assumption is that buried residue decomposes more rapidly than does surface residue (Dabney, 2005). An example of measured data illustrating this apparent difference is shown in Figure 10.6. Like other residue aspects, the difference in decomposition rates for surface and buried residue varied greatly in the data reviewed by Dabney (2005) with no clear trend. Overall, the apparent decomposition rate for buried residue, regardless of residue type, was 1.3 times the decomposition rate of surface residue. Additional adjustment is required to obtain decomposition estimates of unconfined residue because the mesh bag sampling method was used in 10 out of 12 studies reviewed by Dabney (2005).

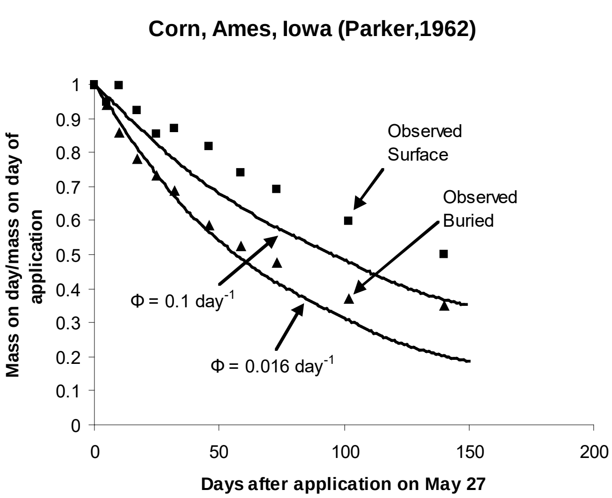

Figure 10.6. Difference in decomposition of residue in bags buried in the soil and placed on the soil surface.

Just as discussed in **Section 10.3.3.2** for surface residue, an adjustment also must be made for the mesh size effect on measured buried residue decomposition.

Instead of multiplying the mesh bag measured residue loss by 2 to obtain an estimate of unconfined surface residue loss, the measured mesh bag buried residue loss should be multiplied by 1.3 to estimate unconfined buried residue loss. Assume that the mesh bag measured surface residue loss is 1000 lbs/acre. The estimated actual loss is 2·1000 = 2000 lbs/acre. The measured mesh bag loss for buried residue is 1.3·1000 = 1300 lbs/acre based on the data reviewed by Dabney (2005), where the 1.3 factor accounts for the apparent higher decomposition rate for buried residue than for surface residue. Next, the 1300 value needs to be multiplied by the 1.3 factor to account for mesh bags underestimating the loss of unconfined buried residue. The buried residue loss of unconfined residue is therefore 1.3·1300 = 1700 lbs/acre. Consequently, these computations show that surface residue is lost at a greater rate (2000 lbs/acre versus 1700 lbs/acre) than is buried residue when the different effect of mesh size on decomposition of surface and buried residue is properly considered. The problem with these computations and with the mesh bag sampling method is the uncertainty involved in adjusting for mesh size and other factors related to how well decomposition in mesh bags represents actual field conditions.

The RUSLE2 intent is not to capture soil differences or placement within soil differences because RUSLE2 does not use soil moisture accounting routines. The buried residue studies cited by Dabney (2005) involved residue mesh bags placed 6 inches deep, which only partly simulates residue burial with a moldboard plow. A moldboard plow distributes residue throughout the disturbed soil layer even though most of the residue is buried in the lower half of the disturbed soil depth (see **Section 8.2.5.2**). Conservation tillage tools like disks, chisel plows, and field cultivators used for primary tillage leave most of the residue in the upper half of the disturbed soil depth (see **Section 8.2.5.2**), which residue buried at six inches does not represent. Furthermore, RUSLE2 uses the residue mass buried in the upper two or three inches to compute the effect of buried residue on erosion (see **Section 6.5**). The soil is drier at this shallow depth than at the six-inch measurement depth, and thus decomposition in this surface layer would be more like decomposition of surface residue than decomposition of residue buried at six inches. Therefore, mesh residue bags buried six inches deep do not represent typical field conditions.

Similarly, the placement of residue filled mesh bags on the soil surface does not represent typical field conditions. As Parker (1962) noted, a distinct boundary between surface residue and the soil surface does not exist in many cropland situations. For example, many residue pieces are both partially buried and exposed in conventional and mulch-till forms of cropping systems where tillage buries a portion of the residue left from the previous year's harvest. Soil splash by raindrop impact and local deposition behind residue pieces bonds the residue to the soil (Brenneman and Laflen, 1982; Toy et al., 2002). Also, the boundary between residue and the soil is not distinct in long-term no-till cropping systems. These effects are not captured by mesh bags placed on the soil surface.

The RUSLE2 objective is to produce reliable erosion estimates for conservation and erosion control planning. Increasing RUSLE2's decomposition rate for buried residue would not improve its erosion estimates but in fact would degrade them. The RUSLE2 computed ratio of erosion during the seedbed period for cropland going from turned sod to conventionally tilled 112 bu/ac yield corn to erosion for the same yield corn continuously cropped is 0.42, whereas the observed value is 0.40 [Table 5-D. AH537 (Wischmeier and Smith, 1978)].[70] However, the RUSLE2 computed ratio value is 0.95 for the second year while the observed value is 0.85. RUSLE2 computes this residual effect from turned sod using buried residue and dead root biomass values in equations 6.48 and 6.49. The first year erosion ratio value is computed well as a function of soil biomass before significant soil biomass loss by decomposition is computed. The fact that an accurate erosion ratio value is computed for the first year indicates that RUSLE2 is computing the proper effect of soil biomass when the estimated soil biomass is accurate. However, the fact that RUSLE2 computes too little soil biomass effect the second year indicates that RUSLE2 is computing too little soil biomass and a corresponding erosion that is too high. Consequently, increasing the decomposition coefficient ϕ value to represent buried residue decomposing more rapidly than surface residue will further degrade RUSLE2's performance for computing the effect of soil biomass.

These RUSLE2 erosion ratio values were computed using a decomposition coefficient ϕ value of 0.0017 day^{-1} for permanent grass vegetation residue. This decomposition coefficient value was originally selected based on comparison with other decomposition coefficient values in the RUSLE2 Core Database. However, recent analysis shown in Figure 10.2 for the blue stem hay shows that 0.012 day^{-1} is an appropriate value for decomposition coefficient ϕ value for blue stem hay. The erosion ratios computed with this ϕ value are now 0.36 compared to the observed 0.4 for the first year and 0.84 compared to the 0.85 observed for the second year, which is a significant improvement.

These results illustrate that the greater requirement is to accurately capture main effects before trying to capture minor effects. No basis exists for RUSLE2 computing decomposition of buried residue at a faster rate than surface residue. The RUSLE2 assumption that surface and buried residue decomposes at the same rate is strongly supported by both data, consideration of actual field conditions, increased accuracy of computed erosion values, and increased RUSLE2 robustness.

10.3.3.4. Roots

Fine roots are the most important roots in RUSLE2. A reasonable assumption is that the decomposition of fine roots is the same as buried residue. This assumption may need

[70] In this case, conventional tillage refers to a spring moldboard plow used for primary tillage followed two weeks later with a tandem disk and harrow or a tandem disk and field cultivator for secondary tillage used to create a seedbed.

reconsideration. Having the decomposition coefficient values the same for residue and roots gives RUSLE2 increased robustness, especially until additional information is learned about the distribution of root sizes and other root properties in the soil, the birth and death of roots, and how roots affect rill-interrill erosion. The RUSLE2 intent is to empirically capture the main effect of roots as an index rather than be a full description of how roots affect erosion.

10.3.3.5. Interdependence among calibration inputs for residue

No reliable data were found where both soil biomass and erosion were measured in the same experiment. Consequently, observed values for buried residue, dead root, and live root biomass were not used to calibrate the soil biomass subfactor equations 6.48 and 6.49 (see **Section 6.5**). Instead, RUSLE2 computed values for soil biomass were used to calibrate the soil biomass subfactor equations. In addition, “observed” soil biomass subfactor values were back-calculated from observed soil loss ratio values given in Table 5, AH537 (Wischmeier, and Smith, 1978) using RUSLE2 computed subfactor values for ground cover, soil surface roughness, ridge height, and soil consolidation for the seedbed crop stage of a silt loam soil at Columbia, Missouri, the RUSLE2 reference (base) location. Equation 6.1 was rearranged to compute values for s_b, the soil biomass subfactor. Soil loss ratio values from Table 5, AH537 are substituted for c in equation 6.1. Values for the other subfactors in equation 6.1 were RUSLE2 computed for the conditions listed in Table 6.5.

This soil biomass subfactor calibration approach has several consequences. The soil biomass subfactor absorbs the error and uncertainty in the other subfactors for the calibration conditions. The seedbed crop stage is the best crop stage for calibrating the soil biomass subfactor. Calibrating the soil biomass subfactor for this crop stage minimizes errors in the other subfactors because they deviate less from unit-plot conditions for the seedbed crop stage than for any other crop stage.

The only independent cover-management input in the calibration of the soil biomass subfactor, equations 6.48 and 6.49, is crop yield. All other cover-management inputs involved in the calibration are derived from yield, RUSLE2 Core Database values, and RUSLE2 procedures such as residue loss by decomposition and redistribution of soil biomass by mechanical soil disturbance. Therefore, a change in either RUSLE2 Core Database values or a RUSLE2 procedure used to compute subfactor values involved in the soil biomass subfactor calibration invalidates the calibration. **Consequently, a change in one of these items without recalibration produces erroneous RUSLE2 computed erosion estimates**.

The RUSLE2 assumption is that buried residue and dead roots decompose at the same rate as surface residue. This calibration approach has the advantage that it is partially self correcting if these assumptions are wrong. The empirically determined coefficient values in equations 6.48 and 6.49 compensate for erroneous soil biomass estimates used in the calibration as long as the relative values are accurate.

RUSLE2 has been developed and carefully validated to ensure that it computes the desired erosion values across the full range of conditions where RUSLE2 is expected to be used. Therefore, a change made to one RUSLE2 procedure, such as residue decomposition, requires a second change to ensure that RUSLE2 continues to compute expected erosion values.

Interdependence among RUSLE2 residue variables must be considered when changes are made so that RUSLE2 computes different ground (surface) cover values. To illustrate, What if RUSLE2 computed surface cover values seem questionable (see the **RUSLE2 User's Reference Guide** for additional discussion)? What RUSLE2 variable should be changed to improve surface cover estimates? The first step is to ensure that the data or observations being used as the basis for a change represent main effects rather than a minor effect or unexplained variability that RUSLE2 is not designed to capture.

The next step is to assess RUSLE2's computed erosion estimates to determine if these values should be changed along with the change in surface cover values. RUSLE2 was calibrated to give expected erosion estimates with an assumed set of values. A difference between an observed surface cover value and a RUSLE2 computed surface cover value does not necessarily mean that RUSLE2 is computing erroneous erosion estimates. What evidence, other than surface cover values, shows that RUSLE2 erosion estimates also need changing? An independence assessment should be made to determine if different erosion values should also be computed.

Changing decomposition coefficient ϕ values changes RUSLE2 computed surface cover values, but changing ϕ values also affects RUSLE2 computed soil biomass values and even soil surface roughness values that are a function of soil biomass. Therefore, a change in a ϕ value affects erosion in more ways than just changing surface cover. The question that should be asked before changing a ϕ value is: What evidence indicates that different soil biomass values should be computed along with different surface cover values?

Another way to change RUSLE2 computed surface cover values is to change above ground biomass as a function of yield. In addition to changing surface cover values, this change also affects soil biomass and soil surface roughness values. Once again, RUSLE2 computed erosion values are affected by changes in other variables besides surface cover.

The simplest way to change RUSLE2 computed surface cover values is to change surface residue mass-cover input values in the residue description (i.e., values for α in equation 10.1). Changing this relationship directly changes surface cover without changing other residue variables that affect erosion.

RUSLE2 changes should be carefully thought out to avoid unintended consequences.

10.3.3.6. Dealing with multiple component residue descriptions

A single RUSLE2 residue description is assigned to each vegetation description. A residue description represents a composite of the residue components produced by the particular vegetation.

Residue produced by vegetation includes: (1) pieces having a wide range in geometry that affect decomposition (e.g., fine and coarse roots and stems); (2) multiple components (e.g. leaves, stems, seed pods, and chaff); (3) variation in composition within a component (e.g., corn stalks having decomposition resistant exterior shells and easily decomposed interior material); (4) components, especially stems, that decompose from the inside out without changing outside dimensions (e.g., wheat straw); (5) decomposition properties that vary with growth stage (e.g., tender young leaves that decompose much more rapidly than mature leaves); (6) differences between above ground and below ground plant components (e.g., leaves that decompose more rapidly than roots); and (7) multiple species within a plant community (e.g., multiple plant species on rangelands and multiple weed species on permanent, unimproved pasture lands and landfills). RUSLE2 uses a single mass-cover coefficient α and decomposition coefficient ϕ to represent residue even though residue is composed of multiple components, each having its own α and ϕ values.

Effective RUSLE2 mass-cover coefficient α and decomposition coefficient ϕ values vary temporally as the residue decomposes. Values for these coefficients are functions of the relative composition of residue components that decompose at different rates. Consequently, the assigned RUSLE2 mass-cover and decomposition coefficient values are a compromise. The result is that RUSLE2 computes decomposition rates that are too slow in the beginning and too fast at the end. However, a review of Figure 10.2 shows that a single value decomposition coefficient ϕ works satisfactorily for a year for residue produced by typical agricultural crops, especially considering the unexplained variability in residue data.

Priority was given to fitting RUSLE2 computed decomposition values to observed values within the first year after residue application. Thus, RUSLE2 most accurately estimates decomposition of the easily and rapidly decomposable portions of the residue and not the residue that remains after one year, as illustrated in Figure 10.7. Most RUSLE2 applications involve a substantial annual input of biomass from crop production or senescence by permanent vegetation, which minimizes errors in RUSLE2 decomposition estimates beyond one year after residue application.

An example of a multiple component residue is the residue produced by a cover crop bi-culture of hairy vetch and rye that is killed at corn planning time in central Illinois (Ruffo and Bollero, 2003). The hairy vetch cover crop residue component (ϕ = 0.032 day^{-1}) decomposes much more rapidly than does the rye cover crop component (ϕ = 0.017 day^{-1}).

Figure 10.8 shows RUSLE2 decomposition computations for hairy vetch and rye grown as mono-culture cover crops and a 1:1 bi-culture cover crop based on dry mass on the day that the cover crop is killed. The curve labeled “by-component” is the decomposition that should be computed for the bi-culture. The “by-component” values shown in Figure 10.8 were computed outside of RUSLE2.

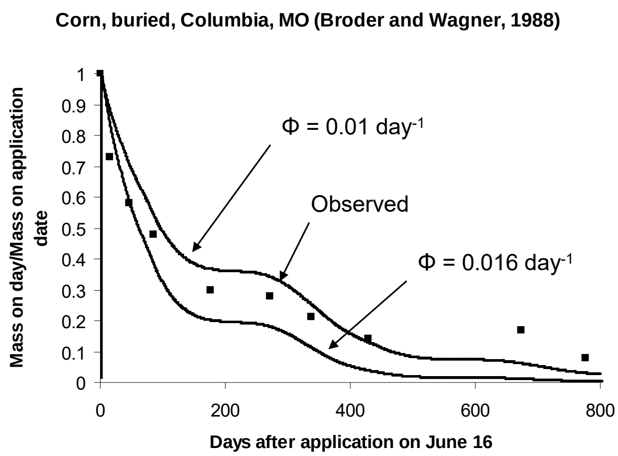

Figure 10.7. RUSLE2’s estimate of residue decomposition over a 2-year period.

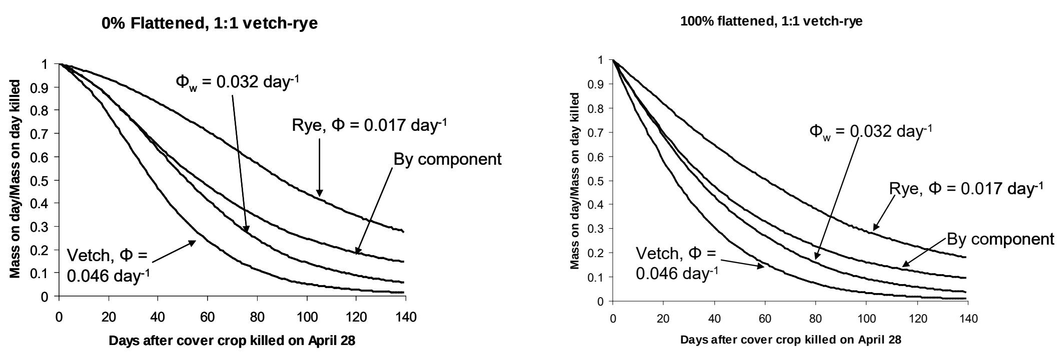

Figure 10.8. RUSLE2 computed decomposition of a 1:1 vetch-rye cover crop killed on April 28 in central Illinois. The Φ_w value is a weighted value based on dry mass on the date that the vegetation was killed.

A single value for the decomposition coefficient ϕ must be entered in the single composite RUSLE2 residue description that must be used to represent the combined residue produced by the hairy vetch and rye. One approach is to enter a weighted ϕ value based on dry mass of the hairy vetch and rye at the time that the cover crop vegetation is killed. As Figure 10.8 shows, initially RUSLE2 accurately computes decomposition but soon computes too much decomposition. The effective decomposition coefficient ϕ value should approach the ϕ value for rye over time as the hairy vetch decomposes much more rapidly than does the rye. An alternative input value for ϕ is an average of the weighted ϕ_w value at the time that the bi-culture cover crop is killed and the ϕ value for rye. RUSLE2 computes too little decomposition initially but computes much improved decomposition values after most of the vetch has decomposed.

Rather than developing a RUSLE2 procedure that adjusts the decomposition coefficient value as decomposition progresses, the best approach would be to modify RUSLE2 to accommodate multiple residue descriptions being assigned to a single vegetation description. In fact, the original RUSLE2 plan was to describe residue by its component parts. Using a residue description for each residue component would significantly improve RUSLE2's computations of residue decomposition and surface residue cover as a function of residue mass. Insufficient data existed for determining decomposition coefficient values for each plant residue component for the vast array of vegetations involved in RUSLE2 applications as a land use independent model.

The large decomposition coefficient ϕ values in Figure 10.8 for the hairy vetch and rye cover crops, 0.046 and 0.017 day^{-1}, respectively, illustrate how the decomposition coefficient ϕ is a function of crop stage. The ϕ value for mature hairy vetch residue is 0.020 day^{-1} while the ϕ value for mature rye is 0.0080 day^{-1}. The RUSLE2 decomposition coefficient values are about twice the values when the vegetation is killed as a cover crop when it is approximately half mature in comparison to the decomposition coefficient values for the vegetation after it reaches full maturity.

10.3.3.7. Effect of loading (application) rate

The decomposition coefficient ϕ seems to be a function of residue mass initially added to the soil surface as illustrated in Figures 10.9 and 10.10 (Steiner et al., 1999; Stott et al., 1990). **If initial surface residue mass affects the decomposition coefficient, the decomposition coefficient ϕ must also be a function of surface residue mass at any time after the residue is added to the soils surface.** The trend in both Figures 10.9 and 10.10 is that the decomposition coefficient ϕ decreases as surface residue mass increases. Therefore, Figure 10.9 and 10.10 imply that decomposition accelerates as surface residue mass decreases. However, this implication is inconsistent with the expectation that decomposition slows as the readily decomposable residue components disappear first, leaving the residue components that resist decomposition.

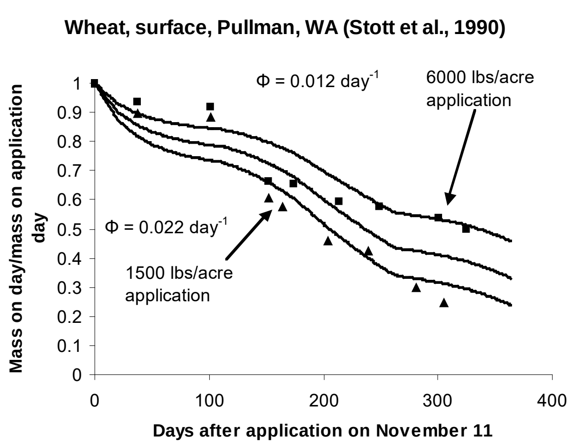

Figure 10.9. Effect of residue application rate on the decomposition coefficient ϕ.

Another concern is the great variability in decomposition coefficient values as illustrated in Figure 10.10. The RUSLE2 decomposition coefficient ϕ is proportional to the k decomposition coefficient in Figure 10.10. The comparable range in

ϕ for the range in k in Figure 10.10 for wheat straw is from 0.004 to 0.012 day^{-1}. RUSLE2 computes that 2100 and 600 lbs/acre of residue remain after 1 year for a 4000 lbs/ace wheat straw application at Columbia, Missouri for the ϕ values of 0.004 and 0.012 day^{-1}, respectively. The respective surface covers are 72 and 30 percent and the respective ground cover subfactor values, assuming **b** = 0.04 $percent^{-1}$ in equation 6.6 (see **Section 6.3**), are 0.0561 and 0.301, which is a 5:1 erosion ratio. The uncertainty in decomposition coefficient ϕ values is much greater than the variation in ϕ as a function of application rate and surface residue mass as shown in Figure 10.10, especially for residue mass less than 6000 lbs/acre (600 g/m^2).

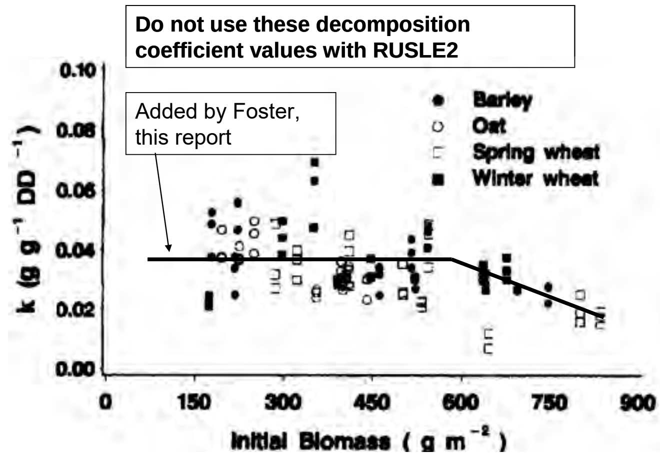

Figure 10.10. Variation of decomposition coefficient k (comparable to ϕ) values from another decomposition model with residue application rate. (Data source: Steiner et al., 1999; Line added by Foster, this report)

Furthermore, are the results illustrated in Figure 10.9 and 10.10 indicative of decomposition of the wide array of vegetation residue including vegetables, corn, wheat, hay, litter on rangelands, Eucalypt forest litter, and erosion control materials used on construction sites? Are the results illustrated in these figures indicative of application conditions that range from wheat straw being blown onto a construction site to wheat straw left in conventionally, reduced, and no-tilled fields?

The conclusion for RUSLE2 purposes is that the decomposition coefficient ϕ is not a function of residue application rate or surface residue mass. The uncertainty illustrated in Figure 10.10 reinforces the conclusion that RUSLE2 represents decomposition differences between major residue and erosion control material types, but not difference in small grain types, for example. An improvement in RUSLE2's decomposition computations can be gained by representing residue components such as legume and grasses and stems, leaves, seed pods, and chaff. Much more research is needed before the RUSLE2's decomposition coefficient ϕ can be made a function of application rate or surface residue mass. Furthermore, a standardized set of decomposition data for a wide range of materials are needed to determine RUSLE2 ϕ values.

10.3.3.8. Effect of irrigation on residue decomposition

RUSLE2's accuracy for estimating increased decomposition caused by irrigation was assessed using data reported by Schomberg et al. (1994) for decomposition of surface and buried alfalfa, wheat, and sorghum residue in mesh bags. Water varying in amounts from 5 to 336 mm was added by sprinkler irrigation during the study year in addition to 305 mm of natural precipitation. The long term average annual precipitation at Bushland, TX is 480 mm. The monthly precipitation and temperature distributions during the study are shown in Figure 10.11. Although monthly temperatures during the study were close to the long term values, the study's monthly precipitation distribution differed significantly from the long average distribution. The water added in each irrigation is given in Figure 10.12.

The objective of this analysis was to determine how well RUSLE2 computes the effect of added irrigation water on residue decomposition, not to determine decomposition coefficient ϕ values. The first step in the analysis was to adjust the decomposition coefficient ϕ value until a good fit was obtained between computed decomposition and

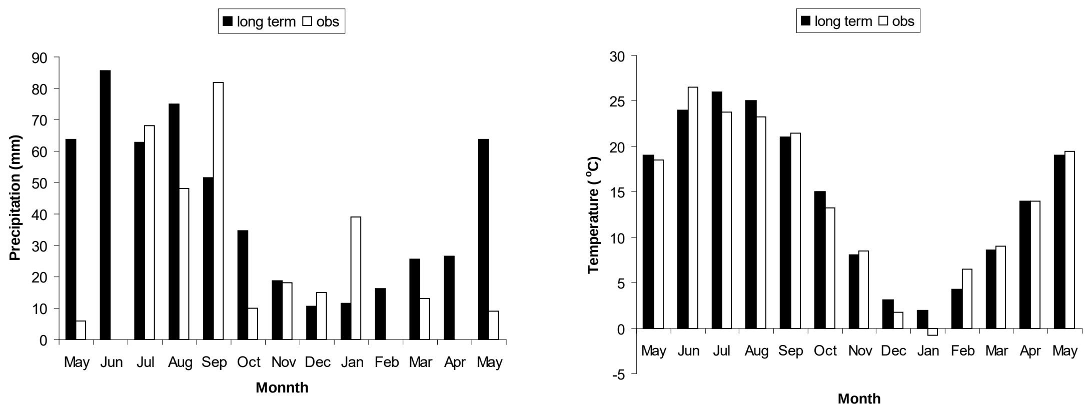

Figure 10.11. Long term average monthly precipitation (480 mm annual) and actual monthly precipitation (305 mm annual) and long term average monthly temperature and actual monthly temperature for Schomberg et al. (1994) study

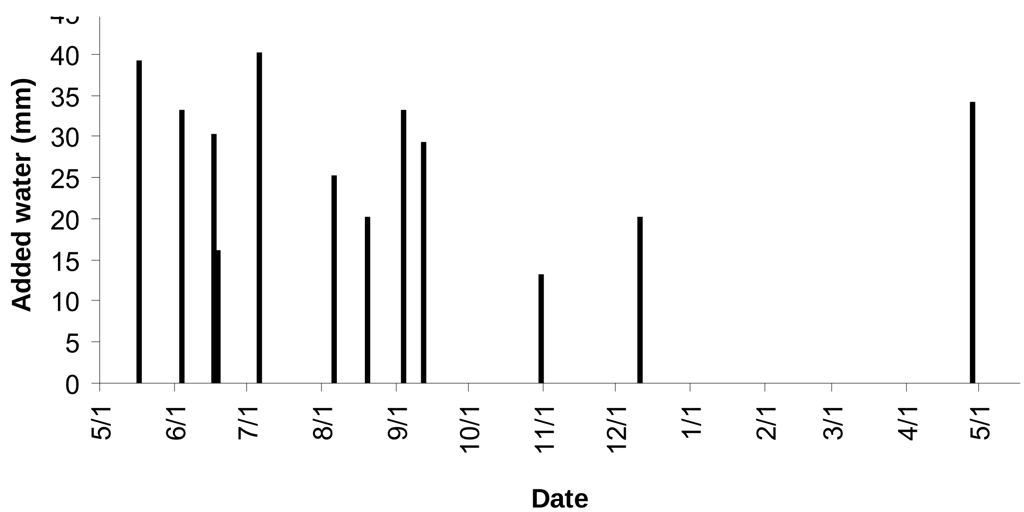

Figure 10.12. Water applied by sprinkler irrigation (total application of 336 mm) in Schomberg et al. (1994) study.

observed decomposition for the no-irrigation (only natural precipitation) condition.

Observed monthly precipitation and temperature values shown in Figure 10.11 were used in the analysis.

The decomposition coefficient ϕ value determined for natural precipitation alone was used to compute decomposition for the 305 mm natural precipitation plus 336 mm of added irrigation water distributed as shown in Figure 10.12. The results of those computations are shown in Figure 10.13.

Variability is a common problem in decomposition data. The data in Schomberg et al. (1994) study also was highly varied. For example, the fraction of surface sorghum residue remaining on December 10 was 53 percent while the fraction remaining on March 10 was 70 percent, which is an obvious error because residue mass does not increase over time. Another problem with these data is that the range in decomposition of surface residue as a function of added irrigation water is not consistent with the range in the observed data for surface sorghum and wheat residue.

As Figure 10.13 shows, the conclusion is that RUSLE2 described well how sprinkler irrigation affects decomposition of both surface and buried residue in the Schomberg et al. (1994) study. Furthermore, RUSLE2 described decomposition well for the natural

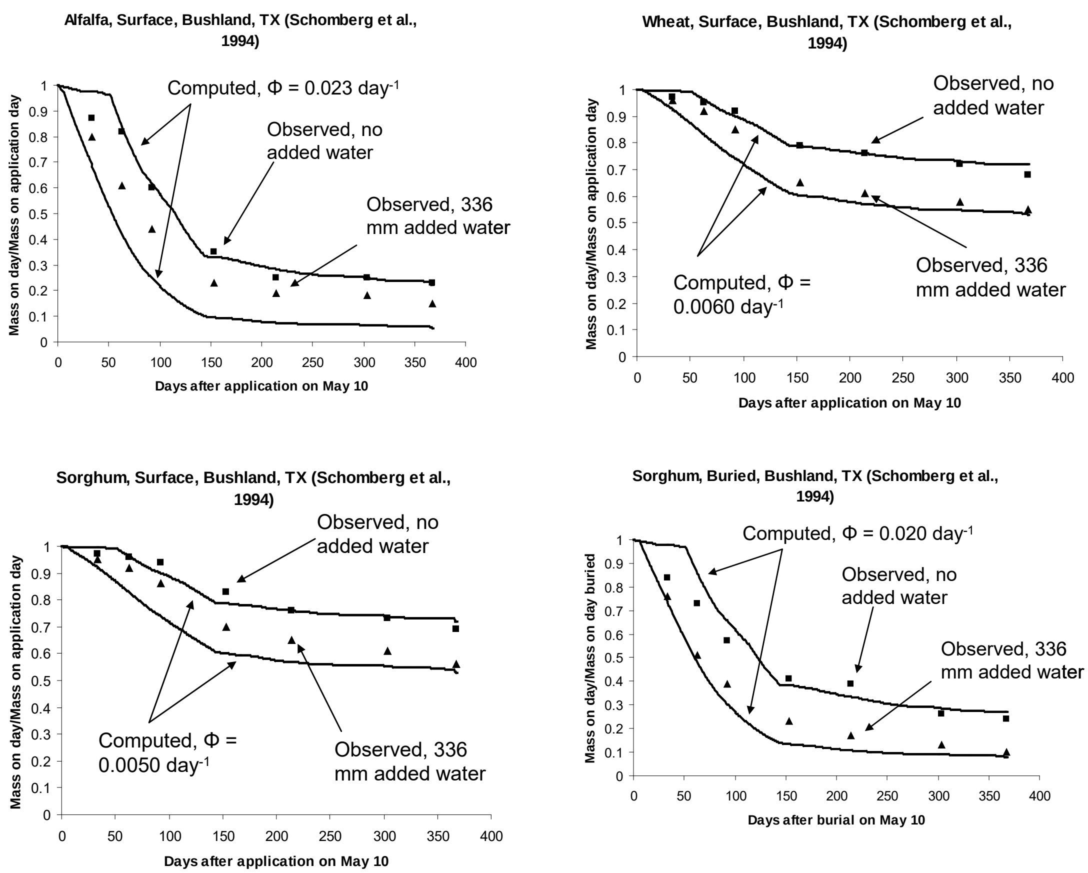

Figure 10.13. Effect of irrigation of buried and surface residue (data source: Schomberg et al., 1994)

precipitation without irrigation even though the actual monthly precipitation distribution did not vary smoothly month to month.

The Schomberg et al. (1994) data show major differences in decomposition rate between surface and buried residue. These differences seem to be a direct result of experimental procedures. That issue is discussed in detail in **Section 10.3.3.2**.

These results also show that decomposition of both surface and buried residue is a dampened process that does not react quickly to changes or irregularities in precipitation or temperature. Surface residue apparently continues to decompose longer after a water-application event that seems to have been assumed in some decomposition models (Schomberg and Steiner, 1997; Steiner et al., 1999). Decomposition of surface residue seems much more related to local soil moisture at the contact between the residue and soil than was previously considered.

An important question is whether residue decomposes the same per unit water added by irrigation as it does by unit water added by natural rainfall. Decomposition may be less per unit water applied by sprinkler irrigation than applied by natural rainfall. Water droplets in the irrigation-applied water have very low impact energy in comparison to natural rainfall. Thus, natural rainfall splashes many more soil particles that increase the contact between the soil and the residue (Foster et al., 1985a) than does sprinkler irrigation applied water. Irrigation-applied water may wash away soil particles previously bonded to the residue by rainfall. Also, deposition of sediment produced interrill-rill erosion (Brenneman and Laflen,1982) increases soil bonding between residue and soil at low residue application rates that does not occur with irrigation-applied water.

The type of irrigation should be considered in selecting irrigation inputs for RUSLE2. This decomposition analysis was based on sprinkler irrigation. The irrigation input values for sprinkler irrigation should be based on the water that actually reaches the soil. This amount can be significantly less than the amount discharged from the irrigation nozzles because of wind and evaporation losses.

Also, decomposition may be less on ridges when furrow irrigation is used than with flood irrigation on a smooth surface. Similarly, decomposition of surface residue may be reduced with drip irrigation. However, be careful in making adjustments to irrigation amounts because RUSLE2 uses the same amount in computing decomposition of both surface and buried residue. Also, RUSLE2 uses irrigation input values to compute temporal soil erodibility (see **Section 4.5**).

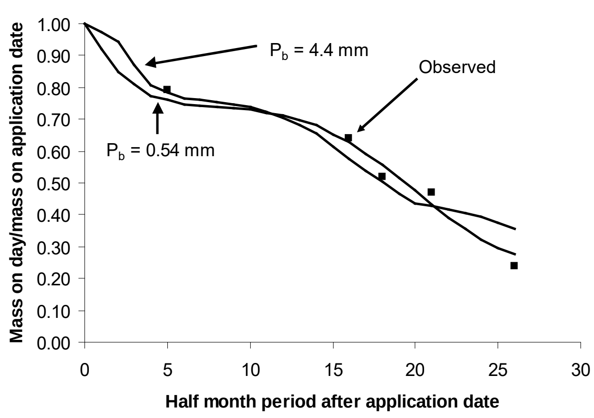

Figure 10.14. Effect of changing the base daily precipitation P_b value in the moisture function used to compute wheat straw residue decomposition at Pullman, Washington.

10.3.3.9. Special considerations for the NWRR and Req zones

The climate in the Northwest Wheat and Range Region

(NWRR), which is within the larger Req zone (see RUSLE2 User's Reference Guide), differs significantly from the climate in non-Req areas. An example is the relationship of monthly precipitation amount relative to number of precipitation events (see **Section 10.3.4.2**). Consequently, should the decomposition equations and coefficient values differ for the NWRR and the entire Req zone from those for other regions? To evaluate this possibility, the base moisture P_b value in the moisture function (W_f, equation 10.5) was determined by fitting the decomposition equations specifically to decomposition data collected at Pullman, Washington. A P_b value of 0.54 mm produced improvement for some data sets as illustrated in Figure 10.10, but not for all data sets. When 0.54 mm is used for P_b in equation10.5, RUSLE2 computes decomposition being controlled throughout the year by the temperature function (T_f, equation 10.6) at Pullman, Washington. When P_b = 4.4 mm, RUSLE2 computes that decomposition is controlled by the moisture function from May through October. Computing that decomposition is controlled by moisture when average monthly precipitation is as low as 0.45 inches (11 mm) in July and 0.64 inches (16 mm) in August seems more appropriate than the temperature function controlling decomposition during these dry months.

Decomposition coefficient ϕ values determined for wheat using P_b = 0.54 mm are essentially the same as decomposition coefficient values determined for wheat in other regions using P_b = 4.4 mm. Consequently, the difference in decomposition coefficient values in Table 10.2 between the NWRR and other regions may not be related to wheat varieties as implied in Table 10.2, but related to having an appropriate description of the moisture function W_f for the NWRR.

The recommendation is that 4.4 mm be used for P_b for the NWRR and Req zone along with the Req specific decomposition coefficient values given in Table 10.3 until additional research is conducted. This additional decomposition research for the Req zone, including the NWRR, can be conducted simultaneously with additional research needed on other RUSLE2 Req relationships throughout the Req zone, especially for locations outside of the central Washington to northern Idaho and Northeastern Oregon region.

10.3.4. Comparison of RUSLE2, RWEQ, WEPP, and WEPS decomposition

The RUSLE2 water erosion and RWEQ (Fryrear et al., 1998) wind erosion prediction technologies use comparable empirical structures involving long-term average monthly climate and management inputs and both were originally intended for conservation planning in USDA-Natural Resources Conservation Service (NRCS) field offices. The NRCS initially placed a high priority on RUSLE2 and RWEQ using the same equations and parameter values for computing residue mass values. Later the NRCS adopted WEPS (Hagan et al., 1996) instead of RWEQ for field office conservation planning. WEPS is a process-based simulation model that uses stochastic climate inputs. The comparable water erosion prediction model is WEPP (Flanagan and Nearing, 1995).

RUSLE2 and WEPS should compute comparable residue mass values because these models are being implemented by NRCS for routine conservation planning, and WEPP may be implemented in the future. Although erosion prediction clients may not know the residue mass values that these models should compute, clients readily recognize differences in values computed by the models and question differences when none should exist. Such differences reduce the creditability of the models and the conservation plans developed using them.

Decomposition estimates of surface applied residue were computed using RUSLE2, RWEQ, WEPP, and WEPS at the locations listed in Table 10.4.

Table 10.4. Locations for RWEQ, WEPP, and WEPS decomposition computations

Location	Annual precipitation (inches)	Model	Comments
Jefferson City, Missouri	37.8	All	Near Columbia, Missouri
Minneapolis, Minnesota	27.0	ALL	
W. Lafayette, Indiana	37.0	RWEQ	
Scottsbluff, Nebraska	15.1	WEPP/WEPS	
Jamestown, North Dakota	18.3	RWEQ	Used in Figure 10.19
Amarillo, Texas	20.1	RWEQ	Near Bushland, Texas
Borger, Texas	20.7	WEPP/WEPS	Near Bushland, Texas
Denton, Texas	33.1	WEPP/WEPS	
Dallas, Texas	36.0	WEPP/WEPS	
Houston, Texas	46.4	WEPP/WEPS	
Galveston, Texas	39.8	WEPP/WEPS	
Holly Springs, Mississippi	54.2	WEPP/WEPS	
Jackson, Mississippi	53.8	RWEQ	
Gulfport, Mississippi	60.0	WEPP/WEPS	
Mobile, Alabama	62.3	All	
Spokane, Washington	16.0	RWEQ	
Tucson, Arizona (Davis)	11.2	RWEQ	Davis-Monthan Air Force Base
Tucson, Arizona (Campbell)	12.4	WEPP/WEPS	University of Arizona Agricultural Experiment Station on Campbell Avenue
Albuquerque, New Mexico	9.3	RWEQ	Used in Figure 10.19

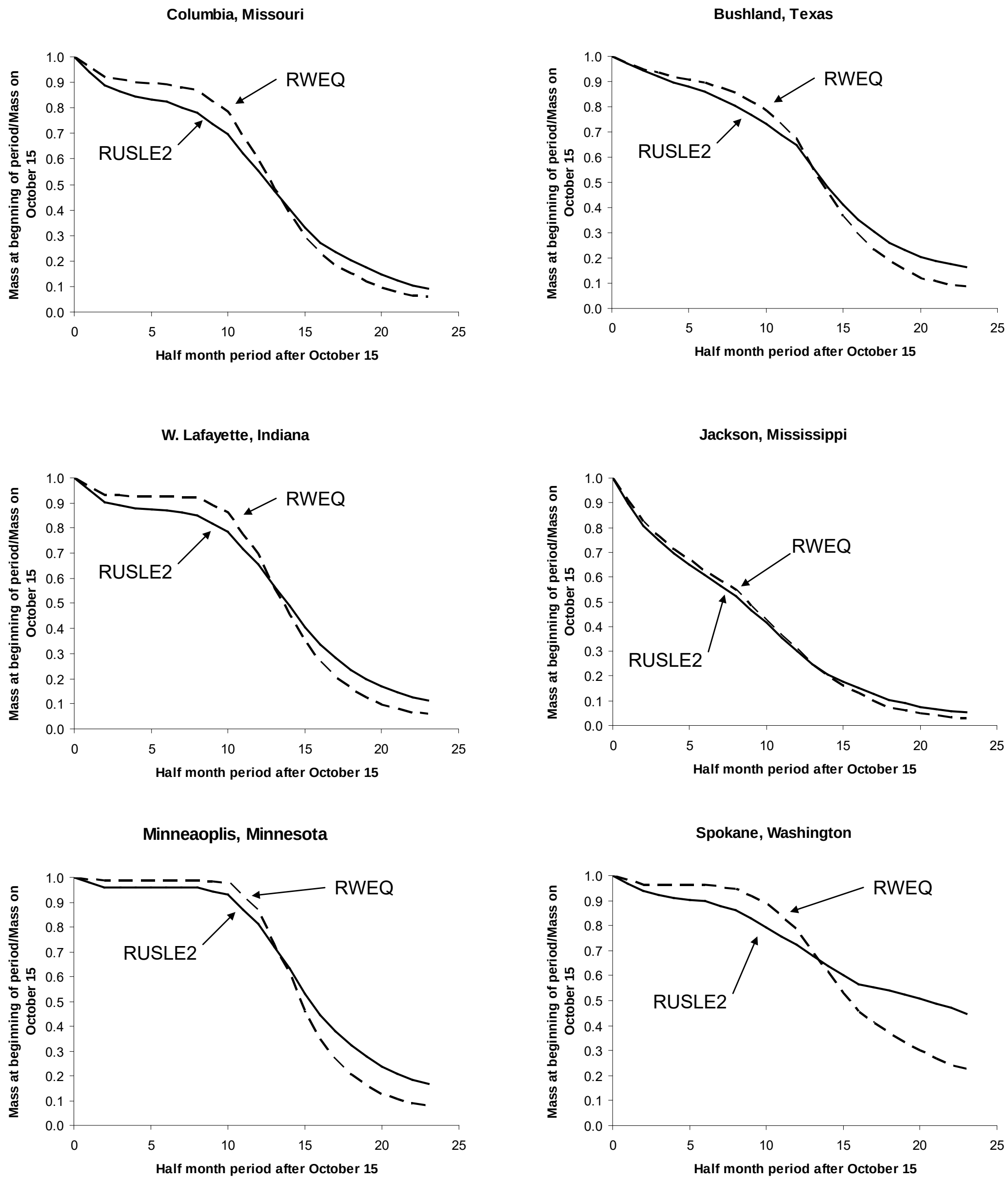

Figure 10.15. Residue decomposition computed with RUSLE2 and RWEQ

For the RWEQ computations, mulch was assumed to be surface applied on October 15 at 4500 lb/acre to a seedbed condition with no existing above ground or below ground biomass for all locations except Tucson, Arizona. The mulch was assumed to be applied on January 1 at Tucson.

The RWEQ decomposition coefficient value was adjusted to give the best fit of computed residue mass to RUSLE2 computed values at Columbia (Jefferson City), Missouri. This RWEQ decomposition coefficient value was used for all other locations, and the same RUSLE2 decomposition value was used for all locations.

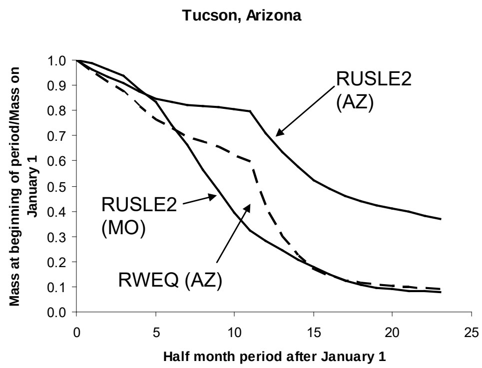

Figure 10.16. Residue decomposition computed with RUSLE2 and RWEQ at Tucson, Arizona

For the WEPP computations,[71] the same 4500 lbs/acre mulch rate was assumed to be applied on May 10, except for Tucson where the mulch was assumed to be applied on January 1. The mulch was applied to a soil that had not been tilled for a year. No above ground or below ground biomass was assumed. WEPP was run for 10 years with the same mulch amount applied each year with no soil disturbance throughout the 10 year simulation period.

WEPP computes daily residue mass for each annual mulch application. Daily computed surface residue mass for each mulch application was averaged for the 10 year simulation period. The WEPP computed residue mass values are equivalent to conducting annual experiments where the fate of mulch applied each year is determined. The WEPP computations represent each annual application placing new mulch on mulch remaining from previous years rather than mulch being applied each year to bare soil.

The RUSLE2 decomposition coefficient ϕ value was adjusted to give the best fit of RUSLE2 computed residue values to WEPP computed values for Columbia (Jefferson City), Missouri for a silt loam soil. This RUSLE2 decomposition coefficient value was used for all locations and the same WEPP decomposition coefficient value was used for the same silt loam soil for all locations.

Decomposition was computed with WEPP at the locations listed in Table 10.4. RUSLE2 computed decomposition values compared well with WEPP computed values for locations where temperature rather than moisture was the factor limiting decomposition. At locations where RUSLE2 computed that moisture limited decomposition, WEPP conputed decomposition amounts that were significantly greater than RUSLE2 computed, which was especially evident a Tucson, Arizona where the WEPP computed decomposition was essentially the same as decomposition computed at Columbia, Missouri even though average annual precipitation at Tucson as only 12 inches in comparison to 38 inches at Columbia, Missouri. Consequently, WEPP seems to be computing too much decomposition in dry locations.[72]

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[71] The WEPP version used in these computations was dated May 18, 2006, which was downloaded from the USA-ARS WEPP Internet site in April 2008. This version is the most recent version available to the public.

[72] These results have been reported to Dennis Flanagan, lead WEPP developer, USDA-Agricultural Research Service, W. Lafayette, Indiana. WEPP developers are investigating whether WEPP may be

The WEPS compuations were made using the WEPS hydrology component rather than WEPS with the WEPP hydrology component.[73] The same 4000 lbs/acre mulch rate was assumed to be annually applied on October 15 at all locations. The management practice used to make the compuations represented a soil tilled with a moldplow plow and a tandem disk that buried all of the previous year's mulch and did not resurface any buried residue. WEPS was run for 15 years. Daily surface residue mass values were averaged

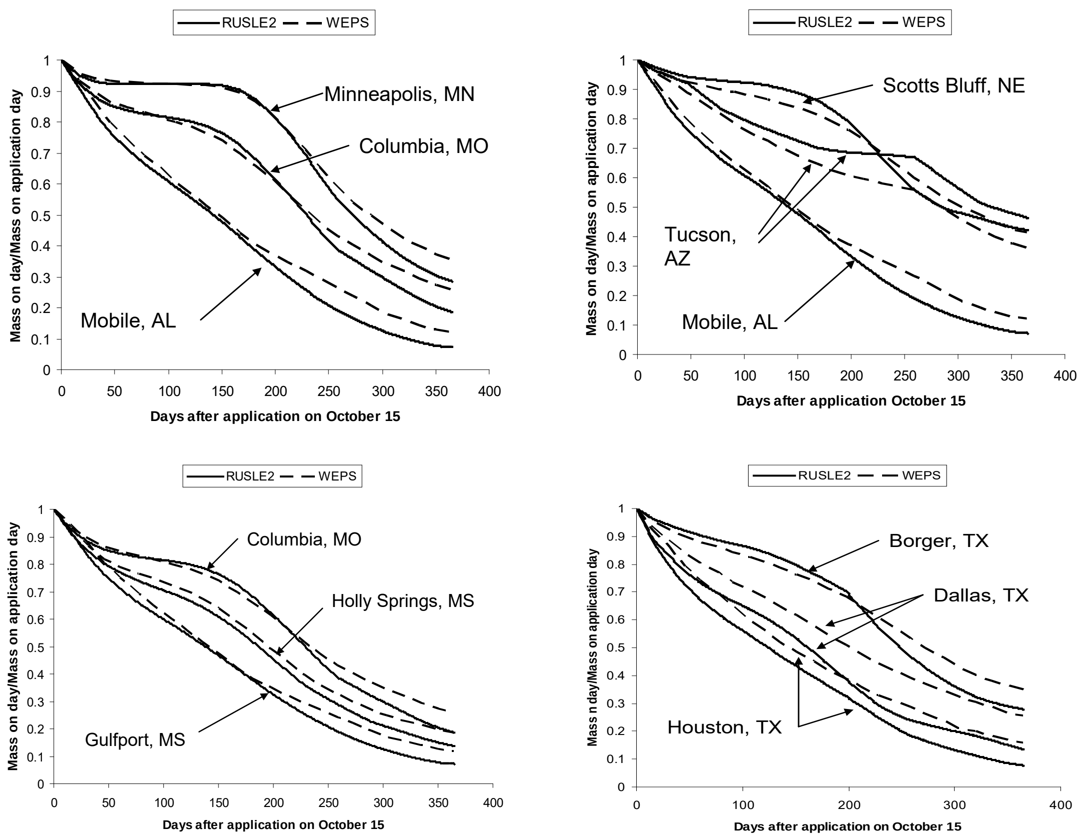

Figure 10.17. Residue decomposition computed with RUSLE2 and WEPS

for the 15 year simulation. The results are plotted in Figure 10.17.

The same WEPS decomposition coefficient value was used for all WEPS computations. The RUSLE2 decomposition coefficient ϕ value was adjusted to give the best fit of

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computing too much decomposition at Tucson and other dry locations. Possible WEPP changes may made sometime soon (May 10, 2008).

[73] The WEPS version used in these computations was dated April 14, 2006, which was provided by Larry Wagner, lead WEPS developer, USDA-Agricultural Research Service, Manhattan, Kansas.

RUSLE2 computed residue values to WEPS computed values for Columbia (Jefferson City), Missouri for the Morley silty clay loam soil. This RUSLE2 decomposition coefficient value was used for all subsequent RUSLE2 computations.

10.3.4.1. Structure of decomposition computations

All four models (RUSLE2, RWEQ, WEPP, and WEPS) use moisture and temperature functions to compute decomposition. RUSLE2, WEPS, and WEPP use equation 10.4 that takes a minimum of the moisture and temperature functions instead of the product of these functions used in RWEQ. The differences in computed decomposition resulting from the RUSLE2 minimum structure and the RWEQ product structure are illustrated in Figures 10.15 and 10.16. With the exception of the Tucson location, the consistent trend is that the product structure computes reduced decomposition during cool periods and increased decomposition during warm periods.

Using a minimum of the moisture and temperature functions was judged to be better than the product of the functions based on an inspection of Figures 10.2 and 10.15.

The minimum of the moisture and temperature functions, which is equation 10.4, is also used in WEPP and WEPS. The Gregory et al. (1985) decomposition model was originally used in RUSLE1, but it was replaced with a modification of the WEPP decomposition model (Stott, 1991; Stott et al., 1995) because the Gregory et al. model also was judged to compute too little decomposition during cool periods and too much decomposition during warm periods.

10.3.4.2. Moisture function

10.3.4.2.1. Comparison with RWEQ

RUSLE2's moisture function used to compute decomposition is given by equation 10.5. The RWEQ moisture function is given by (Fryrear et al., 1998; Schomberg and Steiner, 1997):

$$W_{fwe} = 1.25 N_p / D_p \qquad [10.8]$$

where: W_{fwe} = the RWEQ moisture function used to compute decomposition, N_p = the number of precipitation events in the period D_p (days). The Schomberg and Steiner (1997) justification for using number of precipitation events is that surface residue does not remain moist long after a precipitation event, which conceptually implies that residue moisture content following a precipitation event is independent of the event's precipitation amount, which seems questionable. The moisture retained by residue depends greatly on residue type and mass and its contact with the soil mass. Similarly, the Schomberg-Steiner assumption seems questionable for mulch-till and no-till cropping systems where the soil-residue interface is not well defined and surface residue pieces are partially covered by soil. The assumption also seems questionable during fall and spring periods when evaporation is reduced. Dew may provide a significant moisture source, even on very hot days (Heilman et al, 1992).

Decomposition was computed with RUSLE2 and RWEQ at the locations identified in Table 10.4, and the computed values are shown in Figures 10.15 and 10.16. Except for the Tucson location, the RUSLE2 and RWEQ moisture functions performed similarly. The reason for the similar performance is that number of precipitation events in a given period in the RWEQ moisture function actually serves as a surrogate for precipitation amount used in the RUSLE2 moisture function. Precipitation amount in a given period is highly correlated with number of precipitation events in the period and the relationship is essentially the same across the eastern US as shown in Figure 10.18. However, a disadvantage of the RWEQ moisture function even in this region is that number of precipitation event is more spatially varied than precipitation amount. Also, data on number of precipitation events are much less available than long term monthly precipitation values, such as those that were easily found and used to compute decomposition in Canada (see Figure 10.2) and SW Australia (see Figure 10.3).

The RUSLE2 and RWEQ decomposition estimates differ greatly for Tucson, Arizona as shown in Figure 10.16. In this figure, decomposition was computed at Columbia, Missouri with RWEQ for mulch applied on January 1, the same as for Tucson. RWEQ computed the same decomposition for both Tucson and Columbia even though annual rainfall at Tucson (Davis) was only 11 inches in comparison to 38 inches at Columbia (see Table 10.4). The reason that RWEQ computes the same decomposition at the two locations is that the number of storms is comparable for the two locations even though annual precipitation differs significantly between the locations. Similarly, the number of storms per month in relation to monthly precipitation amount is high at Spokane Washington during the cool period, which is the reason for the difference between decomposition computed by RUSLE2 and RWEQ Spokane being greater than at the other locations in Figure 10.15.

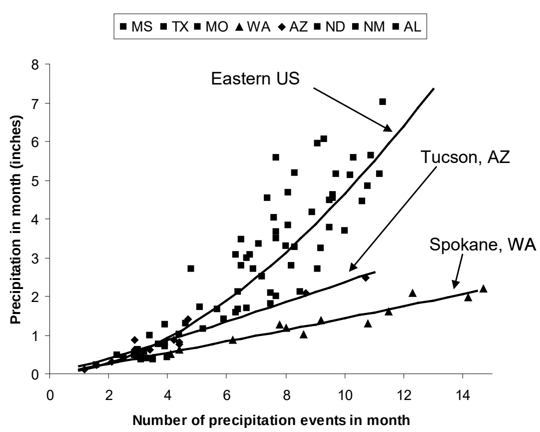

Figure 10.18. Relation of average monthly precipitation to number of precipitation events in a month.

Use of the RWEQ moisture function in RUSLE2 would require varying the decomposition coefficient value with location in the western US. This requirement is similar to the base precipitation value P_b in equation 10.5 needing to be changed so that the same RUSLE2 decomposition coefficient values can be used in the Palouse Region and in the eastern US (see **Sections 3.2.5 and 10.3.2**).

Overall, using precipitation in the RUSLE2 moisture function is judged superior to using number of precipitation events as in RWEQ. Using number of precipitation events would provide no fundamental improvement in RUSLE2's decomposition estimates. Precipitation amount appears to be superior in low precipitation regions in the western

US. Precipitation amounts are much more readily available and spatially stable than number of precipitation events in a given period.

10.3.4.2.2. Comparison with WEPP

The WEPP moisture function is given by (Stott et al., 1995):

$$W_{fwp} = \theta_t / \theta_o \quad [10.9]$$

where: W_{fwp} = the WEPP moisture function used to compute decomposition of surface residue, θ_t = water content (volume of water/volume of bulk soil)[74] of the tilled soil layer and θ_o = the optimum water content (volume water/volume of bulk soil) for decomposition. The WEPP assumption is that the optimum moisture content for decomposition is 0.6 times the soil's pore space (volume pore space/volume of bulk soil). Consequently, the decomposition computed by WEPP should be a function of soil, tillage, and other factors that affect infiltration (e.g., precipitation, soil properties, and cover-management), soil water retention (e.g., soil properties), and soil water extraction (e.g., drainage and evapo-transpiration) (Alberts et al., 1995).

The present WEPP version does not computes the same decomposition amount at Tucson, Arizona as it does in Columba, Missouri, even average annuaj precipitation at Tucson is 12 inches in comparison to 38 inches at Columbia. These WEPP computations were judged tgo be erroneous, thus further computations were not made with WEPP. Changes are anticipated in WEPP to deal with this apparent problem (May 10, 2008).

10.3.4.2.3. Comparison with WEPS

The WEPP moisture function is given by (Hagan et al., 1996):

$$W_{fws} = \theta_s / \theta_f \quad [10.10]$$

where: W_{fws} = the WEPP moisture function used to compute decomposition of surface residue, θ_s = water content (volume of water/volume of bulk soil) of the surface soil layer, which is thinner than the WEPP tilled soil layer, and θ_f = field capacity water content of the surface soil layer (volume water/volume of bulk soil), which is considered to be the optimum water content for decomposition. Soil water content in the surface soil layer is affected by precipitation, infiltration, drainage, and extraction. Consequently, WEPS decomposition should be a function of soil and cover-management.

As illustrated in Figure 10.17, RUSLE2 computed decomposition values compared well with WEPS computed values for locations where temperature rather than moisture was the factor limiting decomposition. However, a difference in trend between the RUSLE2 and WEPS compuated values was apparent at these locations where computed

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[74] Bulk soil includes the volume of both soil particles and pore space.

decomposition rates were less for WEPS than for RUSLE2 during the maximum precipitation period. WEPS computed decomposition was significantly less than RUSLE2 computed decomposition at Tucson, Arizona. RUSLE2 computed less decomposition during the dry periods at Tucson than did WEPS. WEPS computed much less decomposition than did RUSLE2 at Dallas, Texas. The distinguishing feature at Dallas is a double peaked precipitation pattern. Precipitation (≈ 2.1 inches/month) in July and August is about half the precipitation in April and May (≈ 4.6 inches) and September and October (≈ 3.6 inches/month). In contrast to Tucson where RUSLE2 computed less decomposition than did WEPS, RUSLE2 computed more decomposition at Dallas than did WEPS.

Apparently the WEPS soil moisture values are dampened more than are the RUSLE2daily precipitation values used to compute decomposition, even at locations where precipitation is moderately high and greater such as Columbia, Missouri; Holly Springs and Gulfport, Mississippi; and Mobile, Alabama. This same dampening may be responsible for the differences at Tucson and Dallas.

These differences raise questions about the adequacy of the WEPS computed soil moisture values at all locations, but especially at locations where monthly precipitation changes greatly in a short time, and how well the RUSLE2 moisture function performs in dry regions. The decomposition data illustrated in Figure 10.2 are inadequate to definively make a determination about RUSLE2's moisture function used to compute decomposition or to show whether RUSLE2 or WEPS better computes decomposition.

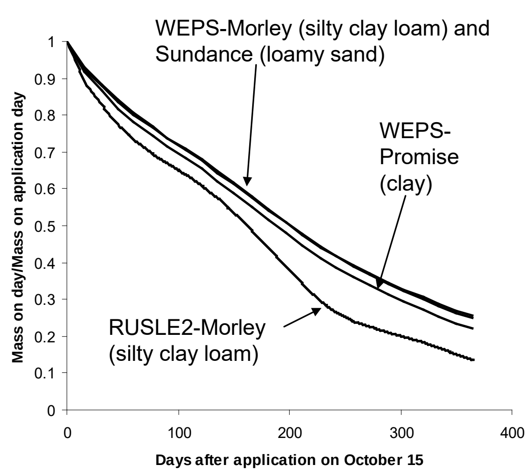

Figure 10.19. Effect of soil texture on WEPS computed decomposition at Dallas, Texas.

Figure 10.19 shows WEPS computed decomposition values for three soil textures at Dallas, Texas. The effect of soil texture on WEPS computed decomposition values are not great. RUSLE2 does not consider soil textue in its decomposition computations.

Figure 10.20 shows the effect of soil disturbance on WEPS computed decomposition. Whether the soil was only moldboard plowed or was moldboard plowed and disked had no effect on WEPS computed decomposition. However, WEPS computed increased decomposition for a soil not disturbed, which is the appropriate direction for computing decomposition for no-till farming practices.

10.3.4.3. Temperature function

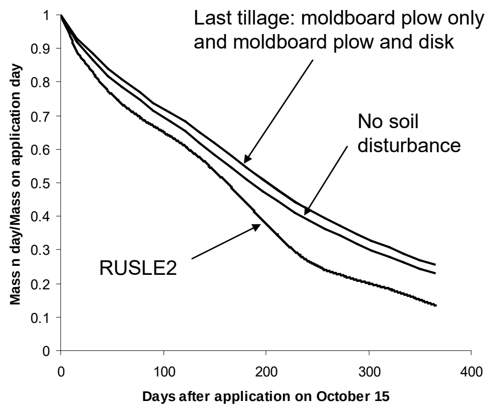

Figure 10.20. Effect of soil disturbance on WEPS computed decomposition

The same basic temperature function, equation 10.6, is used in RUSLE2, WEPP, WEPS, and RWEQ. Both RUSLE2 and WEPP compute a daily temperature function value using average daily temperature computed as the average of the maximum and minimum temperature for the day. RWEQ and WEPS compute a daily temperature function value by computing a temperature function value for both the daily maximum and minimum temperatures and averaging those two temperature function values. RUSLE2 and RWEQ use long term daily and monthly temperature values, respectively, whereas WEPP and WEPS uses stochastically generated daily temperature values.[75]

Each model uses slightly different values for the variables A and optimum temperature T_o in equation 10.6. For example, RWEQ and WEPS use A = 0 ^oC whereas RUSLE2 uses A = - 8 ^oC to compensate for using long-term average daily temperature in RUSLE2. RUSLE2 computes decomposition for a long term average daily temperature as low as -10 ^oC. In WEPP, A = -6.1 ^oC, which compensates for use of daily average temperature in computing a daily temperature function value. The optimum temperature value use in RUSLE2, RWEQ, and WEPS is 32 ^oC while 33 ^oC is used in WEPP.

RUSLE2 and WEPP compute almost identical long term average decomposition for conditions where the temperature function entirely controls rather than the moisture function. Little of the differences between RUSLE2 and WEPS in Figure 10.17 appear to be caused by differences in the temperature functions used to compute decomposition.

The RWEQ/WEPP temperature function approach is superior at high temperatures to the RUSLE2 approach. Flattening the temperature function around the optimum temperature, T_o in equation 10.6 would improve the RUSLE2 temperature function. The best approach would be to replace the RUSLE2 temperature function as described by Schomberg et al. (2002).

The end result is that RUSLE2 computed temperature function values at high temperatures were not a significant factor in fitting the measured decomposition data illustrated in Figure 10.2. In each case, the moisture function was limiting rather than the temperature function when temperatures were high. At low temperatures, the

[75] The RUSLE2 input is long term average monthly that RUSLE2 disaggreagtes into daily temperatures.

temperature function was limiting, where RUSLE2's temperature function is judged adequate.

Schomberg et al. (2002) found no improvement in the fit of RUSLE2 computed decomposition to measured data with their improved temperature function. However, their new temperature function required a decomposition coefficient ϕ value of 0.0048 day^{-1} in comparison to 0.0041 day^{-1} for the temperature function described by equation 10.6. Thus, decomposition coefficient values are moisture and temperature function dependent and model dependent in other ways including how soil moisture is computed for example.

10.3.4.4. Summary comments on RUSLE2 decomposition computations

For RUSLE2, WEPS, WEPP to give comparable long term surface residue cover estimates, decomposition data that best represents field conditions must be identified and used to calibrate all these models.

The RUSLE2 decomposition equations use simple inputs so that RUSLE2 is convenient for use in conservation and erosion control planning. The RUSLE2 purpose is not to accurately model residue decomposition processes in a research context. RUSLE2 users must be aware of RUSLE2 procedures and how to select RUSLE2 inputs to best represent residue for each particular application. Input values described in the RUSE2 User's Reference Guide and in the RUSLE2 Core Database were chosen to ensure that RUSLE2 is adequate for conservation and erosion control planning. RUSLE2 is a complex procedure that involves many mathematical relationships with numerous interactions. Input values must be carefully selected to avoid RUSLE2 computing erroneous erosion values when adjusting RUSLE2 inputs to obtain a desired value for a particular variable such as the portion of the soil surface covered by residue. Avoid changing a single variable such as the decomposition coefficient so that RUSLE2 computes an expected surface residue cover immediately before harvest.

The RUSLE2 decomposition procedures are better than those in RWEQ, a comparable model for wind erosion. Also, RUSLE2 computes decomposition values that are comparable to those computed by WEPS and WEPP, process-based models for wind and water erosion, respectively, when all three models are calibrated to the same data. The soil moisture computations in both WEPS and WEPP should be reveiwed for dry regions and regions when monthly precipitation is double peaked. Decomposition values computed by WEPS do not appear to vary much with soil texture or soil disturbance. Conquently, decomposition computed by RUSELE2 will not differ significantly from the values computed for WEPS when soil and cover-management vary at a location. Advantages of RUSLE2 are that it is robust, uses simple inputs, gives good results, and is easy to use, important attributes for its intended purpose of guiding conservation and erosion control in local field offices.

The RUSLE2 User's Reference Guide describes steps that should be observed in adjusting RUSLE2 input related to values computed for soil surface residue covered.

10.4. Standing residue

10.4.1. Decomposition

Certain operations convert live vegetation to standing residue (see **Section 8**). A portion of the standing residue is assumed to fall each day and become surface residue. Also, standing residue decomposes daily. This decomposition is computed using equations 10.3-10.6 but with a decomposition coefficient ϕ value that is 0.3 of that used to compute surface residue decomposition because reduced moisture is available for decomposition of standing residue.

RUSLE2 computes the decomposition of a unit stem mass assumed to represent decomposition at the base of standing residue stems. This decomposition is computed using equations 10.3 - 10.6 and the same decomposition coefficient ϕ value used to compute surface residue decomposition. That is, decomposition at the stem base is assumed to occur at the same rate as surface residue decomposition.

The portion of the standing residue mass that remains standing over time is assumed to be related to the portion of the remaining unit stem base mass. The RUSLE2 equation for this relationship is:

$$\gamma_t = -2.62\gamma_s^3 + 4.57\gamma_s^2 - 0.95\gamma_s \qquad [10.11]$$

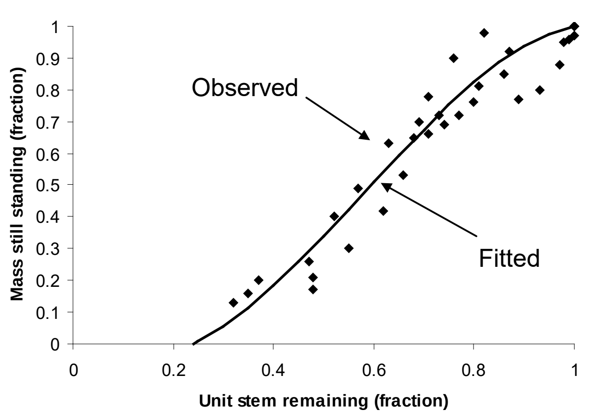

Figure 10.21. Relation of standing residue mass to computed unit stem base mass. (Data source: Steiner et al., 1994)

where: γ_t = portion (fraction) of original standing residue mass that remains and γ_s = portion (fraction) of the original unit stem base mass that remains at any given time. Equation 10.11 was derived by fitting to measured wheat data collected in Texas, Oregon, and North Dakota as illustrated in Figure 10.21 (Steiner et al., 1994). No similar data were found for other vegetation communities. However, equation 10.11 is considered to be adequate for other plant types besides small grain.

10.4.2. Canopy cover-mass relationship

During the live period for a vegetation description, canopy cover is known directly from user input. These canopy cover values are used to estimate temporal values for live above ground biomass (see **Section 9.2.5**).

Once live above ground biomass is transferred to standing residue, the known variable is standing residue mass. This biomass is computed from standing live above ground biomass converted to standing residue on the conversion date, decomposition of standing residue over time, and the amount of the standing residue that has become surface residue computed with equation 10.11.

RUSLE2 computes canopy cover for standing residue using:

$$f_t = \mu B_t^{2/3} \qquad [10.12]$$

where: f_t = canopy cover provided by the standing residue and B_t = daily standing residue biomass (dry mass/area). The value for the coefficient μ is determined from:

$$\mu = f_{to} / B_{to}^{2/3} \qquad [10.13]$$

where: f_{to} and B_{to} = canopy cover and biomass (dry mass/area), respectively, when the standing residue is created from live above ground biomass.

10.4.3. Manning's n, effective vegetation ridge height, and effective fall height for standing residue

Values for the Manning's n and effective ridge height for standing residue are computed using:

$$n_t = n_{to}(B_t / B_{to}) \qquad [10.14]$$

$$H_t = H_{to}(B_t / B_{to}) \qquad [10.15]$$

where: n_t = the daily standing residue Manning's n, n_{to} = the live vegetation Manning's n on the day that the standing residue was created, H_t = daily effective standing residue ridge height (inches), and H_{to} = effective ridge height (inches) of the live vegetation on the day that the standing residue was created. The effective ridge height for standing residue is computed from:

$$h_f = h_{fo}(f_t / f_{to}) \qquad [10.16]$$

where: h_f = the daily effective fall height, h_{fo} = the effective fall height for the vegetation on the day that the standing residue was created, f_t = daily canopy cover, and f_{to} = the canopy cover of the vegetation on the day that the standing residue was created.

Although RUSLE2 uses a single vegetation description on any given day, RUSLE2 tracks multiple standing residue descriptions. RUSLE2 assumes that the overall Manning's n for standing residue and the overall effective ridge height for each standing residue description are the sums of the respective values for each standing residue description. The net effective fall height of the standing residue is weighted by the canopy cover for each standing residue description. These values are independent of corresponding values for live vegetation.

This approach for representing a composite of vegetation and multiple standing residue descriptions should involve interactions similar to those assumed for overlapping ground cover. However, the RUSLE2 procedure is judged to be satisfactory for conservation and erosion control planning. Only a few residue descriptions are used in most cover-management descriptions and most standing residue is removed by tillage or other operations.

10.5. List of symbols

A = a reference temperature in temperature function used to compute decomposition (-8 ^{o}C)

b = coefficient that desribes the effectiveness for a particular residue type for reducing erosion ($percent^{-1}$)

B = mass (dry) in a particular residue/dead root pool (mass/area)

B_s = surface residue dry biomass (mass/area)

B_t = standing residue dry biomass (mass/area)

B_{to} = standing residue dry biomass on day when standing residue is created (mass/area)

c = daily cover-management factor

D = time in period over which decomposition is being computed (days)

D_p = period over which N_p precipitation events occur (days)

$D_{1/2}$ = residue half life (time)

f_g = ground (surface) residue cover (fraction)

f_{gm} = ground (surface) cover for crop residue or mulch assuming no other material is present (fraction)

f_{gn} = net ground (surface) cover provided by total surface residue mass (fraction)

f_{gr} = ground (surface) cover provided by the rock surface residue cover assuming no other surface residue is present (fraction)

f_t = canopy cover provided by the standing residue (fraction)

f_{to} = canopy cover provided by standing residue on day that standing residue is created (fraction)

g_c = daily ground cover subfactor

h_{fi} = effective fall height of standing residue (feet)

h_{fo} = effective fall height for the vegetation on day that the standing residue was created (feet)

H_t = effective standing residue ridge height (inches)

H_{to} = effective ridge height of live vegetation on day that the standing residue was created (inches)

n_t = standing residue Manning's n

n_{to} = live vegetation Manning's n on day that the standing residue was created

I = daily amount of water added by irrigation (inches)

N_p = Number of precipitation events in the period D_p

P = daily precipitation (inches)

P_b = base daily precipitation in moisture function used to compute decomposition (inches)

s_b = daily soil biomass subfactor

T = daily air temperature (^oC)

T_f = daily temperature function used to compute decomposition

T_o = optimum temperature for decomposition (^oC)

W_f = daily moisture function used to compute decomposition in RUSLE2

W_{fwe} = RWEQ moisture function used to compute decomposition

W_{fwp} = WEPP moisture function used to compute decomposition

W_{fws} = WEPS moisture function used to compute decomposition

α = coefficient in equation used to compute surface residue cover for a given residue mass [(mass/area^{-1})]

β = coefficient used to compute residue decomposition (day^{-1})

γ_s = portion of the unit stem base mass (dry basis) that remains

γ_t = portion of standing residue mass (dry basis) that remains

θ_f = field capacity moisture content (volume water/volume bulk soil)

θ_o = optimum soil moisture content for residue decomposition (volume water/volume bulk soil)

θ_s = soil moisture content for the surface soil layer (volume water/volume bulk soil)

θ_t = soil moisture content of the tilled soil layer (volume water/volume bulk soil)

μ = coefficient in equation used to compute canopy cover from standing biomass $(mass/area)^{-2/3}$

ϕ = decomposition coefficient that is a function of biomass type (day^{-1})

ϕ_w = weighted decomposition coefficient for residue description composed of two or more distinct residue types (day^{-1})

Indices

i - day

11. SUMMARY

11.1. RUSLE2 overview

The Revised Universal Soil Loss Equation, Version 2, (RUSLE2) is a tool specifically developed to guide erosion control planning at the local field office. RUSLE2 computes estimates of soil erosion caused by rainfall and its associated overland flow. RUSLE2 computes soil erosion estimates based on site-specific conditions for climate, soil, topography, and land use. Typically, RUSLE2 is used to compute soil erosion estimates for alternative erosion control measures that might be applied at a specific site. The erosion control practices that result in erosion estimates less than the erosion control criteria are considered acceptable. Consequently, erosion control can be tailored to site-specific conditions and requirements by using RUSLE2.

RUSLE2 is land-use independent. It applies to all land conditions where mineral soil is exposed to the erosive forces of raindrop impact and surface runoff produced by Hortonian overland flow. This overland flow occurs when rainfall intensity exceeds the infiltration rate of rainwater into the soil. RUSLE2 applies to cropland; permanent pastureland; construction sites; military training grounds; landfills and similar waste disposal sites; rangelands; disturbed forestlands; right-away along highways, pipelines, and electric transmission lines; and other similar lands.

The basic spatial RUSLE2 computational unit is the overland flow path selected to represent the site. Surface runoff follows this path from its origin to where overland flow becomes collected in a channel. The overland flow path can be divided into segments so that RUSLE2 can capture the effects of soil, steepness, and land use conditions varying along the overland flow path. RUSLE2 computes net erosion or deposition (mass/area) for each segment, sediment load (mass/unit flow width) at the end of each segment and at the end of the overland flow path, and sediment characteristics at the detachment point and in the sediment load at the end of each segment.

RUSLE2 also computes deposition in terrace channels assuming uniform conditions along these channels and deposition in small impoundments used on overland flow areas. RUSLE2 does not compute erosion in concentrated flow areas, referred to as ephemeral gully erosion, that terminate the overland flow path.

The basic temporal RUSLE2 computational unit is the long-term average for each day during the computation period used to represent a site's land-use condition. RUSLE2 management descriptions used to represent land-use conditions can be rotations where land use conditions are repeated in cycles or non-rotations where land-use conditions exist only for a single duration. The rotation cycle duration is the computation period. Rotation-type management descriptions are typically used to represent cropland and similar land uses. Also, rotation-type management practices are used to represent permanent land-use conditions that do not change from year to year.

Non-rotation type management descriptions are used to represent one-time land use conditions, such as reclamation of construction sites and surface mines. The computation period for these examples is from final grading through the number of years required for the site to become stabilized.

RUSLE2 sums long-term average daily erosion values to compute average annual values for the computation period used in the management description, for each year, and other sub-periods within the overall computation period. The average annual erosion value for the overall computation period typically is used in erosion control planning. The RUSLE2 computed average annual erosion for the site is compared to the site's erosion control criteria, which is an allowable average annual erosion rate based on the on-site and off-site damages that soil erosion would cause.

RUSLE2 computes how temporal variability of climate, soil, and land-use conditions affects erosion. Soil erosion is greatest when periods of maximum erosivity coincide with periods when the soil is most susceptible to erosion. Climatic erosivity typically varies greatly during the year. Also, land-use conditions vary during the year, ranging from bare soil after a major mechanical disturbance to dense cover provided by mature vegetation. Even erosion susceptibility of a site in permanent vegetation can vary significantly during the year as above ground and below ground biomass grow and subside. Even if vegetative cover and soil biomass do not vary temporally, soil erodibility varies during the year. Soil erodibility is greatest during periods of high soil moisture.

11.2. RUSLE2 mathematical structure

RUSLE2 is hybrid soil erosion prediction (estimation) technology because it is a combination of the empirical, index-based Universal Soil Loss Equation (USLE) and process-based equations for the detachment, transport, and deposition of soil particles. RUSLE2 computes a long-term average daily sediment production value using the USLE factors for erosivity, soil erodibility, slope length, slope steepness, cover-management, and support practice. Each USLE factor, except the one for slope steepness, is modified in RUSLE2 to compute a daily value rather than the standard USLE average annual value.

The USLE mathematical structure is (Wischmeier and Smith, 1978):

$$A = RKLSCP$$

where: A = average annual erosion (mass/area·year), R = average annual erosivity factor (erosivity units/area·year), K = average annual soil erodibility factor (mass/erosivity unit), L = average annual slope length factor (dimensionless), S = average annual slope steepness factor (dimensionless), C = average annual cover-management factor (dimensionless), and P = average annual support practice factor (dimensionless) . Each USLE factor, except the erosivity factor, has the mathematical structure of:

$$F = \left(\sum_{i=1}^{I} f_i \phi_i \right) \Big/ N$$

where: F = average annual factor, f_i = factor value for the *ith* time period, ϕ_i = the fraction of the annual erosivity that occurs during the *ith* period, I = the number of sub-periods in the computationl period for the management description used to represent a site's land use conditions, N = number of years in the computation period. Thus, the USLE has the mathematical structure of:

$$A = R\left[\left(\sum_{i=1}^{I_k} k_i \phi_i\right)\Big/N_k\right]\left[\left(\sum_{i=1}^{I_l} l_i \phi_i\right)\Big/N_l\right]\left[\left(\sum_{i=1}^{I_s} s_i \phi_i\right)\Big/N_s\right]\left[\left(\sum_{i=1}^{I_c} c_i \phi_i\right)\Big/N_c\right]\left[\left(\sum_{i=1}^{I_p} p_i \phi_i\right)\Big/N_p\right]$$

where: k_i = soil erodibility factor for the *ith* period (mass/erosivity unit), I_k = the number of periods in the N_k years used to determine an average annual soil erodibility factor value, l_i = slope length factor for the *ith* period (dimensionless), I_l = the number of periods in the N_l years used to determine an average annual slope length factor value, s_i = slope steepness factor for the *ith* period (dimensionless), I_s = the number of periods in the N_s years used to determine an average annual slope steepness factor value, c_i = cover-management factor for the *ith* period (dimensionless), I_c = the number of periods in the N_c years used to determine an average annual cover-management factor value, p_i = support practice factor for the *ith* period (dimensionless), and, I_p = the number of periods in the N_p years used to determine an average annual support practice factor value. In practice, the USLE mathematical structure is:

$$A = RKLS\left[\left(\sum_{i=1}^{I_c} c_i \phi_i\right)\Big/N_c\right]P$$

where: temporally constant values for K, L, S, and P are used throughout the computation period.

The basic RUSLE1 mathematical structure is the same as the USLE structure except that a temporal soil erodibility factor is used as (Renard et al., 1997):

$$A = R\left[\left(\sum_{i=1}^{24} k_i \phi_i\right)\Big/24\right]LS\left[\left(\sum_{i=1}^{24N_c} c_i \phi_i\right)\Big/24\,N\right]P$$

where: each year is divided in 24 half month periods and N = years in the overall computation period. Additional sub-periods are added if an operation that disturbs the soil, vegetation, or residue occurs within a half month period.

The RUSLE2 mathematical structure is:

$$A = \left(\sum_{i=1}^{365N} r_i k_i l_i s_i c_i p_i \right) \Big/ N$$

where: r_i = daily erosivity factor (erosivity unit/year), k_i = daily soil erodibility factor (mass/area·erosivity unit), l_i = daily slope length factor (dimensionless), s_i = daily slope steepness factor (dimensionless), c_i = daily cover-management factor (dimensionless), and p_i = daily support practice factor (dimensionless), all long term averages for the *ith* day, and N = number of years in the overall computational period. In practice, a single time-invariant slope steepness S is used instead of a daily s_i slope steepness factor.

The difference in mathematical structure between the USLE, RUSLE1, and RUSLE2 results in the three methods giving different erosion estimates even when each method gives the same average annual values for each USLE factor. Also, RUSLE2 considers much more interdependence between the factors than either the USLE or RUSLE1 considers.

Fundamentally, the USLE applies to a uniform overland flow path where neither soil, steepness, cover-management, nor support practice vary along the flow path. A mathematical procedure is available to apply the USLE to non-uniform overland flow paths where deposition does not occur. The USLE can not be applied to overland flow paths where steepness along the flow path decreases sufficiently to cause deposition.

The same mathematical structure used in process-based erosion prediction technologies to compute deposition along non-uniform overland flow paths is used in RUSLE1 and RUSLE2. Deposition is computed at locations along the flow path where the sediment load exceeds surface runoff's sediment transport capacity. RUSLE2 computes deposition using the equation:

$$D_p = \left(\alpha V_f / q\right)\left(T_c - g\right)$$

where: D_p = deposition rate (mass/area·time), α = an empirically determined deposition coefficient (dimensionless), V_f = the sediment's fall velocity (length/time), q = surface runoff rate (volume/unit overland flow width·time), T_c = surface runoff's sediment transport capacity (mass/unit overflow width·time), and g =sediment load (mass/unit overflow width·time) being transported by surface runoff.

Five sediment classes (primary clay, primary silt, small aggregate, large aggregate, and primary sand) are used in RUSLE2 to represent sediment characteristics. RUSLE2 computes the distribution of the sediment among these classes and the diameters of the aggregate classes at the point of detachment as a function of soil texture. The specific gravity of the aggregate classes is about 65 percent of that for the primary particle classes. RUSLE2 computes how deposition changes sediment characteristics along the overland flow path by applying the deposition equation to each sediment class. RUSLE2 also computes an enrichment ratio based on the specific surface of the sediment load and the specific surface area of the surface soil.

Both the deposition and sediment transport capacity equations are functions of runoff rate. A daily runoff rate index is computed using the NRCS runoff curve number method and the 10 year-24 hour precipitation amount. RUSLE2 computes a daily curve number value as a function of daily cover-management variables.

RUSLE2 computes how soil surface conditions affect runoff's sediment transport capacity. The computation is based on a division of runoff shear stress between that acting on roughness elements, including live vegetation, standing residue, surface residue cover and soil surface roughness, and that acting on the soil grain roughness, which is the part responsible for sediment transport. A daily division of shear stress is computed using daily cover-management variables.

RUSLE2's erosivity and soil erodibility definitions and variables are the same as those used by the USLE, which are based on the unit-plot concept. Also, RUSLE2 can use the standard USLE soil erodibility nomograph to compute soil erodibility factor values for undisturbed soil profiles or a modified nomograph for highly disturbed soil conditions. RUSLE2 computes a daily erodibility factor value that is varied about the base soil erodibility factor values using daily precipitation and temperature values. Daily erosivity is computed as the product of average annual erosivity and the fraction of the annual erosivity that occurs on each day.

The RUSLE2 slope length factor, which is the same as the USLE and RUSLE1 slope length factor, is given by:

$$l_x = (x/\lambda_u)^m$$

where: l_x = slope length factor used to compute erosion at any location x along an overland flow path (dimensionless), λ_u = unit plot length, and m = a slope length factor exponent. Sediment is detached from the soil mass on overland flow area by impacting raindrops (interrill erosion) and surface runoff (rill erosion). Interrill erosion is uniform along a uniform overland flow path, in which case the exponent m = 0. Rill erosion increases along an overland flow path as runoff increases, in which case m = 1. RUSLE2 computes a daily exponent value (between 0 and 1) that depends on the ratio of rill-to-interrill erosion. This ratio is computed as a function of how soil texture, slope steepness, and surface cover affects rill erosion relative to interrill erosion. The rill-to-interrill erosion ratio changes daily as cover-management changes daily.

The RUSLE2 slope steepness factor is the same as the one used in RUSLE1. This factor is time invariant in RUSLE2.

11.3. Land use subfactors

11.3.1. Cover-management subfactors

The use of basic cover-management variables to compute daily cover-management factor and runoff curve number values gives RUSLE2's its land-use independence. Cover-management factor values are computed as the product of several subfactors. These subfactors are canopy, ground (surface) cover, soil surface roughness, soil ridging, soil consolidation, soil biomass, and ponding. An additional soil moisture subfactor is used when RUSLE2 is applied to cropland in certain areas of the northwestern US.

The canopy subfactor describes how above ground canopy (cover that does not touch the soil surface) affects rainfall erosivity. The variables used in this subfactor include fraction of the soil surface covered by canopy and effective fall height of water drops falling from the canopy. RUSLE2 includes equations that estimate effective fall height based on top and bottom canopy heights, canopy shape, and the vertical gradient of canopy mass.

In contrast to canopy cover, ground (surface) cover rests directly on the soil surface. The main component of the equation that computes ground cover subfactor is:

$$c_g = \exp(-bf_g)$$

where: c_g = the subfactor for ground cover. **b** = coefficient for effectiveness of ground cover for reducing erosion (percent^{-1}), and f_g = ground cover (percent). The **b** coefficient, which is a measure of the effectiveness of ground cover for reducing erosion, is a function of the rill-to-interrill erosion ratio. RUSLE2 computed **b** values vary from 0.025 when the erosion is entirely interrill erosion to 0.06 when the erosion is entirely rill erosion. An additional soil surface roughness term is added to this equation in RUSLE2 to account for surface cover having less effect as soil surface roughness increases.

The soil surface roughness subfactor represents how soil surface roughness influences erosion by reducing runoff's erosivity, by causing deposition in local depressions, and by ponding water that protects a portion of the soil surface from direct raindrop impact. Daily soil surface roughness subfactor values are computed as a function of the daily soil surface roughness index. Soil surface roughness decreases daily from the initial soil surface roughness left by a mechanical soil disturbance. RUSLE2 computes the daily decrease in the soil surface roughness index using values for daily precipitation and daily interrill erosion. The soil surface roughness index value left after a mechanical soil disturbance is computed as a function of the soil surface roughness index that exists at the time of the soil disturbance, the soil surface roughness index created by the mechanical soil disturbance applied to a standard soil condition, soil texture, soil biomass, and the degree that the mechanical soil disturbance obliterates existing soil surface roughness.

The soil ridging subfactor represents the effect of ridge side slope on interrill erosion. The soil ridging subfactor is a function of daily ridge height, which is a surrogate for ridge side slope. RUSLE2 decreases daily ridge height from an initial ridge height left by a mechanical soil disturbance as a function of daily precipitation and daily interrill erosion.

The soil consolidation subfactor represents how a bare soil without soil biomass becomes less erodible over time as the soil experiences wetting and drying cycles. Soil consolidation in RUSLE2 refers to the re-bonding of soil particles after a mechanical soil disturbance. The RUSLE2 assumption is that mechanical soil compaction (increase in soil bulk density) does not decrease erosion. RUSLE2 computes soil consolidation subfactor values as a function of the time since the last mechanical soil disturbance. The RUSLE2 time to soil consolidation is seven years but increases to 20 years where average annual precipitation is less than 30 inches.

The soil biomass subfactor represents how soil biomass reduces erosion. RUSLE2 computes daily soil biomass subfactor values as a function of the daily amounts of live roots, dead roots, and buried biomass in the soil and the soil consolidation subfactor. Plant litter, crop residue, manure, and other types of biomass on the soil surface that is incorporated in the soil by mechanical soil disturbance adds to buried soil biomass. Also, injection of manure, sewage sludge, and other organic materials into the soil adds soil biomass. The runoff and erosion reduction computed by the soil biomass subfactor significantly increases as the soil becomes “consolidated” after a mechanical soil disturbance.

The ponding subfactor accounts for how a water layer on the soil surface decreases raindrop impact erosivity in high rainfall regions where land is nearly flat. The variables used to compute ponding subfactor values are land steepness and daily runoff depth, which in turn is a function of the 10 year-24 hour precipitation amount, soil properties, and cover-management.

The antecedent soil moisture subfactor, which is used only on cropland in the northwestern US, accounts for how previous cropping reduces soil moisture that in turn reduces erosion in subsequent cropping periods.

11.3.2. Support practice subfactors

The contouring subfactor computes how contour ridging affects rill erosion and sediment transport by redirecting surface runoff. Contouring subfactor values are computed as a function of daily runoff rate, overland flow path steepness, and ridge-furrow grade

RUSLE2 computes the location along an overland flow path (critical slope length) beyond which contour ridges fail. This computation is a function of the daily runoff rate, daily cover-management conditions, and land steepness.

RUSLE2 computes how profile shape(uniform, convex, concave, and complex) along the overland flow path affects erosion, deposition, and sediment yield from the overland flow path represented in a RUSLE2 computation. RUSLE2 computes the amount of deposition on concave portions of the overland flow path, how this deposition affects sediment characteristics by enriching the sediment in fine and less dense particles.

Strips of dense vegetation placed along overland flow paths can significantly reduce erosion and sediment yield. RUSLE2 computes the reduction in sediment production, the amount of deposition caused by the dense vegetation strips, and the change in sediment characteristics.

Terraces and diversions placed along an overland flow path reduce erosion by decreasing overland flow path length. RUSLE2 also computes deposition and its effect on sediment characteristics in low grade terraces assuming a uniform terrace grade. RUSLE2 does not compute erosion by flow in these channels.

RUSLE2 computes deposition in small impoundments such as small sediment basins used on construction sites and small impoundments created by parallel tile outlet terrace systems. A simple settling-type equation is used to compute deposition by sediment particle class.

The deposition computed by RUSLE2 depends on the characteristics of the sediment reaching the deposition area. Sediment characteristics at the point of detachment are computed as a function of soil texture, but deposition along the overland flow path enriches the sediment in fines and less dense particles that are deposited less readily. Consequently, less deposition is computed in dense grass strips, terrace channels, and in impoundments if upstream deposition has been computed.

RUSLE2 computes how irrigation affects erosion caused by rainfall and its associated overland flow. RUSLE2 takes into account increased yield and increased soil moisture, which increases biomass decomposition and soil erodibility, caused by the irrigation. RUSLE2 does not compute the erosion directly caused by irrigation itself.

The subsurface drainage subfactor represents how subsurface drainage reduces erosion by reducing surface runoff. This subfactor is based on how much subsurface drainage reduces a soil's runoff potential. The runoff potential (permeability) subfactor in RUSLE2's computation of unit-plot soil erodibility is used to adjust the soil erodibility value to account for the subsurface drainage effect.

11.4. Biomass accounting

Biomass on and in the soil has a great effect on soil erosion. The input value for production (yield) level provides the starting point for RUSLE2's biomass accounting. RUSLE2 tracks the conversion of live standing vegetation to dead standing residue by natural and mechanical processes. RUSLE2 accounts for soil surface biomass accumulation from standing residue becoming surface residue caused by standing residue falling by natural processes and mechanical events, by litter fall, and by events that add surface biomass such as straw mulch applications. RUSLE2 estimates the biomass in litter added to the soil surface by senescence based on the decrease in canopy cover.

The RUSLE2 sources of soil biomass are live and dead roots, soil surface biomass that is buried by mechanical soil disturbance, decomposed soil surface biomass that is added to soil, and biomass injected into the soil. RUSLE2 adds the daily decrease in live root biomass to dead root biomass. Live roots decrease annually as a part of the growth cycle of perennial vegetation, and live roots become dead roots when vegetation is killed by a mechanical operation or a natural process such as frost.

RUSLE2 computes the daily decomposition loss of standing residue, surface residue, buried residue, and dead roots as a function of daily precipitation and temperature. The same decomposition coefficient value is used for all plant parts and whether the material is on the soil surface or buried in the soil. However, the decomposition coefficient for standing dead vegetation is assumed to be 30 percent of that for surface and buried material.

RUSLE2 uses a specific set of rules to transfer biomass between standing residue, surface residue, and buried residue pools. For example, live above ground biomass must be converted first to standing residue before live vegetation biomass can become surface residue. Next, standing residue must be converted to soil surface residue. Only surface residue can be buried. That is, standing residue can not be directly buried without first being converted to surface residue. A mechanical soil disturbing operation is required to bury or place residue in the soil, and a mechanical soil disturbing operation is required to resurface previously buried residue.

11.5. Cover-management descriptions

Users provide a cover-management description that RUSLE2 uses to compute how cultural practices affect erosion. A RUSLE2 cover-management description is a list of operations by date, vegetation descriptions and production levels (yields), and residue descriptions and amounts for material added to the soil surface or injected into the soil. A cover-management description is a rotation when the list of operations are repeated in a cycle with a particular duration, which is typical for cropland and permanent vegetation, or a non-rotation when each operation occurs only once over a particular duration, which is typical of construction sites.

11.6. Operation descriptions

Operations are events that affect the soil, vegetation, or residue. The user selects from several processes to describe the effects of an operation. **Begin growth** is the process that tells RUSLE2 to begin using data in a particular vegetation description on a particular date. **Add residue** is used to apply mulch. A residue description that describes the mulch characteristics is assigned in the cover-management description. **Kill vegetation** is the process used to convert live vegetation to standing residue and live roots to dead roots. It is used to describe harvest of an annual crop and to describe frost killing annual vegetation.

The **disturb soil** process describes a mechanical soil disturbance. For example, the operation description for a heavy offset disk includes a **disturb soil** process. The **disturb soil** process includes inputs for burial and resurfacing values for each of the five RUSLE2 residue types, the fraction of the standing residue that is converted to surface residue, the fraction of surface residue that is buried, and the fraction of the buried residue that is resurfaced by the operation. The **disturb soil** process includes a designation for whether the operation buries residue by inverting the soil, by mixing the residue with the soil, by a combination of mixing and inversion, or by pressing the residue into the soil. The **disturb soil** process also includes values for soil disturbance depth, surface roughness left by the operation for a standard condition, and ridge height left by the operation, the degree that the operation obliterates existing soil roughness , and fraction of the soil surface disturbed by the operation.

An operation such as straw baling may include a **remove residue** process to describe reduction in surface residue cover after a small grain harvest, for example.

An operation description can include multiple processes. The sequence of the processes is critically important. For example, having an **add residue** process before a **disturb soil** process gives a very different surface residue cover than if the **add residue** process comes after the **disturb soil** process.

11.7. Vegetation descriptions

Computing the effects of vegetation on erosion is an important RUSLE2 feature. RUSLE2 uses values for vegetation variables including temporal canopy cover, effective fall height, live above ground biomass, and root biomass to compute cover-management subfactor and runoff values. Values for these variables are entered in vegetation descriptions.

RUSLE2 does not model vegetation growth as a function of environmental conditions. Instead RUSLE2 vegetation descriptions apply in particular ecological zones. Each vegetation description is for a particular base production (yield) level. The RUSLE2 user chooses the vegetation description for the site where RUSLE2 is being applied and a appropriate yield for the site is entered in the cover-management description. RUSLE2 adjusts the base vegetation description values according to the input yield value for the site.

11.8. Residue descriptions

A residue description is assigned to each vegetation description to describe the characteristics of residue produced by the vegetation. Also, a residue description is used to describe material added to the soil surface (e.g., straw mulch) and material (e.g., sewage sludge) injected into the soil. The residue description includes a decomposition coefficient value that describes how rapidly the residue decomposes under a standard condition, the fraction of the soil surface covered by a given residue mass, and designation of residue type that denotes the fragility of the residue and how well the residue conforms to the soil surface.

11.9. Climate descriptions

Climate descriptions contain the data on long term average monthly precipitation, temperature, and erosivity values that RUSLE2 uses to compute erosion. Each climate description is for a particular location, county, or rainfall zone.

11.10. Soil descriptions

Soil descriptions contain data on soil properties that RUSLE2 uses to compute erosion and deposition. These properties include soil texture, soil erodibility, runoff potential, rock cover, and time to soil consolidation, all for the reference unit plot condition. RUSLE2 includes soil erodibility nomographs that are used to estimate soil erodibility values from values for basic soil properties.

11.11. RUSLE2 databases

The user runs RUSLE2 by making menu selections from the RUSLE2 database. Each description in the database is stored by an identifier name. In a typical RUSLE2 application, the user selects a climate description by location, soil description by soil mapping unit or some other designator, cultural practice by a cover-management description identifier, and support practices by their identifiers, all appropriate for the site specific conditions. The user enters overland path steepness and length values based on the overland flow path chosen to represent the site.

A wide array of RUSLE2 descriptions, especially for cropland, is available from the USDA-Natural Resources Conservation Service (NRCS). Information can be downloaded and imported into your working RUSLE2 database from the NRCS National RUSLE2 Database and from the database of other RUSLE2 users.

Users can adjust values stored in their working RUSLE2 database to better match site conditions. Also, users can create new database entries. New user chosen values must be consistent with values in the RUSLE2 **Core Database**. RUSLE2 was calibrated using a particular set of **core values**. User input values must be consistent with these **core values** in order to obtain good results with RUSLE2 regardless of how much a user may disagree with the **core values**. If a **core value** were to be changed, other RUSLE2 internal or input values would have to be changed as well, because RUSLE2 has been calibrated to give desired erosion estimates with the **core value**. These core values are contained in the RUSLE2 **Core Database**.

11.12. RUSLE2 validation

The equations for the subfactors were primarily calibrated using data from Agriculture Handbook 537 (Wischmeier and Smith, 1978), which is a summary of more than 10,000 plot-years of data. Additional data from the literature were used to calibrate the equations for conditions not represented by the AH537 data. Erosion values were computed with RUSLE2 for a wide range of conditions, including conditions not represented by existing research data. These values were inspected to ensure that they were consistent with the available research data and consistent with professional judgment.

Ground (surface) cover is perhaps the single most important RUSLE2 variable, at least for cropland conditions. The surface cover left by a cropping system immediately after planting in a key variable used by soil conservationists in judging the effectiveness of a particular cropping system. The adequacy of RUSLE2 for estimating surface cover was very carefully evaluated. An extensive array of literature was reviewed in this evaluation. Scientists have reported differences in RUSLE2 estimates with those made by other comparable erosion models. When RUSLE2 is fitted to the same data used to fit other methods, RUSLE2's estimates of surface cover are almost the same as those estimated by other methods for long term average conditions. The differences were primarily caused by variability in residue data and by differences in techniques used to measure residue mass as it decomposes.

11.13. List of symbols

A = average annual erosion (mass/area·year)

b = coefficient for effectiveness of ground cover for reducing erosion ($percent^{-1}$)

c_g = the subfactor for ground cover (dimensionless)

c_i = cover-management factor for the *ith* period (dimensionless)

C = average annual cover-management factor (dimensionless)

D_p = deposition rate (mass/area·time)

f_g = ground cover (percent)

f_i = factor value for the *ith* time period

F = average annual factor

g =sediment load (mass/unit overflow width·time)

I = the number of sub-periods in the computation period for the management description used to represent a site's land use conditions

I_c = the number of periods in the N_c years used to determine an average annual cover-management factor value

I_k = the number of periods in the N_k years used to determine an average annual soil erodibility factor value

I_l = the number of periods in the N_l years used to determine an average annual slope length factor value

I_p = the number of periods in the N_p years used to determine an average annual support practice factor value

I_s = the number of periods in the N_s years used to determine an average annual slope steepness factor value,

k_i = soil erodibility factor for the *ith* period (mass/erosivity unit)

K = average annual soil erodibility factor (mass/erosivity unit)

l_i = slope length factor for the *ith* period (dimensionless)

l_x = slope length factor used to compute erosion at any location x along an overland flow path (dimensionless)

L = average annual slope length factor (dimensionless)

m = a slope length factor exponent

N = number of years in the computation period

N_c = number of years used to determine an average annual cover-management factor value

N_k = number of years used to determine an average annual soil erodibility factor value

N_l = number of years used to determine an average annual slope length factor value

N_s = number of years used to determine an average annual slope steepness factor value

p_i = support practice factor for the *ith* period (dimensionless)

P = average annual support practice factor (dimensionless)

q = surface runoff rate (volume/unit overland flow width·time)

r_i = erosivity factor for the *ith* period (erosivity unit/area·year)

R = average annual erosivity factor (erosivity unit/area·year)

s_i = slope steepness factor for the *ith* period (dimensionless)

S = average annual slope steepness factor (dimensionless)

T_c = surface runoff's sediment transport capacity (mass/unit overflow width·time)

V_f = the sediment's fall velocity (length/time)

x = distance along overland flow path (length)

α = an empirically determined deposition coefficient (dimensionless)

ϕ_i = the fraction of the annual erosivity that occurs during the *ith* period

λ_u = unit plot length (72.6 ft, 22.1 m)

Indices

i - time period (days)

12. REFERENCES

12.1. References cited

RUSLE2 User's Reference Guide (in publication)

Alberts, E.E. and W.D. Schrader. 1980.Cornstalk decomposition on a till-planted watershed. Agronomy Journal. 72:709-712.

Alberts, E.E., M.A. Nearing, M.A. Weltz, L.M. Risse, F.B. Pierson, X.C. Zhang, J.M. Laflen, and J.R. Simanton. 1995. Soil component. Capter 7. In: D.C. Flanagan and M.A. Nearing (editors). 1995. Technical Documentation, USDA-Water Erosion Prediction Project (WEPP). NSERL Report No. 10. National Soil Erosion Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture. Washington, D.C.

Alonso, C.V., W.H. Neibling, and G.R. Foster. 1981. Estimating sediment transport capacity in watershed modeling. Transactions of the American Society of Agricultural Engineers 24:1211-1220, 1226.

Barfield, B.J., R.I. Barnhisel, M.C. Hirschi, and I.D. Moore. 1988. Compaction effects on erosion of mine spoil and reconstructed topsoil. Transactions of the American Society of Agricultural Engineers 31:447-452

Bengston, R.I. and G. Sabbage. 1988. USLE P-factor for subsurface drainage in a hot, humid climate. ASAE Paper 88-2122. American Society of Agricultural Engineers. St. Joseph, MI.

Birk, E.M. and R.W. Simpson. 1980. Steady state and the continuous input model of litter accumulation and decomposition in Australian Eucalypt forests. Ecology. 6:481-485.

Bonta, J.V. and W.R. Hamon. 1980. Preliminary evaluations of a sediment pond draining a surface mined watershed. Symposium on Surface Mining Hydrology, Sedimentology, and Reclamation. University of Kentucky. Lexington, KY. 371-381.

Borst, H.L.., A.G. McCall, and F.G. Bell. 1945. Investigations in erosion control and reclamation of eroded land at the Northwest Appalachian Conservation Experiment Station, Zanesville, Ohio, 1934-42. Technical Bulletin 888. U.S. Department of Agriculture, Washington, DC.

Box, J.E., Jr. 1981. The effects of slaty fragments on soil erosion by water. Soil Science Society of America Journal. 45:111-116.

Box, Jr, J.E. and E.N. Bui. 1993. Growing corn roots effects on interrill soil erosion. Soil Science Society of America Journal. 57:1066-1070.

Brenneman, L.G. and J.M. Laflen. 1982. Modeling sediment deposition behind corn residue. Transactions of the American Society of Agricultural Engineers. 25:1245-1250.

Broder, M.W. and G.H. Wagner. 1988. Microbial colonization and decomposition of corn, wheat, and soybean residue. Soil Science Society of America Journal. 52:112-117.

Brown, L.C., and G.R. Foster. 1987. Storm erosivity using idealized intensity distributions. Transactions of American Society of Agricultural Engineers 30(2):379-386.

Brown, L.C., G.R. Foster, and D.B. Beasley. 1989. Rill erosion as affected by incorporated crop residue and seasonal consolidation. Transactions of American Society of Agricultural Engineers 32:1967-1978, 1979.

Brown, L.C., R.K. Wood, and J.M. Smith. 1992. Residue management and demonstration and evaluation. Applied Engineering in Agriculture. 8:333-339.

Browning, F.M., R.A. Norton, A.G. McCall, and F.G. Bell. 1948. Investigations in erosion control and reclamation of eroded land at the Missouri Valley Loess Conservation Experiment Station, Clarinda, Iowa, 1931-42. Technical Bulletin 959. U.S. Department of Agriculture, Washington, DC.

Chapman, G. 1948of raindrops and their striking force at the soil surface in a red pine plantation. Transactions of the American Geophysical Union. 29:664-670.

Chow, V.T., 1959. Open-channel hydraulics. McGraw-Hill Book Co. New York, NY.

Cogo, N.C., W.C. Moldenhauer, and G. R. Foster. 1984. Soil loss reduction from conservation tillage practices. Soil Science Society of American Journal 48:368-373.

Colvin, T. S. and J. E. Gilley. 1987. Crop residue - soil erosion combatant. Crops and Soils 39:7-9.

Cooley, K.R. 1980. Erosivity values for individual design storms. Journal of Irrigation and Drainage Engineering Division. American Society of Civil Engineers 106:135-145.

Copley, T.L., L.A. Forrest, A.G. McCall, and F.G. Bell. 1944. Investigations in erosion control and reclamation of eroded land at the Central Piedmont Conservation Experiment Station, Statesville, North Carolina, 1930-40. Technical Bulletin 873. U.S. Department of Agriculture, Washington, DC.

Dabney, S.M., Meyer, L.D., Harmon, W.C., Alonso, C.V., and Foster, G.R. 1995. Runoff and soil loss from cotton plots with and without stiff-grass hedges. Transactions of the American Society of Agricultural Engineers. 38:1719-1729.

Dabney, S.M. 2005. Utility of mesh bag vs. grab sampling methods of measuring residue decomposition for calibrating RUSLE2 residue decomposition routines. Unpublished report. National Sedimentation Laboratory. Agricultural Research Service, U.S. Department of Agriculture. Oxford, Mississippi.

Daly, C., G. Taylor, and W. Gibson. 1997. The PRISM approach to mapping precipitation and temperature, 10th Conf. on Applied Climatology, American. Meteorological Society.

Daniel, H.A., H.M. Elwell, and M.B. Cox. 1943. Investigatins in erosion control and reclamation of eroded land at the Red Plains Cnservation Experiment Station, Guthrie, Oklahoma, 1930-40. Technical Bulletin 837. U.S. Department of Agriclture, Washington D.C.

Desmet, P.J.J. and G. Govers. 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. Journal of Soil and Water Conservation Service 51:427-433.

Dickey, E.C., C.R. Fenster, J.M. Lalen, an R.H. Mickelson. 1983. Effects of tillage on soil erosion in a wheat-fallow rotation. Transactions of the American Society of Agricultural Engineers. 26:814-820.

Dickey, E.C., D.P. Shelton, P.J. Jasa, and T.R. Peterson. 1985. Soil erosion from tillage systems used in soybean and corn residues. Transactions of the American Society of Agricultural Engineers. 28:1124-1129, 1140.

Dissmeyer, G.E. and G.R. Foster. 1981. Estimating the cover-management factor (C) in the universal soil-loss equation for forest conditions. Journal of Soil and Water Conservation 36:235-240.

Douglas, Jr., C.L., R.R. Allmaras, P.E. Rassmussen, R.E. Ramig, and N.C. Roager, Jr. 1980. Wheat straw composition and placement effects on decomposition in dryland agriculture of the Pacific Northwest. Soil Science Society of America Journal. 44:833-837.

Dubeux, Jr., J. C. B.; L. E. Sollenberger, J. M. B. Vendramini, R. L. Stewart, Jr. and S. M. Interrante. (2006). Litter Mass, Deposition Rate, and Chemical Composition in Bahiagrass Pastures Managed at Different Intensities. 46:1299-1304.

Elliot, W.J., J.M. Laflen, K.D. Kohl, K.D. 1989. Effect of soil properties on soil erodibility. ASAE Paper 89-2150. American Society of Agricultural Engineers. St. Joseph, MI.

Ellison, W.D. 1947. Soil erosion studies. Agricultural Engineering. 145-146, 197-201, 245-248, 297-300, 349-351, 402-405, 442-444.

El-Swaify, S.A. and E.W. Dangler. 1976. Erodibilities of selected tropical soils in relation to structural and hydrologic properties. In: Soil Erosion: Prediction and Control. Soil and Water Conservation Society of America. Ankeny, IA. pp. 105-114.

Fennessey, L.A.J. and A.R. Jarrett. 1997. Influence of principal spillway geometry and permanent pool depth on sediment retention of sedimentation basins. Transactions of the American Society of Agricultrual Engineers. 40:53-59.

Finkner, S.C., M.A. Nearing, G.R. Foster, and J.E. Gilley. 1989. A simplified equation for modeling sediment transport capacity. Transactions of American Society of Agricultural Engineers 32:1545-1550.

Flanagan, D.C., G.R. Foster, W.H. Neibling, and J.P. Burt. 1989. Simplified equations for filter strip design. Transactions of American Society of Agricultural Engineers 32(6):2001-2007.

Flanagan, D.C. and M.A. Nearing (editors). 1995. Technical Documentation, USDA-Water Erosion Prediction Project (WEPP). NSERL Report No. 10. National Soil Erosion Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture. Washington, D.C.

Formanek, G.E, E. Ross, and J. Istok. 1987. Subsurface drainage for erosion reduction on croplands of northwestern Oregon. In: Irrigation Systems of the 21st Century. Proceeding Irrigation Division Specialty Conference. American Society of Civil Engineers. New York, NY. pp. 25-31.

Foster, G.R. and L.D. Meyer. 1972. Transport of soil particles by shallow flow. Transactions of the American Society of Agricultural Engineers 15:99-102.

Foster, G.R. and W.H. Wischmeier. 1974. Evaluating irregular slopes for soil loss prediction. Transactions of the American Society of Agricultural Engineers 17(2):305-307.

Foster, G.R. and L.D. Meyer. 1975. Mathematical simulation of upland erosion by fundamental erosion mechanics. *In:* Present and Prospective Technology for Predicting Sediment Yields and Sources. ARS-S-40 U.S. Department of Agriculture. pp. 190-204.

Foster, G.R., L.D. Meyer, and C.A. Onstad. 1977a. An erosion equation derived from basic erosion principles. Transactions of the American Society of Agricultural Engineers 20:678-682.

Foster, G.R., L.D. Meyer, and C.A. Onstad. 1977b. A runoff erosivity factor and variable slope length exponents for soil loss estimates. Transactions of the American Society of Agricultural Engineers 20:683-687.

Foster, G.R. L.J. Lane, J.D. Nowlin, J.M. Laflen, and R.A. Young. 1980a. A model to estimate sediment yield from field sized areas: Development of model. *In:* CREAMS - a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. Vol. I: Model Documentation. Conservation Research Report No. 26. U.S. Department of Agriculture. pp. 36-64.

Foster, G.R., L.J. Lane, and J.D. Nowlin. 1980b. A model to estimate sediment yield from field sized areas: Selection of parameter values. *In:* CREAMS - a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. Vol. II: User Manual. Conservation Research Report No. 26. U.S. Department of Agriculture. pp. 193-281

Foster, G.R., W.H. Neibling, S.S. Davis, and E.E. Alberts. 1980c. Modeling particle segregation during deposition by overland flow. *In:* Proceedings of Hydrologic Transport Modeling Symposium. American Society of Agricultural Engineers. St. Joseph, MI. pp. 184-195.

Foster, G.R. and V.A. Ferreira. 1981. Deposition in uniform grade terrace channels. *In:* Crop Production with Conservation in the 80's. American Society of Agricultural Engineers. St. Joseph, MI. pp. 185-197.

Foster, G.R., L.J. Lane, J.D. Nowlin, J.M. Laflen, and R.A. Young. 1981a. Estimating erosion and sediment yield on field sized areas. Transactions of the American Society of Agricultural Engineers 24:1253-1262.

Foster, G.R., D.K. McCool, K.G. Renard, and W.C. Moldenhauer. 1981b. Conversion of the universal soil loss equation to SI metric units. Journal of Soil and Water Conservation 36:355-359.

Foster, G.R. 1982. Modeling the erosion process. Chapter 8. *In:* Hydrologic Modeling of Small Watersheds. C.T. Haan, H.P. Johnson, D.L. Brakensiek, eds. American Society of Agricultural Engineers. St. Joseph, MI. pp. 297-382.

Foster, G.R., C.B. Johnson, and W.C. Moldenhauer. 1982a. Critical slope lengths of unanchored cornstalk and wheat straw residue. Transactions of the American Society of Agricultural Engineers 25:935-939, 947.

Foster, G.R. C.B. Johnson, and W.C. Moldenhauer. 1982b. Hydraulics of failure of unanchored cornstalk mulches for erosion control. Transactions of the American Society of Agricultural Engineers 25:940-947.

Foster, G.R., L.J. Lane, W.R. Osterkamp, and D.W. Hunt. 1982c. Effect of discharge on rill erosion. Paper No. 82-2572. American Society of Agricultural Engineers. St. Joseph. MI.

Foster, G.R., F. Lombardi, and W.C. Moldenhauer. 1982d. Evaluation of rainfall-runoff erosivity factors for individual storms. Transactions of the American Society of Agricultural Engineers 25:124-129.

Foster, G.R. and R.E. Highfill. 1983. Effect of terraces on soil loss: USLE P factor values for terraces. Journal of Soil and Water Conservation 38:48-51.

Foster, G.R. 1985. Understanding ephemeral gully erosion (concentrated flow erosion). *In:* Soil Conservation, Assessing the National Resources Inventory. National Academy Press. Washington, D.C. pp. 90-125.

Foster, G.R., G.C. White, T.E. Hakonson, and M. Dreicer. 1985a. A model for splash and retention of sediment and soil-borne contaminants on plants. Transactions of the American Society of Agricultural Engineers 28:1511-1520.

Foster, G.R., R.A. Young, and W.H. Neibling. 1985b. Sediment composition for nonpoint source pollution analyses. Transactions of the American Society of Agricultural Engineers 28:133-139, 146.

Foster, G.R., R.A. Young, M.J.M. Römkens, and C.A. Onstad. 1985c. Processes of soil erosion by water. *In:* Soil Erosion and Crop Productivity. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. R.F. Follett and B.A. Stewart, eds. Madison, WI. pp. 137-162.

Foster, G.R., G.A. Weesies, K.G. Renard, J.P. Porter, and D.C. Yoder. 1997. Support practice factor "P". *In:* A Guide to Conservation Planning with the Revised Soil Loss Equation (RUSLE). Agriculture Handbook 703. U.S. Department of Agriculture. Chapter 6.

Fournier, F. 1960. Climat et Erosion. Universitaries de France, Paris.

Fryrear, D.W., A. Saleh, J.D. Bilbro, H.M. Schomberg, J.E. Stout. and T. M. Zobeck. 1998. Revised Wind Erosion Equation. Technical Bulletin No. 1, Cropping Systems Research Laboratory, USDA-Agricultural research Service, Lubbock, Texas.

Ghidey, F. and E.E. Alberts. 1993. Residue type and placement effects on decomposition: Field study and model evaluation. Transactions of the American Society of Agricultural Engineers. 36:1611-1617.

Gilley, J.E., S.C. Finkner, R.G. Spomer, and L.N. Mielke. 1986. Runoff and erosion as affected by corn residue. I. Total losses. Transactions of the American Society of Agricultural Engineers. 29:157-160.

Gilley, J.E. and S.C. Finkner. 1991. Hydraulic roughness coefficients as affected by random roughness. Transactions of the American Society of Agricultural Engineers. 34:897-903.

Gilley, J.E. and E.R. Kottwitz. 1994. Darcy-Weisbach roughness coefficients for surfaces with residue and gravel cover. Transactions of the American Society of Agricultural Engineers. 38:539-544.

Gilley, J.E. and E.R. Kottwitz. 1995. Darcy-Weisbach roughness coefficients for selected crops. Transactions of the American Society of Agricultural Engineers. 37:467-471.

Govers, G. 1991. Rill erosion on arable land in central Belgium: Rates, control, and predictability. Catena. 18:133-135.

Graf, W.H. 1971. Hydraulic of Sediment Transport. McGraw Hill. New York, NY.

Gregory, J.M., T.R. McCarty, F. Ghidey, and E.E. Alberts. 1985. Derivation and evaluation of residue decay equation. Transactions of the American Society of Agricultrual Engineers. 28:98-101.

Ghidey, F. and E.E. Alberts. 1993. Residue type and placement effects on decomposition: Field study and model evaluation. Transactions of the American Society of Agricultural Engineers. 36:1611-1617.

Gunn , R. and Kinzer, G.D. 1949. The terminal velocity of fall for water droplets. Journal of Meteorology. 6:243-248.

Haan, C.T., B.J. Barfield and J.C. Hayes. 1994. Design hydrology and sedimentology for small catchments. Academic Press, New York, NY.

Hagan. L.J., L.E. Wagner, and J. Tatarko. 1996. Technical Documentation, Wind Erosion Prediction System (WEPS). Wind erosion Research Unit, USDA-Agricultural research Service, Manhattan, Kansas.

Hanna, H.M., S.W. Melvin, and R.O. Pope. 1995. Tillage implement operational effects on residue cover. Applied Engineering in Agriculture. 11:205-210.

Hayes, J.C., B.J. Barfield, and R.I. Barnhisel. 1984. Performance of grass filters under laboratory and field conditions. Transactions of the American Society of Agricultural Engineers 27:1321-1331.

Hays, O.E. and O.J. Attoe. 1957. Control of runoff and erosion on Almena silt loam in Wisconsin. ARS 41-16. U.S. Department of Agriculture, Washington, DC.

Hays, O.E., A.G. McCall, and F.G. Bell. 1949. Investigations in erosion control and reclamation of eroded land at the Upper Mississippi Valley Conservation Experiment Station near LaCrosse, Wisconsin, 1933-43. Technical Bulletin 973. U.S. Department of Agriculture, Washington, DC.

Heilman, J.L., K.J. McInnes, R.W. Gesch, and R.J. Lascano. 1992. Evaporation from ridge-tilled soil covered with herbicide-killed winter wheat. Soil Science Society of America Journal. 56:1278-1286.

Hill, H.O., W.J. Peevy, A.G. McCall, and F.G. Bell. 1944. Investigations in erosion control and reclamation of eroded land at the Blackland Conservation Experiment Station Temple, Texas, 1931-41. Technical Bulletin 859. U.S. Department of Agriculture, Washington, DC.

Hill, P.R. and D.E. Stott. 2000. Corn residue retention by a combination chisel plow. Soil Science Society of America Journal. 64:293-299.

Hollinger, S. E., J. R. Angel, and M. A. Palecki. 2002. Spatial Distribution, Variation, and Trends in Storm Precipitation Characteristics Associated with Soil Erosion in the United States. Contract report CR 2002-08. Illinois State Water Survey. Champaign, IL available at: www.isws.illinois.edu/pubdoc/CR/ISWSCR2002-08.pdf .

Hood, G.W. and R.P. Bartholomew. 1956. Soil and water conservation studies in the Ozark Highlands of Arkansas. Agricultural Experiment Station Bulletin 563. University of Arkansas.

Hunt, H.W. 1977. A simulation model for decomposition in grasslands. Ecology 58:469-484.

Jasa, P. J., E.C. Dickey, and D.P. Shelton. 1986. Soil erosion from tillage and planting systems used in soybean residue: Part II - influences of row direction. Transactions of the American Society of Agricultural Engineers. 29:761-766.

Johnson, R.R. 1988. Soil engaging tool effects on surface residue and roughness with chisel-type implements. Soil Science Society of America Journal.52:237-243.

Kay, B.D. and A.J. VanderBygaart. 2002. Conservation tillage and depth stratification of porosity and soil organic matter. Soil and Tillage Research. 66:107-118.

Knisel, W. G. (editor). 1980. CREAMS : a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. Conservation Research Report 26. U.S. Department of Agriculture, Washington, DC.

Laflen, J.M., H.P. Johnson, and R.C. Reeve. 1972. Soil loss from tile outlet terraces. Journal of Soil and Water Conservation. 27:74-77.

Laflen, J. M., J. L. Baker, R. O. Hartwig, W. F. Buchele, and H. P. Johnson. 1978. Soil and water losses from conservation tillage systems. Transactions of the American Society of Agricultural Engineers. 21:881-885.

Laflen, J.M., W.C. Moldenhauer, and T.S. Colvin. 1980. Conservation tillage and soil erosion on continuously row-cropped land. In: Crop Production with Conservation in the 80's. American Society of Agricultural Engineers. St. Joseph, MI. pp. 121-133.

Laflen, J.M. and T.S. Colvin. 1981. Effect of crop residues on soil loss from continuous row cropping. Transaction of the American Society of Agricultural Engineers. 24:605-609.

Laflen, J.M., G.R. Foster, and C.A. Onstad. 1985. Simulation of individual-storm soil loss for modeling the impact of soil erosion on crop productivity. Individual-storm soil loss. Chapter 26. *In:* Soil Erosion and Conservation. S.A. El-Swaify, W.C. Moldenhauer, and Andrew Lo, eds. Soil Conservation Society of America. Ankeny, IA. pp. 285-295.

Laflen, J.M., W.J. Elliot, J.R. Simanton, C.S. Holzhey, and K.D. Kohl. 1991a. WEPP: soil erodibility experiments for rangeland and cropland soils. Journal of Soil and Water Conservation. 46:39-44.

Laflen, J.M., L.J. Lane, and G.R. Foster. 1991b. WEPP-A new generation of erosion prediction technology. Journal of Soil and Water Conservation 46(1):34-38.

Lattanzi, A.R., L.D. Meyer, and M.F. Baumgardner. 1974. Influence of mulch rate and slope steepness on interrill erosion. Soil Science Society of America Proceedings. 38:946-950.

Lindstrom, M. J. and C. A. Onstad. 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. Journal of Soil and Water Conservation. 39:149-152.

Long, O.H. 1959. Root studies on some farm crops in Tennessee. Bulletin 301. Agricultural Experiment Station. University of Tennessee, Knoxville, TN. 42 pp.

Lu, J.Y., W.H. Neibling, G.R. Foster, and E.A. Cassol. 1988. Selective Transport and Deposition of Sediment Particles by Shallow Flow. Transactions of American Society of Agricultural Engineers 31(4):1141-1147.

Lyles, L. and J. Tatarko. 1987. Precipitation effects on ridges created by grain drills. Journal of Soil and Water Conservation. 42:269-271.

Mannering, J.V. and L.D. Meyer. 1963. Effects of various rates of surface mulch reduce soil erosion and runoff velocity. Soil Science Society of America Proceedings. 27:84-86.

Mannering, J.V., C.B. Johnson, and L.D. Meyer. 1968. Effect of cropping intensity on erosion and infiltration. Agronomy Journal. 60:206-209.

Mannering, J.V. 1981. The use of soil loss tolerance as a strategy for soil conservation. In: Soil Conservation: Problems and Prospects. R.P.C. Morgan (ed), John Wiley and Sons, Inc., NY. pp. 337-349.

McCool, D.K., L.C. Brown, G.R. Foster, C.K. Mutchler, and L.D. Meyer. 1987. Revised slope steepness factor for the Universal Soil Loss Equation. Transactions of the American Society of Agricultural Engineers 30:1387-1396.

McCool, D.K., G.R. Foster, C.K. Mutchler, and L.D. Meyer. 1989. Revised slope length factor for the Universal Soil Loss Equation. Transactions of American Society of Agricultural Engineers 32(5):1571-1576.

McCool, D.K., M.T. Walter, and L.G. King. 1995. Runoff index values for frozen soil areas of the Pacific Northwest. J. Soil and Water Conservation. 50: 466-469.

McCool, D.K., G.R. Foster, and G.A. Weesies. 1997. Slope length and steepness factors (LS). Chapter 4. *In:* Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook 703. U.S. Department of Agriculture. Washington, DC.

McCool, D. K., G. R. Foster, A. H. Ingersoll, R. C. McClellan, and R. W. Rickman. 2002. Cover-Management Enhancements for RUSLE2 in the Pacific Northwest USA. Vol. II, p. 513-517. In: Proceedings of the 12th Conference of the International Soil Conservation Organization, Beijing, China. 2002.

McCormack, D.E. and K.K. Young. 1981. Technical and societal implications of soil loss tolerance. 364-376, In: Soil Conservation: Problems and Prospects. R.P.C. Morgan (ed), John Wiley and Sons, Inc., NY.

McGregor, K.C., J.D. Greer, G.E. Gurley, and G.C. Bolton. 1969. Runoff and sediment production from north Mississippi Loessial soil. Bulletin 777. Mississippi Agricultural Experiment Station. Mississippi State College, Mississippi.

McGregor, K.C., R.L. Bengtson, and C.K. Mutchler. 1988. Effects of surface straw on interrill runoff and erosion of Grenada silt loam soil. Transactions of the American Society of Agricultural Engineers. 31:111-116

McGregor, K.C., R.L. Bengston, and C.K. Mutchler. 1990. Surface and incorporated wheat straw effects on interrill runoff and soil erosion. Transaction of the American Society of Agricultural Engineers. 33:469-474.

McGregor, K.C., R.L. Bingner, A.J. Bowie, and G.R. Foster. 1995. Erosivity index values for northern Mississippi. Transactions of the American Society of Agricultural Engineers. 38:1039-1047.

McGregor, K.C., S.M. Dabney, and J.R. Johnson. 1999. Runoff and soil loss from cotton plots with and without stiff-grass hedges. Transactions of the American Society of Agricultural Engineers. 42:361-368.

McIsaac, G.F., Mitchell, J.K., and Hirschi, M.C. 1990. Contour and conservation tillage for corn and soybeans in the Tama Silt Loam Soil: hydraulics and sediment concentration. Transactions of the American Society of Agricultural Engineers. 33:1541-1550.

McIsaac, G.F., J.K. Mitchell, M.C. Hirschi, and L.K. Ewing. 1991. Conservation and contour tillage for corn and soybeans in the Tama silt loam soil: the hydrologic response. Soil and Tillage Research. 19:29-46.

Meyer, L.D., and J.V. Mannering. 1967. Tillage and land modification for water erosion control. In: Proceeding ASAE-ASA-SCSA Tillage Conference. American Society of Agricultural Engineers. St. Joseph, MI. 58-62.

Meyer, L.D. and W.H. Wischmeier. 1969. Mathematical simulation of the process of soil erosion by water. Transactions of the American Society of Agricultural Engineers 12:754-758, 762.

Meyer, L.D., W.H. Wischmeier, and G.R. Foster. 1970. Mulch rates required for erosion control on steep slopes. Soil Science Society of American Proceedings 34:928-931.

Meyer, L.D., W.H. Wischmeier, and W.H. Daniel. 1971. Erosion, runoff, and revegetation of denuded construction sites. Transactions of the American Society of Agricultural Engineers. 14:138-141.

Meyer, L.D., C.B. Johnson, and G.R. Foster. 1972. Stone and woodchip mulches for erosion control on construction sites. Journal Soil and Water Conservation 27:264-269.

Meyer, L.D., G.R. Foster, and M.J.M. Römkens. 1975a. Source of soil eroded by water from upland slopes. *In:* Present and Prospective Technology for Predicting Sediment Yields and Sources. ARS-S-40. U.S. Department of Agriculture. pp. 177-189.

Meyer, L.D., G.R. Foster, and S. Nikolov. 1975b. Effect of flow rate and canopy on rill erosion. Transactions of the American Society of Agricultural Engineers 18:905-911.

Meyer, L.D. and M. A. Ports.1976. Prediction and control urban erosion and sedimentation. Proceedings of National Symposium on Urban Hydrology, Hydraulics, and Sedimentation. Bulletin 111. University of Kentucky. Lexington, KY. pp. 323-331.

Meyer, L.D., W.C. Harmon, and L.L. McDowell. 1980. Sediment sizes eroded from crop row sideslopes. Transactions of the Society of Agricultural Engineers. 23: 891-898.

Meyer, L.D. and W. C. Harmon. 1985. Sediment losses from cropland furrows of different gradients. Trans. ASAE. 28: 448-453, 461.

Meyer, L.D. and W.C. Harmon. 1989. How row-sideslope length and steepness affect interrill erosion. Transactions of the Society of Agricultural Engineers. 32:639-644.

Moldenhauer, W.C. and W.H. Wischmeier. 1960. Soil and water losses and infiltration rates on Ida silt loam as influenced by cropping systems, tillage practices and rainfall characteristics. Soil Science Society of America Journal 24:409-413.

Mutchler, C.K., R.E. Burwell, and L.C. Staples. 1976. Runoff and Soil Losses from Barnes Soils in the Northwestern Corn Belt. ARS NC-36. U.S. Department of Agriculture.

Mutchler, C.K. 1970. Splash of a waterdrop at terminal velocity. Science 169:1311-1312.

Mutchler, C.K. and R.A. Young. 1975. Soil detachment by raindrops. 113-117, In: Present and Prospective Technology for Predicting Sediment Yields and Sources. ARS-S-40. U.S Dept of Agriculture, Science and Education Administration. Washington, DC.

Mutchler, C.K., C.E. Murphree, and K.C. McGregor. 1982. Subfactor method for computing C-factors for continuous cotton. Transactions of the American Society of Agricultural Engineers. 25:327-332.

Mutchler, C.K. and K.C. McGregor. 1983. Erosion from low slopes. Water Resources Research. 19:1323-1326.

Mutchler, C.K. and C.E. Carter. 1983. Soil erodibility variation during the year. Transactions of the American Society of Agricultural Engineers. 26:1102-1104, 1108.

Mutchler, C.K. and J.D. Greer.. 1984. Reduced tillage for soybeans. Transactions of the American Society of Agricultural Engineers. 27:1364-1369.

Mutchler, C.K. L.L. McDowell, and J.D. Greer. 1985. Soil loss cotton with conservation tillage. Transactions of the American Society of Agricultural Engineers. 28:160-163, 168.

Mutchler, C.K. and C.E. Murphree, Jr. 1985. Experimentally derived modifications of the USLE. In: Soil Erosion and Conservation. S.A. El-Swaify, W.C. Moldenhauer, and A. L (editors). Soil and Water Conservation Society, Ankeny , IA. pp. 523-527.

Mutchler, C.K. and L.L. McDowell. 1990. Soil loss cotton with winter cover crops. Transactions of the American Society of Agricultural Engineers. 33:432-436.

Nearing, M.A., G.R. Foster, L.J. Lane, and S.C. Finkner. 1989. A process-based soil erosion model for USDA Water Erosion Prediction Project technology. Transactions of American Society of Agricultural Engineers 32(5):1587-1593.

Neibling, W.H. and G.R. Foster. 1982. Transport and deposition of naturally eroded sediment by shallow flow. Paper No. 82-2088. American Society of Agricultural Engineers. St. Joseph, MI.

Parker, D.T. 1962. Decomposition in the field of buried and surface-applied cornstalk residue. Soil Science of America Proceeding 26:559-562.

Reeder, J.D., C.D. Franks, and D.G. Michunas. 2001. Root biomass and microbial processes. In: The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. R.K. Follett, J.M. Kimble, and R. Lal (eds). Lewis Publisher, Boca Raton, FL.

Renard, K.G. and G. R. Foster. 1983. Soil conservation: Principles of erosion by water. Agronomy Monograph no. 23. *In:* Dryland Agriculture. American Society of Agronomy. Madison, WI. pp. 155-176.

Renard, K.G. and J.R. Freimund. 1994. Using monthly precipitation data to estimate the R-factor in the revised USLE. Journal of Hydrology 157:287-306.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder (coordinators). 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook 703. U.S. Department of Agriculture. Washington, DC.

Richardson, C.W., G.R. Foster, and D.A. Wright. 1983. Estimation of erosion index from daily rainfall amount. Transactions of the American Society of Agricultural Engineers 26:153-156, 160.

Römkens, M.J.M., D.W. Nelson, and C.B.Roth. 1975. Soil erosion on selected high clay subsoils. Journal of Soil and Water Conservation. 30:173-176.

Römkens, M.J.M., C.B. Roth, and D.W. Nelson. 1977. Erodibility of selected clay soubsoils in relation to physical and chemical properties. Soil Science Society of America Journal. 41:954-960.

Römkens, M.J.M., R.A. Young, J.W.A. Poesen, D.K.McCool, S.A. El-Swaify, and J.M. Bradford. 1997. Soil erodibility factor. In: Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook 703. U.S. Department of Agriculture, Washington, DC.

Roth, C.B. and D.W. Nelson, and M.J.M. Römkens. 1974. Prediction of subsoil erodibility using chemical, mineralogical and physical parameters. EPA 660/2-74-043. U.S. Department of Environmental Protection, Washington, DC. 111 pp.

Ruffo, M.L. and G.A. Bollero. 2003. Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. Agronomy Journal. 95:900-907.

Schomberg, H.H., J.L. Steiner, and P.W. Unger. 1994. Decomposition and nitrogen dynamics of crop residues: Residue quality and water effects. Soil Science Society of America Journal. 58:372-381.

Schomberg, H.H. and J.L. Steiner. 1995. Comparison of residue decomposition models used in erosion prediction. Pre-publication copy. Agricultural Research Service. U.S. Department of Agriculture. Bushland, TX.

Schomberg, H.H., J.L. Steiner, S.R. Evett, and A.P. Moulin. 1996. Climatic influence on residue decomposition prediction in the Wind Erosion Prediction System. Theoretical and Applied Climatology. 54:5-16.

Schomberg, H.H. and J.L. Steiner. 1997. Comparison of residue decomposition models used in erosion prediction. Agronomy Journal 89:911-919.

Schomberg, H.H. G.R. Foster, J.L. Steiner, and D.E. Stott. 2002. An improved temperature function for modeling crop residue decomposition. Transactions of the American Society of Agricultural Engineers. 45:1415-1422.

Schwab, G.O., R.K. Frevert, T.W. Edminster, and K.K. Barnes. 1966. Soil and Water Conservation Engineering. John Wiley and Sons, New York, NY. pp. 542-559.

Schwab, G.O. and J.L. Fouss. 1967. Tile flow and surface runoff from drainage systems with corn and grass cover. Transactions of the American Society of Agricultural Engineers. 10:492-493, 496.

Schwab, G.O. 1976. Tile or surface drainage for Ohio's heavy soils? Ohio Report. March-April. Ohio Agricultural Experiment Station. Columbus, OH.

Shelton, C. H. and J. F. Bradley. 1987. Controlling erosion and sustaining production with no-till systems. Tennessee Farm and Home Science. Winter:18-23.

Shelton, D.P., P.J. Jasa, E.C. Dickey. 1986. Soil erosion from tillage and planting systems used in soybean residue: Part I - influences of row spacing. Transactions of the American Society of Agricultural Engineers. 29:756-760.

Siemens, J. C. and W. R. Oschwald. 1976. Erosion from corn tillage systems. Transactions of the American Society of Agricultural Engineers.19:69-72.

Simanton, J.R., E. Rawitz, and E.D. Shirley. 1984. The effects of rock fragments on erosion on semiarid rangeland soils. In: Erosion and Productivity of Soils Containing Rock Fragments. Chapter 7, Special Publication 13. Soil Science Society of American. Madison, WI. Pp. 65-72.

Simanton, J.R., M.A. Weltz, and H.D. Larson. 1991. Rangeland experiments to parameterize the water erosion prediction project model: vegetation canopy cover effects. Journal of Range Management. 44:276-282.

Skaggs, R.W., A Nassehzadeh-Tabrizi, and G.R. Foster. 1982. Subsurface drainage effects on erosion. Journal of Soil and Water Conservation 37:167-172.

Smith, J.H. and R.E. Peckenpaugh. 1986. Straw decomposition in irrigated soil: Comparison of twenty three cereal straws. Soil Science Society of America Journal. 50:928-932.

Smith, D.D., D.M. Whitt and A.W. Zingg. 1945. Investigations in erosion control and reclamation of eroded Shelby and related soils at the Conservation Experiment Station, Bethany, Missouri, 1932-42. Technical Bulletin 883. U.S. Department of Agriculture, Washington, DC.

Spaeth, Jr., K.E. F.B. Pierson, M.A. Weltz, and W.H. Blackburn. 2003. Evaluation of USLE and RUSLE estimated soil loss on rangeland. Journal of Range Management. 56:234-246.

Steiner, J.L. H.H. Schomberg, C.L. Douglas, Jr., and A.L. Black. 1994. Standing stem persistence in no-tillage small-grain fields. Agronomy Journal. 86:76-81.

Steiner, J.L., H.H. Schomberg, and P.W. Unger. 1995. Residue decomposition submodel. In: Wind Erosion Prediction System (WEPS), Technical Documentation, L.J. Hagan et al. (ed). Wind Erosion Research Unit, Agricultural Research Service, U.S. Department of Agriculture, Washington, DC. pp. D1-D12.

Steiner, J.L., H.H. Schomberg, P.W. Unger, and J. Cresap. 1999. Crop residue decomposition in no-tillage small-grain fields. Soil Science Society of America Journal 63:1817-1824.

Steiner, J.L., H.H. Schomberg, P.W. Unger, and J. Cresap. 2000. Biomass and residue cover relationships of fresh and decomposing small grain residue. Soil Science Society of America Journal. 64:2109-2114.

Stott, D.E., H.F. Stroo, L.F. Elliott, R.I. Papendick, and P.W. Unger. 1990. Wheat residue loss from fields under no-till management. Soil Science Society of America Journal. 54:92-98.

Stott, D.E. 1991. RSMAN: A tool for soil conservation education. Journal of Soil and Water Conservation. 46:332-333.

Stott, D.E. 1995. Analysis of RUSLE decomposition and mass-to-cover parameters. Unpublished report. National Soil Erosion Research Laboratory, U.S. Department of Agriculture, Agricultural Research Service, W. Lafayette, Indiana.

Stott, D.E., E.E. Alberts, and M.A. Weltz. 1995. Residue decomposition and management. Chapter 9. In: D.C. Flanagan and M.A. Nearing (editors). 1995. Technical Documentation, USDA-Water Erosion Prediction Project (WEPP). NSERL Report No. 10. National Soil Erosion Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture. Washington, D.C.

Swanson, N. P., Dedrick, A. R., Weakley, H. E., Haise, H. R. 1965. Evaluation of mulches for water-erosion control. Transactions of the American Society of Agricultural Engineers. 8:438-440.

Swanson, N.P., A.R. Dedrick, and A.E. Dudeck. 1967. Protecting steep construction slopes against water erosion. Highway Research Record 206. Highway Research Board. Washington, DC. pp. 46-52.

Thomas, R.J. and N.M. Asakawa. 1993. Decomposition of leaf litter from tropical forage grasses and legumes. Soil Biology and Biochemistry. 25:1351-1361.

Toy, T.J. and G.R. Foster (coeditors). 1998. Guidelines for the use of the Revised Universal Soil Loss equation (RUSLE1.06) on mined lands, construction sites, and reclaimed lands. USDI-Office of Surface Mining. Denver. CO.

Toy, T.J. and G.R. Foster. 2000. Estimating Rill-interrill erosion on converging and diverging hillslopes. Unpublished report submitted to National Sedimentation Laboratory, Agricultural Research Service, U.S. Department of Agriculture. Oxford, Mississippi.

Toy, T.J., G.R. Foster, and K.G. Renard. 2002. Soil Erosion: Processes, Prediction, Measurement, and Control. John Wiley and Son, New York, NY.

U.S. Environmental Protection Agency (USEPA). 1976a. Effectiveness of surface mine sedimentation ponds. EPA-600/2-76-117. Environmental Protection Technology Series. Washington, D.C.

U.S. Environmental Protection Agency (USEPA). 1976b. Erosion and Sediment Control: Surface mingin in the Easter U.S. EPA-25/3-76-006. Environmental Protection Agency Technology Transfer Seminar Publication. Washington, D.C.

Van Doren, C.A., R.S. Stauffer, and E.H. Kidder. 1950. Effect of contour farming on soil loss and runoff. Soil Science of America Proceedings 15:413-417.

Van Klaveren, R.W. and D.K. McCool. 1998. Erodibility and critical shear stress of a previously frozen soil. Transactions of the American Society of Agricultural Engineers. 41:1315-1321.

Van Liew, M.W. and K.E. Saxton. 1983. Slope steepness and incorporated residue effects on rill erosion. Transactions of the American Society of Agricultural Engineers. 26: 1738-1743.

Vigil, M. F. and D. Sparks. 2004. Factors affecting the rate of crop residue decomposition under field conditions. Conservation tillage Fact Sheet #3-95. U.S. Department of Agriculture, Washington, DC.

Wagner, L.E. and R.G. Nelson. 1995. Mass reduction of standing and flat crop residue by selected tillage implements. Transactions of the American Society of Agricultural Engineers. 38:419-427.

Williams, J.R., C.A. Jones, J.R. Kiniry, and D.A. Spanel. 1989. The EPIC crop growth model. Transactions of the American Society of Agricultural Engineers. 32:497-511.

Wischmeier, W.H. and D.D. Smith. 1958. Rainfall energy and its relationship to soil loss. Transactions of American Geophysical Union. 39: 285-291.

Wischmeier, W.H. and D.D. Smith. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains: A guide for selection of practices for soil and water conservation. Agriculture Handbook 282. U.S. Department of Agriculture, Washington, DC.

Wischmeier, W.H. and J.V. Mannering. 1969. Relation of soil properties to its erodibility. Soil Science Society of American Proceedings. 33:131-137.

Wischmeier, W.H., C.B. Johnson, and B.V. Cross. 1971. A soil erodibility monograph for farmland construction sites. Journal of Soil and Water Conservation. 26: 189-193.

Wischmeier, W.H. 1975. Estimating the soil loss equation's cover and management factor for undisturbed areas. In: Present and prospective technology for predicting sediment yields and sources. ARS-S40. U.S. Department of Agriculture. Washington, D.C. pp. 118-124.

Wischmeier, W. H. 1978. Conservation tillage to control water erosion. In: Conservation Tillage: The Proceedings of a National Conference. Soil and Water Conservation Society. Ankeny, IA. pp. 133-141.

Wischmeier, W.H. and D.D. Smith. 1978. Predicting rainfall-erosion losses: A guide to conservation planning. Agriculture Handbook 537. U.S. Dept. of Agriculture, Washington, DC.

Yoder, D.C., J.P. Porter, J.M. Laflen, J.R. Simanton, K.G. Renard, D.K. McCool, and G.R. Foster. 1997. Cover-management factor (C). In: A Guide to Conservation Planning with the Revised Soil Loss Equation (RUSLE). Agriculture Handbook 703. U.S. Department of Agriculture. Chapter 5.

Young, R.A. and C. K. Mutchler. 1969. Soil and water movement in small tillage channels. Transactions of the American Society of Agricultural Engineers. 12:543-545.

Young, R.A. and C.K. Mutchler. 1977. Erodibility of some Minnesota soils. Journal of Soil and Water Conservation. 32:180-182.

Zingg, A.W. 1940. Degree and length of land slope as it affects soil loss in runoff. Agricultural Engineering. 21:59-64.

12.2. References not cited

12.2.1. Contouring References

Diseker, E.G. and R.E. Yoder. 1936. Sheet erosion studies on Cecil clay. Bulletin 245. Alabama Agricultural Experiment Station. Auburn, University. Auburn, AL.

Jamison, V.C., D.D. Smith, and J.F. Thornton. 1968. Soil and water research on a claypan soil. Technical Bulletin 1379. U.S. Department of Agriculture. Washington, D.C.

Knoblauch, H.C. and J.L. Hayes. 1940. The effect of contour cultivation on runoff. Transactions of the American Geophysical Union. 21:499-504.

Lamb, Jr., J., J.S. Andrews, and A.F. Gustafson. 1944. Experiment in the control of soil erosion in southern New York. Bulletin 811. New York Agricultural Experiment Station. Cornell University, Ithaca, NY.

McIsaac, G, F., Mitchell, J. K., Siemans, J.C., Hummel, J. W. 1987. Row cultivation effects on runoff, soil loss and corn grain yield. Transactions of the American Society of Agricultural Engineers. 30:125-128,136.

Nichols, M.L. and H.D. Sexton. 1932. A method of studying soil erosion. Agricultural Engineering. 13:101-103.

Young, R.A., C.K. Mutchler, and W.H. Wischmeier. 1964. Influence of row direction and type of vegetal cover on the soil-loss relationship. Transactions of the American Society of Agricultural Engineers. 7:316-317, 320.

12.2.2. Decomposition References

Collins, H.P., L.F. Elliot, and R.I. Papendick. 1986. 1990. Wheat straw decomposition and changes in decomposition during field exposure. Soil Science Society of America Journal. 54:1013-1016.

Douglas, Jr., C.L. and R.W. Rickman. 1992. Estimating crop residue decomposition from air temperature, initial nitrogen content, and residue placement. Soil Science Society of America Journal. 56:272-278.

Ghidey, F., J. M. Gregory, T. R. McCarty, and E. E. Alberts. 1985. Residue decay evaluation and prediction. Transactions of the American Society of Agricultural Engineers. 28:102-105.

McGregor, K.C. and C.K. Mutchler 1983. C Factors for no-till and reduced-till corn. Transactions of the American Society of Agricultural Engineers. 26:785-788.

Murphree, C.E. and C.K. Mutchler. 1980. Cover and management factors for cotton. Transactions of the American Society of Agricultural Engineers. 23:585-588, 595.

Van Doren, Jr., D.M., W.C. Moldenhauer, and G.B. Triplett, Jr. 1984. Influence of long-term tillage and crop rotation on water erosion. Soil Society of America Journal 48:636-640.

Weaver, J.E. 1947. Rate of decomposition roots and rhizomes of certain range grasses in undisturbed prairie soils. Ecology. 28:221-240.

12.2.3. No-Till and other Conservation Tillage References

Adams, J. E. 1974. Residual effects of crop rotations on water intake, soil loss, and sorghum yield. Agronomy Journal 66:299-304.

Alberts, E. E., R. C. Wendt, and R. E. Burwell. 1985. Corn and soybean cropping effects on soil losses and C-factors. Soil Science Society of America Journal 49:721-728.

Andraski, B. J., D. H. Mueller, and T. C. Daniel. 1985. Effects of tillage and rainfall date on water and soil losses. Soil Science Society of America Journal 49:1512-1517.

Baker, J. L. and Laflen, J. M. 1983. Runoff losses of nutrients and soil from ground fall-fertilized after soybean harvest. Transactions of the American Society of Agricultural Engineers. 26:1122-1127

Blevins, R. L., W. W. Frye, P. L. Baldwin, S. D. Robertson. 1990. Tillage effects on sediment and soluble nutrient losses from a Maury Silt Loam Soil. Journal of Environmental. Quality. 19:683-686.

Blough, R. F., A. R. Jarrett, J. M. Hamlett, and M. D. Shaw. 1990. Runoff and erosion rates from slit, conventional, and chisel tillage. Transactions of the American Society of Agricultural Engineers. 33:1882-1888.

Burwell, R. E. and L. A. Kramer. 1983. Long-term annual runoff and soil loss from conventional and conservation tillage of corn. Journal of Soil and Water Conservation. 38:315-319.

Comis, D.L. 1984. Tennessee researchers find no-till, double-cropped soybeans cut erosion. Soil and Water Conservation News. 5:10.

Dabney, S. M., C. E. Murphree, and L. D. Meyer. 1993. Tillage, row spacing, and cultivation affect erosion from soybean cropland. Transactions of the American Society of Agricultural Engineers. 36:87-94.

Dick, W. A., McCoy, E. L., Edwards, W. M., and Lal, R. 1991. Continuous application of no-tillage to Ohio Soils. Agronomy Journal. 83:65-73.

Dickey, E. C., D. P. Shelton, P. J. Jasa, and T. R. Peterson. 1984. Tillage, residue and erosion on moderately sloping soils. Transactions of the American Society of Agricultural Engineers. 27:1093-1099.

Diezman, M. M., S. Mostaghimi, V. O. Shanholtz, J. K. Mitchell. 1987. Size distribution of eroded sediment from two tillage systems. Transactions of the American Society of Agricultural Engineers. 30:1642-1647.

Gilley, J. E., Finkner, S. C., Varvel, G. E. 1986. Runoff and erosion as affected by sorghum and soybean residue. Transactions of the American Society of Agricultural Engineers. 29:1605-1610.

Gilley, J. E., Finkner, S. C., and Varvel, G. E. 1987. Slope length and surface residue influences on runoff and erosions. Transactions of the American Society of Agricultural Engineers. 30:148-152.

Hairston, J. E., J. O. Sanford, H. C. Hayes, and L. L. Reinschmiedt. 1984. Crop yield, soil erosion, and net returns from five tillage systems in the Mississippi Blackland Prairie. Journal of Soil and Water Conservation. 39:391-395.

Hamlett, J. M., J. L. Baker, S. C. Kimes, H. P. Johnson. 1984. Runoff and sediment transport within and from small agricultural watersheds. Transactions of the American Society of Agricultural Engineers. 27:1355-1363, 1369.

Harrold, L. L., G. B. Triplett, Jr., and W. M. Edwards. 1970. No-tillage corn - characteristics of the system. Agricultural Engineering. 51:128-131.

Harrold, L. L., and W. M. Edwards. 1972. A severe rainstorm test of no-till corn. Journal of Soil and Water Conservation. 27:30.

Harrold, L. L. and W. M. Edwards. 1974. No-tillage system reduces erosion from continuous corn watersheds. Transactions of the American Society of Agricultural Engineers. 17:414-416.

Jasa, P.J., and E.C. Dickey. 1991. Subsoiling, contouring, and tillage effects on erosion and runoff. Applied Engineering in Agriculture. 7:81-85.

Jones, J.N., J. E. Moody, G. M. Shear, W. W. Moschler, and J. J. Lillard. 1968. The no-tillage system for corn. Agronomy Journal. 60:17-20.

Kramer, L. A. 1986. Runoff and soil loss by cropstage from conventional and conservation tilled corn. Transactions of the American Society of Agricultural Engineers. 29:774-779.

Laflen, J. M., Moldenhauer, .W. C., and Colvin, T. S. 1981. Conservation tillage and soil erosion on continuously row-cropped land. In Crop Production with Conservation in the 80's. American Society of Agricultural Engineers. St. Joseph, MI. pp. 121-133.

Laflen, J. M.and T. S. Colvin. 1982. Soil and water loss from no-till, narrow-row soybeans. Paper no. 82-2023. American Society of Agricultural Engineers. St Joseph, MI.

Langdale, G. W., A. P. Barnett, R. A. Leonard, and W. G. Fleming. 1979. Reduction of soil erosion by the no-till system in the Southern Piedmont. Transactions of the American Society of Agricultural Engineers. 21:82-86, 92.

Langdale, G. W., M. C. Mills, and A. W. Thomas. 1992. Use of conservation tillage to retard erosive effects of large storms. Journal of Soil and Water Conservation. 47:257-260.

Langdale, G. W., L. T. West, R. R. Bruce, W. P. Miller, and A. W. Thomas. 1992. Restoration of eroded soil with conservation tillage. Soil Technology. 5:81-90.

Mannering, J. V., L. D. Meyer, and Johnson, C.B. 1966. Infiltration and erosion as affected by minimum tillage for corn. Soil Science Society of America Proceedings. 30:101-105.

McGregor, K. C., J. D. Greer, and G. E. Gurley. 1975. Erosion control with no-till cropping practices. Transactions of the American Society of Agricultural Engineers. 18:918-920.

McGregor, K. C. and J. D. Greer. 1982. Erosion control with no-till and reduced-till corn for silage and grain. Transactions of the American Society of Agricultural Engineers. 25:154-159.

McGregor, K. C. 1983. C factors for no-till and conventional-till soybeans from plot data. Transactions of the American Society of Agricultural Engineers. 26:1119-1122.

McGregor, K. C. and C. K. Mutchler. 1983. C factors for no-till and reduced-till corn. Transactions of the American Society of Agricultural Engineers. 26:785-788, 794.

McGregor, K. C. and C. K. Mutchler. 1992. Soil loss from conservation tillage for sorghum. Transactions of the American Society of Agricultural Engineers. 35:1841-1845.

McIsaac, G, F., Mitchell, J. K., Siemans, J.C., Hummel, J. W. 1987. Row cultivation effects on runoff, soil loss and corn grain yield. Transactions of the American Society of Agricultural Engineers. 30:125-128,136.

McIsaac, G. F., Mitchell, J. K., and Hirschi, M. C. 1988. Runoff and sediment concentration from conservation tillage for corn and soybeans under simulated rainfall. Paper no. 88-2595. American Society of Agricultural Engineers. St. Joseph, MI.

McIsaac, G. F., M.C. Hirschi, and J. K. Mitchell. 1991. Nitrogen and phosphorus in eroded sediment from corn and soybean tillage systems. Journal of Environmental Quality 20:663-670.

McIsaac, G. F, and Mitchell, J. K. 1992. Annual variation in runoff and erosion from simulated rainfall on corn and soybean tillage systems. Paper no.91-2016. American Society of Agricultural Engineers. St. Joseph, MI.

McIsaac,G. F.,and Mitchell, J. K. 1992. Temporal variation in runoff and soil loss from simulated rainfall on corn and soybeans. Transactions of the American Society of Agricultural Engineers. 35:465-472.

Meyer, L. D. and J. V. Mannering. 1961. Minimum tillage for corn: its effect on infiltration and erosion. Transactions of the American Society of Agricultural Engineers. 42:72-75.

Mills, W. C., A. W. Thomas, and G. W. Langdale. 1986. Estimating soil loss probabilities for Southern Piedmont cropping-tillage systems. Transactions of the American Society of Agricultural Engineers. 29:948-955.

Mills, W. C., A. W. Thomas, and G. W. Langdale. 1992. Seasonal and crop effects on soil loss and rainfall retention probabilities: an example from the U.S. Southern Piedmont. Soil Technology. 5:67-79.

Moldenhauer, W. C., W. G. Lovely, N. P. Swanson, and H. D. Currence. 1971. Effect of row grades and tillage systems on soil and water losses. Journal of Soil and Water Conservation. 26:193-195.

Moldenhauer, W. C., G. W. Langdale, W. Frye, D. K. McCool, R. I. Papendick, D. E. Smika, and D. W. Fryrear. 1983. Conservation tillage for erosion control. Journal of Soil and Water Conservation. 38:144-151.

Mostaghimi, S., Dillaha, T. A., and Shanholtz, V. O. 1986. Influence of tillage systems and residue levels on runoff, sediment, and phosphorus losses. Transactions of the American Society of Agricultural Engineers. 31:128-132.

Mueller, D. H., R. C. Wendt, and T. C. Daniel. 1984. Soil and water losses as affected by tillage and manure application. Soil Science Society of America Journal. 48:896-900.

Mutchler, C. K., Murphree, C. E., and McGregor, K. C. 1982. Subfactor method for computing C factors for continuous cotton. Transactions of the American Society of Agricultural Engineers. 25:327-332.

Onstad, C. A. 1972. Soil and water losses as affected by tillage practices. Transactions of the American Society of Agricultural Engineers. 15:287-289.

Salehi, F., A. R. Pesant, and R. Lagace. 1991. Validation of the universal soil loss equation for three cropping systems under natural rainfall in Southeastern Quebeck. Canadian Agricultural Engineering. 33:11-16.

Seta, A.K., R.L. Blevins, W.W. Frye, and B.J. Barfield. 1993. Reducing soil erosion and agricultural chemical losses with conservation tillage. Journal of Environmental Quality. 22:661-665.

Shelton, C. H., F. D. Tomkins, and D. D. Tyler. 1983. Soil erosion from five soybean tillage systems. Journal of Soil and Water Conservation. 38:425-428.

Siemens, J. C. and W. R. Oschwald. 1978. Corn-soybean tillage systems: erosion control, effects on crop production, costs. Transactions of the American Society of Agricultural Engineers. 21:293-302.

Sloneker, L. L. and W. C. Moldenhauer. 1977. Measuring the amounts of crop residue remaining after tillage. Journal of Soil and Water Conservation. 32:231-236.

Stein, O. R., W. H. Neibling, T. J. Logan, and W. C. Moldenhauer. 1986. Runoff and soil loss as influenced by tillage and residue cover. Soil Science Society of America Journal. 50:1527-1531.

Sturgul, S. J., Daniel, T. C., and Mueller, H. D. 1990. Tillage and canopy cover effects on interill erosion from first-year alfalfa. Soil Science Society of America Journal. 54:1733-1739.

Van Doren, D. M., W. C. Moldenhauer, and G. B. Triplett. 1984. Influence of long-term tillage and crop rotation on water erosion. Soil Science Society of America Journal. 48:636-640.

Wendt, R. C. and R. E. Burwell. 1985. Runoff and soil losses for conventional, reduced, and no-till corn. Journal of Soil and Water Conservation. 40:450-454.

West, L. T., W. P. Miller, G. W. Langdale, R. R. Bruce, J. M. Laflen, A. W. Thomas. 1991. Cropping system effects on interrill soil loss in the Georgia Piedmont. Soil Science Society of America Journal. 55:460-466.

Wood, S. D. and A. D. Worsham. 1986. Reducing soil erosion in tobacco fields with no-tillage transplanting. Journal of Soil and Water Conservation 41:193-196.

Yoo, K. Y. and J. T. Touchton. 1988. Surface runoff and sediment yield from various tillage systems of cotton. Transactions of the American Society of Agricultural Engineers. 31:1154-1158.

Yoo, K. Y. and E. W. Rochester. 1989. Variation of runoff characteristics under conservation tillage systems. Transactions of the American Society of Agricultural Engineers. 32:1625-1630.

Yoo, K. Y. and J. T. Touchton. 1989. Runoff and soil loss by crop growth stage under three cotton tillage systems. Journal of Soil and Water Conservation. 44:225-228.

Zhu, J. C., C. J. Gantzer, S. H. Anderson, E. E. Alberts. 1989. Runoff, soil, and nutrient losses from no-till soybean with winter cover crops. Soil Science Society of America Journal. 53:1210-1214.

12.2.4. Redistribution of Material in Soil by Soil Disturbing Operations References

Allmaras R.R., S.M. Copeland, P.J. Copeland, and M. Oussible. 1996. Spatial relations between oat residue and ceramic spheres when incorporated sequentially by tillage. Soil Science Society of America Journal. 60:1209-1216.

Juzwik, J., D.L. Stenlund, R.R. Allmaras, S.M. Copeland, and R.E. McRoberts. 1997.Incorporation of tracers and dazomet by rotary tillers and a spading machine. Sol and Tillage Research. 41:237-248.

Staricka, J.A., P.M. Burford, R.R. Allmaras, and W.W. Nelson. 1990. Tracing the vertical distribution of simulated shattered seeds as related to tillage. Agronomy Journal. 82:1131-1134.

Staricka, J.A., R.R. Allmaras, and W.W. Nelson. 1991. Spatial variation of crop residue incorporated by tillage. Soil Science Society of America Journal. 53:1668-1674.

Staricka, J.A., R.R. Allmaras, W.W. Nelson, and W.E. Larson. 1992. Soil aggregate longevity as determined by the incorporation of ceramic spheres. Soil Science Society of America Journal. 56:1591-1597.

Stenlund, D.L., J. Juzwik, R.R. Allmaras, and S.M. Copeland. 1997. Incorporation of surface-applied materials by tillage implements. General Technical Report PNW 365. Forest Service. U.S. Department of Agriculture, Washington, D.C. pp 29-30.

12.2.5. Root and Root: Top Growth Ratios References

Arnon. I. 1975. Mineral Nutrition of Maize. International Potash Institute. Bern-Worblaufen, Switzerland.

Buyanovsky, G.A. and G.H. Wagner. 1986. Post-harvest residue input to cropland. Plant and Soil. 93:57-65.

Dalrymple, R.L. and D.D. Dwyer. 1967. Root and shoot growth of five range grasses. Journal of Range Management. 20:141-145.

Foth, H.D. 1962. Root and top growth of corn. Agronomy Journal. 54:49-52.

Kramer, J. and J.E. Weaver. 1936. Relative Efficiency of Roots and Tops of Plants in Protecting the Soil from Erosion. Bulletin 12. Conservation and Survery Division, University of Nebraska, Lincoln, NE.

Raper, Jr., C.D. and S.A. Barber. 1970. Rooting systems of soybeans. I. Difference in root morphology among varieties. Agronomy Journal. 62:581-584.

Taylor, R.S. Plant Root Systems: Their Function and Interaction with the Soil. Chapters 2 and 4. MCGraw-Hill Book Company. New York, NY.

Wallace, A., S.A. Bamburg, and J.W. Cha. 1974. Quantitative studies of roots of perennial plants in the Mojave Desert. Ecology. 55:1160-1162.

Weaver, J.E. and G.W. Harmon. 1935. Quantity of Living Plant Materials in Prairie Soils in Relation to Run-Off and Soil Erosion. Bulletin 8. Conservation and Survey Division. University of Nebraska. Lincoln, NE.

A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

Prepared by Pamela C. Dodds, Ph.D., Licensed Professional Geologist
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USER'S REFERENCE GUIDE

Revised Universal Soil Loss Equation
Version 2

(RUSLE2)

Prepared for
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The USDA-ARS was responsible for providing the erosion science on which RUSLE2 is based including the mathematical equations used in RUSLE2, core data values used to calibrate RUSLE2, scientific documentation, and a user's reference guide for RUSLE2.

The USDA-NRCS was the principal client for RUSLE2. The NRCS provided information to ensure that RUSLE2 could be easily used in their local field (district) offices. The NRCS also developed an extensive RUSLE2 operational (working) database, primarily for cropland. The NRCS has developed RUSLE2 templates and user guides specifically for their purposes.

The interests and needs of a wide variety of other users were considered during RUSLE2's development. RUSLE2 was developed to be land-use independent to give RUSLE2 the wide applicability range possible and to accommodate the needs of these users.

The University of Tennessee participated in the development of the mathematical equations used in RUSLE2, developed the computer science used in RUSLE2, and developed the RUSLE2 computer program. They also developed user guides and other RUSLE2 information for their clients.

This RUSLE2 User's Reference Guide was reviewed by USDA-Natural Resources Conservation Service technical specialists from several disciplines; Kenneth G. Renard (retired), USDA-Agricultural Research Service, Tucson, Arizona, and Seth Dabney, USDA-Agricultural Research Service, Oxford, Mississippi.

Preface

This RUSLE2 User's Reference Guide describes RUSLE2 in detail in semi-technical language. This Guide describes how RUSLE2 works, how to select input values, how to apply RUSLE2 to make erosion estimates for the wide range of conditions represented by RUSLE2, how to interpret values computed by RUSLE2, how to evaluate RUSLE2's adequacy for conservation and erosion control planning, RUSLE2's accuracy, and how to conduct sensitivity analysis with RUSLE2. This Guide also describes similarities and differences between RUSLE2 and the USLE and RUSLE1, widely used predecessor technologies, and how to select input values and make interpretations when comparing erosion values estimated by these technologies.

RUSLE2 is land use independent and applies to all land uses where soil erosion occurs by erosive forces applied to exposed mineral soil by raindrop impact and surface runoff produced by Hortonian overland flow. This User's Reference Guide is targeted to technical specialists, who in turn, can use the information in this Guide to develop application-specific RUSLE2 user guides.

This User Reference Guide provides information on contact agencies that can provide additional information on RUSLE2.

A companion RUSLE2 Science Documentation describes the mathematical procedures used in RUSLE2.

Disclaimer

The purpose of RUSLE2 is to guide and assist erosion-control planning. Erosion-control planners should consider information generated by RUSLE2 to be only one set of information used to make an erosion-control decision. RUSLE2 has been verified and validated, and every reasonable effort has been made to ensure that RUSLE2 works as described in RUSLE2 documentation available from the USDA-Agricultural Research Service. However, RUSLE2 users should be aware that errors may exist in RUSLE2 and exercise due caution in using RUSLE2.

Similarly, this RUSLE2 User's Reference Guide has been reviewed by erosion scientists and RUSLE2 users. These reviewers' comments have been faithfully considered in the revision of this document.

Every reasonable effort has been made to ensure that this document is accurate. The USDA-Agricultural Research Service alone is responsible for this document's accuracy and how faithfully the RUSLE2 computer program represents the information in this document.

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Glossary of Terms

Term	Description
10 yr EI	Storm EI with a 10-year return period
10 yr-24 hr EI	Storm EI for the 10 yr-24 hr precipitation amount
10 yr-24 hr precipitation	24 hour precipitation amount having a 10-year return period
Antecedent soil moisture subfactor	See cover-management subfactors.
Average annual, monthly, period, and daily erosion	RUSLE2 computes average daily erosion for each day of the year, which represents the average erosion that would be observed if erosion was measured on that day for a sufficiently long period. Average period, monthly, and annual erosion are sums of the average daily values.
Average erosion	Average erosion is the sediment load at a given location on the overland flow path divided by the distance from the origin of overland flow path to the location.
b value, also b_f value	Coefficient in equation for effect of ground cover on erosion; values vary daily with rill-interrill erosion ratio and residue type
Birth of biomass	Refers to the addition of live aboveground and root biomass simultaneous with the death during growth periods when canopy cover and root biomass is increasing
Buffer strips	Dense vegetation strips uniformly spaced along overland flow path; can cause much deposition
Burial ratio	Portion of existing surface (flat) cover mass that is buried by a soil *disturbing* operation; dry mass basis-not area covered basis
Calibration	Procedure of fitting an equation to data to determine numerical values for equation’s coefficients
Canopy cover	Cover above soil surface; does not contact runoff; usually provided by vegetation
Canopy shape	Standard shapes used to assist selection of effective fall height values for waterdrops falling from canopy
Canopy subfactor	See cover-management subfactors.
Channel order	Relative position of a channel in a concentrated flow network
Climate description	Input values for variables used to represent climate (primarily temperature, precipitation, and erosivity density); stored in RUSLE2 climate database component under a location name
Concentrated flow area	Area on landscape where channel flow occurs; ends overland flow path
Conservation planning soil loss	A conservation planning erosion value that gives partial credit to deposition as soil saved; credit is function of location on overland flow path where deposition occurs
Contouring	Support erosion-control practice involving ridges-furrows that

	reduces erosion by redirecting runoff around hillslope
Contouring failure	Contouring effectiveness is lost where runoff shear stress exceeds a critical value
Contouring description	Row grade (steepness) used to describe contouring; stored in RUSLE2 contouring component database under name for contouring practice; ridge height in *operation* description used in cover-*management* description also key input in addition to row grade
Core database	RUSLE2 database that includes values for base conditions used to validate RUSLE2; input values for a new condition must be consistent with values in core database for similar conditions
Cover-*management* description	Values for variables that describe cover-management; includes dates, *operation* descriptions, *vegetation* descriptions, yields (vegetation production level), applied external residue (*residue* description) and amount applied; named and saved in RUSLE2 management component database
Cover-management subfactors (subfactors used in RUSLE2 listed below in italics)	Cover-management subfactor values used to compute detachment (sediment production) by multiplying subfactor values, subfactor values vary through temporally
Canopy	Represents how canopy affects erosion, function of canopy cover and effective fall height
Ground cover	Represents how ground cover affects erosion; primarily function of portion of soil surface covered
Surface roughness	Represents how soil surface roughness and its interaction with soil biomass affect erosion
Soil biomass	Represents how live and dead roots in upper 10 inches of soil and buried residue in upper 3 inches and less of soil affects erosion
Soil consolidation	Represents how a mechanical disturbance and it interaction with soil biomass affect erosion, erosion decreases over time after last disturbance as the soil consolidates (a soil bonding effect that occurs with wetting and drying of the soil-not a mechanical effect)
Ridging	Represents how ridges increase detachment (sediment production)
Ponding	Represents how a water layer on soil surface reduces erosion
Antecedent soil moisture	Represents how previous vegetation affects erosion by reducing soil moisture, used only in Req zone
Critical slope length	Location along a uniform overland flow path where contouring fails
Cultural practice	Erosion control practice, such as no-till cropping, where cover-management is used to reduce erosion
Curve number	An index used in NRCS curve number method to compute runoff; RUSLE2 computes curve number value as function of hydrologic

	soil group and cover-management conditions
Database	RUSLE2 database stores both input and output information in named descriptions
Dead biomass	Represents live above ground and root biomass that has been converted to dead biomass by *kill vegetation* process in an *operation* description; dead biomass decomposes
Dead root biomass	A *kill vegetation* process in an *operation* description converts live root biomass to dead root biomass, dead roots decompose at the same rate as surface and buried residue
Dead standing biomass	Represents live aboveground biomass converted to dead standing biomass by a *kill vegetation* process in an *operation* description; dead standing biomass does not contact soil surface; dead standing biomass decomposes more slowly than surface and subsurface dead biomass
Dead surface biomass	Represents surface biomass that resulted from live aboveground biomass being killed and flattened to become surface biomass, buried residue that has been brought to the soil surface by a soil disturbing process in an operation description, and material that has been applied as external residue; in contact with soil surface
Death of biomass	Refers to the loss of live aboveground and root biomass simultaneous with birth of live biomass during growth periods when canopy cover and root biomass is increasing; daily death of live aboveground biomass adds to surface residue pool and daily death of root biomass adds to dead root biomass pool
Decomposition	Loss of dead biomass as a function of material properties, precipitation, and temperature; decomposition rates for all plant parts and buried and surface biomass are equal; decomposition rate for standing residue is significantly decreased because of no soil contact
Deposition	Transfers sediment from sediment load being transported by runoff to soil surface; net deposition causes sediment load to decrease with distance along overland flow path; depends on sediment characteristics and degree that sediment load exceeds sediment transport capacity; enriches sediment load in fines; computed as a function of sediment particle class fall velocity, runoff rate, and difference between sediment load and transport capacity
Deposition portion	Portion of overland flow path where net deposition occurs
Detachment	Process that separates soil particles from soil mass by raindrops, waterdrops falling from vegetation, and surface runoff; net detachment causes sediment load to increase along overland flow path; detachment is non-selective with respect to sediment characteristics; computed as function of erosivity, soil erodibility, distance along overland flow path, steepness of overland flow path, cover-management condition, and contouring

Disaggregation	Mathematical procedure used to covert monthly precipitation and temperature values to daily values assuming that values vary linearly; daily precipitation values sum to monthly values; average of disaggregated daily temperature equal average monthly value
Diversion/terrace/ sediment basin	A set of support practices that intercept overland flow to end overland flow path length.
Diversions	Intercepts overland flow and directs it around hillslope in channelized flow; grade is sufficiently steep that deposition does not occur but not so steep that erosion occurs in the diversion
EI_{30}	Storm (rainfall) erosivity; product of storm energy and maximum 30-minute intensity; storm energy closely related to rain storm amount and partly to rainfall intensity
Enrichment	Deposition is selective, removing the coarse and dense particles, which leaves the sediment load with an increased portion of fine and less dense particles
Enrichment ratio	Ratio of specific surface area of sediment after deposition to specific surface area of soil subject to erosion
Ephemeral gully erosion	Erosion that occurs in concentrated flow areas
Eroding portion	Portion of overland flow path where net detachment (erosion) occurs
Erosivity	Index of rainfall erosivity at a location; closely related to rainfall amount and intensity; monthly erosivity is average annual sum of individual storm erosivity values in month; annual erosivity is average sum of values in year; storm rainfall amount must be ½ inch (12 mm) or more to be included in computation of erosivity
Erosivity density	Ratio of monthly erosivity to monthly precipitation amount
External residue	Material, usually biomass, added to soil surface or placed in the soil; affects erosion same as surface residue and buried residue from vegetation
Fabric (silt) fence	Porous fabric about 18 inches wide placed against upright posts on the contour; these barriers pond runoff and cause deposition; widely used on construction sites
Fall height (effective)	Effective fall height is the effective height from which waterdrops fall from canopy; depends on canopy shape, canopy density height gradient, and top and bottom canopy heights
Filter strip	A single strip of dense vegetation located at the end of an overland flow path; can induce high amounts of deposition
Final roughness	Soil surface roughness after roughness has decayed to unit plot conditions, primarily represents roughness provided by soil resistant clods
Flattening ratio	Describes how much standing residue that an operation flattens; ratio of standing residue mass before operation to standing residue mass after operation; depends on operation and residue; dry mass

	basis
Flow interceptors	Topographic features (ridges, channel) on an overflow path that collect overland flow and direct the runoff around hillslope; end overland flow path; diversions, terraces, and sediment basins are flow interceptors
Form roughness	Represents the hydraulic roughness provided by soil surface roughness, vegetation, and residue; reduces detachment and sediment transport capacity of runoff
Gradient terraces	Terraces on a uniform grade (steepness)
Grain roughness	Represents the hydraulic roughness provided by the soil; responsible for detachment and sediment transport by flow
Ground cover	Represents the portion of the soil surface covered by material in direct contact with soil; includes plant litter, crop residue, rocks, algae, mulch, and other material that reduces both raindrop impact and runoff (surface flow) erosivity
Ground cover subfactor	See cover-management subfactors
Growth chart	The collection of values that describe the temporal vegetation variables of live root biomass in upper 4 inches (100mm), canopy cover, fall height, and live ground cover; values are in a vegetation description
Hortonian overland flow	Overland flow generated by rainfall intensity being greater than infiltration rate; although flow may be concentrated in micro-channels (rills), runoff is uniformly distributed around hillslope
Hydraulic (roughness) resistance	Degree that ground cover, surface roughness, and vegetation slow runoff; varies daily as cover-management conditions change
Hydraulic element	RUSLE2 hydraulic elements are a channel and a small impoundment
Hydraulic element flow path description	Describes the flow path through a sequence of hydraulic elements, named and saved in RUSLE2 hydraulic element component database
Hydraulic element system description	Describes a set of hydraulic element paths that are uniformly spaced along the overland flow path described without the hydraulic element system being present; named and saved in RUSLE2 hydraulic path component database
Hydrologic soil group	Index of runoff potential of a soil profile at a given geographic location, at a particular position on the landscape, and with the presence or absence of subsurface drainage
Impoundment	A flow interceptor; impounds runoff; results in sediment deposition, represents typical impoundment terraces on cropland and small sediment basins on construction sites
Impoundment parallel terrace	Parallel terraces-impoundments (PTO) where terraces cross concentrated flow areas; impoundment drains through a riser into

	underground pipe
Incorporated biomass	Biomass incorporated (buried) in the soil by a *soil disturbing* operation; also biomass added to the soil from decomposition of surface biomass; amount added by decomposition of surface material is function of soil consolidation subfactor
Inherent organic matter	Soil organic matter content in unit-plot condition
Inherent soil erodibility	Soil erodibility determined by inherent soil properties; measured under unit-plot conditions (see soil erodibility)
Initial conditions	Cover-management conditions at the beginning of a no-rotation cover-management description
Initial input roughness	Soil surface roughness index value assigned to *soil disturbing* operation that occurs on the base condition of a silt loam soil with a large amount of biomass on and in the soil; actual initial roughness value used in computations is a function of soil texture, soil biomass, existing roughness at time of soil disturbance, and tillage intensity
Injected biomass	Biomass placed in the soil using an *add other residue/cover* process in a *soil disturbing* operation description (see *operation* processes); biomass is placed in lower half of disturbance depth
Interrill erosion	Erosion caused by water drop impact; not function of distance along overland flow path unless soil, steepness, and cover-management conditions vary; interrill areas are the spaces between rills where very thin flow occurs
Irrigation	Water artificially added to the soil to enhance seed germination and vegetation production
Land use independent	RUSLE2 applies to all situations where Hortonian overland flow occurs and where raindrop impact and surface runoff cause rill and interrill erosion of exposed mineral soil; the same RUSLE2 equations are used to compute erosion regardless of land use
Live aboveground biomass	Live aboveground biomass (dry matter basis); converted to standing residue (dead biomass) by a *kill vegetation* process in an *operation* description.
Live ground (surface) cover	Parts of live aboveground biomass that touches the soil surface to reduce erosion.
Live root biomass	RUSLE2 distributes input values for live root biomass in upper four inches of soil profile over a constant rooting depth of 10 inches for all vegetation types and growth stages. A *kill vegetation* process in an *operation* description converts live root biomass to dead root biomass. Primarily refers to fine roots that are produced annually; RUSLE2 uses live and dead root biomass in the upper 10 inches of soil profile to compute a value for the soil biomass subfactor
Local deposition	Deposition that occurs very near, within a few inches, from the point of detachment in surface roughness depressions and in

	furrows between ridges; given full credit for soil saved
Long term roughness	Soil surface roughness that naturally develops over time; specified as input in cover-*management* description; depends on vegetation characteristics (e.g., bunch versus sod forming grasses, root pattern near soil surface) and local erosion and deposition, especially by wind erosion; RUSLE2 computes roughness over time; develops fully by time to soil consolidation
Long term vegetation	Permanent vegetation like that on pasture, range, reclaimed mined land, and landfills; vegetation description can include temporal values starting on seeding date through maturity, any arbitrary date after seeding date, or only for the vegetation at maturity
Management alignment offset	Used to sequence cover-*management* descriptions along an overland flow path to create alternating strips
Mass-cover relationship	Equation used to compute portion of soil surface covered by a particular residue mass (dry basis)
Mass-yield relationship	Equation used to compute standing biomass (dry basis) of vegetation as a function of production (yield) level
Maximum 30-minute intensity	Average rainfall intensity over the continuous 30 minutes that contains the greatest amount in a rain storm
Non-erodible cover	Cover such as plastic, standing water, snow, and other material that completely eliminates erosion, material can be porous and disappear over time
Non-uniform overland flow path	Soil, steepness, and/or cover-management vary along an overland flow path; path is divided into segments where selections are made for each segment
NRCS curve number method	Mathematical procedure used in RUSLE2 to compute runoff using precipitation amount; a daily runoff value is computed using the 10 yr-24 hr precipitation amount. Daily runoff amount varies as daily curve number varies based on temporally varying cover-management conditions
NWWR	Northwest Wheat and Range Region; a region in the Northwestern US covering eastern Washington and Oregon, northern Idaho; see Req zone
Operation	An operation changes soil, vegetation, or residue; typically represents common farm and construction activities such as plowing, blading, vehicular or animal traffic, and mowing; also represents burning and natural processes like killing frost and germination of volunteer vegetation
Operation disturbance depth	Surface residue buried by a soil disturbing operation is a function of depth of soil disturbed by operation (operation disturbance depth)
Operation description	Information used to describe an operation; named and stored in the operation component of the RUSLE2 database
Operation processes	Processes used to describe an operation; describes how an operation changes cover-managements and soil conditions that affect erosion,

(processes used in RUSLE2 listed below in italics)	net result of an operation depends on sequence of processes used to describe a particular operation
No effect	Has no effect on computations; commonly used to reference dates in a cover-*management* description and to cause RUSLE2 to display information for a particular set of dates
Begin growth	Tells RUSLE2 when to begin using data from a particular *vegetation* description
Kill vegetation	Converts live aboveground biomass to standing residue and to convert live root biomass to dead root biomass
Flatten standing residue	Converts a portion of the standing residue to surface residue
Disturb (soil) surface	Mechanically disturbs soil (removes consolidation effect for portion of soil surface disturbed); required to bury surface residue; resurfaces buried residue; creates soil surface roughness and ridges; required to inject external residue directly into the soil
Add other cover	Adds external residue to the soil surface and/or places it in the soil
Remove live above ground biomass	Removes a portion of the live aboveground biomass, leaves a portion of the affected biomass as standing and surface (flat) residue
Remove residue/cover	Removes a portion of standing and surface (flat) residue
Add nonerodible cover	Adds nonerodible cover such as plastic, standing water, snow, or other material that allows no erosion for portion of soil surface covered; nonerodible cover disappears over time, cover can be porous; nonerodible cover has no residual effect, not used to represent erosion control blankets and similar material.
Remove nonerodible cover	Removes nonerodible cover, nonerodibile cover has no residual effect
Operation speed	Surface residue buried by a *soil disturbing* operation is a function of operation speed.
Overland flow path	Path taken by overland flow on a smooth soil surface from its point of origin to the concentrated flow area that ends the overland flow path; runoff is perpendicular to hillslope contours
Overland flow path description	Described by steepness values, *soil* descriptions, and cover-*management* descriptions for segments along an overland flow path; a uniform profile (overland flow path) is where steepness, soil, and cover-management do not vary with distance along overland flow path, a convex profile is where steepness increases with distance along the overland flow path; a concave profile is where steepness decreases with distance along the overland flow

	path; a complex profile is a combination of convex, concave, and/or uniform sub-profiles; description involves segment lengths and segment steepness; Soil and cover-management can vary along overland flow paths
Overland flow path length	Distance along the overland flow path from the origin of overland flow to the concentrated flow area (channel) that intercepts runoff to terminate overland flow; does not end where deposition begins (see USLE slope length and steepness)
Overland flow path segments	Overland flow path is divided into segments to represent spatial variability along an overland flow path; conditions are considered uniform within each segment
Overland flow path steepness	Steepness along the overland flow path; not hillslope steepness (see USLE slope steepness)
Permeability index	Index for the runoff potential of the unit-plot soil condition; used in RUSLE2's soil erodibility nomographs; inversely related to hydrologic soil group
Plan description	Collection of RUSLE2 *profile* (overland flow path) descriptions; used to computed weighted averages for a complex area based on the portion of the area that each profile represents; description named and saved in plan component of RUSLE2 database
Ponding subfactor	See cover-management subfactors
Porous barriers	Runoff flows through a porous barrier; does not affect overland flow path length; typically slows runoff to cause deposition; examples are stiff grass hedges, grass filter strips, fabric (silt) fences, gravel dams, and straw bales
Precipitation amount	Includes all forms of precipitation; RUSLE2 disaggregates input monthly values into daily values to compute residue decomposition and temporal soil erodibility
Production (yield) level	A measure of average annual vegetation live aboveground biomass production; user defines yield measure and preferred units on any moisture content basis; input value used to adjust values in a *vegetation* description at a base yield; maximum canopy cover in *base vegetation* description must be less than 100 percent
Profile (overland flow path) description	Information used to describe profile (overland flow path); includes names for location, topography, soil, cover-management, and support practices used to make a particular RUSLE2 computation; *profile* descriptions are named and stored in the profile component of the RUSLE2 database
Profile shape	See overland flow path description
Rainfall (storm) energy	Computed as sum of products of unit energy and rainfall amount in storm intervals where rainfall intensity is assumed uniform; storm energy is closely related to rain storm amount
Rainfall intensity	Rainfall rate express as depth (volume of rainfall/per unit area) per unit time

Relative row grade	Ratio of row grade to average steepness of overland flow path
Remote deposition	Deposition that occurs a significant distance (tens of feet) from the point where the sediment was detached; examples include deposition by dense vegetation strips, terraces, impoundments, and toe of concave overland flow paths; only partial credit is given to remote deposition as soil saved; credit depends on location of deposition along overland flow path; very little credit is given for deposition near end of overland flow path
Req	Equivalent erosivity for the winter months in the Req zone, used to partially represent Req effect
Req effect	Refers to Req equivalent erosivity; erosion per unit rainfall erosivity in the winter period in the Req zone is much greater than in summer period; increased Req winter effect is mainly because of a greatly increased soil erodibility; effect partially results from an elevated soil water content, increased runoff, and soil thawing
Req zone	Region where erosion is elevated in the winter months because of the Req effect, region is primarily in eastern WA and OR, portions of ID, CA, UT, CO, and limited area in other western US states
Residue	Has multiple meanings in RUSLE2; generally refers to dead biomass, such as crop residue, created when vegetation is killed; plant litter from senescence; and applied mulch material such as straw, wood fiber, rock, and erosion control blankets used on construction sites; material is assumed to be biomass that decomposes; also used to represent material like rock that does not decompose by setting a very low decomposition coefficient value
Residue description	Values used to describe residue; named and stored in the residue component of the RUSLE2 database
Residue type	Refers to fragility and geometric residue characteristics; affects residue amount buried and resurfaced by of an operation; affects degree that residue conforms to surface roughness; affects erosion control on very steep slopes
Resurfacing ratio	Portion (dry mass basin) of the buried residue in the soil disturbance depth that a *soil disturbing* operation brings to the soil surface; function of residue and operation's *soil disturbing* properties
Retardance	Degree that vegetation (live aboveground biomass) and standing residue slows runoff; varies with canopy cover; function of production (yield) level; part of vegetation description
Ridge height	Height of ridges created by a *soil disturbing* operation; major variable, along with row grade, that determines contouring effectiveness; decays as a function of precipitation amount and interrill erosion
Ridge subfactor	See cover-management subfactors
Rill erosion	Caused by overland flow runoff; increases with distance along the

	overland flow path
Rill to interrill erosion ratio	Function of slope steepness, rill to interrill soil erodibility, and how cover-management conditions affect rill erosion different from interrill erosion
Rock cover entered in *soil* description	Rock cover entered in the soil description; represents naturally occurring rock on soil surface; operations do not affect this rock cover, rock cover created by an operation that *adds other cover* (rock residue) is treated as external residue; *soil disturbing* operations bury and resurface rock added as external residue
Root biomass	See dead and live root biomass
Root sloughing	Annual decrease in root biomass; RUSLE2 adds the decrease in live root biomass to dead residue biomass pool
Rotation	Refers to whether a list of *operation* descriptions in a cover-*management* description is repeated in a cycle; length of cycle is rotation duration; list of *operation* descriptions are repeated until average annual erosion value stabilizes; eliminates need to specify initial conditions for rotations; operation descriptions in a no-rotation cover-management descriptions are sequentially processed a single time; first operation descriptions in cover-*management* description establish initial conditions in a no-rotation cover-*management* description
Rotation duration	Time (cycle duration) before the list of operation descriptions in a rotation type cover-*management* description repeats; rotation duration is time period over which RUSLE2 makes its computations in a no-rotation cover-*management* description
Rotational strip cropping	A rotation type cover-*management* description that involves periods of dense vegetation that are sequenced along the overland flow path to create strips of alternating dense vegetation that cause deposition
Row grade	Grade along furrows separated by ridges; usually expressed as relative row grade
Runoff	Computed using NRCS curve number method and the 10 yr-24 hour precipitation amount; used to compute contouring effect, contouring failure (critical slope length), and deposition by porous barriers, flow interceptors, and concave overland flow paths
Sediment basin	Small impoundment typical of those used on cropland and construction sites; discharge is usually through a perforated riser that completely drains basin in about 24 hours
Sediment characteristics	Deposition computed as a function of sediment characteristics, which are particle class diameter and density and the distribution of sediment among particle classes
Sediment particle classes	RUSLE2 uses sediment particle classes of primary clay, silt, and sand and small and large aggregate; diameter of aggregate classes and the distribution of sediment among particle classes at point of detachment are computed as function of soil texture; RUSLE2

	computes how deposition changes the distribution of sediment particle classes
Sediment load	Mass of sediment transported by runoff per unit hillslope width
Sediment transport capacity	Runoff's capacity for transporting sediment, depends on runoff rate, overland flow path steepness, and hydraulic roughness; deposition occurs when sediment load is greater than transport capacity
Sediment yield	Sediment load at the end of the flow path represented in a RUSLE2 computation; flow path ends at overland flow path unless hydraulic elements (channel or impoundment) are represented in RUSLE2 computation; sediment yield for site only if RUSLE2 flow path ends at site boundary
Segments	The overland flow path divided into segments to represent spatial variation of steepness, soil, and cover-management
Senescence	Decrease in vegetation canopy cover; senescence adds biomass to surface (flat) residue unless RUSLE2 is instructed that a decrease in canopy cover, such as leaves drooping, does not add to surface residue
Shear stress applied by overland flow	Function of runoff rate and steepness of overland flow path; total runoff shear stress is divided into two parts of shear stress acting on the soil (grain roughness) and shear stress acting on surface residue, surface roughness, live vegetation, and standing residue (form roughness); shear stress acting on the soil is used to compute sediment transport capacity, total shear stress is used to compute contouring failure
Short term roughness	Roughness created by a soil disturbing operation; decays over time as a function of precipitation amount and interrill erosion
Slope length exponent	Exponent in equation used to compute rill-interrill erosion as a function of distance along overland flow path; function of rill to interrill erosion ratio.
Soil biomass subfactor	See cover-management subfactors
Soil consolidation effect	Represents how wetting/drying and other processes cause soil erodibility to decrease over time following a mechanical soil disturbance; increase in soil bulk density (mechanical compaction) not the major cause; affects accumulation of biomass in upper 2 inch (50 mm) soil layer and effect of soil biomass on runoff and erosion
Soil consolidation subfactor	See cover-management subfactors
Soil description	Describes inherent soil properties that affect erosion, runoff, and sediment characteristics at point of detachment; named and saved in soil component of RUSLE2 database
Soil disturbance width	Portion of the soil surface disturbed; weighted effects of disturbance computed as a function of erosion on disturbed and

	undisturbed area used to compute effective values for time since last disturbance, effective surface roughness, and effective ground cover
Soil disturbing operation	*Operation* description that contains *disturb soil* process
Soil erodibility	RUSLE2 considers two soil erodibility effects, one based on inherent soil properties and one based on cover-management; inherent soil erodibility effect represented by K factor value empirically determined from erosion on unit plot; part related to cover-management is represented in cover-management subfactors
Soil erodibility nomograph	Mathematical procedure used to compute a K factor value, i.e., inherent soil erodibility
Soil loss	Proper definition is the sediment yield from a uniform overland flow path divided by the overland flow path length; loosely used as the net removal of sediment from an overland flow path segment
Soil loss from eroding portion	Net removal of sediment from the eroding portion of the overland flow path
Soil loss tolerance (T)	Erosion control criteria; conservation planning objective is that "soil loss" be less than soil loss tolerance T value; special considerations must be given to non-uniform overland flow paths to avoid significantly flawed conservation and erosion control plans
Soil mechanical disturbance	Mechanical soil disturbance resets soil consolidation effects; *disturb soil* process must be included in an operation description to create surface roughness and ridges and to place biomass into the soil
Soil saved	Portion of deposited sediment that is credited as soil saved; computed erosion is reduced by soil saved to determine a conservation planning soil loss value; credit depends on location of deposition along overland flow path
Soil structure	Refers to the arrangement of soil particles in soil mass; used to compute soil erodibility (K) factor values
Soil texture	Refers to the distribution of primary particles of sand, silt, and clay in soil mass subject to erosion
Standing residue	Created when live vegetation is killed; decomposes at a reduced rate; falls over at a rate proportional to decomposition of surface residue
Strip/barrier description	Support practice; describes porous barriers; named and stored in the strip/barrier component of the RUSLE2 database
Subfactor method	See cover-management subfactors
Subsurface drainage description	Support practice that lowers water table to reduce soil water content, runoff, and erosion; RUSLE2 uses difference between hydrologic soil groups for drained and undrained conditions to compute erosion as affected by subsurface drainage
Support practices	Erosion control practice used in addition to cultural erosion control

	practices, hence a support practice; includes contouring, filter and buffer strips, rotational strip cropping, silt (fabric) fences, stiff grass hedges, diversions/terraces, gravel dams, and sediment basins
Surface (flat) residue	Material in direct contact with the soil surface, main source is plant litter, crop residue, and applied mulch (external residue).
Surface roughness	Random roughness; combination of soil peaks and depressions that pond runoff; created by a *soil disturbing* operation, decays as a function of precipitation amount and interrill erosion
Surface roughness index	A measure of soil surface roughness; standard deviation of surface elevations measured on a 1 inch grid about mean elevation; effect of ridges and land steepness removed from measurements
Surface roughness subfactor	See cover-management subfactors
Temperature	Input as average monthly temperature; disaggregated into daily values; used to compute biomass decomposition and temporal soil erodibility
Template	Determines the computer screen configuration of RUSLE2 and inputs and outputs; determines the complexity of field situations that can be described with RUSLE2
Terraces	Flow interceptors (channels) on a sufficiently flat grade to cause significant deposition
Three layer profile schematic	Some RUSLE2 templates include a overland flow path schematic having individual layers to represent cover-management, soil, and topography; used to graphically divide the overland flow path into segments to represent complex conditions
Tillage intensity	Degree that existing soil surface roughness affects roughness left by a *soil disturbing* operation
Tillage type	Identifies the relative position within soil profile where a soil disturbing operation initially places buried residue, also relates to how operation redistributes buried residue and dead roots
Time to soil consolidation	Time required for 95 percent of the soil consolidation effect to be regained after a soil disturbing operation
Topography	Refers to steepness along the overland flow path and the length of the overland flow path
Uniform slope	Refers to an overland flow path where soil, steepness, and cover-management do not vary along the overland flow path
Unit rainfall energy	Energy content of rainfall per unit of rainfall; function of rainfall intensity
Unit plot	Base condition used to determine soil erodibility; reference for effects of overland flow path steepness and length; cover-management, and support practices; continuous tilled fallow (no vegetation; tilled up and downhill, maintained in seedbed conditions; topographic, cover-management, support practice factor values equal 1 for unit plot condition; land use independent, i.e.,

	applies to all land uses including undisturbed land such as pasture, range, and forest lands
USLE slope length and steepness	Distance from origin of overland flow to a concentrated flow area (e.g., terrace or natural waterway) or to the location where deposition occurs; USLE soil loss is sediment yield from this length divided by length (mass/area); USLE steepness is steepness of the slope length; uniform actual overland flow path is often represented with uniform steepness
Validation	Process of ensuring that RUSLE2 serves its intended purpose as a guide to conservation and erosion control planning.
Vegetation description	Information used by RUSLE2 to represent the effect of vegetation on erosion; includes temporal values in growth chart, retardance, and biomass-yield information; named and stored in vegetation component of RUSLE2 database
Verification	Process of ensuring RUSLE2 correctly solves the mathematical procedures in RUSLE2
Worksheet description	Form in RUSLE2 program; used to compare conservation and erosion control practices for a given site; used to compare *profile* descriptions; named and saved in the worksheet component of the RUSLE2 database

1. WELCOME TO RUSLE2

Version 2 of the Revised Universal Soil Loss Equation (**RUSLE2**) estimates soil loss, sediment yield, and sediment characteristics from rill and interrill (sheet and rill) erosion caused by rainfall and its associated overland flow. **RUSLE2** uses factors that represent the effects of climate (erosivity, precipitation, and temperature), soil erodibility, topography, cover-management, and support practices to compute erosion. RUSLE2 is a mathematical model that uses a system of equations implemented in a computer program to estimate erosion rates. The other major component of RUSLE2 is a database containing an extensive array of values that are used by the RUSLE2 user to describe a site-specific condition so RUSLE2 can compute erosion values that directly reflect conditions at a particular site.

RUSLE2 is used to evaluate potential erosion rates at specific sites, guide conservation and erosion control planning, inventory erosion rates over large geographic areas, and estimate sediment production on upland areas that might become sediment yield in watersheds. **RUSLE2 is land use independent. It can be used on cropland, pastureland, rangeland, disturbed forestland, construction sites, mined land, reclaimed land, landfills, military lands, and other areas where mineral soil is exposed to raindrop impact and surface overland flow produced by rainfall intensity exceeding infiltration rate (i.e., Hortonian overland flow)**.

The RUSLE2 computer program, a sample database, user instructions, a slide set that provides an overview of RUSLE2, and other supporting information are available for download from the USDA-Agricultural Research Service (ARS) Official RUSLE2 Internet Site at http://www.ars.usda.gov/Research/docs.htm?docid=6010. The University of Tennessee also maintains a RUSLE2 Internet site where older versions of the RUSLE2 can be downloaded and where additional RUSLE2 information is available. The address is www.rusle2.org. The USDA-Natural Resources Conservation Service (NRCS) also provides and distributes information on RUSLE2 including databases and other materials that it uses to apply RUSLE2 in each of its county level offices across the US. Contact the NRCS Internet site at http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm or contact the NRCS state agronomist in your state to obtain NRCS information on RUSLE2. The NRCS Internet site contains an extensive RUSLE2 database that must be used in NRCS-related applications involving RUSLE2. Information in this database can also be downloaded for other RUSLE2 applications as well. Other organizations that use RUSLE2 may also have RUSLE2 Internet sites that contain databases for their specific RUSLE2 applications.

2. WHY UPGRADE FROM RUSLE1 TO RUSLE2?

RUSLE2 is a second generation of RUSLE1, but it is not simply an enhancement of RUSLE1. **RUSLE2** is a new model with new features and capabilities. If you are using any version of RUSLE1, you should upgrade to **RUSLE2.** **RUSLE2** uses a modern, powerful graphical user interface instead of the text-based interface of RUSLE1. ***RUSLE2** can be used in either US customary units or SI units.* **RUSLE2** can globally switch between the two systems of units or the units on individual variables can be changed to one of several units. Those who work with metric units will find **RUSLE2** much easier to use than RUSLE1. **RUSLE2** can also manipulate attributes of variables, which includes graphing, changing units, and setting number of significant digits. **RUSLE2** is much more powerful than RUSLE1, has improved computational procedures, and provides much more output useful for conservation planning than does RUSLE1.

Even though **RUSLE2** appears quite different on the computer screen from RUSLE1, it has many similarities with RUSLE1. The general approach is the same and many of the values in the database are the same for **RUSLE2** and RUSLE1. Thus, conversion from RUSLE1 to **RUSLE2** should be relatively easy.

3. ABOUT RUSLE2 USER'S GUIDES AND DATABASES

3.1. RUSLE2 User Instructions

RUSLE2 is a straight forward, easily used computer program that is best learned by using it. A set of user instructions is available on the **USDA-Agricultural Research Service (ARS)** RUSLE2 Internet site http://www.ars.usda.gov/Research/docs.htm?docid=6010 to help you get started with RUSLE2. A self-guided tutorial is available on the **University of Tennessee** http://bioengr.ag.utk.edu/rusle2/tutorial.htm to help you learn the mechanics and operation of the **RUSLE2** computer program. The **USDA-Natural Resources Conservation Service (NRCS)** Internet site http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm provides instructional material and database information that helpful for any RUSLE2 user, but is required for NRCS-related **RUSLE2** applications. Also, other organizations provide training and instructional materials targeted to a specific land use such as construction sites that you can also use to learn RUSLE2.

3.2. RUSLE2 Database

The **RUSLE2** download on the USDA-ARS RUSLE2 Internet site includes a sample database. This sample database should only be used to help you become acquainted with **RUSLE2** and how it works. This database is not intended for use in actual **RUSLE2** applications. You can obtain that database information by downloading from the USDA-Natural Resources Conservation Service (NRCS) national **RUSLE2** database or from another database having values that have been properly established for your purpose. You can download information from the NRCS national **RUSLE2** database by contacting the Internet site http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm. Additional information can be obtained by contacting the State Agronomist in each NRCS State Office.

Values in your **RUSLE2** operational database must be based on the **RUSLE2 core database** (see **Section 16**). Values in your operational database must be consistent with those in the core database to ensure that **RUSLE2** give expected results and to ensure consistency in **RUSLE2** applications among clients, locations, and other situations where similar erosion estimates are expected. This consistency is very important when **RUSLE2** is used by a national agency where adequacy of the erosion prediction technology is partly judged on consistency of estimates. The NRCS national **RUSLE2** database has been extensively reviewed to ensure consistency, minimal error, and expected erosion values computed with **RUSLE2**. Make sure that the same quality control has been used in the preparation of other **RUSLE2** databases that you might use for the source of data in your **RUSLE2** operational database.

Some values in the RUSLE1 database can be used in **RUSLE2** and directly transferred to the **RUSLE2** database using procedures included in **RUSLE2.** However, the best approach is download values from a quality-controlled **RUSLE2** database, such as the NRCS national **RUSLE2** database, rather than transfer values from a RUSLE1 database. Values for several input variables are different in **RUSLE2** from those in RUSLE1. Also, new input variables have been added to **RUSLE2** that are not in RUSLE1. Furthermore, core values, including those for rainfall erosivity, in the **RUSLE2** database have updated based on new analysis.

3.3. RUSLE2 HELP

The **RUSLE2** computer program contains an extensive set of **HELP** information. Most of the **HELP** information is arranged by variable within **RUSLE2**. Information on a particular variable can be obtained at the location within **RUSLE2** where the variable occurs.

3.4. RUSLE2 Slide Set

A **slide set** is available with the **RUSLE2** download at the ARS RUSLE2 Internet site. This **slide set** provides an extensive overview of **RUSLE2**. The speaker notes that accompany many of the slides provide additional background. Also, slides can be used for **RUSLE2** training and for making presentations on **RUSLE2**.

3.5. RUSLE2 User Reference Guide

This **User's Reference Guide** describes **RUSLE2**, its factors, selection of input values, and application of **RUSLE2**. The **Table of Contents** lists the topics covered by the **User's Guide.** Rather than reading the entire **User's Guide**, specific topics can be selected from the **Table of Contents** and individually reviewed. Also, the **Glossary of Terms** provides information on specific topics.

This **User's Reference Guide** is intended to serve as a **reference** for RUSLE2 technical specialists rather than a guide for the routine RUSLE2 user. User guides and manuals for these users should be developed for specific applications based on information in this **Guide**.

3.6. Getting Started

Like all other hydrologic models, **RUSLE2** requires a proper approach for selecting input values, running the model, and interpreting its output values. **RUSLE2** has particular limitations that must be considered. Before applying **RUSLE2,** you should become well acquainted with **RUSLE2** and its factors by reviewing the **RUSLE2 Slide Set**. After installing **RUSLE2**, run the sample database that can be downloaded with **RUSLE2** that includes several example overland flow path profiles. Change selected variables including location, soil, overland flow path length and steepness, and cover-management and support practices in these examples to help learn the mechanics of the **RUSLE2** computer program and to help learn how main inputs affect computed erosion and other output variables. Start out with the uniform slope templates rather than the complex slope templates.

3.7. Scientific and Technical Documentation

The **RUSLE2** Scientific Documentation describes the equations and mathematical procedures used in RUSLE2. It is available from the USDA-Agricultural Research Service
http://www.ars.usda.gov/SP2UserFiles/Place/64080530/RUSLE/RUSLE2_Science_Doc.pdf.

4. CUSTOMER SUPPORT

If needed information is not available in **RUSLE2** documentation, contact one of the **RUSLE2** experts. The USDA-Agricultural Research Service (ARS) is the lead research agency, in cooperation with the University of Tennessee, that developed **RUSLE2**. The USDA-Natural Resources Conservation Service (NRCS), the major user of **RUSLE2,** has much experience in RUSLE2 applications and developed extensive database information for many different types of applications of **RUSLE2** across the US and other locations. Contact your NRCS State Agronomist to obtain additional databases, information, and direct assistance on **RUSLE2** applications.

RUSLE2 Contacts

Topic: Science and new applications

Seth M. Dabney, Research Agronomist
USDA-Agricultural Research Service
National Sedimentation Laboratory
P.O. Box 1157
Oxford, Mississippi, 38655, USA
Telephone: 662-232-2975
Email: seth.dabney@ars.usda.gov

Topic: Computer program, interface, and linking to RUSLE by other programs

Daniel C Yoder, Professor
Department of Biosystems and Environmental Science
P.O. Box 1071
Knoxville, TN, 37901, USA
Telephone: 865-974-7116
Email: dyoder@utk.edu

Topic: NRCS databases and applications

Dave Lightle, Conservation Agronomist
USDA-Natural Resources Conservation Service
National Soil Survey Center
100 Centennial Mall North, Room 152
Lincoln, NE 68508-3866, USA
Telephone: 402-437-4008
Email: dave.lightle@lin.usda.gov

5. ABOUT RUSLE2

5.1. Fundamental Definitions

RUSLE2 uses several important terms to describe erosion (see **Glossary of Terms**). In the mid-1940's, W. D. Ellison defined erosion as, "... a process of detachment and transport of soil particles."[1] **Detachment** is the separation of soil particles from the soil mass and is expressed in units of mass/area. Soil particles separated from the soil mass are referred to as **sediment**. Sediment movement downslope is sediment transport, described as **sediment load** expressed in units of mass/width of slope. The sediment load at the end of the **RUSLE2** hillslope profile is defined as sediment yield or sediment delivery. **Deposition**, expressed as mass/area, is the accumulation of sediment on the soil surface.

Detachment transfers sediment from the soil mass to the sediment load so that sediment load increases along the hillslope where detachment occurs. Conversely, deposition transfers sediment from the sediment load to the soil mass with a corresponding accumulation of sediment on the soil surface. Deposition is a selective process that **sorts** sediment. This process **enriches** the sediment load in fines in comparison to the soil where detachment originally produced the sediment.

RUSLE2 considers two types of deposition, local and remote. **Local deposition** is sediment deposited very near, within a few inches of where it was detached. Deposition in micro-depressions (**surface roughness**) and in low gradient furrows is an example of local deposition. The difference between local detachment and local deposition is called **net detachment** (or **net deposition**). **Remote deposition** is sediment deposited some distance, 10's of feet (several meters) from the origin of the sediment. Deposition on the toe of a concave slope, at the upper side of vegetative strips, and in terrace channels is an example of remote deposition. **Full credit for soil saved** is taken in **RUSLE2** for local deposition. Only **partial credit** that depends on the location of the deposition is given to remote deposition for soil saved. Sediment deposited at the end of an overland flow path is given very little credit as soil saved.

5.2. Hillslope Overland Flow Path (Hillslope Profile) as the Base Computational Unit in RUSLE2

The base **RUSLE2** computational unit is a single overland flow path along a hillslope profile as illustrated in Figure 5.1. An **overland flow path** is defined as the path that runoff flows from the origin of overland flow to where it enters a major flow concentration. **Major flow concentrations** are locations on the landscape where sides of a hillslope intersect to collect overland flow in defined channels. **Ephemeral or**

[1] Ellison, W.D. 1947. Soil erosion studies. Agricultural Engineering. 28:145-146.

classical gully erosion occurs in these channels. These defined channels are distinguished from **rills** in two ways. Rills tend to be parallel and are sufficiently shallow that they can be obliterated by typical farm tillage and grading operations as a part of construction activities. When the rills are reformed, they occur in new locations determined by **microtopograpy** left by soil disturbing operations like tillage. In contrast, concentrated flow areas occur in the same locations, even after these channels are filled by tillage. Location of these channels is determined by **macrotopography** of the landscape.

An infinite number of overland flow paths exist on any landscape. A particular overland flow path (**hillslope profile**), such as the one labeled **A** in Figure 5.1, is chosen for the one on which the conservation plan is to be based. The overland flow path (profile) that represents the 1/4 to 1/3 most erodible part of the area is often the profile selected for

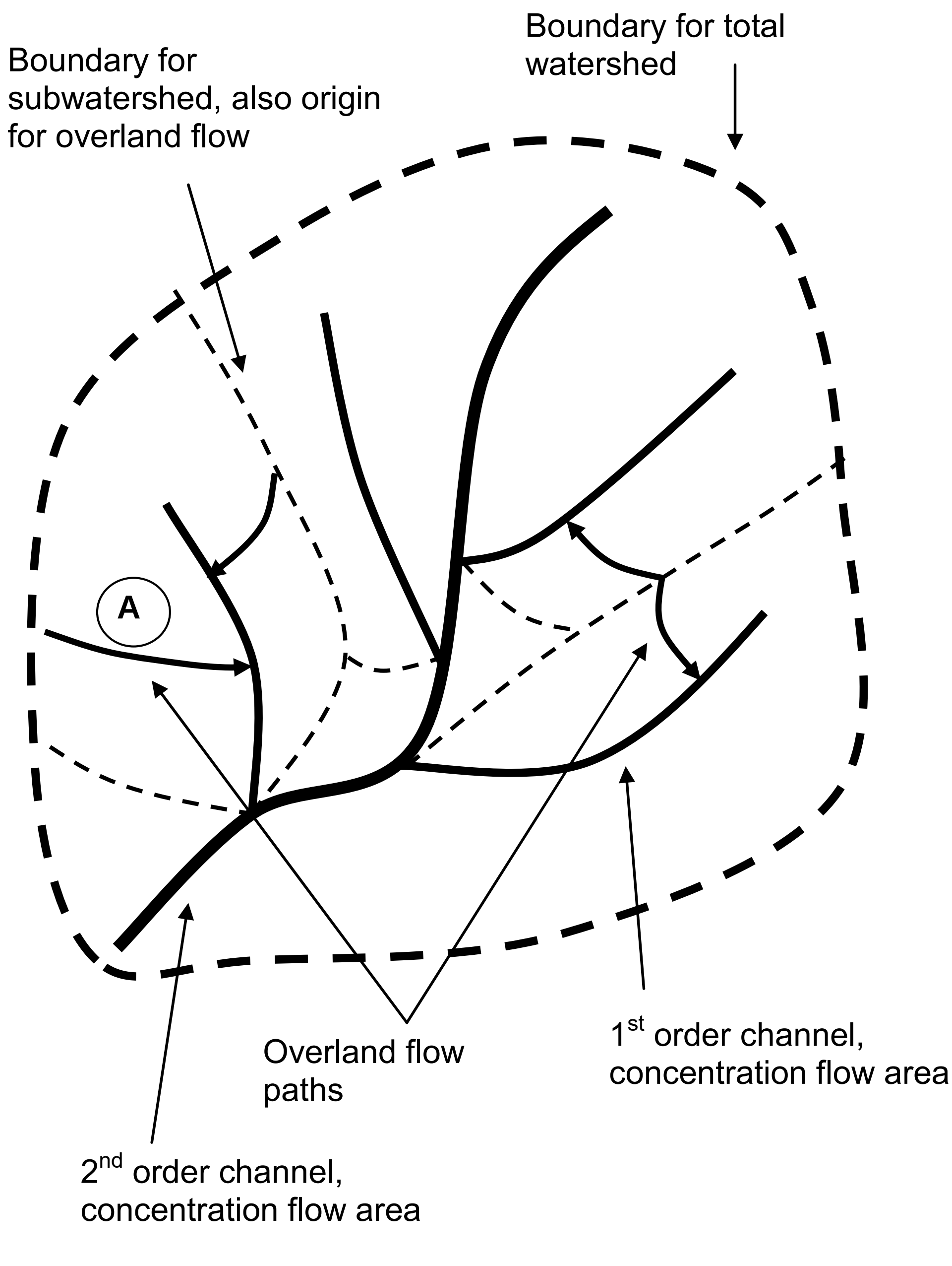

Figure. 5.1. Overland flow paths in a typical application of RUSLE2

applying RUSLE2 when the **conservation planning** objective is to protect the soil resource from degradation by excessive erosion. **RUSLE2** is used to estimate erosion for this profile for each of several alternative land use practices that might be used at the site. Those practices that give a RUSLE2 estimated soil loss that meets the **conservation planning** criteria are considered to provide acceptable erosion control. Organizations such as the NRCS have specific guidelines on how **RUSLE2** is to be used in their programs.

The first step in describing the selected profile is to identify a base point on the hillslope through which the overland flow path is passes. The overland flow path through that point, such as profile **A** in Figure 5.1, is described by dividing the slope into segments and specifying distance and steepness for each segment. The overland path is traced from the origin of overland flow through the base point to where the overland flow is terminated by a concentrated flow channel as illustrated in Figure 5.1.

Figure 5.2 shows the shape of a typical overland flow path on a common natural landscape. This **complex** hillslope profile has an upper **convex** section and a **concave** lower section. This profile has two important parts. The upper part is the **eroding portion** where **net erosion** occurs, and the lower part is the **depositional portion** where **net deposition** occurs. The average erosion rate on the eroding portion of the hillslope is defined as **soil loss** (mass/area). Soil loss on the eroding portion of the landscape degrades the soil on that portion of the landscape and the landscape itself. A typical conservation planning objective is to reduce soil loss to a rate less than **soil loss tolerance (T)** or another quantitative planning criterion. Keeping soil loss to less than T protects the soil so that its productive capacity is maintained and the landscape as a whole is protected from excessive erosion.

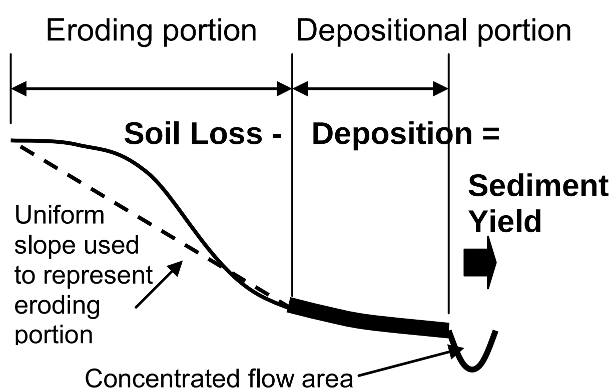

Figure 5.2. Complex hillslope, convex-concave profile

Sediment yield from the hillslope profile and the site is also an important conservation planning consideration. Excessive sediment leaving a site can cause downstream sedimentation and water quality problems. Sediment yield is less than soil loss by the amount of deposition. The sediment yield computed by **RUSLE2** is the sediment leaving the overland flow path represented in **RUSLE2**. This sediment yield will be the sediment yield for the site only if the **RUSLE2** flow path ends at the boundary of the site.

Many conservation-planning applications involve only the eroding portion of the hillslope, which can be approximated by a **uniform slope** as illustrated in Figure 5.2. The **slope length (overland flow path length)** in this application is the distance from the origin of overland flow to where deposition begins, which is the traditional definition of **slope length** in the USLE and RUSLE1. However, soil loss estimated using a uniform slope of the same average steepness and slope length as a non-uniform shaped profile will differ from the average erosion rate for the non-uniform profile, sometimes by as much as 15%. The difference is especially important on convex shaped hillslopes where the erosion rate near the end of the overland flow path can be much larger than the erosion rate at the end of a uniform profile. Deposition like that in Figure 5.2 for concave hillslope sections does not occur on the **uniform** and **convex** shaped hillslopes illustrated in Figure 5.3. Sediment yield equals soil loss on those profiles.

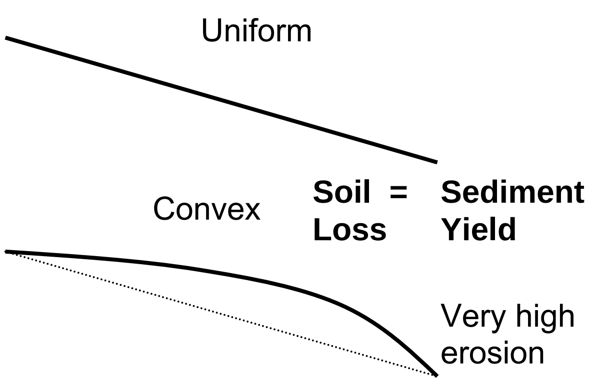

Figure 5.3. Sediment yield equals soil loss on uniform and convex slopes

Another important **complex** hillslope shape is shown in Figure 5.4 where a **concave** section occurs in the middle of the hillslope. A field example is a cut slope-road-fill slope that is common in hilly terrain being logged. **Deposition** can occur on the mid-section of the hillslope where the roadway is located if steepness of the roadway is sufficiently flat. Soil loss occurs on the cut slope and downslope on the fill slope in situations where overland flow from the cut slope continues across the roadway onto the fill slope. Although the steepness and length of the fill slope is the same as that for the upper cut slope, erosion rate is much greater on the fill slope than on the cut slope because of increased overland flow. Although the USLE and RUSLE1 cannot easily describe this hillslope, **RUSLE2** easily determines appropriate **overland flow path lengths**, and computes **erosion** on the two **eroding portions** of the overland flow path, **deposition** on the **depositional portion** of the overland flow path, and **sediment yield** from the overland flow path. Note that the **overland flow path** used in RUSLE2 does not end where deposition begins for this overland flow path.

In addition to computing how slope shape affects erosion, RUSLE2 can also compute how variations in soil and management along a hillslope profile affect erosion.

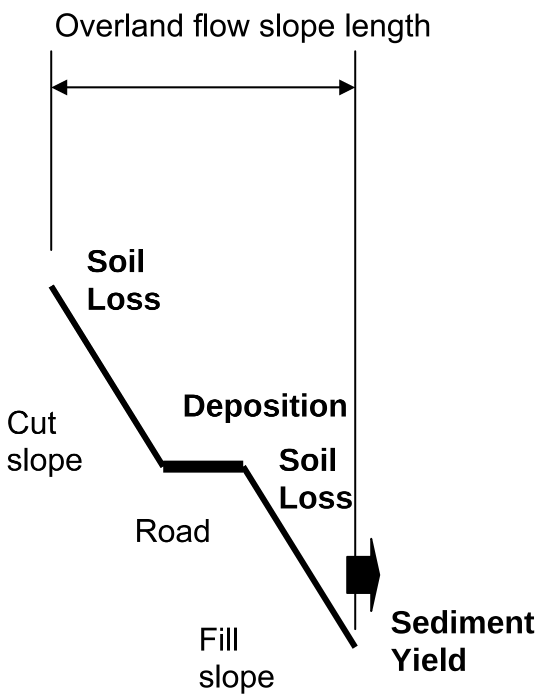

Figure 5.4. Soil loss, deposition, and sediment yield from a complex slope, concave-convex shape.

5.3. Does RUSLE2 Not Apply to Certain Conditions?

5.3.1. Rill erosion or concentrated flow erosion?

RUSLE2 does not apply to concentrated flow areas where ephemeral gully erosion occurs. **Whether or not RUSLE2 applies to particular eroded channels is not determined by size or depth of the channels.** The determination depends on whether the channels in the field situation would be included if RUSLE2 plots were to be placed on that landscape. The core part of **RUSLE2** that computes **net detachment** (**sediment production**) is empirically derived from data collected from plots like those illustrated in Figures 5.5 and 5.6. The length of these plots typically was about 75 ft (25 m) and width ranged from 6 ft (2 m) to about 40 ft (13 m) wide with plots as wide as 150 ft (50 m) at one location. These plots were always placed on the sides of the hillslope where overland flow occurred, not in the swales where concentrated flow occurs. Thus, RUSLE2 can estimate soil loss for rills 15 inches (375 mm) deep on sides of hillslopes because these rill would be in plots placed on this part of the landscape but not erosion from a 4 inch (100 mm) deep ephemeral gully or 10 ft (3 m) deep classical gully in a concentrated flow area because plots were not be placed in these locations.

5.3.2. Can RUSLE2 be Used to Estimate Sediment Yield from Large Watersheds?

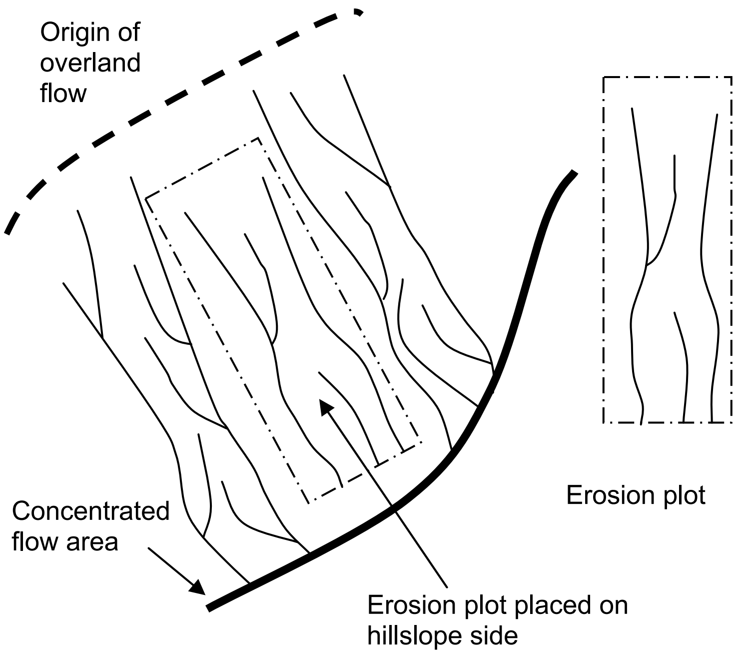

Figure 5.5. Relation of erosion plots to landscape

Sediment yield from most large watersheds is often less than sediment production within the watershed. Thus, much sediment is deposited within a typical watershed. **RUSLE2**, in contrast to the USLE and RUSLE1, can estimate the deposition that occurs on the overland flow portion of the landscape. This deposition, up to 75 percent of the sediment produced on the eroding portion of the hillslope, can be substantial on many hillslopes. **If RUSLE2 is used to estimate sediment yield in watersheds, it should be applied only to the eroding portion of the landscape to compute a soil loss comparable to that computed by the USLE. Otherwise, a different set of sediment delivery ratio values from those used by the USLE would have to be used with RUSLE2 to take into account deposition on overland flow areas.**

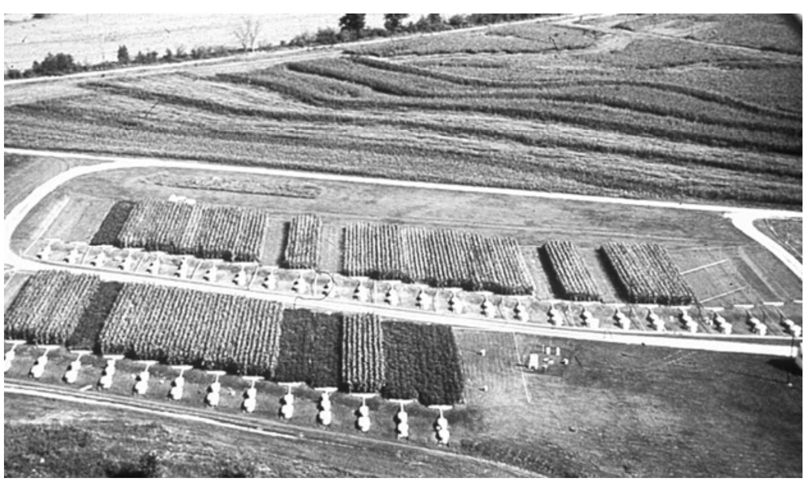

Figure 5.6. Erosion plots 12 ft wide (3.65 m) and 72.6 ft (22.1 m) long near Columbia, MO.

In addition to the sediment produced by interrill and rill erosion on upland areas (estimated by **RUSLE2)**, erosion in concentrated flow areas (ephemeral gullies), classical gullies, stream channels, and mass movement of material into channels are other major sources of sediment that contribute to sediment yield, which are not estimated by **RUSLE2**.

5.3.3. Estimating Soil Loss with RUSLE2 for Large Areas

RUSLE2 can be used to estimate soil loss for large areas. The approach is to select sample points over the inventory area where RUSLE2 will be applied to compute soil loss. These sample points should be selected according to the requirements of the inventory, giving special attention to required accuracy and how soil loss estimates will be aggregated according to soil, topography, land use, and conservation practice. RUSLE2 can be applied in several ways. One way is to estimate a "point" soil loss at the sample point. A slope length[2] to the point and values for steepness, soil, and cover and management at each sample point are determined. A slope segment 1 ft (0.3 m) long at the end of the slope length along with the other RUSLE2 input values for the segment are used in RUSLE2 to compute soil loss at the point.

Another approach is to determine a slope length through the point that extends to the location that deposition begins or to a concentrated flow area if deposition does not occur. Values for conditions along the slope length are used in RUSLE2 to compute a soil loss for the slope length. A limitation of this approach is that soil loss values cannot be aggregated based on conditions that vary along a slope length, such as multiple soil types.
A third approach, which was used by USDA-NRCS for the National Resources Inventory (NRI), uses the slope length through the point to either deposition or a concentrated flow area and conditions at the point to compute soil loss. This approach does not provide an estimate of soil loss at the point. Soil loss values cannot be aggregated for variables that are related to position on the slope. For example, the same soil loss is computed at the top of slope as at the bottom of slopes when slope steepness is the same for both locations.[3] A major advantage of computing soil loss for the entire slope length is that the number of sample points needed to obtain an accurate estimate of average soil loss for the area is significantly reduced. However, this procedure can not be used where the main variables, such soil erodibility or steepness, depend on landscape position.

An approach that absolutely should not be used is to determine spatially averaged values for slope length and steepness, soil, and cover-management conditions for the inventory area and use these values in RUSLE2 to compute a single soil loss value for the area. Soil loss estimates by this method are inaccurate because of nonlinearities in the RUSLE2 equations. No simple, universally applicable method can be developed to select the proper input values for this method. The issue is directly related to the proper

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2 Slope length refers to the traditional USLE definition of slope length, which applies to the eroding portion of the RUSLE2 overland flow path length.

3 For discussion of the mathematics related to this approach, see Foster, G.R. 1985. Understanding ephemeral gully erosion (concentrated flow erosion). In: Soil Conservation, Assessing the National Resources Inventory. National Academy Press. Washington, D.C. pp. 90-125.

mathematical procedures for spatial integration, which is exactly the reason why RUSLE2 is much superior mathematically to the USLE or RUSLE1 as discussed below.

5.4. Equation Structure of RUSLE2

RUSLE2 uses an equation structure similar to the Universal Soil Loss Equation (USLE) and RUSLE1. RUSLE2 computes long-term average soil loss on each *ith* day as:

$$a_i = r_i k_i l_i S c_i p_i \qquad \textbf{[5.1]}$$

where: a_i = long-term average soil loss for the *ith* day, r_i = erosivity factor, k_i = soil erodibility factor, l_i = soil length factor, S = slope steepness factor, c_i = cover-management factor, p_i = supporting practices factor, all on the *ith* day.[4] The slope steepness factor S is the same for every day and thus does not have a subscript. To emphasize, values for these factors are long–term averages for a particular day—not for the year, which is the reason that lower case symbols are used rather than upper case as in RUSLE1 and USLE. Equation 5.1 is exactly like the USLE except that it computes soil for a given day rather than an annual soil loss.

RUSLE2 computes deposition when sediment load exceeds transport capacity on overland flow profiles like the one illustrated in Figure 5.2 using:

$$D_p = (V_f / q)(T_c - g) \qquad \textbf{[5.2]}$$

where: D_p = deposition, V_f = fall velocity of the sediment in still water, q = overland flow (runoff) rate per unit width of flow, T_c = sediment transport capacity, and g = sediment load. **RUSLE2** computes runoff rate using the 10-yr, 24 hr storm amount, the NRCS curve number method, and a runoff index (curve number) computed from cover-management variables. **RUSLE2** computes sediment transport capacity using:

$$T_c = K_T q s \qquad \textbf{[5.3]}$$

where: s = sine of the slope angle and K_T = a transport coefficient computed as a function of cover-management variables. The steady state conservation of mass equation is to compute sediment load as:

$$g_{out} = g_{in} + \Delta x D \qquad \textbf{[5.4]}$$

where: g_{out} = sediment load leaving the lower end of a segment on the slope, g_{in} =

4 Lower case letters are used to denote daily variables in comparison to the upper case letters used in the USLE and RUSLE1 that denote average annual values.

sediment load entering the upper end of the segment, Δx = length of segment, and D = net detachment or deposition within the segment. The sign convention is "+" for detachment because detachment adds to the sediment load, and "-" for deposition because it reduces the sediment load. Equation 5.4 is graphically illustrated in Figure 5.7.

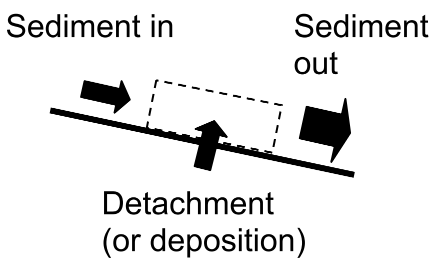

Figure 5.7. Schematic of conservation of mass equation for computing sediment load along the slope

Equations 5.2-5.4 are solved for each of the five particle classes of primary clay, primary silt, small aggregate, large aggregate, and primary sand. The distribution among these classes at the point of detachment is computed by RUSLE2 as a function of soil texture. The wide range in fall velocity for sediment particle classes allows equation 5.2 to compute the sorting of sediment where coarse and dense sediment are deposited first, which enriches the sediment load in fines and less dense particles.

Average annual soil loss is computed as:

$$A = \left(\sum_{i=a}^{365m} a_i \right) \Big/ m \qquad \textbf{[5.5]}$$

where: A = average annual soil loss, m = number of years in the analysis period, and 365m = the number of days per year. The value for m is 1 for continuous vegetation on range, pasture, and other lands where conditions are the same year after year, while m = the number of years of cropping-management rotations on cropland and the number of years following a disturbance such as construction, logging, grading of a reclaimed surface mine, or closing of a land fill where conditions are changing year to year.

For comparison, RUSLE1 is:

$$A = RLSP \left\{ \left[\sum_{k=1}^{24m} \left(f_k k_k \right) \right] \Big/ m \right\} \left[\sum_{k=1}^{24m} \left(f_k c_k \right) \right] \Big/ m \qquad \textbf{[5.6]}$$

where: R = average annual erosivity, f_k = distribution of erosivity by half month period, L = slope length factor, P = supporting practices factor, and k = index for the half month period. The 24 in equation 5.6 is the number of half month periods in a year. Values for the terms K and C are computed from:

$$K = \left[\sum_{k=1}^{24m} \left(f_k k_k \right) \right] \Big/ m \qquad \textbf{[5.7]}$$

and:

$$C = \left[\sum_{k=1}^{24m} \left(f_k c_k \right) \right] \Big/ m \qquad \textbf{[5.8]}$$

Values for K and C were computed and placed in tables so that RUSLE1 could be used in a “paper version” as A=RKLSCP. A computer program for RUSLE1 is also available to compute K, C, and P factor values from basic subfactor variables along with a procedure for computing soil loss for non-uniform shaped overland flow paths.

The USLE is:

$$A = RKLSP \left[\sum_{j=1}^{N} \left(f_j c_j \right) \right] \Big/ m \qquad \textbf{[5.9]}$$

where: j = the index for crop stage periods and N = the number of crop stages over the analysis period. A crop stage period is one where the cover-management factor c can be assumed to be constant. Values for C were computed from:

$$C = \left[\sum_{j=1}^{N} \left(f_j c_j \right) \right] \Big/ m \qquad \textbf{[5.10]}$$

Values for C were placed in tables so that the USLE could be used easily in a “paper version” as A=RKLSCP.

The numerical integration used in RUSLE2 to solve equations 5.1 and 5.5 is much superior to the approximations used in RUSLE1 and the USLE. The difference in soil loss estimates between RUSLE2 and the other equations can be as much as 15 percent because of differences in the mathematical integration procedures. Modern computers are readily available to solve complex equations to eliminate the need for a “paper version” of RUSLE2. The equations and procedures in RUSLE2 are too complex for a “paper version.” Although RUSLE2 can compute C factor values, RUSLE2 does not use the standard RKLSCP factor values to compute erosion.

The USLE, introduced in the early 1960's and revised in 1978,[5] was totally empirical, having been derived from more than 10,000 plot years of data from natural runoff plots and an estimated equivalent of 2,000 plot-years of data from rainfall simulator plots. The strength of the USLE is its empiricism, which is also its weakness. The USLE cannot be applied to situations where empirical data are not available for a specific field condition to derive appropriate factor values. Also, the USLE subfactor procedure for non-cropland (Table 10, AH537) is missing important variables including soil surface roughness and biomass production level.

Federal legislation in the 1980's required erosion prediction technology applicable to almost every cropland use, a requirement that the USLE could not meet. A "subfactor" method that estimates values for the cover-management factor C allows RUSLE1 to be applied to any land use. Process-based equations were also added to estimate the values for the support practice factor P so that soil loss could be estimated for modern strip cropping systems that could be estimated with the USLE. Data needed to derive USLE P factor values were not available for these systems. This hybrid approach of starting with an empirical structure and then adding process-based equations where empirical data were limited greatly increased the power of RUSLE1 over the USLE.

RUSLE2 significantly expands on this hybrid approach by combining the best of empirical-based and process-based erosion prediction technologies. Modern theory on erosion processes of detachment, transport, and deposition of soil particles by raindrop impact and surface runoff was used to derive **RUSLE2** relationships where the required equations could not be derived from empirical data. **RUSLE2** is well-validated erosion prediction technology that builds on the success of the USLE and RUSLE1. **RUSLE2** validation is described in **Section 17**.

5.5. Major Factors Affecting Erosion

The four major factors affecting interrill and rill erosion are: (1) climate, (2) soil, (3) topography, and (4) land use.

5.5.1. Climate

Rainfall drives interrill and rill erosion. The most important characteristics of rainfall are rainfall intensity (how hard it rains) and rainfall amount (how much it rains). Soil loss is high in Mississippi where much intense rainfall occurs, whereas soil loss is low in the deserts of Nevada where very little rainfall occurs. Thus, rainfall erosivity varies by location. Specifying the location of a site identifies the erosivity at the site.

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5 Wischmeier, W.H. and D.D. Smith. 1978. Predicting rainfall-erosion losses: A guide to conservation planning. U.S. Dept. of Agriculture, Agriculture Handbook # 537.

5.5.2. Soil

Some soils are naturally more erodible than are other soils. Erosion by raindrop impact is not easily seen, but varying degrees of rilling indicate differing erodibility among soils. Knowledge of basic soil properties such as texture provides an indication of erodibility. For example, soils high in clay and sand have low erodibilities while soils high in silt have high erodibilities. Soils are mapped and named as map units and components that make up map units. Soil properties, including erodibility, are assigned by soil component and map unit. These properties are, in effect, specified when the name of a soil mapping unit is selected. Soils on highly disturbed lands like reclaimed mine sites can not be mapped and require special considerations to determine erodibility.

5.5.3. Topography

Topography, especially steepness, affects soil loss. Intense rilling is evidence that steep slopes like road cuts and fills experience intense erosion when bare. Runoff that accumulates on long slopes (overland flow path lengths) is also highly erodible, especially when it flows onto steep slopes. Thus, slope steepness and overland flow path length, to a lesser extent, are major indicators of how topography affects erosion. Slope shape (steepness along the overland flow path), illustrated in Figure 5.2, 5.3, and 5.4, also affects erosion and deposition as evidenced by both erosion and deposition on concave slopes.

5.5.4. Land Use

Erosion occurs when soil is left bare and exposed to raindrop impact and surface runoff. Vegetative cover greatly reduces soil loss. Two types of practices are used to control soil loss. One type is cultural practices like vegetative cover, crop rotations, conservation tillage, and applied mulch. The other type is supporting practices like contouring, strip cropping, and terraces that “support” cultural management practices. Of the factors of climate, soil, topography, and land use, land use is most important. It has the greatest range of effect on soil erosion, and it is the one that can be changed most readily to control soil loss and sediment yield.

A powerful feature of RUSLE2 is that it is land use independent. By using fundamental variables to represent cover-management effects, RUSLE2 can be applied to any land use. These variables include percent canopy cover; fall height; ground cover provided by live vegetation, plant litter, crop residue, and applied materials; surface roughness; soil biomass; degree of soil consolidation, and ridge height. RUSLE2 applies to cropland, rangeland, disturbed forestland, construction sites, reclaimed mined land, landfills, military training sites, and other areas where “mineral” soil is exposed to the forces of raindrop impact and overland flow produced by rainfall in excess of infiltration.

5.6. Computing Soil Loss with RUSLE2

RUSLE2 computes soil loss and other erosion values using inputs for climate, soil, topography, and use practices and conditions. These values stored in the RUSLE2 database under names for locations, which identify climatic variables; soil; cover-management conditions and practices; and supporting practices. The user selects a name from a menu list for each of these factors to compute erosion. RUSLE2 “pulls” the values associated with each input name from the RUSLE2 database. The user changes values of particular variables from those stored in the database as needed to represent site-specific conditions related to topography, yield (production level), rock cover, and type and amount of applied materials like manure and mulch.

In many ways, RUSLE2 is a set of database components that operate like a spreadsheet. Values are stored in each database component for the variables that RUSLE2 uses in its computations. When the user changes a particular value to represent a site-specific condition, RUSLE2 immediately updates its computations, much like a spreadsheet updates its computations when a change is made in a cell.

RUSLE2 is never started from a “blank sheet.” It always starts with information already stored in a database component. The user changes the values for particular variables if the values stored in the database are not appropriate for the field conditions where RUSLE2 is being applied.

5.6.1. Computational Database Components

All RUSLE2 database components accept input and make computations. However, three RUSLE2 database components are the primary computational components. These components are the (hillslope) **profile**, **worksheet**, and **plan view** components.

The overland flow path along a hillslope **profile** is the basic computational unit of RUSLE2. Information on the location (climate), soil, cover-management, supporting practices, and topography of a specific overland flow path describes a particular hillslope **profile**. Once this information has been entered in RUSLE2 to describe a particular hillslope profile, the profile can be named and saved in the **profile** component of the RUSLE2 database.

The RUSLE2 **worksheet** component is used to facilitate conservation planning by computing erosion for a set of alternate conservation practices for a **uniform** hillslope profile for a particular location, soil, and topography. The worksheet provides a convenient way to compare alternatives. Another RUSLE2 worksheet is available that can be used to compare hillslope profiles where conditions including location, soil, topography, cover-management, and supporting practice can vary along hillslope profiles and among the profiles.

The RUSLE2 **plan view** component can be used to compute average soil loss and other erosion variables for a spatial area like a field or watershed where profiles vary over the area.

Individual profile, worksheets, and plan views can be named and saved.

5.6.2. RUSLE2 Database Components

The major components of the RUSLE2 database are listed in Table 5.1. With the exception of a few site-specific inputs, RUSLE2 uses values stored in its database to make its computations. Later sections discuss the major variables in each RUSLE2 database component. Information on each variable and how it is used along with information on how to select input values is provided.

Table 5.1. RUSLE2 database components

Components	Comment
Plan view	Computes average erosion for a spatial area like a field or watershed
Worksheet	Computes erosion for alternative management practices and alternative hillslope profiles (overland flow paths)
Profile	Computes soil loss for a single hillslope profile (overland flow path), the basic computational unit in RUSLE2
Climate	Contains data on erosivity, precipitation amount, and temperature
Storm erosivity	Contains data on the distribution of erosivity during the year
Soil	Contains soil data including erodibility, texture, hydrologic soil group, time to consolidation, sediment characteristics, soil erodibility nomographs
Management	Contains descriptions of cover-management systems; includes dates, operations, vegetation, type and amount of applied materials
Operation	Contains data on operations, which are events that affect soil, vegetation, and residue; includes the sequence of processes used to describe each operation; whether an operation places residue in the soil; includes values for flattening, burial, and resurfacing ratios; ridge heights; and initial soil roughness
Vegetation	Contains data on vegetation; includes residue types associated with particular vegetations, yield, amount of aboveground biomass at maximum canopy, senescence, flow retardance, root biomass, canopy cover, fall height, live ground cover
Residue	Contains data that describe the residue description assigned to each vegetation description; includes values for decomposition, mass-cover

	relationship, how residue responds to tillage
Contouring	Contains values for row grade used to describe degree of contouring
Strips/barriers	Contains data that describes filter strips, buffer strips, and rotational strip cropping; includes cover-management in strips, width of strips, number of strips across slope length, whether or not a strip is at the end of the slope; and offset of rotation by strip; includes information on barriers used on construction sites.
Hydraulic system	Identifies the hydraulic elements and their sequence used to describe hydraulic systems of diversions, terraces, and impoundments; includes number across overland flow path length and whether or not a system is at the end of the slope; includes specific locations of practice on the overland flow path length
Hydraulic element	Contains data on grade of named channel for terraces and diversions
Subsurface drainage system	Contains data on the percent of the area covered by optimum drainage

5.6.3. Templates

RUSLE2 uses **control files** known as **templates** and **access/permission files** that control the RUSLE2 computer screen and the variables accessible to the user. **Templates** determine the appearance of the computer screen and the complexity of the problems that can be analyzed. **Templates** can be customized by the user to change the appearance of the screen. Two standard templates, **uniform slope** and **complex slope**, are available for download from the **USDA RUSLE2 Internet site** at http://www.ars.usda.gov/Research/docs.htm?docid=6038. The **uniform slope** template is for application of RUSLE2 to uniform slopes where all conditions are the same along the slope except for regularly spaced strips such as buffer strips and strip cropping. The **uniform slope** template should be used to learn RUSLE2. It is also the template that makes RUSLE2 most comparable to the USLE and RUSLE1 for estimating soil loss. The **complex slope** template can be used to analyze slopes where conditions such as soil, steepness, cover-management conditions, and certain support practices vary along the slope.

RUSLE2 can display information on many more variables than is displayed on the **uniform slope** and **complex slope** templates. Contact your RUSLE2 administrator for information on how to obtain templates that display additional output. Also, you can edit templates yourself to add a display of certain variables to your current templates. The revised template can be saved under an existing name or saved with a new name. **Of course, saving a template under an existing name means that the template as it existed before the change is lost.** Templates can be transferred among users.

5.6.4. Access/Permission Files

RUSLE2 uses **access/permissions** files that can be named and saved. These files determine the variables that are seen and the variables that are seen but cannot be edited. A main benefit of **access/permissions** files is to protect users from making unauthorized changes in a database. Contact your RUSLE2 administrator for information on changing RUSLE2 access control especially if you find that you cannot manipulate key variables because you are apparently locked out of them. In some cases, you can change values and store the information under a new name. Also, don't be surprised to learn that RUSLE2 has many other variables of interest that someone "upstream" has chosen to keep hidden from you.

5.6.5. Computer Program Mechanics

Information on RUSLE2 computer interface mechanics is summarized in documents available on the USDA-ARS (http://www.ars.usda.gov/Research/docs.htm?docid=6010), University of Tennessee (www.rusle2.org), and USDA-NRCS (http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm) Internet sites.

When the RUSLE2 program is first started, the opening screen provides two choices. Select either a **profile** or **worksheet** to perform erosion computations or select one of the other **database components** to work on stored input values such as those for cover-management and support practices, vegetation, operation, residue, and soil properties, and climate inputs. The second choice is to select a **template**. Templates control the appearance of the RUSLE2 interface and determine the complexity of the field problems that can be analyzed. RUSLE2 is easiest to use for a simple uniform slope, which is the **uniform slope** template. As you become familiar with RUSLE2, move to the **complex slope** and other templates to analyze complex slopes. Also, once you learn the program, you can change the program so that the program starts with alternative screens and **default profiles, worksheets, and plan views**.

Input values in the database can be changed during a particular RUSLE2 analysis. However, you may be locked out of certain database elements because of settings in the RUSLE2 **access control file**.

6. CLIMATE DATABASE COMPONENT

This section describes the variables in the **climate database component**, the role of each variable, and how to determine values for key variables. Values on erosivity, precipitation amount, and temperature are the principal information in the climate database component.

Three types of erosivity inputs can be used in RUSLE2. The preferred method is to enter values for **erosivity density**, which is the ratio of monthly erosivity to monthly precipitation. Erosivity density values were recently determined from analysis of modern weather data as a part of the RUSLE2 development. The second method is to enter monthly erosivity values. The third method is to enter an average annual erosivity value along with an erosivity distribution curve for the EI zone containing the site where RUSLE2 is being applied. The third method is the same as that described in AH703 for RUSLE1. However, do not use values from AH703 because those values are based on old data from the 1930's to 1950's period. **Erosivity values determined from the modern data are about 10 percent larger on average than values based on the older data.**[6]

RUSLE2 uses a storm with a 10 year recurrence interval in its runoff computations. **Two types of inputs for this storm can be used in RUSLE2 (see Section 6.5.2).** One option, which is recommended, is to enter a value for the 10 year-24 hour precipitation amount. RUSLE2 computes a corresponding 10 yr EI. The other option is to enter a 10 yr EI value. RUSLE2 computes a corresponding 10 yr-24 hr precipitation amount. Although the two options yield similar results in the eastern US, entering the 10 yr-24 hr precipitation amount yields significantly improved results in the western US.

6.1. Major Climate Variables

Table 6.1 lists the variables in the RUSLE2 **climate database component** for the **preferred erosivity density** approach, which should be used when applying RUSLE2 to locations within the continental US. Table 6.2 lists the erosivity variables for the annual

6 This overall 10 percent increase in average annual erosivity should not be attributed necessarily to climate change. The increase could be related to differences in measurement techniques and equipment and analytical procedures used to determine erosivity values from the measured data. Data limitations including temporal and spatial variability, missing data, and errors in weather data do not allow conclusions contribute to the difference. In general, the monthly distributions of erosivity changed less than the overall increase in erosivity. The erosivity values produced by this analysis are superior to previous erosivity values, especially for the Western US, for conservation and erosion control planning using RUSLE2. This 10 percent difference in erosivity values must be interpreted along with RUSLE2's accuracy in the context of the particular RUSLE2 application (see **Section 17**).

R and EI distribution zone approach, which may be convenient when applying RUSLE2 outside of the US.

Table 6.1. Variables in climate database component for **erosivity density** procedure		
Variable	**Symbol**	**Comment**
Monthly erosivity density	α_m	Ratio of monthly erosivity to monthly precipitation; RUSLE2 uses these values and monthly precipitation to compute monthly erosivity
Annual erosivity	R	RUSLE2 sums monthly erosivity values to determine an annual erosivity value (not an input)
Monthly erosivity	R_m	RUSLE2 computes monthly erosivity using monthly values for erosivity density and precipitation (not an input)
Daily erosivity	r_i	RUSLE2 "disaggregates" monthly erosivity values into daily values (not an input)
Monthly precipitation	P_m	Average annual monthly precipitation (rainfall plus snow), used to compute monthly erosivity, the temporal variation of soil erodibility, and decomposition of dead plant materials (litter, residue, roots)
Daily precipitation	p_i	RUSLE2 "disaggregates" monthly precipitation values into daily values (not an input)
Annual precipitation	P_t	RUSLE2 computes annual precipitation from the monthly precipitation values; used to compute time to soil consolidation (not an input)
10 yr 24 hr precipitation	$P_{10y,24h}$	This precipitation, representative of a moderately infrequent erosive rain, is used to compute a storm erosivity and runoff; these variables, in turn, are used to compute transport capacity and deposition for concave slopes, vegetative strips, and channels; reduction of erosion by ponding; effectiveness of contouring; and critical slope length for contouring
EI for 10 yr 24 hr precipitation	$EI_{10y,24h}$	RUSLE2 determines this values from 10 yr 24 hr precipitation and maximum monthly erosivity density value (not an input)
Monthly temperature	T_m	Average annual monthly temperature, used to compute the temporal variation of soil erodibility and decomposition of dead plant materials (litter, residue, roots)
Daily temperature	T_i	RUSLE2 "disaggregates" monthly temperature values into daily temperature values (not an input)
In Req Area?	Yes or no	The Req area is a region in the Northwestern part of the US where the erodibility of certain cropland and other highly disturbed soils is greatly increased during winter months; answer **Yes** to use Req relationships for these land uses

Use Req distribution?	Yes or no	Wintertime adjustment for increased erodibility does not apply to land uses like pasture and rangeland; if answered no, Req relationships will not be used
R equivalent	R_{eq}	The effect of the greatly increased erodibility is accounted for in the Req region by using an equivalent erosivity value based on annual precipitation (not an input)
EI distribution for Req	-	An erosivity distribution that describes the greatly increased erodibility during the winter
Adjust for soil moisture	Yes or no	An adjustment is made for soil moisture when the Req relationship is selected for cropland and other situations of highly disturbed soil, only applies to Req zone
Vary soil erodibility with climate	Yes or no	With the exception of when the Req relationships are used, select **Yes** to vary soil erodibility values through time as a function of monthly precipitation and temperature (may not be available on most templates)
Note: Not all of these Req-type variables are available on some templates. For example, if **No** is the input for **In Req area?,** then RUSLE2 automatically varies soil erodibility with climate.		

Table 6.2. Variables in climate database component for monthly or annual R and EI distribution procedure. Note: Refer to AH703 for information on these variables.

Variable	**Symbol**	**Comment**
Average annual erosivity	R	An erosivity index that indicates how the erosivity of rainfall varies by location
Erosivity distribution	EI zone identifier	Describes how erosivity varies during the year by half-month periods. Not an input when monthly erosivity values are entered.
Monthly erosivity	R_m	RUSLE2 computes monthly erosivity using annual erosivity value and erosivity (EI) distribution by half month period when method of entering annual erosivity is used.
Daily erosivity	r_i	RUSLE2 "disaggregates" half month erosivity values into daily values (not an input)
10 year storm erosivity	EI_{10yr}	This storm represents a moderately infrequent erosive rain; EI_{10yr} value is used to compute runoff, which along with the storm erosivity, is used to compute transport capacity and deposition for concave slopes, vegetative strips, and channels; reduction of erosion by ponding; effectiveness of contouring; critical slope length for contouring

6.2. Basic Principles

RUSLE2 is based on the assumption that net **detachment** caused by a single storm is directly proportional to the product of a storm's **energy E** and its **maximum 30-minute intensity I_{30}**. **The relationship between detachment and storm erosivity EI is linear**, which means that individual **storm EI** values can be summed to determine monthly and annual erosivity values. This linear relationship also means that average annual erosion can be mathematically computed for each day as represented by Equation 5.1 even though erosion does not occur on every day during a year.

The **average annual erosivity value R** is an index of erosivity at a location. For example, R-values in central Mississippi are about 10 times those in Western North Dakota. If all things are equal, erosion in central Mississippi is 10 times that in Western North Dakota. Erosivity reflects the effects of both rainfall amount and rainfall intensity on erosion. Thus, erosivity values can vary significantly among locations having nearly equal rainfall amounts because of difference in rainfall intensity among locations.

6.2.1. Computing Erosivity for Individual Storms

Storm erosivity EI is the product of a storm's total **energy E** and its **maximum 30-minute intensity I_{30}**. A storm's total energy is most related to the total amount of rainfall in a storm. It is also partially related to intensity because the energy content per unit rainfall (**unit energy**) is related to rainfall intensity. Rainfall intensity also has a direct affect on erosion besides its effect on storm energy. The **maximum 30-minute intensity** is a better measure of the intensity effect than either **average intensity** or **peak intensity**. The 30-minute time period over which to average intensity was determined from analysis of empirical erosion data for the continental US. Other time periods such as 15 minutes are better in other places of the world where rainfall characteristics differ from those in the continental US. **The EI product for storm erosivity captures the effects of the two most important rainfall variables that determine erosivity; how much it rains (rainfall amount) and how hard it rains (rainfall intensity).**

Total energy for a storm is computed from:

$$E = \sum_{k=1}^{m} e_k \Delta V_k \qquad \textbf{[6.1]}$$

where: e = unit energy (energy per unit of rainfall), ΔV = rainfall amount for the *kth* period, k = an index for periods during a rain storm where intensity can be considered to be constant, and m = number of periods. Unit energy is computed from:

$$e = 0.29[1 - 0.72\exp(-0.082i)]$$ **[6.2]**

where: unit energy e has units of MJ/(ha·mm) and i = rainfall intensity (mm/h).[7] Table 6.3 illustrates computation of total energy for a storm. The total energy for the example storm is 8.90 MJ/ha.

The next step is to determine the maximum 30-minute intensity I_{30}. Maximum 30-minute intensity is the average intensity for the continuous 30 minutes with the maximum rainfall. (Also, I_{30} = 2·amt of rain in the 30 minutes having the maximum rainfall amt) Plotting cumulative rainfall for the storm as illustrated in Figure 6.1 is helpful for determining maximum 30-minute rainfall. This storm is unimodal (single peak), which means that the 30 minutes with the most rainfall contains the time that the peak intensity occurs. The amount of rainfall is 27.4 mm for the 30 minutes with the most rainfall, which gives an intensity of 57.4 mm/h for I_{30}.

Table 6.3. Sample computation of erosvity EI for an individual storm

Time (hrs:min)	Duration of interval (minutes)	Cumulative rain depth (mm)	Rainfall in interval (mm)	Intensity (mm/h)	Unit energy (MJ/ha* mm)	Energy in interval (MJ/ha)
4:00		0.0				
4:20	20	1.3	1.3	3.8	0.137	0.17
4:27	7	3.0	1.8	15.2	0.230	0.41
4:36	9	8.9	5.8	38.9	0.281	1.64
4:50	14	26.7	17.8	76.2	0.290	5.15
4:53	3	30.5	3.8	76.2	0.290	1.10
5:05	12	31.8	1.3	6.4	0.166	0.21
5:15	10	31.8	0.0	0.0	0.081	0.00
5:30	15	33.0	1.3	5.1	0.152	0.19
Total	90		33			8.88

The erosivity for the storm is the product of 8.90 MJ/ha (storm energy) and 57.4 mm/h (maximum 30-minute intensity) = 512 MJ·mm/(ha·h). **The computation of storm erosivity in US customary units is similar, except that storm erosivity values are divided by 100 to provide convenient working numbers.**

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7 Equation 6.2 differs from the corresponding equation used in RUSLE1 (AH703). The 0.082 coefficient in equation 6.2 was 0.05 in AH703. For additional discussion, see McGregor, K.C., R.L. Bingner, A.J. Bowie, and G.R. Foster. 1995. Erosivity index values for northern Mississippi. Transactions of the American Society of Agricultural Engineers. 38(4):1039-1047.

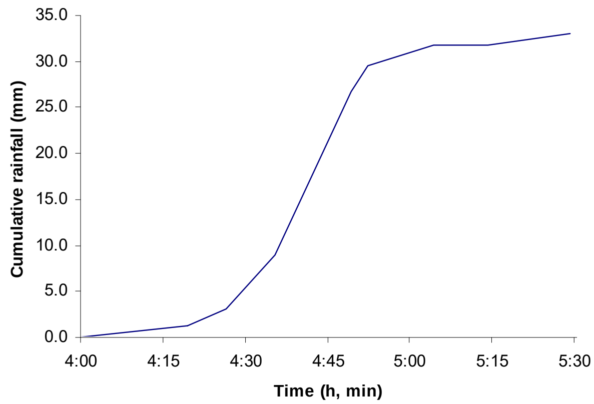

Figure 6.1. Cumulative rainfall for a storm.

Rains less than 0.5 inch (12.5 mm) and separated from other rains by more than 6 hours are not included in the computations unless the maximum 15-minute intensity exceeds 0.5 inch/hour (12.5 mm/h). When erosivity values were first computed in the late 1950's, these small storms were omitted to significantly reduce the amount of rainfall data that must be processed in an era before data could be processed with computers. These storms add little to the total annual erosivity. However, storms less than 0.5 inch (12.5 mm) were also deleted in computing erosivity for RUSLE2 to give some effect of computing reduced erosion at low rainfall amounts and intensities because of little or no runoff.

Average annual erosivity is the sum of the storm erosivities over M number of year as:

$$R = \left[\sum_{m=1}^{M} \sum_{j=1}^{J(m)} (EI_{30})_j \right] \Big/ M \qquad \textbf{[6.3]}$$

where: R = average annual erosivity, EI_{30} = the erosivity of an individual storm, j = an index for each storm, J(m) = number of storms in the *mth* year, and m = an index for year.[8]

6.2.2. Why New Erosivity Values were Computed from Modern Data

A concern has existed for sometime that erosivity values for the eastern US needed to be recomputed based on modern precipitation data. Average annual erosivity values in AH703 for the Eastern US, as well as erosivity values in AH282 and AH537, were based on data collected in the approximate period of 1935 to 1957. This period included two major droughts in large regions of the US. Also, a possible climate change over the last 70 years may have increased rainfall amounts and intensities and caused a corresponding increase in erosivity. To address these concerns, precipitation data from the 1960's through 1999 were analyzed to develop a modern set of erosivity values.[9] **Based on this**

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[8] The R factor has units. In this guide, the US customary units for R are hundreds of (ft tons in)/(ac yr hr). Metric units in the SI system are (MJ mm)/(ha∗h) for erosivity and (t h)/(MJ mm). See AH703 for additional information.

[9] Precipitation data from 15-minute stations across the US were assembled by the Illinois State Water Survey (ISWS), who computed storm energy and maximum 30-minute intensity for the qualifying

analysis, modern average annual erosivity is about 10% greater over much of the eastern US than that for the1935-1957 period.

Differences in erosivity values derived from the 1930's-1950's data and those derived from the 1960's-1990's data should not be interpreted as having been caused by climate change. Differences in record length, analysis procedures, and interpretation at different points in time and by different people prevent such a direct comparison of values.

Erosivity values described in this RUSLE2 User Reference Guide determined from the modern data should be accepted as representing the best erosivity values currently available for applying RUSLE2 at the local field office level for conservation and erosion control planning—nothing more, nothing less.

6.2.3. Erosivity Density Values

The erosivity density method used to derive erosivity values was developed to maximize the precipitation data that could be used to compute erosivity values and to provide a consistent set of erosivity value for conservation and erosion control planning. **Erosivity density** is the ratio of the monthly erosivity to monthly precipitation. Erosivity density values were computed across the US at about 1610 stations. Statistical analysis showed that erosivity density is independent of elevation, which means that the erosivity density could be smoothed and mapped using GIS techniques for the entire continental US as a spatial unit (See the RUSLE2 Scientific Documentation for additional information). Precipitation data with intensity values needed to compute erosivity are very limited

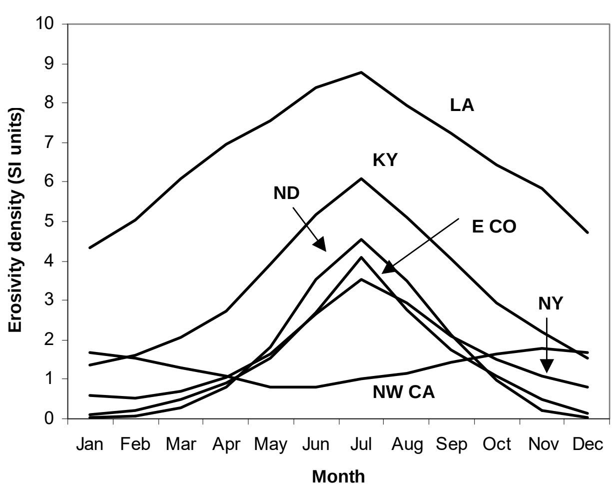

Figure 6.2. Erosivity density at selected locations. LA-Louisiana, KY-Kentucky, ND-North Dakota, E CO-Eastern Colorado, NY-New York, NW CA-Northwestern California

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rainstorms. The ISWS and the USDA-NRCS National Water and Climate Center (NWCC) analyzed the data to remove storms with greater than a 50-yr return period, snow events, and invalid data because of equipment failure, a short record length, or other reasons. University of Tennessee personnel performed the spatial analysis of the data.

at higher elevations. The applicability of erosivity density values is limited at elevations higher than about 3,000 m (10,000 ft), especially in the winter months.[10]

Erosivity density is a measure of erosivity content per unit of precipitation. Erosivity density is low during the winter months and high during the summer months with the exception of the western most portion of the US. Erosivity density is greater in the southern part of the US than in the northern part. Erosivity density is more uniform over the year in the southern part of the US than in other parts of the US.

Unsmoothed erosivity density values directly computed from the weather data at individual stations are both spatially and temporally irregular. Trends are sometimes difficult to discern when comparing data among individual weather stations. However, patterns like those in Figure 6.2 emerge when data from several stations are averaged over areas like the quadrants of Indiana.[11] The erosivity density values were spatially smoothed using GIS techniques to provide spatial and temporal consistency required by conservation and erosion control planning applications of RUSLE2. The objective in RUSLE2 is to represent the main geographic trends in the historical data and not the details in historical weather data. Preferably the probability of weather events, both dry and wet, would be the same at all locations in the climate data used by RUSLE2.

Erosivity density values for the continental US are shown in Figure 6.3-6.14. RUSLE2 users can read values from these figures to create entries in their RUSLE2 operational database. However, RUSLE2 users are advised to download values for their RUSLE2 application from the NRCS RUSLE2 National Database rather than to create their own RUSLE2 entries by reading values from these Figures. However, some users may wish to create an entry in their database for a specific site rather than use the NRCS database values. Values for erosivity density can be read from these figures with sufficient accuracy to apply RUSLE2.

The principal application of RUSLE2 is for conservation and erosion control planning. The objective is to capture main effects and consistency so that farmers, contractors, and others impacted by RUSLE2 are treated fairly, especially where costs, benefits, and regulatory impacts are involved. No one should be penalized or rewarded based on unusual events occurring at a location.

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[10] Erosivity density values are highly variable in the western US. Also, the number of locations is very limited. Because of these data limitations, statistical tests that show that the hypothesis that erosivity density values are not a function of elevation are not robust. Obviously erosivity density values decrease with elevation in the winter because of increasing amounts of snow at higher elevations. Also, erosivity density values probably decrease slightly with elevation in the summer.

11 See RUSLE2 Science Documentation, USDA-Agricultural Research Service.

6.2.4. Monthly Erosivity Values

RUSLE2 computes a monthly erosivity by multiplying monthly erosivity density by monthly precipitation as:

$$R_m = \alpha_m P_m \quad \textbf{[6.4]}$$

where: R_m = monthly erosivity, α_m = monthly erosivity density, and P_m = monthly precipitation. Annual erosivity is computed as the sum of the monthly erosivity values. Figures 6.15 and 6.16 illustrate average annual R-values for the continental US. The values in these figures are for illustration only. Actual values used in RUSLE2 should be downloaded from the NRCS national RUSLE2 database. Average annual erosivity values for the western US and the mountainous regions of the eastern US are much more variable than indicated in these figures. Nevertheless, these figures can be compared to similar figures in AH282, AH537, and AH703.

6.3. Input Values for Monthly Erosivity Density, Precipitation, and Temperature

6.3.1. Selecting Climate Input Values for Continental US

RUSLE2 requires monthly values for erosivity density, precipitation, and temperature appropriate for the site where RUSLE2 is being applied. A sample set of these values are included with the download of RUSLE2. A complete set of these values can be obtained from the NRCS national RUSLE2 database or by contacting the NRCS state agronomist in your particular state of interest.

The climate values in the NRCS national RUSLE2 database have been assigned by county for those counties in the US where the values can be considered to be uniform over the county. In mountainous areas, the RUSLE2 weather inputs vary over space because of elevation effects. In those regions, NRCS has organized the data by precipitation depth zones that vary with elevation. The precipitation and temperature values in the NRCS national RUSLE2 database are based on 1961-1990 data.

RUSLE2 users in the US should generally use RUSLE2 climate input values from the NRCS national RUSLE2 database. However, in some cases, climate values may be needed for a specific location rather than for the precipitation depth zones used in the NRCS national RUSLE2 database. Erosivity density values at a particular location can be read from Figure 6.3-6.14. Precipitation and temperature values at a specific location can be obtained from the PRISM database available from the USDA-NRCS. PRISM monthly and precipitation values are on a 4 km by 4 km grid throughout the continental US.[12]

Current PRISM values are based on historical data from 1961-1990. The data were not processed to remove unusually dry or wet events. That is, the return periods (probability) of events vary significantly by location, resulting in spatial variability that is inappropriate for conservation and erosion control planning. The PRISM model, considered state-of-the-art, produces precipitation values that can vary greatly over a relatively short distance, which can result in a corresponding wide variation in erosion estimates.

6.3.2. Climate Input Values Outside of Continental US

When RUSLE2 is applied outside of the continental US, input climate data should be assembled using procedures outlined above if possible.[13] However, RUSLE2 is frequently applied where detailed weather data are not available.

Several points should be considered in developing input values for RUSLE2 where weather data are limited. RUSLE2 is a conservation and erosion control planning tool that captures main effects of the variables that affect rill and interrill erosion and general spatial trends. Weather data can be very irregular between locations, especially if the period of record is short. While short records may have to be used out of necessity, the values should be carefully inspected and smoothed based on technical judgment by those knowledgeable of local and regional weather and climate conditions.

Estimating erosivity as outlined above requires precipitation data that include rainfall intensity values. However, these intensity data may not be available. Erosivity can be estimated from monthly and daily precipitation data, provided sufficient data are available to calibrate the procedures.

[12] These PRISM-based values were developed by the NRCS, Oregon State University, and other cooperators using the PRISM model that takes measured precipitation and temperature station (point) data and spatially distributes these values taking into account effects of elevation, proximity to a major water body, atmospheric inversions, and other factors (see Daly, C., G. Taylor, and W. Gibson. 1997. The PRISM approach to mapping precipitation and temperature, 10th Conf. on Applied Climatology, American. Meteorological Society.)

[13] The NRCS National RUSLE2 Database contains values for Alaska, Hawaii, Puerto Rico and US Territories in the Pacific Basin and Virgin Islands.

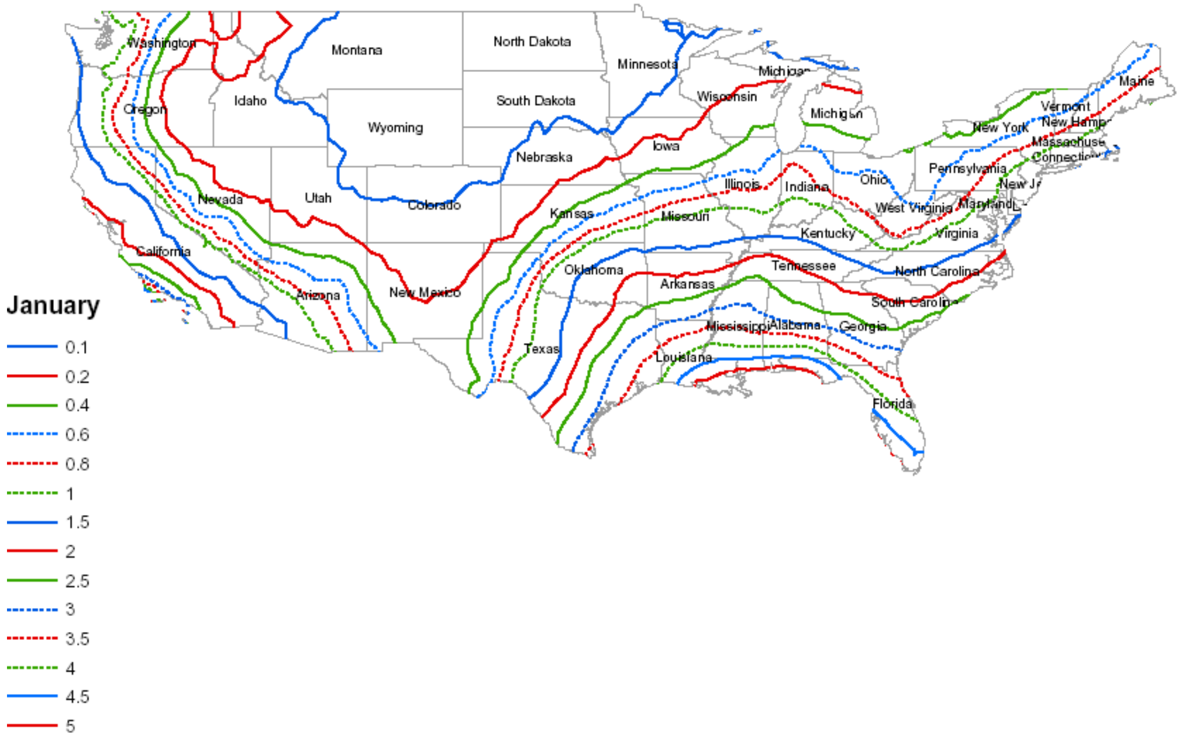

Figure 6.3. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] for January.

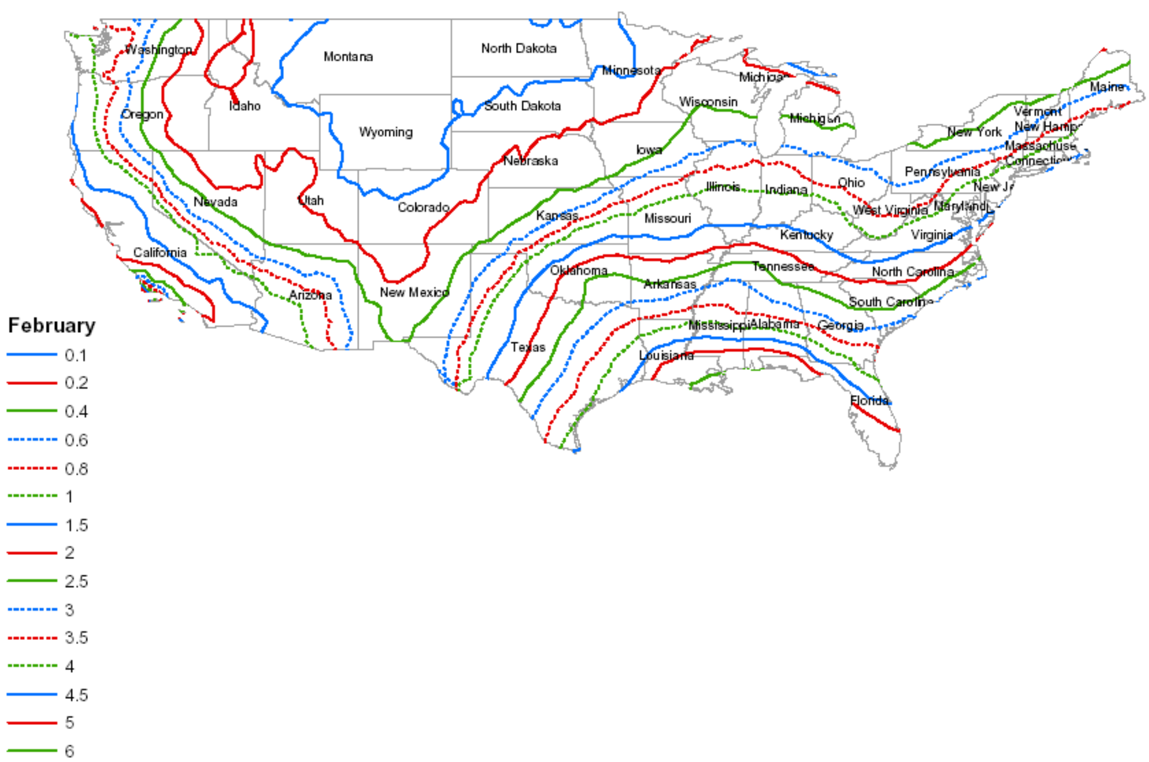

Figure 6.4. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] for February.

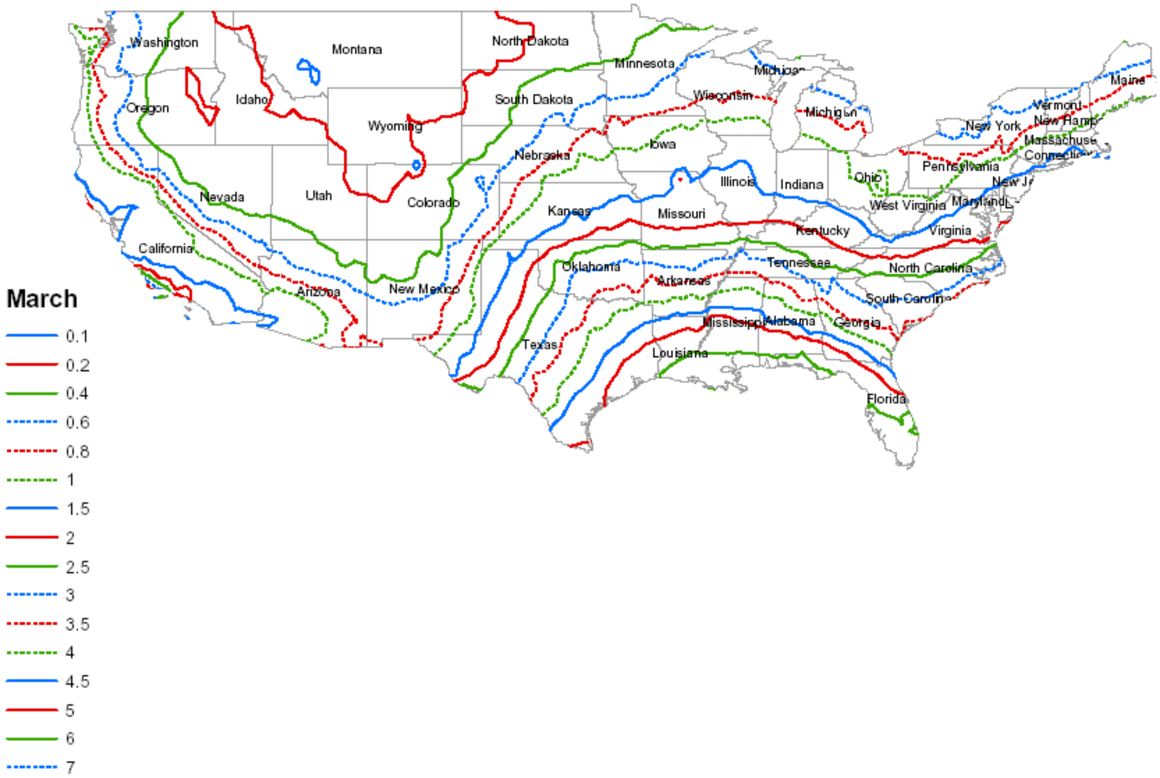

Figure 6.5. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] for March.

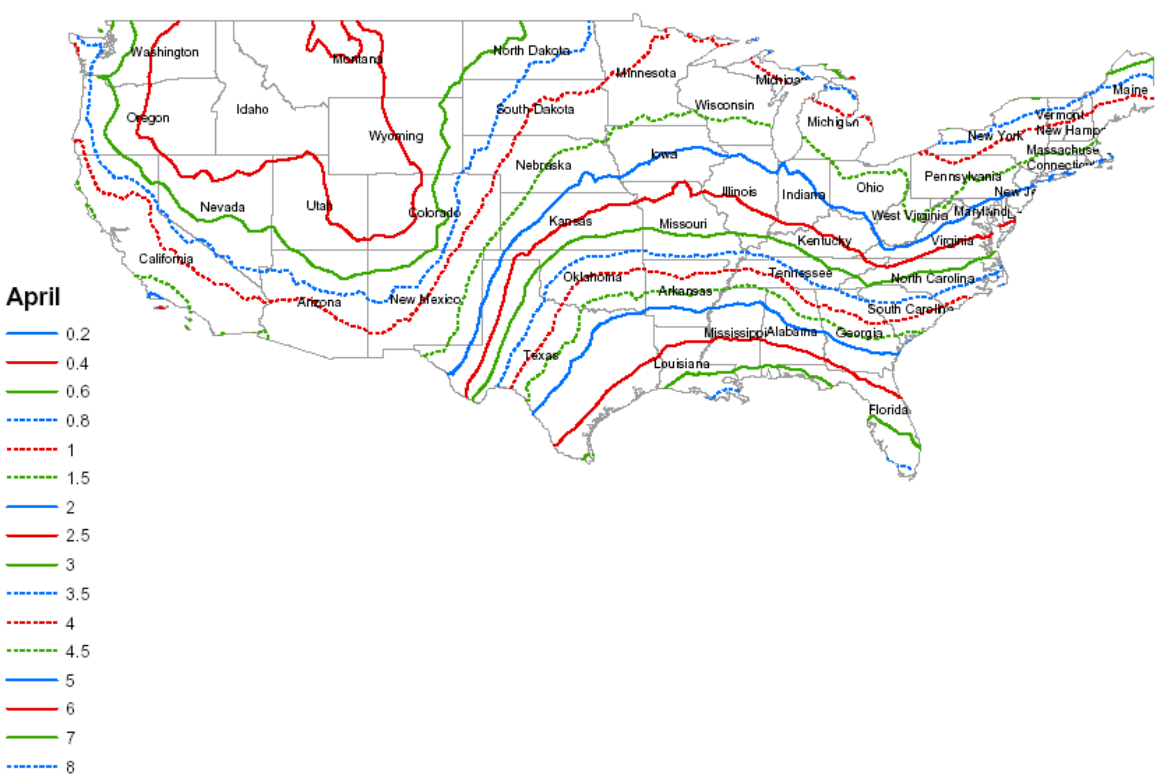

Figure 6.6. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] for April.

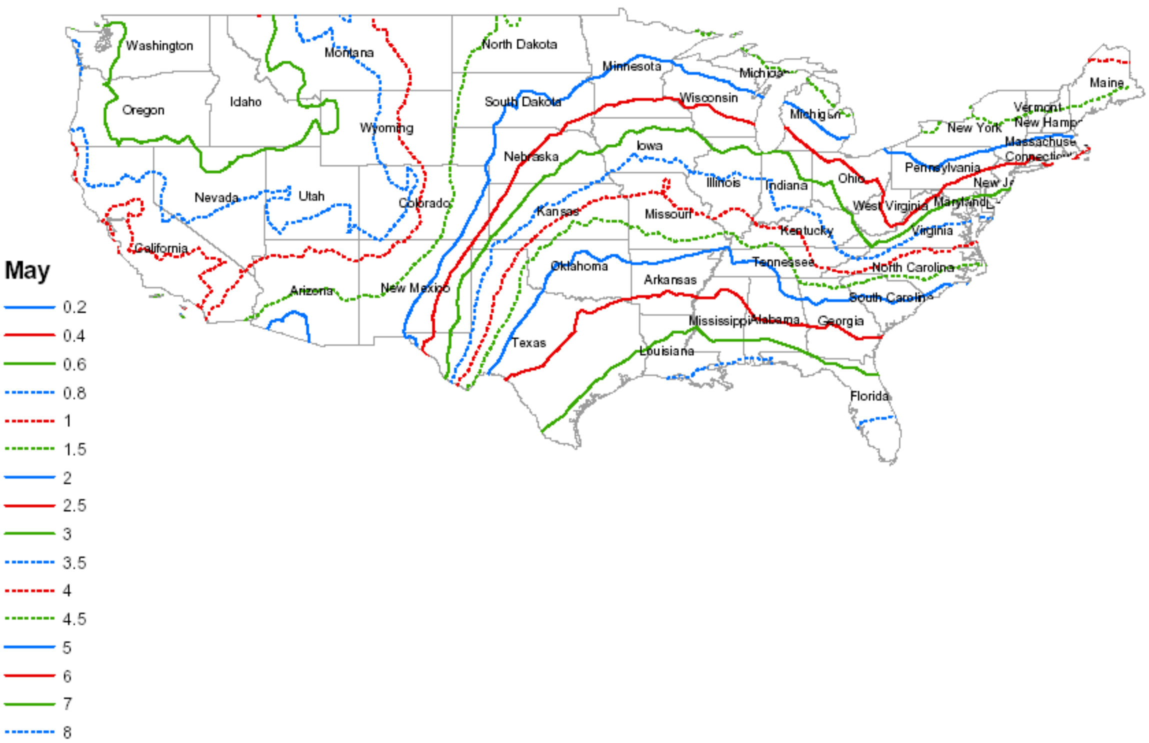

Figure 6.7. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] for May.

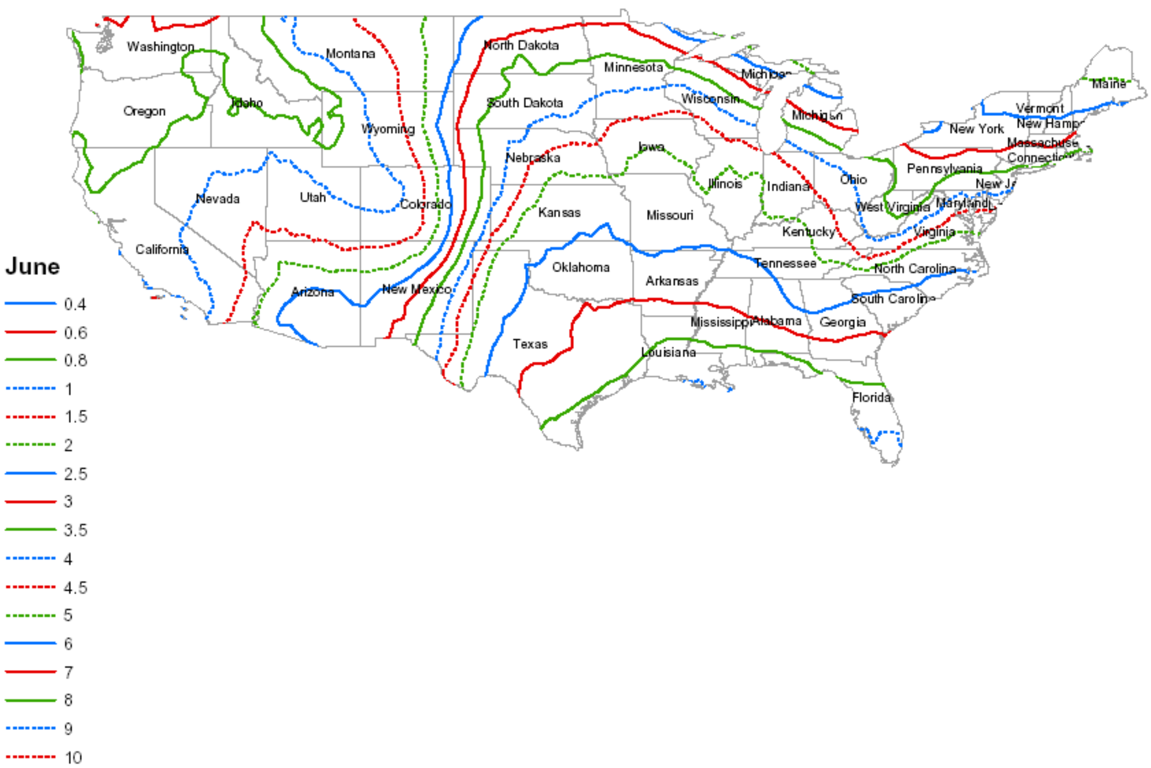

Figure 6.8. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] for June.

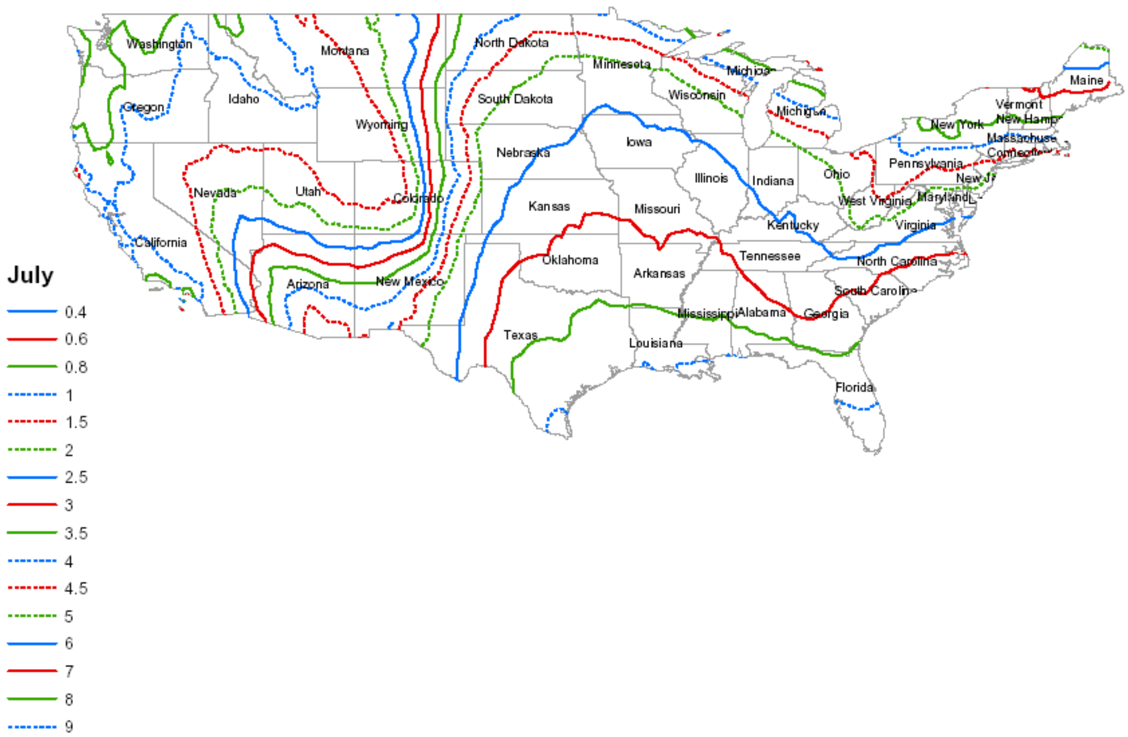

Figure 6.9. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] for July.

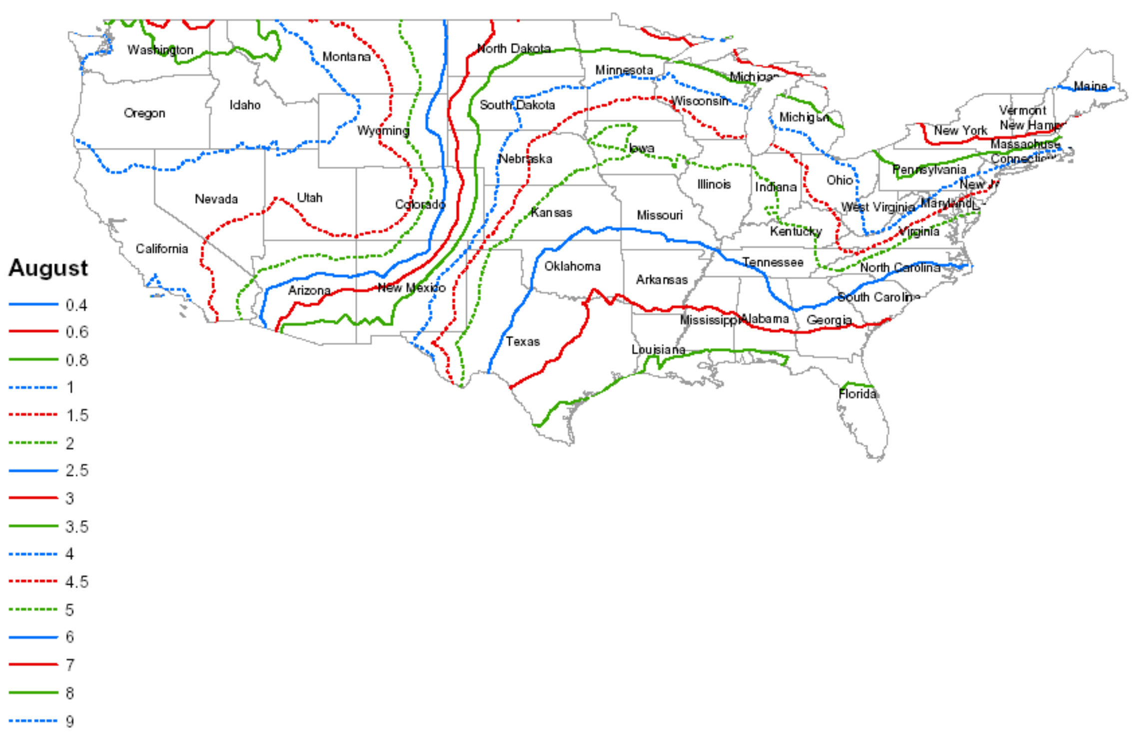

Figure 6.10. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] for August.

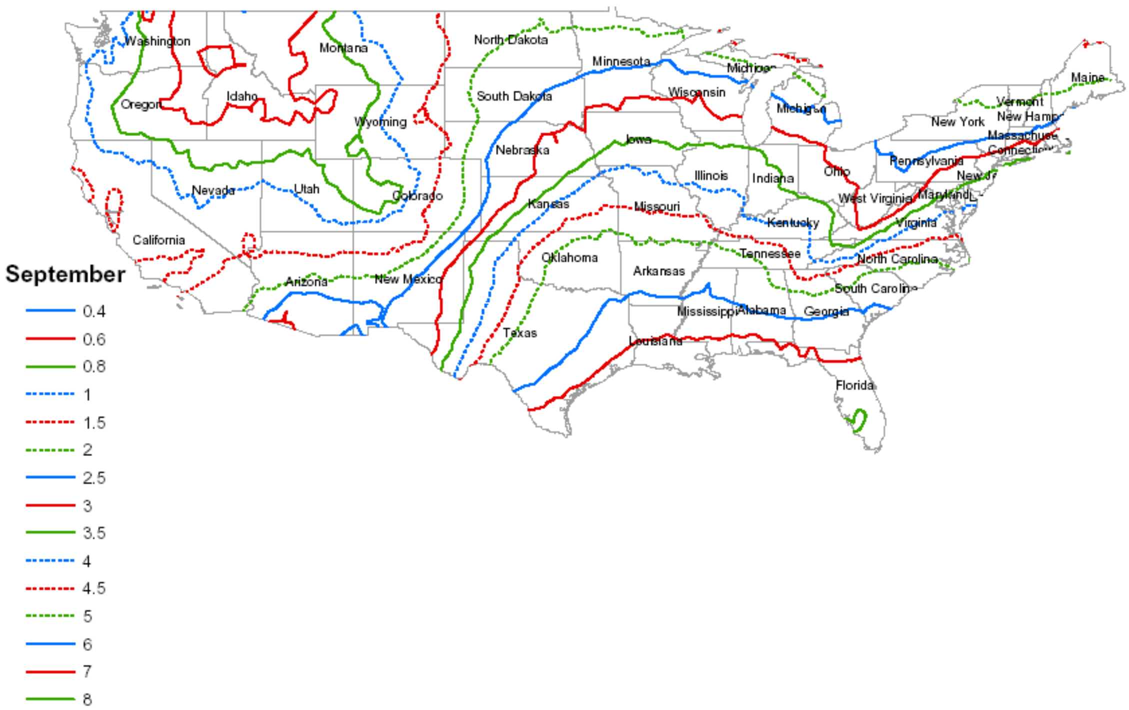

Figure 6.11. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] September.

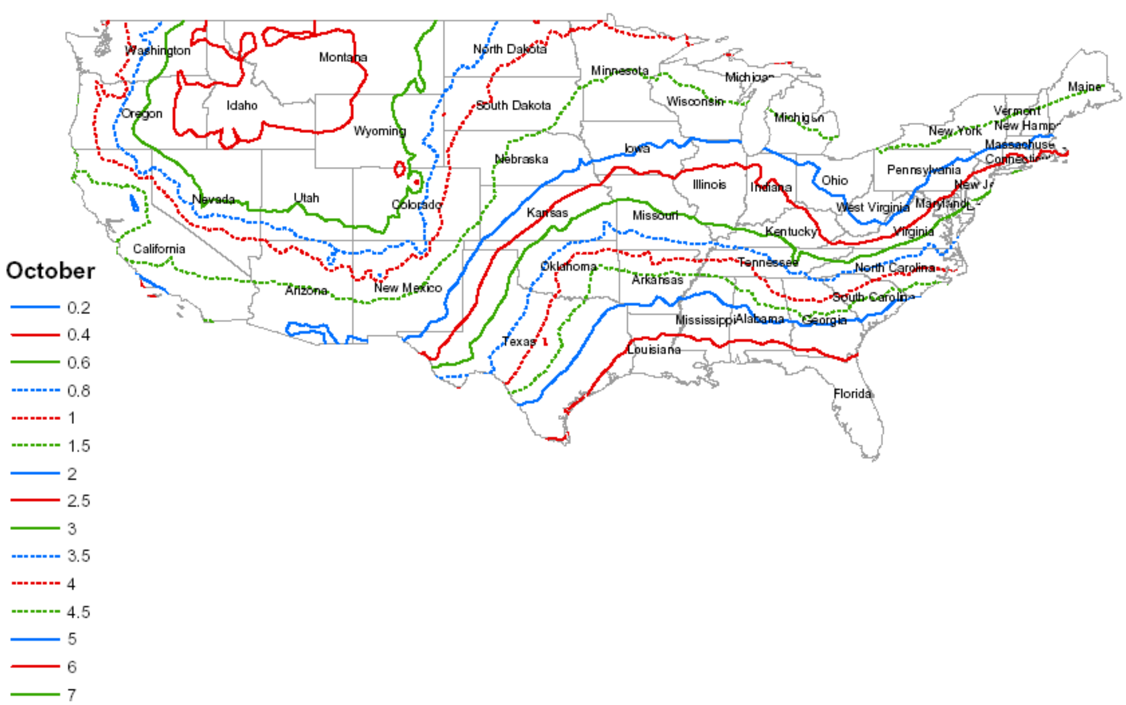

Figure 6.12. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] October.

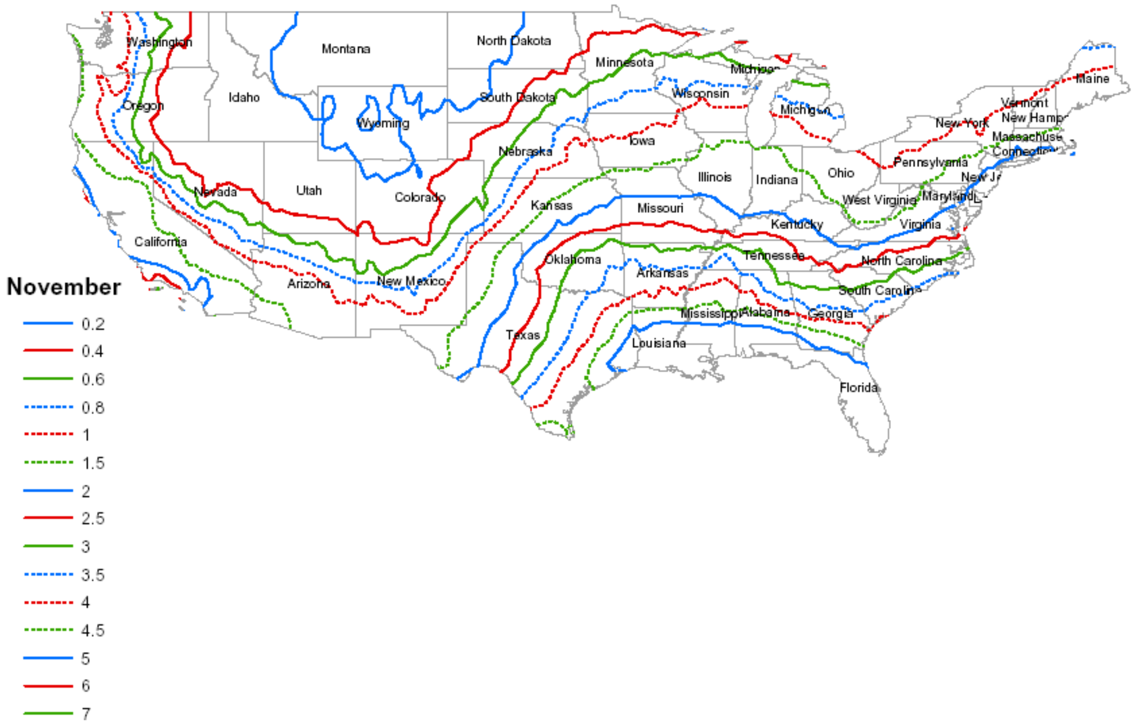

Figure 6.13. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] November.

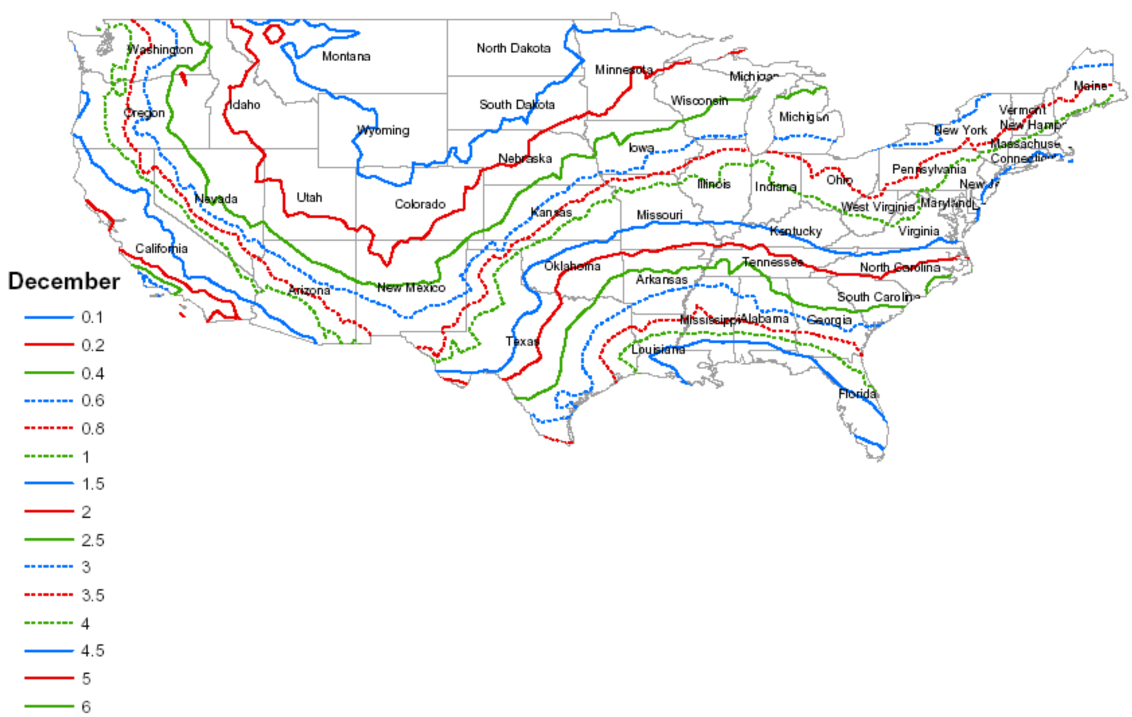

Figure 6.14. Monthly erosivity density [monthly erosivity (SI units)/monthly precip (mm)] December.

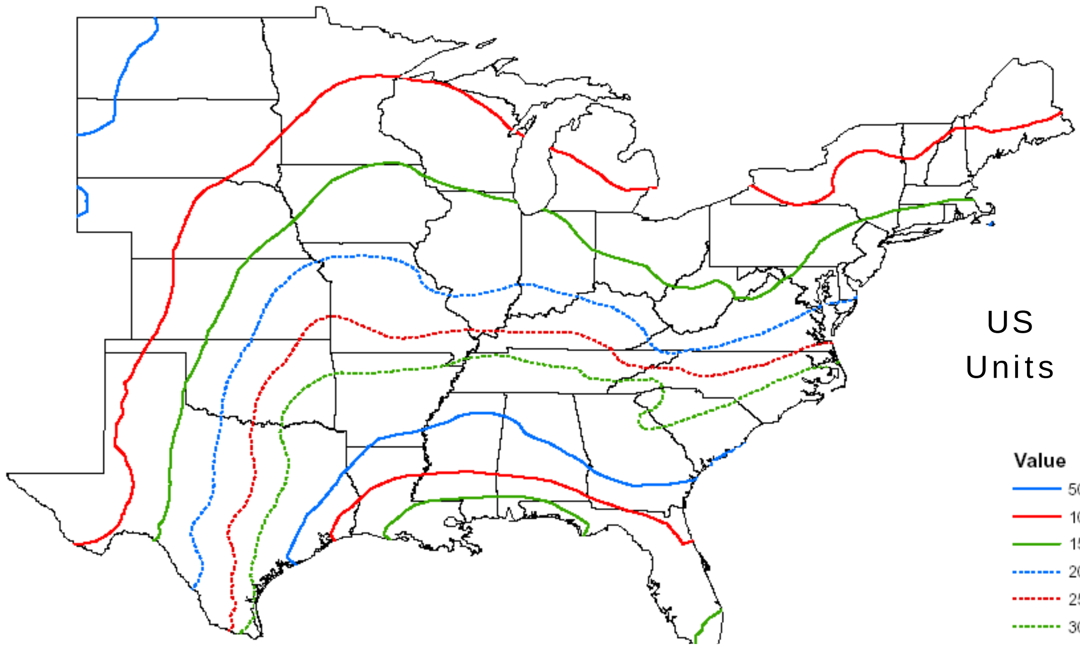

Figure 6.15. Average annual erosivity R-values for the eastern US in customary US units (See Foster, G.R., D.K. McCool, K.G. Renard, and W.C. Moldenhauer. 1981. Conversion of the universal soil loss equation to SI metric units. Journal of Soil and Water Conservation 36(6):355-359.

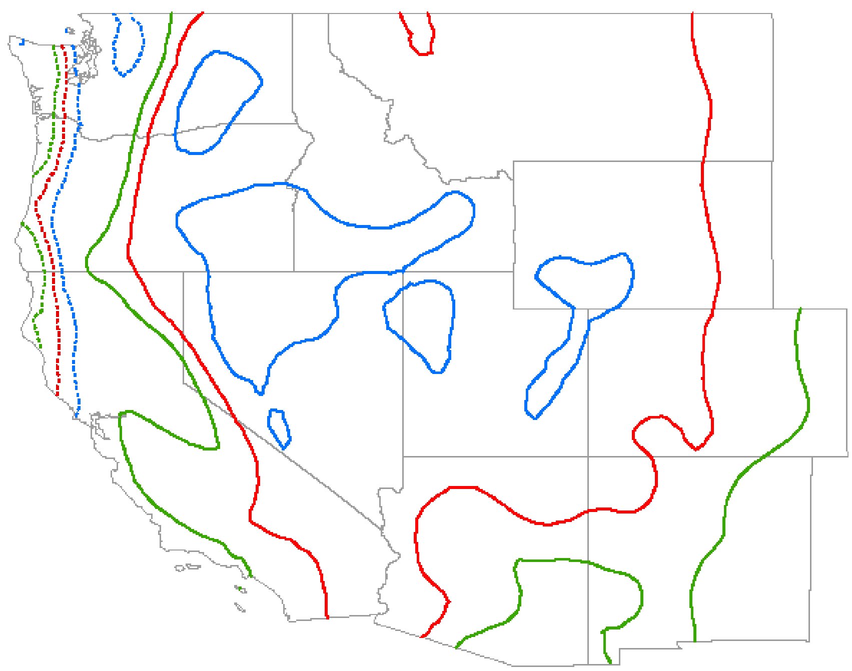

Figure 6.16.Average annual erosivity R values for western US. (For illustration to show broad trends. Local values vary greatly.)

When storm data are used to estimate erosivity, storm erosivity can be computed from storm rainfall amount using the non-linear equations:

$$R_s = aP_s^b \qquad \textbf{[6.5]}$$

where: R_s = storm erosivity, P_s = storm precipitation amount, and values for coefficients **a** and **b** are determined by **nonlinear** analysis of empirical data. A logarithmic transform and linear regression does not return the proper values for the **a** and **b** coefficients in equation 6.5. The coefficient **a** and exponent **b** varies by season of the year and by location as represented by the different shaped curves in Figure 6.2.

Monthly precipitation can also be used to estimate monthly erosivity from empirically derived equations. Equation 6.4 implies a linear relationship between monthly precipitation and monthly erosivity. However, the relationship between monthly erosivity and monthly precipitation is actually non-linear. A linear equation can only be used to estimate monthly erosivity using monthly precipitation when the year is divided into months and having erosivity density values that vary by location and by month in sufficient spatial resolution to stepwise approximate non-linear temporal and spatial variations in erosivity. That is, linear equations can be used in a stepwise fashion to approximate non-linear equations if the temporal and spatial steps have sufficient resolution.

6.3.3. Erosivity Values for High Elevation, Snow Cover, Snow Melt, and Req Zone

Applying RUSLE2 to high elevations, periods when a snow cover is present, and snow melt are discussed below in **Section 6.9** related to applying RUSLE2 in the special **Req** zone.

6.3.4. Erosivity Values for Irrigation

The major types of irrigation are surface applied and sprinkler applied water. RUSLE2 can not be used to estimate erosion from surface irrigation systems because runoff and erosion decrease along the flow path for surface irrigation, whereas RUSLE2 assumes an increase.

Most sprinkler irrigation systems apply water at a sufficiently low intensity that erosion does not occur. Thus, the applied water has little or no erosivity. However, irrigation does affect rill-interrill erosion by increasing soil moisture, and increasing vegetation production (yield) level, which decreases erosion. The increased soil moisture increases runoff and erosion when rainfall occurs during irrigation periods, and the added water increases decomposition of biomass on and in the soil. **Section 14.5** describes how to use RUSLE2 to estimate how irrigation affects rill-interrill erosion caused by rainfall.

6.3.5. Erosivity Values for Subsurface Drainage

Subsurface drainage reduces both soil moisture, which reduces runoff and erosion. RUSLE2 uses a soil erodibility factor value for the drained situation that differs from the soil erodibility value for the undrained condition to compute how subsurface drainage affects erosion. Subsurface drainage also increases vegetation production (yield) level, which reduces erosion. **Section 14.4** describes how to use RUSLE2 to estimate how subsurface drainage affects erosion.

6.4. Disaggregation of Monthly Values into Daily Values

As indicated by Equation 5.1, RUSLE2 uses long term average daily values in its computations. RUSLE2 uses a disaggregation procedure to compute long term average daily weather values from long term daily monthly values. This procedure uses linear equations that interpolate between the monthly values. The RUSLE2 disaggregation equations compute daily values that preserve monthly averages in the input data. The resulting daily values are sometimes not smooth, especially for rainfall values that vary up and down from month to month in comparison to the smooth trends in temperature. Preserving average monthly values was considered to be more important than having a smooth curve. Disaggregation of the monthly erosivity and temperature values for Birmingham, AL is shown in Figure 6.17.

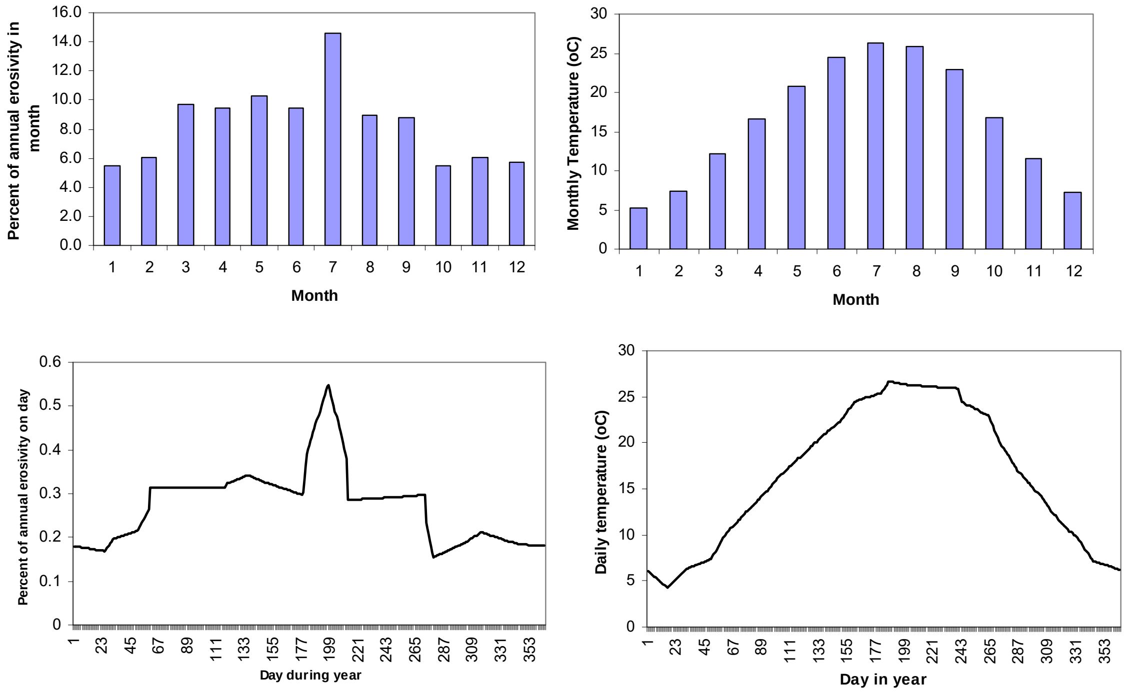

Figure 6.17. Disaggregation of monthly erosivity and temperature into daily values for Birmingham, AL.

6.5. Ten Year Storm

RUSLE2 uses a storm having a 10 year recurrence interval in its runoff computations. Two ways are provided in RUSLE2 for obtaining values for this storm. The strongly recommended way, especially for the eastern US, is to enter values for the 10-year-24 hour precipitation amount. The second way is to enter values for the 10 year EI event like that used in RUSLE1. The 10 year EI event is the storm erosivity that a 10 year recurrence interval.

6.5.1. 10 Year-24 Hour Storm

RUSLE2 uses the 10 year-24 hour (P_{10y24h}) storm to compute storm erosivity and runoff values that are used to compute factor values for contouring, critical slope length for contouring, sediment transport capacity, and the effect of ponding on reducing erosivity. Sediment transport capacity is used to compute deposition by runoff entering slope segments with a concave shape, dense vegetation, high ground cover, or rough soil surface. The 10 year-24 hour precipitation value is the storm amount that occurs in a 24 hour period that has the probability of occurring once every 10 years (a 10-year return period). Values for the 10 year-24 hour precipitation amounts in the NRCS national RUSLE2 database are by county in the eastern US and by precipitation depth zone in the eastern US. Those values were taken from the most recent National Weather Service published values. Values for the 10 yr-24 hour precipitation are illustrated in Figure 6.18 for the eastern US and for New Mexico in Figure 6.19 as an example of the values available for the western US. These figures are taken from older publications (national maps have not been updated) and are for illustration purposes only. More recent data are available that should be used. The modern data are available at http://hdsc.nws.noaa.gov/hdsc/pfds/.

Figure 6.18. (Full illustration only) 10 yr-24 hour precipitation for the US

The P_{10y24h} value is used to compute an erosivity value associated with this precipitation. The procedure used by RUSLE2 computes an EI_{10y24h} value as:

$$EI_{10y24h} = 2\alpha_m P_{10y24h} \quad \textbf{[6.6]}$$

where: m = the month with the largest erosivity density value.

6.5.2. 10-Year EI Storm

Although use of the 10 year-24 hour storm is the preferred storm input in RUSLE2, the 10-year EI storm has been retained in RUSLE2 as an option. The 10-year EI method gives good results in the eastern US but not in the western US. The 10-year EI value is used to estimate a precipitation amount that is used in the same way that the 10 year-24 hour precipitation amount is used in RUSLE2. The reason that this method does not work well in the western US is that the precipitation amount for this storm is underestimated because the erosivity density (erosivity content per unit precipitation) is much less in the western US than in the eastern US.

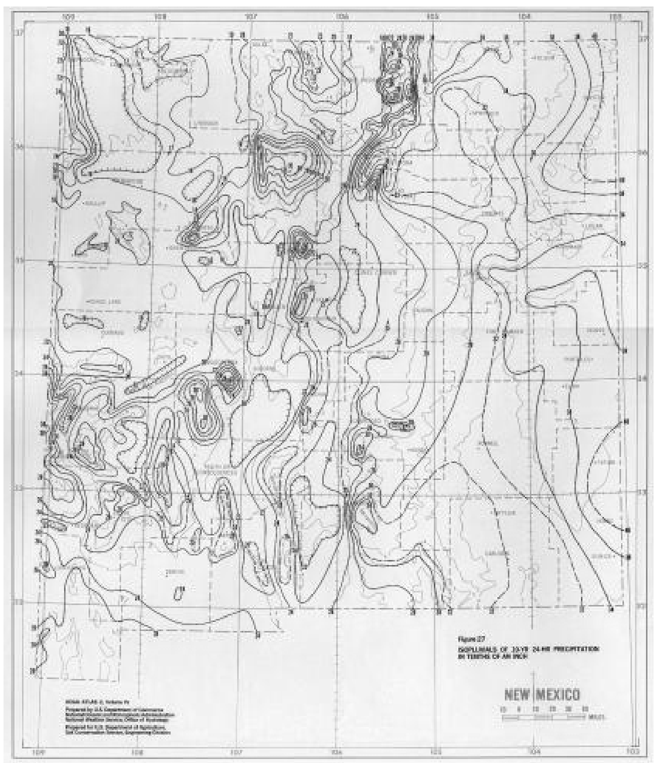

Figure 6.19. (For illustration only) 10 yr 24 hr precipitation for New Mexico.

The map of 10-year EI values has been revised from that in AH703 to greatly smooth the lines to only capture the major trends across the eastern US rather than local variations that reflect unexplained variability in the data rather than "real" differences. The 10-year EI values shown in Figure 6.20 should be used in RUSLE2 and in RUSLE1 rather than the values given in AH703.

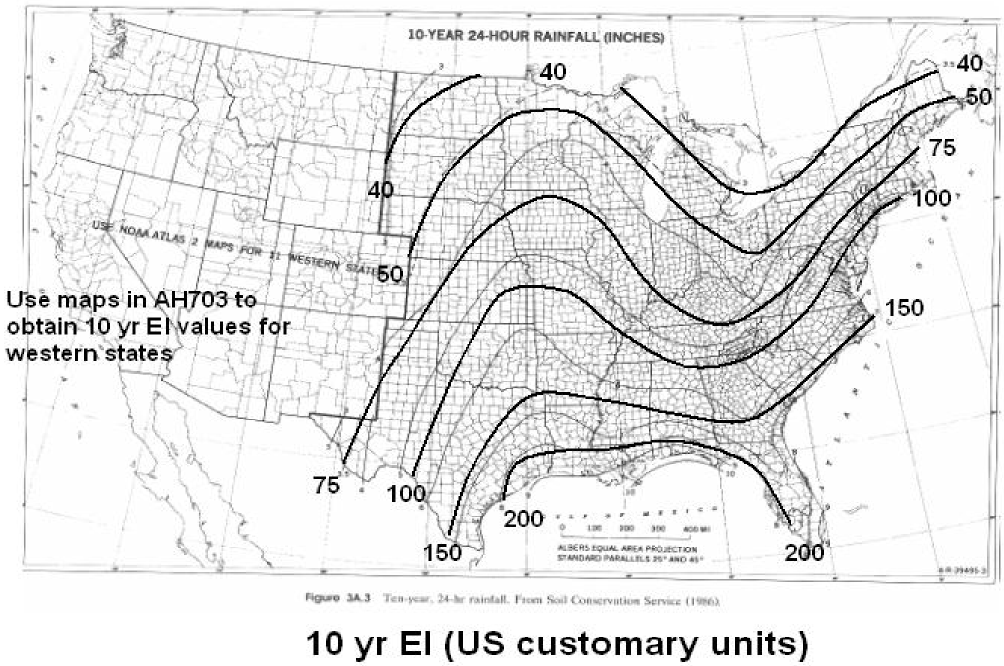

Figure 6.20. 10-year EI values.

6.6. Distribution of Erosivity During the Year

Figure 6.2 illustrates how erosivity density varies temporally by location. Monthly erosivity is computed as the product of erosivity density and precipitation values. Daily erosivity values are computed from the monthly values using the disaggregation procedure discussed in **Section 6.4**. Figure 6.21 illustrates how daily erosivity varies by locations. In central Louisiana, erosivity is nearly the same throughout the year. In contrast, erosivity is very peaked in North Dakota and in eastern Colorado, but the peak occurs at different times of the year. The erosivity density in central Kentucky and New York is similar, but the erosivity tends to be concentrated later in the year in New York than in Kentucky. The climate in northwest California, and other parts of the western continental US, is quite different from that for the eastern US. In this western region of the US, erosivity is highest in the winter months and lowest in the summer months.

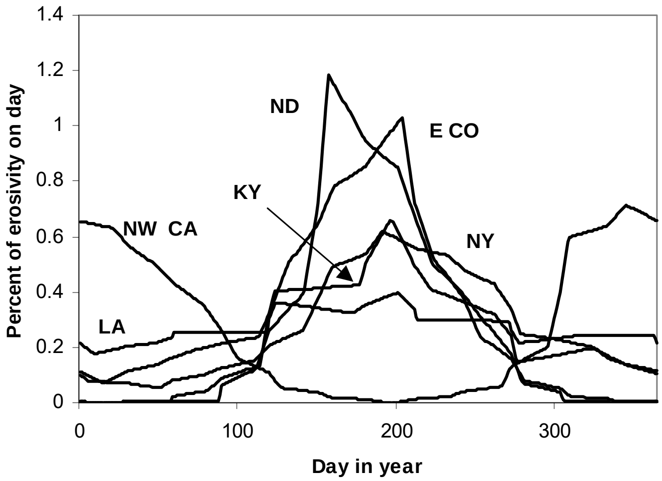

Figure 6.21. Temporal erosivity distribution for several US locations.

The temporal distribution of erosivity significantly affects soil erosion if the soil is exposed during the peak erosivity periods. For example, almost 60% of the annual erosivity in North Dakota occurs in June and July, a period when clean tilled row crops are especially susceptible to erosion because little cover is present. Therefore, on a relative basis, greater erosion occurs with clean tilled crops like corn per unit **annual erosivity R** in North Dakota than in New York because much of the erosivity in New York occurs after a significant canopy cover has developed, leaving the soil less susceptible to erosion. Growing a crop like wheat, rather than corn, that provides the greatest protection during peak erosivity can significantly reduce erosion. Thus, an erosion control practice is to change crops to ones that provide maximum protection during the most erosive period. Similarly, one way to reduce erosion on construction sites is to perform operations that expose the soil at times other than periods of peak erosivity.

6.7. Varying Soil Erodibility with Climate

RUSLE2 varies soil erodibility as a function of monthly precipitation and temperature. This capability is used for all locations and conditions where the standard erosivity relationships are used. However, RUSLE2 does not vary the soil erodibility with climate for the Req zone described in **Section 6.9**. This variation is taken into account in the temporal erosivity distribution used in the Req zone.

6.8. RUSLE2 Reduces Erosivity for Ponding

Intense rainfall on slopes less than about 1 percent steepness causes ponded water that reduces the erosivity of raindrop impact, an effect very important in the Mississippi Delta Region where both precipitation amount and intensity are high. RUSLE2 automatically computes the effect of ponding on erosivity using a cover-management sub-factor (See **Sections 9.1 and 9.2.7**). The reduction is computed as a function of slope steepness and the 10 yr-24 precipitation amount. The 10 yr-24 hr storm captures the effect of a moderately intense and moderately infrequent storm where ponding is most likely to have its greatest effect. In contrast to RUSLE1, RUSLE2 assumes that ponding reduces erosivity on both flat and ridged surfaces. The adjustment for ponding in RUSLE2 cannot be "turned off" as it could in RUSLE1.

6.9. Req Erosivity Relationships

6.9.1. Req Definition, Zones, and Values

The erosion processes in the Northwestern Wheat and Range Region (NWRR),[14] adjacent areas with similar climate, and certain other areas of the western US differ from those in other regions. Erosion from rainfall and/or snowmelt on thawing cropland, construction sites, and other sites of highly disturbed soils in this region is much greater than expected based on standard **R**-values computed according to Equations 6.1 and 6.2. Therefore, equivalent **R**-values, $\mathbf{R_{eq}}$ values, are used to apply **RUSLE2** to these special conditions. In addition, a modified erosivity distribution and special equations for the topographic and cover-managements factors are also used. The Req erosivity distribution is described in this section and the topographic and cover-management relationships are described in **Sections 8 and 9.**

These conditions occur in the Req zones illustrated in Figures 6.22 and 6.23. Northwestern Colorado, southwestern Colorado, southeastern Utah, and northern California are special transitional areas that use different relationships from those in the Req zone. Values for R_{eq} are used instead of standard R-values in the Req zones. Values for Req are computed from annual precipitation as:

$$R_{eq} = 7.86P_a - 50.5 \qquad \textbf{[6.7]}$$

[14]The Northwest Wheat and Range Region (NWRR) includes about 10 million acres of non-irrigated cropland in parts of eastern Washington, north central Oregon, northern Idaho, southeastern Idaho, southwestern Montana, western Wyoming, northwestern Utah, northern California, and other western US regions. Runoff and erosion processes in this area are dominated by winter events. Many of these events involve rainfall and/or snowmelt on thawing soils. The thawing soils remain quite wet above the frost layer and are highly erodible until the frost layer thaws allowing drainage and soil consolidation. The transient frost layer near the surface limits infiltration and creates a super-saturated moisture condition such that almost all rainfall and snowmelt runs off. This condition occurs most intensively on cropland where the soil has been finely tilled and a well defined interface exists between the tilled soil and the untilled soil. In addition, mechanical soil disturbance (tillage in most cases) has mechanically broken the soil matrix into small soil aggregates. This mechanical soil disturbance breaks bond within the soil and greatly reducing its strength under super-saturated thawing conditions. The effect seems less under cropping management systems like no-till and pasture where little mechanical disturbance has occurred or if mechanical disturbance has not occurred for three or more years. Also, the Req region is characterized by frequent periodic, wide swings in temperature above and below freezing during the winter months. Another important feature is the probability of having rainfall during a thaw of the soil surface when the soil has low strength and is highly vulnerable to erosion.

where: R_{eq} = the equivalent erosivity (US units) and P_a = average annual precipitation (in). Equation 6.7 is an empirical equation developed primarily for the Req zone illustrated in Figure 6.22 across eastern Washington into Idaho. Equation 6.7 should not be applied to situations that give an R_{eq} value greater than 200 US erosivity units. Similarly, an R_{eq} value greater than 200 US erosivity units should not be used in RUSLE2. See **Section 6.10** for guidance on applying RUSLE2 to high elevations where Req > 200 US units.

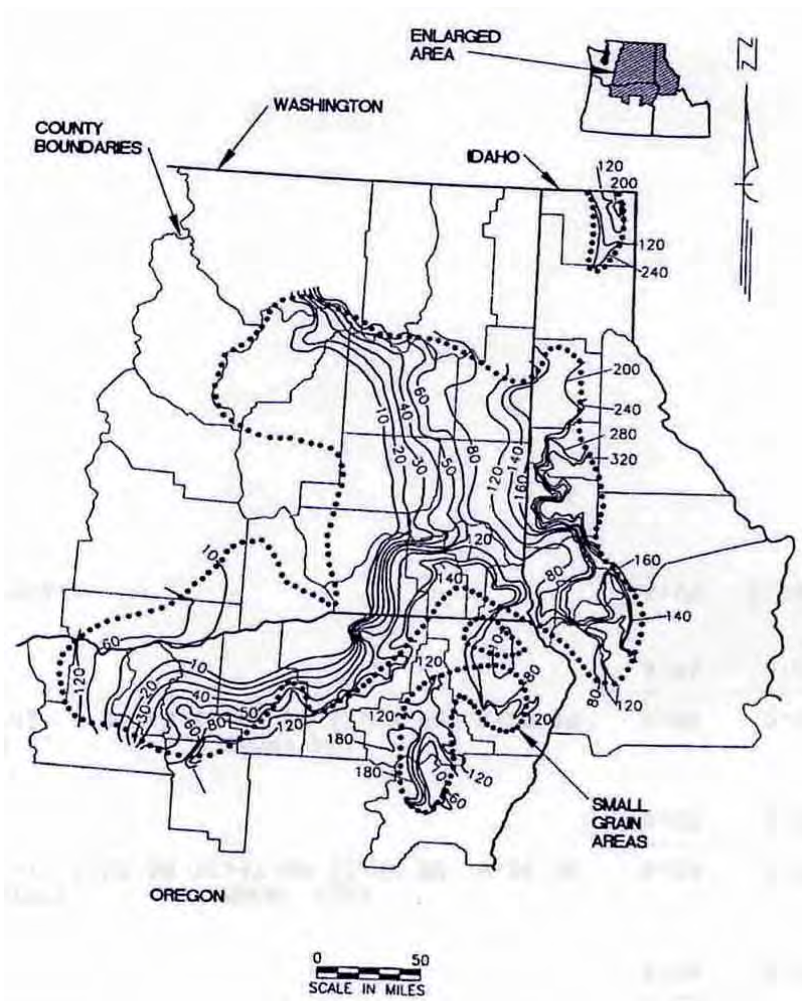

Figure 6.22. Outline of Req zone in Washington, Oregon, and northern Idaho. Only the boundary of area is important. Disregard contour lines.

The Req procedure using equation 6.7 in RUSLE2 can probably be applied to the Req zone illustrated in Figure 6.23. However, the temporal erosivity distribution has to be adjusted to account for differences in temporal precipitation patterns between the Req zones illustrated in Figures 6.22 and 6.23. Also, the Req procedure using equation 6.7 can not be used in the transitional zones in Colorado, Utah, and other areas.

Another consideration in applying the Req approach in the transitional zones is the topographic and cover-management equations. The RUSLE2 equations for the effect of topography and cover-management for the "standard" erosivity regions differs from those for the Req zones.[15] RUSLE2 uses a single set of these equations for the year. That is, RUSLE2 does not apply one set to the winter months when the Req effect occurs and another set to the summer months when the “standard” erosivity effect occurs. This selection of equation is made when the Req choice is made.

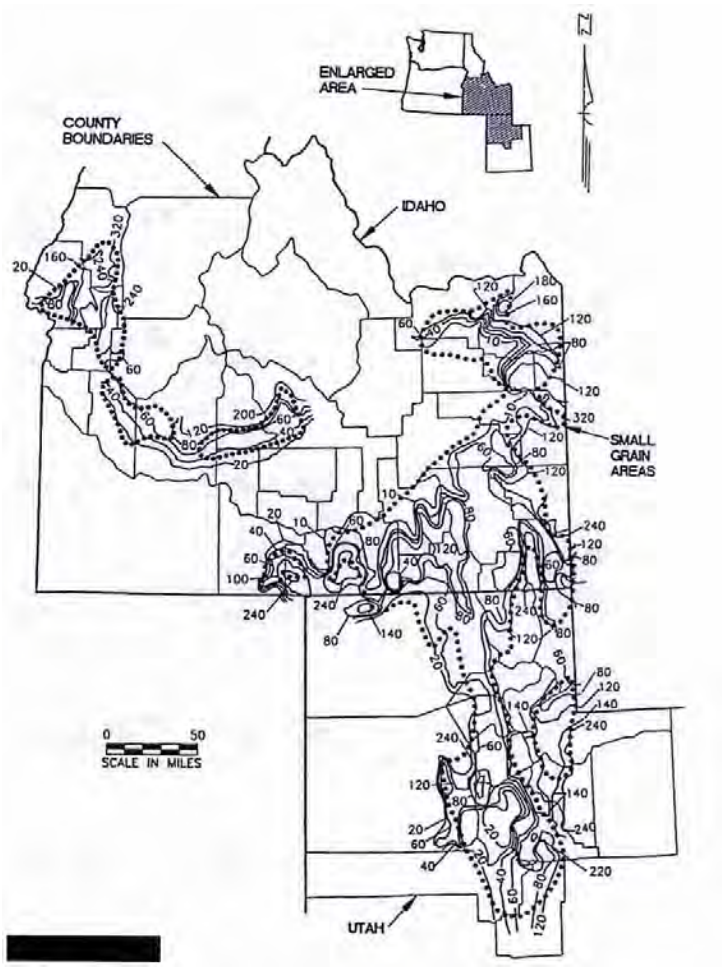

Figure 6.23. Req zone in southern Idaho and northern Utah. Only the boundary of the area is important. Disregard contour lines.

A value for R_{eq} can be entered directly into the RUSLE2 climate database for a particular location, or RUSLE2 can compute it from average annual precipitation using equation 6.7.

At first, the $\mathbf{R_{eq}}$ effect may appear to apply to areas beyond the Req zones illustrated in Figures 6.22 and 6.23 where frozen soils and runoff from snowmelt occurs, such as the northern tier of states in the U.S. However, that region does not experience the repeated freezing and thawing that is characteristic of the Req zone. Instead, the freezing, thawing, and runoff on thawing soils in those areas is limited to about one month instead of occurring repeatedly throughout the winter months as occurs in the Req zones. Research at Morris, Minnesota showed that only about seven percent of the annual erosion at that location is associated with erosion during the spring thaw. The soil is much more susceptible to erosion during the thawing period. That effect is partially considered in the

[15] Req-type effects occur in many locations of the western US. Also, these effects vary greatly within a local region. The Req procedures in RUSLE2 should be used very carefully when used in regions outside of the Req zone illustrated in Figure 6.22. Consult with ARS or NRCS RUSLE2 support personnel for advice on a recent RUSLE2 version to represent Req-type effect.

temporally varying soil erodibility factor **K** for all areas of the US except for the Req region. The Req value and the Req erosivity distribution account for the temporal variation of soil erodibility.

Rainfall and runoff on thawing soil is common to the upper Mid-South, lower Midwest regions, and similar regions of the US that experience repeated freezing and thawing events and where rainfall routinely occurs during the winter. Even though repeated freezing and thawing is experienced, the soil is not super-saturated by a restricting frost layer several millimeters (a few inches) below the soil surface as in the Req zone. The temporally varying soil erodibility factor **K** partially takes into account the increased erosion during freezing and thawing in the non-Req regions. In contrast to the western US, the increased erosion in late winter and early spring is small relative to the total annual erosion. As mentioned above, erosion during this period at Morris, Minnesota, where annual erosivity is low relative to other parts of the eastern US, is only seven percent of the annual soil loss.

6.9.2. Req distribution

A special erosivity distribution is needed for the Req zone to account for the greatly increased erosion that occurs during the winter months. The Req erosivity distribution is shown in figure 6.24 along with the erosivity distribution based on standard erosivity computations. The distribution shown in Figure 6.24 is for the Pullman, WA area where about 87% of the erosion on the unit plot[16] condition occurs during the winter months. This Req distribution is referred to as an 87-13 Req distribution. This distribution can be used throughout the Req zone illustrated in Figure 6.22. A different distribution should be used in the Req zone illustrated in Figure 6.23 and in the transitional Req zones like north and southwestern Colorado, northern

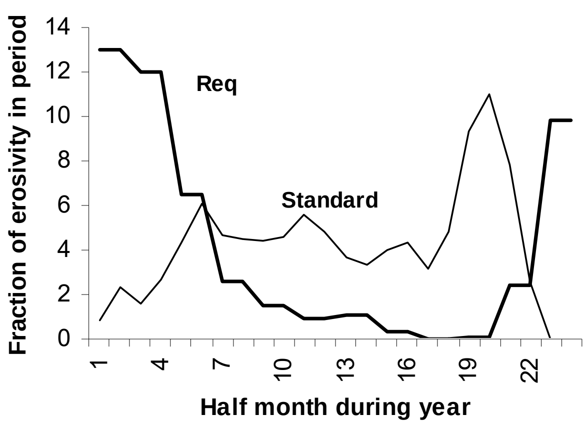

Figure 6.24. 87-13 Req erosivity distribution compared to distribution for standard erosivity at Pullman, WA.

[16] See **Section 7.2** for a definition of unit plot.

California, southeastern Utah, northern Arizona, and northern New Mexico. Less erosivity is concentrated in the winter in these areas. Contact ARS or NRCS personnel for information on Req values and Req erosivity distribution values for these regions.

6.9.3. Should Req Zone be Selected? Yes or No?

Several considerations are necessary in applying RUSLE2 in the Req zone. The first consideration is whether or not to use the Req relationships. Definitely the Req relationships are used for cropland where annual tillage disturbs 100 percent of the soil surface. The Req relationships also apply to certain recently disturbed areas where a well defined soil interface exists just below the soil surface and the upper soil layer is much like a finely tilled cropped soil. However, if the last disturbance occurred more than three years ago, the Req relationships should not be used. Thus, the Req relationships do not apply to undisturbed lands like pasture and rangelands.

Special consideration is required for hay and similar lands where mechanical soil disturbance (cultivation) occurs infrequently. Also, special consideration is required as time elapses after landfill closure or final grading of a reclaimed mine site. Erosion is computed assuming both the Req relationships and the standard erosivity relationships. A soil loss is interpolated between these two values depending on how frequently a mechanical soil disturbance occurs or how much time has elapsed since a disturbance. These same interpolations can be used in the transitional Req zones. RUSLE2 does not make smooth transitions in its computations between Req and standard zones or conditions, which requires professional judgment in applying RUSLE2. These considerations in applying RUSLE2 emphasizes that RUSLE2 is a guide to conservation and erosion control planning.

If the Req relationships, including those for topography and cover, are to be used, answer **Yes** to the question **In Req area?** and **Yes** to the question **Use Req EI distribution**. The standard Req erosivity distribution that is in the RUSLE2 sample database should be used throughout the Req zone illustrated in Figure 6.22. Contact ARS and NRCS personnel regarding Req values and Req distributions for locations outside of the zone illustrated in Figure 6.22.

Answer **Yes** to the question **adjust for soil moisture** when the Req relationships are used in RUSLE2. The amount of moisture in the soil profile during the winter months greatly affects erosion in the Req zone. Certain management practices and crops grown ahead of the winter greatly reduce soil moisture, runoff, and erosion. Answering **Yes** instructs RUSLE to take these effects into account. Answer **No** to the question **Vary soil erodibility with climate** when the Req relationships are used. Answer **Yes** for **varying soil erodibility with climate** when the standard erosivity is used, including all other

The soil moisture relationships are unique to the Req zone and should not be used outside of the Req zone.

areas of the US, including the Western US.

6.10. Applying RUSLE2 at High Elevations in Western US

Special considerations are required when applying RUSLE2 at high elevations in the western continental US. A major consideration involves snow. **If snow is continuously present on the soil surface, RUSLE2 does not apply to those months that the snow cover is present.** RUSLE2 can be applied to the non-winter months by using the standard erosivity relationships and by **turning RUSLE2 off** during the winter period. The way to **turn erosion off** is to use an operation that **adds a non-erodible cover** on the date that the winter period begins and an operation that **removes the non-erodible cover** on the date that the winter period ends. The choice of dates can be based on local observations or long term weather data for snow cover. An alternate approach is to use the date that RUSLE2 computes that the average daily temperature decreases to 1.7 ^{o}C (35 ^{o}F) temperature in late fall or early winter as the beginning date for the non-erdoble winter period. The ending date of the non-erodible winter period date in late winter or early spring is the date that RUSLE2 computes that average daily temperature increases to 7.2 ^{o}C (45 ^{o}F).

Special consideration is required where annual precipitation gives Req values greater than 200 US units. The first factor to consider is whether the Req relationships should be applied to the particular land use. Unless the land use is cropland or a particular type of highly disturbed land condition, the Req relationships probably do not apply. Also, if the precipitation is sufficiently high that a snow cover is present much of the winter and rarely disappears during the winter, the Req relationships do not apply. Even if all of the conditions are met for using the Req relationships but the Req value exceeds 200 US units, RUSLE2 should not be used during the winter months at that location. RUSLE2 is not considered sufficiently accurate to extrapolate it to Req values greater than 200 US units.

A statistical analysis of the erosivity density values showed that erosivity is not a function of elevation. **This statistical result is valid based on the data.** Unexplained variability in the data and the lack of precipitation data at elevations much above 3000 m (10,000 ft) prevent a rigorous testing of the hypothesis that erosivity density does not vary with elevation. This assumption of no elevation effect on erosivity density values is sufficient in the eastern US, but not in the western US during the winter for elevations higher than 3000 m (10,000 ft). The assumption is accepted as valid during the summer months at all locations in the continental US, with the understanding that erosivity is probably being slightly over estimated at elevations above 3000 m (10,000 ft) in the western US.

6.11. Snowmelt Erosivity

RUSLE2 is not designed to estimate erosion caused by snowmelt. The Req relationships do not apply to conditions where snow covers the soil for most of the winter months nor does it estimate the erosion that occurs when the snow melts. RUSLE2 can be **turned off** during the winter period by applying a non-erodible cover at the start of the snow cover and **turned on** after the snowmelt has ended by removing the non-erodible cover using operation descriptions described in **Sections 13.1.9 and 13.1.10.**

However, empirical values that account for snowmelt erosivity can be added to the standard monthly erosivity values to obtain effective monthly erosivity values. These effective monthly erosivity values can be entered in RUSLE2 using the monthly erosivity procedure when the standard topographic and cover-management relationships are being used. An Req value and an appropriate temporal Req erosivity distribution is developed if the Req topographic and cover-management relationships are used. Consult ARS or NRCS personnel for guidance.

7. SOIL DATABASE COMPONENT

This section describes the variables in the **soil database component**, the role of each variable, and how to determine values for key variables. Values for soil erodibility, soil texture, hydrologic soil group, rock cover, and time to soil consolidation are the principal information in the soil database component. These values are available from the local NRCS office in their soil survey database for cropland and similar land uses. These values are also included in the NRCS national RUSLE2 database. Values for most highly disturbed lands like construction sites and reclaimed mined lands must be obtained from on-site determinations.

7.1. Major Soil Variables

The values included in the RUSLE2 **soil database component** are listed in Table 7.1.

Table 7.1. Variables in soil component of RUSLE2 database

Variable	**Symbol**	**Comment**
Soil erodibility factor	K	Obtain from NRCS soil survey for cropland and similar lands; must be determined from on-site measurements for highly disturbed lands; **includes no effect of rock surface cover, but includes effect of rock in soil profile**
Soil texture		USDA soil texture class. If sand, silt, and clay content entered, RUSLE2 assigns appropriate textural class
Sand, silt, clay content		Based on USDA classification; if texture entered, RUSLE2 selects values for sand, silt, and clay % in mid-point of textural class
Hydrologic soil group (undrained)		Index for potential of undrained soil to produce runoff under unit plot conditions; a (lowest runoff potential), B, C, D (highest runoff potential)
Hydrologic soil group (drained)		Index for potential of soil to produce runoff under unit plot conditions with a high performing subsurface drainage system; **hydrologic soil group not automatically an A for drained conditions because soil properties may limit drainage**
Rock cover		Portion of soil surface covered by rock fragments sufficiently large not to be moved by runoff; rock diameter generally must be larger than 10 mm (3/8 inch) to qualify as cover
Calculate time to soil consolidation		Answer **Yes** for RUSLE2 to compute time to soil consolidation
Time to soil		Time for soil erodibility to decrease and level out after a soil

consolidation		mechanical disturbance. Enter a value or have **RUSLE2** compute based on average annual precipitation.
T value	T	Value used as criteria in conservation or erosion control planning; NRCS soil loss tolerance T value is typically used for protecting soil; another value besides T may be used for highly disturbed lands based on local regulatory or other requirements; criteria for sediment yield control depend on off-site conditions affected by sediment delivery

7.2. Basic Principles

Soils vary in their inherent susceptibility to erosion. The soil erodibility **K** factor is a measure of erodibility for the **unit plot** condition. The unit plot is 72.6 ft (22.1 m) long on a 9 percent slope, maintained in continuous fallow, tilled up and down hill periodically to control weeds and break crusts that form on the soil surface. Unit plots are plowed, disked, and harrowed, much like for a clean tilled row crop of corn or soybeans except no crop is grown. The first two to three years of erosion data after a unit plot is established are not used to determine a K value. Time is required for residual effects from previous cover-management to disappear, especially following high production sod, forest conditions with lots of roots and litter, or any condition with high levels of soil biomass. About 10 years of soil loss data are required to obtain an accurate estimate of K. The data record should be sufficiently long to include moderate and large storms.

The K value for a soil is the slope of a straight line passing through the origin for measured erosion data plotted versus storm erosivity as illustrated in Figure 7.1. The equation for this line is:

$$A_u = EI_{30}K \quad \textbf{[7.1]}$$

where: A_u = the soil loss from the unit plot measured for an individual storm and EI_{30} = the erosivity of the storm that produced the storm soil loss. Data from storms less than 12.5 mm (0.5 inch) are not included in the analysis.

The unit plot procedure determines empirical K values for specific soils where the effect of cover-management on soil erodibility has been removed. Not all soils occur where erosion can be measured under unit plot conditions. The equations used by RUSLE2 for topographic and cover-management can be used to adjust measured erosion data to unit plot conditions. These equations are discussed in later sections.

The soil erodibility factor **K** represents the combined effect of susceptibility of soil to detachment, transportability of the sediment, and the amount and rate of runoff per unit rainfall erosivity for unit plot conditions. Fine textured soils high in clay have low **K** values, about 0.05 to 0.15 tons per US erosivity unit, because they are resistant to detachment.[17] Coarse textured soils, such as sandy soils, have low **K** values, about 0.05 to 0.2 tons per US erosivity unit, because of low runoff even though these soils are easily detached. Medium textured soils, such as silt loam soils, have moderate **K** values, about 0.25 to 0.45 tons per US erosivity unit, because they are moderately susceptible to detachment and they produce moderate runoff. Soils having very high silt content are especially susceptible to erosion and have high **K** values. Sediment is easily detached from these soils, which also tend to crust, produce large amounts and rates of runoff, and produce fine sediment that is easily transported. Values of **K** for these soils typically exceed 0.45 tons/acre per US erosivity unit and can be as large as 0.65 tons per US erosivity unit.

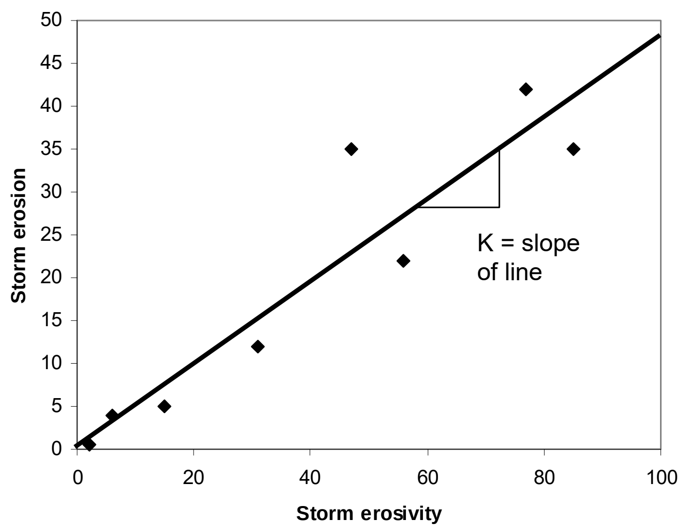

Figure 7.1. Determining a value for the soil erodibility K factor from measured erosion data for unit plot conditions.

The RUSLE2 soil erodibility factor is an **empirical measure** defined by the erosivity variable EI_{30} (product of storm energy and maximum 30 minute intensity) used in RUSLE2. It is not directly related to specific erosion processes, and it is not a soil property like texture. RUSLE2 K values are unique to this definition, and erodibility values based on other erosivity measures, such as runoff, must not be used for K. Values for K are not proportional to erodibility factor values for other erosivity measures. Also, K values may not increase or decrease in the same sequence as other definitions of soil erodibility. For example, the RUSLE2 K value for a sandy soil is low whereas an erodibility factor value based on runoff is high for sand.

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[17] The R and K factors have units. In this guide, the US customary units for R are hundreds of (ft tons in)/(ac yr hr). The corresponding US customary units on K are tons /[(hundreds of ft tons in)/(ac hr)]. Metric units in the SI system are (MJ mm)/(ha∗h) for erosivity and (t h)/(MJ mm) for erodibility. See AH703 for additional information.

Soil organic matter reduces the K factor value because it produces compounds that bind soil particles and reduce their susceptibility to detachment by raindrop impact and surface runoff. Also, organic matter increases soil aggregation, which increases infiltration and reduces runoff and erosion. Permeability of the soil profile affects **K** because it affects runoff. Soil structure affects **K** because it affects detachment and infiltration. Soil structure refers to the arrangement of soil particles, including primary particles and aggregates, in the soil. Soil mineralogy has a significant effect on **K** for some soils, including subsoils, soils located in the upper Midwest of the US, and volcanic soils in the Tropics.

Many factors affect soil erodibility. Values for the RUSLE2 soil erodibility K factor, which is a measure on inherent soil erodibility, are for unit plot conditions where the effects of management have been removed. These RUSLE2 definitions were also used in the USLE and RUSLE1.

Values for **K** for several "benchmark" soils have been determined from experimental erosion data. Values for **K** can be estimated for other soils by comparing their properties with those of the benchmark soils and assigning K values based on similarities and differences in properties that affect K values. As a part of its soil survey program, the USDA-NRCS has determined K values for cropland and other similar lands where the soil profile has not been disturbed or the soil mixed.[18] RUSLE2 includes two soil erodibility nomographs, discussed in **Section 7.3.2.,** that can be used to estimate K values. See AH703 for additional information on the soil erodibility factor K.[19]

7.3. Selection of Soil Erodibility K Values

7.3.1 From NRCS soil survey

Values for **K** should be selected from the USDA-Natural Resources Conservation Service (NRCS) soil survey for RUSLE2 applications where the soil profile has not been disturbed and mixed. Values for K for both topsoil and subsoil layers are available for most US soils. The greatest detail is for cropland soils and less for rangeland and forestland soils. Values for K are not available for soils on construction sites, landfills, and reclaimed surface mines because of soil mixing and soil-like materials associated

[18] The USDA-NRCS has mapped most US soils on cropland and other land uses where the soil profile has not been disturbed. Soils were mapped as soil map units (names). Descriptions and properties of each soil map unit are published in soil surveys by US county or other survey area. Soils information is available in a computer database and paper form at local USDA-NRCS offices. The soils data required by RUSLE2 have been extracted from the NRCS soil survey database and included in the NRCS national RUSLE2 database.

[19] Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder. 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). U.S. Dept. of Agriculture, Agriculture Handbook 703, 404 pp. Much of the information in AH703 on soil erodibility applies to RUSLE2, except for the part on temporal variability of K.

with surface mining. The RUSLE2 modified soil erodibility nomograph can be used to estimate K values for these soils.

Make sure that K values extracted from the NRCS soil survey are the ones where no adjustment has been made for rock on the soil surface and where the effect of rock in the soil profile has been considered.

Multiple K values for a given soil mapping unit are given in the NRCS soil survey database. Select the K value where no adjustment has been made for rock fragments on the soil surface. Using a K value that has been adjusted for surface rock fragments can cause a major error in RUSLE2 erosion estimates. RUSLE2 uses a single composite ground cover that takes into account overlap of rock by crop residue and plant litter. The RUSLE2 mathematical relationships used to compute the effect of ground cover on erosion are nonlinear. Treating each ground cover individually causes errors because of this nonlinearity.

7.3.2. Estimating K values with the RUSLE2 soil erodibility nomographs

7.3.2.1. Background on nomographs.

RUSLE2 includes two soil erodibility nomographs that can be used to estimate soil erodibility K factor values. One nomograph is the **standard nomograph** described in AH703.[20] This nomograph is used to estimate soil erodibility values for cropland and similar soils where the soil profile has not been disturbed. The other nomograph is the **RUSLE2 modified nomograph**. This nomograph is used to estimate soil erodibility K factor values for highly disturbed lands where the soil profile has been disturbed and the soil mixed.

The difference between the standard and the modified soil erodibility nomographs is in the structure effect. The standard nomograph gives K values that decrease as structure changes from a blocky, platy structure to a granular structure. This trend is inconsistent with accepted science on how erosion varies with soil structure. The standard nomograph was derived from about 55 soils, primarily in Indiana, that were mostly medium textured soils without a wide, uniform sample of soil textures and soil structures. The result is that K values from the standard erodibility nomograph are too high for very high clay soils and too low for very high silt soils. The **standard nomograph** is satisfactory for most cropland soils.

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[20] For background information, see Wischmeier, W.H., C.B. Johnson, and B.V. Cross. 1971. A soil erodibility monograph for farmland and construction sites. J. Soil Water Conservation. 26:189-193. However, information provided in this RUSLE2 User Guide determines the RUSLE2 application of the nomograph rather than information from other sources.

The **RUSLE2 modified soil erodibility nomograph** should be used to estimate K factor values for highly disturbed lands like constructions sites, landfills, military training sites, and reclaimed mined land. The RUSLE2 modified nomograph gives more credit to the effect of soil structure than does the standard nomograph. The RUSLE2 modified soil erodibility nomograph is exactly the same as the standard nomograph except that the equation for soil structure has been reversed. The two nomographs give the same K values for a moderate to coarse granular soil structure.

AH703 lists equations for estimating K factor values for special cases. Those equations were not included in RUSLE2 because some input values can not be obtained easily or K values computed by some of the equations seemed questionable. Carefully examine those equations and review original source materials before using values from those equations in RUSLE2.

7.3.2.2. Nomograph inputs.

The inputs for both the **RUSLE2 modified** and the **standard** soil erodibility nomographs are the same. Therefore, the single set of inputs listed in Table 7.2 applies to both nomographs. The definitions and variable descriptions used in the nomograph must be carefully followed.[21]

Table 7.2. Variables used in RUSLE2 soil erodibility nomographs

Variable	**Symbol**	**Comment**
Sand content		Based on mass (weight), proportion of the total for the clay, silt, and sand, 0.050 mm < sand dia ≤ 2.0 mm
Silt+very fine sand content		Based on mass (weight), proportion of the total for the clay, silt, and sand, 0.002 mm < silt dia ≤ 0.050 mm, 0.050 mm < very fine sand dia ≤ 0.10 mm; RUSLE2 can estimate very fine sand content.
Inherent organic matter content		Based on mass (weight), proportion of the total clay, silt, sand, and organic matter; **organic matter content is for unit plot conditions; do not use organic matter content in nomograph to reflect management different from the unit plot conditions.**
Structure class		Arrangement of primary particles and aggregates in soil
Permeability class		Used to indicate runoff potential under unit plot conditions. Represents the entire soil profile, not just soil surface layer. Should not be determined from a pereameter measurement.
Is		Select **Yes** and RUSLE2 assumes that the permeability class

[21] See the USDA-NRCS soil survey manual for a description of the terms used in the soil erodibility nomograph and procedures for determining values for the nomograph variables. This manual is available on the NRCS Internet site www.nrcs.usda.gov.

permeability with coarse fragments present		has been chosen giving consideration to rock in the soil profile. **Strongly recommend selecting permeability based on professional judgment rather than allowing RUSLE2 to adjust for rocks in soil profile.** Select **No** and RUSLE2 will adjust the permeability class for rock in the soil profile. This adjustment does not apply to soils with large rock fragments like mined land.
Coarse fragment content		Based on mass (weight) proportion of total soil made up of rock fragments > 3 in (75 mm) diameter

7.3.2.3. Special nomograph considerations.

Organic matter content is a major variable in the soil erodibility nomographs. **The input value for this variable is the organic matter content of the soil in the unit plot condition after previous land use effects have disappeared.** RUSLE2 has an upper limit of 4% for this organic matter content input. Applying animal manure, plowing under "green" manure, improving residue management, and other management practices that add biomass significantly reduce erosion. **RUSLE2 considers this important effect using equations for cover-management effects rather than the soil erodibility factor.** The soil erodibility factor is for a base condition where the effects of management have been removed.[22]

Adjusting K to account for organic matter as influenced by land use is double accounting and is a misuse of RUSLE2. Similarly, the permeability class in the soil erodibility nomographs is not adjusted to represent how cover-management and support practices affect runoff.

The permeability effect in the nomographs is based on how the **entire soil profile** affects runoff for unit plot conditions. The input permeability code **should not** be based only on the upper 4 inches (100 mm) to 6 inches (150 mm) of soil. Permeability tests on soil samples from this layer should not be the sole basis for determining the permeability input to the nomographs. The input permeability code entered in the nomograph should take into account how restricting layers, such as a rock, fragipan, caliche, or clay layer, below the soil surface affect runoff. The input permeability code should also reflect how

[22] Considering how land use affects organic matter and soil erosion by adjusting the organic matter input in the soil erodibility nomographs to compute K values seems possible because the nomographs include an organic matter variable. However, the erodibility nomographs must not be used for this purpose. RUSLE2 is an empirical equation based on certain definitions that must be carefully followed. Adjusting K to account for the effect of cover and management on organic matter and runoff is inconsistent with RUSLE2 definitions, structure, and equations.

restricting layers, such as a plow pan or a dense compacted layer created by construction traffic, if these layers that are not routinely broken up by ordinary tillage or other soil distributing operations. RUSLE2 takes into account how subsoiling affects erosion by breaking up these layers.

Values computed with the RUSLE2 soil erodibility nomographs apply to a central, base location, which is Columbia, Missouri.[23] Soil erodibility K factor values vary by location even when soil properties are exactly the same between locations. The K factor values are higher (or lower) at those locations where rainfall amount and frequency and other factors caused increased (or decreased) runoff per unit rainfall in relation to climatic conditions at Columbia, Missouri. This effect is taken in account by computing temporal soil erodibility factor values that are referenced to the climate at Columbia, Missouri (see **Section 7.4**)

The K factor values computed by the RUSLE2 nomographs are solely a function of soil properties. Theoretically, these K values should be increased or decreased as the ratio of runoff to rainfall varies by location. Although, this adjustment is seldom made, RUSLE2 takes the effect into account in its computation of temporal soil erodibility values.

The soil erodibility nomograph does not apply to soils of volcanic origin, organic soils such as peat, Oxisols, low activity clay soils, calcareous soils, and soils high in mica. Also, the nomograph is less accurate for subsoils than for topsoils. Professional judgment is used to assign K values for those soils. Contact the NRCS State Soil Scientist in your state for assistance.

7.4. Temporal Variability in K

Soil erodibility K factor values vary during the year. The values tend to be high during and immediately following thawing and other periods when the soil is wet. The values tend to be low when soil moisture and runoff is low because of increased soil evaporation caused by high temperatures. The input K value is a base value that is assumed to represent an average value during the "frost free" period, which is defined as the time that the temperature is above 4.4 ^{o}C (40 ^{o}F). Temporal soil erodibility values computed by RUSLE2 are shown in Figure 7.2 for Columbia, Missouri; St. Paul, Minnesota; Birmingham, Alabama; and Tombstone, Arizona.

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[23] Columbia, Missouri is used as a base location in both RUSLE1 and RUSLE2. USLE values for slope length and steepness effect, soil loss ratio, and support practice factors are assumed to apply at Columbia, MO. RUSLE2 adjusts its values for these factors about the Columbia, MO base values. The weather at Columbia, Missouri is near the "middle" of the data for the Eastern US.

RUSLE2 computes the ratio of daily **K** values to the base K value as a function of the ratio of daily temperature to the base average frost free temperature at Columbia, Missouri and the ratio of daily precipitation to the base average frost free precipitation at Columbia, Missouri. The ratio of daily K to base K increases as the ratio of daily precipitation to base average frost free precipitation increases. This effect represents the increased runoff per unit precipitation caused by increased soil moisture during high precipitation periods. The ratio of daily K to base K decreases as the ratio of daily temperature to base average frost free temperature increases. This effect represents decreased runoff per unit precipitation because of decreased soil moisture on the unit plot conditions during periods when soil evaporation is high. The relative effect of precipitation is greater than that of temperature in these computations. The effect of cover-management on soil erodibility is computed using equations described in **Sections 7 and 9** for cover-management effects.

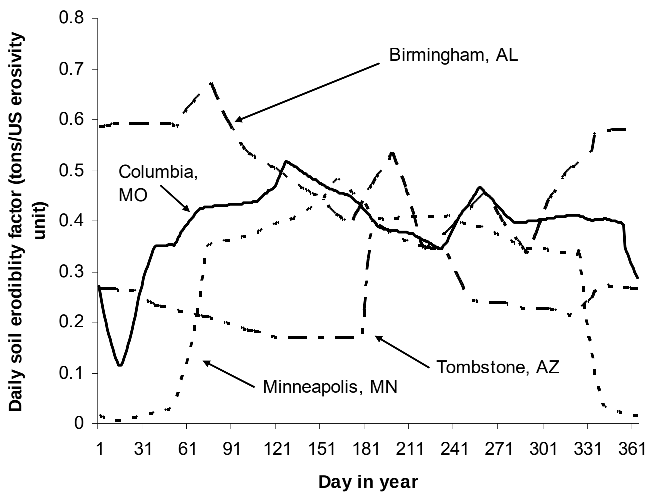

Figure 7.2. Temporal soil erodibility factor values. Base K is 0.42 US units.

When temperature decreases below -1.1 °C (30 °F), RUSLE2 reduces K values exponentially as a function of temperature until the K factor value becomes very close to zero at a temperature of -9.4 °C (15 °F). The very low K values for Minneapolis, Minnesota during the winter months represent frozen soil that is nonerodible. The same effect is seen for Columbia, Missouri where K values are partially reduced during the winter.

RUSLE2 does not represent increased erodibility during and immediately after the thawing period. The observed data are too few to empirically determine a relationship for this period. Also, the increased erosion during this period is small relative to the total annual erosion for the eastern US. For example, research measurements at Morris, Minnesota showed that erosion during this period was less than 7% of the total annual erosion. This percentage decreases for locations further south. However, the increased erodibility during this period is important in southwestern Colorado, Southeastern Utah, and similar locations in the western US where annual erosivity is low. The relative contribution of the erosion during and immediately after the thawing period is much greater in the western US than in the eastern US. Adjustments can be made in the monthly erosivity values to account for the increased erosion during this period. See **Sections 6.9 and 6.10**.

The peak in erodibility values for Birmingham, AL in March results from increased rainfall, not from the thawing effect. The main influence of temperature on temporally varying K values is in late summer when increased temperature increases soil evaporation and reduces runoff and erosion. The peak erodibility occurs during the summer for Tombstone, AZ because most of the annual rainfall at this location occurs during this period.

As described in Section 7.3.2.3, the RUSLE2 soil erodibility nomographs computes soil erodibility values solely as a function of soil properties. These nomographs do not take into account how soil erodibility factor values are increased in wet locations such as Birmingham, Alabama and are decreased in dry locations such as Tombstone, Arizona. The temporal soil erodibility equations used in RUSLE2 take this effect into account. For example, Figure 7.2 illustrates how the annual average soil erodibility value is much lower at Tombstone than at Birmingham even though the base soil erodibility factor value computed with a RUSLE2 soil erodibility nomograph is the same at both locations.

A constant erodibility value that does not vary during the year can be used in RUSLE2 by answering **No** to the question **Vary erodibility with climate** in the Climate database component. Assuming that soil erodibility varies temporally is recommended for all areas except the Req zones because the Req procedure captures the increased erodibility during the winter in these regions (See **Section 6.9**). The fit of the equation that computes temporal soil erodibility K factor values is weak, and statistically the hypothesis that soil erodibility does not vary with time can not be rejected.[24]

In contrast to RUSLE1 where the time varying soil erodibility relationships were not used in the Western US, the temporally varying erodibility relationships should be used in the Western US for RUSLE2, except in Req applications.

7.5. Soil Texture

Soil texture is the distribution of the primary particles of sand, silt, and clay in the soil. RUSLE2 uses values for sand, silt, and clay fractions to compute soil erodibility, the

[24] A major difference between RUSLE2 and RUSLE1 is in the temporal soil erodibility computations. The differences in erosion between the models can be as large as 25% in the central Midwest and in the New England regions because of the difference in erodibility computations. The RUSLE1 equations (See AH703) were heavily influenced by data from the Morris, MN and Holly Springs, MS locations. While the relationship for temporal erodibility was well defined at these locations, it was not well defined at eight other locations. Given the overall data, a new temporal erodibility relationship was developed for RUSLE2. The current recommendation is that a constant K value be used in RUSLE1.

distribution of the sediment particle classes at the point of detachment, and the diameter of the small and large aggregate particle classes. See **Section 7.5** for a description of the RUSLE2 sediment classes used.

The fractions for soil texture are based on mass (weight) of the total of these three primary particle classes. The sizes of these classes, which are based on the USDA classification, are given in Table 7.3. Refer to the USDA-NRCS soil survey manual for procedures to determine soil texture from soil samples.[25] These procedures involve dispersing a soil sample to breakup soil aggregates into their constituent primary particles. Sieves are typically used to determine the size distribution of the sand classes and the total sand content. Sieves are screens having various sized openings that sort particles by size. A hydrometer or pipette is typically used to determine clay content. This technique is based on fall velocity. Strongly aggregated soils, including some Tropic soils of volcanic origin, may be difficult to disperse and require special procedures. Silt content is 1.0 minus the clay and sand contents.

Table 7.3. Diameter of primary particle classes. Based on USDA classification.

Primary particle class	**Diameter (mm)**
Clay	dia ≤ 0.002
Silt	0.002 < dia ≤ 0.05
Sand	0.05 < dia ≤ 2
Very fine sand	0.05 < dia <0.1
Fine sand	0.1 ≤ dia < 0.5
Coarse sand	0.5 < dia < 1
Very coarse sand	1 ≤ dia < 2

Primary particles are the smallest, discrete mineral soil particles. Obviously, aggregates are larger than the primary particles that form them. The density of aggregates is less than the density of primary particles because of open space within aggregates. This open space can be partially filled with water, and the rate that pore space becomes filled (rate of soil wetting) greatly affects aggregate stability, soil erodibility, and sediment aggregate size. Rapid wetting significantly reduces aggregate stability and increases soil erodibility. Difference in rate of soil wetting is partially why erosion varies greatly between similar storms.

RUSLE2 input values for sand, silt, and clay content (soil texture) are for the upper soil layer susceptible to erosion. This layer is usually assumed to be 4 inches (100 mm) thick depending on the degree and depth of rill erosion. Soil texture values in the NRCS soil survey database can be used as input in RUSLE2 without processing soil samples from the site **provided the soil profile has not been disturbed and soil mixing has not occurred.** The site is located on a soil survey map to identify the soil map unit at the site. Texture values for that soil map unit are given in the NRCS soil survey database.

If the soil profile has been disturbed and the soils mixed, such as at a construction site or reclaimed mine, soil samples from the site must be processed to determine RUSLE2 soil input values.

[25] Soil Survey Manual available on the Internet site www.ftw.nrcs.usda.gov/tech_ref.

RUSLE2 assigns the appropriate textural class when values are entered for sand, silt, and clay content.

If the sand, silt, and clay content is not known, select the soil textural class as the RUSLE2 input if it is known or can be determined by professional judgment such as from feel of the soil. RUSLE2 assigns central values for sand, silt, and clay content for the input textural class based on the textural triangle. The values assigned by RUSLE2 are shown in Table 7.4.

Sometimes the sand, silt, and clay of a soil are known, but the very fine sand content is not known. RUSLE2 can estimate the very fine sand content using the equation:

$$f_{vfsandt} = 0.74 f_{sand} - 0.62 f_{sand}^{2} \quad [7.2]$$

where: $f_{vfsandt}$ = the fraction of the total primary particles (sand+silt+sand) that is composed of very fine sand and f_{sand} = the fraction of the primary particles that is sand. This equation was derived by regression analysis using data in the NRCS soil survey database for Lancaster County in southeastern Nebraska.

7.6. Sediment Characteristics at the Point of Detachment

RUSLE2 uses values for sediment characteristics to compute deposition. Values used to describe sediment can be computed by RUSLE2, which is the recommended approach, or values can be user entered to create a custom sediment distribution.

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7.6.1. RUSLE2 computes sediment characteristics

Rill and interrill erosion produces sediment that is a mixture of primary particles and aggregates. RUSLE2 uses the five particle classes of primary clay, primary silt, small aggregate, large aggregate, and primary sand to represent sediment. The sediment distribution for many soils has two peaks, one in the silt size range and one in the sand size range. Comparison of sediment size distributions before and after dispersion shows that much of the sediment in these peaks is aggregates. The two aggregate classes represent this sediment. The primary clay, silt, and sand classes represent the sediment that is eroded as primary particles.

RUSLE2 computes the distribution of these five particle classes and the diameters of the small and large aggregate classes at the point of detachment as a function of soil texture.[26]

[26] The equations used by RUSLE2 are described by Foster, G.R., R.A. Young, and W.H. Neibling. 1985. Sediment composition for nonpoint source pollution analyses. Trans. ASAE 28(1):133-139, 146.

Cover-management also affects sediment characteristics. Increased soil biomass increases the fraction of the sediment composed of aggregates and the size of the aggregates. However, sufficient experimental data are not available to derive equations to describe how cover-management affects sediment characteristics.

In general, the fractions and diameters for the aggregate classes increase as the soil's clay content increases. Clay is assumed to be a binding agent that increases aggregation. .

Table 7.4. Sand, silt, and clay contents assigned for a textural class. Based on USDA classification.

Textural class	**Sand (%)**	**Silt (%)**	**Clay (%)**
Clay	20	20	60
Clay loam	33	33	34
Loam	41	41	18
Loamy sand	82	12	6
Sand	90	6	4
Sandy clay	51	5	44
Sandy clay loam	60	13	27
Sandy loam	65	25	10
Silt	8	87	5
Silt loam	20	65	15
Silty clay	6	47	47
Silty clay loam	10	56	34

Table 7.5. Characteristics of sediment classes assume

Sediment class	**Density (specific gravity)**	**Diameter (mm)**	
Primary clay	2.6	0.002	Fraction = 0.2
Primary silt	2.65	0.01	Fraction strong
Small aggregate	1.8	0.03 to 0.1	Fraction and d
Large aggregate	1.6	0.3 to 2	Fraction and d
Primary sand	2.65	0.2	Fraction strong

Values assumed by RUSLE2 for each sediment class are listed in Table 7.5. Fall velocity V_f of each sediment class is used in equation 5.2 to represent sediment "depositability." Fall velocity is a function of diameter and density of the sediment particles. RUSLE2 computes fall velocity using Stokes law for the small particle classes and standard drag relationships for the large particle classes assuming that the sediment particles are spheres.

Table 7.6. Sediment characteristics for a silt loam soil (20% sand, 60% silt, 20% clay) at detachment and (0% sand, 56% silt, 44% clay) after deposition by a dense grass strip on the lower 10% of slope length.

Sediment class	Diameter (mm)	% at detachment	% after deposition
Primary clay	0.002	5	43
Primary silt	0.01	24	54
Small aggregate	0.03	36	3
Large aggregate	0.4	28	0
Primary sand	0.2	7	0

Deposition enriches the sediment load in fines, which RUSLE2 computes as illustrated in Table 7.6. Deposition changes the distribution of the sediment classes from that at the point of detachment. RUSLE2 also computes the sand, silt, and clay content in the sediment leaving the RUSLE2 hillslope profile. RUSLE2 computed that the fraction of primary clay sediment class leaving the grass filter strip after deposition is 43% in comparison to 5% at the point of detachment in the example illustrated in Table 7.6. Also, the total clay content in the sediment was 44% versus 20% in soil surface layer.

RUSLE2 assumes that small aggregates are composed of clay and silt primary particles and that large aggregates are composed of clay, silt, and sand primary particles. RUSLE2 computes the distribution of these particles in each aggregate class as a function of soil texture. RUSLE2 also computes an enrichment ratio as specific surface area of the sediment at the lower end of the last RUSLE2 element divided by the specific surface area of the sediment at the point of detachment. The enrichment ratio for the Table 7.6 example is 1.9, which means that the specific surface area of the sediment is almost twice that of the soil. The specific surface areas assumed in RUSLE2 for primary particles are 20 m^2/g for clay, 4 m^2/g for silt, and 0.05 m^2/g for sand. Specific surface area indicates the relative importance of each primary particle class as a binding agent and for transporting soil-absorbed chemicals. The specific surface area of each aggregate class depends on the composition of primary particles.

7.6.2. User entered values.

Although the RUSLE2 names assigned the five sediment classes are arbitrary, the names of the classes and the number of classes can not be changed. However, values for fraction, diameter, and density assigned to each class can be user overwritten to create a custom sediment description. RUSLE2 does not properly compute enrichment if these values are manually overwritten.

7.7. Rock Cover

Rock cover on the soil surface acts as ground cover and reduces erosion much like plant litter, crop residue, and applied mulch, except that rock does not decompose and add biomass to the soil. RUSLE2 combines rock cover with other ground cover to obtain a single composite ground cover value, taking into account the overlap of plant and applied materials on the rock cover. This single ground cover value is used in the equations that compute cover-management effects on erosion (See **Section 9.2.2**.). This overlap of cover is the reason that values for rock cover and other ground cover cannot be added to obtain the total cover. Also, the effects of rock and other ground cover cannot be computed separately and then combined to determine the total ground cover effect because of the nonlinearity in the equation used to compute the ground cover effect on erosion.

The nonlinearity in the equations used to compute the ground cover effect is the reason that a K factor value cannot be used in RUSLE2 where an adjustment has already been made for rock cover.

RUSLE2 handles "rock cover" entered as a soil input differently than ground cover added through a cover-management input. The soil input rock cover remains constant through time, is not buried, and does not decompose. The rock cover variable can also be used to represent mosses, which provide substantial ground cover on rangelands, and other types of ground cover that can be assumed remain constant through time.

See Section 12 for special considerations needed when a mechanical soil disturbance is used to bury rock or other material that does not decompose.

The soil rock cover input is a site-specific entry based on field measurements. The same technique used to measure other ground cover like plant litter and crop residue can be used to measure rock cover.[27] To be counted as ground cover, rock must be sufficiently large not be moved by raindrop impact or surface runoff. The minimum rock size that is measured is site specific, but as a guideline, the minimum rock size is 10 mm (3/8 inch) diameter except on coarse texture rangeland soils where the minimum size is 5 mm (3/16 inch).

[27] A typical procedure used to measure ground cover is to lay a line transect, such as a knotted string or measuring tape, across the soil surface diagonal to any cover orientation. An estimate of ground cover is the percentage of knots or markings on a tape that contact ground cover. Another approach is to photograph the surface, lay a grid over the photograph, and count the intersection points that touch ground cover.

Do not use rock cover values or rock content in the soil profile from the NRCS soil survey database to determine rock cover. The definitions of rock cover in that database do not correspond with RUSLE2 definitions.

The appropriate time to measure rock cover is during the 1/4 to 1/3 period of the year or crop rotation when the hillslope is most susceptible to erosion. Measure rock cover on cultivated land after rainfall has exposed the rock so that the rock and its influence can be readily seen.

7.8. Hydrologic Soil Group

Hydrologic soil group is an index of the runoff potential of the soil under unit plot conditions. These designations are A (lowest potential), B, C, and D (highest potential). **RUSLE2** uses the hydrologic soil designation in the NRCS curve number method to compute runoff. Hydrologic soil group designations are available by map unit and component in the NRCS soil survey database. The USDA-NRCS hydrology manual provides information on assigning hydrologic soil group designations for those soils not included in the NRCS soil survey.[28] The soils with the lowest runoff potential, such as deep sandy soils, are assigned an A hydrologic soil group. The soils where almost all of the rainfall becomes runoff are assigned a D hydrologic soil group. Examples of hydrologic group D soils include high clay soils and silt soils that readily crust causing significantly reduced infiltration. Soils having a restrictive layer like a fragipan, rock, plow pan, or traffic pan near the soil surface also are assigned a D hydrologic soil group.

RUSLE2 uses the hydrologic soil group designations for drained and undrained conditions to compute the soil loss reduction caused by tile and other drainage practices. The equation used in the soil erodibility nomographs for the effect of permeability on soil erodibility are used to compute the effect of drainage on erosion. The four hydrologic soil groups are scaled over the six permeability classes so that a hydrologic soil group designation can be converted to a permeability class to use the erodibility nomograph equation.[29]

Two hydrologic soil group designations are entered for a soil. One is for the **undrained** condition and one for the **drained** conditions. Runoff potential can be high because of a perched water table or the soil occupying a low-lying position on the hillslope even though soil properties would indicate a low runoff potential. Artificially draining these

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[28] Contact the NRCS Internet site at www.nrcs.usda.gov for additional information

[29] Although hydrologic soil group and the permeability class are directly related, RUSLE2 requires separate inputs for these two variables. Therefore, the user needs to ensure that the inputs for these variables are consistent when one of the nomograph is used to compute a K value.

soil with deep parallel ditches or buried tile lines can greatly increase internal drainage and reduce surface runoff and erosion.

The hydrologic soil group assigned for the drained condition represents runoff potential under drained conditions based on soil properties and assuming a high performance drainage system. A drained soil does not imply that an A hydrologic soil group should be assigned. For example, a drained sandy soil might be assigned an A hydrologic soil group whereas a drained clay soil might be assigned a C hydrologic soil group because the clay limits internal drainage and infiltration.

7.9. Time to Soil Consolidation

RUSLE2 assumes that the soil is 2.2 times as erodible immediately after a mechanical disturbance than after the soil has become "fully consolidated."[30] Erosion decreases with time and "levels out" as illustrated in Figure 7.3. A double exponential decay curve is used to describe this decrease in erodibility. The equation used in RUSLE2 for this curve was derived from erosion data at Zanesville, OH that were collected over time after tillage stopped on a fallow plot. The time required for the erosion rate to "level out" after a mechanical disturbance is the **time to soil consolidation**. Erodibility of a fully "consolidated" soil is 45 percent of that immediately after mechanical disturbance. The time to consolidation is at the time when 95 percent of the decrease in erodibility has occurred.[31]

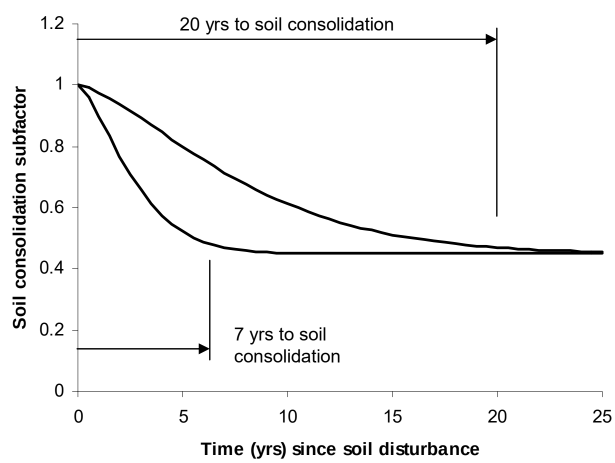

Figure 7.3.Effect of time on decrease in soil erodibility following a mechanical disturbance.

This decrease in erodibility occurs because of soil wetting and drying and biological soil activity. RUSLE2 assumes seven years for the **time to soil consolidation,** but another value can be entered. Also, RUSLE2 can compute the time to soil consolidation based on average annual precipitation as describe below.

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[30] Soil consolidation does not refer to the physical process of the bulk density of the soil increasing over time. Instead, it refers to a change in erodibility over time.

31 The 95 percent is used rather than 100 percent because the equation from is such that an infinitely long time is required for the computed values to actually reach the fully consolidated condition.

Time to soil consolidation is a function of soil properties. However, insufficient data are available to derive a relationship between soil properties and time to soil consolidation and soil properties and the degree of soil consolidation. The degree of soil consolidation (i.e., the increase in erodibility because of a mechanical disturbance, is less for a high sand soil than for a high clay soil. Also, the relative effect of mechanical disturbance seems to be greater for rill erosion than for interrill erosion.

Answering **Yes** to the question, **Calculate time to consolidation from precipitation**, causes RUSLE2 to compute a **time to soil consolidation** that is a function of average annual precipitation. RUSLE2 assumes seven years for the **time to soil consolidation** where average precipitation exceeds 30 inches (760 mm) and computes a **time to soil consolidation** that increases to 20 years in the driest areas of the Western US, as illustrated in Figure 7.3. The time to soil consolidation increases linearly from 7 years to 20 years between as average annual precipitation decreases from 30 inches (760 mm) to 10 inches (250 mm). A value of 20 years for time to soil consolidation is assumed for average annual precipitation less than 10 inches (250 mm). This increased time to soil consolidation reflects how the effects of a mechanical soil disturbance persist longer in low precipitation areas where reduced water is available and less frequent wetting and drying cycles occurs.

7.10. Soil Loss Tolerance (T)

The objective in conservation and erosion control planning is to control average annual erosion to an acceptable level.

7.10.1. Purpose of "T-value" input

The "T-value" in the RUSLE2 soil database component is the acceptable average annual rill-interrill erosion rate for a particular situation. RUSLE2 is used to identify erosion control practices that give estimated rill-interrill erosion equal to or less than the "T-value" assumed in the particular conservation planning application. In many cases, the T-value used in conservation planning will the NRCS-assigned soil loss tolerance value.

The "T-value" varies with the situation. For example, the "T-value" can be increased from the standard soil loss tolerance T-value for construction sites where the soil is exposed to erosion for a relatively short time. The standard soil loss tolerance T-value is used for cropland where long term productivity must be maintained or landfills where the buried waste must be protected from exposure by erosion over hundreds of years. An especially low "T-value" may be required to control off-site sediment delivery to protect a sensitive downstream resource such as a fish habitat. In many RUSLE2 applications, the "T-value" is determined by applicable government program or regulations.

The "T-value" entered in the RUSLE2 soil database component should be appropriate for the particular application.

Rather than reducing erosion to an absolute "T-value," the erosion control objective in some applications is to reduce erosion by a certain percentage relative to a base condition. Although a "T-value" is not needed in those applications, a nonzero "T-value" must be entered so that RUSLE2 can compute the ratio of segment erosion to the "T-value" adjusted for slope position, as discussed below.

7.10.2. NRCS-assigned soil loss tolerance values

Soil loss tolerance values assigned to each soil map unit by NRCS as a part of its soil survey program are often entered in RUSLE2 as the "T-value." Soil loss tolerance values range from 1 tons/acre (2 t/ha) per year to 5 tons/acre (11 t/ha) per year based primarily on how erosion is judged to harm the soil and to cause other damage. Shallow and fragile soils that can not be easily reclaimed after serious erosion are assigned low soil loss tolerances values. Limiting erosion rate to soil loss tolerance protects the soil as a natural resource and maintains the soil's long term productive capacity. Soil loss tolerance values consider the damages caused by erosion and the benefits of soil conservation. Also, soil loss tolerance values include a socio-economic element by considering the availability of reasonable and profitable erosion control technology.[32]

Although soil loss tolerance values were principally developed for cropland soils, soil loss tolerance values are also used for erosion control planning for reclaimed surface mines, landfills, and military training sites. Applying mulch controls erosion and promotes seed germination and early growth of vegetation. Erosion control facilitates establishing and maintaining vegetation, which is essential to long term site protection and similar to cropland requirements. Reclaimed land regulations require that excessive rill erosion be prevented. A rule of thumb is that rill erosion begins when soil loss for the eroding portion of the overland flow path exceeds about 7 tons/acre (15 t/ha) per year. A major concern on waste disposal sites is that buried waste not be exposed by rill erosion. Controlling soil loss to less than 5 tons/acre (11 t/ha) per year significantly reduces the likelihood of rill erosion. A well designed surface runoff collection system in addition to the rill and interrill erosion control practice is also required to prevent incised gully erosion.

Soil loss tolerance values are primarily for protecting the soil as a natural resource and not for protecting offsite resources from excessive sedimentation or water quality degradation. The criteria for controlling sediment yield from a site should be based on potential off-site sediment damages.

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[32] The factors considered in assigning soil loss tolerance values are discussed by Toy, T.J., G.R. Foster, and K.G. Renard. 2002. Soil Erosion: Processes, Prediction, Measurement, and Control. John Wiley and Son, New York, NY. The definition for soil loss tolerance given in AH537 implies that erosion can occur indefinitely at soil loss tolerance even though soil loss tolerance values exceed soil formation rates by about a factor of ten.

7.10.3. Taking hillslope position into account

A uniform slope for the **eroding portion** of the overland flow path is usually assumed in analyses where soil loss tolerance values are used in erosion control planning. See **Section 5.2** and Figures 5.2 and 5.3 for illustrations of overland flow paths and the eroding portion of an overland flow path. **Soil loss** is computed for this uniform profile and compared to the soil loss tolerance value. A satisfactory erosion control practice is one that reduces soil loss to the "T-value" or less.

However, special considerations should be given to applying soil loss tolerance values where steepness varies along the overland flow path. Average erosion for the profile is underestimated when a uniform profile is assumed for convex shaped profiles and overestimated for concave profiles. This difference is illustrated in Table 7.7 were average erosion is computed for uniform and convex profiles of the same length and average steepness. The average erosion for the convex profile is about 25% greater than the average erosion for the uniform profile. The difference in the erosion between the profiles increases as the degree of curvature of the convex profile increases. The ratio of steepness at the end of the convex slope to average steepness is a measure of curvature. In this example, the steepness at the end of the convex slope is about 1.7 times the average steepness of the profile.

An erosion control approach is to reduce the average erosion for the convex profile to the "T-value," which is illustrated in the two right hand columns of Table 7.7. Average erosion rate does not adequately account for the high erosion rate at the end of convex profiles. The erosion rate on the last segment at the end of the convex profile illustrated in Table 7.7 is more than twice the average erosion rate for the profile. The erosion rate at the very end of the convex profile is higher yet. Therefore, average erosion for the entire profile is not a satisfactory erosion control measure for a convex profile, especially one with significant curvature. Extra protection is needed on the lower end of the convex profile to provide comparable erosion control to that on the uniform profile.

Table 7.7. Soil loss along uniform and convex profiles of same length and average steepness. A = average erosion for entire profile and Adj T = T-value adjusted for position on profile. Assume "T-value" = 5.0.

	Uniform			Convex				
				Same practice as uniform profile			Practice changed to give same A as for uniform profile	
Segment	Steepness (%)	Segment erosion	Erosion/ Adj T	Steepness (%)	Segment erosion	Erosion/ Adj T	Segment erosion	Erosion/ Adj T
1	6	2.50	0.99	2	1.09	0.32	0.88	0.26
2	6	4.22	1.00	4	2.85	0.65	2.29	0.52
3	6	5.29	1.00	6	5.29	1.00	4.26	0.81
4	6	6.12	1.00	8	8.44	1.40	6.81	1.10
5	6	6.84	1.00	10	13.10	1.80	10.50	1.50
		A = 5.0			A = 6.2		A = 5.0	

An erosion control approach for convex profiles could be to reduce erosion rate on the last segment to the "T-value." However, erosion rate for each segment is a function of the segment length. Basing erosion control on segment erosion would make erosion control a function of segment length, which is improper. An alternative approach is to reduce "point" erosion rate to be less than the "T-value," but this approach provides greater protection for the convex profile than is considered necessary for the uniform profile having the same average steepness as the convex profile. Thus, the two profiles are not being compared on an equal basis.

Erosion rate increases along a uniform profile so that the erosion rate at the end of the uniform profile is substantially higher than the "T-value" when average erosion for the profile equals the "T-value." The erosion rate on the last segment on the uniform profile illustrated in Table 7.7 is 6.8, which is about 35% greater than the "T-value." Therefore, a procedure is needed that puts non-uniform profiles on the same basis as uniform profiles when comparing segment erosion to "T-values."

RUSLE2 computes the ratio of segment erosion to T adjusted for position to put erosion on an equal basis when comparing non-uniform shaped profiles.

RUSLE2 computes a **ratio of segment erosion to a "T-value" adjusted for position along the profile** so that erosion on non-uniform shaped profiles can be compared on an equal basis to erosion on uniform profiles when selecting erosion control practices.[33] The reason for having the comparison on an equal basis is that the soil loss tolerance concept is based on a uniform profile. The erosion control objective is that the ratio of segment erosion to "T-value" adjusted for position should be one or less. Note that this ratio is 1

[33] See AH703 for a discussion of this adjustment, including the mathematics used to make the adjustment.

everywhere along the uniform profile illustrated in Table 7.7, which shows that the ratio takes out the position effect along the profile in comparing segment erosion values to “T-values.”

The analysis involving the ratio of segment erosion to “T-values” adjusted for position along the profile should be for the eroding portion of the profile and not include depositional portions of concave profiles.

The same level of erosion control is achieved on the convex profile as on the uniform profile when the ratio of segment erosion to “T-value” adjusted for slope position is one or less for all segments. In the example in Table 7.7, the convex profile requires increased erosion control on the last two segments than is required on the uniform profile of the same average steepness as the convex profile because the convex profile accelerates erosion near its end. Similarly, less erosion control is needed on the upper three segments than on the uniform profile because the ratio of segment erosion to “T-value” adjusted for position is less than 1. In this example, the average erosion for the convex profile must be reduced to 3.3 tons/acre to provide the same level of erosion control on the last segment of the convex profile as provided on the last segment of the uniform profile.

8. TOPOGRAPHY

Topographic information is stored in the profile and worksheet components of the RUSLE2 database. Topography is a part the overall description of an **overland flow path** that includes information on cover-management, soil, and steepness along the flow path. This description involves three layers of information, illustrated in Figure 8.1. An overland flow path is also referred to as a RUSLE2 **hillslope profile**.

Segments are created for each layer by specifying the locations where cover-management, soil, or steepness changes along the flow path. Inputs are selected from the RUSLE2 database for each management and soil segment, and values for segment break locations and steepness are user entered. Thus, RUSLE2 computes how change in cover-management, soil, and steepness along the overland flow path affect erosion and deposition. Segment break locations need not coincide among the layers as illustrated in Figure 8.1.

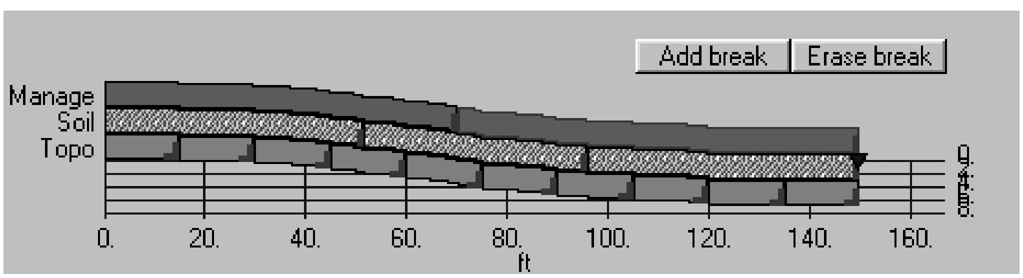

Figure 8.1. Schematic of the three layers that represent an overland flow path (a RUSLE2 hillslope profile).

8.1. Basic Principles

RUSLE2 uses equation 5.4 to compute erosion along an overland flow path. For generality, assume that all RUSLE2 profiles are composed of multiple segments, like Figure 8.1. Each layer (management, soil, topography) has its own segments. RUSLE2 assembles the segments for each layer into a composite set of segments. A composite segment end is located at a change in any one of the three layers.

8.1.1. Detachment

The computations that solve equation 5.4 start at the upper end of the overland flow path and step down slope segment by segment, which "routes" the water and sediment down slope. The sediment load g_{in} entering a particular segment is known from the computation of the sediment load g_{out} leaving the adjacent upslope segment. No sediment enters the first segment because it is at the origin of the overland flow.

The amount, expressed as mass per unit area, of net detached sediment (sediment produced) within the *ith* segment is computed with:

$$D_i = rkScp_c(x_i^{m+1} - x_{i-1}^{m+1}) / \lambda_u^m (x_i - x_{i-1}) \qquad \textbf{[8.1]}$$

where: D_i = net detachment (mass/area), r = erosivity factor, k = soil erodibility factor, S = slope steepness factor, c = cover-management factor, p_c = contouring factor, x_i = distance to lower end of the segment, x_{i-1} = distance to the upper end of the segment, λ_u = length of the unit plot (either 72.6 ft or 22.1 m), and m = slope length exponent. All variables are for a particular day and for the *ith* segment.34 Equation 8.1 is equation 5.1 applied to a segment.

The slope length exponent **m** for the *ith* segment is computed from:

$$m = \beta/(1+\beta) \qquad \textbf{[8.2]}$$

where: β = ratio of rill to interrill erosion for the *ith* segment, which in turn is given by:

$$\beta = \left[\frac{k_r}{k_i}\right]\left[\frac{c_{pr}}{c_{pi}}\right]\left[\frac{\exp(-0.05 f_g)}{\exp(-0.025 f_g)}\right]\left[\frac{(s/0.0896)}{3s^{0.8}+0.56}\right] \qquad \textbf{[8.3]}$$

where: k_r/k_i = the ratio of rill erodibility to interrill erodibility; c_{pr}/c_{pi} = the ratio for below ground effects for rill and interrill erosion, respectively, which is a prior land use type effect; exp(-0.05f_g/exp(-0.025 f_g) = the ratio of the ground cover effect on rill and interrill erosion, respectively; (s/0.0896)/(3$s^{0.8}$+0.56) = the ratio of slope effects for rill and interrill erosion, respectively; s = sine of the overland flow path slope angle; and f_g = percent ground cover.[35] All variables in equation 8.3 are for the *ith* segment. The ratio k_r/k_i is computed as a function of soil texture where the ratio decreases as clay increases because clay makes the soil resistant to rill erosion. The ratio increases as silt increases because silt decreases the resistance of soil to rill erosion. The ratio c_{pr}/c_{pi} represents how rill erosion decreases relative to interrill erosion as both soil consolidation and soil biomass increase. The term exp(-0.05f_g)/exp(-0.025f_g) represents how ground cover has a greater effect on rill erosion than on interrill erosion. The term (s/0.0896)/(3$s^{0.8}$+0.56) represents how slope steepness has a greater effect on rill erosion than on interrill erosion.

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[34] See the RUSLE Science Documentation for a complete description of the equations used in RUSLE2. The equations in this RUSLE2 User's Reference Guide are for illustration only and are not the complete equations.

[35] Equation 8.3 replaces the selection of an LS "Table" in RUSLE1.05 and earlier RUSLE1 versions and replaces having to select a land use in RUSLE1.06. RUSLE2, in effect, selects the proper LS relationship based on cover-management conditions.

A constant value of 0.5 is used for m in the Req zone.

The RUSLE2 slope length effect from equation 8.1 is:

$$L_i = (x_i^{m+1} - x_{i-1}^{m+1}) / \lambda_u^m (x_i - x_{i-1}) \qquad \textbf{[8.4]}$$

where: L_i = the slope length factor for the *ith* segment. The slope length effect in RUSLE2 adjusts soil loss from the unit plot up or down depending on whether the ith segment position is located less or greater than the unit-plot length λ_u of 72.6 ft (22.1 m) from the upper end of the overland flow path. Values for the slope length effect are less than 1 when location of the segment is less than the unit plot length and greater than 1 when the location is greater than the unit plot length.

The slope length effect in RUSLE2 is a function of rill erosion relative to interrill erosion except in the Req zone. Interrill erosion is assumed to be caused by raindrop impact and therefore independent of location along the overland flow path, assuming that the variables that affect interrill erosion are constant along the overland flow path. Rill erosion is assumed be caused by surface runoff and to vary linearly along the overland flow path because of runoff accumulation. The slope length exponent **m** in equation 8.2 varies between 0 and 1 and reflects the relative contribution of rill and interrill erosion. The exponent m is near 0 when almost all of the erosion is by interrill erosion, such as on a flat slope, and m is near 1 when almost all of the erosion is from rill erosion, such as on a bare, steep slope. Slope steepness, cover-management, and soil affect RUSLE2's slope length effect because of their different effect on rill erosion relative to interrill erosion. The RUSLE2 slope length effect varies daily as cover-management conditions change. The USLE slope length factor is independent of the other USLE factors, except for slope steepness. The RUSLE1 slope length factor only partially varies with the other RUSLE1 factors.

RUSLE2 spatially integrates equation 5.4 in its computations. A spatial integration of the USLE and RUSLE1 is possible for a limited set of conditions, but the integration must be done manually and is laborious. Few users perform the integration. RUSLE2 performs the integration internally without extra steps required of the user other than to divide the overland flow path into segments and specify the inputs for each segment. Just as RUSLE2 differs from RUSLE1 and the USLE in temporal integration, RUSLE2 also differs from them in spatial integration and interaction among factors. Although RUSLE2 uses fundamentals from the USLE and RUSLE1, RUSLE2 is essentially a new model. These mathematical differences give RUSLE2 much more power than the other equations.[36]

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[36] The difference in temporal integration can result in as much as 20% differences in erosion estimates between RUSLE2 and the USLE and RUSLE1. The difference in spatial integration between RUSLE2 and RUSLE1 is generally not great provided the proper selections are made in RUSLE1. However, few users

The RUSLE2 slope steepness factor is computed with:

$$S = 10.8s + 0.03 \qquad \text{slope} < 9\% \qquad \textbf{[8.5]}$$

$$S = 16.8s - 0.50 \qquad \text{slope} \geq 9\% \qquad \textbf{[8.6]}$$

for all areas except the Req zone, where equation 8.7 is used.

$$S = (s / 0.0896)^{0.6} \qquad \text{slope} \geq 9\% \qquad \textbf{[8.7]}$$

where: slope = slope steepness in percent.[37] The slope steepness factor S has a value of 1 for a 9% slope. Values for the S factor are less than 1 for slope steepness less than 9 percent and greater than 1 for slope steepness greater than 9 percent. The slope steepness factor in RUSLE2 adjusts the soil loss values from the unit plot up or down depending on whether the field slope is steeper or flatter than the 9 percent steepness of the unit plot.

The slope steepness S factor should be a function of the soil and cover-management similar to equation 8.3. However, neither the empirical data nor theory is sufficient for incorporating those effects into RUSLE2.

8.1.2. Runoff

RUSLE2 uses discharge (flow) values for runoff to compute sediment transport capacity, contouring effectiveness, and critical slope length for contouring. Discharge rate at a location is computed from:

$$q = q_{i-1} + \sigma_i (x - x_{i-1}) \qquad \textbf{[8.8]}$$

where: q = discharge rate (volume/width·time) at the location x between the segment ends x_{i-1} and x_i, q_{i-1} = discharge rate at x_{i-1}, and σ_i = excess rainfall rate (rainfall rate - infiltration rate) on the *ith* segment. Excess rainfall rate is computed using the NRCS runoff curve number method that computes runoff depth. RUSLE2 assumes that runoff rate is directly proportional to runoff depth. RUSLE2 computes curve number values, the major parameter in the NRCS curve number method, as a function of hydrologic soil group, soil surface roughness, ground cover, soil biomass, and soil consolidation to represent the effect of cover-management on runoff. In general, RUSLE2 computes reduced runoff as these variables increase, except for soil consolidation that interacts with soil biomass. If soil biomass is very low, soil consolidation increases runoff, typical of a bare construction site. If soil biomass is high, typical of high production pasture, soil

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properly select inputs for RUSLE1 to achieve this similarity in results.

[37] The slope factor equations are the same in RUSLE2 and RUSLE1.

consolidation decreases runoff.[38] The curve number method is configured within RUSLE2 to compute negative values for rainfall excess (σ) so that RUSLE2 can compute decreasing discharge along a segment having very high infiltration that receives run-on from upslope.

Discharge in RUSLE2 is typically used as a ratio of discharge computed for a given condition to a base runoff computed for moldboard plowed, clean tilled, low yielding corn grown on a silt loam soil in Columbia, MO. RUSLE2 starts with empirical erosion factor values taken from AH537, which is a summary of data collected over a wide range of conditions at many locations. RUSLE2 uses ratios, such as the one involving discharge, in process-based equations to adjust the empirical erosion factor values up or down from a base value. RUSLE2 often computes a departure from a base value rather than an absolute value. Computing departures is more stable and robust than computing absolute values. This approach combines the best of empirically based and process based variables and equations.

Columbia, MO is used as a base because it is centrally located in the US and represents "typical" weather values in the eastern US. The moldboard plowed, clean-tilled, row cultivated corn best represents the condition for contouring and critical slope length values in AH537. These AH537 values are directly related to runoff and serve as calibration data.

8.1.3. Sediment transport capacity

Sediment transport capacity ($T_{c,up}$ and $T_{c,low}$) is computed at both the upper (x_{i-1}) and lower (x_i) ends of each segment using equation 5.3 and the discharge rates and slope steepness of the segment. This approach results in a step change in sediment transport capacity at segment ends, even when steepness varies smoothly in continuous fashion. Slope steepness values for adjacent segments could have been averaged to obtain a smoothly varing transport capacity along the slope. However, such an approach would have increased the difficulty for users to represent sharp changes in steepness, such as the flat top and steep sideslope of a landfill. Transport capacity is also a step function where cover-management conditions, such as at the upper end of a grass strip change as a step function, or slope steepness changes as a step function, such as the change in steepness from the top of a landfill to the sideslope. RUSLE2 computes transport capacity at the lower end of a segment based on conditions for that segment and at the upper end of the adjacent segment using the conditions for that segment to capture step changes. These step changes in transport capacity are illustrated in Figure 8.2.

The product qs in Equation 5.3 represents runoff erosivity. It is proportional to runoff's total shear raised to the 3/2 power. Total shear stress is divided between that acting on the soil (skin friction) and that acting on form roughness elements (form friction). The

[38] Soil consolidation is used as an indicator variable, not as a cause and effect variable.

shear stress acting on the soil is assumed to be responsible for runoff transporting sediment. The coefficient K_T is a measure of the fraction of the flow's total shear stress that acts on the soil to transport sediment. Values for K_T and transport capacity decrease as form hydraulic roughness increases even though total hydraulic roughness increases..

Manning's n is a measure of form and grain (skin) roughness combined. RUSLE2 uses Manning's n values to compute K_T values. In turn, RUSLE2 computes values of Manning's n as a function of standing live and dead vegetation, ground cover, and surface roughness, which are form roughness elements.

The variable K_T is also a calibration coefficient that represents transportability of the sediment. RUSLE2 does not vary K_T as a function of sediment properties, which means that sediment transport capacity is not a function of sediment characteristics. A base value for K_T was determined by calibrating RUSLE2 to a field plot experiment of deposition on a concave slope. The steepness of this concave slope decreased from 18% at the its upper end to 0% at its lower end. Deposition began at the location where steepness was 6%. This condition was assumed to represent moldboard plowed, clean tilled, low yield corn on a silt loam soil at Columbia, MO. The calibration was checked against general field observations and data from laboratory experiments on sediment transport and deposition.

8.1.4. Sediment routing

Several cases must be considered in routing the sediment down slope (i.e., solving equation 5.4 sequentially by segment starting at the upper end of the overland flow path).

8.1.4.1. Case 1: Detachment over the entire segment

Detachment occurs over the entire segment when the transport capacity $T_{c,up}$ at the upper end of the segment is greater than the incoming sediment load g_{in} and the transport capacity $T_{c,low}$ at the lower end of the segment is greater than the maximum possible sediment load at the lower end of the segment. The maximum possible sediment load is the incoming sediment load plus the sediment produced within the segment by detachment. This case occurs on uniform and convex shaped slopes and the upper portion of a concave slope.

Sediment load at the lower end of the segment is given by:

$$g_{out} = g_{in} + D_i(x_i - x_{i-1}) \qquad \textbf{[8.9]}$$

where: D_i = net detachment (sediment production) computed with equation 8.1 for the *ith* segment.

Another possibility is that the potential sediment load computed with equation 8.9 exceeds transport capacity at the lower end of the sediment while the potential sediment load based on interrill erosion is less than transport capacity. If this condition exists, RUSLE2 computes a reduced rill erosion so that the sediment load at the end of the segment just fills transport capacity without overfilling it.

RUSLE2 assumes that interrill erosion always occurs at a "capacity" rate. Interrill erosion is computed like net detachment (equation 8.1) except for an interrill erosion slope steepness factor, the slope length factor being 1 (i.e., interrill erosion does not vary by location along the overland flow path), and multiplying by 0.5 based on the assumption that interrill erosion equals rill erosion for unit-plot conditions. The RUSLE2 equation for interrill erosion rate is:

$$D_{ir,i} = 0.5rk(3s^{0.8} + 0.56)cp_c \qquad \textbf{[8.10]}$$

No local deposition occurs for **Case 1** conditions when slope steepness is sufficiently steep.[39] However, at low steepness, interrill erosion can be greater than sediment transport capacity, which causes local deposition. Local deposition occurs where interrill erosion rate exceeds the increase in transport capacity with distance (i.e, $D_{ir} > dT_c/dx$). Equation 8.1 empirically includes local deposition in its computation of net detachment. Local deposition is selective causing coarse particles to be deposited and the sediment load to be enriched in fine particles. RUSLE2 uses the procedure that computes deposition in **Case 2** to compute sediment characteristics and the enrichment ratio for this local deposition (See **Section 7.5**).

The distribution of the sediment added to the sediment load by detachment is the sediment distribution at the point of detachment described in **Section 7.5**. The particle class distribution in the sediment load is the same as that at the point of detachment unless local deposition or remote deposition is computed.

8.1.4.2. Case 2: Deposition over the entire segment

Deposition occurs along an entire segment when the sediment load exceeds transport capacity at both the upper and lower ends of the segment. An example of this case is deposition in a narrow grass strip illustrated in Figure 8.2. Table 7.6 shows values computed by RUSLE2 for an example like this case.

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[39] **Local deposition** is deposition very close (few inches, tens of millimeters) to the detachment point. Deposition in the depressions on a rough soil surface is an example of local deposition. **Remote deposition** is deposition a considerable distance (tens of feet, several meters) from the detachment point.

Equation 5.2, which computes deposition, is applied to each particle class. Sediment characteristics used in these computations are described in **Section 7.5.** The transport capacity for each particle class is computed by dividing the total sediment transport capacity computed with equation 5.3 among the particles in proportion to the mass distribution of the sediment classes in the total sediment load. The distribution of sediment transport capacity among the particle classes changes as deposition occurs along the overland flow path because each particle class is deposited at a different rate based on fall velocity

Equation 5.2 has two unknowns, deposition rate and sediment load. Equation 5.2 is combined with the continuity equation to solve for deposition rate and sediment load. The continuity equation for **Case 2** is:[40]

$$\Delta g / \Delta x = D_{ir} + D_p \qquad \textbf{[8.11]}$$

where: $\Delta g/\Delta x$ is the change in sediment load Δg over the distance Δx, D_{ir} = interrill erosion and D_p = deposition rate.

An important assumption involves interrill erosion in equation 8.11. **Does interrill erosion occur simultaneously with deposition?** CREAMS assumes that rill erosion **does not** occur simultaneously with deposition, while RUSLE2 assumes that interrill erosion **does** occur simultaneously with deposition. This assumption is valid for interrill erosion on ridges where deposition occurs in the furrows between the ridges. However, the assumption is not clear-cut where deposition occurs on flat soil surfaces, such as the toe of a concave slope. Deposition is dynamic and spatially varied. Flow depth and transport capacity vary considerably across the slope leaving "exposed" areas where interrill erosion occurs. Deposition and flow patterns change during deposition.[41]

While not a perfect assumption, RUSLE2 assumes that interrill erosion occurs simultaneously with deposition. A consequence of this assumption is that less enrichment of sediment in fines is computed than when no interrill erosion is assumed.

Equations 5.2 and 8.11 and transport capacity being distributed among particles classes based on their distribution in the sediment load creates a very complex and interactive set of equations to be solved. The equations are solved numerically in RUSLE2 because simple, closed form solutions were not found. The RUSLE2 numerical solution divides the portion of the overland flow path where deposition occurs into small sub segments. Decreasing sub segment length increases computational accuracy but noticeably

[40] The sign convention is that detachment is positive (increases the sediment load) and deposition is negative (decreases the sediment load).
[41] See Toy et al. (2002) for additional discussion.

increases computational time, which required a compromise between the two. The procedure was carefully designed to minimize differences related to how a user segments the overland flow path. The user will seldom see much effect of segment division on RUSLE2 results. The accuracy of the deposition computation with respect to the numerical solution matching the "true" mathematical solution is well within the overall accuracy of RUSLE2.

RUSLE2 computes deposition rate, total sediment load, and the sediment load of each particle class along each segment. The sediment load g_{out} leaving the segment is the sediment load computed at the end of the segment, which is the sediment load g_{in} entering the next downslope segment. The distribution of the particle classes in the sediment load indicates how deposition enriches the sediment in fines. RUSLE2 computes an enrichment ratio based on specific surface area of the sediment at the end of the last segment on the overland flow path (See **Section 7.5**). The value computed for enrichment ratio is related to the fraction of the sediment load that is deposited. The enrichment ratio increases as the deposition fraction increases.

8.1.4.3. Case 3: Deposition ends within the segment

Deposition ends within a segment when deposition occurs at the upper end of the segment and transport capacity increases within the segment at a rate greater than interrill erosion rate if the segment is sufficiently long as illustrated in Figure 8.3. Sediment load exceeds transport capacity at the upper end of the segment and decreases within the segment while transport capacity increases within the segment. The two become equal within the segment, which is the location x_e that deposition ends. RUSLE2 computes deposition and the sediment load on the upper portion of the segment using the deposition procedure described for **Case 2.**

The same conditions described for **Case 1** exist for the lower portion of the segment beyond the location x_e where deposition ends. Net detachment is computed using equation 8.1 where x_e is substituted for x_{i-1}. Rill erosion is reduced, if necessary, to avoid the sediment load "overfilling" transport capacity. Sediment load at the end of the segment is computed from:

$$g_{out} = g_{xe} + D_{>xe}(x_i - x_e) \qquad \textbf{[8.12]}$$

where: g_{xe} = sediment load at the point where deposition ends and $D_{>xe}$ = net detachment on the lower portion of the segment beyond the location where deposition ends.

8.1.4.4. Case 4: Deposition begins within the segment

Deposition begins within a segment when the transport capacity at the upper end of a segment is greater than sediment load, and transport capacity decreases within the segment to become less than sediment load. This case occurs on a segment where cover-management and/or soil change so that infiltration rate is so high that runoff and transport capacity decrease within the segment. This case is illustrated in Figure 8.4.

Deposition begins at the location where sediment load and transport capacity become equal. RUSLE2 computes the deposition on the lower portion of the segment using the procedure described for **Case 2.**

8.1.5. Computing sediment yield, soil loss from eroding portion, total detachment, conservation planning soil loss, and erosion by segment

RUSLE2 displays several values produced by these computations. These output values are used in conservation and erosion control planning to select erosion control measures appropriate for the site conditions.

8.1.5.1. Sediment yield

Sediment yield is the amount of sediment leaving the overland flow path.[42] It is used in erosion control planning where the objective is to reduce the amount of sediment leaving the site. RUSLE2 computes sediment yield as sediment load at the end of the overland flow path divided by the overland flow path length. That is:

$$SY = g_{out,I} / \lambda_{ofpl} \qquad \textbf{[8.13]}$$

where: SY = sediment yield from the overland flow path length (mass/area), $g_{out,I}$ = the sediment load at the end of the last segment on the overland flow path, I = the index of the last segment, and λ_{ofpl} = the overland flow path length.

8.1.5.2. Soil loss from eroding portion

The eroding portions of an overland flow path are where no deposition occurs, except for local deposition. Figure 5.2 illustrates the eroding portion of a complex shaped profile for an overland flow path. The **soil loss from eroding portion** is used in conservation planning where the objective is to protect eroding areas from excessive erosion to maintain soil productivity, prevent rilling, and reduce sediment yield.

The soil loss for the eroding portion of the overland flow path is computed from:

$$A_{ep} = \sum (g_{out,k} - g_{in,k}) \Big/ \sum (x_{out,k} - x_{in,k}) \qquad \textbf{[8.14]}$$

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[42] This sediment yield is the sediment yield for the site only if the overland flow path ends at the site boundary.

where: A_{ep} = soil loss (mass/area) for the eroding portions of the overland flow path and the index k refers to each portion of the overland flow path that is an eroding rather than a depositional area. Soil loss for the eroding portions of the overland flow path is the total sediment produced on the eroding portions divided by the total length of the eroding portions.

8.1.5.3. Total Detachment

Total detachment represents the sediment produced for the entire overland flow path, including depositional areas. In contrast, soil loss for the eroding portion of the overland flow path excludes depositional areas.

Total detachment for the overland flow path is the sum of the detachment amount (sediment production) for each segment divided by the overland flow path length. That is:

$$D_T = \sum D_{f,i}(x_i - x_{i-1}) / \lambda_{ofpl} \qquad \textbf{[8.15]}$$

where: D_T = the total detachment (mass/area) for the overland flow path length and D_f = the sediment production for each segment. Sediment production for a segment is the value computed by equation 8.1 if rill erosion is not limited as described in **Section 8.1.4.1** or remote deposition does not occur as described in **Sections 8.1.4.2-8.1.4.4.** If rill erosion is limited, the sediment production is the sum of the interrill erosion and the rill erosion required to just fill transport capacity. If remote deposition occurs, sediment production equals interrill erosion.

8.1.5.4. Conservation planning soil loss

Neither **soil loss for the eroding portion** or **total detachment** take any **credit** for **remote deposition** as "**soil saved**," although RUSLE2 gives full credit to **local deposition** as "soil saved" because local deposition is empirically considered in equation 8.1 that computes net detachment. **Giving credit to remote deposition is a matter of judgment.** In the USLE (AH282, AH537), half credit was given to deposition by gradient terraces and full credit was given to deposition by rotational strip cropping.[43] No credit was given to deposition on the toe of concave slopes because this deposition ended the USLE slope length. RUSLE1 gave credit to deposition by terraces based on

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[43] Gradient terraces are terraces on a uniform grade less than about 1% and may be level for moisture conservation. These terraces reduce overland flow path length and "save" soil by causing deposition uniformly along their length. The deposited sediment is spread by periodic mechanical operations required to maintain flow capacity. Rotational strip cropping is a system of alternating uniform width strips of dense vegetation that deposit sediment and strips where erosion is significantly higher than with the dense vegetative strips. The strips are systematically rotated by position on the hillslope over the crop rotation cycle.

terrace spacing. If the terraces were close together, about half credit was taken, and the credit was reduced to none as terrace spacing increased to 300 ft (100 m). Credit for deposition with narrow permanent vegetative strips (e.g., buffer and filter strips) was not discussed in AH282 or 537. In RUSLE1, the amount of credit given to deposition depended on the location of the deposition. Deposition near the end of the overland flow path was given very little credit. The credit increased to more than 60% for deposition near the origin of the overland flow path.

The **conservation planning soil loss** computed by RUSLE2 gives full credit for deposition with rotational strip cropping, i.e., the **conservation planning soil loss equals sediment yield**. RUSLE2 gives partial credit to deposition that occurs with permanent vegetative strips based on the location of the deposition. Very little credit is given to deposition at the end of the overland flow path, and the credit increases to about 60% for deposition located close to the overland flow origin. The same credit is given to deposition on concave portions of an overland flow path. Very little credit is given for the deposition if it is near the end of the overland flow path like that illustrated in Figure 5.4 and increased credit is given to deposition near the origin of the overland flow path.

The justification of the conservation planning soil loss in RUSLE2 is based on the following principles.

1. Deposition is beneficial. The quality of the soil, hillslope, and landscape is better with the deposition than without it. That is, deposition has a **soil saved** benefit.
2. Deposition that occurs and remains on very small areas relative to the entire hillslope area provides much less benefit that deposition that occurs on and is spread over a significant sized area by mechanical operations such as tillage and terrace maintenance.
3. Deposition that occurs near the end of the overland flow path has almost no value for maintaining the quality of the overall hillslope. Deposition in these locations is essentially “lost” from the hillslope with little chance for recovery.
4. Deposition upslope on the hillslope represents soil that is captured and not “lost” from the hillslope. A benefit can be gained by spreading the deposited sediment using common mechanical operations without having to physically transport the sediment upslope.

In general, the **conservation planning soil loss** is greater than **sediment yield**, except for rotational strip cropping where the conservation planning soil loss equals sediment yield. The conservation planning soil loss is less than the **total detachment** for the slope. The difference between total detachment and the conservation planning soil loss represents the **credit taken for deposition**. **Soil loss on the eroding portion** of the slope is the highest value of the set.

8.1.5.5. Erosion by segment

RUSLE2 computes erosion along the overland flow path. The user can obtain these erosion values by dividing the overland flow path into segments. The average **erosion for a segment** depends on segment length because point erosion varies with distance within the segment.

Point erosion at a can be computed with RUSLE2 using a very short segment such as 1 ft (0.3 m) at the location where the point erosion is desired.

Net erosion for a segment is computed as:

$$a_i = (g_{out,i} - g_{in,i})/(x_i - x_{i-1}) \qquad \textbf{[8.16]}$$

where: a_i = erosion for the *ith* segment (mass/area). A positive value means that the segment experiences a net loss of sediment (detachment) and a negative value means that the segment experiences a net gain of sediment (deposition). Even though either net detachment or net deposition occurs overall for a segment, a part of the segment can

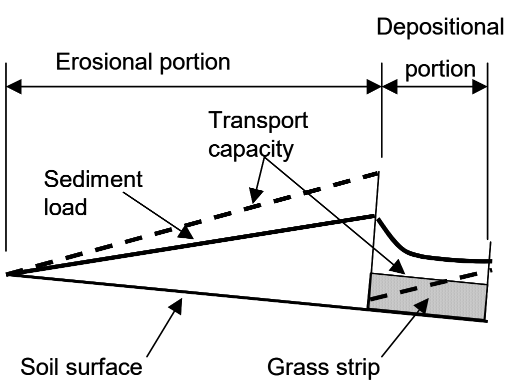

Figure 8.2. Narrow grass where deposition occurs over entire segment

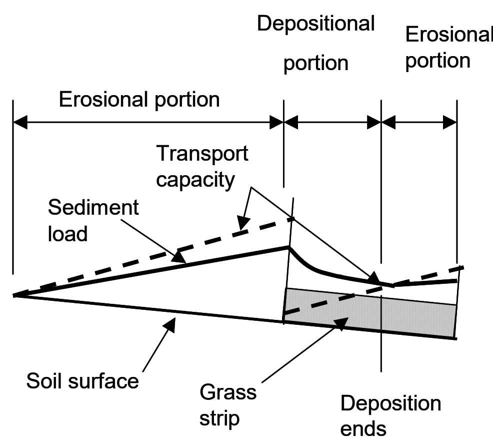

Figure 8.3. Grass strip sufficiently wide that deposition ends within segment and erosion occurs on lower portion of segment

experience net detachment while another part experiences net deposition, such as illustrated in Figures 8.3 and 8.4.

The segment erosion values must be carefully interpreted with respect to the erosion control planning criteria. **Is the erosion control criterion for point erosion or for average erosion for a uniform shaped slope, such as the soil loss tolerance value?**

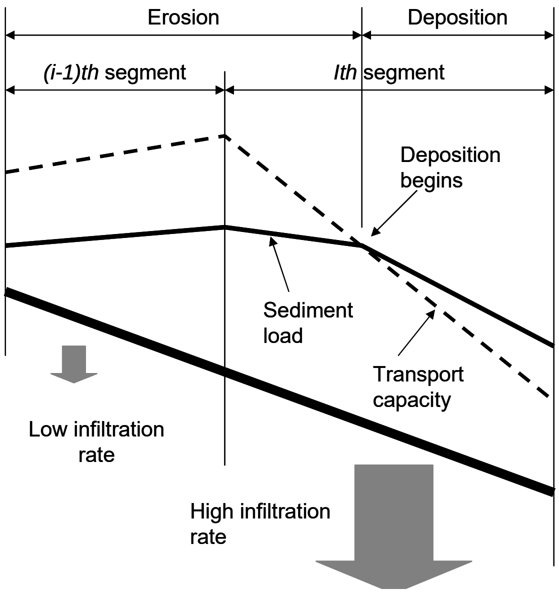

Figure 8.4. Deposition begins within a segment on a segment with a very high infiltration rate

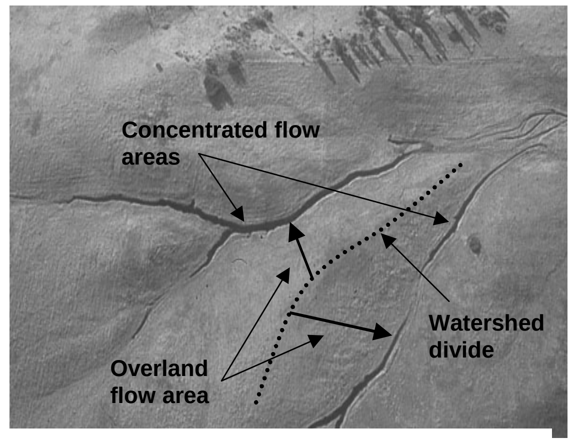

Figure 8.5. A natural landscape with concentrated flow areas and divides where overland flow originates

Comparing a point erosion value computed by RUSLE2 with an erosion control criteria based on average erosion for a uniform slope can produce misleading results and under designed erosion control practices that do not provide sufficient protection or over designed erosion control practices that are too costly. See **Section 7.9** for information on how to interpret RUSLE2 segment erosion values with respect to erosion control criteria based on average erosion for a uniform slope.

8.1.5.6. General comments

RUSLE2 displays a variety of erosion values that can be used in conservation and erosion control planning. Also, RUSLE2 can be applied in variety of ways to a field site. For example, RUSLE2 can be applied in the traditional USLE way by assuming a uniform slope and that deposition ends slope length. The erosion values computed by RUSLE2 can be compared with soil loss tolerance values or other erosion control criteria just as USLE soil loss values were used.

The other option is to apply RUSLE2 to an overland flow path that passes through depositional areas and is terminated by a concentrated flow area. The effect of variability in soil, steepness, and cover-management on erosion along the overland flow path can be analyzed. The RUSLE2 sediment yield estimates are greatly superior to the USLE soil loss estimates for estimating the sediment amount leaving a site. RUSLE2 provides detailed information about how erosion varies along the overland flow path so that a cost effective erosion control practice can be tailored to the specific site conditions better than could be done with the USLE.

Users must understand how to apply RUSLE2 and interpret its computed values. The user must be aware of differences between the USLE, RUSLE1, and RUSLE2 when comparing these models and values from by them. The user must not assume that USLE and RUSLE1 procedures apply automatically to RUSLE2.

8.2. Representing Overland Flow Path Profiles

8.2.1. General considerations

Applying RUSLE2 requires selecting and describing an overland flow path. A hillslope involves an infinite number of overland flow paths. **Section 5.2** describes how to choose overland flow paths for applying RUSLE2 in conservation and erosion control planning.[44]

A point on the hillslope is selected through which the overland flow path passes. The overland flow path is traced from its origin through the point to the concentrated flow area that ends that particular overland flow path as illustrated in Figures 5.1 and 8.5. This flow path is traced perpendicular to the contour lines assuming that the soil surface is flat and ignoring how ridges or micro topographic features affect flow direction.

Overland flow paths are best determined by visiting the site, pacing flow paths, and making measurements directly on the ground. Contour map intervals greater than 2-ft (1-m) should be used cautiously, if at all, to determine overland flow paths. Contour map intervals of 10-ft (3-m) should not be used because concentrated flow areas that end overland flow paths cannot be adequately delineated. Also, these maps do not provide the detail needed to identify depositional areas and the slope steepness with sufficient precision to accurately compute deposition (See **Section 8.2.5**). Overland flow paths are generally much too long when contour intervals greater than 10 ft (3 m) are used to determine them.

Overland flow path lengths on many landscapes generally are less that 250 ft (75 m), and usually do not exceed 400 ft (125 m). Path lengths longer than 1000 ft (300 m) can not be used in **RUSLE2** because the applicability of **RUSLE2** at these long path lengths is questionable. Overland flow often becomes concentrated flow on most landscapes before

[44] See AH703 for additional discussion on identifying, selecting, and describing overland flow paths.

such lengths are reached. The maximum of 1000 ft (300 m) is an extrapolation from the longest plot of about 650 ft (200 m).

RUSLE2 applies to overland flow path lengths as short as zero, which means that RUSLE2 can be applied to ridges and beds like those used in vegetable production as discussed in **Section 8.3.6.2**.

RUSLE2 applies to steepness between flat (0%) and a 100% (1:1) maximum. This maximum of 100% is an extrapolation from 30%, the maximum steepness of the plots used to derive RUSLE2.

Length values like overland flow path segment lengths, distance from the origin of overland flow to lower segment end, overland flow path length, and land area are based on a horizontal measure for internal computations in **RUSLE2**. However, such length values can be input into RUSLE2 based on measuring along the hypotenuse (i.e., parallel to the soil surface). Field measurement parallel to the land surface is easier than measuring horizontally. The difference between horizontal and hypotenuse measurements is insignificant for slope steepness less than 20 percent. Distance and areas measured from maps is a horizontal measure. All references to land areas in RUSLE2 are horizontally based, even if the overland flow path length values were entered on a hypotenuse basis.

Overland flow profiles are segmented to represent differences in steepness, soil, and cover-management along the overland flow path. Topographic segments can be entered in RUSLE2 by distance from the origin of the overland flow path to the lower end of the segment or by segment length. The choice of entry method is based on user preference.

8.2.2. Profile shapes

The profiles for overland flow paths have various shapes as illustrated in Figure 8.6.[45] Simple shapes are uniform, concave, and convex. A uniform shaped profile is one where steepness is the same everywhere along the overland flow path. A convex profile is one where steepness increases everywhere along the overland flow path. RUSLE2 computes net detachment everywhere along uniform and **convex** profiles such that the entire profile is an **eroding portion** (See **Section 5.2**). A **concave** profile is one where steepness decreases everywhere along the overland flow path. If the lower part of a concave profile is sufficiently flat, transport capacity is less than sediment load and deposition occurs. These profiles have an upper **eroding portion** and a lower **depositional portion,** as

[45] Although the terms **hillslope profile** and **overland flow path profile** are often used interchangeably, the two terms are different. A RUSLE2 overland flow path profile does not start at the top of a hill and run to the bottom of the hill. Instead, a RUSLE2 overland flow path profile starts at the origin of overland flow, which is a runoff divide, and perpendicularly crosses contour lines. A RUSLE2 overland flow path is ended by a concentrated flow area.

illustrated in Figure 5.2. However, if the profile does not flatten sufficiently, deposition will not occur and the entire profile is an **eroding portion**.

Deposition does not occur on all concave shaped profiles. A decrease in steepness is not enough by itself to cause deposition.

Simple profile shapes are combined to form complex shaped overland flow profiles. A complex:convex-concave profile is one where the upper part is convex and the lower part is concave. Deposition occurs on the concave portion if steepness flattens sufficiently for transport capacity to become less than sediment load. If deposition occurs, the upper part of the profile is an eroding portion and the depositional area is the depositional portion as illustrated in Figure 5.2. Another complex shaped profile is complex:concave-convex. Deposition occurs on the concave portion if it flattens sufficiently. Runoff can continue as overland flow across the depositional area onto the lower convex portion. If deposition occurs, this profile has both an upper and lower eroding portion separated by the depositional portion. Erosion on the lower eroding portion is directly related to runoff that originates on the upper portion of the overland flow path. Therefore, the path length used to compute erosion on the lower eroding portion of the profile must include the entire path that generates runoff that flows onto the lower eroding portion.

Deposition does not end an overland flow path in RUSLE2.

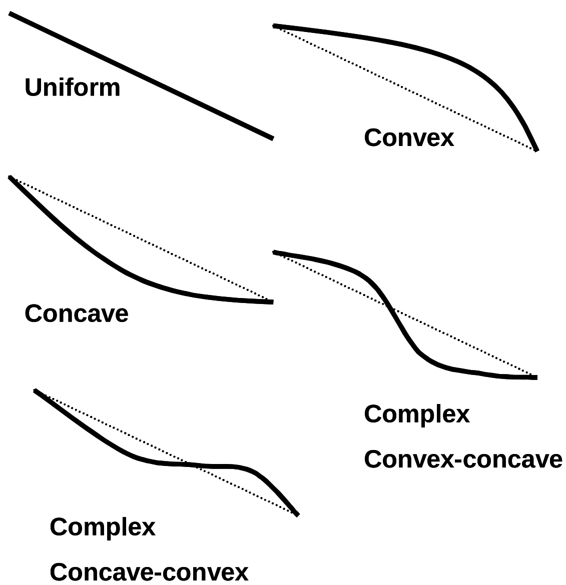

Figure 8.6. Overland flow path profiles

8.2.3. Importance of representing non-uniform profile shapes in RUSLE2

Many conservation and erosion control planners using USLE and RUSLE1 assumed uniform profiles even though procedures were available for applying these models to irregular slopes. This section discusses how profile shape affects RUSLE2 erosion estimates.

The overland flow path profile is a complex:convex-concave shape for many natural landscapes. This profile is illustrated in Table 8.1 along with RUSLE2 computed erosion values. The length of this profile is 250 ft (76 m) and has an average steepness of 4.1%. RUSLE2 computed erosion values are also shown for uniform and convex profiles having the same length and average steepness as the complex profile.

Table 8.1. Computed erosion by segment for three profle shapes, all having the same length and average steepness

			Convex-Concave			Uniform			Convex		
Segment Number	Distance to lower end of segment (ft)	Segment length (ft)	Steepness (%)	Erosion (tons/acre)	Sediment load (lbs/ft width)	Steepness (%)	Erosion (tons/acre)	Sediment load (lbs/ft width)	Steepness (%)	Erosion (tons/acre)	Sediment load (lbs/ft width)
1	28	28	2	4	5	4.1	7	8	0.5	1	2
2	64	36	4	10	22	4.1	11	26	1.5	4.2	9
3	107	43	8	28	78	4.1	14	53	2.8	9	27
4	149	42	6	25	125	4.1	16	84	4.2	16	58
5	181	32	4	-1	125	4.1	17	109	5.4	24	94
6	218	37	2	-28	77	4.1	19	141	6.6	34	151
7	250	32	1	-21	46	4.1	20	170	7.7	44	216
Average			4.1	4		4.1	15		4.1	19	

The computed erosion values differ greatly for the three profile shapes. The average erosion on the complex profile is 4 tons/acre (8.8 t/ha) while the average erosion on the uniform profile is 15 tons/acre (33 t/ha). Negative segment erosion values indicate net deposition for the segment. The reason for the large difference is deposition on the complex profile. Although the average erosion for the complex profile is much lower than average erosion for the uniform profile, the maximum segment erosion of 28 tons/acre (62 t/ha) for the complex profile is significantly larger than the maximum segment erosion of 20 tons/acre (44 t/ha) for the uniform profile. Figures 8.7 and 8.8 illustrate the variation in segment erosion and sediment load along the complex profile.

Another comparison is between the convex profile and the uniform profile. As expected, deposition is not computed for either the uniform or the convex profile. However, the average erosion of 19 tons/acre (42 t/ha) for the convex profile is significantly higher than the average erosion of 15 tons/acre (33 t/ha) for the uniform profile. This difference illustrates that uniform profiles underestimate average profile erosion when a uniform profile is assumed to represent a convex profile. The maximum segment erosion on the convex profile is 44 tons/acre (97 t/ha) while the maximum segment erosion is 20 tons/acre (44 t/ha) for the uniform profile. The uniform profile seriously underestimated maximum segment erosion for the convex profile.

Another comparison involves the average erosion for the eroding portion of the profile. The eroding portion of the profile represented in Table 8.1 is between the origin of overland flow and 165 ft (50 m), where deposition begins. The eroding portion of the slope can be approximated with a uniform profile with a length of 165 ft (50 m) on a steepness of 5.2%, which is the average steepness of the eroding portion. The average erosion for the uniform profile is 16 tons/acre (35 t/ha), while the erosion computed with

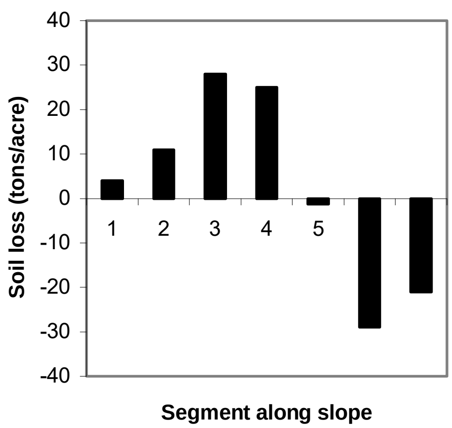

Figure 8.7. Segment erosion along a complex convex-concave hillslope profile

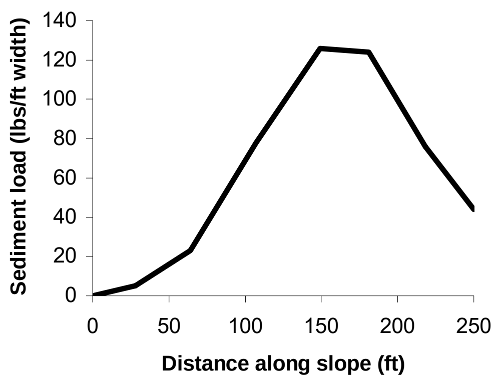

Figure 8.8. Sediment load along a complex convex-concave hillslope profile

the actual non-uniform profile is 18 tons/acre (40 t/ha) for the eroding portion. The average erosion for the eroding portion is about the same with these two methods. However, the maximum segment erosion computed with the non-uniform profile is 28 tons/acre (62 t/ha) while it is 23 tons/acre (51 t/ha) computed with the uniform profile approximation. The uniform profile approximation significantly underestimates the potential for rill erosion on the convex portion of the overland flow path

8.2.4. Implications of using uniform profiles to represent non-uniform profiles for conservation and erosion control planning

Assuming a uniform profile is common when the USLE and RUSLE1 were used in conservation and erosion control planning. A uniform profile is easy to describe, requiring only a length and steepness. The computational procedure for applying the USLE to non-uniform profiles is cumbersome and laborious. The non-uniform slope procedure in RUSLE1 is easy to use, but it only considers the effect of non-uniform steepness. It does not consider variation of soil erodibility or cover-management along the overland flow path.

Interpreting segment erosion values along non-uniform profiles (overland flow paths) is complex where using an erosion control criteria based on average erosion for a uniform profile. RUSLE2 is much more powerful than either the USLE or RUSLE1. RUSLE2 considers the interactive effects of spatial variation in soil and cover-management relative to position along non-uniform profiles. The RUSLE2 inputs are easy to enter, and RUSLE2 provides aids for interpreting segment erosion values (See **Section 7.9)**.

Based on the discussion in **Section 8.2.3**, the implications of using uniform profiles of the same length and average steepness to represent non-uniform profiles are:

1. Uniform profiles underestimate profile (average erosion over the profile length) for convex profiles depending on degree of curvature of the convex profile. The difference can easily be as large as 20%.
2. Uniform profiles seriously underestimate local (segment) erosion for convex profiles and results in inadequate erosion control for rill erosion on the lower end of the convex profile. The difference can easily be as high as a factor of two or more.
3. Uniform profiles overestimate profile erosion for concave profiles. The error can be very large if most of the eroded sediment is deposited on the concave profile. The difference can be large as a factor of five or more.
4. Uniform profiles applied to the eroding portion of concave profiles overestimate profile erosion. The difference can be as large as 20%.
5. Uniform profiles applied to the eroding portion of a concave profile give maximum erosion that is comparable to maximum erosion on the concave profile.
6. Uniform profiles applied to complex:convex-concave profiles overestimate average profile erosion if deposition occurs on the concave portion.
7. Uniform profiles applied to the eroding portion of a complex:convex-concave profile can give about the same average erosion for the eroding portion as representing the non-uniform profile.
8. Uniform profiles applied to the eroding portion of a complex:convex-concave profile can significantly underestimate maximum erosion on the eroding portion of the profile.
9. Deposition does not end the overland flow part on complex:concave-convex profile.
10. Dividing a complex:concave-convex into two separate uniform profiles seriously underestimates erosion on the lower convex portion of the profile.

The strong recommendation is that non-uniform overland flow profiles be represented in RUSLE2, especially convex shaped profiles. Users should recognize that representing a convex profile with a uniform profile will result in erosion control being less than needed (under-designed). Using a uniform profile to represent the eroding portion of a concave profile will result in erosion control being greater than needed (over-designed).

8.2.5. Implications for using RUSLE2 for estimating sediment yield for watersheds

RUSLE2 computes deposition on overland flow areas and the sediment leaving the overland flow path represented in the RUSLE2 computations. For example, RUSLE2 computes a sediment delivery of 4 tons/acre (8.4 t/ha) from the overland flow path as Table 8.1 illustrates. That sediment delivery is the sediment yield for the site only if the overland flow path ends at the site boundary. RUSLE2 overland flow profiles end in concentrated flow areas illustrated in Figures 5.1 and 8.5. These concentrated flow areas are typically within the site boundary. Both erosion (ephemeral gully) and deposition can occur in the concentrated flow areas so that the sediment delivered from site can differ significantly from the RUSLE2 computed sediment delivered from the end of the overland flow profile. That is, sediment leaving the overland flow portion of the site may only be a portion of the site sediment yield because of erosion and/or deposition that occurs in concentrated flow areas.

The USLE is widely used to estimate sediment yield from watersheds by multiplying USLE soil loss estimates by a sediment delivery ratio (SDR).[46] Sediment delivery ratios are typically less than one to account for the deposition that occurs in many watersheds. The sediment mass leaving the watershed is typically less than the sediment produced by rill and interrill erosion. Much of this deposition occurs on the overland flow areas of the watersheds.[47] Although RUSLE2 can compute the deposition on overland flow areas, RUSLE2 should be used to compute erosion on the eroding portion of the overland flow profile because the sediment delivery ratio values already reflect the deposition on overland flow areas as well as deposition by concentrated and channel flow areas.

[46] The USLE soil loss has a particular meaning. It is sediment mass delivered to the end of the uniform slope assumed to represent the eroding portion of the overland flow path. The USLE soil loss is expressed as mass delivered to the end of the ULSE slope length per unit width divided by the USLE slope length.
[47] See Toy et al. (2002) for a discussion of this deposition.

Thus, the proper way to use sediment delivery ratio values with USLE soil loss estimates is to use RUSLE2 to compute erosion on the eroding portion of the overland flow profile. That erosion value, which is comparable to the USLE soil loss value, is multiplied by the sediment delivery ratio to obtain a sediment yield for the watershed. For example, assume that the sediment delivery ratio is 0.15 for a particular watershed that contains the representative profile described in Table 8.1. Sediment yield is computed by multiplying the 18 tons/acre (39.6 t/ha) erosion value for the eroding portion of the overland flow path by the sediment delivery ratio of 0.15 to give a sediment yield of 2.7 tons/acre (5.9 t/ha). Multiplying the RUSLE2 computed sediment yield value of 4 tons/acre (8.8 t/ha) for the overland flow path by sediment the delivery ratio value based on a USLE type soil loss value gives a sediment yield that is much too low.

8.2.6. Importance of properly representing steepness at end of concave profiles where deposition occurs

The deposition computed by RUSLE2 is directly related to sediment transport capacity. Accurately computing deposition is very difficult because slight variability in the flow hydraulics on a depositional surface can greatly affect sediment transport capacity. The error in deposition computations is much greater than error in detachment computations.

Even if the computations could be made perfectly, an accurate description of the steepness along the flow path where deposition is needed. For example, the sediment yield from the complex profile illustrated in Table 8.1 is 4.0 tons/acre (8.8 t/ha ac). If the steepness for the last segment, which covers a relatively small portion of the profile, had been estimated at 2%, the estimated sediment yield would have been 7.8 tons/acre (17.2 t/ha). If the steepness had been estimated at 0.5%, the estimated sediment yield would have been 2.6 tons/acre (5.7 t/ha). These differences illustrate the importance of carefully determining the steepness at the end of the overland flow path on concave profiles where deposition occurs.

Deposition estimates are much less accurate than detachment estimates. Also, obtaining accurate deposition estimates requires a more carefully measured steepness than does detachment, especially where deposition occurs at the end of an overland flow profile.

8.3. Applying RUSLE2 to particular profile shapes

This section describes how to apply RUSLE2 to particular overland flow profile shapes commonly encountered in conservation and erosion control planning.

8.3.1. Uniform profile

Uniform profiles (slopes) are often assumed because only a slope steepness and slope length are required to topographically describe them.[48] Uniform slopes are used to represent the eroding portion of overland flow paths, not the entire path (See **Section 5.2**). The **slope steepness** of the uniform slope is set to the average steepness of the eroding portion of the overland flow path.

Slope length, as used in the USLE, is the distance from the origin of overland flow to the upper edge of deposition for concave profiles, illustrated in Figure 5.2, or to concentrated flow areas for convex profiles, illustrated in Figure 5.3. See AH703 for additional illustrations.

The best approach for determining slope length and steepness is to make measurements during a site inspection.

Determining the upper edge of deposition is easy on cropland, construction sites, and other land areas that readily erode. However, deposition may not be apparent where rill erosion does not occur and deposition is low, where heavy vegetative cover obscures the soil surface, or where recent mechanical soil disturbance has mixed deposited sediment with underlying soil.

A rule of thumb is that deposition begins where steepness is one half of the average steepness of the concave portion of the profile.

Two examples illustrate the procedure. The first example is a concave profile that decreases from 18 percent steepness at the upper end to 2 percent steepness at the lower end. The average steepness is 10 percent and one half of the average steepness is 5 percent. Deposition begins at the location where the flow path has flattened to 5 percent steepness as shown in Figure 8.7.

The second example is a concave profile that decreases from 4 percent at the upper end to 2 percent at the lower end. The average steepness is 3 percent and one half of the average steepness is 1.5 percent. Deposition does not occur because the steepness at the lower end of this profile is greater than the steepness where deposition would be expected to occur.

This procedure only captures how degree of profile curvature affects deposition. Other factors also affect deposition. Deposition occurs when

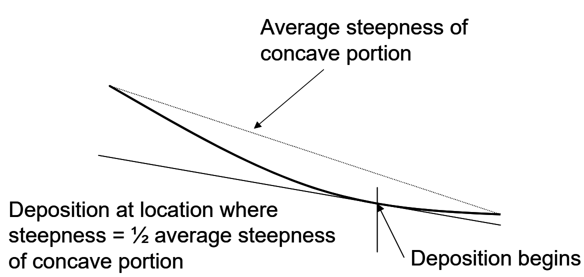

Figure 8.7. Rule of thumb for location of upper edge of deposition on a concave profile

4… Reference Guide. It is the length of the
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sediment load produced by upslope erosion exceeds transport capacity of the runoff. If the sediment load produced by upslope erosion is low relative to transport capacity, deposition begins further downslope than when sediment load is high relative to transport capacity.

RUSLE2 can estimate the location of deposition by segmenting the overland flow profile and entering steepness values for each segment. Negative segment erosion values indicate deposition. RUSLE2 computes erosion for the eroding portion of the overland flow path that can be used in conservation and erosion control planning (See **Section 8.1.5.2**).

Terraces, diversions, grassed waterways, ephemeral gullies, and similar concentrated flow areas are easily identified as ending slope length. Slope length can often be easily determined on cut and fill slopes involved in construction, landfills, and surface mine reclamation. Many landscapes include converging areas where overland flow is collected in defined channels, which are areas where ephemeral gully erosion occurs. These channels are illustrated in Figures 5.1 and 8.5. Slope length ending concentrated flow areas on natural landscapes, such as western rangelands, may not be obvious because the concentrated flow areas are not eroding channels.

The fact that experts can look at the same landscape and choose different slope lengths may seem troubling. Determining slope length involves judgment, and the variability in slope length among RUSLE2 users is a part of the uncertainty in RUSLE2 erosion estimates (See **Section 17.4**). One element in the judgment is how well plots used to derive RUSLE2 represent the specific field site where RUSLE2 is being applied. The data used to determine RUSLE2 were collected from plots that ranged in width from about 6 ft (2 m) to 12 ft (4 m), with some as wide as 75 ft (25 m). Plots lengths were as long as 350 ft (100 m) in two cases, but most plots were about 75 ft (25 m). These plots are illustrated in Figures 5.5 and 5.6. Slope length should not extend beyond the hillslope location where plots of these dimensions and flow conditions would represent erosion.

The depth of an eroded channel on a hillslope does not determine whether RUSLE2 applies. Is this channel parallel to other channels and of comparable size to neighboring channels as illustrated in Figure 5.6? Or is the channel much larger than neighboring channels because runoff has been collected rather than being spread uniformly across the hillslope?

Fortunately RUSLE2 erosion estimates are not sensitive to slope length for slope steepness less than 2 percent. For example, slope length being off by a factor of two for a 0.5 percent steepness has almost no effect on estimated erosion. Estimated erosion is less sensitive to slope length than to slope steepness for steepness between 2 and 20 percent. Above 20 percent steepness, estimated erosion is almost as sensitive to slope length as to slope steepness. Therefore, the uncertainty in estimating slope length does not have a major effect on estimated erosion for steepness less than 10 percent. Much more careful attention should be given to estimating slope steepness than to slope length.

Slope length and steepness values should be determined from field measurements, but site inspections may not be feasible. Problems associated with using contour maps and digital elevation data are discussed in **Section 8.2.1**. In general, those data are seldom satisfactory for determining slope lengths and often are not satisfactory for determining slope steepness because the data do not have sufficient resolution.

Slope length and steepness values have been assigned to soil map units in some cases.[49] These values may be acceptable for large scale regional analyses, but they should not be used for site-specific conservation and erosion control planning. The range in slope steepness across soil map units can give widely different estimated erosion values. For example, the land steepness of a soil map unit can range from 1 percent to 5 percent. The average steepness is 3 percent, which might give an estimated erosion rate of 12 tons/acre (26 t/ha). The estimated erosion values for the extremes of the slope steepness for the soil map unit are 4 tons/acre (9 t/ha) and 22 tons/acre (48 t/ha) for the 1 percent and 5 percent steepness, respectively. The importance of profile shape, especially if the profile is convex, should not be overlooked.

A principle in applying RUSLE2 is that a similar level of precision be used for all inputs for a specific site. Therefore, if a uniform slope is assumed, then a single soil and a single cover-management should be assumed for the slope. Uniform width and uniform spaced cover-management strips can be placed on the uniform slope to represent filter and buffer strip and rotational strip cropping support practices. However, soil and cover-management (e.g., to represent the variation of yield along the slope) should not be varied along a uniform slope that is being used to represent a non-uniform profile, especially a convex profile shape. For example, high soil erodibility at the end of a convex profile can give far higher erosion rates than will be computed assuming a uniform slope.

Not using the same level of precision for all inputs can result in very seriously flawed conservation plans when the planning criteria is to an absolute standard such as soil loss tolerance.[50] This problem is reduced but not eliminated for conservation planning to a relative standard, such as an 80 percent erosion reduction. Profile (overland flow path) averages can be very misleading for both concave and convex profiles because of non-linearity in the RUSLE2 equations. Soil map units sometimes involve multiple soil components where soil erodibility differs significantly among the components.

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[49] Griffin, M.L., D.B. Beasley, J.J. Fletcher, and G.R. Foster. 1988. Estimating soil loss for topographically nonuniform field and farm units. J. Soil and Water Conservation 43:326-331.

[50] An analogy is using a micrometer to measure the sand grain roughness in a concrete pipe while guessing at the diameter of the pipe and expecting an estimate of discharge rate to be of comparable precision to the sand grain measurements.

Sometimes one of the components is chosen as the dominant component if it occupies more than 50 percent of the soil map unit. An alternative is to take averages. However, a soil component that occupies about 25 percent of the overland flow path with a very high soil erodibility located at the lower end of a convex shaped profile is the dominant soil in terms of the erosion on the profile. The soil component that occupies most of the profile is not necessarily the dominant soil in terms of erosion, although it may be the dominant soil for other processes such as crop production.

If the spatial variation in soil and/or cover-management is sufficient to warrant dividing the overland flow profile into segments, then the variation in steepness along the overland flow path should be entered as well.

The problem is not limited to convex profiles. A uniform profile computes maximum erosion at the end of the profile whereas maximum erosion occurs on a concave profile in the upper part of the profile, not at the end. The positioning of soil components along the profile strongly interacts with profile shape. The result is that erosion computed with uniform slopes and assuming a spatially average soil erodibility or a dominant soil component based on occupying the highest fraction of the profile can produce erosion estimates that greatly differ from those computed using a non-uniform profile shape and the proper placement of the soil and cover-management conditions along the profile.

RUSLE2 users must be aware of the importance of precision in the inputs and the importance of spatial interaction among variables. The same level of precision should be applied to all RUSLE2 inputs. Even though uniform slopes have long been standard practice in conservation planning, most conservation planners have little awareness of the impact of that assumption on the adequacy of the resulting plans.

8.3.2. Complex:convex-concave profile

The profile for overland flow paths on many natural landscapes is complex:convex-concave (See **Section 8.2.2**). The potential for deposition always exists on concave shaped profile sections. The segments used to represent the profile must be carefully chosen to ensure that RUSLE2 correctly make its computations, especially where deposition occurs. The critical choices are number of segments and steepness of the last segment experiencing deposition.

Segments can be long where steepness changes slowly. Segments should be shorter where steepness changes most rapidly. The deposition computations are more sensitive to changes in steepness than are the detachment computations. Therefore, shorter segments are needed in depositional areas than in the detachment areas. The rule of thumb given in **Section 8.3.1** can be used as a first approximation where deposition begins to help in initially choosing segments for the depositional portion of the profile.

A minimum of three, preferably four, segments should be used in the depositional area. If segments are too long in the depositional area, RUSLE2 will incorrectly show no or much too little deposition. A minimum of three segments, preferably four, should be used to describe the eroding portion of the profile. However, each non-uniform profile behaves differently depending on degree of curvature of the convex and concave sections of the profile.

As discussed in **Section 8.2.6,** steepness of the last segment experiencing deposition has a major impact of estimated sediment yield. Make sure that this segment is not too long to help avoid entering a steepness at the end of the profile that is too steep resulting in computed sediment yield being too high. The difference between 1 percent steepness and 2 percent steepness can affect sediment yield by a factor of two.

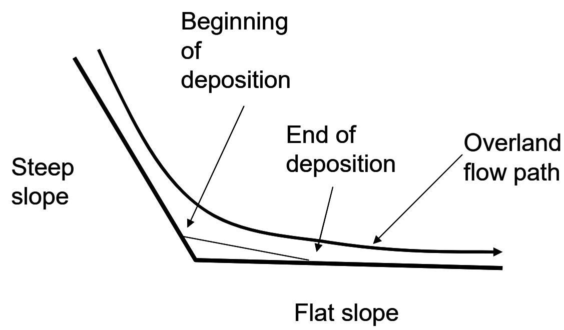

Figure 8.10. Flat uniform slope at toe of uniform steep slope.

Varying segment length is more efficient than using uniform segment lengths for the entire profile. Profile sections of uniform steepness do not need to be divided into segments. A relatively flat slope at the toe of a steep slope is a special case of a concave slope that illustrates that profiles sections of uniform steepness do not need to be divided into segment. This profile is illustrated in Figure 8.10. This profile can be described with two segments, one for the steep slope and one for the flat slope. RUSLE2 computes deposition over a short distance on the upper portion of the flat slope and erosion over the lower portion of the flat slope. RUSLE2 correctly makes these computations without dividing the flat slope into segments.

The most important factor in selecting segments to represent profiles where steepness varies along the profile is that shorter segments are needed where steepness changes most rapidly. Also, shorter segments are needed in depositional than in detachment areas.

8.3.3. Complex:concave-convex profile

Deposition potentially occurs on the lower end of the concave part of the profile provided steepness is sufficiently flat. The guidelines in **Section 8.3.1** can be used to initially estimate whether deposition will occur on the profile and where the depositional area might be as a guide to choosing segments to represent the profile. The same guidelines above for the complex:convex-concave profile (See **Section 8.3.2**) apply for choosing segments to represent a complex:concave-concave profile. An increased number of segments is needed in the depositional area and where steepness is changing most rapidly. An easily made mistake on this profile is to choose segments that are too long in the depositional area. If the segment are too long, RUSLE2 will incorrectly show no deposition when deposition should have been computed.

Deposition on the concave portion of the profile does not end the overland flow path assuming that the flow continues across the depositional area onto the lower part of the slope as overland flow.

The cut-roadway-fill profile illustrated in Figure 8.10 is a special case of a complex: concave-convex profile. Runoff from the cut slope is assumed to flow across the roadway onto the fill slope. If the roadway slopes outward at a sufficient steepness, erosion rather than deposition occurs on an earthen roadway. The overland flow path begins at the top of the cut and extends across the roadway to the bottom of the fill slope assuming that the flow remains as overland flow.

The roadway can be on a sufficiently flat steepness that deposition occurs on the roadway. If the runoff continues across the roadway as overland flow onto the fill slope, the overland flow path begins at the upper end of the cut slope, continues across the roadway, and ends at the bottom of the fill slope. The flow on the fill slope is composed of runoff generated from the cut slope above the roadway so far as runoff produced on the fill slope. The overland flow path length reflects the amount and rate of runoff, which is the reason that it includes the fill slope in this case even though deposition may occur on the roadway. Deposition on the roadway does not end slope length so far as computing soil loss from the fill slope provided the runoff flows across the roadway onto the fill slope as overflow and does not become concentrated flow, perhaps because of a ridge left by a road grader on the outer edge of the road.

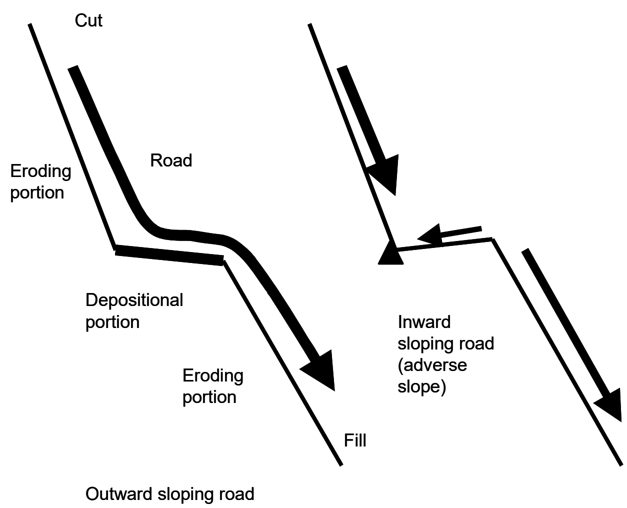

Figure 8.10. Cut-road-fill hillslope illustrating how an inward and outward sloping road section affects overland flow path lengths and that deposition on the outward sloping road does not end overland flow path length

Erosion on the cut slope can be significantly reduced by intercepting and diverting runoff so that the runoff from the cut slope and the roadway do not flow onto the fill slope. A diversion could be placed at the top of the fill slope to intercept the runoff, which is illustrated in **Section 8.3.5**. Placing the diversion at the top of the fill slope reduces erosion on the fill slope, but deposition still occurs on the roadway, which is objectionable.[51]

A better solution is to slope the roadway inward on an adverse steepness back toward the cut slope, as illustrated in Figure 8.10. This profile configuration can be represented very simply in RUSLE2 by entering a negative value for steepness on the roadway to represent an adverse slope. This profile configuration can be described in RUSLE2, as illustrated in Table 8.2, by entering a negative steepness value for the roadway segment. Sloping the road inward creates three overland flow path lengths, one each for the fill slope, roadway, and cut slope segments. RUSLE2 analyzes both profiles illustrated in Figure 8.10 without having to break the analysis into parts. Segments that describe each portion of the profile are entered into RUSLE2, and RUSLE2 automatically determines and handles the overland flow path lengths.

[51] Diversions are considered to be support practices in RUSLE2. Support practices include contouring (ridging), diversions, terraces, vegetative strips, porous barriers, and small sediment basins. See **Section 14** that discusses diversions.

Entering an adverse slope for the roadway causes RUSLE2 to create a channel at the intersection of the cut slope and the roadway. This channel intercepts runoff from the cut slope and collects runoff from the roadway. The sediment yield computed by RUSLE2 is the total sediment yield for the entire profile.

RUSLE2 automatically places a channel where a profile segment with a positive steepness intersects with a profile segment with a negative steepness (an adverse slope). This channel can be described with a grade to compute deposition if the grade is sufficiently flat. RUSLE2 does not compute erosion in channels. This channel ends the overland flow path.

Table 8.2. Erosion on a cut-road-fill slope

Segment #	Distance to lower end of segment (ft)	Segment length (ft)	Segment type	Steep-ness (%)	Soil loss (tons/acre)	Segment type	Steep-ness (%)	Soil loss (tons/acre)
1	75	75	fill	33	162	fill	33	162
2	95	20	outward sloping	2	-493	inward sloping	-2	5.8
3	170	75	cut	33	353	cut	33	162
			Sediment yield = 169 tons/acre			Sediment yield = 143 tons/acre		

8.3.4. Overland flow path with porous barriers (e.g., vegetative strips, fabric fences) and flow interceptors (e.g., diversions, terraces)

RUSLE2 represents two major types of flow barriers. One type is porous barriers where the overland flow is assumed to continue through the barrier onto the portion of the profile downslope of the barrier. Examples of porous barriers include vegetative strips (filter, buffer, stiff grass), fabric fence, gravel bags, and straw bales. The other type of barrier is flow interceptors that cut off the runoff and redirect it around the slope in defined channels. Examples of flow interceptors are diversions and terraces. Diversions and terraces function exactly the same way in terms of intercepting runoff. The difference is that diversions are defined in RUSLE2 as channels that are placed on a sufficiently steep grade that no deposition occurs in them but the grade is not so steep that erosion occurs in the channel. Conversely, terraces are intentionally placed on a sufficiently flat grade that deposition does occur in them. Diversions are placed at critical places on the overland flow profile to intercept runoff and prevent it from flowing onto a steep part of the profile, such as on the landfill example illustrated in Figure 8.12. In contrast, terraces are typically installed as system of uniform spaced channels.

Both diversions and terraces required a runoff disposal system to move the collected runoff down the slope without causing channel erosion. RUSLE2 does not consider the water disposal channel system.

The purpose of porous barriers is to cause substantial deposition. Even though these barriers induce deposition, the overland flow path length does not end at the deposition because the runoff continues through the strip as overland flow. A profile with multiple grass strips that induce deposition has only one overland flow path length as illustrated in figure 8.11b.

Deposition at a grass strip does not end the path length with a new one beginning below the strip. Cover-management segments do not end the overland flow path.

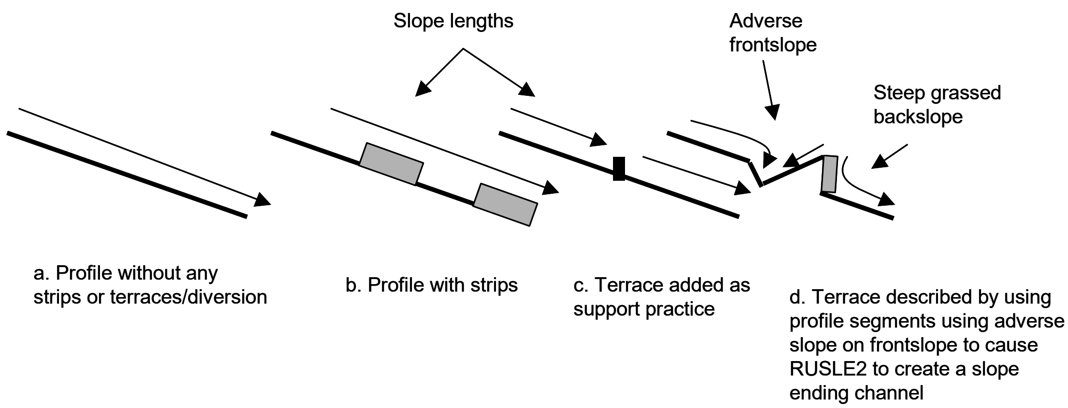

Figure 8.11. How vegetative strips and terraces are described in RUSLE2 and how these practices affect slope lengths assumed by RUSLE2

In contrast, terrace and diversion channels intercept runoff in concentrated flow areas that end the overland flow path. A new overland flow path begins at the terrace/diversion ridge because that is where overland flow originates that flows across the next portion of the profile.

Terraces and diversions can be described in one of two ways in RUSLE2. One approach is used in most conservation planning. RUSLE2 assumes that the terrace/diversion channel and ridge are infinitely thin as illustrated in Figure 8.11c. This approach is used in RUSLE2 where terraces/diversions are represented as a support practice. The other approach is to describe the actual hillslope profile configuration, including the cover-management on each segment such as the grass on a steep backslope of a terrace/diversion.

The overland flow path that is entered in RUSLE2 is the path without the terraces/diversions. The segments are added to create the profile illustrated in Figure 8.11d. RUSLE2 automatically creates a channel where segments with a positive and a negative (adverse) steepness intersect. Such channels end the overland flow path. RUSLE2 determines the appropriate overland flow path lengths without the analysis having to be broken into parts.

8.3.5. Overland flow path for diversions that intercept runoff above steep slopes

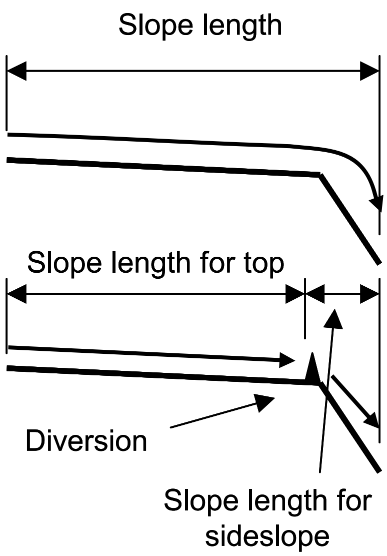

Figure 8.12. Landfill with relatively flat top and steep side slope, with and without a diversion

Table 8.3. Soil loss on a landfill with and without a dversion at the top of the steep sideslope

Segment	Distance to end of segment (ft)	Steep-ness (%)	Soil loss(tons/acre) Without diversion	With diversion
1	250	2	9	9
2	300	33	538	130

Erosion is high at the end of convex shaped hillslope profiles and where runoff from a long slope flows onto a steep slope like the sideslope of a landfill. Placing a diversion at the top of the sideslope as illustrated in Figure 8.12 is an effective practice for reducing erosion on the steep sideslope as shown in Table 8.3. The entire profile description is entered into RUSLE2 and then a diversion is applied at the top of the steep sideslope. RUSLE2 automatically ends the overland flow path for the relatively flat top slope and begins a new overland flow path at the top of the steep sideslope. As expected, the diversion did not reduce erosion on the top of the landfill but significantly reduced erosion on the sideslope.

8.3.6. Overland flow path for contouring (ridging)

The effect of contouring, ridging, and bedding on erosion can be represented in three ways in RUSLE2.[52] The **first method** is that the surface can be represented using a ridge (bed)-furrow description where the overland flow path length is from the top of the ridge (bed) to the furrow that separates the ridges or beds **provided** the ridges and beds are so well defined, so high, and on a sufficiently uniform grade that the runoff flows in the furrows separating the ridges or beds that the flow flows in the furrows along their total length until reaching the end of the furrow or a defined concentrated flow area. The **second method** to describe an overland flow path along the ridges-furrows when the ridges are well defined and flow stays within the ridges as just described.

[52] The effect of contouring on erosion is highly variable and is very difficult to accurately predict. Slight variations can result in wide variations in erosion. For example, under certain conditions, contouring can actually increase erosion, while in other similar conditions, the same contouring can be highly effective. The high variability in effectiveness is partly related to storm severity. The contouring relationships in RUSLE2 represent the main effects that supported by the data. See **Section 14.1** for additional discussion.

The **third method** is to describe an overland flow path assuming a flat soil surface without the ridges and without considering how the ridges affect the flow pattern. This method is used in ordinary cases of ridges like those left in farm fields by tillage equipment such as tandem disks, chisel plows, and field cultivators or those left by ridgers on highly disturbed lands such as reclaimed mine sites.

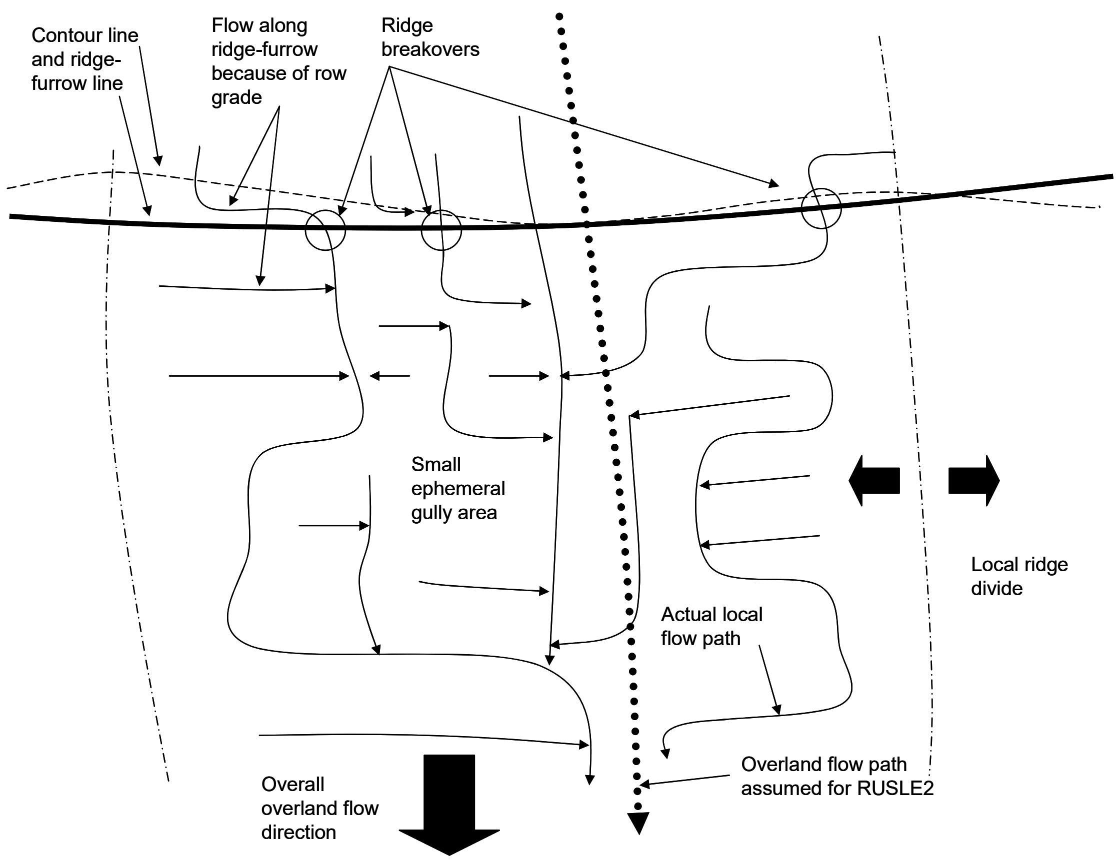

Figure 8.13. Overland flow patterns in a typical field where local runoff flows along ridge-furrows because of a row grade, breaks over in local areas, and accumulates in small local ephemeral gully areas.

These field situations are illustrated in Figure 8.13. Runoff flows along the furrows a distance [a few to several ft (m)] before breaking over one or more ridges before the runoff is intercepted by a sufficiently large ridge to direct runoff along a furrow. The breakovers are located randomly between the major concentrated flow areas. Breakover locations are random and can not be determined after the ridge forming operation in advance of the erosion event because of non-uniform ridge height and non-uniform grade along the furrows. **The first two methods should not be used for the conditions illustrated in Figure 8.13**.

These three methods can give significantly different results, which partially reflects the great difficulty of accurately estimating the effect of contouring (ridging). Use RUSLE2 as a guide to conservation and erosion control planning rather than considering it to provide absolute erosion estimates for any particular site.

8.3.6.1. Overland flow path for ordinary contouring, ridging, and bedding

Contouring, including ridging and bedding, is normally treated as a support practice in RUSLE2. See **Section 14.1** for a description of contouring as a support practice. To treat contouring, ridging, and bedding as a support practice, enter the overland path description in RUSLE2 as the path that the overland flow would follow as if the soil surface is flat and no ridges are present to influence the flow pattern.

8.3.6.2. Overland flow path for a ridge (bed)-furrow description

RUSLE2 can directly compute erosion on ridges and beds and the deposition in the furrows that separate them. RUSLE2 can accommodate overland flow path lengths as short as a zero length. Thus, RUSLE2 can be applied to ridge-furrow and bed systems, like those illustrated in Figure 8.14 for vegetable production.[53] RUSLE2 can also be applied where plastic is added and removed on the beds (See **Section 13.1.9** for a description on how to use RUSLE2 to describe the effect on erosion of adding and removing plastic to beds).

[53] Actually a finite, small number like 0.001 ft (0.5 mm) must be entered, which gives the same result as entering a zero. The erosion rate at a zero overland flow path length is entirely interrill erosion. An erosion rate exists for a zero overland flow path length but the amount of erosion is zero because erosion amount for a uniform profile is the product of average erosion rate for the overland flow path and the overland flow path length.

Representing ridges and beds as the overland flow path and "hillslope profile" is used when the ridges and beds are so high that flow is unquestionably contained in the furrows between the ridges and beds until it reaches a well defined concentrated flow area. RUSLE2 can also compute deposition that occurs in the furrows but not erosion by flow in them.

The overland flow path length is one half of the spacing of the ridges and beds. In this example, 20% is assumed for the steepness of the bed sideslope, and 1% is assumed for the steepness of the top of the beds and 50% is assumed for the steepness of the bed

Table 6.14. Soil loss for ridges and beds

Ridges				Beds			
Segment #	Segment length (ft)	Steepness (%)	Soil loss (tons/acre)	Segment #	Segment length (ft)	Steepness (%)	Soil loss (tons/acre)
1	1.5	20	20	1	0.9	1	3
2	1.5	-20	20	2	0.6	50	27
				3	0.6	-50	3
				4	0.9	-1	27
Soil loss = 20 tons/acre				Soil loss = 13 tons/acre			

sideslope. An adverse steepness (negative values), illustrated in Table 6.14 is used for the segments on either side of the beds. The positive steepness of one sideslope intersecting with the negative (adverse) steepness on the adjacent ridge or bed causes RUSLE2 to create a channel that ends the overland flow path length. The grade that RUSLE2 automatically assumes for the default channel is so steep that no deposition occurs. However, the actual grade can be entered so that RUSLE2 can compute deposition that occurs in the furrows between the ridges or beds.

8.3.6.3. Summary comments

RUSLE2 does not give the same results for all these three approaches for representing ridges-furrows. The approach of explicitly describing the configuration of the ridges and beds works when the ridges contain the flow until a major well-defined concentrated flow area is reached. Although RUSLE2 can estimate deposition in furrows on a relatively flat grade, RUSLE2 can not estimate erosion in the furrows, which RUSLE2 has represented as channels.

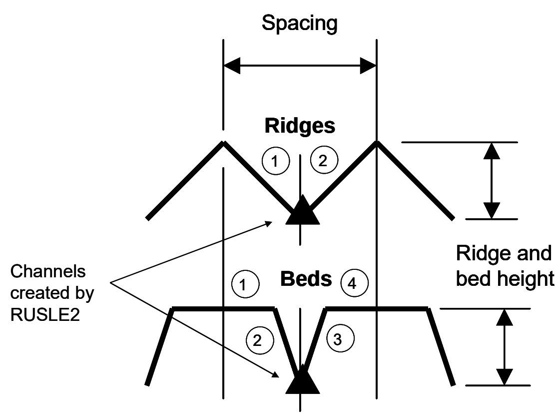

Figure 8.14. Ridge and bed systems.

The approach of representing the overland flow path as if the ridges-furrows are not present works best when the flow pattern is irregular as illustrated in Figure 8.13.

8.4. Influence of Upslope Areas on Overland Flow Path

RUSLE2 is sometimes applied to a field site that is downslope from an area that contributes runoff to the site. The recommended approach is to represent the entire overland flow path even though the upslope area is not a part of the analysis area. The soil loss computed for the downslope area should not be compared to soil loss tolerance, but the procedure described in **Section 7.9.3** where a ratio of soil loss to T value adjusted for position on the slope is computed. A conservation practice should be chosen that reduces this ratio to 1.

RUSLE2 takes into account cover-management conditions on an upslope area for computing transport capacity on downslope segments where cover-management is quite different from the upslope area. However, RUSLE2 does not fully take into account how reduced runoff from the upslope area reduces detachment on the downslope segment. In some applications, **RUSLE2** is applied to a field downslope from an upslope area that is very different from the field. The following approach can be used to take into account how reduced runoff from the upslope segment affects detachment on the downslope segment. If runoff production on the upslope segment is less than that on the downslope segment, the overland flow path length to the upper edge of the downslope segment should be shortened. An example is an undisturbed forest on the upslope area where the overland flow path length begins at the upper edge of the site because no surface runoff is assumed to occur from the undisturbed forest. If the upslope area is pasture and only produces half the runoff that a downslope field produces, the overland flow path length at the upper edge of the field should be one half the distance of the slope length across the pasture area.

Conversely, if the upslope area produces more runoff than does the field, the overland flow path length at the upper edge of the field should be greater than the actual distance in proportion to the differences in runoff potential for the two areas.

9. COVER-MANAGEMENT SUBFACTORS

Cover-management refers to how vegetation, soil condition, and material on and in the soil affect erosion. RUSLE2 describes the effects of cover-management using basic variables applicable to any cover-management system. The basic cover-management variables used in RUSLE2 are canopy (vegetative material not in contact with soil surface), ground (surface) cover (material in contact with soil surface), soil surface roughness, soil ridge height, below ground biomass (live and dead roots and incorporated material), and soil consolidation and antecedent soil moisture in the Req zone (see **Section 6.9**).

RUSLE2 is land use independent, which means that it can be applied to any land use where mineral soil is exposed to raindrop impact and Hortonian overland flow. RUSLE2 can be applied to crop, pasture, hay, range, disturbed forest, mined, reclaimed, construction, landfill, waste disposal, military training, park, wild, and other lands. RUSLE2 does not apply to undisturbed forestlands and lands where no mineral soil is exposed and surface runoff is produced by a mechanism other than rainfall intensity exceeding infiltration rate.

Because RUSLE2 is land use independent, it applies to transitions between land uses. For example, a lightly disturbed military training site may behave much like a pasture or rangeland, a moderately disturbed site may behave like a cropped field, and a highly disturbed site may behave like a very rough construction site. A "fresh" landfill and a recently reclaimed mine site not yet vegetated may behave like a freshly graded construction site but behave like pasture or range land over time. Pasture and rangeland may be periodically converted to and from cropland.

Erosion models based on specific land uses typically do not produce the same erosion values at a common point between land uses resulting in uncertainty between erosion estimates. RUSLE2 does not have this problem.

9.1. Basic Principles

Equation 7.1 estimates soil loss for the unit plot, which is a fallow (no vegetation) condition periodically tilled up and down slope to break the crust and to control weeds. This special condition is used to define and determine soil erodibility factor values (see **Section 7.2**). The daily cover-management factor **c** in equations 5.1 and 8.1 "adjusts" the unit-plot erosion to site-specific field conditions as affected by cover-management.

The cover-management factor c describes how cover-management affects both erosivity and erodibility. For example, vegetation and ground cover affect erosivity by reducing the erosive forces applied to the soil by raindrop impact and surface runoff. Both live and dead roots and organic material in the soil increase infiltration, which reduces erosivity by reducing runoff. These materials reduce erodibility by decomposing in the soil to produce chemical bonding agents that increase the soil's resistance to detachment. Soil mechanical disturbance, which creates a very rough soil surface that ponds water, reduces the erosivity of both raindrop impact and surface runoff. Large soil clods that form the roughness peaks reduce erodibility by being resistant to detachment in comparison to a mechanical disturbance that finely pulverizes the soil. Thus, the effects of both erosivity and erodibility are included in other RUSLE2 factors besides just the erosivity and erodibility factors in equation 8.1.

RUSLE2 uses an index-based method to estimate soil loss without mimicking (explicitly modeling) erosion processes. RUSLE2 involves specific definitions and rules that must be followed, even when logic suggests something different.

A subfactor method used in RUSLE2 to compute values for the cover-management factor c gives RUSLE2 its land use independence.[54] This method uses subfactors that are universally important in how any cover-management system affects rill and interrill erosion. The RUSLE2 subfactors, listed in Table 9.1, are canopy, ground cover, soil roughness, ridge height, soil biomass, soil consolidation,[55] and antecedent soil moisture used in the Req zone. RUSLE2 computes a value for each subfactors for each day and uses equation 9.1 to compute a daily c factor value in equation 8.1.

$$c = c_c g_c s_r r_h s_b s_c p_p a_m \qquad [9.1]$$

where: c_c = canopy subfactor, g_c = ground cover subfactor, s_r = soil surface roughness subfactor, r_h = ridge height subfactor, s_b = soil biomass subfactor, s_c = soil consolidation subfactor, p_p ponding effect subfactor, and a_m = antecedent soil moisture subfactor.

Cover-management variables also affect the RUSLE2 topographic and support practice factors. Thus, the topographic, cover-management, and support practice factors must be examined to see the entire effect of land use and management on RUSLE2 erosion estimates.

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[54] The RUSLE2 daily cover-management factor c is comparable to the soil loss ratio used in the USLE and RUSLE1. Soil loss ratios in the USLE applied to a crop stage period and to a 15-day period in RUSLE1. The C factor in the USLE and RUSLE1 is an average soil loss ratio value weighted by the temporal distribution of erosivity (EI distribution). Although RUSLE2 can compute a C factor value, RUSLE2 does not use a C factor value and a C factor value from another source can not be entered into RUSLE2 to compute erosion. The RUSLE2 subfactor method involves more variables and a different set of equations than used in the USLE or RUSLE1.

[55] Soil consolidation refers to how erosion decreases with time after a mechanical soil disturbance. Soil consolidation includes how the increase in soil bulk density after a mechanical soil disturbance affects erosion, but the major effect is how wetting and drying and other processes cement soil particles.

Table 9.1. Cover-management subfactors used in RUSLE2.		
Subfactor	Symbol	Comment
Canopy cover	c_c	Influence of above-ground vegetative material not in contact with soil surface; includes both live and dead vegetation
Ground cover	g_c	Material in contact with soil surface; includes both live and dead plant material and other material like manure, mulch, and "roll" erosion control materials applied to the soil surface
Soil (surface) roughness	s_r	Random roughness created by a mechanical soil disturbance; includes peaks and depressions that are randomly shaped and located without an orientation to runoff direction
Ridge height	r_h	Ridges formed by a mechanical soil disturbance; ridges and furrows between ridges redirect flow if not oriented up and down hill
Soil biomass	s_b	Includes plant and other organic material in the soil that has been incorporated by a mechanical soil disturbance, grown there as live roots that become dead roots, or moved into the soil by worms or other organisms
Soil consolidation	s_c	Refers to how a mechanical soil disturbance loosens the soil to increase erosion and the degree to which erosion has decreased following a mechanical soil disturbance
Antecedent soil moisture	a_m	Used in the Req zone; refers to how previous vegetation reduces soil moisture so that subsequent runoff and erosion is decreased

9.2. Cover-Management Subfactors

This section describes each cover-management subfactor and how RUSLE2 computes a value for each subfactor.

9.2.1. Canopy

Canopy is live and dead vegetative cover above the soil surface that **intercepts raindrops** but does not contact the **surface runoff**. The portion of the **above ground plant biomass** touching the soil surface is treated as **live ground cover**.

9.2.1.1. Canopy effects

Canopy intercepts raindrops. Some of the intercepted rainfall reforms as waterdrops that fall from the canopy. The erosivity of these drops is directly related to their impact energy. The impact energy of a waterdrop is one half of the product of mass (determined by drop diameter) and the square of impact velocity (determined by fall height). In contrast to raindrops that vary over a wide size range, all water drops falling from canopy are nearly of an equal size (about 3 mm) that is significantly larger than the median raindrop size (about 1.5 mm). Even though the mass of each waterdrop falling from canopy is greater than the mass of most raindrops, the impact velocity of waterdrops falling from canopy is generally much lower than the impact velocity of raindrops because of the low fall heights from plant canopy. However, if the bottom of the canopy is greater than about 30 ft (10 m), the erosivity of waterdrops falling from canopy is greater than that of raindrops because of the increased mass of the drops falling from canopy.

Some of the rainwater intercepted by canopy flows along plant stems to the soil surface. While this water has no erosivity to detach soil particles by waterdrop impact, it provides water for runoff, but the delay caused by the water flowing along the stems to the soil surface reduces peak runoff rate, which in turn reduces runoff erosivity. Dense canopies retain a significant amount of water that never reaches the ground because it is evaporated after the storm. While this water is not significant for large storms, it can significantly reduce runoff for small storms.

The equation used to compute a value for the canopy subfactor is:

$$c_c = 1 - f_c \exp(-0.1 h_f) \qquad [9.2]$$

where: f_c = canopy cover (fraction) and h_f = effective fall height (ft). The two canopy variables of **canopy cover** and effective **fall height** are used to describe the effect of canopy on erosion.

9.2.1.2. Canopy cover (f_c)

Canopy cover is the portion of the soil surface covered by canopy in a horizontal plan view. The fraction of the soil surface covered by canopy is 1 minus the fraction of open space, which is the space through which a raindrop can fall to the soil surface without being intercepted by the plant canopy. Open space can be seen by looking down on the canopy from above and identifying the open space between the outer perimeter of the individual plant canopies and the open space within the outer perimeter of individual plant canopies. The

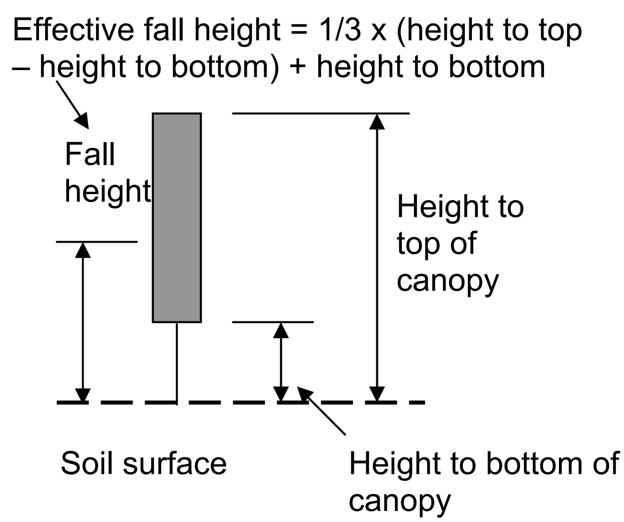

Figure 9.1. Effective fall height for a cylindrical shaped canopy of uniform density

effect on wind on the erosivity of raindrops or on how canopy intercepts raindrops is not considered in RUSLE2.

9.2.1.3. Effective fall height (h_f)

Waterdrops fall from various heights within the plant canopy, and some of the drops are intercepted by lower canopy. The total impact energy of these waterdrops is the sum of the impact energy of each drop on the soil surface. Effective fall height is the single fall height that gives the total energy if all drops fell from a single height. Effective fall height varies with plant maturity and shape, density gradient within the canopy, and heights to the top and bottom of the canopy. If the canopy shape is cylindrical and canopy density is uniform with height, the fall height is assumed to be one third of the way up from the bottom of the canopy as illustrated in Figure 9.1. The lower than average height reflects the likelihood that waterdrops falling from higher in the canopy are intercepted by lower canopy.

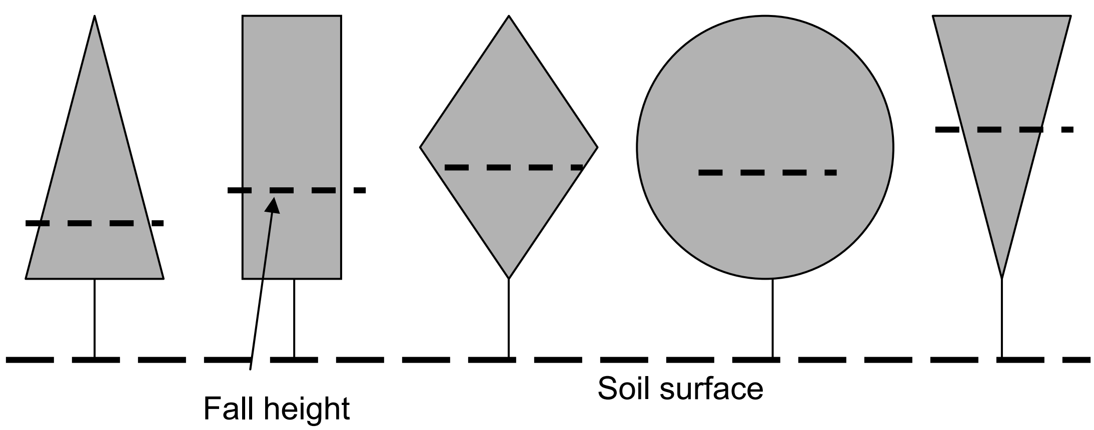

Figure 9.2. Effect of canopy shape on fall height

Canopy shape and density gradient of the canopy material with height influence effective fall height because lower canopy can intercept waterdrops that fall from higher in the canopy. Effective fall height is low when the canopy material is concentrated low in the canopy because of shape and density gradient as illustrated in Figures 9.2 and 9.3. If most of the leaves and branches of the plant are concentrated in the upper portion of the canopy, the effective fall height is one half to two thirds of the distance from the bottom to the top of the canopy. RUSLE2 includes a procedure that uses graphical shapes of these figures to assist in assigning effective fall height values for any particular vegetation throughout its growth.

Fall height assigned to a vegetation (plant community) should be assigned based on how the canopy of the particular plant community affects erosion relative to other plant communities. Fall height must be consistent among vegetations in the RUSLE2 database and consistent with fall heights in the Core Database.

Because the effect of fall height in equation 9.2 is nonlinear, the heights cannot be averaged to determine an effective fall height.

Fall height can be measured at regular intervals along a transect where a rod is lowered through the canopy to the ground. The height to the lowest part of the canopy touching the rod is measured. Rather than averaging these values, the proper approach is to compute a canopy subfactor value by using equation 9.2 for each height and assuming that $f_c = 1$. These subfactor values are averaged and the effective fall height is computed from:

$$h_{fe} = -\ln(1 - c_{ca})/0.1 \qquad [9.3]$$

where: h_{fe} = effective fall height (ft) and C_{ca} = average canopy subfactor.

9.2.1.4. Understory

RUSLE2 uses a single vegetation description at any point in time. The values in this description are for the composite of the plant community that exists at the given point in time. RUSLE2 cannot take components of a plant community and aggregate values for each component into a composite value. The user directly assigns and enters a composite value for each RUSLE2 variable used to describe a particular vegetation.

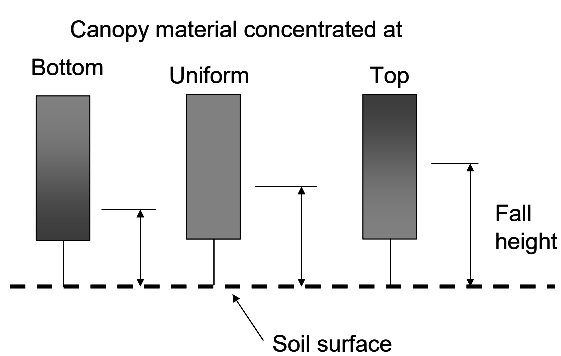

Figure 9.3. Effect of canopy density distribution on fall height

Some plant communities have distinct canopy components of over and understories. Examples include grass under shrubs on a rangeland, grass under vines on a vineyard, a legume interseeded in a small grain, a rye cover crop interseeded in corn, and volunteer weeds that begin to grow as crops approach maturity. Consideration must be given to overlapping canopies in determining an effective fall height. **The understory is often dominant in determining fall height especially if the understory is dense.**

9.2.1.5. Interaction with ground cover

Canopy that is directly above ground cover is assumed not to affect erosion. Thus, the effective canopy cover is computed from:

$$f_{ce} = f_c(1 - f_g) \qquad [9.4]$$

where: f_{ce} = effective canopy cover (fraction) and f_g = portion of soil surface cover by ground cover (fraction).[56] Also, RUSLE2 compares the canopy subfactor value with the ground cover subfactor value computed with the canopy cover value. RUSLE2 does not allow the canopy subfactor value to be less than this ground cover subfactor value. The effect of this comparison is that canopy cover behaves as ground cover as fall height approaches zero.

9.2.1.6. Effect of production level (yield)

RUSLE2 does not "grow" vegetation like a plant model "grows" vegetation. The user describes vegetative growth by entering values for retardance and above-ground biomass at maximum canopy, and values for root biomass, canopy cover, fall height, and live ground cover that vary through time. These values are entered in the vegetation component of the RUSLE2 database to describe a particular vegetation.

Variables used in RUSLE2 to describe vegetation are a function of production level (yield). **RUSLE2** can vary these values for these variables as a function of yield so that a vegetation description does not have to be created for each production (yield) level. A single vegetation description is created for a base yield, which RUSLE2 adjusts to the site specific yield.[57]

The purpose of entering a site-specific production (level) yield is so that RUSLE2 can determine values for biomass on and in the soil. Sources of biomass are **above-ground biomass** and **root biomass** from the vegetation grown on site and from **external residue**

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[56]The RUSLE2 interaction between canopy and ground cover is similar to the one assumed in the USLE (AH537). No interaction between canopy cover and ground cover was assumed in RUSLE1 (AH703). As a result, the effect of canopy at low fall heights was too great in RUSLE1. In fact, RUSLE1erroneously computed a zero erosion for a 100% percent canopy cover when fall height was zero, rather than erosion for 100% ground cover. The RUSLE1 technique of using a zero fall height to shut off erosion for special purposes such as plastic mulch can not be used in RUSLE2. The **add** and **remove nonerodible cover processes** used to describe **operations** serves this purpose in RUSLE2.

[57] RUSLE2 differs from RUSLE1 in this regard. Different yields could only be accommodated In RUSLE1 by creating a vegetation description for each yield. A single base vegetation description is created In RUSLE2 for a base yield. RUSLE2 adjusts the base vegetation description to fit the specific site yield entered. However, a vegetation description for specific yields can be used in RUSLE2 just as in RUSLE1.

applied to the soil surface and/or incorporated into the soil. External residue includes straw, wood fiber, wood chips, organic-based roll erosion control materials, compost, leaves and forest debris, manure, and other similar materials that are typically applied to control erosion.[58]

Biomass values must be on a dry weight basis. The dry weight of external residue is known at the time of application from the user input value. The dry weight values for the above-ground and root biomass is determined from the production (yield) level entered by the user to represent a particular field site. RUSLE2 adjusts the aboveground biomass value at maximum canopy as a function of yield according to:

$$M_a = M_0 + b_a Y \qquad [9.5]$$

where: M_a = dry weight aboveground biomass at maximum canopy for the site specific yield, M_0 = the aboveground biomass at maximum canopy for a zero yield, and Y = yield in units chosen by the user. RUSLE2 determines values for M_0 and the slope term b_a from values entered by the user for two different yields. RUSLE2 uses a similar relationship to vary retardance with yield (see **Section 11.1.4**).

Dry weight values for root biomass are entered in RUSLE2 for a vegetation description at the base yield. RUSLE2 assumes that dry weight root biomass varies directly with yield, that canopy and live ground cover vary with the square root of yield, and that effective fall height varies with yield to the 0.2 power.

The base vegetation used to create vegetation descriptions at a new yield should be for a base yield where maximum canopy cover is less than 100 percent. The base maximum canopy cover must be less than 100 percent for the RUSLE2 yield adjust function to fully work. If the maximum canopy cover is 100 percent, RUSLE2 can adjust only for yield values greater than the base yield. RUSLE2 does not directly adjust vegetation values as a function of seeding rate, population, or row spacing. RUSLE2 can indirectly adjust for seeding rate and population by assuming a relationship between yield and these variables. Row spacing can only be considered in RUSLE2 by having a vegetation description for each row spacing. If canopy characteristics vary significantly between crop varieties, plant communities, or management practices, a vegetation description must be constructed to reflect each significant difference.

RUSLE2 computes the variation of above-ground biomass through time by assuming that above-ground biomass varies with the 1.5 power (see **Section 11.1.3.1**) of canopy cover.[59] RUSLE2 calibrates this relationship using the user entered values for above-

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[58] External residue also includes inorganic materials such as rock and roll erosion control materials applied to the soil surface. These materials require special consideration. See **Section 12**.

[59] RUSLE2 tracks aboveground biomass through time, which is different from RUSLE1. A biomass value entered in RUSLE1 had to correspond to the date of an operation that affected aboveground biomass.

ground biomass at maximum canopy and the amount of above-ground biomass remaining after full senescence has occurred. This approach allows an operation to be entered at any date during a cover-management system without the user having to explicitly enter the biomass at that point in time. In some cases, the assumed relationship between canopy and aboveground biomass may not give the proper value for the aboveground biomass when an operation with a **kill** vegetation process occurs before the vegetation reaches maturity.[60] A vegetation description can be created where the above-ground biomass at maximum canopy is the aboveground biomass at the time that the vegetation is killed rather than the above-ground biomass at maximum canopy as the vegetation approaches maturity.

The yield entered in RUSLE2 for the vegetation at a particular field site must be consistent with the site climatic, soil, and management conditions. **RUSLE2 assumes that the user has selected a vegetation description and yield appropriate for the site.** Because RUSLE2 does not model vegetation growth, it can not determine the appropriateness of a vegetation description for a particular site nor does RUSLE make adjustments based on climatic, soil, or management conditions. For example, an operation description must be used to tell RUSLE2 to represent frost killing vegetation.

In RUSLE2, the users define production (yield) level in any terms that they choose, although customary usage is recommended. For example, yield can be expressed in terms of a "fresh" weight or a "dry" weight. Equation 9.5 converts the specified yield, which might be in fresh weight units, to the dry weight values that RUSLE2 needs for biomass.

Accounting for all of the biomass involved in a particular cover-management system is not necessary. **The amount of biomass left in the field to affect erosion is the critical variable.** The amount of biomass that leaves a field is unimportant.

RUSLE2 does not have this requirement. The biomass values are entered at maximum canopy and RUSLE2 tracks biomass through time. An operation can be entered in RUSLE2 at any time in a cover-management system without having to specify (enter) a biomass value in the vegetation description on the date of the operation.

[60] **Kill vegetation** has a particular definition in RUSLE2. Kill vegetation is one of several processes used to describe an operation. Killing vegetation converts live vegetation to dead vegetation. See **Section 13** for the RUSLE2 rules regarding manipulation of vegetation. A **kill vegetation process** must be used in an operation description to tell RUSLE2 that vegetation has died by maturity or has been killed by frost.

RUSLE2 uses a description of site specific conditions to compute erosion. The user carefully follows the RUSLE2 definitions and procedures to create this description. Multiple approaches can often be used to create a description. In general, RUSLE2 was designed so that vegetation descriptions can be created independently of the operations used to manipulate vegetation. For example, this approach allows RUSLE2 to use a single description for corn grown for grain and corn grown for silage. However, some cases may occur where a vegetation description is created to reflect the manipulations of an operation that can not be conveniently created using an operation. The important consideration is that RUSLE2 gets the values that it needs for its computations.

9.2.1.7. Senescence and other canopy losses

Canopy cover increases during the growth period when plants accumulate aboveground biomass. As plants become maturity, some vegetation, such as soybeans and perennial grasses, lose canopy cover by senescence. Other plants, such as cotton, lose canopy cover by being defoliated with chemicals. This loss of canopy cover transfers biomass from standing vegetation to plant litter (residue) on the soil surface. Once canopy material falls to the soil surface, RUSLE2 begins to compute its decomposition. Some plants, like corn, lose canopy cover by leaves drooping without falling to the soil surface, which RUSLE2 also considers (see **Section 11.2.4**).

Plants such as hay and pasture crops and permanent vegetation on rangeland, closed landfills, and other undisturbed areas experience a simultaneous birth and death of aboveground biomass during the growth period while cover is increasing. The death of live aboveground biomass adds a substantial amount of biomass to the surface litter (residue) pool. The daily death of live aboveground biomass is approximately one percent of the live aboveground biomass on that day.

The other way that canopy is lost is by **operations** that **remove live biomass**. Harvest, shredding, mowing, grazing, and burning are typical operations that reduce canopy cover (see **Section 13.1**).

9.2.1.8. Assigning values for canopy

Canopy values assigned to represent a particular vegetation must be consistent with those in the **RUSLE2 Core Database** and with values for other plant communities in the **vegetation component** of the RUSLE2 database. Core values are used to guide assigning values to new vegetation descriptions entered in the RUSLE2 vegetation database. Using consistent values with those in the Core Database helps ensure that RUSLE2 gives the expected erosion estimate and that erosion estimates are consistent between plant communities.

9.2.2. Ground Cover

Ground cover, which is material in contact with the soil surface, slows surface runoff and intercepts raindrops and waterdrops falling from canopy. Ground cover includes all material that touches the soil surface. Examples are rock fragments, portions of live vegetation including basal area and plant leaves that touch the soil, cryptogams (mosses), crop residue, plant litter, and applied materials including manure, mulch, and roll erosion control materials. Ground cover is probably the single most important variable in RUSLE2 because it has more effect on erosion than almost any other variable, and applying ground cover is the simplest, easiest, and most universal way of controlling erosion.

To be counted as ground cover, the material must remain in place and not be moved downslope by surface runoff during a rainstorm. Also, the material must contact the soil surface so that runoff does not flow between the material and the soil to cause erosion.

Operations in RUSLE2 do not affect rock cover entered in the soil component of the RUSLE2 database. Rock fragments added as an external residue are manipulated just like any other "residue" by operations in RUSLE2. See *Section 12* for special consideration regarding treating rock as an external residue

Rock fragments on the soil surface require special consideration. Generally rock fragments must be larger than 5 mm on coarse textured soils in arid and semi-arid regions where runoff is low and larger than 10 mm in other regions to be counted as ground cover. Rock fragments on the soil surface can be treated in one of two ways. They can be considered to be a part of the soil where a rock cover value is entered in the **soil component** of the RUSLE2 database (see Section 7.6). Rock fragments can also be "applied" as an **external residue**.[61]

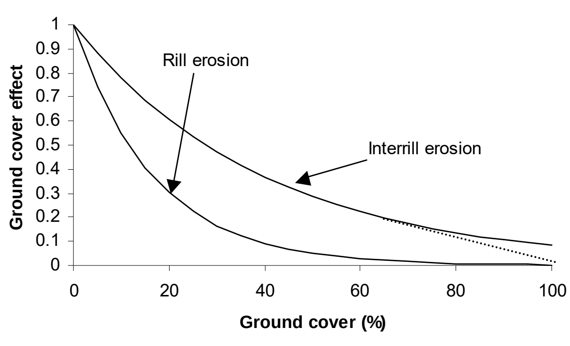

Figure 9.4. Effect of ground cover on rill and interrill erosion

9.2.2.1. Ground cover effect

Ground cover reduces erosion by protecting the soil surface from direct raindrop impact, which reduces **interrill erosion**. Ground cover also slows surface runoff and reduces its detachment and transport capacity, which reduces **rill erosion**. If

[61] **External residue** is RUSLE2 nomenclature that refers to any material added to the soil surface or placed in the soil from a source other than vegetation grown on site.

ground cover is low (less than about 15%) and ground cover pieces are long and oriented across slope, ground cover reduces soil loss by causing deposition in small ponds above ground cover pieces. As ground cover increases, deposition ends and ground cover reduces runoff detachment capacity, which reduces rill erosion. The ground cover effect for both interrill and rill erosion is illustrated in Figure 9.4.

Ground cover reduces rill erosion more than interrill erosion. That is, the ground cover subfactor is less for rill erosion than for interrill erosion for a given ground cover percent as illustrated in Figure 9.4. The net or overall effectiveness of ground cover depends on the relative contributions of rill and interrill erosion. The ground cover subfactor value is less when rill erosion makes the greater contribution to total erosion than when interrill erosion makes the greater contribution.

Factors that affect the relative contributions of rill and interrill erosion affect the ground cover subfactor. These variables include ratio of soil erodibility for rill erosion to soil erodibility for interrill erosion, soil biomass, soil consolidation, ground cover type, and the anchoring and bonding of ground cover to the soil. Obviously ground cover provides the greatest erosion control when it is well anchored and bonded to the soil. Conversely, ground cover is least effective where mulch pieces bridge across soil roughness so that runoff flows under the ground cover and where runoff moves poorly anchored ground cover. RUSLE2 partially represents these effects by reducing erosion for a given amount of ground cover when increased soil biomass is present.

These mechanical effects reduce the forces applied to the soil by waterdrop impact and surface runoff. An indirect effect is ground cover's effect on infiltration and runoff. Infiltration rate can be very high and runoff low on a freshly tilled soil without a surface seal.[62] If ground cover is placed on the soil before a crust is formed, the ground cover will reduce seal formation and help maintain high infiltration and low runoff. Therefore, ground cover has a lesser effect on reducing erosion when placed on a soil after it becomes crusted or placed on a soil where internal soil properties, such as a high clay content or high bulk density, reduce infiltration. A given amount of ground cover reduces erosion more for cover-management systems, such as no-till cropping, that maintain high soil biomass, improve soil quality, and reduce crusting because of increased infiltration. An interaction between soil biomass and soil consolidation is a major variable used by RUSLE2 to compute values for the ground cover subfactor.

Size and shape of ground cover material vary widely. Sizes and shapes include round rock fragments; thin, flat leaves; long slender pieces of unchopped wheat reside; long and increased diameter unchopped corn stalks; large pieces of woody debris left by logging operations; and continuous roll erosion control blankets. The portion of the soil surface

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[62] A surface seal is a thin, dense layer of soil particles at the soil surface caused by soil particle dispersion associated with raindrop impact and other processes. This thin layer, which reduces infiltration, is known as a surface **seal** when wet and a **crust** when dry.

covered is used as a single variable to describe the effect of ground cover on erosion. Even though the geometry of individual ground cover pieces can vary greatly, even for the same type of ground cover, the portion of the soil surface covered integrates the effects of varying geometry of ground cover pieces on erosion, as illustrated in Figure 9.4. Ground cover (crop residue) provided by above-ground biomass from a typical agricultural crop includes leaves, pods, hulls, cobs, stems, and stalks and fine and coarse roots for below-ground biomass. Ground cover (slash) on a disturbed forest ranges from leaves and needles to broken tree limbs. Furthermore, certain operations, especially harvest operations, frequently reduce size of biomass pieces that becomes ground cover. Even though size and shape of residue pieces vary over a wide range for a particular residue, a single **residue type** is selected to represent the residue. **Residue type** is an entry in the **residue component** of the RUSLE2 database that is selected based on size and toughness of the residue.

Several types of ground cover may occur at a specific site and overlap each other. Examples include rock fragments, live ground cover (basal area and plant leaves), and plant litter. RUSLE2 assumes that ground cover produced by vegetative biomass and ground cover from external residue overlap rock cover represented in the soil description. RUSLE2 also assumes that live ground cover overlaps all other types of ground cover. RUSLE2 assumes that the last ground cover that arrives on the soil surface overlaps existing ground cover, except for live ground cover. RUSLE2 accounts for the overlap of individual ground cover pieces instead of adding the cover provided by each ground cover type.

The important consideration is the net effect of the composite ground cover, not how the individual ground cover materials affect erosion. RUSLE2 uses the net ground cover to compute a value for the ground cover subfactor. The best way to visualize the net ground cover is to determine the fraction of bare, exposed soil and subtract that value from one.

RUSLE2 accounts for ground cover on a mass per unit area basis (e.g., tons/acre, t/ha). RUSLE2 converts mass (weight) values to a percent (fraction) of the soil surface covered (see **Section 12**), accounts for overlap, and uses a net (effective) ground cover value to compute a value for the ground cover subfactor.

Although RUSLE2 tracks ground cover by mass, RUSLE2 displays ground cover in percent (fraction) to aid conservation planning that if often based on maintaining a certain ground cover percent.

9.2.2.2. Equation for ground cover subfactor

The main equation used in RUSLE2 to compute a value for the ground cover subfactor is:

$$g_c = \exp(-bf_g) \qquad [9.6]$$

where: **b** = a coefficient that describes the relative effectiveness of ground cover and f_g = ground cover (percent). The effectiveness of ground cover varies with the site-specific condition. For example, a 50% ground cover can reduce soil loss by 95% under some conditions while only reducing soil loss by 65% under other conditions. Values for **b** in RUSLE2 range from about 0.025 for the interrill erosion ground cover effect to 0.06 for the rill erosion ground cover effect, illustrated in Figure 9.4, to represent this variation in ground cover effectiveness.

Therefore, the net **b** value depends how interrill erosion varies relative to rill erosion. Consequently, the **b** value used by RUSLE2 in equation 9.6 varies daily with the ratio of rill to interrill erosion. RUSLE2 computes a net **b** value using equations based on rill and interrill erosion as:

$$a_t = a_r \exp(-0.06 f_g) + a_i \exp(-0.025 f_g) \qquad [9.7]$$

$$b = -\ln[(a_t /(a_i + a_r)]/ f_g \qquad [9.8]$$

where: a_t = total relative erosion with ground cover, a_r =relative rill erosion on the same bare soil with all other conditions the same as when ground cover is present, and a_i = relative interrill erosion on a bare soil with all other conditions the same as when cover is present. Values for relative interrill and rill erosion in equations 9.7 and 9.8 are computed using the variables in equation 8.3. These equations compute daily **b** values daily that capture the main effects of how the net effectiveness of ground cover on rill-interrill erosion is affected by soil, cover-management, and by slope steepness. These effects are described in **Section 9.2.2.1**.[63]

In Req applications, a constant **b** value of 0.046 is used because the majority of the erosion is assumed to occur from rill erosion. The 0.046 value is based on analysis of plot data.

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[63] RUSLE2 eliminates the need to choose a **b** value for the effectiveness of ground cover required in RUSLE1.05 or the choice of a land use required in RUSLE1.06. RUSLE2 automates a manual selection of **b** required in RUSLE1. RUSLE2 computes **b** values as cover-management conditions vary through time that RUSLE1 did not compute.

RUSLE2 does not compute a composite ground cover subfactor value by computing a subfactor value for each ground cover type and then multiplying those values. That procedure would be an improper mathematical operation. Therefore, rock fragment cover must be combined with other ground cover considering overlap rather than using a soil erodibility factor value already adjusted for rock cover.

RUSLE2 reduces the effect of ground cover on steep slopes with little soil biomass. This feature represents how mulch is less effective on steep construction sites than crop residue and plant litter on crop, range, pasture, and disturbed forestland. RUSLE2 takes into account how small ground cover pieces that conform closely to the soil surface reduce erosion more than long pieces of ground cover that bridge across roughness elements like soil clods. This effect is greatest on steep, construction-like soil and slope conditions.

RUSLE2 assumes an interaction between soil surface roughness and ground cover such that the effectiveness of ground cover is reduced as surface roughness increases. For example, ground cover in the bottom of a depression filled with ponded water does not reduce erosion as much as does the same ground cover on a flat soil surface.
RUSLE2 computes a low **b** value for flat slopes where interrill erosion dominates, a high **b** value on steep slopes where rill erosion dominates, and an increased **b** value on no-till and other soils conditions where ground cover increases infiltration. The interaction of soil consolidation and soil biomass is used to indicate conditions where ground cover increases infiltration. RUSLE2 also compute increased **b** values for soils susceptible to rill erosion based on soil texture and decreased **b** values for increased soil consolidation that is assumed to reduce rill erosion more than interrill erosion.

RUSLE2 b values are not always comparable to b values reported in scientific literature. In many cases, literature b values are based on plotting soil loss versus percent ground cover without considering other variables such as soil surface roughness, soil biomass, and soil consolidation. Values determined on that basis cannot be compared with RUSLE2 b values because RUSLE2 represents those effects in other variables. Also, reported b values are as large as 0.1, which are larger than can be obtained by RUSLE2. These high b values represent extremes rather than the typical condition represented by RUSLE2.

9.2.2.3. How ground cover is added to and removed from the soil surface

RUSLE2 biomass residue pools:
1. Standing (canopy cover)
2. Flat (ground cover)
3. Buried

Ground cover is added to the soil surface by live vegetation (live ground cover), senescence causing canopy material to fall to the soil surface, natural processes causing standing residue to fall over, an operation (e.g., harvest)[64] flattening standing residue, an operation (e.g., tillage) resurfacing previously buried residue, or an operation applying **external residue** (e.g., mulch, manure, roll erosion control product) to the soil surface. Ground cover is removed when plant growth reduces leaves or other live plant parts from touching the soil surface, an operation (e.g., tillage) buries ground cover, or an operation (e.g., straw baling, burning) removes ground cover.

Live ground cover values are entered in the **vegetation descriptions** in the **vegetation component** of the RUSLE2 database (see **Section 11**). Live ground cover is controlled entirely by these values, and live ground cover does not decompose. **The mass of live ground cover is accounted for in the above-ground biomass of the live vegetation.** Senescence transfers material from the live above-ground biomass (canopy) to the soil surface where it is treated as ground cover (flat residue). Once on the soil surface, this residue decomposes as a function of daily rainfall, daily temperature, and decomposition half life (coefficient) assigned in the **residue description** entered in the **residue component** of the RUSLE2 database (see **Section 12**).
.
When live vegetation is **killed**, it becomes **standing residue**. Over time this residue falls over because of natural processes and becomes ground cover (i.e., becomes surface residue). The rate that standing residue "falls" (i.e., mass is converted from standing residue to surface residue) is proportional to the decomposition rate at the base of the dead standing residue. The base of the standing residue is assumed to decompose at the same rate as the **flat (surface) residue**.

Standing residue, which is not in contact with the soil surface, decomposes at a much slower rate than flat or buried residue because of no soil contact to provide moisture to accelerate decomposition.[65] Standing residue can also be converted to ground cover (flat residue) by an **operation** that includes a **flattening process**. **Flat residue** is lost by decomposition and burial by operations. **Buried residue** is also reduced by decomposition at the same rate as flat residue, and buried residue can be resurfaced by an operation that includes a **(mechanically) disturb soil process**, which adds material to ground cover. **External residue** can also be added to the soil surface by an operation that includes an **add other cover process**. External residue decomposes at the rate determined by the decomposition half life (coefficient) entered for the **residue description** in the **reside component** of the RUSLE2 database**.** See **Section 13** for a description of how operations manipulate ground cover.

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[64] An operation is an event that mechanically disturbs the soil, changes the vegetation, or changes the residue.

[65] RUSLE2 assumes that flat residue, buried residue, and dead roots all decompose at the same rate. Standing residue is assumed to decompose at a much slower rate than residue in the other pools. Decomposition rate at the base of standing residue, which determines the rate that standing residue falls, is the same as the decomposition rate for flat residue.

The information in each RUSLE2 database component and the rules for manipulating RUSLE2 variables are a "language" and procedure used to describe field conditions through time. The objective in RUSLE2 is to describe field conditions as they exist, not to model processes as a way to describe field conditions. A check should always be made before making a RUSLE2 computation to verify that the user created description matches the actual field situation. RUSLE2 uses your field description to estimate erosion.

Nonerodible cover can be added to the soil surface to represent adding a plastic mulch used in vegetable production, a water layer used in rice production, a snow cover in winter months, and to shut off erosion for particular computational reasons. Nonerodible cover acts like other kinds of ground cover except that it completely shuts off erosion for the portion of the soil surface that it occupies. Half life and permeability are parameters used to describe nonerodible cover (see **Section 13.1.9**).

Most types of ground cover can be removed from the soil surface. Live ground cover is removed controlled by the values assigned through time in the **vegetation description**. Rock cover assigned in the **soil description** can not be removed. Other forms of ground cover can be removed by using an **operation** that has a **remove residue/cover process.** Buried residue biomass in the soil can be removed by using an operation to **resurface** the residue to become ground cover and then using another operation that removes this ground cover. Neither live nor dead roots can be removed from the soil. **RUSLE2**

RUSLE2 rules for transfer of residue among pools:
1. Residue is added to the soil surface by senescence, standing residue falls over by natural processes, standing residue that is flattened by an operation, or application of external residue
2. Senescence transfers biomass from live canopy to the soil surface, adding ground cover (flat residue)
3. Live vegetation cannot be flattened or buried
4. Killing live vegetation creates standing residue (dead plant material)
5. Standing residue becomes flat residue by falling over from natural processes or by being flattened by an operation
6. Only flat residue can be buried (standing residue must first be flattened by natural processes or by an operation before it can be buried)
7. Flat residue can only be buried by an operation that mechanically disturbs the soil
8. Twenty five percent of the daily decomposed flat (ground cover) residue becomes buried residue in the upper 2 inch (50 mm) soil layer where it decomposes again
9. Only buried residue can be resurfaced; roots can not be resurfaced
10. Buried residue can only be resurfaced by an operation mechanically disturbs the soil

assumes that a decrease in the live root biomass in the vegetation description represents root sloughing that becomes a part of the dead root biomass pool (see **Section 11.2.6.3**). **Also, RUSLE2 can represent daily additions to the dead root pool by root death during growth periods (i.e., when live root biomass is increasing).**

9.2.2.4. Conversion of residue mass to portion of soil surface that is covered

RUSLE2 uses the following equation to convert ground cover (residue) mass to portion of the soil surface that is covered:

$$f_g = 1 - \exp(-\alpha M_g) \qquad [9.9]$$

where: α = a coefficient that is a function of residue characteristics (units depend on the units of M_g) and M_g = residue mass per unit area (e.g., lbs/acre, kg/ha) expressed on a dry matter (weight) basis. Figure 9.5 shows a plot of equation 9.9 for four residue types.

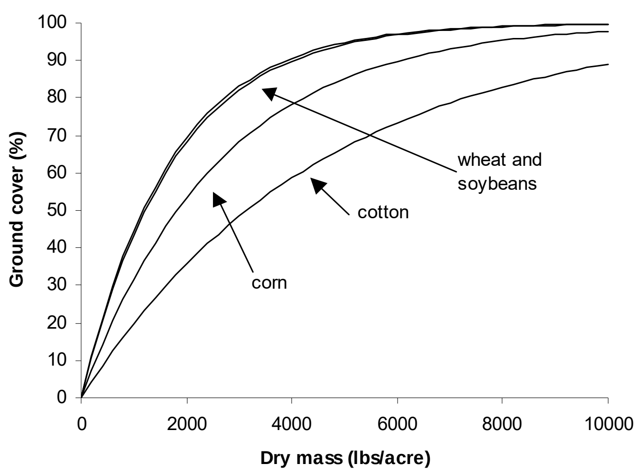

Figure 9.5. Relationship of ground cover to dry mass for four types of residue.

RUSLE2 uses data points entered in the **residue description** in the **residue component** of the RUSLE2 database to determine a value for α in equation 9.9 for each residue description in the residue component of the RUSLE2 database (see **Section 12.3**).

Figure 9.5 illustrates differences in residue types. Cotton residue is mainly composed of very coarse, woody stems, which requires a large mass of these residue pieces to produce a given ground cover. The other extreme is soybean residue, which is a mixture of several plant components including leaves, stems, and seed pods. The curve for wheat residue is similar to the one for soybean residue, but in this case, not a particularly large mass of hollow wheat stems is required to provide significant ground cover. Also, a significant amount of wheat residue is composed of leaves. Corn residue is intermediate. Much of the corn residue is large stalks that are solid but less dense than cotton stems. Also, much of the corn residue is composed of leaves.

The portion of the soil surfaced covered by residue does not change greatly as residue mass (weight per unit area) changes at high amounts of ground cover. For example, reducing the mass of the ground cover material by 50% has little effect on ground cover if mass of material on the soil surface is very large. In contrast, a slight change in mass per unit area at low mass values can significantly change ground cover. The small change in ground cover at large mass values is a major reason that RUSLE2 computes burial and resurfacing of material based on mass rather than on percent cover.

The best approach for selecting values for a residue description in the RUSLE2 database is to choose values based on information in the **core database** rather than making site specific field measurements. Field data are highly variable and should be avoided unless a large mass of data collected under research conditions are available (see **Section 9.2.2.6**).

Be cautious in developing residue descriptions for different crop varieties. Differences reported in scientific literature often represent unexplained variability rather than real differences.

RUSLE2 uses a single composite residue description for a particular residue although crop residue and plant litter are composed of a wide variety of plant components of different sizes. This approach is a compromise. A small mass of leaves gives a much greater percent ground cover than does the same mass of stems. Therefore, the relationship between cover and mass depends on the relative proportion of leaves and stems, or other plant components. This relationship changes through time because the residue components decompose at different rates. For example, leaves decompose much more rapidly than do stems. Consequently the mass-cover relationship is very different immediately after harvest when many leaves are present than later after the leaves have decomposed with only stems remaining. Also, the mass-cover relationship for a residue type can appear to differ by location for a particular plant community, when in reality the mass-cover relationship is reflecting how the proportion of leaves to stems varies by time and location.

The mass-cover values for the residue descriptions in the RUSLE2 core database were primarily chosen so that RUSLE2 computes erosion estimates that compare well with measured erosion values in research studies.[66] Also, the core database residue descriptions were chosen to represent the overall mass-ground cover relationship for the first year after harvest rather than fitting ground cover values at a specific point in time, such as one year after harvest. The result is that RUSLE2 may underestimate cover

[66] The major reason for having and using a RUSLE2 **core database** is to help ensure consistency in RUSLE2 estimates, especially by cover-management system and by location. Consistency is a major requirement when RUSLE2 is used to implement cost sharing and regulatory type programs so that all clients are treated fairly.

beyond about 12 months. The core database values were chosen to compute average annual erosion as a function of main effects rather than secondary effects associated with residue components decomposing at different rates. Fitting secondary effects, especially with limited data, is often fitting unexplained variability. The core database values represent several data sets rather than focusing on a single data set.

9.2.2.5. Spatially non-uniform ground cover

This section describes how to apply RUSLE2 where ground cover is concentrated in strips and patches. Examples of non-uniform ground cover are narrow strips mechanically disturbed by tillage and planting equipment, residue strips left by harvest operations, natural processes that cause residue to collect in strips, "patches" of highly disturbed soil left by logging and military training operations, and grass/shrub "clumps" on rangeland.

RUSLE2 uses different **cover-management descriptions** along the overland flow path to compute erosion for these conditions. Segments are created in the **management layer** illustrated in Figure 8.1. Cover-management descriptions are assigned to segments to represent non-uniform ground cover and disturbed soil along the flow path.

RUSLE2 assumes that ground cover is uniformly distributed for a particular cover-management description. RUSLE2 values for flattening, burial, and resurfacing ratios used to describe the manipulation of residue by operations are based on the entire area, not the local area where the residue is manipulated, such as in a tilled strip where seeds are planted.

The first example is the patchiness common to disturbed forest lands and military training sites where ground cover and soil disturbance vary randomly. The boundaries between the patches are the location of segment breaks. Cover-management descriptions are applied to each segment to represent each cover-management condition along the flow path.

A second example is landfills where vegetation and ground cover vary along the flow path because of soil differences. Segments are created in both the soil layer and the management layer in Figure 8.1. Appropriate soil and cover-management descriptions are assigned to each segment.

A third example is residue strips left by a combine without a straw spreader. Two cover-management descriptions are used to represent this condition. One description is for the strip that has standing residue with no flat residue from the vegetation just harvested. An operation with a **remove residue/cover process** is used to remove the flat residue that RUSLE2 assumes to be uniformly distributed. The cover-management description for the other strip is the same except it **applies external residue** to add the residue removed in the first cover-management description. The management layer in Figure 8.1 is divided into segments based on the width of each cover-management strip and the appropriate cover-management description is applied to each strip.

A fourth example is for mechanically disturbed strips, such as in vineyard or orchard where clean tilled strips are maintained within a relatively undisturbed area. A cover-management description is created for each strip and the management layer in Figure 8.1 is divided into segments to represent each of these strips along the overland flow path. If the strips are uniform along the flow path, the **strip/barrier descriptions** can be used to facilitate dividing the flow path into segments (see **Section 8**). Dividing the profile illustrated in Figure 8.1 into many segments can be tedious and laborious. The important variable is the ratio of the sum of the segment lengths of one strip type to the entire overland flow path length. This variable is more important than the actual number of strips along the flow path provided the number of strips exceeds a total of about 20 for the combination of strips (10 of one strip type and 10 of the other strip type). The inputs for number of strips and width of strips must be coordinated to ensure that the relative portion of the flow path occupied by each strip type is maintained.

A RUSLE2 template that includes the profile schematic illustrated in Figure 8.1 must be used to apply this procedure. This template allows non-uniform segment lengths. Also, strips are not constrained to be on the contour.

HOWEVER, CARE SHOULD BE TAKEN IN APPLYING RUSLE2 TO STRIPS. THE POSSIBILITY OF RUNOFF RUNNING ALONG THE UPPER EDGE OF HIGH RETARDANCE STRIPS BELOW ERODIBLE AREAS MUST BE CONSIDERED.

9.2.2.6. What to do when RUSLE2 computes a ground cover value that is not the expected value

Ground cover is a key variable used in conservation and erosion control planning and in determining whether a conservation or erosion control plan has been properly implemented. Residue ground cover immediately after planting is often the key value for conservation planning on cropland. RUSLE2 is expected to provide a good estimate of this ground cover value. The acceptability of RUSLE2 is sometimes judged on the basis of this value. Comparisons are made between the RUSLE2 estimated residue cover values with research data, site-specific field measurements, and professional judgment. This section provides guidance on making these comparisons and how to adjust RUSLE2 inputs if ground cover estimates do not meet expectations.

Several factors must be considered in comparing RUSLE2 residue ground cover values with field observations. RUSLE2 computes "typical," average annual daily residue cover values rather than residue cover at any specific time. Residue cover values measured at a particular site vary greatly from year to year, requiring at least three years of data where a range of production (yield) levels and weather conditions occurred to obtain measured values comparable to RUSLE2 estimates. Also, residue cover varies greatly from location to location within a field site requiring numerous measurements at a site depending on the measurement procedure (e.g., a beaded string versus photographs of a meter (yard) square area).

Great care must be taken in measuring residue cover when the cover is spatially non-uniform in strips and patches to ensure that the sample density is sufficient when measuring residue cover using the bead-string or similar method, especially if the strips are narrow and residue cover is heavy in one strip type. In fact, the best way to measure residue cover for this condition is to use transects within each strip type rather than diagonally across strips and weight the values based on area represented by each strip type.

The RUSLE2 mass-cover and erosion equations are highly nonlinear. As a consequence, using residue cover averaged over the entire area to estimate erosion with RUSLE2 likely will not give the same result as that obtained when the spatially non-uniform cover is analyzed using segments as described in **Section 9.2.2.5**. Remember, the purpose of RUSLE2 is to serve as a tool to guide conservation and erosion control planning rather than being a scientific tool.

The error in residue cover measurements can be large for residue cover less than about 20 percent. Sometimes residue mass is estimated based on field measurements of residue cover percent converted to a mass using curves like those in Figure 9.5. The error in mass can be large, sometimes by as much as a factor of two, for residue cover values greater than 75 percent. The residue mass can change by a large amount with only a small change in ground cover because of the flatness of the mass-cover curve at high cover values. Also, the data used to develop curves like those in Figure 9.5 are highly variable based on the relative portion of leaves to stems and other factors.

Very carefully compare the values determined from site-specific field measurements with values in the **core database** and values reported in the literature. Ask the question, "Are the field measured values consistent with commonly accepted values and reasonable when the data as a whole are considered? If the measured values differ significantly from other values, can the differences be reasonably explained?"

Getting a good comparison between the RUSLE2 residue cover estimate and a measured value at a particular point in time, such as immediately before harvest, does not ensure a good average annual erosion estimate. The best average annual erosion is obtained from a good estimate of residue cover over the two to three month period during the most erodible part of the year. The most erodible period is determined by a combination of peak erosivity and peak susceptibility of the field condition to erosion. RUSLE2 templates that display erosion through time can be used to identify the most erodible period.

RUSLE2 was constructed and calibrated, and values in the core database were carefully chosen to ensure that RUSLE2 produces average annual erosion estimates consistent with commonly accepted erosion scientific knowledge and the uncertainty in the research erosion measurements (see **Section 17** for a discussion of the uncertainty in erosion data and RUSLE2 erosion estimates). RUSLE2 was developed to capture main effects rather than secondary variability, which often reflects statistically unexplained viability. Thus, fitting RUSLE2 to data from a specific research study or measurements made at a specific field site often does not improve RUSLE2 estimates and in fact may degrade the quality of estimates. Residue cover can vary greatly from year to year as yield and weather vary.

Don't make changes just to get a better fit to local conditions. Always compare against a broad data set. Look at RUSLE2 estimates as representing main effects and typical conditions in a conservation planning context, not in a research context. Make sure that data being fitted are high quality, and collect as much supplemental data as possible, including yield, residue mass, and how residue cover varies during the year.

ALWAYS CHECK RUSLE2'S ESTIMATED EROSION. CHANGING INPUTS THAT AFFECT RESIDUE COVER ALSO AFECTS OTHER RUSLE2 COMPUTATIONS. DO NOT AUTOMATICALLY ASSUME THAT A RESIDUE COVER VALUE AT A PARTICULARLY TIME, SUCH AS IMMEDIATELY AFTER PLANTING OR BEFORE HARVEST, CORRECTLY COMPUTED BY RUSLE2 ENSURES A CORRECT AVERAGE ANNUAL EROSION ESTIMATE.

If one concludes that RUSLE2 is not computing the desired residue cover values, how does one change input values to obtain the desired residue cover values? The main factors that affect residue cover must be considered in a systematic, stepwise manner. The factors that affect residue cover affect many other RUSLE2 computations. Adjusting a particular RUSLE2 input may give the expected residue cover but adversely affect the RUSLE2 erosion estimate because other RUSLE2 computations were affected. The main variables to consider and the order to consider them are: (1) the amount of residue at harvest, (2) the distribution between standing and flat residue at harvest, (3) the mass-ground cover relationship, (4) values for the burial and resurfacing ratios of the operations, and (5) the decomposition half life (coefficient) value. Estimated residue cover and erosion values should be checked at each step. Sometimes changing a particular variable gives unexpected results. For example, changing the value for the decomposition half life affects not only ground cover, but standing residue, buried residue, and dead roots as well.

9.2.3. Soil (Surface) Roughness

Soil (surface) roughness, illustrated in Figure 9.6, refers to the random peaks and depressions left by soil disturbing operations. This random roughness does not affect general overland flow direction in contrast to oriented roughness (ridges and furrows) that redirects runoff. Roughness characteristics at the time that the roughness is created depend on soil disturbing operation that creates the roughness, soil properties including texture and soil moisture, live vegetation, standing and flat residue, and soil biomass. Different types of soil disturbing operations produce widely differing distributions of aggregates and clod sizes depending on soil conditions, which affect roughness. Surface roughness decays over time to a smooth surface, except for a few persistent clods on some soils.

Figure 9.6. Soil surface with a 1.0 inch roughness just created by a mechanical disturbance.

9.2.3.1. Soil (surface) roughness effect

Soil surface roughness affects erosion in several ways. The depressions formed by surface roughness pond water and slow runoff, which reduce the erosivity of raindrops, waterdrops falling from vegetation, and surface runoff. Runoff's transport capacity through the depressions is very low, which causes local deposition. Soil surface roughness decays over time as deposition fills the depressions with sediment, interrill erosion wears away the roughness peaks, and the presence of water and weathering cause the soil to subside.

Soil clods resistant to detachment primarily form the roughness illustrated in Figure 9.6. Surface roughness is a partial measure of clodiness left by a soil disturbance. Large clods also produce deep depressions. Fine soil particles produced during the creation of the roughness are often left in the depressions where they are protected from erosion. Thus, erodibility of a rough soil surface is less than that of a smooth, finely pulverized soil surface. The degree that a soil forms clods depends on soil texture and soil moisture at the time of the soil disturbance. RUSLE2 does not consider the effect of soil moisture on soil roughness, mainly because RUSLE2 is an average annual model. Clods are smaller and less stable for coarse textured soils than for fine textured soils (see **Section 7.4**).

Soil surface roughness increases infiltration, which reduces runoff. Also, cloddy, rough soils resist sealing and crusting in comparison to finely pulverized soils that readily seal and crust, especially if soil biomass is low. Thus, rough soils reduce erosion because of decreased runoff.

RUSLE2 considers a **short term roughness** and a **long term roughness**. Short term roughness is created by tillage equipment, earth moving machines, and similar operations that mechanically disturb the soil. Long term roughness evolves over time after the last mechanical soil disturbance on pasture, range, landfills, and reclaimed land. Long term roughness is related to vegetation type (bunch versus sod forming), plant roots near the soil surface, local erosion and deposition by both water and wind, and animal traffic. RUSLE2 simultaneously keeps track of the decay of short term roughness and the natural development of long term roughness over the **time to soil consolidation** (see **Section 7.8**). Daily short term roughness decay is computed as a function of daily precipitation and daily interrill erosion. The effect of soil conditions at any point in time is captured by the effect of soil conditions on the initial roughness discussed in Section 9.2.3.3. Long term roughness is computed as a function of time and the final roughness roughness value that is a user input.

9.2.3.2. Roughness measure

RUSLE2 uses a roughness index that is the standard deviation of the micro-surface elevations about the mean elevation as a measure of soil surface roughness. Machines like scarifiers, moldboard plows, and heavy offset disks create rough soil surfaces [e.g., $R_m > 1.5$ inch (35 mm), R_m = field measured roughness value] while machines like rotary tillers pulverize the soil and leave a smooth soil surface [e.g., $R_m < 0.2$ in (5 mm)]. Machines, like bulldozers and road graders having blades that cut the soil also leave a smooth surface with a low roughness value.

The method of laying a roller chain on the soil surface and estimating roughness by how much the horizontal measurement between the ends of the chain is shorter than the chain length should not be used to measure roughness for RUSLE2. This procedure does not capture all roughness features important in RUSLE2.

Micro-relief meters are used in research to measure surface roughness. These meters measure micro-surface elevations over a grid by lowering pins to the soil surface or by using a laser system.[67] Because roughness index values depend on grid spacing, a standard spacing of 1 inch (25 mm) should be used to determine roughness index values for RUSLE2. Also, a plane should be fitted to the elevation data, and deviations taken

[67] Toy, T.J., G.R. Foster, and K.G. Renard. 2002. Soil Erosion: Processes, Prediction, Measurement, and Control. John Wiley and Son, New York, NY.

with respect to the plane to remove the effects of land slope. Also, the effect of ridges (oriented roughness) should be avoided or taken out of the data by analysis as well.

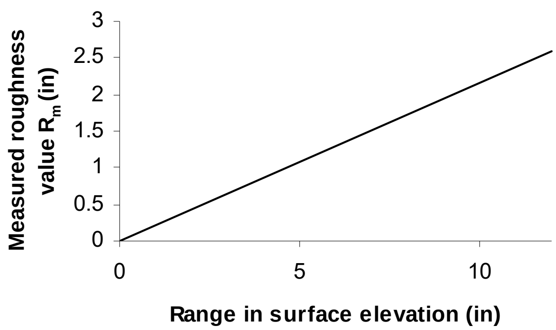

Figure 9.7. Relation of measured surface roughness value to range in elevation from highest roughness peak to deepest depression

Figure 9.7 provides an approximate estimate of surface roughness if a micro-relief meter is not available. The range in surface elevation from the highest roughness peak to the bottom of the deepest depression is measured by laying a 6 ft (2 m) straight edge across the roughness peaks.[68] A third approach for estimating surface roughness is to compare the appearance of the soil surface with photographs for soil surfaces having measured roughness values.[69]

Roughness values used in *operation descriptions* in the *operation component* of the RUSLE2 database are selected from the core database, not from field measurements at the site where RUSLE2 is being applied.

9.2.3.3. Soil surface roughness subfactor

Values for the RUSLE2 soil surface roughness subfactor are computed from:

$$s_r = \exp[-0.66(R_a - 0.24)] \qquad [9.10]$$

where: R_a = adjusted roughness value (inches) and 0.24 inches (6 mm) = the adjusted roughness value assigned to unit plot conditions (see **Section 7.2** for a description of unit plot conditions). The value for the roughness subfactor for the unit plot conditions is 1 by definition. Roughness subfactor values are less than 1 when the surface roughness effect of the site-specific condition is greater than on the unit plot and greater than 1 when the site-specific surface roughness effect is less than on the unit plot. An example of a soil surface that is smoother than the unit plot is a soil finely tilled with a rotary tiller for vegetable seeding. A soil surface with an adjusted roughness greater than the 0.24 in (6 mm) of the unit has roughness subfactor values less than 1. Roughness subfactor

[68] See Figure C-10, AH703 for details.
[69] See AH703.

values can range from almost 1.2 for a perfectly smooth surface to lower than 0.3 for an exceptionally rough surface as illustrated in Figure 9.8.

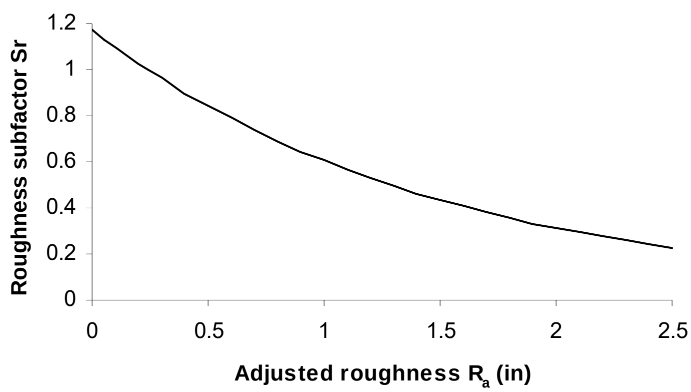

Figure 9.8. Relation of roughness subfactor to adjusted roughness

Computation of the adjusted roughness R_a starts with the initial base R_{ib} roughness assigned to **operation descriptions** having a **disturb soil process** in the **operations component** of the RUSLE2 database. The **initial base roughness** is assigned according to the roughness that the operation would produce for a smooth silt loam soil having a high soil biomass similar to a soil with a dense sod grass cover.

The input roughness value assigned to an operation is the roughness that the operation would create on a silt loam soil where the soil biomass is very high.

The first step in computing an adjusted roughness value to use in equation 9.10 is to adjust the initial roughness value R_{ib} for the effect of soil texture by multiplying by a soil texture adjustment factor. Soil texture adjustment factor values computed with the RUSLE2 equations for the midpoint of the soil texture classes are shown in Table 9.2.

The roughness adjustment factor is greater for high clay soils than for high sand soils. Consequently, RUSLE2 uses a higher roughness value for high clay soils than for high sand soils for a given initial (input) base roughness values, which means that soil surface roughness reduces erosion more on high clay soils than on high sand soils for a given operation. The adjustment factor for a silt loam soil is 1.0 because it is the base condition.[70]

The next adjustment is for soil biomass computed with:

$$R_a = 0.24 + (R_{it} - 0.24)\{0.8[1 - \exp(-0.0015 B_{ta})] + 0.2\} \qquad [9.11]$$

70 The difference between 1.0 and the 1.02 value in Table 9.1 results from rounding and not being able to fit the equation to exactly 1.0 for the mid-point of the silt loam texture.

where: R_{it} (inches) = the initial (input) roughness adjusted for soil texture and B_{ta} = the total mass (dry weight basis) of buried residue and dead roots averaged over the soil disturbance depth after the operation (lbs/acre per inch depth). Figure 9.9 illustrates how the input roughness value is adjusted for soil biomass for a range of input roughness values.

Table 9.2. Factor to adjust input roughness as a function of soil texture

Soil texture class	Adjustment factor
clay	1.39
clay loam	1.22
loam	1.05
loamy sand	0.78
sand	0.69
sandy clay	1.25
sandy clay loam	1.13
sandy loam	0.90
silt	0.81
silt loam	1.02
silty clay	1.33
silty clay loam	1.23

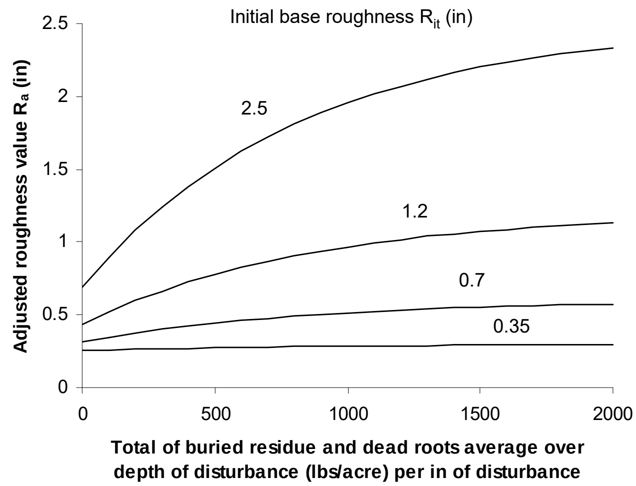

Figure 9.9. Roughness value adjusted from input value for soil biomass effect.

The effect of soil biomass on roughness can be observed in the field by comparing roughness after sod field is plowed with the roughness after a field in continuous low residue vegetable cropping is plowed. The difference in roughness can also be observed when a permanent grass strip beside a continuously cropped field is plowed. Soil surface roughness is much larger on the sod field and grass strip than on the continuously cropped fields having much lower biomass than the sod and grass conditions. The soil plowed out of sod turns up in "chunks" as if it is held together by roots. A similar effect occurs in chisel plowed wheat stubble fields.

The effect of roughness in a sod, meadow, and hay fields on erosion is very significant. According to Table 5-D, AH537[71] erosion immediately after moldboard plowing a high biomass condition is one fourth of that immediately after moldboard plowing a continuous row cropped field where biomass is reduced. The biomass effect on erosion depends on the sod, meadow, or hay production (yield) level, which determines the biomass of roots and buried residue. The roughness effect for moldboard plowing in a continuous cropped corn is also a function of yield as illustrated in Table 5, AH537. For example, the roughness subfactor value is about 0.55 for a 110 bu/ac yield and about 0.75 for a 50 bu/ac yield. A roughness related to biomass effect is also illustrated in Table 5,

[71] Wischmeier, W.H. and D.D. Smith. 1978. Predicting rainfall-erosion losses: A guide to conservation planning. U.S. Dept. of Agriculture, Agriculture Handbook # 537.

AH537 where the residue is removed, which reduces soil biomass. For example, the soil surface roughness subfactor is about 0.90 where the residue is removed for a 110 bu/acre corn yield while it is about 0.55 where the residue is not removed. The values in Tables 5 and 5-D, AH537 are based on measured soil loss data. Another illustration of how soil biomass affects the soil surface roughness is that a soil surface is noticeably smoother after tillage following soybeans than tillage following corn.

When roughness data from field research are analyzed to develop input roughness values for RUSLE2, field measured roughness R_m values must be adjusted for soil texture using Table 9.2 and for soil biomass using Figure 9.10. The best approach is to make roughness measurements under high soil biomass conditions to minimize the amount of adjustment required for biomass. As illustrated in Figure 9.10, biomass does not have much effect on the soil surface roughness value for soil biomass values (buried residue plus dead roots) greater than about 1000 lbs/acre per inch depth of disturbance.

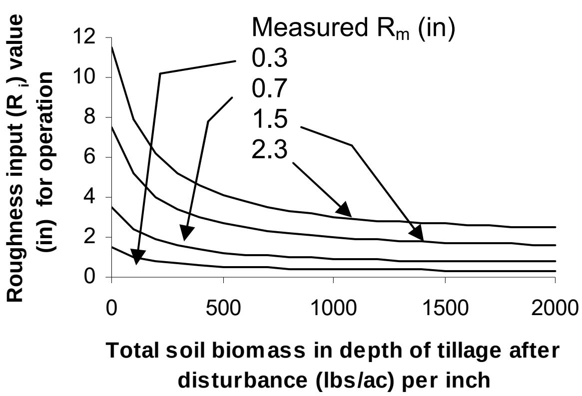

Figure 9.10. Conversion of a measured roughness value (R_m) to a roughness input value (R_i) (silt loam soil)

Roughness measurements made with yields of 200 bu/acre corn, 70 bu/acre wheat, and 4 tons/acre on hay or pasture land are conditions where measured roughness values need little if any adjustment for soil biomass.

The following example illustrates how to use Figure 9.10 to adjust a measured roughness value for biomass. Assume that the measured roughness is 1.5 inches (40 mm) and the average soil biomass is 500 lb/ac per inch depth of disturbance after the operation. A value of about 3.2 in (80 mm) is read from Figure 9.10, which would be the input roughness value for the operation that produced this roughness on a silt loam soil.

The input roughness values in the **operation descriptions** in the **operation component** of the RUSLE2 database are greater than are typically measured in the field because of the biomass effect. Roughness values computed by RUSLE2, rather than input values, should be compared to measured roughness values. Even then, field measured roughness values may not match those computed by RUSLE2. As described in **Section 9.2.3.1,** the RUSLE2 soil surface roughness subfactor captures more than just the physical effect of roughness geometry on soil loss. It also captures the effect of soil management as represented by soil biomass on aggregate size distribution and stability and their effect on infiltration and erodibility. The roughness input value and the roughness subfactor have been developed together to reflect these effects. Priority is given to capturing these effects rather than reproducing roughness values that can be measured in the field.

Perhaps more than any other RUSLE2 variable, roughness values from the *core database* should be used rather than using roughness values measured at the specific site specific for input into RUSLE2.

9.2.3.4. Effect of existing roughness (tillage intensity effect)

The input roughness values represent the roughness that a particular operation creates when used on a smooth soil surface of silt loam texture and having high soil biomass as discussed in **Section 9.2.3.3.** The field roughness left by an operation depends on the roughness existing at the time of the operation. For example, the roughness left by a spike tooth harrow following a moldboard plow is much greater than the roughness left by the spike tooth harrow following a tandem disk. The spike tooth harrow has relatively little effect on roughness such that the roughness left by the harrow strongly depends on the existing roughness at the time of the operation. The roughness is only slightly greater when a tandem disk follows a moldboard plow than when it follows another tandem disk. The roughness following a moldboard plow is independent of existing roughness.

The influence of existing roughness is represented by the **tillage intensity** variable in RUSLE2. A soil disturbing operation where existing roughness has no effect on the roughness created by the operation is assigned a tillage intensity of 1. That is, the operation "wipes" out all effects of the existing roughness. Operations are assigned a tillage intensity less than 1 based on the degree that the roughness left by an operation is influenced by existing roughness at the time of the operation. For example, tillage intensity values of 0.4, 0.75, and 1 are assigned to spike harrows, tandem disks, and moldboard plows, respectively.[72]

A tillage intensity of 0.4 means that the operation converts 40 percent of the existing roughness to the operation's assigned roughness and leaves 60 percent of the existing roughness. A tillage intensity of 1 means that that 100 percent of the existing roughness

[72] RUSLE1 does not use a tillage intensity effect. RUSLE1 uses an absolute concept where an operation is assumed to create a particular roughness regardless of the existing roughness. That is, the roughness following a spike tooth harrow in RUSLE1 is the same regardless of whether the harrow follows a moldboard plow or a tandem disk. Input roughness values are the same for RUSLE1 and RUSLE2 for operations where the tillage intensity is 1. However, input roughness values for operations where tillage intensity is less than 1 are smaller in RUSLE2 than in RUSLE1 to achieve comparable roughness values in both models. However, the two models can not compute the same roughness values for all situations because of the tillage intensity factor effect.

is “wiped out,” and the resulting roughness is 100 percent of the operation’s assigned roughness.

Tillage intensity does not indicate the roughness left by an operation performed on a smooth surface. Soil disturbing operations like moldboard plows and heavy offset disks are assigned 1 for tillage intensity and leave a very rough surface. In contrast, a rotary tiller is also assigned 1 for tillage intensity value but leaves a very smooth surface. The key factor in both cases is that existing roughness has no effect on the resulting roughness, which is the basis for assigning a tillage intensity value of 1, not the roughness left by the operation.

If existing roughness is less than that created by an operation on a smooth soil surface, the surface roughness computed by RUSLE2 is not affected by the tillage intensity factor.

9.2.3.5. How RUSLE2 handles roughness when soil disturbance is in strips

Some operations like strip tillage, manure injection, and planting only disturb a portion of the soil surface. **The input roughness base value for these operations applies only to the portion of the soil surface that is disturbed.** RUSLE2 does not average the roughness values for the disturbed and undisturbed portions to determine an average roughness value because of non-linearity in equation 9.10 used to compute the roughness subfactor value. Instead RUSLE2 computes a roughness subfactor value using equation 9.10 for each strip (disturbed and undisturbed) and computes a composite roughness subfactor value based on the portion of the surface disturbed by the operation. This composite roughness subfactor value is used in a rearrangement of equation 9.10 to compute an effective roughness value for the entire surface. This effective roughness is then decayed based on rainfall amount and interrill erosion as described in **Section 9.2.3.7.**

The approach used to handle roughness with strips differs from the way that ground cover in strips is handled. Input roughness values only apply to the portion disturbed whereas input values for flattening, burial, and resurfacing ratios apply to the entire area.

9.2.3.6. Assigning roughness values

Input roughness base values for soil disturbing operations are assigned by selecting a value from the RUSLE2 “core database” by comparing characteristics of an operation with characteristics of operations in the “core database.” Basing input values on the “core database” values helps ensure consistency between RUSLE2 applications. Consult the research literature if no operations are in the “core database” that are sufficiently close to your operation,. Use the largest possible database to estimate input roughness values and apply the adjustment procedures described in **Section 9.2.3.3.** Make sure that field measurements were carefully made and that sufficient measurements were taken to deal with spatial and temporal variability.

Field measurements should not be made at the specific site where RUSLE2 is being applied to determine an input roughness value for RUSLE2. Rather, values based on the RUSLE2 core database should be used.

9.2.3.7. Roughness decay

RUSLE2 decays the adjusted roughness, R_a in equation 9.10, each day based on daily precipitation and interrill erosion. About 40 percent of the roughness decay is by rapid subsidence and the remainder is by interrill erosion. Precipitation amount is used to compute the rapid subsidence of roughness that is assumed to be caused by soil wetting. Roughness decay by interrill erosion represents impacting waterdrops wearing away soil peaks and filling depressions with sediment. Interrill erosion is computed using the terms in the denominator of equation 8.3. The result is that roughness persists longer in dry climates than in wet climates and longer when the soil is protected from interrill erosion than when the soil is exposed to raindrop impact.

Roughness decays over time to a "final" roughness that is entered as an input for each **operation description** having a **disturb soil process** (see **Section 13.1.5**). A value of 0.24 inches (6 mm) is typically used for **final roughness** to represent the long term persistence of a few exceptionally stable soil clods. Although the final roughness value would seem to be a function of soil texture, a value of 0.24 inches (6 mm) is used for all soils. The reason for applying the 0.24 in (6 mm) value to all soils is to compute a surface roughness subfactor value of 1 for the unit plot condition for all soils when all roughness has decayed.

The expectation is that the final roughness value should be higher for high clay soils where clods persist than for sand soils that have no clods. However, such an adjustment should not be made because that effect is empirically considered in the K factor value.

However, an input final roughness other than 0.24 inches (6 mm) is used in RUSLE2 to represent conditions where an operation leaves the soil smoother than the unit plot condition. For example, rotary tiller and blading operations leave a smoother soil surface than exists for unit plot conditions. When a **final roughness** value less than 0.24 in (6 mm) is entered, an **initial roughness** value equal to the **final roughness** value must be entered. RUSLE2 does not compute a change in roughness when the final roughness value is less than 0.24 inches (6 mm). Also, if the input initial roughness is greater than 0.24 inches (6 mm) and the input final roughness is less than 0.24 inches (6 mm), RUSLE2 will not decay the roughness to less than 0.24 inches (6 mm).

The rate of roughness decay is not a function of soil conditions in RUSLE2. RUSLE2 captures the effect of soil conditions on roughness at any time by making the initial roughness a function of soil conditions.

9.2.3.8. Long term roughness

As described in **Section 9.2.3.1**, RUSLE2 computes a long term development of soil roughness to an input natural roughness value. The development of long term roughness is assumed to be directly proportional to the soil consolidation subfactor value. The starting point for the development of long term roughness is 0.24 inches (6 mm). Long term roughness is reset to this value each time a soil disturbing operation occurs. If only a portion of the soil surface is disturbed, a weighted value for the long term roughness is computed as described in **Section 9.2.3.5.**

9.2.3.9. Overriding RUSLE2 roughness values

Sometimes the way that RUSLE2 computes roughness needs to be overridden for research purposes. Set the initial and final input roughness values to the same value and RUSLE2 will use this roughness value in equation 9.10 to compute roughness subfactor values. This procedure can be used in RUSLE2 so that RUSLE2 can use measured roughness values directly in its computations. However, RUSLE2 does not compute roughness decay when this procedure is used.

The adjustments that RUSLE2 makes for soil texture and soil biomass can not be easily overridden while retaining the RUSLE2 procedure for computing roughness decay. The only approach that can be used is to adjust RUSLE2 input values until RUSLE2 computes adjusted roughness values that correspond to the measured field values. A special template must be obtained to display the adjusted roughness values.

The proper approach for applying RUSLE2 in conservation and erosion control planning is to use roughness values from the core database and allow RUSLE2 to make its adjustments for soil texture and soil biomass rather than attempt to use field measured roughness values.

9.2.4. Ridges

Ridges affect soil erosion in two ways. One effect is on sediment production, which is discussed in this section, and the other effect is runoff flow direction, which is discussed in **Section 14.1**. Ridges, and the furrows that separate them, are referred to as oriented roughness because they redirect runoff from a direct, downslope direction (perpendicular to the contour) when the ridges are oriented in direction besides directly up and down slope. Orienting ridges parallel with the contour is an important conservation (support) practice known as contouring that can significantly reduce soil loss if the ridges are sufficiently high.

9.2.4.1. Ridge subfactor effect

The ridge subfactor describes how ridges affect sediment production by increased interrill erosion on steep ridge sideslopes. Erosion can be as much as twice that from a level soil surface for land slopes up to 6 percent.[73] The increase in soil loss caused by ridges is related to ridge sideslope steepness where interrill erosion increases according to $3s^{0.8}+0.56$ where s_i = sine of the ridge sideslope angle. This equation computes interrill erosion from a 30 percent steep ridge sideslope that is about three times the interrill erosion from a flat, level soil surface. Even when land slope is flat, the local ridge sideslope can be very steep, such as 30 percent so that interrill erosion is very high on the ridge sideslope.[74]

Figure 9.11. Ridge subfactor values as a function of ridge height for land slopes less

Figure 9.11 shows RUSLE2 ridge subfactor values as a function of ridge height when the land slope is less than 6 percent and the ridges are oriented up and down hill. Ridge height is used to represent ridge sideslope steepness because ridge height values can be easily visualized and measured for ridge forming operations. Using ridge sideslope steepness in RUSLE2 would require that a value for ridge spacing be entered, which is not always available, in addition to a ridge height value. Also, more ridges are often present than is often recognized. For example, the ridge spacing assumed for row crops is often the spacing of the rows. However, the planter may leave several small, but very important ridges besides the ridges directly associated with the

[73] Young, R.A. and C. K. Mutchler. 1969. Soil and water movement in small tillage channels. Trans. ASAE. 12(4):543-545. Also, personal communication with K.C. McGregor and C.K. Mutchler, USDA-Agricultural Research Service, National Sedimentation Laboratory, Oxford, MS.

[74] RUSLE1 does not include a ridge sufactor. RUSLE2 can compute up to twice the erosion for high ridges on slope less than six percent than that computed by RUSLE1.

plants. Determining ridge height is much easier for construction machines like scarifiers and bulldozer treads than determining ridge spacing.

A value of 1 corresponds to the ridge subfactor value for a unit plot. The unit plot condition based on being tilled up and down slope with a harrow is assumed to have a 1 inch (25 mm) ridge height. Thus, values for the ridge height subfactor as less than 1 for ridge heights less than 1 inch (25 mm) because of the unit plot condition being the reference in RUSLE2 and the unit plot having a 1 inch (25 mm) ridge.

The effect of ridges on sediment production diminishes in RUSLE2 as land slope steepness increases above 6 percent because the local steepness of the ridges becomes almost equal to the land slope at steepness above 30 percent. For example, the local steepness of the ridge sideslopes is 42 percent when the ridge sideslope is 30 percent and the land slope is 30 percent. Figure 9.12 shows ridge subfactor values as landslope increases above six percent. As illustrated, ridge subfactor values converge to 1 at steep land slopes. The values in Figure 9.11 were derived from experimental data while the values in Figure 9.12 were derived from a simple rill-interrill erosion model where rill erosion varies linearly with land slope steepness and interrill erosion with $3s^{0.8}+0.56$.

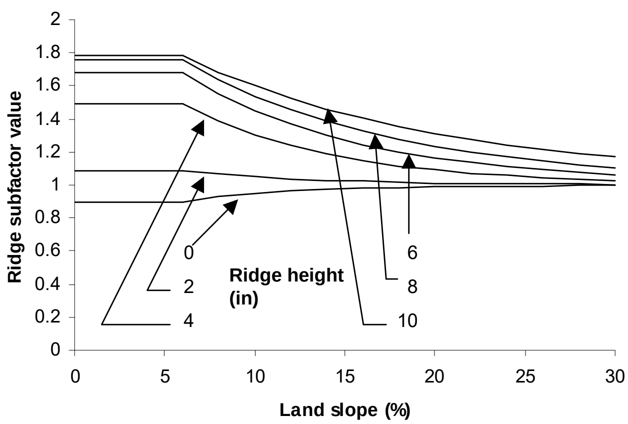

Figure 9.12. Ridge subfactor values as a function of ridge height and land slope steepness

9.2.4.2. Effect of ridge orientation on ridge subfactor

The ridge subfactor values in Figures 9.11 and 9.12 apply when ridges are oriented up and down slope. When the ridges are oriented on a direction different from up and down slope, ridge subfactor values decrease to 1 as ridge orientation approaches the contour. The relationship used to adjust ridge subfactor values as a function of ridge orientation (row grade) is shown in Figure 9.13. This relationship is a mirror image of Figure 14.3, the one used to adjust contouring factor values for ridge orientation, which is discussed in **Section 14.1**. The net effect of ridges is a composite of Figure 9.13 and Figure 14.3.

The need for Figure 9.13 seems questionable. Why does ridge orientation with respect the land slope affect sediment production? It doesn't. The reason for these adjustments is related to the empirical structure of RUSLE2 and constructing RUSLE2 so that it gives the expected erosion values with contouring.

9.2.4.3. Ridge formation and decay

Ridges are described in RUSLE2 by using a **soil disturbing operation**. An input ridge height value is entered in the **operation** component of the **RUSLE2 database** for each soil disturbing operation. This input value is the "typical" (representative) ridge height created by the operation. A "typical" ridge height is used because ridge height can vary with soil and cover-management condition, factors not considered in RUSLE2 in contrast to random roughness that RUSLE2 computes as a function of soil texture and soil biomass. The assumption is that ridge height is far more controlled by the physical mechanics of the operation than by soil conditions. Operations having different ridge heights for different soil conditions can be created for RUSLE2 to compute how ridge height affected by soil condition affects erosion.

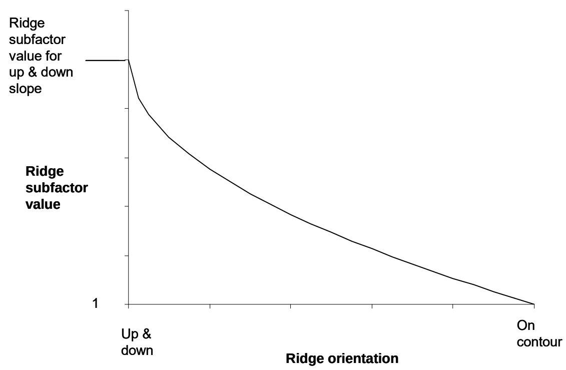

Figure 9.13. Effect of ridge orientation (row grade) on ridge subfactor

RUSLE2 computes a daily decay of ridge height as a function of daily precipitation and interrill erosion. The decay in ridge height by precipitation is independent of soil and cover-management conditions. The decay of ridge height by interrill erosion depends on rainfall erosivity, canopy cover, and ground cover. About 40 percent of the ridge height decay is from precipitation, which represents how the presence of water causes soil settlement. The remainder is from interrill erosion, which represents the wearing away of the ridge by raindrop impact.

The only way that ridges exist in RUSLE2 is to create them with a soil disturbing operation.

9.2.4.4 Assignment of input ridge height values

RUSLE2 input values for ridge height for an operation should be selected by comparing the characteristic of the operation with operations having ridge height values assigned in the RUSLE2 "core database." Ridge heights should not be selected based on field measurements. Ridge heights should be assigned very carefully to ensure consistency. Keep in mind that ridge heights affect both sediment production and contouring on erosion. Ridge height values in the RUSLE2 **core database** were selected very carefully to ensure that RUSLE2 computes the proper contouring effect. The tendency is to assign ridge height values that are too low and then be surprised that RUSLE2 computes too little contouring effect. Although RUSLE2 has been constructed to use easily measured field values, ridge heights is a situation where assigning values based on the **core database** gives far better results than can be obtained by entering field measurements of ridge height.

The effectiveness of contouring in RUSLE2 depends on ridge height: no ridge height, no contouring effect. To have a contouring effect, ridges must be present.

9.2.5. Soil biomass

Soil biomass in RUSLE2 includes live and dead roots, buried plant litter and crop residue from vegetation "grown" on-site, and added materials (external residue) that were buried or directly placed in the soil. These materials, including rock added as an "external residue," are assumed to be organic materials that decompose and reduce soil erodibility.

Buried inorganic materials including rock require special consideration. An extremely low value is entered for the decomposition coefficient for materials, such as rock, that do not decompose so that essentially no mass is lost by decomposition. RUSLE2 assumes buried inorganic material has the same effect as buried organic material, which may be too much effect.[75] For example, non-organic materials do not produce compounds that reduce soil erodibility. This problem can be accounted for in RUSLE2 by reducing the amount of inorganic material that is entered as having been added to an amount that has the expected effect on erosion. However, if this adjustment is made, the mass-cover relationships for the inorganic material must be adjusted so that RUSLE2 uses the proper ground cover percent in computing how a surface application of this material would affect erosion.

9.2.5.1. Soil biomass effect

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[75] Rock cover entered in the **soil descriptions** in the **soil component** of the RUSLE2 database remains constant and is not subject to burial or decomposition. This rock cover is unaffected by operations in contrast to rock added as an external residue that is manipulated by operations.

Live roots affect soil loss by mechanically holding the soil in place, resisting erosive forces if the roots are exposed, and producing exudates that reduce soil erodibility. Also, live roots are a measure of plant transpiration that reduces soil moisture, which in turn increases infiltration and reduces runoff and soil loss.

When vegetation is "killed" in RUSLE2 by an operation that has a **kill process**, live roots becomes **dead roots** and begin to decompose. The physical presence of dead roots reduces erosion by reducing runoff erosivity if the dead roots are exposed, and dead roots also seem to hold the soil in "clumps" when the soil is mechanically disturbed.[76] Also, dead roots decompose to produce organic compounds that reduce soil erodibility and increase infiltration and reduce runoff.

Exposed **buried residue**[77] acts similar to exposed dead roots by physically reducing runoff's erosive forces applied to the soil, but buried residue does not mechanically hold the soil like roots hold the soil. Residue decomposes and produces organic compounds that reduce soil erodibility and increase infiltration and decrease runoff and erosion. Overall, buried residue is less effective than roots on reducing erosion because buried residue does not mechanically hold the soil in place, and buried residue is not associated with plant transpiration like roots.

Although buried residue occurs in a wide range of sizes and types of vegetative and organic material, the effect of all buried residue is treated the same based on experimental research that compared how crop residue, "green" manure, compost, animal manure, hardwood litter, and pine needles affected erosion.[78] However, preference is given to fine roots instead of coarse roots when root biomass values are entered in a **vegetation description** in the **vegetation component** of the **RUSLE2 database**. Fine roots have greater surface area per unit mass than coarse roots and often are very close to the soil surface where they have a greater effect on runoff and erosion than coarse roots. Fine roots readily slough and become a part of the soil organic matter pool. Not much of

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[76] Some of the effect may well be roots mechanically holding the soil together. Another effect is that roots produce compounds that have caused a local increased in soil strength. Another effect is that the soil fractures along lines that expose the roots as if they are holding the soil in place. The fact is clearly obvious that soil roughness is increased with high levels of soil biomass when soil is disturbed.

[77] Buried residue is RUSLE2 nomenclature for organic material in the soil that affects soil loss that has been buried or placed in the soil by an operation. Buried residue also includes non-organic material in the soil, but this material requires special considerations.

[78]Browning, F.M., R.A. Norton, A.G. McCall, and F.G. Bell. 1948. Investigations in erosion control and reclamation of eroded land at the Missouri Valley Loess Conservation Experiment Station, Clarinda, Iowa, 1931-42. USDA Technical Bulletin 959.

Copley, T.L., L.A. Forrest, A.G. McCall, and F.G. Bell. 1944. Investigations in erosion control and reclamation of eroded land at the Central Piedmont Conservation Experiment Station, Statesville, North Carolina, 1930-40. USDA Technical Bulletin 873.

Hays, O.E., A.G. McCall, and F.G. Bell. 1949. Investigations in erosion control and reclamation of eroded land at the Upper Mississippi Valley Conservation Experiment Station near LaCrosse, Wisconsin, 1933-43. USDA-Technical Bulletin 973.

the mass of coarse roots is entered for root biomass because coarse roots are assumed to have relatively little effect on erosion.

9.2.5.2. Soil biomass subfactor

Equation 9.12 is used in RUSLE2 to compute values for the soil biomass subfactor.

$$s_b = c_b \exp(-0.0026B_{rt} - 0.00066B_{rs} / s_c^{0.5}) \qquad [9.12]$$

where: s_b = soil biomass subfactor, c_b = 0.951,[79] B_{rt} = the sum of the live and dead root biomass averaged over a 10 inch (250 mm) depth (lbs/acre per inch of depth), B_{rs} = the amount of buried residue averaged over a depth that linearly ranges from 3 inches (75 mm) if the soil is not consolidated (i.e., c_s = 1) to 1 inch (25 mm) if the soil is fully consolidated (i.e., s_c = 0.45), and s_c = the soil consolidation subfactor (see **Sections 7.8 and 9.2.6** for discussion of the soil consolidation subfactor). The coefficients 0.0026 for root biomass B_{rt} and 0.00066 for buried residue B_{rs} are multiplied by 1.65 for Req applications. Most of the erosion in Req situations is assumed to be caused by rill erosion. Soil biomass has a much greater effect on rill erosion than on interrill erosion.

All soil biomass variables are on a dry weight basis.

Equation 9.12 was empirically derived by fitting it to soil loss ratio values for the seedbed crop stage period[80] in Table 5 and accompanying tables in AH537.[81] These soil loss ratio values were for a wide range of soil biomass and soil consolidation conditions, including pasture and hay lands; no-till and reduced-till forms of conservation tillage for corn grain; and conventional clean-till corn grain, corn silage, soybean, and wheat cropping over a range of yields. Also, soil loss data on the effect of incorporation of green manure, animal manure, compost, hardwood litter, and pine needles into the soil were analyzed. Erosion data from rainfall simulator studies were used to determine values for effective root biomass for rangeland (see **Section 17.4.1.4**).

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[79] Equation 9.12 also has a second part for very low soil biomass where c_b increases from 0.95 to 1 so that the soil biomass subfactor equals 1 when no soil biomass is present.

[80] Soil loss ratio values in AH537 are the ratio of soil loss with a given cover-management system at a particular crop stage period to soil loss from the unit plot for the same crop stage. The seedbed crop stage period is when the soil has been tilled to prepare a relatively smooth surface for seeding a crop so that the major effect is from soil biomass.

[81] The soil loss ratio values in AH537, except for conservation tillage and "undisturbed" land, are a summary of field measured soil loss for more than 10,000 plot-years of data. Erosion data are quite variable for unexplained reasons. Also, the length of record often varied between studies and locations, and the number of treatments and replications and other variables differed between locations, which prevents the data from being analyzed by common statistical procedures. Instead, the data must be analyzed and interpreted for main effects, which was expertly done by W.H. Wischmeier and D.D. Smith in AH537. The soil loss ratio values in AH537 are the most comprehensive available by far for calibrating RUSLE2 and are much better for calibrating and validating RUSLE2 than the original soil loss data.

The 10-inch (250 mm) depth over which root biomass is averaged was the best of several depths analyzed. A 3-inch (75 mm) depth over which buried residue is averaged also was the best of several depths analyzed. This 3 inches (75 mm) depth is linearly reduced in RUSLE2 to 1 inch (25 mm) as the soil consolidation subfactor c_s decreases from 1 to 0.45 to give increased credit to buried residue B_{rs} in the upper soil layer with no-till cropping and other cover-management systems that leave residue at the soil surface and do not disturb the entire soil surface. A similar feature is the division of the variable buried residue B_{rs} by the square root of the soil consolidation subfactor c_s, which also gives increased credit to buried residue as the soil consolidates. A major advantage of no-till cropping is the accumulation of organic matter in the upper two inches (50 mm) of soil. This layer promotes earthworm burrowing and other processes that decrease runoff and soil erodibility. Tillage and other mechanical soil disturbances disrupt this layer and cause an immediate increase in soil erosion. This zone requires about 5 years to develop in the eastern US, which is consistent with using 7 years for the time to soil consolidation to represent this time.

Soil consolidation refers to lack of soil disturbance and the soil becoming less erodible over time after a soil disturbance rather than the soil necessarily becoming dense.

Table 9.3. Effect of corn yield and tillage system on the soil biomass subfactor at Columbia, MO

	Soil biomass subfactor		
	Type tillage system		
Yield (bu/acre)	Clean till	Reduced till	No till
50	0.78	0.74	0.57
100	0.66	0.60	0.38
200	0.48	0.40	0.16

Table 9.4. Effect of production level of a grass on the soil biomass subfactor

	Soil biomass subfactor		
Yield (lbs/acre)	St. Paul, MN	Columbia, MO	Baton Rouge, LA
1000	0.47	0.51	0.56
2000	0.22	0.27	0.33
4000	0.05	0.08	0.11

Tables 9.3 and 9.4 illustrate values for the soil biomass subfactor for the three corn tillage systems at different yield levels and grass at three production levels. The values for the soil biomass subfactor computed by equation 9.12 decrease as yield increases as illustrated in Table 9.3 because of increased buried residue and live and dead roots. The difference between the clean-till and reduced-till systems is that the reduced-till system leaves additional residue near the soil surface where it has greater effect than residue buried more deeply by the moldboard plow in the clean-till system. The major difference in the no-till system from the other systems is from additional residue near the soil surface and the additional credit given in equation 9.12 for buried residue B_{rs} because of a reduced soil consolidation subfactor c_s. The reduced soil consolidation subfactor has even greater effect in the grass system that has no soil disturbance than in the no-till system where narrow strips are disturbed to plant the seeds. Another factor that reduces the soil

biomass subfactor s_b in the grass system is greater live and dead root biomass at the high grass production level than for the high corn yield. More dead root biomass is produced by root sloughing (death) with the grass than is left after the corn harvest.

The soil biomass subfactor is a function of location as illustrated in Table 9.4 because decomposition of buried residue and dead roots is related to monthly precipitation and temperature, which vary by location. For example, the soil biomass subfactor for the 2000 lbs/acre grass production level is 0.22, 0.27, and 0.33 at St. Paul, MN; Columbia, MO; and Baton Rouge, LA, respectively. Decomposition is much higher at Baton Rouge, LA than at St. Paul, MN because of increased temperature and precipitation, especially during winter at Baton Rouge, LA where temperatures are sufficiently high for significant decomposition to occur. The relative effect of location increases as production level (i.e., biomass level) increases.

Values for the soil biomass subfactor are significant and comparable in magnitude to values for other subfactors. Although ground cover is frequently considered to be the single most important variable in RUSLE2, the soil biomass subfactor can be equally important. Perhaps most important is the total amount of biomass in a cover-management system and how that biomass is distributed between the biomass pools.

All features of cover-management systems should be considered rather than focusing on a single variable such as ground cover as a measure of erosion control effectiveness.

9.2.5.3. How biomass is added to and removed from the soil

9.2.5.3.1. Live root biomass. RUSLE2 obtains values for live root biomass from the **vegetation description** in the **vegetation component** of the RUSLE2 database for the **current vegetation**. A name for a vegetation description is entered for each operation with a **begin growth process** in each **cover-management description** in the RUSLE2 database. RUSLE2 begins to use values for this vegetation description on the date of the operation that contains the begin growth process.

The live root biomass values in a vegetation description are for the upper 4 inches (100 mm), whereas equation 9.12 uses live root biomass values for the upper 10 inches (250 mm). RUSLE2 uses the live root distribution illustrated in Figure 9.14 to compute live root biomass in the upper 10-inch (200 mm) depth from the input values for the 4 in (100 mm) depth.[82] The distribution in Figure 9.14 is used for all vegetations[83] and all time.

[82] RUSLE2 divides the soil into 1-inch (25 mm) layers to account for soil biomass. Depths of disturbance are rounded to the nearest 1-inch (25 mm) so that the depth of disturbance corresponds with the bottom of a soil layer. The number of layers considered in an operation depends on the number of 1-inch (25 mm) in the depth of disturbance. Thus, an operation with a 2-inch disturbance depth only involves two layers. The

Figure 9.14 shows that most of the live root biomass is in the upper 4 inches (100 mm) of soil, which is a major reason for the 4-inch (100 mm) depth used for the root biomass input values in the RUSLE2 database.[84]

An input for rooting depth is not required by RUSLE2, which does not consider how rooting depth varies with vegetation or plant maturity.

9.2.5.3.2. Dead root biomass. Live roots become dead roots in one of three ways. One way is by including an operation in the **cover-management description** that has a **kill process**. The live root biomass for the **current vegetation** on the date of this operation is added to the dead root biomass pool and the live root biomass becomes zero.

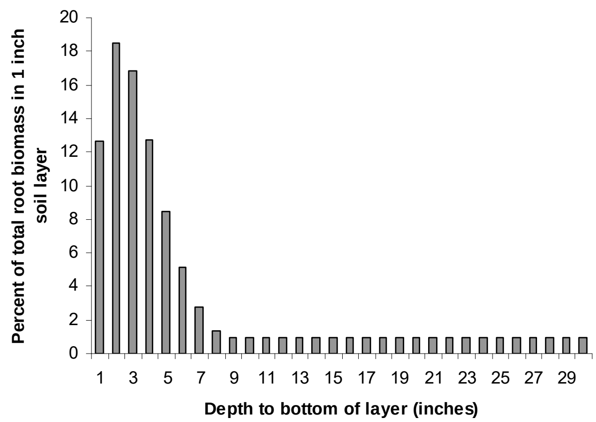

Figure 9.14. Distribution of live root biomass assumed for RUSLE2.

The second way that live root biomass becomes dead root biomass is by root sloughing and root death during growth periods, similar to canopy senescence (and live aboveground death during growth periods). Root death and sloughing is an important source of dead root biomass for perennial and similar types of vegetation to create a soil organic pool. The amount of root sloughing in a year ranges from about 25 to 40 percent of the root biomass.[85]

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minimum depth that RUSLE2 recognizes is 1 inch (25 mm).

[83] Data from several literature sources for major agricultural crops of corn, soybeans, wheat, and cotton, several hay and pasture crops, and for selected vegetable crops were reviewed to determine the distribution in Figure 9.14 at plant maturity. The relative shape of the root distribution was very nearly the same for all crops. The rooting depth for the fine roots judged to have the most effect on soil loss did not vary among crops, except that the rooting depths for field and pasture crops was about twice that for vegetable crops. Even though rooting depth differs among plant types and with plant development, RUSLE2 empirically captures the main effect of roots on soil loss.

[84] The root distribution in RUSLE2 differs between from the one used in RUSLE1. RUSLE1 assumes that the root biomass in the second 4 inch (100 mm) soil layer is 75 percent of that in the top 4 inch (100 mm) layer and that no roots occur below 8 inches (200 mm). Based on Figure 9.14, RUSLE1 assumed significantly too much root biomass below the 4 inch (100 mm) soil layer below the upper 4 inches (100 mm) of soil.

[85] For additional information, see Reeder, J.D., C.D. Franks, and D.G. Michunas. 2001. Root biomass and microbial processes. In: The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. R.K. Follett, J.M. Kimble, and R. Lal (eds). Lewis Publisher, Boca Raton, FL.

RUSLE2 represents daily root death during growth periods by multiplying daily live root biomass by a fraction. RUSLE2 represents root sloughing by a decrease in the root biomass during the year, much like RUSLE2 determines senescence by a reduction in canopy. Input values for root biomass increase when growth occurs and decrease after plant maturity when live root biomass is being lost by root sloughing.[86] Roots develop more rapidly than does canopy and reach maturity while the canopy is still adding biomass. Root sloughing can be assumed to either precede or parallel canopy senescence. Values for the temporal distribution of root biomass can be manually developed and entered for vegetations in the RUSLE2 database. Also, RUSLE2 includes an easy-to-use procedure that can be used to construct temporally varying root biomass values based on dates of maximum and minimum root biomass and root biomass values at those dates. RUSLE2 also has a procedure that estimates root biomass using built-in values for the ratio of root biomass to aboveground biomass production for selected plant communities. See **Section 11** that describes the vegetation component of the RUSLE2 database for additional information.

RUSLE2 determines the amount of root sloughing on each day by comparing the live root biomass values on a given day with the live root biomass on the previous day. RUSLE2 assumes that a decrease in live root biomass from one day to the next is caused by root sloughing and adds the decrease to the dead root biomass pool. RUSLE2 computes daily root biomass death by multiply daily root live biomass by a fraction. Daily root death biomass is added to the dead root biomass pool.

Using a single root biomass for the entire year for perennial type plants, including pasture and hay crops grown for several years, causes RUSLE2 to over estimate erosion because the dead root biomass pool that accumulates from root sloughing is not represented.

The third way that live root biomass becomes dead root biomass is when the live root biomass on the first day of a new **vegetation description** is less than the live root biomass on the last day when the current vegetation is used. The difference in live root biomass is added to the dead root biomass. This procedure is used when only a portion of the live root biomass is to be transferred to the dead root biomass pool because the **kill process** in an operation transfers the entire live root biomass to dead root biomass.

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[86] The time invariant C factor in RUSLE1 uses a single representative value for root biomass for the entire year and does not consider root sloughing and the accumulation of a dead root biomass pool that can significantly reduce soil loss. Also, the time invariant C factor in RUSLE1 does not consider the accumulation of a buried residue biomass pool that can significantly reduce soil loss. Although the time invariant C factor in RUSLE1 was easy to use, it could seriously over estimate soil loss by not considering these important soil biomass pools. Thus, RUSLE2 does not include a time invariant cover-management computation, but it does include many of the easy to use features of the RUSLE1 time invariant C factor so that root sloughing can be easily considered using simple inputs that mimic RUSLE1 inputs. RUSLE1 can consider these soil biomass pools by using its time variant C factor with temporally varying canopy and root biomass values.

This procedure is used to apply RUSLE2 to intercropping type situations. Intercropping involves growing multiple crops at the same time where they typically have different seeding and harvest dates. Examples include planting a cover crop before silage harvest, planting a legume in small grain where the legume is harvest for hay after the grain is harvested, and weeds that develop before a crop is harvested. The procedure is illustrated where a cover crop is seeded before a silage corn crop is harvested. The cover crop provides vegetative cover to control erosion after the silage crop is removed by harvest. Values for live root biomass for this cover-management description are given in Table 9.5.

This **cover-management description** involves three **vegetation descriptions**. The first one is for the silage corn. The second one is for the composite of the rye, which is seeded on June 8, and the silage corn growing together. The third vegetation description is for the rye after the silage corn is harvested on August 8.

RUSLE2 detects that the live root biomass for the new vegetation, which is the rye after the silage has been harvested on August 8, is less than the live root biomass of the current vegetation, which is the composite of the corn and rye, on August 8. The difference of 950 lbs/acre in the upper 4 inches between the 1380 lbs/acre on August 8 for the current vegetation and the 430 lbs/acre for the new vegetation is the amount of live root biomass that is put in the dead root biomass. This 950 value represents the live root biomass of the silage corn on the date that it was harvested and killed. The live root biomass value for the rye vegetation immediately after the silage harvest represents conditions on the first day that this particular **vegetation description** is used, not the date that the vegetation was seeded.

Root biomass and other values used in the vegetation description can start at any time as required to describe the vegetative conditions for a cover-management system. The values for day zero and beyond describe conditions on the day that RUSLE2 is to begin using that vegetation description.

The **silage harvest operation** does not include a **kill process** to kill the corn. If a kill process had been included in the operation, the entire live root biomass would have been transferred to the dead root biomass. Only the corn live root biomass is to be transferred to the dead root biomass. The difference of 950 lbs/acre in the upper 4 inches represents the change in live root biomass from "killing" the corn and allowing the rye to continue "growing." RUSLE2 adds this difference to the dead root biomass pool.

Dead root biomass is lost by decomposition, which is a function of daily precipitation and temperature, and the decomposition half life for the roots. RUSLE2 uses the same decomposition half life for the dead roots as for aboveground biomass. RUSLE2 maintains a biomass pool for dead roots, much like a litter layer on the soil surface. The amount of biomass that RUSLE2 computes is a function of location. The biomass in these pools is greater at locations where decomposition is less because of reduced temperature and rainfall, such as the Northern US in comparison to the Southern US. The accumulation of biomass in the dead root biomass pool can significantly reduce erosion as computed by equation 9.12.

Although operations that include a disturb soil process resurface buried residue, these operations do not resurface dead roots. The dead roots that are most important for influencing rill and interrill erosion are fine roots that are assumed to be tightly bound to the soil so that they are not resurfaced.

Table 9.5. Values for two vegetations: silage corn interseeded with rye to provide cover after the silage is harvested

Calendar date	Days since begin growth	Root biomass (lbs/acre in top 4 inches)	Comment
10-Mar	0	0	Operation with begin growth process that uses silage corn vegetation description
25-Mar	15	40	
9-Apr	30	160	
24-Apr	45	320	
9-May	60	480	
24-May	75	760	
8-Jun	0	950	Operation with begin growth process that uses a vegetation description for the composite of the silage and rye; rye seeded on this day
23-Jun	15	980	
8-Jul	30	1080	
23-Jul	45	1280	
8-Aug	60	1380	Silage harest operation, silage corn harvested which removes the corn vegetative cover, kills corn roots, rye continues to grow
8-Aug	0	430	Silage harvest operation contains a begin growth process as last process in list of processes used to describe that operation. This begin growth process begins to use the rye vegettion description having values on day 0 appropriate for the date of the silage harvest
22-Aug	15	530	
7-Sep	30	610	

actual vegetation description includes additional dates to complete growth of the rye

9.2.5.3.3. Buried residue. Buried residue is added to the soil in three ways: (1) a fraction of the decomposed ground cover biomass is added, (2) a fraction of the ground cover biomass is buried by certain operations, and (3) biomass is placed directly into the soil with certain operations.

Each day, RUSLE2 arbitrarily adds a fraction of the surface (flat) layer of biomass (i.e., crop residue, plant litter) that decomposes on that day to the upper 2 inch (50 mm) soil layer. The fraction varies from zero if the soil has been recently mechanically disturbed to 0.25 if the soil is fully consolidated as a function of the soil consolidation subfactor s_c. RUSLE2 uses this procedure to accumulate organic matter at the soil surface on pastureland, rangeland, no-till cropland, and other lands not regularly tilled or mechanically disturbed.

Operations with a **disturb soil process** transfer (bury) a portion of the surface (flat) layer of biomass to the buried residue pool. The amount of residue that is buried is the product of the surface residue mass and a **burial ratio**. Values for the burial ratio are entered for each **operation description** having a disturb soil process in the **operation component** of the RUSLE2 database. RUSLE2 distributes the residue that it buries according to one of **three mixing distributions** illustrated in Figure 9.15. A distribution is selected when a **tillage type** is selected to describe an operation having a disturb soil process. The distributions **inversion with some mixing** is for operations like a moldboard plow that invert the soil. Most of the buried residue is placed in the lower half of the depth of disturbance. The distribution **mixing with some inversion** is for operations like a tandem disk, chisel plow, and field cultivator that place most of the residue in the upper half of the depth of disturbance. These operations bury residue primarily by mixing but involve some burial by inversion. The distribution **mixing only** applies where almost all of the burial is by mixing with very little burial by inversion for operations like rotary tillers, subsoilers, and manure and fertilizer injectors that place most of the residue in the upper one third of the depth of disturbance. One of these three mixing distributions is assigned to each operation with a **disturb soil** process when data for the operation are entered into the RUSLE2 database. The placement distribution for the **lifting and fracturing** and **compression** tillage types place the buried residue using the **mixing only** distribution.

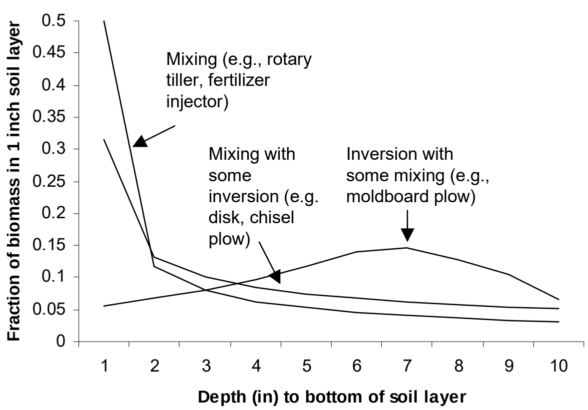

Figure 9.15. The initial distribution when residue is buried by an operation.

Buried residue can also be added to the soil in RUSLE2 by placing **external residue** in the soil with an operation that includes an **add residue process**. A disturb soil process must be included in the operation description to place external residue in the soil because the assumption is that the soil must be disturbed to place material in it. External residue is placed in the lower half of the disturbance depth as illustrated in Figure 9.16.

Buried residue is lost from the soil by being resurfaced by an operation that includes a **disturb soil process** and by decomposition. Buried residue is removed from the soil by being resurfaced and transferred to the surface (flat residue) pool by soil disturbing operations. The amount of **resurfaced residue** is the product of the amount of buried residue in the depth of disturbance at the time of the operation and a **resurfacing ratio** value assigned to the operation description in the RUSLE2 database. The resurfaced residue is extracted layer by layer by first taking out the entire buried residue in the layer, if necessary, from the top soil layer and then moving to the next and succeeding layers until the total mass of resurfaced residue is obtained. In many cases, only a portion of the buried residue in the top 1-inch (25 mm) layer is extracted. Extraction seldom extends beyond the second layer. RUSLE2 does not resurface dead roots as discussed in **Section 9.2.5.3.2.**

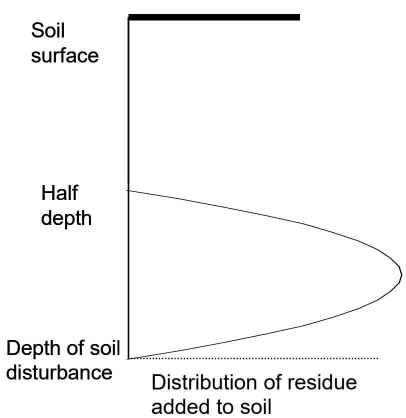

Figure 9.16. Distribution of residue placed in by an operation that has an "add residue" process.

Buried residue lost by decomposition as function of daily precipitation and temperature and the decomposition half life of the buried residue. RUSLE2 assumes that the decomposition half life is the same for buried residue as for the surface, flat residue. RUSLE2 maintains biomass pools for buried residue like it does for dead roots and a litter layer on the soil surface that is a function of location. The biomass in these pools is greater at locations where decomposition is less because of reduced temperature and rainfall, such as the Northern US in comparison to the Southern US. The accumulation of biomass in the buried residue pool can significantly reduce erosion as computed by equation 9.12.

Table 9.6. Retention coefficient values for redistributing residue among soil layers

Layer	Mixing distribution: Inversion w/mixing	Mixing w/inversion	Mixing
1 (top)	0.40	0.32	0.50
2	0.40	0.39	0.56
3	0.40	0.47	0.61
4	0.40	0.54	0.67
5	0.40	0.62	0.72
6	0.40	0.69	0.78
7	0.40	0.77	0.83
8	0.40	0.84	0.89
9	0.50	0.92	0.94
10	1.00	1.00	1.00

9.2.5.4. Redistribution of dead roots and buried residue in soil by soil disturbing operations

Operations with a **disturb soil process** redistribute buried residue and dead roots according to the **mixing distribution** assigned to that operation. When a soil disturbing operation occurs, RUSLE2 first redistributes the buried residue and dead roots and then buries the residue. Two steps are involved for an operation that has an **inversion with some mixing** distribution. The first step is to invert the soil layers with their buried residue and dead roots by layer so that the biomass in the bottom layer becomes the biomass in the top layer, the biomass in the next to bottom layer becomes the biomass in the next to the top layer, and so forth. The second step transfers biomass between soil layers. A **filtering** concept is used in RUSLE2 where each soil layer is **sifted** so that some of the biomass in each layer is retained in the layer and the remainder of the biomass moves down to the next layer. The amount retained is the product of the biomass in the layer and a retention coefficient having values shown in Table 9.6.[87] The retention values for the **inversion with some mixing** distribution are all equal except for the values for the bottom two layers. The value for the bottom layer must be 1 so that no biomass passes through the bottom layer and the slightly higher value for the next to bottom layer was empirically determined to give a good fit between experimental data and computed values. The equal retention values imply that the biomass is equally likely to move downward in the lower part of the disturbance depth as in the upper part. In effect, the soil is uniformly "stirred, mixed, and sifted" over the disturbance depth.

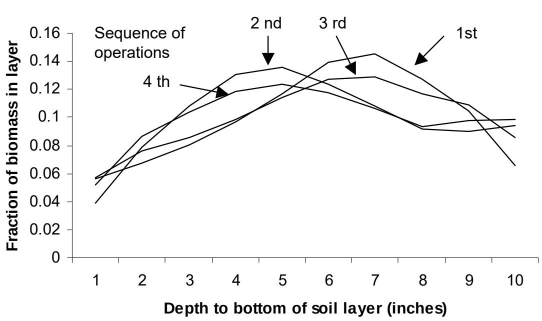

Figure 9.17. Initial burial and redistribution of residue by repeated operations with an inversion mixing distribution (e.g., moldboard plow)

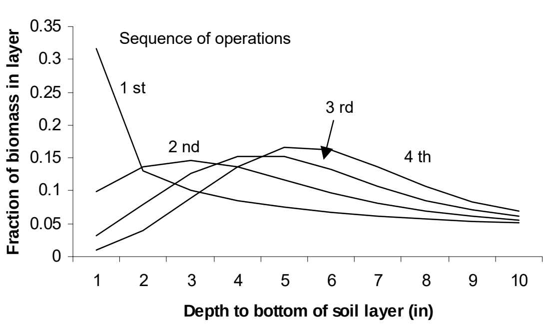

Figure 9.18. Initial burial and redistribution of residue by repeated operations with a mixing and some inversion mixing distribution (e.g., tandem disk)

Only one step is involved in redistributing biomass with the two mixing distributions that minimally involve inversion. The retention coefficient for the top layer is assumed to be same as the fraction of residue placed in the top layer by burial. The values for the retention coefficients for the remaining layers are linearly increased with depth to a value of 1 as shown in Table 9.6. The value of 1 for the last layer prevents biomass from passing through the bottom layer. The increase in retention values with depth means that biomass is more likely to move down in the upper part of the disturbance depth than in the bottom part and that stirring and mixing decrease with depth.

Figure 9.17 shows the buried residue distributions after each of four repeated

dure used to distribute buried residue in the soil
ts is described in **Section 13**. The RUSLE2
here material becomes uniformly distributed in
RUSLE1 assumes that the material is uniformly

operations for a moldboard plow that has an **inversion with some mixing** distribution where no additional residue is buried after the first operation. The buried residue distribution gradually becomes more uniform with each operation. Figure 9.18 shows buried residue distribution with repeated operations with a tandem disk where residue burial is mainly by mixing. After repeated operations, a bulge of biomass develops that moves downward in the soil. The bulge becomes increasingly concentrated with each operation and moves downward less with each operation. Thus rather than the distribution becoming increasingly uniform as assumed in some models, RUSLE2 computes an increasingly non-uniform distribution for the mixing type distributions. Implements like tandem disks and rotary tillers are assumed to bury residue uniformly in the soil, but in fact they only bury residue uniformly under certain conditions, which occurs with about two passes as can be seen from Figure 9.18.

9.2.5.5. Spatial non-uniformity of soil biomass

The soil biomass for live and dead roots and buried residue is spatially non-uniform for row crops, widely disperse plants like clumps of shrubs and grass on rangelands, and tree seedlings in a forest. However, RUSLE2 assumes that all soil biomass is uniformly distributed, even when the operation only disturbs a portion of the soil surface.

9.2.5.6. Assigning input values that determine soil biomass

The amount of soil biomass is a critical variable in determining how a cover-management system affects erosion. The three principal sources of soil biomass are from live root biomass, plant litter and crop residue, and externally added residue. The mass of external residue is based on dry matter basis and is known. Root biomass values for a **vegetation description** should be selected by comparing the vegetation's characteristics with those of vegetation descriptions in the RUSLE2 **core database**. When selecting root biomass values for a particular vegetation description, the role of fine roots versus coarse roots must be considered. For example, even though carrots and potatoes make up root biomass, their mass is not considered in assigning root biomass values because those "coarse roots" have little effect on erosion. In cases where some credit is to be taken for coarse roots, some, but not all, of their biomass is entered along with the biomass of the fine roots.

A key factor in selecting input root biomass values is to account for the temporal variation in root biomass so that the effect of root sloughing is captured by RUSLE2.

Do not make field measurements of root biomass values to determine input values for RUSLE2. Measuring root biomass is very difficult, tedious, and tiresome and should only be done in a research setting. Large errors are common unless extreme care is taken and even then the results may show much variability. The ratio values in the RUSLE2

core database used to determine root biomass values for rangeland plant communities have been chosen based on measured soil loss values obtained during rainfall simulator experiments.[88] Other root biomass values in the RUSLE2 **core database** have been selected from the scientific literature and these values were used when equation 9.12 was fitted to erosion data.

Use of root biomass values that have not been checked for consistency with values in the RUSLE2 *core database* can cause serious errors in RUSLE2.

The other major source of soil biomass is from decomposition of plant litter and crop residue on the soil surface and from the incorporation of crop residue into the soil. The amount of plant litter is determined by senescence of the plant canopy and the amount of biomass associated with that loss of canopy. The amount of residue produced by a crop is determined by the residue to yield relationships defined for the crop and is entered in the vegetation component of the RUSLE2 database. The other important factor that determines the amount of buried residue is the flattening, burial, and resurfacing ratios used to describe operations in the operation component of the RUSLE2 database.

Even though a plant community may be a mixture of species, RUSLE2 represents the plant community as a single vegetation description where input values are selected to describe the composite effects of the vegetation. RUSLE2 "grows" only one vegetation at a time. RUSLE2 cannot take data from two vegetation descriptions, such as corn and rye, and combine them into a single composite vegetation.

9.2.5.7. Comments

RUSLE2 does not consider how soil texture or other soil properties affect the distribution of residue and roots in the soil. Although RUSLE2 adjusts amount of biomass buried by a soil disturbing operations as a function of speed and depth, RUSLE2 does not adjust the distribution of the residue as a function of operation speed or depth.

9.2.6. Soil consolidation[89]

A mechanical disturbance loosens soil and increases its erodibility, which in turn increases erosion. After a mechanical soil disturbance, soil erodibility decreases as soil

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[88] The data used to calibrate RUSLE2 to rangelands were collected as a part of the Water Erosion Prediction Project (WEPP) by R. Simantion and others, USDA-ARS, Tucson, AZ. See Table 5-4 in AH703.

[89] A prior land use (PLU) subfactor was used in RUSLE1. This subfactor was the product of the soil consolidation subfactor and the soil biomass subfactor. This same product is used to display RUSLE2 subfactor values in some of the templates.

primary particles and aggregates become cemented together by wetting and drying and

Soil consolidation in RUSLE2 refers to the decrease in soil erodibility following a mechanical soil disturbance rather than an increase in bulk density.

other soil processes, which is the main soil consolidation effect. A mechanical soil disturbance decreases the bulk density of soil. Increases in soil bulk density do not greatly reduce soil erodibility, except when compaction is extreme.

9.2.6.1. Soil consolidation effect

Figure 7.3 is a plot of the soil consolidation subfactor s_c as it decreases with time after a mechanical soil disturbance. The soil is assumed to be 0.45 times as erodible at full consolidation as it is immediately after a disturbance. A soil disturbance resets the soil consolidation subfactor to 1 and it begins to decrease again with time. Seven (7) years is normally assumed for the time for the soil to become fully consolidated after a mechanical disturbance in the Eastern US where rainfall events are sufficiently frequent for the soil to experience repeated wetting and drying cycles required for the cementing process (See **Section 7.8**). RUSLE2 computes an increased **time to soil consolidation** up to 20 years as annual precipitation decreases from 30 inches (760 mm) to 10 inches (250 mm). A constant 20 years for time to soil consolidation is used where annual precipitation is less than 10 inches (250 mm). This increased time to soil consolidation reflects how the effects of a mechanical soil disturbance persist longer in low precipitation areas where reduced water is available and less frequent wetting and drying cycles occur.

The soil consolidation effect is greatest for those soils that have the greatest and most active cementing agents. These agents are most closely related to clay and organic matter particles because of their high specific surface area. Thus, the soil consolidation effect is greatest for soils having a high organic matter content, characteristic of cover-management systems involving a high level of soil biomass. The effect of organic matter content as affected by cover-management system is captured in the soil biomass subfactor s_b computed with equation 9.12.

The soil consolidation effect is also a function of soil texture because of the role of clay in cementing soil particles. The soil consolidation effect is greatest for fine textured soils with a high clay content and least for coarse textured soils with a low clay content. However, RUSLE2 does not consider the effect of soil texture on the soil consolidation subfactor.[90]

[90] The soil consolidation subfactor in RUSLE2 is one of the variables least well defined by scientific research. Its effect varies with many factors, but the research data are not sufficient to derive an empirical equation for the effect of soil conditions on the time to soil consolidation. Although, the soil consolidation

9.2.6.2. Importance of soil consolidation subfactor to other variables

The soil consolidation subfactor has indirect effects in RUSLE2 by being a variable in equations used to compute values for other cover-management subfactors. For example, the consolidation subfactor s_c is used in equation 9.12 to compute values for the soil biomass subfactor s_b. The soil consolidation subfactor is used to compute the rill-to-interrill erosion ratio in equation 8.3 where soil consolidation is assumed to reduce rill erosion much more than interrill erosion. The ratio of rill-to-interrill erosion affects the slope length effect and the ground cover subfactor g_c. Mulch is assumed to have reduced effectiveness on steep, cut construction slopes, which are detected in RUSLE2 by a low soil consolidation subfactor and low soil biomass values.

The soil consolidation subfactor is also a variable in RUSLE2 equations used to compute runoff index values (curve numbers) and runoff, which is used to compute how support practices affect soil loss (see **Section 14**). For example, when the soil is consolidated (i.e., s_c values near 0.45), infiltration is assumed to be low and runoff high if no soil biomass is present. A construction site where a surface soil layer was cut away without disturbing the underlying soil represents this condition. However, if the soil is undisturbed, which is indicated by a low s_c value, and contains a high level of soil biomass, infiltration is assumed to be high and runoff low. A high production permanent pasture represents this condition.

An undisturbed soil is required for a layer of high organic matter to develop at the soil surface on range, pasture, and no-till cropland. The soil consolidation subfactor is used as an indicator of the potential for this layer to develop. This effect is captured in equation 9.12 for the soil biomass subfactor s_b.

The portion of the soil surface that is mechanically disturbed during a cover-management system determines the overall effect of soil consolidation. The effects of the portion of the soil surface disturbed and the soil consolidation subfactor are illustrated in Figure 9.19 for a no-till corn cropping system at Columbia, MO.[91] One of the curves in Figure 9.19 is where the only soil disturbance is by a no-till planter that disturbs the soil in strips for a place to plant the seeds. The portion of the soil surface disturbed by the planter was varied from none to full width disturbance. No other variable such as burial ratio that would normally vary with the portion of the soil surface disturbed was changed. Thus the only effect represented is the effect of soil consolidation as reflected by portion of the soil surface disturbed. The other curve is where a fertilizer injector that disturbs 50

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subfactor equation was primarily derived from soil loss measured at the single location Zanesville, OH, limited data from other locations indicate that the equation is valid in general.

[91] The effects computed for the soil consolidation subfactor differ between the non-Req and Req applications. The Req applications give increased credit for soil biomass, which is affected by the soil consolidation subfactor, but the Req applications do not adjust the slope length factor and the ground cover subfactor values as a function of the rill-to-interrill ratio that are used in non-Req applications.

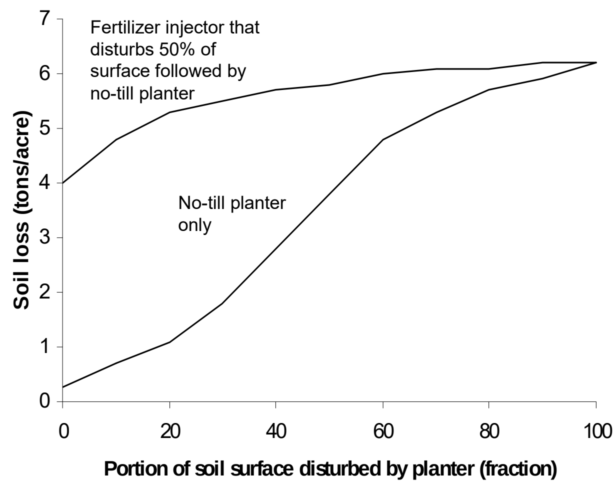

Figure 9.19. Effect of portion of soil disturbed on soil loss at Columbia, MO for no-till corn at 110 bu/acre. Fertilizer injector does not bury or resurface residue.

percent of the soil surface precedes the planter. Portions of the soil surface disturbed by the planter were varied while the 50 percent portion disturbed by the fertilizer injector was fixed.

The ratio of soil loss for the no-till planter with no disturbance and without the fertilizer injector to soil loss with full disturbance in Figure 9.19 is 0.04, which is much more effect than the 0.45 value for the full soil consolidation subfactor for no disturbance. Several variables cause additional effects beyond the 0.45 value directly associated with the soil consolidation subfactor. The soil consolidation affects the soil biomass subfactor as computed with equation 9.12. Another variable is the soil depth over which buried residue mass is averaged for equation 9.12 is reduced as the soil consolidation subfactor decreases. Another variable is the reduced slope length effect that is computed as a function of the rill to interrill erosion ratio that RUSLE2 computes as the soil consolidation subfactor decreases (see **Section 8.1.1**). Another variable is a decreased ground cover subfactor that is computed as a function of the rill-interrill erosion ratio that is a function of the soil consolidation subfactor (see **Section 9.2.2**).

The second curve in Figure 9.19 where a fertilizer injector precedes the no-till planter illustrates the importance of considering all soil disturbing operations in a cover-management system instead of giving attention solely to a single operation like a planter or drill. Varying the portion of the soil surface disturbed by the planter when it follows the fertilizer injection that disturbs a relative large portion of the soil surface had relatively little effect on erosion. The fertilizer injector is the dominant operation in terms of the soil consolidation subfactor effect. Most of the benefits of no-till cropping are lost by the fertilizer injector. The fertilizer injector disturbs the soil more than the no-till planter that follows the fertilizer injector. Consequently, adjusting the portion of the soil surface disturbed by the planter had little effect on the RUSLE2-computed soil loss..

9.2.6.3. Definition of mechanical soil disturbance

Soil disturbance, as used in RUSLE2, occurs when an operation fractures and loosens the soil, displaces soil, mixes soil and surface residue so that the interface between the residue and the surface soil is no longer distinct, and disrupts a high organic matter layer at the soil surface.

Operations that seed crops like corn, soybeans, and wheat in rows and that inject fertilizer and manure with thin shanks disturb only strips of soil and not the entire soil surface. An important input value, as illustrated in Figure 9.19, is the portion of the soil surface disturbed by each operation. A definition of mechanical soil disturbance is required to assign values for the portion of the soil surface that is disturbed by an operation.

A lower limit of 15% for portion of the soil surface disturbed should be used for no-till implements. This limit is related to the computational accuracy of RUSLE2; it is not related to definitions of no-till as used by NRCS or others.

When an operation displaces soil, the source area of the soil is included in the soil surface disturbed and the receiving area is included under certain conditions. The receiving area **is not** included in the area disturbed if the resulting soil depth from the displaced soil is so thin, less than 0.5 inch (10 mm) as a guide, that it has little effect on detachment by raindrop impact (interrill erosion) or detachment by runoff (rill erosion). The soil surface should be essentially level after an operation to assign a low value to the portion of the soil surface disturbed. The receiving area **is** included in the disturbed area if the surface residue and soil were mixed by the operation or any high organic matter soil layer at the soil surface was disrupted. The receiving area **is** included in the area disturbed, even though the surface residue has not been mixed with soil or high organic matter layer at the soil surface has not been disrupted, if displaced soil is deeper than about 0.5 inches (10 mm) such that significant amounts of interrill and rill erosion occurs because of exposed bare soil. Ridges and furrows are an indication of a high portion of the soil surface disturbed, especially where soil thrown from either side meets to form the ridge. Machines and implements, like scarifiers and hoe drills that involve shanks and shovels typically disturb a greater portion of the soil surface than implements that involve straight coulters. However, concave coulters and disks can throw large amounts of soil, resulting in almost the entire surface being disturbed.

New input values for portion of soil disturbed by an operation should be carefully examined for consistency and guidelines established so that input values are consistently assigned for other new operations.

9.2.6.4. How RUSLE2 handles strips

RUSLE2 does not keep track of individual strips of disturbed areas through time. RUSLE2 computes only a single composite soil consolidation subfactor value at any time. When an operation occurs that disturbs only a portion of the soil surface, RUSLE2 computes a composite soil consolidation subfactor value based on the portion of the soil surface that is disturbed by using a subfactor value of one (1) for the portion of the soil surface disturbed and the subfactor value at the time for the undisturbed portion at the time of the operation. This composite soil consolidation subfactor value is used in the RUSLE2 soil consolidation subfactor equation, represented by Figure 7.3, to compute an effective time after last soil disturbance. RUSLE2 accounts for time after a soil disturbance by starting with this effective time after last disturbance and proceeds.

9.2.6.5. Assigning values for portion of soil disturbed

A value of one (1) is assigned to the portion of the soil surface disturbed for most full width operations like scarifiers, moldboard plows, offset disks, tandem disks, chisel plows, and field cultivators. The portion of the soil surface disturbed by implements like row cultivators, planter, drills, and fertilizer and manure injectors that disturb strips of soil may be, but are not necessarily, less than one (1). Values for the portion of the soil surface disturbed selected for these operations should be consistent with values assigned to comparable operations in the RUSLE2 **core database**, which should be consulted first before values are assigned to new operations being put in the operation component of the RUSLE2 database. However, the portion disturbed can depend on local conditions, specific machines, and individual operators. Thus, input values may need to be adjusted from the **core values** based on the guidelines in **Section 9.2.6.3.**

Blading and grading used in construction operations must be carefully considered when a value for the portion of the soil disturbed is assigned to these operations. A grading operation for fill material should include a **disturb soil** process that uses a value of one (1) for the portion of the soil surface disturbed, even if the soil has been compacted with a roller or other compaction device. Compaction of the soil does not greatly reduce soil erodibility. Repeated wetting and drying and related soil processes must occur to cement the soil particles for the soil to be **consolidated**. A zero (0) is assigned to portion of the soil surface disturbed for a grading operation that cuts and removes a soil layer and leaves the underlying soil undisturbed. Thus, RUSLE2 assigns a value of one (1) for the soil consolidation subfactor for a fill slope and a value of 0.45 to a cut slope. However, if the cut slope has been ripped with a scarifier, disked for a seedbed, or mulch crimped in, a value is assigned to the portion of the soil disturbed according to the guidelines in **Section 9.2.6.3.**

Important RUSLE2 rules:
Surface material cannot be buried without using an operation with a *disturb soil* process
Material cannot be placed in the soil (e.g., manure injection) without an operation with a *disturb soil* process
Roughness cannot be created without an operation with a *disturb soil* process
Select values for portion of soil surface disturbed based on guidelines in section 9.2.6.3.

9.2.7. Ponding effect

Water ponds on flat lands during intense rainfall. The ponded water depth reduces rainfall erosivity. The effect is greatest along the Gulf Coast and the lower Atlantic Coast of the US. For example, RUSLE2 computes that the ponding effect reduces erosion by 46 percent at New Orleans, Louisiana on a 0.5 percent slope.

RUSLE2 computes values for the ponding sub-factor as a function of the 10 yr-24 hr precipitation amount and land steepness. The ponding effect sub-factor decreases as the 10 yr-24 hr precipitation amount increases, which is indicative of increased rainfall intensity. The ponding effect sub-factor increases as land steepness increases. For example, RUSLE2 computes only a 6 percent reduction in erosion because of the ponding effect for a 5-percent land steepness at New Orleans.

The RUSLE2 assumption is that the ponding effect is not affected by soil-surface roughness or soil ridges.

9.2.8. Antecedent soil moisture

The level of soil moisture affects infiltration and runoff to some degree at all locations. However, the effect is least where large amounts of rainfall frequently occur such as in the humid Southeastern US. The effect is more pronounced in the Western portion of the Great Plains in the US. Soil moisture is removed by growing crops depending on the type of crop and its production level. Soil loss is less following a crop that extracted much of the soil moisture in a low rainfall area. This effect is especially pronounced in the NWRR where rainfall is relatively low and environmental conditions associated with timing of rainfall and the freezing and thawing of soil under either high or low soil moisture content. A soil moisture subfactor is needed in the NWRR for Req applications to account for these special effects.

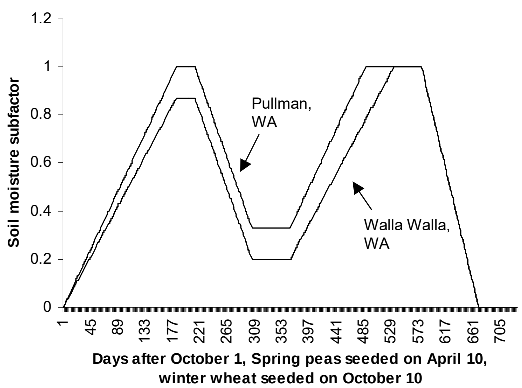

Figure 9.20. Antecedent soil moisture subfactor values for two locations in Washington for a winter wheat-spring pea rotation. The first peak is the effect of the winter wheat and the second one is the effect of spring peas.

9.2.8.1. Antecedent soil moisture subfactor effect

Values for the antecedent soil moisture subfactor s_m are illustrated in Figure 9.20. Subfactor values are 1 when the soil profile is “filled” relative to the unit plot and less than 1 when the soil profile is depleted of moisture relative to the unit plot.

As Figure 9.20 illustrates, the effect is a function of both location and type of crop. Antecedent soil moisture subfactor values are lower at Walla Walla, WA than at Pullman, WA because of less precipitation. Also, the values are lower following wheat than following spring peas because of the water usage difference between the two crops. As always, the values for the antecedent soil moisture subfactor are one (1) for unit plot conditions.

9.2.8.2. Assigning input values

An input value is assigned to each **vegetation description** in the **vegetation component** of the RUSLE2 database. Values are listed in **Section 11.1.6** and in the RUSLE2 **core database** that can be used as a guide for assigning input values used in the antecedent soil moisture subfactor.

The antecedent soil moisture subfactor must only be used in the NWRR for Req applications.

10. COVER-MANAGEMENT DATABASE COMPONENT

The **cover-management component** of the RUSLE2 database contains the **cover-management descriptions** that RUSLE2 uses to compute how cultural practices such as tillage systems for cropped fields, temporary erosion control practices for construction sites, and long term vegetation on a reclaimed mine sites affect erosion.

A **RUSLE2** cover-management description is primarily a list of operations and the dates on which each operation occurs. An **operation** is an event that changes the vegetation, residue, and/or soil in some way. Examples of operations are given in Table 10.1.

Table 10.1. Examples of operations

Operation	Effects	Comment
Moldboard plow	Kills vegetation, disturbs soil, buries residues, redistributions biomass in soil	Primary tillage, first step in growing a crop
Planting	Disturbs a strip of soil, seeds a crop	Includes a **begin growth** process. The name for the appropriate vegetation description is entered to represent the crop being grown
Broadcast seeding	Seeds a particular vegetation. This seeding operation does not disturb the soil.	Includes a **begin growth** process. The name for the appropriate vegetation description is entered to represent the vegetation that is seeded.
Volunteer weeds	Starts growth of volunteer weeds	Includes a **begin growth** process. The name for the appropriate vegetation description is entered to represent the volunteer weeds
Harvest	Kills vegetation and flattens some of the standing residue	Typical operation for crops like corn, soybeans, and wheat
Baling straw	Removes residue, flattens standing residue	Removes residue and flattens remaining standing residue
Silage harvest	Removes live biomass, kills vegetation	Leaves a portion of the live biomass in the field to represent harvest losses
Mowing	Removes live biomass, add cut material back as external residue, regrow vegetation	Cuts the live biomass but leaves it in the field. Does not kill vegetation. **Begin growth** process calls vegetation description that regrows vegetation after mowing
Baling hay	Remove live biomass,	**Begin growth** process calls vegetation

	regrows hay	description for vegetation that regrows after the hay harvest
Frost kills vegetation	Uses a **kill vegetation** process	RUSLE2 does not model plant growth. Must tell RUSLE2 when vegetation is killed, even if it occurs naturally
Fire	Remove residue/cover	RUSLE2 can not remove dead roots from the soil
Apply mulch	Add other residue/cover	Use to apply mulch to represent construction sites
Apply plastic mulch in a vegetable field, water in a rice field, or deep snow at a construction site in mountains	Apply non-erodible cover	Shuts off erosion for period that non-erodible cover is present. Use a **remove non-erodible cover** process to remove cover and to restart erosion.

The cover-management description includes the names of vegetation and residue descriptions needed by certain operations. An operation that includes a **begin growth** process requires that a vegetation description be specified for that operation. The **begin growth** process signals RUSLE2 to begin using information from the specified vegetation description on the operation's date. Similarly, operations with an **add other residue/cover** process require specifying a residue description and the amount of the material being added for the operation. RUSLE2 adds the cover at the specified amount on the date of the operation.

Additional non-event based information is also entered as a part of the cover-management description. For example, the user specifies whether the list of operations is repeated in a cycle (rotation) with a particular frequency or whether RUSLE2 is to compute erosion based on a single occurrence of each operation.

The variables in a cover-management description associated with the list of operations are listed in Table 10.2. The non-event variables that apply to a cover-management description are listed in Table 10.3.

Table 10.2. Variables in a cover-management description

Variable	Comment
List of dates	List of dates for the operations used to describe the cover-management condition (practice)
List of operations	Name of operation description in operation component of the RUSLE2 database containing values that RUSLE2 uses to

	describe the effect of the operation on erosion. Operations are events that change vegetation, residue, and/or soil. The list of operations is the main part of a cover-management description, which represent how cultural practices affect erosion.
List of vegetation descriptions	Name of vegetation description in the vegetation component of the RUSLE2 database containing values used by RUSLE2 to represent the effect of vegetation on erosion. Only one vegetation description is used at a time by RUSLE2. That is, RUSLE2 can not combine multiple vegetation descriptions into a single description.
Yield	Identifies production (yield) level in user defined units
Operation depth	Specifies the disturbance depth of operations that disturbs the soil. Default value is "recommended" value in operation description in operation component of RUSLE2 database. RUSLE2 will adjust for a depth value different from the default value.
Operation speed	Specifies the speed of operations that disturbs the soil. Default value is "recommended" value in operation description in operation component of RUSLE2 database. RUSLE2 will adjust for a speed value different from the default value.
External residue	Name of material (residue description in residue component of RUSLE2 database) added to soil surface and/or placed in soil. RUSLE2 uses values in residue description to compute how material affects erosion. Vegetation produces plant litter and crop residue. That material is considered by operations that manipulate vegetation and its biomass. External residue is material other than that associated with the vegetation descriptions in the cover-management description. Typical external residue includes manure and mulch (applied erosion control materials),
Residue added/removed	User entered mass value (dry weight basis) for material added when external residue is applied. Value shown is for the amount of plant material added from the "current" vegetation is computed by RUSLE2.
Cover from residue addition	Portion of soil surface covered by the added external or vegetation material. Value is computed by RUSLE2. This value is only for the added material and does not include existing surface (flat) cover.
Vegetative retardance	Refers to the degree that the vegetation slows surface runoff. RUSLE2 computes value based on user enter information in the vegetation description.

Table 10.3. Non-event variables used in a cover-management description

Rotation and duration	Is RUSLE2 to process the list operations multiple times in a cycle (rotation) with a certain frequency to represent steady state conditions for the cycle? Duration is the time for the cycle to be repeated. Crops are frequently grown in a crop rotation. The same crop grown each year (e.g., continuous corn) has a one-year rotation. Constructions sites are typically analyzed as a no-rotation. That is, the list of operations in the cover-management description are processed as a single pass through them.
Long term roughness	The soil surface roughness index value that evolves over time after the last soil disturbance.
Build new rotation with this management	Use this procedure to combine existing cover-management descriptions to create a new cover-management description.
Relative row grade	Can be used to specify cover-management description used as a part of a contouring system
Management alignment offset	Specifies the timing of operations when the same cover-management description is used on multiple segments along the overland flow profile.

10.1 Creating a cover-management description

The cover-management description provides information that RUSLE2 uses to compute values for the cover-management subfactors described in **Section 9**.[92] Table 10.4 illustrates a cover-management description for a corn-soybean-wheat rotation while Table 10.5 illustrates a cover-management description for a construction site where mulch is applied, a temporary cover crop is seeded, and permanent vegetation is seeded.

Table 10.4. List of operations for a corn-soybean-wheat 3-yr rotation

Date	Operation	Vegetation	Yield
4/15/1	Twisted shovel chisel plow		
5/1/1	Tandem disk		
5/5/1	Field cultivator		
5/10/1	Planter	Corn 112 bu/ac base yield	150 bu/ac
6/10/1	Row cultivator		
10/15/1	Harvest		
4/15/2	Moldboard plow		
5/1/2	Tandem disk		
5/5/2	Field cultivator		

[92] See Section 17.4.1.4 for information on creating a cover-management description for range, pasture, idle, undisturbed, and similar lands using a time invariant approach.

5/10/2	Planter	Soybeans 25 bu/acre base yield	35 bu/ac
9/10/2	Harvest		
9/15/2	Tandem disk		
9/20/2	Double disk drill	Wheat 35 bu/acre base yield	50 bu/ac
7/1/3	Harvest		
Non-event variable	Long term roughness	0.24 inches (6 mm)	
Non-event variable	Rotation	Yes	
Non-event variable	Duration	3 years	
Non-event variable	Management alignment	Not applicable	
Non-event variable	Relative row grade	10 percent	

Table 10.5. Cover-management description for applying straw mulch, seeding spring barley as temporary vegetation, and seeding a local native grass for permanent cover at a construction site

Date	Operation	Vegetation	Yield	External residue	Amount external residue added/removed
4/1/1	Blade fill material				
4/2/1	Broadcast seed	Spring barley 35 bu/ac base yield	25 bu/ac		
4/3/1	Apply mulch			Wheat straw	4000 lbs/ac
9/15/1	Killing frost				
9/16/1	Shred standing vegetation				
9/17/1	Double disk drill	Local native grass	1000 lbs/ac		
Non-event variable	Long term roughness	0.6 inches (15 mm)			

Non-event variable	Rotation	No			
Non-event variable	Duration	10 years			
Non-event variable	Management alignment	Not applicable			
Non-event variable	Relative row grade	Not applicable			

The first step in creating a RUSLE2 **cover-management description** is to list the dates and events that affect the soil, vegetation, and/or residue. A RUSLE2 **operation description** is selected from the **operation component** (see **Section 13**) of the RUSLE2 database to describe each of these events, even if the event is a natural occurrence such as frost killing vegetation. In general, the list of operations mimics actual events. However, only events that affect erosion are included in the list. For example, an aerial pesticide application would not be included. Be careful not to overlook an important natural event, such as a killing frost. The second step is to add supporting information such as the names for required **vegetation and external residue descriptions** and **application rates** for external residue. RUSLE2 procedures and definitions must be followed in creating a cover-management description to describe a field situation, keeping mind that RUSLE2 is not a simulation model. The input is a description for the field conditions that affect erosion.

A cover-management description can involve as many operations and vegetation descriptions as required. A field description can often be created in multiple ways. An example is the development of permanent, perennial vegetation from seeding to maturity after erosion has stabilized. The **duration** of the cover-management description is longer than the time for the vegetation to reach maturity to allow time for a stable litter layer and soil biomass pool to develop. Assume that three years is required for the vegetation to reach maturity and that an additional three years is needed for the litter layer and soil biomass pool to fully develop. The additional time for the litter layer and soil biomass pool to fully develop depends on temperature and precipitation at the location. The duration of the cover-management description is six years to include time for RUSLE2 to compute the effect on erosion of a fully developed litter layer and soil biomass pools.

The vegetation for this condition can be described with a single vegetation description that covers the entire six year period where the last four years involve duplicate values. A second way to apply RUSLE2 is to create three vegetation descriptions, one for the first year, one for the second year, and one for the third and subsequence year. Each of the six years represented in the cover-management description includes an operation description with a **begin growth** process where the appropriate vegetation description is assigned to the particular year.

RUSLE2 is often used to evaluate erosion for the maturity period alone without concern for erosion during establishment of the permanent vegetation. Examples include estimating erosion on pasture, range, reclamined mine, and waste disposal lands. In this case, a vegetation description of one year is created to represent the vegetation at maturity. Values at the end of the year equal those at the beginning of the year to represent a complete annual cycle. The cover-management description is a 1-year rotation. RUSLE2 cycles through the annual vegetation description a sufficient number of times so that RUSLE2 computes a stable litter layer and soil biomass pool and thus computes a stable erosion rate representative of condition where the permanent vegetation is fully established.

The same agricultural crop such as corn, soybeans, or wheat can be grown year after year (continuous cropping). The same crops can also be grown in a rotation such as a corn-soybean rotation. A cover-management description can be created for each possible combination, although the number of cover-management descriptions becomes large and difficult to manage.

An alternative is to use the **rotation builder** in RUSLE2. The rotation builder is used to combine multiple cover-management descriptions into a single cover-management description. The rotation builder most often is used to combine annual cover-management descriptions to create multiple year cover-management descriptions. The rotation builder can also be used to combine partial year cover-management descriptions for a single crop to create a single year cover-management description such as for vegetable cropping. Another example is using the rotation builder to combine a one-year wheat cover-management description with a two-year corn-soybean cover-management description to create a three-year corn-soybean-wheat cover-management description. In general, the rotation builder can also be used to combine cover-management descriptions of any duration.

The RUSLE2 rules must be carefully followed.

10.2. Discussion of variables used in a RUSLE2 cover-management description[93]

10.2.1. Dates

10.2.1.1. Operations as discrete events and representing continuous activity

Operations are discrete events that occur on a particular day. More than one operation can occur on a given day. Having each operation occur on individual days in RUSLE2

[93] The variables displayed in RUSLE2 depend on the template used to configure the RUSLE2 computer screen. Variables are discussed that you may not see displayed in RUSLE2 depending on the template you are using.

rather than on the same day is sometimes useful for seeing the effect of individual operations and for locating errors in cover-management descriptions. **However, this procedure can cause very serious errors in certain situations.** An example is creating ridges and applying mulch on a construction site. These two operations should be on the same day to avoid erroneous critical slope length values (see **Section 14.1.2.5**).

Representing continuous activity like grazing requires applying an operation multiple times over the period that the activity occurs. For example, a grazing operation description might be used once a week for each week that the grazing occurs. A sensitivity analysis should be conducted to determine how best to represent a continuous activity with a set of discrete events. In many cases, such as grazing, the best way to represent a continuous activity is to create vegetation descriptions that include the effect of the activity rather than using multiple operations.

Keep in mind that RUSLE2 uses descriptions to compute erosion. In many cases, the desired description can be created in multiple ways.

10.2.1.2. Representing the year in dates

The year of the operation can be any integer provided the years are in sequential order (e.g., 1, 2, 3, …; 2004, 2005, 2006, …; 75, 76, 77). The years 1, 2, 3 were used in Tables 10.4 and 10.5 to represent the calendar year of the rotation.

10.2.1.3. Tracking time in RUSLE2

RUSLE2 begins tracking time on the date of the first operation in the cover-management description. RUSLE2 computes average annual erosion based on the date of the first operation. Sometimes annual erosion estimates are needed on a calendar year basis or time needs to start at the same point when erosion estimates from alternative cover-management descriptions are being compared. A **no operation** operation description, which is described with a single **no effect process**, is used as the first operation in each cover-management description. A no operation only marks time and has no effect on the RUSLE2 computations. The date of a no operation is set to **January 1, 1** so that RUSLE2 will display erosion estimate on an actual calendar year basis. The no operation can also be placed on another date such as September 1 as the starting point for annual erosion accounting.

10.2.1.5. Allowing RUSLE2 to set duration

RUSLE2 scans the dates in the list of operations to determine the **duration** of the cover-management description. Using a no operation in the last year of the duration ensures that RUSLE2 makes the correct determination of duration. See **Section 10.2.8** for a discussion of rotation and duration.

A value for the duration can be entered in the cover-management description. RUSLE2 may over ride this duration based on the dates in the list of operations. An inadvertent error can occur that will not be noticed. To avoid this error, include a *no operation* in the list of operations to ensure that RUSLE2 determines the proper duration from the dates for the list of operations.

10.2.1.6. Initial conditions

The operations must always be in the proper sequence. The starting operation is unimportant for a rotation because RUSLE2 loops through the list of operations until the erosion computations become stable. Because of this computational feature, values for initial conditions for RUSLE2 are not required for rotations.

However, initial conditions are needed where the cover-management description is a **no rotation** such as applying RUSLE2 to a construction site. In this case, initial conditions must be set in RUSLE2. The first set of operations in the cover-management description are selected to create the desired initial condition. The default initial condition assumed by RUSLE2 is that the soil is bare, fully consolidated, and has no soil biomass. This condition is like that created by a blade and cutting away the surface layer of soil below the root zone without disturbing the underlying soil. If this situation is applicable to the actual field situation, no operations are needed to set initial conditions. Start with the first operation, which might be an application of mulch on a construction site. A common condition on construction sites is placing mulch on a freshly graded fill. An operation description named **blade fill material** can be used as the first operation description in the list of operations. This operation includes a **disturb soil** process with the result that the soil is not consolidated in contrast to the cut, default condition. Erosion on the fill slope will be twice that on the cut slope because of the soil consolidation effect. An initial condition of a rough soil can be created by using an operation description to create a rough surface keeping in mind that a disturb soil process is required in the operation to create the roughness that also eliminates soil consolidation at the time of the operation.

The initial condition may also involve soil biomass, a litter cover, and growing vegetation. The appropriate initial conditions are created by using an initial set of operations that create the desired description. A **no operation** can be used before and after the initial set of operations used to create the initial conditions to mark time so that RUSLE2 displays erosion on the desired date. Be sure to set up operations so that RUSLE2 displays average annual erosion starting on the desired date. Keep in mind that the average annual erosion displayed by RUSLE2 is for the entire cover-management description including the operation descriptions used to establish initial conditions.

RUSLE2 displays average annual erosion for each year that provides the erosion values that can be used to compute average annual erosion for any period during the entire duration of the cover-management description.

10.2.2. Operations

Operations are events that affect soil, vegetation, and/or residue. RUSLE2 uses the information in **operation descriptions** to compute how operations effect erosion.

Many RUSLE2 operations are created and named to represent actual events such as tilling, seeding, harvesting, burning, frost, grading, and applying mulch. A single operation description can often be created to represent an event such as tillage. However, cases arise where multiple RUSLE2 operations are used to represent a single actual field event. An example is a harrow drawn behind a tandem disk through the field as a single unit. A more accurate representation of how the composite implement buries residue can be obtained in RUSLE2 by representing the effects of tandem disk separate from the effects of the harrow. Thus, two operation descriptions are used on the same day, one to represent the tandem disk and one to represent the harrow, to represent a single actual field event. The operation descriptions can be put on two consecutive dates so that the effects of the tandem disk can be seen separate from the effects of the harrow in a test computation, but the two operations should be on the same day for the erosion control planning computation..

Having the operations in the proper sequence is an absolute necessity.

Operations represent discrete events. Representing a continuous activity like grazing is discussed in **Section 10.2.1.1**.

See **Section 13** for a complete discussion of operation descriptions.

10.2.3. Vegetation

RUSLE2 uses the information in a **vegetation description** in the **vegetation component** of the RUSLE2 database to compute erosion when vegetation is present. **Operation descriptions** with a **begin growth** process in a **cover-management description** instruct RUSLE2 to begin using data from a particular vegetation description in its computations. Thus, the name of a vegetation description must be entered for each operation that includes a **begin growth** process. RUSLE2 begins using data from the selected vegetation description on the date of the operation and references the first date, day zero, in the vegetation description to this date.

Various approaches are used in RUSLE2 to create cover-management descriptions involving vegetation. In the case of annual crops, a vegetation description for each crop is used, which requires an operation description with a **begin growth** process to call a vegetation description for the appropriate crop in a **rotation** like a corn-soybeans-wheat rotation. The vegetation descriptions for annual crops like corn, soybeans, and wheat represent a year or less.

Multiple vegetation descriptions can also be used during a year. An example is using multiple vegetation descriptions to represent sequential planting and harvesting of two or more vegetable crops during the year.

A particular plant community can be divided into multiple vegetation descriptions. For example, the following sequence of vegetation descriptions can be used to represent a hay crop. The first vegetation description is for the period from fall seeding of alfalfa and through early growth, senescence, dormancy through the winter, and spring growth to the first harvest in the first harvest year. The second vegetation description describes the regrowth following the first and second harvests in the first harvest year. The third vegetation description describes the regrowth after the last harvest in the first harvest year, senescence, winter dormancy, and spring regrowth to first harvest in the second harvest year. The fourth vegetation description describes regrowth after the first and second harvests in the second harvest year. Additional vegetation descriptions are used as required to complete the rotation. Each vegetation description should represent the progression of growth in terms of **yield**, **canopy**, **live ground cover**, and **live root biomass**. For example, yield typically increases in the early years of a hay rotation while it may decrease in latter years.

Another example of using multiple vegetation descriptions is when RUSLE2 is applied to **intercropping**. Intercropping is when two crops grow together at the same time. An example is planting a legume crop in late winter in a small grain crop. The small grain is harvested in early summer. The legume crop continues to grow after the small grain is harvested until the legume is harvested for hay in late summer. Another example is planting a rye cover crop in corn before it is harvested for silage so that vegetative cover will be present after the vegetative cover is removed when the corn is harvested for silage. Another example of intercropping is ally-way cropping in commercial tree production and grass growing in the alley ways in vineyards and orchards. Another example is volunteer weeds that grow in crops like corn, soybeans, or cotton, especially in the southern US, as the canopy cover decreases after the crop matures. The weeds continue to grow after the crop is harvested.

The small grain-legume cropping system illustrates use of multiple vegetation descriptions. The cover-management description starts in the fall with primary tillage followed by secondary tillage and seeding of the small grain. The first vegetation description is for the period between the time that the small grain is seeded and the time that the legume is seeded. The second vegetation description is for the period between the time that the legume is seeded and the small grain is harvested when the combined growth of both the small grain and legume is represented. The values for canopy, live ground cover, and live root biomass on day zero in this vegetation description should be the same as the same as the corresponding values on the last day that the previous vegetation description is used. The third vegetation description used in this 1-year rotation is for the period between the small grain harvest and the harvest of the legume. The values for canopy, live ground cover, and live root biomass on day zero in this vegetation description are less than corresponding values on the last day that the previous vegetation description was used to reflect the dead above ground and root biomass that was created with the harvest of the small grain.

RUSLE2 is often used to estimate erosion for a perennial plant community like that on a range, pasture, landfill, or reclaimed mine lands. The cover-management description to represent this condition is a 1-year rotation involving a single vegetation description. The **vegetation description** describes the vegetation over an entire year.

Another important application of RUSLE2 is to estimate erosion during the period immediately following grading of a construction site, landfill, or reclaimed mine to when the permanent vegetation becomes fully established. Temporary vegetation is seeded in the spring followed by seeding of the permanent vegetation in the fall. The vegetation description for this **no-rotation** cover-management description can be represented in two ways.

The first approach uses two **vegetation descriptions**. The first **vegetation description** represents the period between when the temporary vegetation is seeded and the permanent vegetation is seeded. The second vegetation description is for the period after the permanent vegetation is seeded until a stable litter layer and soil biomass pool has developed. The values for each year over the last few years of the description are repeats where the vegetation has matured and become stable on an annual cycle. The **long-term vegetation tool** discussed in **Section 11.2.6** can be used to create these vegetation descriptions.

The second approach uses multiple **vegetation descriptions** of the permanent vegetation. The first **vegetation description** is for the temporary vegetation. The second **vegetation description** is for the first year of the permanent vegetation. The third **vegetation description** is for the second year of the permanent vegetation. The fourth **vegetation description** is for the third year of the permanent vegetation, which represents maturity for this particular vegetation. The third year **vegetation description** is used as many years as necessary for the litter layer and soil biomass to become stable.

The RUSLE2 rules related to **vegetation descriptions** must be carefully observed. In particular RUSLE2 only uses a single **vegetation description** at a time, which is referred to as the **current** vegetation description. An **operation description** with a **begin growth** process is required to tell RUSLE2 when to begin using data from a particular vegetation description. A vegetation description can start at anytime during the growth cycle of the vegetation. A vegetation description is simply that, a description of the vegetation at a given time. The first date in the vegetation description is day zero, which is referenced to the date that an operation calls that vegetation description. Decreases in **live root biomass** are assumed to become dead biomass that are put in the **dead root biomass** pools, respectively. Thus, the ending values of one vegetation description must properly match those of the next vegetation description used in a cover-management description. For example, the **canopy**, **live ground cover**, and **live root biomass** values at the end of a vegetation description used to represent a mature perennial plant community should be the same as corresponding values at the beginning (day zero) of that vegetation description.

Important RUSLE2 rules related to vegetation

1. **RUSLE2 uses only one vegetation description at a time. This vegetation description is referred to as the *current* vegetation.**
2. **A vegetation description describes the *composite* of plants present at a given time.**
3. **The length of time in a vegetation description should be as long as that vegetation description is used in a cover-management description. If the length of the vegetation description is too short, RUSLE2 uses the values on the last date in the vegetation description until a new current vegetation description is established.**
4. **A new, current vegetation is established by using an operation having a *begin growth* process.**
5. **A *decrease* in *live root biomass* between the first day (day zero in the vegetation description) of the new current vegetation description and the last day that the previous vegetation was used is considered to be dead roots and is added to the *dead root biomass* pool.**

The vegetation descriptions selected in a cover-management description must be consistent with site conditions. RUSLE2 does not check appropriateness of a vegetation description based on environmental conditions or other factors. RUSLE2 simply uses the values in the selected vegetation description. For example, RUSLE2 uses the same values for non-irrigated corn grown in a humid area as in a desert area.

Must be sure that the selected vegetation description is appropriate for the cover-management description and for the site specific environmental conditions.

See **Section 11** for a complete discussion of vegetation descriptions.

10.2.4. Yield

Each **vegetation description** is created for a particular **yield**. Multiple vegetation descriptions can be created for various yield values. A vegetation description having the desired yield can be selected when creating a **cover-management description**. RUSLE2 does not adjust yield based on environmental, management, or other factors. The input yield value must be consistent with site specific conditions, including precipitation, irrigation, temperature, soil, fertility, pest control, plant variety, and management, where RUSLE2 is being applied,.

Instead of selecting a vegetation description created for the desired yield, a vegetation description at a base yield can be selected. RUSLE2 assumes the base yield as the default yield, which the user can change to a value appropriate for the specific RUSLE2 application. RUSLE2 will adjust values in the base vegetation description to the input yield value. The base vegetation should be chosen so that maximum yield is less than 100 percent cover. The RUSLE2 yield adjusting equations, described in **Section 11.2.1**, can not adjust to yield values less than the base yield if maximum canopy of the base vegetation description is 100 percent. However, RUSLE2 can adjust to yield values greater than the base yield when maximum canopy is 100 percent.

The input yield value is in the user defined units for that particular vegetation description. Vegetation descriptions are typically created to use customary units. However, units vary among users applying RUSLE2 to various land uses. Open the vegetation description to determine how yield is defined for a particular vegetation description. If the units defined for that particular vegetation description are not the preferred units, create a new yield unit definition. The input yield units can be wet weight, dry volume, or number of items per unit area, for example. Also, the units can be non-customary and even original units created specifically for a particular RUSLE2 application. When defining units, the user enters values that RUSLE2 uses to convert input units values to dry mass values needed to compute subfactor values in equation 9.1 and related equations.

The input yield value must match site specific conditions.

10.2.5. Operation depth and speed

Operation **depth** refers to the **depth of disturbance** for those **operation descriptions** that include a **disturb soil** process. The default depth of disturbance is the recommended depth entered in the operation description. Similarly, operation **speed** refers to the speed of operation descriptions that include a disturb soil process. The default speed is the recommended speed entered in the operation description.

The amount of surface (flat) cover, crop residue in cropping-management systems, that is buried depends on machine depth of disturbance and speed. In general, **recommended** depth and speed values should be accepted and used in RUSLE2 computations. However, varying input values for depth and speed provides an indication of how residue cover can be affected by depth and speed of soil disturbing implements. Input values must fall within **limits** entered in the operation description.

A common assumption is that residue cover, especially in conservation tillage systems, can be easily manipulated by how tillage implements are operated. The two variables easiest to vary are depth and speed. The RUSLE2 relationships for the effect of these variables on residue burial are based on a very careful study of the research data. If RUSLE2 does not produce the desired residue ground cover value over the range of depths and speeds that are possible in the RUSLE2 inputs, then a particular ground cover can not be reasonably achieved by changing depth and/or speed.

The adjustments that RUSLE2 makes for operation depth and speed are discussed in **Section 13.1.5.3**.

Be very careful in assuming that practically any residue cover can be achieved with any implement based on changes in depth and speed. The RUSLE2 values are based on sound research. Assumptions for varying residue cover by adjusting implement depth and speed that are inconsistent with RUSLE2 computations should be rejected.

10.2.6. External residue and amount added

External residue refers to material added to the soil surface or placed in the soil. This material is usually organic material such as straw mulch, certain erosion control roll products, manure, and compost. In general, RUSLE2 assumes that external residue is organic material that produces organic compounds that reduce soil erodibility when the external residue decomposes. Some materials like rock such as gravel mulch do not decompose. Other materials, such as some roll erosion control products, deteriorate by a different process than the one assumed in RUSLE2. See **Section 12** for a discussion on how to handle these situations.

External residue can be placed entirely on the soil surface, entirely in the soil, or divided between the two. An **operation description** that includes an **add other cover** process tells RUSLE2 that external residue is being added. When an operation description having this process is in the list of operation descriptions in a **cover-management description**, a **residue description** from the **residue component** (see **Section 12**) of the RUSLE2 database is selected to identify the external residue being added. RUSLE2 uses the information in the selected residue description to compute how that external residue affects erosion. Important residue variables include residue type that affects how soil disturbing operations bury the residue and the degree that the residue conforms to the micro-topography of the soil surface, the portion of the soil surface covered by a given residue mass, and a decomposition coefficient that determines how rapidly that the material decomposes as a function of daily precipitation and temperature at the location.

When external residue is placed in the soil, a **disturb soil** process must follow the **add other cover** process in the operation description used to apply the external residue. The information for this process determines the depth in the soil that the external residue is placed. RUSLE2 assumes that external residue placed in the soil is placed in the lower half of the disturbance depth with most of the residue concentrated near the three fourths disturbance depth as illustrated in Figure 9.16.

The value entered for amount of external residue added must be a mass value based on dry weight. Also, the value must be consistent with the mass values used in the residue description to describe the relationship for portion of the soil surface covered by a given residue mass.

Residue, including residue from vegetative growth and applied external residue, can be removed from the soil surface by using an operation description that includes a **remove residue/cove**r process. This process removes standing and flat residue but not buried residue. Operation descriptions use this process to represent burning and straw baling for example. **Buried residue** in the soil can be removed, by burning for example, by using an operation description that includes two steps. The first step is to resurface the desired amount of buried residue with a **disturb soil** process and then remove the resurfaced residue from the soil surface with a **remove residue/cover** process. The **resurfacing coefficient** in the disturb soil process is set so that the desired amount of buried residue is resurfaced. The value for the **portion of the soil surface disturbed** for this soil disturb process is usually set to 100 percent, which sets the **soil consolidation** subfactor to 1 (a fully disturbed soil) because RUSLE2 assumes that buried residue can not be removed from the soil without disturbing the soil. However, resetting the soil consolidation effect can be eliminated by setting the portion of the soil surface disturbed in the disturb soil process disturbed to 1 percent.

RUSLE2 does not resurface dead roots in the soil because the fine roots, which are the most important roots in affecting erosion, are assumed to be so tightly bound to the soil that a mechanical disturbance can not resurface them.

See **Section 12** for a detailed discussion of residue descriptions.

10.2.7. Long term soil surface roughness

Long term soil surface roughness is the roughness that develops over time by natural processes such as local erosion and deposition by both wind and water erosion (See

Section 9.2.3.1.) Long term soil surface roughness is also a function of vegetation characteristics such as grasses being bunch or sod forming grasses and the density of the vegetation.

Long term soil surface roughness begins to develop after the last soil disturbing operation. The time over which this roughness is assumed to develop is the **time to soil consolidation** (See **Section 7.8**.).

Entering an appropriate value for long term soil surface roughness is most important for range, pasture, reclaimed mine, and landfills lands where permanent vegetation exists. Recommended values for long term soil surface roughness are given in Table 10.6. Long term soil surface roughness is generally set to 0.24 inch (6 mm) for cropping-management systems.

Table 10.6. Long term roughness values for range and similar lands. (Source: AH703)

Condition	Long term soil surface roughness	
	(inches)	(mm)
California annual grassland	0.25	6
Tallgrass prairie	0.30	8
Shortgrass, desert	0.80	20
Mixed grass, prairie	1.00	25
Natural shrub	0.80	20
Pinyon/Juniper interspace	0.60	15
Sagebrush	1.10	28
Bare with rock fragments	0.6	15
Moderate pitted	1.10	28
Deep pitted	2.00	50
Root plowed	1.30	32

10.2.8. Rotation and duration

Rotation in RUSLE2 refers to whether or not the list of operations in the **cover-management description** is to be repeated as a cycle (rotation). The length of the cycle is the **duration** of the rotation.

Designating a cover-management description as a rotation causes RUSLE2 to cycle through the list of operations until average annual erosion for the cycle (rotation) becomes stable. Most RUSLE2 cropland applications involve cover-management descriptions that are rotations. The value entered for duration for a rotation-type cover-management description is the number of years from the first operation in the list of operation descriptions until that operation is repeated in the next cycle. Continuous cropping, such as for corn, has a 1-year duration. Also, a rotation-type cover-management description for three vegetable crops grown in the same year has a 1-year duration. A 1-year duration is used to apply RUSLE2 to permanent vegetation on range, pasture, reclaimed mine, landfill, and similar lands. A 2-year rotation applies to corn and soybeans grown in subsequent years. A corn-soybean-wheat rotation is an example of a 3-year rotation. Three years elapses from the date of the first operation in the rotation until that operation is repeated in the next cycle.

Duration is not the same as the number of calendar years over which the operations occur. For example, operations for the corn-soybean-wheat rotation occur in four calendar years while 3 years is the duration for the rotation.

An actual field event need not occur in each year of a rotation. For example, corn could be grown in a 2-year corn-fallow rotation where no operations occur in the fallow year. This rotation is a 2-year duration because two years elapses between an occurrence of the first operation in the list of operations until its occurrence when the cycle is next repeated.

The listing of operation descriptions in a rotation can begin with any operation in the list. RUSLE2 cycles through the list until the average annual erosion rate becomes stable. Specifying initial conditions for rotations is not required because of this feature.

A **no-rotation** designation for a cover-management description instructs RUSLE2 to start its computations with the first operation in the list of operation descriptions and proceed through the list. The time period over which RUSLE2 computes erosion begins on the date of the first operation and continues through the number of years specified for duration. Cover-management descriptions for construction sites, establishment periods for vegetation on reclaimed mine and landfills, and recovery from disturbances on range, pasture and disturbed forest land are typically designated as no-rotations. RUSLE2 computes an average annual erosion for the duration, as well as average annual erosion for each year of the duration. See **Section 10.2.1.3** for guidance on how to use an operation description with a **no effect** process to set RUSLE2's starting point in its computations and to display output at desired times.

In a no-rotation cover-management description, the first few operations are used to establish initial conditions, which is discussed in **Section 10.2.1.6.**

RUSLE2 scan the dates in the list of operation descriptions to determine the duration of the cover-management description. In several cases, this computation needs to be over ridden by the user entering a different value for duration. An example is the corn-fallow rotation mentioned above where operations only occur in the first year of the rotation but the actual duration is two years. Another example is a construction site where mulch is applied and the site is temporarily seeded. An average annual erosion estimate is needed over the next two years before the final grading and seeding occur. In these examples, RUSLE2 sets the duration to 1 year when the proper value is 2 years.

Even when proper values are entered for duration, RUSLE2 can unexpectedly change the duration, which causes serious errors. To prevent such errors, enter a *no-operation* operation description (an operation using a single *no effect* process) in each year (*not each calendar year*) of the duration for the cover-management description.

10.2.9. Build new rotation with this management

The **rotation builder** is a RUSLE2 tool that can be used to combine individual cover-management descriptions, including both rotation and no-rotation type cover-management descriptions, into a single cover-management description. The combined cover-management description can be named, saved, and used later in a RUSLE2 erosion computation. Also, the combined cover-management description can be used directly in a RUSLE2 erosion computation without naming and saving it. This tool is most often used in RUSLE2 cropland applications where the combination of single year cover-management descriptions into multi-year rotations is almost limitless. Having a cover-management description for each combination results in a large and cumbersome set of cover-management descriptions in the RUSLE2 database.

RUSLE2 has editing capability for copying and pasting between cover-management descriptions, which can be used to combine cover-management descriptions. The disadvantage of this approach is that the year in the dates must be changed for each individual cover-management description except for the first one. The rotation builder greatly facilitates the manipulation of these dates.

Refer to the RUSLE2 Summary User Manual at http://www.ars.usda.gov/SP2UserFiles/Place/64080530/RUSLE/RUSLE2_User_Manual.exe for information on the mechanics of using the rotation builder.

10.2.10. Relative row grade

Contouring is a support practice used in conjunction with cover-management practices to reduce erosion, especially on cropland. **Ridging** is a comparable practice used on reclaimed mined land and similar lands. The effectiveness of contouring (ridging) depends on ridge height and row grade, two major variables directly related to the cover-management practice. Ridge height is determined by values entered in **operation descriptions** that include a **disturb soil** process (soil disturbing operations). See **Section 13.1.5.4** for information on specifying ridge heights. Thus, one of the most important variables that determines effectiveness of contouring is actually specified in the **cover-management descriptions** rather than in a **support practice description**.

Row grade is the grade along the ridge-furrows created by soil disturbing operations. Contouring is most effective when row grade is perfectly level, but level row grades are seldom obtained in actual field contouring. The effectiveness of contouring decreases as row grade increases.

The recommended row grade input in RUSLE2 is **relative row grade**, which is the ratio of row grade to land steepness along the overland flow path assuming that the soil surface is flat (no ridges to redirect flow) so that runoff flows perpendicular to the topographic contours. Inputting relative row grade according to the guidelines in **Section 14.1.5** provides a more accurate RUSLE2 estimate of how contouring affects erosion than inputting absolute row grade. A major advantage of inputting relative row grade in a cover-management description is that the contouring effectiveness of a cover-management practice can be represented within a cover-management description. A cover-management description using relative row grade can be applied to any overland flow path without considering site-specific topography. This capability is advantageous for applying RUSLE2 in erosion inventories.

See **Section 14.1.5** for information on how to specify relative row grade to represent various conditions.

10.2.11. Management alignment offset

Rotational contour strip cropping is a support practice that uses a rotation cover-management practice having a combination of erodible and dense vegetation conditions. The hillslope is divided into a series of contour strips where the same rotation cover-management practice is applied to each strip. However, the rotation is sequenced differently among the strips along the overland flow path so that dense vegetation strips are alternated with erodible strips. The dense vegetation strips induce deposition to reduce net erosion.

The **management alignment offset** is the years that the rotation cover-management description is offset (delayed) relative the starting date in the cover-management description on the base strip, which is typically the uppermost strip but can be any of the strips. RUSLE2 applies the offset assigned to each strip to achieve the alternating pattern of erodible-dense vegetation strips along the overland flow path.

See **Section 14.2** for detail discussion of rotational contour strip cropping.

11. VEGETATION DATABASE COMPONENT

The **vegetation descriptions** in the **vegetation component** of the RUSLE2 database provide RUSLE2 with the information that it uses to compute how vegetation affects rill-interrill erosion. The RUSLE2 descriptions do not contain all of the information commonly used to describe vegetation. For example, RUSLE2 assumes the same rooting depth for all growth stages, plant types, and soil profiles. Even though rooting depth may affect erosion, the empirical erosion data used to develop RUSLE2 are not adequate for determining how rooting depth affects erosion. The main rooting effect captured in the data is the effect of root biomass.

RUSLE2 does not model vegetation growth. Instead, the RUSLE2 user explicitly describes the vegetation at the site where RUSLE2 is being applied. RUSLE2 does not compute how climate, soil, or management affects production (yield) level, canopy cover, height, or any other vegetative property that affect erosion.

When RUSLE2 users create vegetation, residue, operation, and cover-management descriptions, they should choose input values that ensure that RUSLE2 is using expected values for the variables that affect rill-interrill erosion. These variables include canopy cover, effective fall height, live ground cover, live root biomass, surface residue added by litter fall, standing and surface residue created at harvest, and dead roots created by root sloughing (death) and harvest.

Accounting for all of the biomass produced by the vegetation is not important in RUSLE2. The important biomass is the biomass that affects erosion. For example, the biomass left in the field after a hay harvest is a critical variable, not how much biomass left the field. Yield is only important as it is used to determine values for the biomass variables used in its computations.

RUSLE2 users create vegetation descriptions using RUSLE2 rules and procedures. These descriptions contain values for the variables that RUSLE2 uses to compute erosion. RUSLE2 vegetation descriptions are created with the focus on the information needed by RUSLE2 to compute erosion. The focus is not on accounting for biomass that leaves the site and has economic value.

Thee variables in a RUSLE2 vegetation description are listed in Table 11.1. The RUSLE2 vegetation descriptions also include **tools** listed in Table 11.2 used to develop input values for some of the variables listed in Table 11.2.

Table 11.1. Variables in a RUSLE2 vegetation description

Variable	Comment
Base production (yield) level	Production (yield) level for which a particular vegetation description applies. Value units defined by user.

Production (yield) level definition	User provided information that defines units for production (yield) level.
Amount of biomass at maximum canopy	RUSLE2 uses this information to determine amount of aboveground biomass based on canopy percent over the time represented in the growth chart. Value important in determining the amount of crop residue available at harvest and the amount of senescence (litter) fall. Values are on a dry weight basis.
Retardance	Indicates degree that vegetation retards (slows) runoff to affect critical slope length and transport capacity.
Residue	Name for residue description that applies to this vegetation description.
Relative moisture depletion rate	**Used only for Req applications.** Describes the degree that the vegetation extracts moistures during growth that affects erosion after the vegetation.
Growth chart involves the following variables	
Age (days)	Points through time used to describe temporal variation of vegetation. Starts at zero. RUSLE2 references day zero to the calendar date of the operation containing the begin growth process that tells RUSLE2 to begin using this vegetation description.
Root biomass	Mass (dry weight basis) of roots in upper 4 inch (100 mm) of soil.
Canopy cover	Portion of soil surface covered by canopy that intercept raindrops falling vertically.
Fall height	Effective height from which water drops fall where canopy has intercepted rainfall.
Live surface cover	Portion of the soil surface covered by live plant parts that touch the soil surface and affect erosion.

Table 11.2. Tools used to input values in vegetation description.	
Tool	Comment
Develop growth chart for a production (yield) level other than base level	Used to create a growth chart for a new production (yield) level that can be used in a vegetation description.
Estimate fall height	A graphical tool that estimates fall height values based on heights to the top and bottom of canopy and a graphical description of canopy.
Develops the relationship between aboveground biomass and production (yield) level	User inputs aboveground biomass values at two yield values so that RUSLE2 can develop a relationship between aboveground biomass and production (yield) level.
Develops the relationship for senescence	User inputs canopy values that RUSLE2 uses to develop a relationship between canopy cover and aboveground biomass that is used to compute the mass of plant material

	that falls to the soil during senescence.
Develops a relationship between retardance and production (yield) level	User inputs retardance values at two production (yield) levels that RUSLE2 uses to determine a relationship for retardance as a function of production (yield) level.
Develops a growth chart for long term vegetation	Used to develop temporal values for perennial and permanent vegetation on range, pasture, reclaimed mine, wastes disposal, and similar lands.

11.1. Variables in a RUSLE2 vegetation description

11.1.1. Base production (yield) level

The RUSLE2 vegetation variables are a function of production (yield) level. Therefore, each **vegetation description** in the **vegetation component** of the RUSLE2 database is for a particular **production (yield) level**. When RUSLE2 is applied to a particular site, the vegetation's production (yield) level must match site-specific conditions. The vegetation and its production (yield) level must be consistent with the location's climate, irrigation, soil, fertility, pest control, and other management conditions. Because RUSLE2 is not a plant growth model, it does not adjust vegetation variables to match site-specific conditions. Production (yield) level is a user site-specific input that reflects long-term production levels rather than production in any specific year. Although RUSLE2 can indicate how erosion varies between dry and wet years, it is not intended for such applications.

The RUSLE2 production (yield) level input can be handled in one of two ways. One way is to create a vegetation description for a set of production (yield) levels where the user selects a vegetation description for the production (yield) level that is appropriate for the site. The second way is for the user to select a vegetation description at a base production (yield) level and input the site production (yield) level value. RUSLE2 will then adjust values in the base vegetation description to ones appropriate for the input production (yield) level value.

RUSLE2 can adjust to a production (yield) level value that is higher than the production (yield) level of the base vegetation description. However, the maximum canopy cover in the base vegetation must be less than 100 percent for RUSLE2 to adjust to a production (yield) level lower than the base production (yield) level. This restriction is related to the RUSLE2 equations used to adjust for production (yield) level. The user can alternately create a new vegetation description for a new production (yield) level if the RUSLE2 adjustments are not satisfactory.

The units for the production (yield) level are user defined (see **Section 11.1.2)** and can be almost any units that a user prefers.

Yield is important in RUSLE2 only to indicate the yield to which a particular vegetation description applies or as a variable that can be used to adjust values in a given vegetation description to the desired yield. The biomass associated with a harvestable part of vegetation and its yield are important only if that biomass in the harvestable part directly affects erosion and is represented by a RUSLE2 vegetation variables. For example, accounting for the biomass in the harvestable corn grain is not important. Accounting for the biomass in a harvestable hay crop is only important until the hay is harvested. The biomass in watermelons before harvest is not important, but the ground cover provided by watermelons may be important. The biomass left behind in the field after harvest is important, not the biomass taken from the field. RUSLE2 procedures are used to create a field description of the variables that affect erosion, not to account for vegetation in its entirety.

11.1.2. User definition of production (yield) level units

Almost any user preferred units can be created for inputting values for **production (yield) level** in RUSLE2. These units can be on any basis including dry or wet, mass (weight), volume, standard moisture such as 14 percent for corn grain, number such as bales of hay or straw, or even an original user created basis. The production (yield) level input must be on a per unit area basis. These units should be common usage for intended RUSLE2 users, convenient, and a reliable indicator of how values for RUSLE2 vegetation variables change with production (yield) level.

Two inputs are used to define the production (yield) level units. The first input is the displayed yield unit, typically a common unit such as bushels per acre (liters/ha), lbs per acre (kg/ha), tons per acre, or hundred weight per acre.

The second input is a **conversion factor.** RUSLE2 multiplies the user production (yield) level input value by this conversion factor to convert the input value, which may be a mass, volume, or number per unit area value, to a mass value. Converting the production (yield) level input to a mass value facilitates using rules of thumb for estimating crop residue at harvest. The production (yield) level value expressed as a mass is multiplied by a residue:yield ratio to estimate residue at harvest.

To illustrate, the conversion factor for corn is 56 lbs/bushel at the standard 14 percent moisture content. Multiplying a 100 bu/acre corn yield by this conversion factor gives a corn grain yield of 5600 lbs/acre in terms of mass. Multiplying this mass value by the 1:1 to the residue:yield rule of thumb gives an estimate of 5600 lbs/acre of corn residue at harvest. A linear equation, discussed in **Section 9.2.1.6** is used in RUSLE2 to estimate residue at harvest rather than a simple residue:yield ratio because the residue:yield ratio varies with yield. The input data needed for this equation are discussed in **Section**

11.2.1.

The conversion factor value for converting production (yield) level inputs to a mass value is plant specific. The conversion factor for corn is 56 lbs/bushel while it is 32 lbs/bushel for oats. The input units for some plants, such as hay, are already a mass value. The conversion factor for those plants can be one (1) or it may be different from 1 if a conversion from a wet to dry basis is involved. A conversion of dry basis can either be made in this conversion factor on in the computation of aboveground biomass as a function of production (yield) level.

RUSLE2 uses the production (yield) level input to compute aboveground biomass values. This computation involves two steps. One is to multiply the input production (yield) level value by a conversion factor to obtain a mass value and the second is to convert the production (yield) level value to aboveground plant biomass values on a dry basis. The user arranges these two steps as desired to end up with the appropriate aboveground biomass values. For example, a wet to dry basis conversion can be made in the first step or the second step. The input and conversion values must be consistent so that the final result is a mass on a dry basis.

11.1.3. Live Aboveground biomass at maximum canopy cover

RUSLE2 computes daily values for live aboveground biomass as a function of daily canopy cover. Coefficient values in the equation for this computation value are determined from user input values for **live aboveground biomass at maximum canopy cover** and the value for **live above ground biomass at minimum canopy cover.**

11.1.3.1. Basic principles

The input values entered in a **vegetation description** are selected to provide RUSLE2 with the values that it needs to compute erosion. Consequently, not all of a plant's aboveground biomass is necessarily included in the input for **aboveground biomass at maximum canopy cover**. Only that plant material that becomes litter fall or that will become standing, surface, or incorporated residue is included in the input. For example, harvestable grain is not included in this input because the grain is removed from the field without affecting erosion. If a harvestable product is left in the field to provide standing or surface (flat) residue or is incorporated into the soil to provide soil biomass, it should be included in the aboveground biomass input.

RUSLE2 uses the input for aboveground biomass at maximum canopy cover to estimate daily live aboveground biomass during the time period represented by a vegetation description. Three stages of vegetation growth are represented in RUSLE2. These stages are: (1) new growth, (2) senescence/regrowth, and (3) stem growth, which are illustrated in Figure 11.1.

The general equation for all three stages is:

$$B = B_0 + \alpha(C - C_0)^{1.5} \qquad [11.1]$$

where: B = live aboveground biomass (mass/area), B_0 = live aboveground biomass at the canopy cover C_0, C = canopy cover (percent), and α = a coefficient. Figure 11.1 represents these growth stages for a plant community that reaches is already or reaches maturity in a single growth cycle. RUSLE2 determines values for B_0, C_0, and α from user input values.

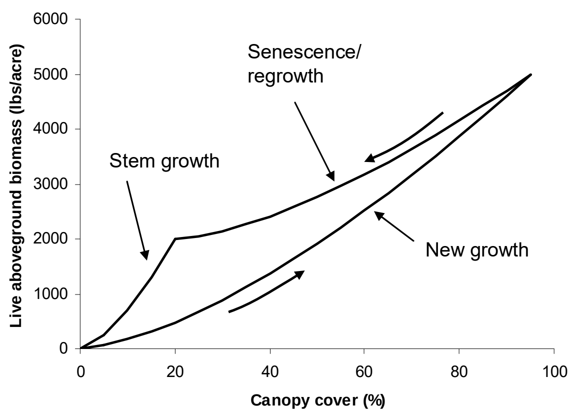

Figure 11.1. Canopy cover-live aboveground biomass relationship for a plant community that reaches maturity in a single growth cycle.

Equation 11.1 works best where maximum canopy cover is less than 100 percent. It works less well for conditions where aboveground biomass increases significantly after canopy cover reaches 100 percent. Equation 11.1 was chosen for its simplicity, robustness, and ability to be calibrated with minimal user inputs after an evaluation of alternate equation forms, including exponential forms.

A plant community well represented by Figure 11.1 is soybeans. The new growth period represents the relation between canopy cover and live aboveground biomass from plant emergence after seeding until full maturity and senescence begins. Equation 11.1 for the new growth period is:

$$B_n = \alpha_n C_n^{1.5} \qquad [11.2]$$

where: B_n = live aboveground biomass and C_n = canopy cover during the new growth stage. RUSLE2 computes a value for α_n using:

$$\alpha_n = B_{mx} / C_{mx}^{1.5} \qquad [11.3]$$

where: B_{mx} = the user entered value for live aboveground biomass at maximum canopy cover C_{mx}.

Senescence occurs during the period of decreasing canopy after the plant community has reached maturity. Equation 11.1 during the senescence stage is:

$$B_r = B_{mn} + \alpha_r (C_r - C_{mn})^{1.5} \quad [11.4]$$

where: B_r = live aboveground biomass and C_r = canopy cover during the senescence period and B_{mn} = the user entered value for live aboveground biomass at minimum canopy cover C_{mn}.

RUSLE2 computes a value for α_r using:

$$\alpha_r = (B_{mx} - B_{mn})/(C_{mx} - C_{mn})^{1.5} \quad [11.5]$$

In general, RUSLE2 assumes that any decrease in canopy cover within a vegetation description represents senescence, except for special plants like corn. Leaves droop on those plants that reduce canopy cover but do not fall to the soil surface. A user input tells RUSLE2 to not apply equation 11.4 to those plant communities.

The stem growth stage represents conditions when canopy cover is less than the minimum canopy cover that results after senescence is completed. This growth stage is important, for example, when a plant community is mowed or hay is harvested, which leaves a canopy cover that is less than the minimum canopy cover after full senescence. Equation 11.1 for the stem growth stage is:

$$B_s = \alpha_s C_s^{1.5} \quad [11.6]$$

where: B_s = the live aboveground biomass and C_s = the canopy cover during the stem growth stage. RUSLE2 computes a value for the coefficient α_s using:

$$\alpha_s = B_{mn} / C_{mn}^{1.5} \quad [11.7]$$

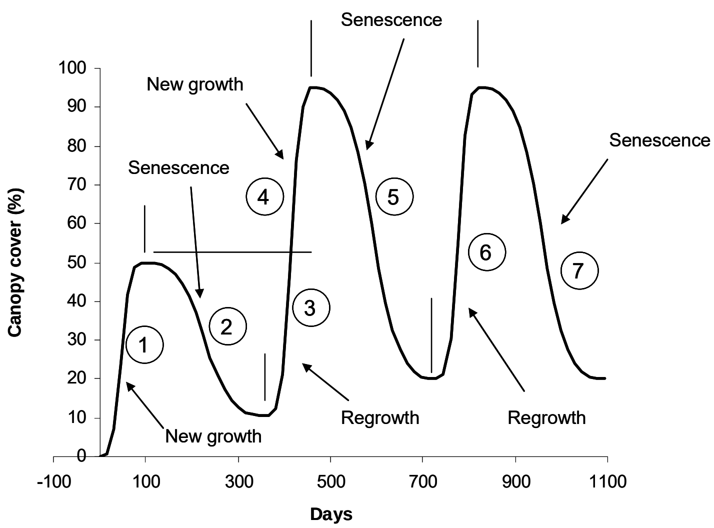

Figure 11.2. Canopy cover for a plant community that requires two cycles to reach maturity

Figure 11.2 illustrates canopy cover for a plant community that takes two growth cycles to reach maturity. The third growth cycle in Figure 11.2 represents full maturity. The plant community can be described in RUSLE2 by using the **long-term vegetation tool** or by creating a vegetation description for each growth cycle. The principles that are used in the long-term vegetation tool should be used in creating individual vegetation descriptions for plant communities like those represented in Figure 11.2.

Period 1 is new growth that begins on day zero and continues to the date of the maximum canopy cover in the first growth cycle. Period 2 is senescence that begins at maximum canopy cover in the first growth cycle and continues until minimum canopy cover at the end of the first growth cycle. Period 3 is regrowth that begins at the minimum canopy cover at the beginning of the second growth cycle and ends on the date that the canopy cover in the second growth cycle reaches the maximum canopy cover in the first growth cycle. Period 4 is new growth that begins at the date that canopy cover in the second growth cycle reaches maximum canopy cover in the first growth cycle and continues until maximum canopy cover in the second growth cycle. Period 5 is senescence that begins at maximum canopy cover in the second growth cycle and continues until minimum canopy cover at the end of the second growth cycle. Period 6 is regrowth that begins at minimum canopy cover at the beginning of the third growth cycle, which is the first full mature growth cycle. The regrowth period 6 continue until the maximum canopy cover of the third growth cycle. Period 7 is senescence that begins at maximum canopy cover in the third growth cycle and continues until the minimum canopy cover at the end of the third growth cycle. A growth cycle that represents full maturity does not contain any new growth periods.

Figure 11.3 shows the canopy cover-live aboveground biomass relationships for the plant community illustrated in Figure 11.2. Period 1 represents the new growth period in the first growth cycle. Period 2 represents senescence in the first growth cycle. Period 3 represents regrowth in the second growth cycle. Plant regrowth stage is assumed to retrace canopy loss during the previous senescence. Consequently, the same equation is used for the regrowth stage that follows the immediately previous senescence stage. That is, the same equation is used to describe both periods 2 and 3. Another equation is used to describe both periods 5 and 6.

Once canopy cover reaches the maximum canopy cover in the previous growth cycle, plant growth shifts from regrowth to new growth. Plant growth "rejoins" the previous new growth. The same equation is used for new growth in all growth cycles. Plant communities that have three or more growth cycles to reach maturity are represented using these same principles. These principles are repeatedly applied to each growth cycle until maturity is reached. New growth stages are not involved in the growth cycle that represents plant maturity.

The user inputs in the RUSLE2 **long-term vegetation tool** are **live above ground biomass for maximum canopy cover at maturity** and **live above ground biomass at minimum canopy cover at maturity**. RUSLE2 uses these inputs and the canopy cover

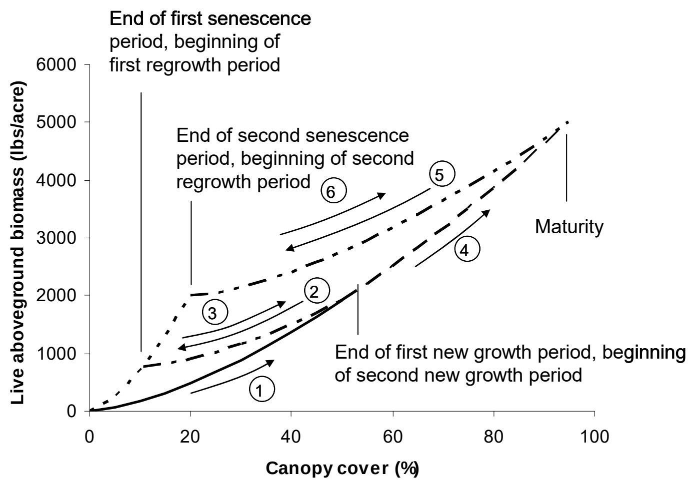

Figure 11.3. Canopy cover-live aboveground biomass relationship for a plant community that reaches maturity in two growth cycles.

values entered by the user to determine similar values for local maxima and minima canopy covers for growth cycles before plant maturity. A RUSLE2 assumption is that canopy cover for the local minimum canopy cover at the end of a growth cycle equals the product of minimum canopy cover at maturity and the ratio of local maximum canopy cover for the growth cycle to the maximum canopy cover at maturity. Another RUSLE2 assumption is that the live aboveground biomass, minimum canopy cover data point for each growth cycle must lay on the stem growth curve given by equations 11.6 and 11.7.

The other RUSLE2 option for describing plant communities having multiple growth cycles is to create a vegetation description for each growth cycle. The assumptions used in the RUSLE2 **long-term vegetation tool** should be used in creating these vegetation descriptions to ensure continuity between the individual vegetation descriptions.

Maintaining continuity between vegetation descriptions in a cover-management description is very important.

Equation 11.1 allows RUSLE2 to use the same **vegetation description** in different **cover-management descriptions** where the vegetation is killed on different dates.[94] For example, a wheat cover crop used to provide winter erosion control is killed on different spring dates depending on the main crop (e.g., corn versus cotton) and early or late planting. RUSLE2 needs an aboveground biomass estimate on the date that the wheat crop is killed and the main crop is planted. RUSLE2 estimates a value for that biomass by substituting the canopy cover value in the vegetation description on the date that the

[94] RUSLE1 differs from RUSLE2 regarding the input value for biomass when the vegetation is killed. The RUSLE1 vegetation descriptions contain the values for residue mass at the time that the vegetation is killed. Separate RUSLE1 vegetation descriptions are required for each date that the vegetation is killed. Also, two separate RUSLE1 vegetation descriptions are required for silage corn and grain corn. In RUSLE2, the same vegetation description can be used for both silage and grain corn, and the same vegetation description can be used when the vegetation is killed on different dates.

wheat is killed into equation 11.1. Without equation 11.1, RUSLE2 would require a vegetation description for each date that the wheat is killed in alternative cover-management descriptions.

RUSLE2 can also use vegetation descriptions that end on the date that the vegetation is killed where the input for aboveground biomass is for the maximum canopy cover on that day. This input technique can be used to ensure that RUSLE2 uses a particular value for aboveground biomass on the date that the vegetation is killed rather than the one computed with equation 11.1. This procedure can be used when equation 11.1 is considered to be a poor representation of the canopy cover-live aboveground biomass.

Perennial vegetation including hay and pasture crops and plant communities on rangelands, closed landfills, and other undisturbed areas exhibit a simultaneous birth and death of live aboveground biomass during new and regrowth periods. RUSLE2 computes a daily death amount of aboveground biomass as a fraction, approximately 0.01, of the live aboveground biomass on that day (see **Section 11.2.6**). This daily biomass amount is added to the surface litter (residue) biomass on that day.

RUSLE2 also considers a daily "mechanical" loss of live aboveground biomass that is added to surface litter. This daily addition is a fraction of the daily live aboveground biomass. This computation represents the loss of live aboveground biomass by mechanical processes such as animal traffic or by vehicular traffic (see **Section 11.2.6**).

11.1.3.2. Consistency between inputs for aboveground biomass at maximum canopy cover with processes in operation descriptions

RUSLE2 inputs for cover-management, vegetation, residue, and operation are descriptions based specifically on RUSLE2 rules and procedures. A particular field condition can often be described in multiple ways. However, the individual vegetation, residue, and operation descriptions used to create a cover-management description must be consistent with each other. A key element in this consistency is ensuring that the input value for aboveground biomass at maximum canopy cover in the vegetation description is consistent with the operation descriptions.

The value entered in a *vegetation description* for *aboveground biomass at maximum canopy cover* must be consistent with the *processes* in the *operation descriptions* in the *cover-management description* to ensure that RUSLE2 has the proper biomass values for standing residue, flat residue, and soil biomass for its computations.

Four examples are used to illustrate selecting values for aboveground biomass that are consistent with operation descriptions.

Example 1. Corn
Corn is grown for grain or silage. When corn is grown for harvestable grain, all of the aboveground biomass, except for the grain, is left in the field as standing and flat residue. When corn is grown for silage, almost all of the aboveground biomass is removed from the field as a harvestable product. Only a small amount of plant material is left in the field as standing and flat residue.

Table 11.3 lists **processes** that would be used in a **harvest operation description** for alternative input values for aboveground biomass at maximum canopy cover. Alternative 1 for corn grain is where the input value for aboveground biomass at maximum canopy cover is the amount of biomass that will be left in the field after the actual harvest removes the harvestable grain from the field. Alternative 2 is where the input value for aboveground biomass includes the entire aboveground plant material (i.e., fodder and grain). The harvest operation description for this vegetation description must include either a **remove live biomass process** before the **kill process** or a **remover residue/cover process** after the **kill process** to remove the grain. These processes are not required in Alternative 1 because the biomass for the grain is not included in the accounting. If the grain is not removed in Alternative 2, the amount of residue assumed by RUSLE2 after the harvest will be too high. Alternative 1 is the recommended procedure for corn grain.

The RUSLE2 objective is not to fully account for all of the biomass, but to describe only the biomass that affects erosion.

The alternatives for corn silage are similar to those for corn grain. Alternative 1 is where the aboveground biomass includes only the fodder without the grain, which is the same vegetation description as Alternative 1 for the corn grain. The harvest operation for this alternative includes a remove live biomass process before the kill process. Just as in Alternative 2 for the corn grain, a remove residue/cover process can be used after a kill process. In any case, plant material must be removed so that RUSLE2 has the proper value for the residue left in the field after the actual field operation. Alternative 2 for the corn silage is where the input value for aboveground biomass value at maximum canopy cover is the amount of residue that exists in the field after the actual field harvest operation.

Table 11.3. Harvest operation descriptions for corn grain and corn silage production			
Grain		Silage	
Alternative 1		Alternative 1	
Process	Comment	Process	Comment
Alternative 1 Aboveground biomass at max canopy does not include grain		Alternative 1 Aboveground biomass at max canopy includes all of the aboveground plant material except the grain	
Kill vegetation	Converts live aboveground biomass to standing residue, amount of standing residue directly related to input for aboveground biomass at maximum canopy	Remove live biomass	Removes most of live aboveground biomass from RUSLE2's accounting of aboveground biomass but leaves behind a small portion as flat residue
Flatten standing residue	Converts a portion of the standing residue to flat residue	Kill vegetation	Converts the remaining live aboveground biomass to standing residue
		Flatten standing residue	Converts a portion of the standing residue to flat residue
Alternative 2 Aboveground biomass at max canopy includes grain		Alternative 2 Aboveground biomass at max canopy is only the residue that will be left after the harvest operation	
Remove live biomass	This process removes the grain and leave the remaining as material that will become residue	Kill vegetation	Converts live aboveground biomass to standing residue
Kill vegetation	Converts live aboveground biomass to standing residue	Flatten standing residue	Flatten the portion of the standing residue that is to be left as flat residue
Flatten standing residue	Flatten the portion of the standing residue that is to be left as flat residue		

Example 2. Harvesting hay and mowing permanent vegetation.
Forage crops such as alfalfa regrow after each hay harvest. Similarly, permanent vegetation such as that on a landfill regrows after it is mowed. The objective is to provide RUSLE2 with inputs so that it can determine the amount of surface residue added by a hay harvest or mowing operation. Two alternatives, illustrated in Table 11.4, can be used for the hay harvest/mowing operation descriptions. In Alternative 1, the input value for the aboveground biomass at maximum canopy cover includes all of the aboveground plant material. RUSLE2 uses equation 11.1 to compute the aboveground biomass on each day, including the date of the hay harvest/mowing. Given a particular aboveground biomass on the date of the hay harvest or mowing, what is the amount of

this biomass that is added to the surface residue? The two processes of **remove live biomass process** and a **begin growth process** are used in both the hay harvest and mowing operation descriptions. The begin growth process identifies the vegetation description that RUSLE2 is to use immediately after the hay harvest/mowing operation. In addition to the input for aboveground biomass at maximum canopy cover, the other key inputs are the **portion of the aboveground biomass that is affected** and the **portion of the affect biomass that is left as surface residue** for the remove live biomass process.

To illustrate, assume that the aboveground biomass on the date of the hay harvest is 3600 lbs/acre. The input for the portion affected in the remove live biomass process in the hay harvest operation is 98 percent, which means that 3528 lbs/acre of biomass is affected. The input for the portion of the affected biomass that is left is 5 percent, which means that 176 lbs/acre is added to surface residue as a result of the hay harvest operation.

The inputs used to describe mowing a short grass permanent vegetation are similar to those used to describe the hay harvest. Assume that the amount of aboveground biomass on the date of the mowing is also 3600 lbs/acre. The input value is assumed to be 50 percent for the portion of the aboveground biomass affected by the mowing, which is 1800 lbs/acre. The input value for the portion of the affected biomass that is left as added surface residue is 100 percent, which means that 1800 lbs/acre is added to the surface residue as a result of the mowing.

The input values for these operation descriptions are both machine and vegetation specific. For example, assume that the permanent vegetation is a tall grass at the same production 3600 lbs/acre level as the short grass. Assume that 75 percent of the aboveground biomass is affected by the mowing with the tall grass in comparison with the short grass because of differences in vegetation characteristics even though the mower is operated at the same height with both vegetations. The amount of affected aboveground biomass is 2700 lbs/acre. The portion of the affected biomass that is added to the surface residue is still 100 percent, which means that 2700 lbs/acre of biomass is added to the surface residue for the tall grass mowed at the same height as the short grass where aboveground biomass was the same for both grasses. The portion of the aboveground biomass that is affected depends on the vegetation, the machine, and its cutting height.

These inputs, which can be cumbersome and confusing, must be handled very carefully according the RUSLE2 rules and procedures to avoid errors. The intent in RUSLE2 is not to mimic machines, their operations, and settings, but to provide a way to enter information that RUSLE2 needs to determine the surface residue cover and the vegetation conditions after the operation. The operation and vegetation descriptions must be consistent and considered together to ensure that RUSLE2 has the desired values for its computations.[95]

Alternative 2 applies when RUSLE2 is to use a user-entered value for the surface residue added by a hay harvest or mowing operation. The input value for aboveground biomass at maximum canopy is only important in determining the litter fall and the aboveground biomass on the date that the vegetation is killed. In contrast to Alternative 1, it plays no role in determining the surface residue added by the hay harvest/mowing operation. The **processes** in the hay harvest/mowing operation descriptions are **remove live biomass**, **add external residue/cover**, and **begin growth**. The input values for the **remove live biomass process** are 100 percent for the portion of the aboveground biomass affected and 0 percent for the portion of the affected biomass that is left behind as added surface residue. This process removes all of the aboveground biomass on the date of the hay harvest/mowing operation. The **add external residue/cover process** is used to add a specific user entered value for the biomass added to the surface residue by the hay harvest/mowing operation. The inputs for the **add external residue process** are a residue description for the material that is to be added to the soil surface by the operation and the amount of the material that is added. In the mowing example, the value entered for amount of external residue added might be 2000 lbs/acre.

An advantage of this approach is that the effect of cutting height can be quickly and easily evaluated by changing the input value for amount of external residue added. A disadvantage of Alternative 2 is that RUSLE2 does not automatically change this input value as production (yield) level changes because the effect of yield can only be accommodated by manually entering different values for the amount of external residue added. The value for surface residue added that RUSLE2 computes in Alternative 1 does vary with yield as expected.

Table 11.4. Alternative descriptions for hay harvest/mowing operations.			
Alternative 1. Operation description uses aboveground biomass to estimate surface residue added by operation		Alternative 2. Operation description assigns surface residue added by a direct input	
Process	Comment	Process	Comment
Remove live biomass	Removes a portion of the live aboveground biomass at the time of harvest and leaves a part of it in the field as surface residue added	Remove live biomass	Removes all of the live aboveground biomass from the system

[95] RUSLE2 was not designed to use absolute cutting height for hay harvest and mowing operations so that user-entered information is not required on the vertical biomass distribution for each vegetation description and how that changes through time. Such inputs for describing vegetation are not readily available. A major advantage of the RUSLE2 approach, which may seem crude, is that practically any situation can be represented with simple, easy-to-understand inputs.

Begin growth	Identifies the vegetation description that RUSLE2 to use after the hay harvest/mowing operation	Add other cover	Adds external residue in a user entered amount to represent the surface residue added by the operation
		Begin growth	Identifies the vegetation description that RUSLE2 is to use after the hay harvest/mowing operation
Note: A kill vegetation process was not used. A kill vegetation process transfers the live root biomass into the dead root biomass pool, which does not occur in a hay harvest or mowing operation for vegetation that regrows following the operation.			

Example 3. Cover crop.
Vegetation such as rye can be used as a cover crop to reduce erosion over the winter after harvest of the main crop until it is replanted in the spring. A **vegetation description** for a cover crop can be created in either of two ways.

The preferred approach is to develop a vegetation description that extends beyond the last possible date when the cover crop would be killed. The input value for above-ground biomass at maximum canopy cover is for the day in the vegetation description having the maximum canopy cover. This vegetation description can be used in **cover-management descriptions** where the date of the **operation description** that kills the cover crop can vary from day zero until the last day in the vegetation description. RUSLE2 uses equation 11.1 to estimate aboveground biomass on the date on the cover crop killing operation description.

Another approach is to describe the cover crop from its seeding date to the date that the cover crop is killed. The input value for the aboveground biomass at maximum canopy is the amount of aboveground biomass on the date that the cover crop is killed, assuming that the cover crop has not reached maturity and canopy cover is still increasing. The ending date of this vegetation description should coincide with or be within a few days of the date for the cover crop killing operation description. A disadvantage of this approach is that getting these dates to coincide is cumbersome and inconvenient. Another disadvantage is that a separate vegetation description is needed for each date that the cover crop might be killed, which varies according to main vegetation (e.g., cotton is planted later than corn) and early or late planting. The advantage of this approach is that the user can control the amount of biomass at the time that the vegetation is killed instead of letting RUSLE2 use equation 11.1 to estimate aboveground biomass at the date that the cover crop is killed. If the cover crop killing date occurs before the last date in the vegetation description, RUSLE2 will still use equation 11. 1 or 11.2 to estimate aboveground biomass on the date that the cover crop is killed. A few days difference in the killing date and the last date in the vegetation description has only a minimal effect on the results. If the date of the cover crop killing operation occurs after the last day in the vegetation description, RUSLE2 assumes the value on the last day of the vegetation description for all later days. Make a careful check to avoid this condition.

Example 4. Green beans.
Green beans can be cropped in several ways. Mechanically harvested green beans often involve a single harvest that kills the green beans. A vegetation description for green beans can be developed specifically for this cover-management description where the last date in the vegetation description corresponds with the mechanical harvest date. The input value for the above-ground biomass at maximum canopy cover would be for the harvest date, assuming that plant maturity and maximum canopy cover are not reached before the harvest.

A second way of cropping green beans is to hand pick them multiple times before the green beans are mechanically killed by tillage or chemically killed to plant the vegetable crop that follows the green beans. A vegetation description for the green beans is constructed that ends on the date of the operation description that kills the green beans. The input for above-ground biomass at maximum canopy cover would differ in this vegetation description from corresponding input in the vegetation description for the mechanically harvest green beans because the green beans would be killed later than with the single mechanical harvest green beans.

A third way that green beans can be grown is to hand pick the green beans multiple times and let the green beans grow until they die naturally. A vegetation description for this cropping method describes the green beans from seeding until the date that the green beans are assumed to die naturally. An operation description with a kill vegetation process must be included in the cover-management description on the date that the green beans are assumed to die naturally. This operation is needed to convert the live aboveground biomass and live roots to standing residue and dead root biomass.

The input for aboveground biomass at the natural maximum canopy cover is the aboveground biomass amount just before senescence begins. This vegetation description can also be used for the other two types of green bean production methods. This vegetation description has the advantage of not requiring a vegetation description for each production method and also has the advantage of not requiring the cumbersome process of matching the last date in the vegetation description with the date in the cover-management description for the operation description that kills the green beans. The advantage of ending the vegetation description on the date that the green beans are killed is that the user can control the value that RUSLE2 uses for aboveground biomass on the date that the green beans are killed rather than relying on RUSLE2 to use equation 11.1 to estimate the live aboveground biomass value on that date.

11.1.3.3. Residue:yield ratio

The value for aboveground biomass at maximum canopy cover can be entered in one of two ways. The recommended way is to directly enter a value for biomass in terms of dry biomass per unit area. The alternative is to enter a value for residue:yield ratio. RUSLE2 multiplies the value for this ratio by the input yield value and the conversion factor that computes a yield mass (see **Section 11.1.2**) to compute a value for aboveground biomass at maximum canopy cover. See Section **11.2.1** for a discussion on how RUSLE2 adjusts aboveground biomass as a function of production (yield) level.

Make sure that when the residue:yield ratio, yield, and conversion factor are all combined, the resulting aboveground biomass value is on a dry basis.

Residue:yield ratios are primarily rules of thumb, which are useful if values for aboveground biomass are not available. Residue:yield ratio values are a function of yield. Assuming a constant residue:yield ratio value over a working range is acceptable for several crops, but residue yield ratio values can be significantly larger at low yield than at high yields.

The residue:yield ratio values can vary by crop variety. Some of the common rule of thumb residue:yield ratio values were developed 40 or more years ago. Make sure that those values, although widely used, apply in your situation.

Be slow in having different residue:yield ratios in an attempt to compute how crop variety affects erosion. RUSLE2 is not sufficiently accurate for basing conservation planning on such differences. The main intent of RUSLE2 is to represent how main plant types, such as wheat, affect erosion in relation to another crop type, such as corn. The same is true for capturing the differences between plant community types for permanent vegetation on pasture, range, reclaimed mine, and landfills.

11.1.3.4. Selecting input value for aboveground biomass at maximum canopy cover

The input for aboveground biomass at maximum canopy is one of the most important inputs in RUSLE2 because this value determines the amount of litter fall and crop residue that ends up on the soil surface as ground cover to affect erosion. In most situations involving disturbed land, ground cover has more effect on erosion than any other variable. The input value for this aboveground biomass should be chosen very carefully and must be consistent with the values in the **RUSLE2 core database**. The values shown in the RUSLE2 core database were used to calibrate RUSLE2. If a user assumes different values for the RUSLE2 core database conditions than were used by the RUSLE2 developers in their calibration of RUSLE2, then RUSLE2 will give erroneous results.

Consistency between inputs and the RUSLE2 core database must be followed.

Scientific literature is a source of data for values for aboveground biomass at maximum canopy cover. These data can be quite variable. Assemble as much data as possible and review the data as a whole. Select input values that represent the data as a whole rather than trying to capture the effects of individual studies. Some or even most of the differences between individual studies can be unexplained by variability that occurs between particular years and locations.

11.1.4. Vegetative retardance

Vegetative retardance refers to the degree that vegetation slows runoff to reduce its erosivity and transport capacity. Vegetative retardance depends on type, growth stage, and density of the vegetation. For example, the retardance of dense, sod forming grasses is much greater than that of vines in a vineyard. The retardance of sod forming grasses is greater than that for bunch grasses. The retardance of a sod forming grass is very low if its production (yield) level is very low. Retardance increases during the growing season as plant material develops. Plant material must be in contact with the soil surface and slow the runoff to affect vegetation retardance. Additional factors such as soil surface roughness, surface residue cover, and live ground cover are considered by RUSLE2 to determine the overall retardance as it varies through time in a RUSLE2 computation.

Eight retardance classes ranging from none to the greatest, which is for a dense sod forming grass, are used to represent the vegetation retardance at maximum canopy cover at the base yield. RUSLE2 adjusts the class selected to represent the vegetation description as canopy cover changes during the time and as yield varies from the base yield represented by the vegetation description.

The input for retardance class for a **vegetation description** is discussed in **Section 11.2.5**. The retardance class that RUSLE2 assigns to the vegetation description at the input yield value is displayed in the **cover-management description** window of the RUSLE2 computer program for certain **user template** RUSLE2 program configurations. The purpose for giving the user access to vegetation retardance class during a RUSLE2 computation is to allow the user to manually override RUSLE2's selection of the retardance class for the input yield, if desired.

11.1.5. Residue

As described in **Section 11.1.3,** aboveground plant material can reach the soil surface as litter fall or by mechanical operations such as mowing and harvesting. RUSLE2 uses data on plant material properties to compute how this material, referred to as **residue** in RUSLE2 terminology, affects erosion. These properties include how well the material conforms to the soil surface, resists breaking into smaller pieces when the soil surface is mechanically disturbed (fragility), the portion of the soil surface cover by a given mass of material, and the rate that the material decomposes under a standard environmental condition.

Data for these properties are input for **residue descriptions** contained in the **residue component** in the RUSLE2 database. A residue description is selected and assigned to each **vegetation description** depending on how a vegetation description is used in a **cover-management description**. Plant litter (residue) is typically composed of several plant components including leaves, seed pods, chaff, and fine and coarse stems that vary greatly in their properties. A residue description represents a composite of all plant components present in the residue at the time that residue description is being used in RUSLE2. Assigning a residue description to a vegetation description is almost always a compromise. For example, immediately after harvest, the leaves in soybean residue provide a high degree of soil cover, but these leaves decompose very rapidly so that the residue becomes composed primarily of stems. The stems cover a far smaller area than do the leaves for a given mass, and the stems decompose far more slowly than do the leaves. Thus, the net properties of the soybean residue change greatly through time as the relative mass of the residue components change through time.

RUSLE2 does not consider how the properties of a residue description change through time.

Select a residue description to obtain the best overall results, which is usually an estimate of average erosion rather than erosion for a particular period. Values for residue and other variables in the RUSLE2 core database were chosen to give good estimates for average annual erosion.

However, cases arise where a different residue description should be selected for a particular plant community, such as wheat, depending on how the vegetation description is used in a cover-management description. Mature wheat straw decomposes much more slowly than does wheat residue when the wheat is killed in its early growth stage. Thus, two wheat residue descriptions should be developed, one for wheat grown to maturity where the grain is harvested and wheat straw remains and one for wheat grown as a cover crop that is killed before the wheat reaches maturity. Thus, the residue assigned to wheat depends on whether the wheat vegetation description is used in a cover-management description for grain or in a cover-management description where the wheat is used as a cover crop that is killed before reaching maturity.

The same residue description can be used for multiple vegetation descriptions. For example, several vegetation descriptions can be developed for corn based on days to maturity. The same residue description can be used for all of these corn descriptions.

11.1.6. Relative moisture depletion

A value for the variable **relative moisture depletion** is entered in vegetative descriptions used when RUSLE2 is applied to Req zones (see **Section 6.9**). This variable describes how a previous crops depletes soil moisture, which reduces runoff and erosion in subsequent periods in a crop rotation.[96] Recommended values for relative moisture depletion are given in Table 11.5.

A value of 0.00 for relative moisture depletion means that the vegetation (crop) does not remove sufficient water to significantly affect erosion. In comparison, a crop such as winter wheat is assigned the maximum value of 1.00. See **Section 9.2.7** for discussion on how this variable affects erosion computed by RUSLE2.

Table 11.5. Recommended value for relative moisture depletion for vegetation description used in applying RUSLE2 to Req zones. (Source: AH703)

Crop	Relative moisture depletion input value
Winter wheat and other deep rooted crops	1.00
Spring wheat and barley	0.75
Spring peas and lentils	0.67
Shallow-rooted crops	0.50
Summer fallow	0.00

11.1.7. Growth chart variables

A **vegetation description** includes arrays of input values for the **temporal variables** of age (time), live root biomass, canopy cover, effective fall height, and live surface (ground) cover. The collection of these values is referred to as the **growth chart** for a vegetation description. A value for each variable is entered for each **time** in the growth chart. Each entered value is the value for a variable on that day, not an average or representative value over a time interval.

RUSLE2 uses a descriptive procedure to input values for vegetation variables that affect erosion rather than using a plant model to compute values for those variables. The focus in creating and using vegetation descriptions is to describe, not to model. This RUSLE2 feature gives RUSLE2 great power and flexibility.

A vegetation description is just that, a description of the vegetation condition over the time represented in the growth chart. This description is for the composite field condition on each day. RUSLE2 can not combine vegetation descriptions from multiple

[96] Contact Donald K. McCool, USDA-Agricultural Research Service, Pullman, WA for additional information.

plant communities into a new vegetation description for a plant community composed of multiple components. That is, a single set of vegetation values are used to describe intercropping, where two or more plant types are growing at the same time, rather than combine values for the component parts. For example, the input values for canopy cover and fall height are the values that you want RUSLE2 to use to represent the composite field condition on each day. See **Section 10.2.3.**

11.1.7.1. Age

Age in days is the time variable used in the growth chart. The first entry in a growth chart is always for **day zero (0),** which represents conditions on the date that this **vegetation description** begins to apply. RUSLE2 references day 0 to the date in the **cover-management description** for the **operation description** with a **begin growth process** that instructs RUSLE2 to begin using this particular vegetation description. A set of time (age) values are chosen to describe the temporal variables in the vegetation description. RUSLE2 assumes that variables are linear between each time value. Only a time at the beginning and a time at the end of a period are entered if values for all of the temporal variables do not change over the time period. Similarly, only times at the beginning and end of a period are entered if the temporal variables vary linearly over the time period. Additionally, closely spaced times are used to represent periods when one or more of the temporal variables change non-linearly. A sensitivity analysis (see **Section 17.3**) may be needed to determine the spacing of the times in these non-linear periods.

The growth chart for a RUSLE2 vegetation description often uses days on a 10-day or 15-day internal for convenience.[97]

The days in the growth chart for a vegetation description need not be on a fixed interval.

Day zero in a vegetation description is not necessarily the date that the vegetation is seeded. The values on day 0 describe conditions that exist on the day that RUSLE2 begins to use this vegetation description. Value for day 0 should be entered very carefully. RUSLE2 compares the root biomass and canopy cover values on day 0 with corresponding values for the last day that the previous vegetation description is used. RUSLE2 assumes that a decrease in live root biomass between two vegetation descriptions represents an event where the decrease in live root biomass should be added to the dead root biomass pool. An example is the wheat-legume intercropping cover-management description discussed in **Section 10.2.3.** The live root biomass on day 0 for

[97] Vegetation descriptions in RUSLE1 must be on a 15-day time interval. Although that 15-day time interval is often retained where RUSLE1 data files are imported into RUSLE2, day values in RUSLE2 can be on any interval and the interval can vary throughout a RUSLE2 vegetation description.

the legume vegetation description that represents conditions after the wheat harvest is less than the live root biomass of the combined wheat-legume vegetation on the day of wheat harvest. The effect represented by this decrease is that the wheat harvest killed the wheat and transferred the wheat's live root biomass to the dead root biomass pool. A harvest operation with a **kill vegetation process** is not used in this cover-management description because that process would have transferred the entire live root biomass, not just the wheat live root biomass, to the dead root biomass pool.

The last day in the vegetation description should be carefully selected as discussed in **Section 11.1.3.2.** The last day in the vegetation description should be later than the date in the cover-management description for the operation description that kills the vegetation. In special cases, the last day in the vegetation description and date of the kill vegetation operation should be the same or nearly the same to ensure that RUSLE2 uses a particular value for aboveground biomass at maximum canopy cover. However, if the last day in the vegetation description is less than the date of the kill vegetation operation, RUSLE2 uses values for the last day in the vegetation description until RUSLE2 begins to use the next vegetation description.

No time limit exists for the last day in a vegetation description. Many vegetation descriptions are for a year or less.[98] For example, the duration of vegetation descriptions vary from 60 days for spring broccoli, 120 days for corn grain, 255 days for winter wheat, and 365 days for a mature pasture. In RUSLE2, the time can be as long as desired to represent the full duration of the vegetation, which can be multiple years. For example, the vegetation description for seeding and establishment of permanent vegetation on a landfill or reclaimed mine may be 10 years that includes the initial three-year establishment period and an addition seven years required for a stable litter and soil biomass pool to develop. The RUSLE2 long term vegetation tool described in **Section 11.2.6** can be used to construct these multi-year vegetation descriptions. A set of three vegetation descriptions can be used in this example rather than using one long 10-year vegetation description. Three 1-year vegetation descriptions would be used, one for the first year starting at seeding, one for development during the second year, and one for the third year and every year thereafter, which represents maturity. An operation with a begin growth process is used each year to tell RUSLE2 which vegetation description to use for that year.

Another example where multiple vegetation descriptions are used is to represent mowing permanent vegetation and hay harvests (see **Section 11.1. 3.2**). The main use of the multiple vegetation description is to represent regrowth of the vegetation following mowing or hay harvest. Simultaneous with the representation of mowing and harvest, multiple vegetation descriptions can be used to represent both the increase and decrease of vegetative production between renovations of the vegetation. See **Section 10.2.3** for a

[98] The duration of a vegetation description in RUSLE1 is limited to 1 year. Vegetation descriptions in RUSLE2 can be of any duration.

discussion of an alfalfa cover-management description where multiple vegetation descriptions are used.

11.1.7.2. Live root biomass

Live roots reduce erosion by mechanically protecting and holding soil in place, producing exudates that reduce soil erodibility, becoming a part of the soil dead root biomass by root sloughing (death) or the vegetation being killed, and indirectly representing increased infiltration, reduced runoff, and reduced erosion (see **Section 9.2.5**). The most important roots are the fine ones very near the soil surface. Coarse roots, especially tap roots, have much less effect on erosion than the fine roots. A value for **live root biomass per unit area in the upper four inches (100 mm) of soil** is entered for each time in the **growth chart**. RUSLE2 uses each value in the array to estimate live root biomass values for the entire rooting depth according to the distribution illustrated in Figure 9.14.

Live root biomass values for annually seeded plants, such as the corn and winter wheat illustrated in Figure 11.4, start from zero on day zero (0) in the growth chart and increase through time to a maximum value. In the case of spring planted corn, the values increase as an S-shaped curve and level off at a maximum. The pattern for fall planted winter wheat differs from that for the spring planted corn. The winter wheat experiences early growth during the fall and dormancy during the winter, reflected by the plateau from about day 50 to day 170 in Figure 11.4. The degree of fall growth for the winter wheat and the length of dormancy is climate dependent. RUSLE2 does not adjust vegetation descriptions to account for those climatic differences. Instead, users create multiple vegetations by climatic regions, such as cropping zones. Figure 11.4 illustrates vegetation descriptions for annually seeded crops. Figure 11.5 illustrates vegetation descriptions for permanent vegetation. Two types of erosion analysis are made for permanent vegetation. One analysis is to compute erosion from the date of seeding until the vegetation becomes mature, fully established along with a fully developed litter layer and soil biomass pool. The other analysis is to estimate erosion for a fully established permanent vegetation (see **Section 10.2.8**).

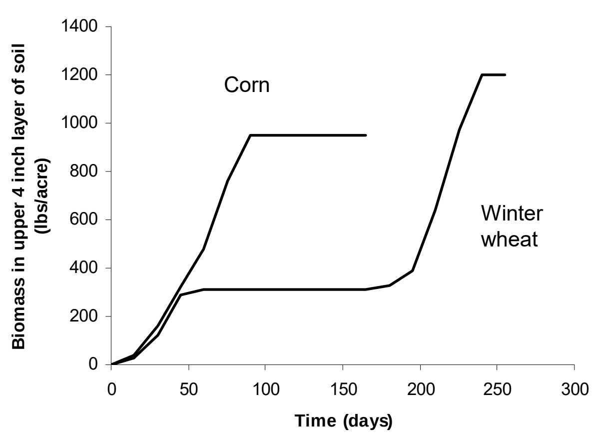

Figure 11.4. Live root biomass values for corn and winter wheat.

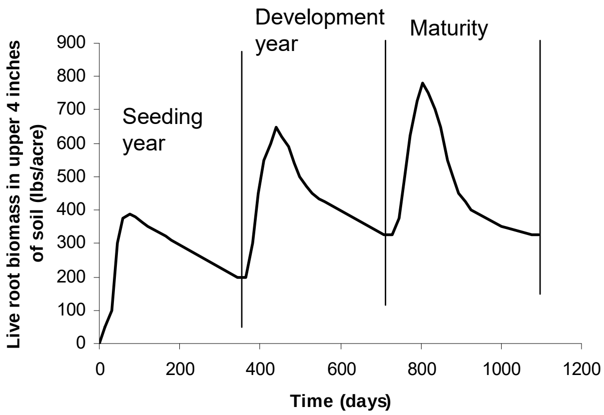

Figure 11.5. Live root biomass for three vegetation descriptions used in series to represent the establishment of permanent vegetation

A single **vegetation description** can be created to describe the vegetation from seeding through complete establishment. The vegetation can also be described with a set of three vegetation descriptions as illustrated in Figure 11.5. The time period for each vegetation description is an entire year. The ending live root biomass for one vegetation description matches the live root biomass at the beginning of the next vegetation description. In the mature year, the beginning live root biomass matches the ending live root biomass. The vegetation description for the mature year is repeated for as many years as necessary for RUSLE2 to compute a stable litter layer and soil biomass pool. This **cover-management description** is a **no-rotation** with a **duration** sufficiently long for fully established conditions to be represented.

Only the vegetation description for the mature year is used to compute erosion for a vegetation completely established. This cover-management description is a **rotation** with a 1-year **duration**. RUSLE2 automatically repeats the computations for as many years as necessary to compute the development of a stable litter layer and soil biomass pool.

The value for live root biomass on day 0 begins at zero for plants started from seed. However, live root biomass on day 0 begins at a value greater than zero when describing vegetable transplants, for example, to reflect the presence of live root biomass is when RUSLE2 begins to use this vegetation description.

Live root biomass is the source of the dead root biomass pool represented by RUSLE2. An **operation description** with a **kill vegetation process** transfers the entire live root biomass that exists on the date of the kill vegetation operation description to the dead root biomass pool. Live root biomass becomes zero on that day and the dead root biomass pool is increased by this amount of live root biomass.

A kill vegetation process in an operation description transfers the entire live root biomass to the dead root biomass pool. Sequential vegetation descriptions without a kill vegetation operation description are used to transfer only a portion of an existing live root biomass pool to the dead root biomass pool.

Root sloughing (death) is also a major source of dead root biomass for permanent vegetation on range, pasture, landfills, and reclaimed mine lands. Up to 40 percent of the annual root biomass can be sloughed (see **Sections 9.2.5.1 and 9.2.5.3.2**). RUSLE2 assumes that a decrease in live root biomass, as illustrated in Figure 11.5, during the time represented by a vegetation description is root sloughing. RUSLE2 can also compute death of root biomass during growth periods by assuming that daily root biomass death is a fraction of the daily live root biomass. The decrease in live root biomass between days is added each day to the dead root biomass pool. Using a constant live root biomass in a permanent vegetation description prevents RUSLE2 from computing an accumulation of dead root biomass, which can result in a serious overestimate of erosion.[99]

Time varying root biomass values should be used in vegetation descriptions for permanent, multiple year forage crops, and similar vegetation.

Situations, such as intercropping, exist where only a portion of an existing live root biomass pool should be transferred to the dead root biomass pool. An example is the small grain-legume **cover-management description** discussed in **Section 10.2.3.** A similar situation is winter weed growth in southern US regions. The canopy of crops like corn, soybeans, and cotton decrease before harvest so that volunteer weeds begin to grow and continue to grow after crop harvest. These weeds provide vegetative cover during the winter to significantly reduce erosion, which is especially important because of the high erosivity during winter months in this region.

Sequential vegetation descriptions are used in RUSLE2, such in these cover-management descriptions, when only a portion of an existing live root biomass pool is to be transferred to the dead root pool. Three vegetation descriptions are used: (1) the wheat only period from seeding until the legume is seeded (corn only), (2) the period when the wheat and legume grow together until wheat harvest (corn and weeds together), and (3) the period after wheat harvest where the legume continues to grow (also, weeds after corn harvest). RUSLE2 makes no change to the dead root biomass pool between periods 1 and 2 because the live biomass values at the end of period 1 equals the live root biomass at the beginning of periods. RUSLE2 adds to the dead root biomass pool between periods 2 and 3 because the live root biomass decreases from that at the end of period 2 to the live biomass at the beginning of period 3. The addition to be dead root biomass pool is the amount of the decrease in the live root biomass. This procedure represents harvest

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[99] The time-invariant C-factor procedure in RUSLE1 does not directly account for the effect of dead root biomass on erosion.

killing one vegetation while allowing growth of another vegetation to continue.

Figure 11.5 illustrates a situation where no live root biomass should be transferred to the dead root biomass when RUSLE2 switches vegetation descriptions in the cover-management description. The vegetation descriptions for Figure 11.5 were constructed with the biomass value at the end of one vegetation description matching the live root biomass value at the beginning of the next vegetation description in the sequence so that a smooth continuous condition in live root biomass is represent between vegetation descriptions.

Hay harvest of forage crops that regrow after harvest and permanent vegetation that regrows after mowing are cover-management descriptions where an event causes a major change to occur in the aboveground biomass but no change in the live root or dead root biomass pools. Principally two vegetation descriptions are used, one to represent conditions through the day of the hay harvest/mowing and one to represent regrowth conditions after hay harvest/mowing. The live root biomass value at the end of the first vegetation description matches the live root biomass value at the beginning of the second vegetation description. The two live root biomass values should be equal on the day of harvest and the day after harvest so that no change in the dead root biomass occurs. Multiple vegetation descriptions can be created to shows a progression of live root biomass over time where a hay (pasture) crop reaches maximum production and then declines until the hay (pasture) crop is renovated.

RUSLE2 makes no change in the dead root biomass when the live root biomass increases either within a vegetation description or between vegetation descriptions.

Inspect the vegetation descriptions used in a cover-management description to avoid an unintended decrease in live root biomass and addition to dead root biomass between vegetation descriptions.

The recommended approach for selecting input values for live root biomass is to use the values listed in the **RUSLE2 core database** as a guide. Start by selecting a vegetation description in the RUSLE2 core database that is similar to the plant community for which you are selecting input live root biomass values. Modify the live root biomass values for the selected core database plant community based on how you think differences between the two plant communities would affect live root biomass. This approach for selecting live root biomass values is far better than making field measurements of live root biomass values. Measuring root biomass is very difficult and time consuming, which is evident by the huge range of values given in the literature for wildland type plant communities (see **AH703**). The variability is much less for agricultural and pasture land crops, but is still significant. If input values for live root biomass are to be selected based on field measurements, make many measurements, being careful to measure the fine roots, which have the greatest effect on erosion.

The research literature is a source of live root biomass values that are reliable for vegetable and field crops but not for wildland plant communities. Be very careful in selecting live root biomass values based on literature sources. Many data sources should to be reviewed to determine overall main effects. The best way to select live root biomass values for wildland plant communities is to use the ratio of effective root biomass to average annual aboveground biomass production listed in **Section 17.4.1.4**. These values were obtained by using measured erosion data to back calculate effective live root biomass values using the subfactor equations described in **Section 9**.

A major problem with using measured root biomass values for wildland type plant communities is knowing the credit to give to fine roots versus the credit to give to coarse roots. The input values for live root biomass should be based primarily on the annual production of fine roots. However, erosion and root research has not provided definitive information on how to measure root biomass for use in RUSLE2, which was overcome in the RUSLE2 approach that back calculates effective live root biomass values from measured erosion data.

A major requirement is that input values for live root biomass values are consistent with values in the RUSLE2 core database to ensure that RUSLE2 computes the expected erosion values. RUSLE2 was calibrated with the values given in the RUSLE2 core database to give expected average annual erosion estimates. If input values are not consistent with the core values used to calibrate RUSLE2, then RUSLE2 may give erroneous results. Do not use live root biomass values without checking them for consistency with RUSLE2 core values.

11.1.7.3. Canopy cover

Canopy cover is the portion of the soil surface covered by plant material that is above the soil surface. Canopy cover intercepts raindrops but has no effect on surface runoff, (see **Section 9.2.1**). Canopy cover is a major variable in the canopy subfactor, and it is also used by RUSLE2 to estimate live aboveground biomass during the time represented by a **vegetation description** (see **Section 11.1.3.1**).

Canopy cover values are entered for each time value in the **growth chart**. RUSLE2 interprets an increase in canopy cover as plant growth adding aboveground biomass. Conversely, RUSLE2 interprets a decrease in canopy cover as a transfer of live aboveground biomass to the soil surface. Senescence and litter fall are natural processes where leaves fall from mature plants to the soil surface and become surface (flat) cover. Most permanent vegetation and some agricultural crops like soybeans experience senescence. Also, a senescence type process is chemically induced in cotton just before harvest. Not all decreases in canopy cover represent a transfer of biomass from the live aboveground biomass to surface residue. For example, mature corn leaves droop without falling to the soil surface. RUSLE2 uses data are entered in the **senescence tool** in the vegetation description to calibrate equation 11.2 that computes values for live aboveground biomass as a function of canopy cover.

A decrease in canopy cover between the last day of the previous vegetation description and the canopy cover on day zero of the next vegetation description has no significance to RUSLE2. RUSLE2 makes no changes in residue cover when canopy cover changes between vegetation descriptions. In contrast, RUSLE2 assumes that a decrease in live root biomass between vegetation descriptions is dead root biomass that is added to the dead root biomass pool. **Operation processes**, such as **kill vegetation**, in **operation descriptions** to explicitly describe changes in standing and surface residue between vegetation descriptions.

A **kill vegetation process** in an **operation description** converts the entire live aboveground biomass to standing reside rather than just a part. **Understanding this feature is important** for describing intercropping represented in the wheat-legume cover-management description discussed in **Section 10.2.3**. The wheat harvest creates a large pool of standing and flat wheat straw residue. However, the live aboveground biomass for the legume should remain unchanged after the wheat harvest.

A similar situation is hay crops that regrow after hay harvest and permanent vegetation that regrows after mowing. These **cover-management descriptions** typically involve a harvest operation description that includes a **remove live biomass process** to manipulate the live aboveground biomass amounts to add the desired amount of surface (flat) residue and a **begin growth process** to identify the vegetation description that RUSLE2 is to use immediately after harvest. **The value that RUSLE2 uses for standing residue needs to be checked to ensure that RUSLE2 is leaving the proper amount of standing residue. This check is critically important in cover-management descriptions like wheat-legume intercropping because of the large mass of residue left by the wheat harvest.**

Input values for canopy cover should be selected by comparing your vegetation description with vegetation descriptions contained in the **RUSLE2 core database**. Select canopy cover values by adjusting core database values based on differences in characteristics between your vegetation and the core database description being used as a guide.

The literature is a source of canopy cover values. However, make especially sure that the canopy cover values reported in the literature are consistent with **RUSLE2 definitions**. For example, literature values often includes leaves touching the ground as **canopy cover** that the RUSLE2 definitions require counting as **live ground cover** (see **Sections 9.2.2.1 and 11.1.7.5**). Review as many data sources as possible because of data variability. The data should be reviewed to determine overall main effects rather than focusing on the data for a single location.

In some cases, field measurements may be necessary. One way to estimate canopy cover is to sum the open space between plants and open space within the perimeter of the plant canopy and subtract this sum expressed as a percent of the total area from 100. Canopy cover can be estimated from plan view photographs for certain plant communities like corn where live vegetation does not touch the soil surface. A better approach for measuring canopy cover of permanent vegetation on range, pasture, landfills, and reclaimed mine land where some of the live vegetation touches the ground is to lay a transect across the field slope, lower a pointed rod vertically to the soil surface, and count the number of hits for canopy cover, surface (flat) residue (litter), and live parts of the vegetation touching the soil surface (live ground cover). Make sure that a large number of measurements are taken to properly deal with spatial and temporal variability, such as that associated with hillslope position.

11.1.7.4. Canopy Fall Height

Canopy fall height is the effective height from which intercepted rainwater forms drops that fall from the plant canopy (see **Section 9.2.1.1**). **Effective fall height** is less than the canopy height but greater than the height to the canopy bottom. Effective fall height is also a function of canopy shape and the vertical density distribution within the canopy. Some plant communities like grass growing under shrubs on rangelands have two distinct canopies. The understory is the main determinant of effective fall height if the understory is dense. Enter an effective fall height value for each time in the **growth chart**.

Several procedures are available for selecting effective fall height values. One approach is to compare characteristics of your vegetation with **vegetation descriptions** in the **RUSLE2 core database** and assign effective fall height values based on that comparison. Another approach is to inspect plants in the field or in photographs and assign effective fall height values. Another approach is to measure the height to the lowest part of the canopy at locations along a transect. Effective fall height is the average of those values. A fourth approach is to use the **fall height tool** in a RUSLE2 vegetation description to estimate effective fall height. This procedure uses height values to the top and bottom of the canopy, canopy shape, and the density gradient within the plant canopy to estimate effective fall height (see **Section 9.2.1.3**).

Review effective fall height values to ensure consistency among vegetation descriptions so that RUSLE2 computes expected differences in erosion among plant communities.

11.1.7.5. Live ground cover

Live ground cover is live vegetation that touches the soil surface to affect raindrop impact and surface runoff as does other ground cover (see **Section 9.2.2.1**). Live ground cover is one form of ground cover along with crop residue, plant litter, and rock fragments. The portion of the soil surface covered by live ground cover can be very high in early plant growth when the vegetation is composed almost entirely of very low leaves. As the vegetation grows and stems develop, live ground cover can decrease, even to the point that no part of the plant, other than the stems, touches the soil surface to provide live ground cover. Live ground cover inputs also include basal area of the vegetation. A value for live ground cover is entered for each time value in the **growth chart**.

The best way to select live ground cover input values for a vegetation description is to make comparisons with **vegetation descriptions** in the **RUSLE2 core database**. Field measurements can also be made. Many measurements are needed to deal with both temporal and spatial variability. Field measurements can be made using points along a transect. Live ground cover is measured even if it lies on top of plant litter, crop residue, rock, or other types of ground cover. RUSLE2 accounts for overlap of ground cover from different sources. Input values for live ground cover should be reviewed for consistency among the vegetation descriptions in the RUSLE2 database. Also, field inspections of plant communities are helpful, especially if field measurements of live ground cover are not made.

The mass in live ground cover is included in the live aboveground biomass inputs. RUSLE2 does use a relationship between cover and mass for live ground cover as it does for crop residue, plant litter, or applied residue.

11.2. Tools used to develop input values for vegetation descriptions

11.2.1. Develop growth chart for a new production (yield) level

Each **vegetation description** in the RUSLE2 database is for a particular **production (yield) level**. Adjustments are required in a vegetation description to apply RUSLE2 to other production (yield) levels (see **Section 9.2.1.6**). Two options are available to make the adjustments.

One option is to enter the desired production (yield) level value in the **cover-management description** where the vegetation descriptions are selected. RUSLE2 can adjust any vegetation description to a production (yield) level greater than the assigned value for the selected vegetation description. However, the maximum canopy cover must be less than 100 percent in the selected vegetation description for RUSLE2 to adjust to a production (yield) level less than the assigned value for the selected vegetation description. RUSLE2 adjusts values for aboveground biomass at maximum canopy; live root biomass, canopy cover, effective fall height, and live ground cover in the growth chart; and retardance index values to represent the new value entered for production (yield) level. Live aboveground biomass at maximum canopy is assumed to vary with yield according to equation 9.5. RUSLE2 assumes that live root biomass varies linearly with aboveground biomass at maximum canopy cover; canopy and live ground cover vary with the square root of live aboveground biomass at maximum canopy cover; and effective fall height varies with the 0.2 power of live aboveground biomass at maximum canopy. RUSLE2 varies the retardance index as a linear function (retardance index = a + b·yield) (see **Section 11.2.5**).

The second option is to use the RUSLE2 tool **develop growth chart for new production (yield) level** to create a new vegetation description for the desired production (yield) level. This RUSLE2 tool starts with the selection of a base vegetation description at its assigned production (yield) level. A value is entered for the new production (yield) level and RUSLE2 creates a new vegetation description for the new production (yield) level. This new vegetation can be saved in the RUSLE2 database and used in other RUSLE2 computations. The same requirements and equations discussed above for entering a new production (yield) level in a cover-management description apply in the **develop new growth chart tool**. The advantage of using the develop new growth chart tool is that the adjustments do have to be made by hand and manually entered in a new vegetation description in the RUSLE2 database.

11.2.2. Estimate effective fall height based on canopy characteristics

As discussed in **Section 9.2.1.2, effective fall height** varies with heights to the top and bottom of the canopy, canopy shape, and the vertical density gradient of plant material within the canopy that affects fall height. The RUSLE2 tool that estimates **effective fall heights as a function based on canopy characteristics** can be useful in assigning effective fall height values and improves consistency among users assigning effective fall height values.

Effective fall height varies temporally during plant growth and senescence. Input values for canopy characteristics are entered into the fall height tool at selected times during the period represented by a **vegetation description**. These inputs include values for heights to the top and bottom of the canopy, selection of a canopy shape from those illustrated in Figure 9.2, and selection of a canopy density gradient. The canopy density gradient refers to whether canopy material affecting fall height is uniformly distributed with height in the canopy, concentrated near the bottom of the canopy, or concentrated near the top of the canopy. The base condition is for a uniform canopy density gradient where effective fall height is one third of the difference in heights between the top and bottom of the canopy plus the height to the bottom of the canopy as illustrated in Figure 9.1. The effective fall height is adjusted up or down with respect to canopy shape as illustrated in Figure 9.1 and adjusted up if the plant material affecting fall height is concentrated near the top of the canopy or down if the material is concentrated near the bottom of the canopy.

RUSLE2 computes an effective fall height at each of the times where values are entered for canopy characteristics. RUSLE2 then linearly interpolates between these effective fall height values to assign effective fall height values for each time value in the **growth chart**.

11.2.3. Live aboveground biomass at maximum canopy as a function of production (yield) level

The input for **live aboveground biomass at maximum canopy cover** determines the mass of vegetative material that becomes standing and surface (flat) residue, both of which have a major effect on erosion (see **Sections 9.2.2, 9.2.5, and 11.1.3**). The amount of live aboveground biomass varies with production (yield) level as illustrated in Figure 11.6. RUSLE2 uses equation 9.5, represented by the fitted line in Figure 11.6, to estimate live aboveground biomass at maximum canopy cover as a function of **production (yield) level** (see **Section 9.2.1.6**).

The **biomass-yield tool** [live aboveground biomass at maximum canopy as a function of production (yield) level] is used to input values that define the fitted line illustrated in Figure 11.6 for a particular vegetation description. The procedure is to plot observed data for live aboveground biomass at maximum canopy as a function of production (yield) level and fit a straight line to the data. The production (yield) level units in this relationship are the ones created for this particular **vegetation description** (see **Section 11.1.2**).

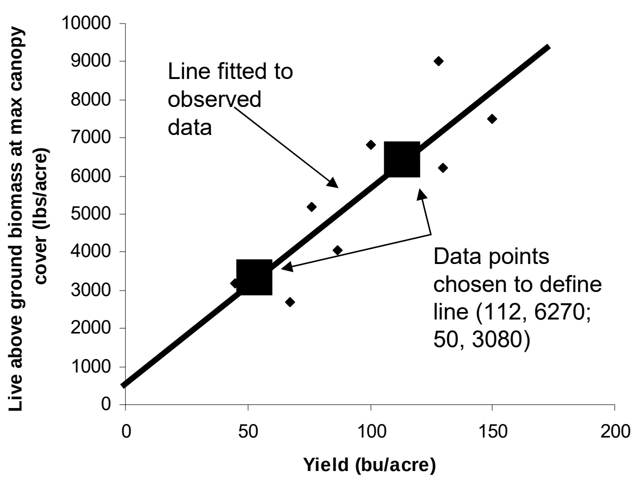

Figure 11.6. Fitting line to aboveground biomass data as a function of yield.

Values for two data points on the line are chosen and entered in the biomass-yield tool. RUSLE2 uses these two data points to compute values for the coefficients M_0 and b_a in equation 9.5. The data point for the higher production (yield) level is the production (yield) level for which the vegetation description applies and the second data point is at a lower production (yield) level. If the same values are entered for both data points, RUSLE2 assumes that the value for the intercept M_0 is zero (0) and that the slope b_a equals the value entered for live aboveground biomass live divided by the production (yield) level. This procedure can be used to describe forage crops and permanent vegetation. Otherwise, this procedure should only be used within a limited production (yield) range. See the discussion later in this section related to the variation of the ratio of live aboveground biomass to production (yield) level.

The value for the intercept (coefficient M_0) represents the live aboveground biomass at maximum canopy at zero production (yield) level. The intercept value is greater than zero for grain and vegetable crops like corn, soybeans, wheat, green beans, and cucumbers, while the intercept value is zero for the typical production (yield) level definitions used for forage crops and permanent vegetation. The value for the coefficient b_a is the slope of the line fitted to the data illustrated in Figure 11.6. It represents the increase in the live aboveground biomass at maximum canopy for a unit increase in production (yield) level.

The input values for live aboveground biomass at maximum canopy must be on a dry basis. The input values are for the live aboveground biomass at maximum canopy cover, not the live aboveground biomass at harvest. RUSLE2 accounts for loss of live aboveground biomass by senescence using the live aboveground biomass at maximum canopy cover as its starting point. Input values used by RUSLE2 to calibrate equation 11.4 to compute loss of live aboveground biomass by litter fall and senescence tool are entered in the senescence tool (see **Section 11.2.4**).

The two input values for live aboveground biomass provide RUSLE2 with the information it uses to compute the mass of above ground plant material that influences erosion. The objective is not to account for all of the biomass in the system but only that biomass that affects erosion. For example, harvested soybean grain does not end up on the soil surface to affect erosion, but pods around the grain do and should be counted in the live aboveground biomass input. Another example is woody-type vegetation such as shrubs on rangelands. The amount of aboveground biomass that becomes litter fall is the only important biomass under most permanent vegetation conditions. However, if the woody-type material becomes surface residue, perhaps as a part of rangeland renovation, then the woody-type biomass must be accounted for in the vegetation description and in the **residue description** selected for the vegetation description.

The values entered for live aboveground biomass at maximum canopy must be consistent with values entered in the senescence tool in a vegetation description.

Input values for the biomass-yield tool can be obtained in several ways. One way is to compare your vegetation with vegetation descriptions in the **RUSLE2 core database** and select input values based on this comparison. A data source is residue-yield research data published by agricultural experiment stations to which you can use to fit equation 9.5. Ensure that yield definitions used in these data are consistent with the RUSLE2 yield definition used in the vegetation description. Also, adjustments may be needed in crop residue data measured at harvest where senescence has occurred. The input values used by RUSLE2 are for the live aboveground biomass at maximum canopy, which is different from the aboveground biomass at harvest after senescence has occurred and surface residue has been lost by decomposition.

Research data vary greatly from study to study. Assemble as much data as possible and choose values that best represent the data as a whole rather than focusing on data from a single location or localized region. Also, be careful about attempting to represent differences between crop varieties. RUSLE2 was calibrated to represent main effect differences between plant communities such as between corn and wheat and not differences between crop varieties.

Rule of thumb values for residue:yield ratios can be used to estimate values for the two input data points in the RUSLE2 biomass-yield tool (see **Section 11.1.3.3**). Values for residue:yield ratios are given in Appendix D of Agriculture Handbook (AH) 703 for particular crops for a range of yields. Assume that the residue:yield ratio value applies to the middle of the yield range. Enter the yield value for the midpoint of the yield range and the residue:yield ratio for the first residue-yield data point. For the second data point, enter the yield for the lower end of the yield range in AH703 and the residue:yield ratio times 1.1. For example, the value for the residue:yield ratio value for corn in AH703 is 1.0. The residue to yield ratio value that would be entered for a 50 bu/ac yield, the lower end of the yield range in AH703, would be 1.0·1.1=1.1.

The assumption of a constant residue:yield ratio only applies over an upper range of yield values for vegetation descriptions where the intercept M_0 value is greater than zero. The equation for residue:yield ratio derived from equation 9.5 is:

$$M_a / Y = M_0 / Y + b_a \qquad [11.8]$$

where: M_a/Y = the ratio of live aboveground biomass at maximum canopy to production (yield) level, which is equivalent to residue:yield ratio after proper consideration for senescence. Residue:yield ratio values for the data illustrated in Figure 11.6 are shown in Figure 11.7. Note that residue:yield ratio values approach infinity at a zero yield and decrease to almost a constant value for yield greater than 50 bu/acre. The change in residue:yield ratio for these data is sufficiently small that a constant residue:yield ratio value could be assumed for yields greater than 50 bu/acre. A constant residue:yield ratio can be used in vegetation descriptions provided the production (yield) level does not vary too widely. However, the best approach is to enter values for live aboveground biomass at maximum canopy at two production (yield) levels rather than residue:yield ratio values. If the intercept M_0 for equation 9.5 is zero, the ratio of live aboveground biomass at maximum canopy to production (yield) level is constant and equal to the b_a coefficient in equation 9.5, which is appropriate for forage crops and permanent vegetation.

Crop residue cover immediately after planting is used as an indicator of the level of erosion control provided by conservation tillage systems. If RUSLE2 does not compute expected residue cover values, users can make changes in RUSLE2 inputs so that RUSLE2 computes the expected cover values. These changes should be made very carefully to avoid unexpected consequences. For example, change the live aboveground biomass at maximum canopy cover does affect the residue cover after planting computed by RUSLE2. Changing this value also affects the amount of belowground biomass computed by RUSLE2, which can have a significant effect on RUSLE2's erosion computations. Consider the following variables, their interactive effects, and their effects on other variables that affect erosion estimates in making changes to RUSLE2 inputs related residue cover after planting:

1. **Amount of live aboveground biomass at maximum canopy cover**
2. **Relationship between portion of soil surface covered for a given residue mass (mass-cover relationship in residue description)**
3. **Decomposition coefficient (half life) value in the residue description selected for the vegetation description**
4. **Flattening, burial, and resurfacing ratio values entered for the operation descriptions used in the cover-management description**

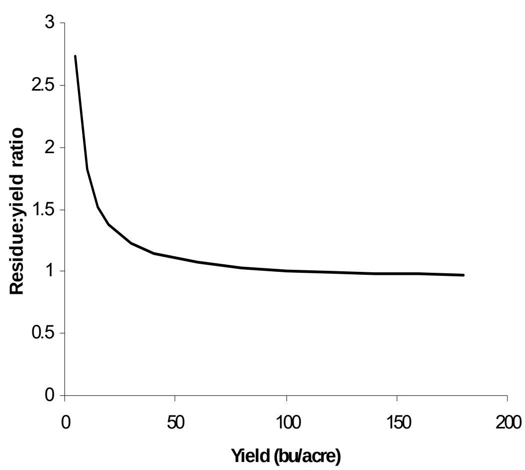

Figure 11.7. Residue:yield ratio for data illustrated in Figure 11.6.

11.2.4. Senescence

Values are entered in the **senescence tool** that RUSLE2 uses to calibrate equation 11.4 to represent senescence and litter fall as a transfer of live aboveground biomass to the surface (flat) residue pool. RUSLE2 computes senescence and litter fall as a function of a decrease in canopy cover (see **Section 11.1.3.1**). The two inputs entered in the senescence tool are portion of the live aboveground biomass at maximum canopy that is subject to senescence (litter fall) and canopy cover after complete senescence has occurred.

As permanent vegetation and agricultural crops like soybeans approach maturity, leaves fall from the plant canopy to the ground, which is senescence and litter fall. The decrease in live aboveground biomass results in a corresponding increase in biomass in the surface (flat) residue pool. In most cases, the entire live aboveground biomass is not subject to senescence. The value entered for portion of the live aboveground biomass subject to senescence is greater than the actual amount that falls to account for the fact that most of this plant material is leaves. A value of 0.6 for the ratio of biomass that falls during senescence to the aboveground biomass at maximum canopy seems to work well for crops like soybeans and cotton. A high value, perhaps up to 0.9, is appropriate for some grass-type vegetation. RUSLE2 multiplies this fraction by the live aboveground biomass at maximum canopy cover to estimate the potential biomass that will be transferred to the soil surface. RUSLE2 distributes the transfer over time using equation 11.2 and the decrease in canopy cover values entered in the **growth chart** of the **vegetation description**. The input in the senescence tool for canopy cover after complete senescence should be less than the minimum canopy cover that occurs after maximum canopy cover in the growth chart.

The standard assumption in RUSLE2 is that senescence occurs during the period of decreasing canopy cover. However, litter fall can also occur during growth periods when canopy cover is increasing, especially for perennial vegetation. RUSLE2 computes the daily litter fall by death during growth periods by multiply the live aboveground biomass on each day by a fraction that is typically 0.01, unless more specific information is available. If RUSLE2 is not to compute litter fall during growth periods, a zero (0) is entered for the death coefficient. Similarly RUSLE2 can compute death of the live root biomass during growth periods entering a non-zero (0) value for the death coefficient for live roots. Generally the same value (0.01) should be used for both live aboveground and root biomass.

Some plants lose canopy cover without aboveground biomass falling to the soil surface. An example is corn where the leaves droop as the plant approaches maturity. For this and similar types of vegetation that lose canopy cover without losing canopy mass, enter a zero for the portion of the aboveground biomass that experiences senescence. This entry prevents RUSLE2 from computing a decrease in aboveground biomass along with an increase in surface (flat) residue when canopy cover decreases.[100]

The objective is to account for the dead biomass that reaches the soil surface in association with a decrease in canopy cover rather than perfectly model senescence as a process.

The reason that a high value is entered for the portion of the live aboveground biomass subject to senescence is related to RUSLE2 using a single **residue description** to represent a composite of plant components that vary greatly in their properties. Above ground plant material is composed of leaves, stems, seed pods, chaff, and other

[100] This input in RUSLE2 is comparable to the input in RUSLE1 for no senescence in the table where operations are entered for each vegetation in the time variant C factor.

components. Leaves cover a much greater portion of the soil surface per unit mass than do stems. Leaves decompose much more rapidly than do stems. The value for a property in a residue description depends on the relative mass of the plant components in the residue. This distribution changes through time because the components decompose at greatly different rates, which means that residue properties change through time even though RUSLE2 assumes constant residue properties.

Consequently, the input for the portion of the live aboveground biomass subject to senescence is a compromise. The values entered in the residue description for the mass-cover relationship often gives priority to stems because the stems remain long after the leaves have disappeared. Entering a value for the actual amount of fallen plant material significantly underestimates the ground cover provided by senescence and litter fall because most of this material is leaves that provides high ground cover for their mass. To offset the underestimation in ground cover, an artificially high value is entered for the portion of live aboveground biomass subject to senescence to give ground cover values that more closely match actual field ground cover values during the senescence period. This approach works satisfactorily for agricultural and vegetable crops like soybeans, cotton, and green beans because of the importance in the portion of the soil surface covered in the erosion computations and the relatively short time between the beginning of senescence and harvest that converts live aboveground biomass to standing and flat residue.

Both the portion of the soil covered by plant material transferred by senescence and litter fall and the biomass amount must be considered when selecting inputs for permanent vegetation. The residue description for permanent vegetation should represent the composite of plant material that reaches the soil surface during an annual growth cycle. Similarly, the input values for live aboveground biomass at maximum canopy and the portion of this biomass that reaches the soil by senescence and litter fall should represent the actual biomass transfer rather than the artificially high values used for agricultural and vegetable crops discussed above. The residue description for permanent vegetation that is never mowed can be different from the residue description for permanent vegetation that is periodically mowed. The decomposition rate for biomass reaching the soil surface by mowing could be greater than the biomass from the same vegetation that reaches the soil surface by litter fall after plant maturity because of differences in decomposition properties of plant material at different growth stages. These residue descriptions are similar to having a residue description for wheat grown a cover crop that is killed well before maturity and different from the residue description for wheat grown to maturity and harvested for grain.

An approach that sometimes can be used to better represent differences among residue properties at certain times is to use multiple vegetation and residue descriptions for the same vegetation. For example, the residue description assigned in the vegetation description that applies to the senescence period reflects residue being mostly composed of the leaves that fall during senescence. The residue description assigned to the vegetation description for the period that begins immediately after the end of senescence reflects a high proportion of coarse plant parts like stems.

The best guidance for selecting input values to describe senescence and litter fall is to compare your vegetation with the vegetation descriptions in the **RUSLE2 core database**. Consistency between your values for a particular vegetation description and values in the RUSLE2 core database and values for other vegetation descriptions in your database is very important to ensure that RUSLE2 computes expected erosion values. Assigning these input values involves judgments that may seem counter intuitive.

11.2.5. Retardance

Retardance describes the degree that vegetation slows overland flow. RUSLE2 uses information on vegetation retardance, along with information on ground cover and soil surface roughness, to compute values for Manning's n, a hydraulic roughness index. The retardance index and Manning's n are used to compute the contouring effectiveness of rows of closely spaced vegetation, transport capacity used to compute deposition caused by dense vegetation strips, and critical slope length associated with contouring (see **Section 14**). Retardance depends primarily on the type, stiffness, and density of vegetation parts that touch the soil surface to slow surface runoff. Retardance is two dimensional, having a value for vegetation grown in strips on the contour perpendicular to the overland flow and a value for the same vegetation grown in rows up and down slope parallel to the overland flow direction.

Retardance for vegetation in contour strips is specified using one of eight classes listed in Table 11.6. These eight retardance classes represent the entire range in retardance from no retardance where the vegetation hardly slows the runoff to maximum retardance produced by a dense, sod forming grass. **The eighth class, retardance index 7, is a special case used to represent exceptionally dense, erect, stiff grass strips, fabric (silt) fences, gravel dams, straw bales, and similar erosion control measured used on overland flow areas.**

A retardance class is selected for a vegetation description along this scale based on the degree that the vegetation is judged to slow runoff considering vegetation type, stiffness, and density. Crops at typical yields are listed with each retardance class to guide the selection of a retardance class.

Table 11.6. RUSLE2 retardance classes for overland flow through vegetation in strips on the contour.

Retardance class at maximum canopy cover	Class index value	Comment

No retardance	0	Vegetation has no appreciable effect on slowing runoff
Low retardance	1	Slightly slows runoff, much like corn at 125 bu/acre
Moderate low retardance	2	Slows runoff somewhat, much like soybeans at 35 bu/acre, cotton at 1 ½ bales/ac, corn at 200 bu/acre
Moderate retardance	3	Slows runoff moderately, much like wheat at 45 bu/acre
Moderately high retardance	4	Slows runoff significantly, much like a moderate yield (3 tons/acre) legume hay before mowing
High retardance	5	Slows runoff very significantly, much like moderate yield (3 tons/acre) legume-grass hay before mowing, dense bunch grass
Very high retardance	6	Slows runoff almost to the maximum degree, like a dense, sod forming grass
Extreme retardance	7	Used as a special class to represent the retardance of stiff, erect, very dense grass strips (hedges), fabric (silt) fences, gravel dams, and straws bales used on overland flow areas

Retardance is also a function of plant growth stage and production (yield) level. The **retardance tool** is used to enter retardance classes at two production (yield) levels for a vegetation description at maximum canopy cover. RUSLE2 uses these inputs to calibrate a linear equation that computes retardance as a function of production (yield) level as illustrated in Figure 11.8. RUSLE2 internally treats the retardance as a continuous variable rather than an integer that changes stepwise. Thus, computed erosion values affected by retardance vary in a continuous fashion rather than in a stepwise fashion between retardance classes. RUSLE2 computes a base hydraulic roughness index value as a function of retardance at maximum canopy cover. RUSLE2 uses this base values to compute a daily hydraulic roughness index that varies with the 0.3 power of daily effective fall height.

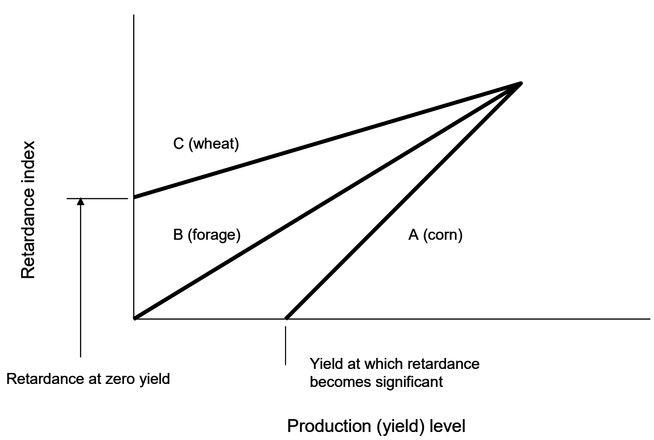

Figure 11.8. Retardance index relationships for different vegetation types

Figure 11.8 shows retardance index-yield relationships for three types of vegetation. Type A vegetation is where plant population must increase to a significant level before retardance becomes significant. For example, corn yield must exceed 100 bu/acre before retardance becomes significant. The entry for this condition in the retardance tool is **Yes** for **Does no retardance apply for a yield greater than zero?** and the second entry is the **Maximum yield at which no retardance applies**, which is 100 bu/acre in this example. RUSLE2 assumes that corn provides no retardance for yields less than 100 bu/acre and that retardance increases linearly for yields greater than 100 bu/acre as illustrated in Figure 11.8

The question **Does no retardance apply to a yield greater than zero?** is answered **No** for vegetation types B and C. RUSLE2 then asks that a retardance class be selected for a zero yield. Type B vegetation is forage-type vegetation grown on hay, pasture, landfills, and reclaimed mine lands. This vegetation is sufficiently dense and stiff to provided retardance that begins to develop at a zero yield. The **no retardance** class is selected for a zero yield, even for a dense sod forming grass that provides maximum retardance at a high yield. Type C vegetation is vegetation like wheat that provides significant retardance at zero yield. The retardance selection for Type C vegetation at zero yield depends on the stiffness and density of the vegetation at zero yield. The type of vegetation and the retardance entries at zero yield are related to the yield definition used in the vegetation description.

Information on retardance at a high yield is entered in the retardance tool for a second data point. The input for this data point along with the entry for the first data point discussed above are used by RUSLE2 to determine values for the coefficients that define the linear equations depicted in Figure 11.8. This second yield point need not correspond with the yield for which the vegetation description applies. In fact, the best yield for the second data point is the highest yield for which this vegetation description might possibly be applied.

Vegetation type in relation to retardance and the entries used to describe the retardance-yield relationship depend on the yield definition used in the vegetation description. For example, a woody-type vegetation could have a significance retardance index for a zero yield where the yield definition is based on annual production rather than the accumulation of biomass over several years.

The second major input in the retardance tool is used by RUSLE2 to define retardance when the vegetation is grown in rows parallel with the assumed flow direction (up and down slope). Row spacing is used as an indicator of this retardance. The retardance for up and down hill rows ranges from no retardance for widely spaced rows and for vegetation grown on ridges where the vegetation does not contact the down slope overland flow to maximum retardance when the vegetation is in a random pattern. The retardance for the random pattern (i.e., no orientation effect) is assumed to be the same as the retardance for the vegetation grown in a contour strip perpendicular to the overland flow. A retardance class for a particular vegetation description is selected from the six classes listed in Table 11.7 between these extremes using row spacing as an indicator.

Although row spacing is used as an indicator, the selection is actually the degree that the vegetation affects retardance at maximum canopy when rows of the vegetation are oriented in an up and down hill direction.

Table 11.7. Row spacing classes used to indicate retardance for vegetation at maximum canopy cover in rows oriented up and down slope.

Row spacing class	Comment
Wide row	Vegetation provides no retardance to overland flow. Row spacing for typical agricultural crops would be 30 inches or wider.
Vegetation on ridges	Vegetation is on ridges sufficiently high that vegetation does not come in contact with overland flow and provides no retardance to the flow. Actual spacing is unimportant.
Moderate	Rows of vegetation and vegetation characteristics such that the vegetation provides a slight but significant retardance relative to the same vegetation in a random pattern. Row spacing for typical agricultural crops would be 15 inches.
Narrow	Rows of vegetation and vegetation characteristics provide moderate retardance relative to the same vegetation in a random pattern. Row spacing for typical agricultural crops would be 7 inches.
Very narrow	Rows of vegetation and vegetation characteristics provide major retardance so that retardance in the down slope direction is almost as great as retardance when the vegetation is in a random pattern. Row spacing for typical agricultural crops would be 3 inches.
No rows, random, broadcast	Characteristics of the vegetation are such that orientation has no effect on retardance because the vegetation is grown in a random pattern.

RUSLE2 adjusts retardance between the value for vegetation grown in rows up and down slope and retardance for contour vegetation strips based on relative row grade to take into account row orientation of the vegetation. For example, if row grade is up and down slope and the vegetation has been assigned a wide row spacing, RUSLE2 will compute no retardance for the vegetation and no deposition will be computed if the vegetation in grown in strips with an up and down hill row orientation.

The best approach for selecting input values for retardance is to use values in the **RUSLE2 core database** as a guide. Maintaining consistency with the RUSLE2 core database is critically important because RUSLE2 was calibrated and validated against values in the RUSLE2 core database.

11.2.6. Long-term vegetation

The **long-term vegetation tool** is useful for creating multiple year duration **vegetation**

descriptions for permanent vegetation. In many cases, the long term vegetation tool can create a vegetation description that can be used without manual adjustments. Even when manual adjustments are required, the long term vegetation tool greatly facilitates the creation of long duration vegetation descriptions. A graph of canopy cover in a vegetation description created with the long term vegetation tool is illustrated in Figure 11.9. This 10-year vegetation description covers the time from seeding, through development, and into full maturity. The long term vegetation tool is most useful for creating vegetation descriptions for permanent vegetation like that on pasture, range, landfills, reclaimed mine, and similar lands.

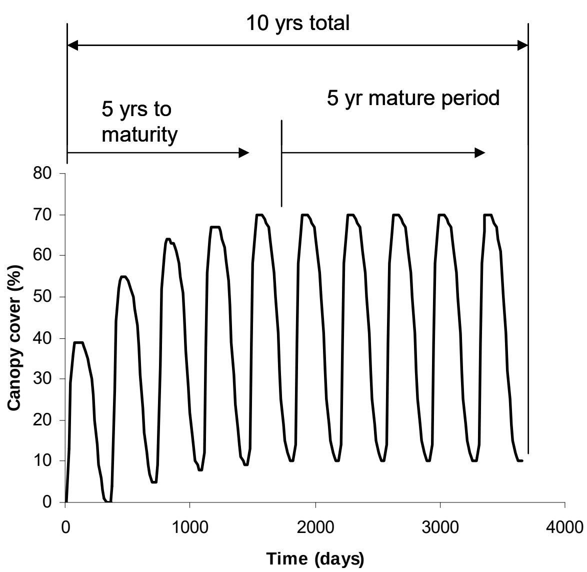

Figure 11.9. 10-year long term vegetation description created with long term vegetation tool.

The inputs entered in the long term vegetation tool are listed in Table 11.8. RUSLE2 uses spline-type equations to temporally distribute values between those entered for the minima and maxima of the variables in the **growth chart** of a vegetation description based on duration and annual timing inputs.

11.2.6.1. Duration inputs

The first set of inputs in the long term vegetation tool is related to **duration** of the vegetation description. The duration of a vegetation description is one year when RUSLE2 is used to estimate erosion for mature vegetation (see **Section 10.2.8**). The **yes-no** input for **rotation** in the **cover-management description** is set to **Yes** with a **1-year duration**. A value of **0** is entered for the **number of years to maturity** and a value of **1 year** is entered for the duration of the vegetation description **(# of years to include in growth pattern**) in the long term vegetation tool to create a vegetation description for mature vegetation.

The long term vegetation tool can also be used to create a vegetation description that starts on the seeding date and continues through the development phase and into the completely mature phase, like the vegetation description illustrated in Figure 11.9. This vegetation description can be used in RUSLE2 to analyze erosion during the establishment period for permanent vegetation on landfills, construction sites, and reclaimed mine lands. The duration of this vegetation description includes a mature period sufficiently long for RUSLE2 to compute a stable litter layer and soil biomass pool.[101] In the example illustrated in Figure 11.9, the development period is five years (time to maturity), and the mature period is five years. A value of **5 years** is entered for the time required for the vegetation to reach maturity (the development phase) and a value of **10 years** is entered for the entire duration.

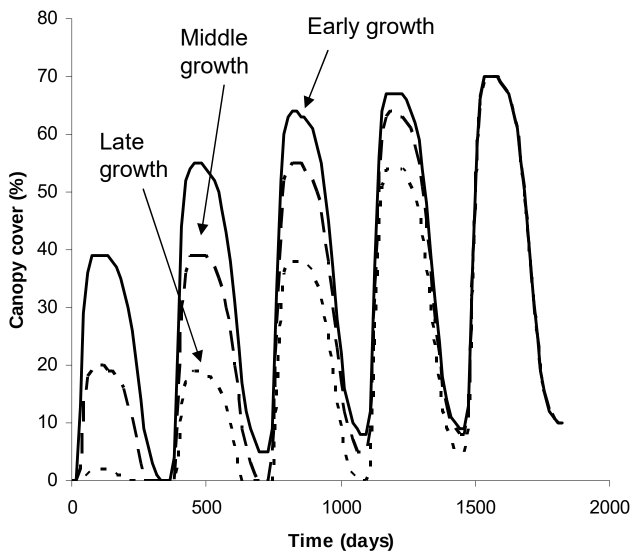

Figure 11.10. Fast growth in the early, middle, or late part of development stage.

The next input is a selection for the period when overall growth is most rapid during the development phase. The choices of **early**, **middle**, and **late** are illustrated in Figure 11.10. Values for all three choices converge in the mature year. Choose the entry appropriate for your vegetation considering seeding date and environmental conditions related to climate, soil, and management at the location where RUSLE2 is being applied. An input of **early** was selected for the vegetation description illustrated in Figure 11.9.

11.2.6.2. Annual timing inputs

The next set of inputs are the **annual timing inputs** related to dates of annual maximum and minimum live aboveground biomass and when most rapid growth and decline occur during the year.

The first timing input is the date of the annual maximum live aboveground biomass, which is also the date when all other temporal variables, including live ground cover, are at a maximum. This date for the example illustrated in Figure 11.9 is July 1. The maximum values occur on this date for every year in the vegetation description created with the long term vegetation tool.

The second timing input is the date that live annual aboveground biomass is minimal, which is also the date that the values for all temporal variables are minimal. RUSLE2 assumes this date for day zero for the vegetation description. The values for all temporal variables are zero on day zero unless the vegetation description has been created for

[101] Stability is defined in terms of litter and soil biomass daily values repeating each year.

mature vegetation.[102] In the example illustrated in Figure 11.9, the date of annual minimum live aboveground biomass is April 1. The date of the **operation description** in the **cover-management description** that uses this vegetation description should be April 1.

Inspect the main vegetation description, including all of the support tools discussed in Section 11.2, to ensure that the proper values are entered and displayed. The long-term vegetation does not transfer all required information into the main vegetation description and the supporting tools.

The time between the dates for maximum and minimum biomass can be any value. Six months between these dates gives a symmetrical distribution during the year. The long term vegetation tool creates non-symmetrical distributions when dates are more or less than six months apart as illustrated in Figure 11.9.

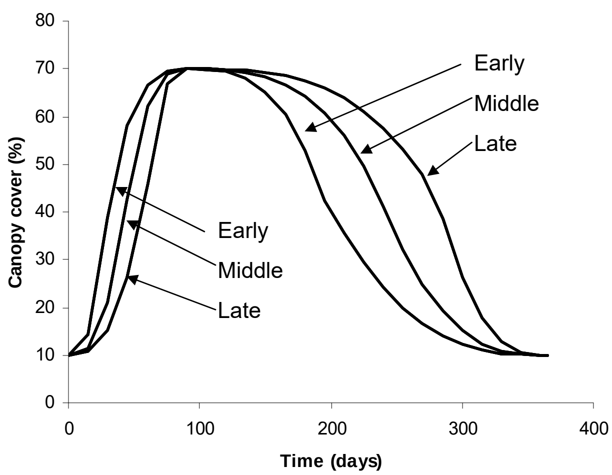

Figure 11.11. Timing of rapid growth and senescence during year.

An important consideration is whether the date of minimum live aboveground biomass corresponds with the seeding date. In the example illustrated in Figure 11.9, the seeding date and date of minimum biomass are the same. However, that assumption is not true for fall seeding when the annual minimum live aboveground biomass occurs in the spring. The long term vegetation tool has no provision for dealing with situations where seeding date and date of minimum live above ground do not correspond. However, the long term vegetation tool is still useful for developing a vegetation description even though manual adjustments are required for these situations. For example, assume that the seeding date is September 1 rather than April 1. The same input values would be used as in the example illustrated in Figure 11.9, but with a change in the selection for the **time that most rapid growth occurs during the development period** and **the time to maturity**. Rather than entering **early,** as in the example, a **middle** selection is made. The time to maturity would be six rather than five years. The

102 This statement applies to vegetation descriptions created with the **long-term vegetation tool**. RUSLE2 can also use multiple annual vegetation descriptions. The temporal values would not be zero on day zero for these vegetation descriptions. However, such annual vegetation descriptions can not be created with the **long-term vegetation tool**.

user manually make changes to values in the vegetation description **growth chart** to correspond to a September 1 seeding date. The manually adjusted values are blended into the values created by the long term vegetation tool. Manual entry of the entire vegetation description is not required.

The third and fourth timing inputs are the times during the year when most rapid growth (gain in live aboveground biomass) and senescence (litter fall, decline in live aboveground biomass) occur. The choices are **early**, **middle**, and **late**. These choices are illustrated in Figure 11.11. One selection can be made for the growth period, such as **early** in the example illustrated in Figure 11.9, and another selection can be made for the senescence period, such as **middle** for the example illustrated in Figure 11.9.

11.2.6.3. Biomass inputs

The **biomass inputs**, which must be on a dry basis, in the **long term vegetation tool** are the same as those in the main part of the **vegetation description** and the **growth chart** discussed in **Section 11.1**. However, a few of the inputs are in a different form. The values entered for **maximum annual live ground biomass** and the corresponding **canopy cover** are for the date of annual maximum canopy cover after the vegetation has reached maturity, which is the date entered in the **annual timing inputs** for maximum biomass. The values entered for **minimum annual live ground biomass** and the corresponding **canopy cover** are for the date of annual minimum canopy cover after the vegetation has reached maturity, which is the date entered in the **annual timing inputs** for minimum biomass.

The input value for annual minimum live aboveground biomass is similar to, but different from, the inputs entered in the senescence tool (see **Section 11.2.4**). The input entered in the long term vegetation tool for annual minimum live aboveground biomass is the ratio f_{mx} of annual minimum live aboveground biomass to annual maximum live aboveground biomass after the vegetation has reached maturity. The value for annual minimum live aboveground biomass is given by:

$$B_{amn} = f_{mx} B_{amx} \qquad [11.9]$$

where: B_{amn} = annual minimum live aboveground biomass at maturity, B_{amx} = annual maximum live aboveground biomass at maturity, and f_{mx} = the ratio of the annual minimum live aboveground biomass at maturity to annual maximum live aboveground biomass at maturity. Essentially the same information must be entered in the **senescence tool**, and it must correspond to the information entered in the long term vegetation tool. The entry in the senescence tool related to biomass is the portion f_s of the annual maximum live aboveground biomass that is available for senescence. The annual minimum live aboveground biomass computed with f_s is given by:

$$B_{amn} = B_{amx} - f_s B_{amx} \quad [11.10]$$

$$B_{amn} = B_{amx}(1 - f_s) \quad [11.11]$$

Combining equations 11.9 and 11.11 shows that the fraction of maximum live aboveground biomass available for senescence that is entered in the senescence tool is related to the ratio of annual minimum live aboveground biomass to annual maximum live aboveground biomass as:

$$f_s = 1 - f_{mx} \quad [11.12]$$

That is, the value entered in the senescence tool equals one minus the ratio of annual minimum live aboveground biomass to annual maximum live aboveground biomass, which is the value entered in the long term vegetation tool for minimum annual live aboveground biomass.

The value entered for canopy cover after full senescence in the senescence tool should be the same as the canopy cover value entered in the long-term vegetation tool for canopy cover for annual minimum live aboveground biomass at maturity.

A value of zero (0) for the **death rate coefficient** for the death of live aboveground is entered biomass when the process of litter fall during the growth period is not be represented. Enter a value of approximately 0.01 when this process is to be represented. A value of 0.01 seems appropriate for a wide range of plant communities.103

The production (yield) level definition, value for production (yield) level and the biomass-yield relationship inputs should be entered in the vegetation description. These values should be carefully checked to ensure that the live aboveground biomass value displayed in the vegetation description is the maximum live aboveground biomass intended from the inputs made in the long term vegetation tool.

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[103] Dubeux, Jr., J. C. B.; L. E. Sollenberger, J. M. B. Vendramini, R. L. Stewart, Jr. and S. M. Interrante. (2006). Litter Mass, Deposition Rate, and Chemical Composition in Bahiagrass Pastures Managed at Different Intensities. 46:1299-1304.

Thomas, R.J. and N.M. Asakawa. 1993. Decomposition of leaf litter from tropical forage grasses and legumes. Soil Biology and Biochemistry. 25:1351-1361.

Enter the value for **effective fall height** for the annual maximum live aboveground biomass at maturity. See **Sections 9.2.2.2 and 11.1.7.4** for guidelines for selecting effective fall height values as a function of heights to top and bottom of the canopy, canopy shape, and density gradient within the canopy. Also, the **effective fall height tool** discussed in **Section 11.2.2** can be used to adjust the temporal effective fall height values created by the long term vegetation tool.

Values for **live ground cover** should be entered for most permanent vegetation on range, pasture, landfills, reclaimed mine and similar lands. Enter values to represent live (green) leaves, the basal area, and other live vegetative parts that slow runoff during a rainfall event. The temporal pattern of the live ground cover values created by the long term vegetation tool is exactly the same as the temporal pattern for canopy cover values. This pattern may not be appropriate for live ground cover. For example, live ground cover may develop early in the annual growth period ahead of canopy cover and then decrease while canopy cover is still developing. The values created by the long term vegetation tool can be manually adjusted in the vegetation description as desired.

The long-term vegetation tool multiples the input value for the **ratio of live root biomass to live aboveground biomass** by the value for live aboveground biomass to create values for live root biomass. This ratio is for the biomass (dry basis) of predominantly fine roots in the upper 4 inches (100 mm) of soil to the average annual production of aboveground biomass. RUSLE2 assumes that the ratio of live root biomass to live aboveground biomass is constant over time, which means that live root biomass values follow exactly the same pattern as the live aboveground biomass values. In the field, annual live root development usually precedes development of the live aboveground biomass and root sloughing usually precede senescence and litter fall. The RUSLE2 assumption that the two are the same is considered adequate for erosion estimates used in conservation and erosion control planning. RUSLE2 is designed to be an easy-to-use tool for conservation and erosion control planning rather than a model of actual processes. However, RUSLE2 is quite flexible. The live root biomass values can be manually adjusted in the growth chart to represent any desired pattern.

Obtaining reliable information on live root biomass values is very difficult as discussed in **Section 11.1.7.2**. The recommendation is that the ratio values previously stored in RUSLE2 by plant community be used rather than selecting values from the literature or making field measurements. Selecting a plant community in the long term vegetation tool selects the ratio value stored in RUSLE2 for that plant community. A RUSLE2 previously stored plant community ratio value can be overridden by entering another value. The values for ratio of live root biomass to live aboveground biomass stored in RUSLE2 by plant community types are based on field simulated rainfall erosion experiments where values for these ratios were back calculated using RUSLE2 subfactor equations and measured erosion values. Values for these ratios are given in **Section**

17.4.1.4.[104]

RUSLE2 assumes that a daily decrease in live root biomass represents root sloughing where this decrease represents live roots that become dead roots that is added to the dead root pool. RUSLE2 can also compute root death during the growth period when live root biomass is increasing. If this root death process is not to be represented enter a zero (0) for the daily fraction of live root biomass that becomes dead roots during the growth period. If this process is to be represented, enter a value of 0.01, which is the daily fraction of the live root biomass that becomes dead roots during the growth period. In general, the value selected for this fraction should the same as the value for the comparable fraction of daily live aboveground biomass that becomes surface litter.

Table 11.8. Inputs in the long-term vegetation tool used to create vegetation descriptions for permanent vegetation on pasture, range, landfills, reclaimed mine, and similar lands.

Input	Comment
Duration inputs	
Number of years to maturity (development phase)	If a vegetation description for mature vegetation is being created, enter 0; otherwise, enter the number of years required for the vegetation to reach a stable annual pattern (5 yrs for example in Figure 11.9)
Total number of years in the vegetation description (duration)	Enter total number of years in the vegetation description; should include enough years after maturity for a stable litter layer and soil biomass pool to develop at the location where vegetation description is being used; (10 yrs for example in Figure 11.9)
Fastest growth in development period occurs when? (early, middle, late)	Select the time period during the development phase when most rapid development occurs; (Early for example in Figure 11.9); see Figure 11.10 for illustrations of each period.)
Annual timing inputs	
Annual day of maximum live aboveground biomass at maturity (month/day)	Select date of annual maximum canopy cover, which is also the date of annual maximum live aboveground biomass; maximum of all temporal variables is assumed to occur same date; same date assumed for all years in vegetation description; (7/1 for example in Figure 11.9)

[104] The time invariant C factor procedure in RUSLE1 is frequently used to estimate erosion for permanent vegetation. Single values that represent temporal conditions over the year are used as input rather than the temporal values used in RUSLE2. Also, this RUSLE1 procedure does not include the accumulation of a soil biomass pool or the effect of decomposition of the litter layer at the soil surface. Both RUSLE1 and RUSLE2 can give comparable results if the recommended procedures for each model are carefully followed.

Annual day of minimum annual biomass (month/day)	Select date of annual minimum canopy cover, which is also the date of annual minimum live aboveground biomass; minimum of all temporal variables is assumed to occur on same date; same date assumed for all years in vegetation description; (4/1 for example in Figure 11.9)
Fastest growth occurs when during year? (early, middle, late)	Select early to describe vegetation where most rapid growth occurs early in annual cycle; select late to describe vegetation where early development is slow and most rapid development occurs just before maximum live aboveground biomass is reached; (early for example in Figure 11.9); see Figure 11.11 for illustration.
Fastest decline in growth occurs when during year? (early, middle, late)	Select early to describe vegetation where most canopy is lost immediately after senescence (litter fall) begins in annual cycle; select late to describe vegetation where loss of canopy mass is very slow after maximum aboveground biomass is reached and is very high just before the end of senescence; (middle for example in Figure 11.9); see Figure 11.11 for illustration.
Biomass inputs	
Maximum annual live aboveground biomass at maturity (dry basis)	Enter the live aboveground biomass at maximum canopy for the vegetation when it is mature; in general, annual biomass production rather than long term accumulation of biomass is used for this input; the yield value in main vegetation description where yield is defined must correspond with this value; (1000 lbs/acre for example in Figure 11.9)
Canopy cover at maximum biomass (maximum canopy) at maturity	Enter the canopy cover at annual maximum live aboveground biomass at maturity; (70% for example in Figure 11.9)
Effective fall height at maximum canopy cover at maturity	Enter the effective fall height value at annual maximum canopy cover at maturity; (0.3 ft for example in Figure 11.9)
Live ground cover at annual maximum live aboveground biomass at maturity	Enter the live ground cover at annual maximum live ground cover; check live ground cover computed by tool; values may need adjustment so that live ground cover develops earlier than canopy cover; (15% for example in Figure 11.9)
Ratio of annual minimum live aboveground biomass at maturity to annual maximum live aboveground biomass at maturity (dry basis)	The amount for the annual minimum live aboveground biomass is the product of the ratio entered and the annual maximum live aboveground biomass; this value must correspond to the value entered in the senescence tool for amount of annual live aboveground biomass that is available for senescence; (20 % for example in Figure 11.9)
Canopy cover at minim live	Enter the minimum canopy cover provided the annual

aboveground biomass	minimum live aboveground biomass; value must correspond with value entered in senescence tool; (10% for example in Figure 11.9)
Death fraction for live above ground biomass	Enter the fraction of live aboveground biomass that becomes daily surface litter by death during the growth period when canopy cover is increasing (use 0.01 unless other information is available)
Mechanical loss coefficient	Fraction of live aboveground that is added daily to the surface litter biomass; represents mechanical processes such as animal trampling and vehicular traffic
Plant community	Select the plant community that this vegetation description represents; selection of a plant community causes RUSLE2 to select a ratio of live root biomass to live aboveground biomass; select **Enter root mass/live aboveground biomass** if your plant community is not in the list so that you can enter your own value for this ratio; (southern grasses selected for example in Figure 11.9)
Ratio for live root biomass in upper 4 inches (100 mm) of soil/live aboveground biomass ratio (dry basis)	Selection of a plant community causes RUSLE2 to use the ratio value assigned and stored in RUSLE2 for this plant community; user can override value by entering a new value; (4.5 is stored in RUSLE2 for plant community in the example in Figure 11.9)
Death fraction for live root biomass	Enter the fraction of live root biomass that becomes daily dead root biomass by death during the growth period when live root biomass is increasing (use 0.01 unless other information is available, value should generally be the same as that used for comparable fraction for live aboveground biomass)
Grazing/haying/mowing inputs	
Dates	Enter dates that operations begin
Duration	Enter duration (days) of operation
Regrowth period	Enter days in regrowth period
Fraction live aboveground biomass remaining after operation	Enter the fraction of the live aboveground biomass that remains at the end of the operation; fraction is based on live aboveground biomass that exists on day that operation begins

12. RESIDUE DATABASE COMPONENT

Residue descriptions in the **residue component** of the RUSLE2 database contain values that RUSLE2 uses to compute how residue affects erosion. A residue description is assigned to each **vegetation description** and to **external residue**. A residue description assigned to a vegetation description describes the material that remains after the vegetation is killed with an **operation description** having a **kill vegetation process**. A residue description represents a composite of all plant components including leaves, stems, seed pod, and roots present in a sufficient amount to affect erosion. Thus, the values in a residue description for vegetation depend on the relative mass of each plant component in the residue.

The **residue description** selected for an **operation description** that adds **external residue** is used to describe materials added to the soil surface or placed in the soil that affect erosion. External residue includes applied mulch (e.g., straw), manure, gravel, compost, papermill waste, pine needles, roll erosion control products, and other similar materials. The materials represented by residue descriptions are assumed to be organic and decompose much like natural plant materials. Non-organic materials require special considerations that are described in this section.

The variables used to describe residue are listed in Table 12.1.

Table 12.1. Variables used to describe residue

Variable	Comment
How residue responds to mechanical disturbance (residue type)	Describes fragility (how easily material fractures into smaller pieces) to mechanical disturbance and the size and stiffness of the residue pieces in relation to how well the residue conforms to the soil surface to affect erosion
Decomposition coefficient	A variables that determines the rate that residue decomposes under the standard condition of non-limiting moisture and a temperature of 90 ^{o}F (32.2 ^{o}C)
Decomposition half life (days)	Time required for one half of the residue mass to decompose under the standard conditions of non-limiting moisture and a temperature of 90 ^{o}F (32.2 ^{o}C)
Mass-cover relationship	Portion of the soil surface covered by a given mass on a dry weight basis

12.1. How residue responds to mechanical soil disturbance (residue type)

RUSLE2 includes five predefined residue types listed in Table 12.2. Residue type represents two important residue properties that are related. One is the fragility and size of residue pieces that determine how much residue is flattened, buried, and resurfaced by an operation and the size and stiffness of residue pieces that determine how closely the residue conforms to the soil surface. Assigning a residue type to a residue description requires consideration of both properties.

Table 12.2. RUSLE2 predefined residue types.	
Residue type	Comment
Fragile-very small	Small pieces (about 1 inch, 25 mm), easily broken into smaller pieces, moderate conformity to soil surface, similar to soybean residue
Moderately tough-short	Short to moderate pieces (1 to 5 inch, 25-125 mm), moderately tough (resistant) to being broken into smaller pieces, moderate conformity to soil surface, similar to wheat residue run through a straw chopper
Non fragile-medium	Moderate length pieces (3 to 10 inch, 75- 250 mm), non fragile, not easily broken into smaller pieces, low conformity to soil surface, similar to corn residue run through a combine
Woody-large	Long pieces (> 10 inch, 250 mm), very tough, only breaks into smaller pieces with a very aggressive machine, low conformity to soil surface, similar to woody debris left on disturbed forest land by logging, debris left by aggressive mechanical renovation of shrub dominated rangelands
Gravel	Small to moderate sized pieces with gradation of sizes to fill voids, pieces are not reduced in size by mechanical operations, high conformity to soil surface, similar to gravel and crushed stone about ¾ inch (20 mm) used on driveways.
Note: Woven and netting type erosion control products like erosion control blankets are assigned a residue type based primarily on their conformity to the soil surface micro-topography.	

Mechanical soil disturbance by tillage, construction, logging, and similar equipment break residue into smaller pieces. The susceptibility to residue being broken into smaller pieces is referred to as residue fragility. Conversely, the resistance of residue to size reduction is referred to as residue toughness. The size, length, and fragility of residue pieces affect residue flattening, burial, and resurfacing by operations. Consequently, the ratio values for these processes assigned in operation descriptions (see **Section 13.1**) vary with residue properties represented by the five residue types. Fragile residue like soybeans is more easily buried and conforms more to the soil surface than tough residue like woody debris. Long, stiff, and tough residue is not easily buried and does not conform to the soil surface. Gravel and rock fragments conform very closely to the soil surface.

The residue type assigned to roll erosion control products like blankets that are woven or bound together with netting is determined by their conformity to the soil surface. Similarly, a residue type is assigned to spray products used to control erosion on construction sites. The mechanical fragility of these erosion control products is not important unless mechanical operations are performed on the soil after these materials are placed that affects their coverage of the soil surface. The size and nature of residue pieces is not important in assigning a residue type to these products. For example, a gravel residue type can be assigned to these products where the material conforms very closely to the soil surface and perfect contact with the soil exists.

The degree that residue conforms to the soil surface is the other factor considered in selecting a residue type for a residue description. Small, flexible, stable residue pieces that closely conform to the soil surface provide greater erosion control than do long, stiff residue pieces that bridge soil clods. Runoff can partially or completely flow under the residue pieces with greater erosivity than when residue fully contacts the soil surface.

Selection of a residue type assigns one of three conformity index classes to the residue description to describe how the residue conforms to and is in contact with the soil surface. The three residue conformity index classes are low, moderate, and high. The **gravel** residue type listed in Table 12.2 are assumed to provide high conformity (contact with the soil surface), **fragile-very small** (e.g, chopped soybean residue) and **moderately tough-short** (e.g., chopped wheat straw) residue types are assumed to provide moderate conformity, and **non fragile-medium** (e.g., not-chopped corn stalks) and **woody** (e.g., slash on a logged site) residue type is assume to provide low conformity. The conformity class associated with each residue type is internal in RUSLE2 and can not be changed by the user.

The residue conformity index is most important when applying RUSLE2 to steep (greater than 33%), bare construction-type slopes. For example, the residue conformity index makes only about 14 percent difference in RUSLE2 erosion estimates between the low and high residue conformity class for corn residue in a no-till **cover-management description** applied to a 6 percent steep slope. The effect of residue conformity decreases as soil biomass increases. In contrast, the residue conformity makes about 110 percent difference in RUSLE2 estimated erosion between a residue type with low conformity and one with high conformity for a fully consolidated, cut slope with no soil biomass on 33 percent steepness. The difference in RUSLE2 estimated erosion between residue types with low and high conformity class is 40 percent for recently graded fill material on a 33 percent steep slope. RUSLE2 assumes better contact between soil and residue on recently graded fill material than on hard, fully consolidated soil.

The relative effectiveness of residue for controlling erosion decreases as slope steepness increases above about 33%. The loss of erosion control effectiveness is greater for residue types that provide low conformity than for those residue types that provide high conformity.

Residue types in terms of fragility (toughness) are defined only by the values entered for flattening, burial, and resurfacing ratios in the operation descriptions. However, conformity classes for each residue type are internally assigned in RUSLE2 and can not be changed by the user.

12.2. Decomposition coefficient (decomposition half life)

The decomposition rate of organic residue depends on the organic properties of the material, area and thickness of residue pieces, mechanical fracturing (e.g., fine chopping) of residue pieces to expose easily decomposed material inside a decomposition-resistant outer shell (e.g., corn stalks), and the relative composition of plant parts including leaves, seed pods, chaff, stems, and coarse and fine roots. Residue decomposition rate changes through time as these characteristics change through time. For example, leaves decompose at a much faster rate than stems, which leaves residue main composed of stems that slowly decompose.

The decomposition coefficient value assigned to each residue description is used by RUSLE2 to compute residue loss as a function of daily precipitation and temperature at the location where RUSLE2 is being applied. The decomposition coefficient ϕ value for a residue description is determined by fitting the RUSLE2 decomposition equations to empirical field data. A residue with a large decomposition coefficient ϕ value decomposes more rapidly than does a residue with a low decomposition ϕ value for particular environmental conditions.

Decomposition half-life is another way to express the decomposition coefficient ϕ. Half-life is the time required for half of the residue to be lost under the standard condition of 90 ^{o}F (32.2 ^{o}C) temperature with plentiful, non-limiting moisture. A residue with a long half-life is lost more slowly than residue with a short half-life. The relationship between half-life and the decomposition coefficient is an inverse one where half-life values increase as the decomposition coefficient values decrease. The mathematical relationship between the two is give by:

$$d_{1/2} = 0.693/\phi \qquad [12.1]$$

where: $d_{1/2}$ = residue decomposition half-life (days) and ϕ = residue decomposition coefficient (days^{-1}).

Decomposition computations are based on residue mass. Residue cover is computed using the mass-cover relationship assigned to the residue description. Half-life refers to residue decomposition under the standard condition of 90 ^{o}F (32.2 ^{o}C) and plentiful moisture, which differs from residue decomposition under actual field conditions.

Figure 12.1 illustrates how RUSLE2 computes residue decomposition as a function of location and residue half-life. Decomposition occurs more rapidly in central Mississippi than in central Missouri because of increased precipitation and temperature, especially in the fall and winter. The 43 day half-life residue decomposes much more rapidly than does the 86 day half life residue. Field decomposition rates are slower than the optimum decomposition conditions used to express half-life values.

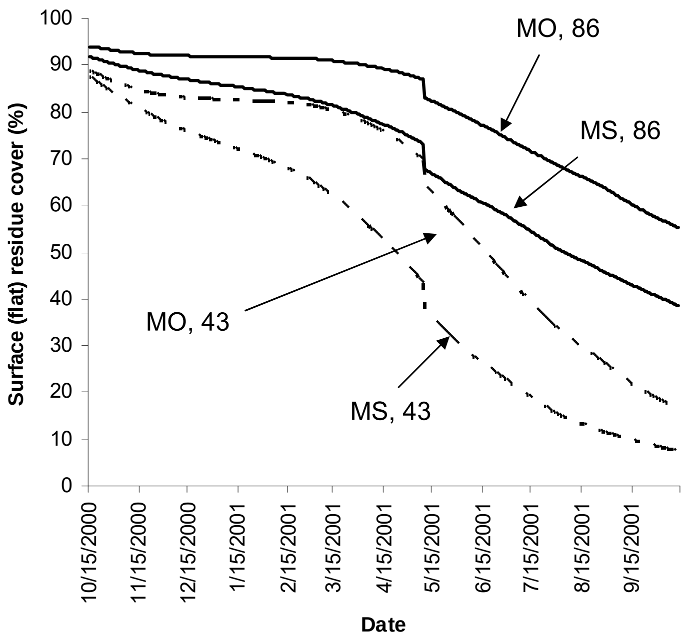

Figure 12.1. Effect of location (Columbia, MO, Jackson, MS) and decomposition half life (43, 86 days) on decomposition of corn residue in a no-till cover-management description.

The intent in RUSLE2 as an erosion control and conservation planning tool is to reflect the main effects of the material (as represented by the decomposition coefficient) and location (represented by precipitation amount and temperature that varies with location) on decomposition. By intent, RUSLE2 does not capture everything that affects decomposition. The following comments discuss particular areas where RUSLE2 represents a compromise and adjustments that users might make to partially overcome the RUSLE2 limitations while retaining RUSLE2's utility.

12.2.1. Soil Moisture

RUSLE2 does not directly consider the effect of soil moisture on decomposition other than how soil moisture is empirically related to precipitation in the decomposition data used to determine RUSLE2 decomposition coefficient ϕ values. Soil moisture is influenced by both cover-management and soil texture. Decomposition coefficient ϕ values can be increased for soil and cover-management conditions that retain water because soil moisture increases decomposition when moisture, rather than temperature, limits decomposition. Thus, the effect of soil texture and cover-management on soil moisture affecting residue decomposition can be partially captured in RUSLE2 by adjusting decomposition coefficient ϕ values. Decomposition coefficient ϕ values are assigned to residue descriptions based on how soil texture and soil moisture are assumed to affect decomposition at that location. A residue description having a decomposition coefficient ϕ value that reflects site-specific field conditions is chosen. However, based on comparisons with the WEPS and WEPP models, the effect of soil moisture as influenced by soil texture and cover-management is so small that the effect is best ignored in RUSLE2. Therefore, the same decomposition coefficient ϕ value is used for soil, cover-management, and climatic conditions except in the Northwestern US (Req region).

12.2.2. Above ground and below ground biomass decomposition

Buried residue is expected to decompose more rapidly than flat residue on the soil surface. However, research data used to derive decomposition coefficient ϕ values for RUSLE2 were inconclusive regarding this expected difference, especially when adjustments are taken into account for how residue confined in mesh bags used in decomposition measurements decomposes at a different rate than unconfined residue typical of field conditions. Therefore, RUSLE2 uses the same decomposition coefficient ϕ value for residue lying flat on the soil surface and residue buried in the soil. Most error, if any) that exists because RUSLE2 uses the same decomposition coefficient ϕ value for buried residue as surface residue is minimized because the RUSLE2 equation for the soil biomass subfactor (equation 9.12) is calibrated using RUSLE2 computed soil biomass values, not measured values (see the **RUSLE Science Documentation**).

RUSLE2 computes decomposition at the base of standing residue at the same rate as residue lying on the soil surface. RUSLE2 uses decomposition rate at the base of standing residue to compute the rate that standing residue is flattened by natural processes (see **Section 9.2.2.3**). However, RUSLE2 assumes that the decomposition coefficient value for standing residue is three tenth of the decomposition coefficient value for surface (flat) residue. Standing residue is assumed to decompose much more slowly than surface residue because of the lack of moisture that soil contact provides to surface residue.

The RUSLE2 user can not change decomposition coefficient values to reflect decomposition differences between surface and buried residue or between above ground plant components and roots. Also, the user can not change the ratio of the decomposition coefficient for standing residue to the decomposition coefficient for surface residue. Decomposition coefficient values can not be entered for individual plant components.

12.2.3. Differences in decomposition among plant components

Individual plant components of leaves, pods, stems, stalks, coarse roots, and fine roots decompose at different rates. For example, leaves decompose much more rapidly than stems, and finely chopped stems decompose more rapidly than intact stems. RUSLE2 uses a single residue description with a single decomposition coefficient ϕ value to represent a composite of plant components. The single, constant decomposition coefficient ϕ value for a residue description causes RUSLE2 to compute decomposition rates that are too low immediately after harvest before the leaves decompose and too high after most of the residue has decomposed. Residue decomposition slows over time as the residue becomes increasingly composed of decomposition-resistant plant parts, which RUSLE2 does not take into account with its constant decomposition coefficient value. Differences between computed and observed residue mass are illustrated in Figure 12.2.[105]

The RUSLE2 composite residue structure and its equations for computing decomposition are a compromise. Separately tracking individual plant components such as leaves and stems with their own decomposition coefficient value would be better scientifically than the RUSLE2 composite approach. However, the RUSLE2 developers' judged that data were not available to derive the decomposition coefficient values for individual plant components for the wide range of residue descriptions needed by RUSLE2 when used as a conservation and erosion control planning tool.

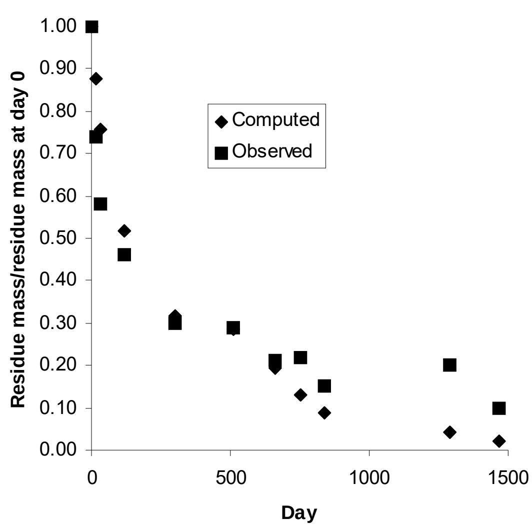

Figure 12.2. Comparison of computed residue mass with observed residue mass for corn in Missouri. (Parker, 1962)

The RUSLE2 composite residue structure must be considered when evaluating residue cover values computed by RUSLE2. Decomposition coefficient values were determined by empirically fitting the RUSLE2 decomposition equations to field residue data to give the best overall fit during the first year after harvest. In many agricultural cropping systems, the annual harvest residue input is much larger than the residue mass immediately before harvest. Errors in residue mass immediately before harvest has little effect on the overall residue mass. Also, errors in residue cover immediately before harvest are often not significant because of low erosion rates at that time. Residue cover should be accurately estimated during the most erosive period,

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105 Parker, D.T. 1962. Decomposition in the field of buried and surface-applied cornstalk residue. Soil Science Society of America Proceedings. 26:559-562.

which is the late spring and early summer before complete canopy develops for most US row crops. The most important RUSLE2 residue cover estimates at a point in time are those immediately after planting. The RUSLE2 residue decomposition may be too high for times longer than a year for agricultural crops where harvest does not provide a large residue mass input. Overall decomposition coefficient values are chosen to give good residue cover estimates during the most erosive period rather than residue cover values at particular points in time, especially if residue cover errors at those times have little effect on estimated erosion.

These concerns with estimating residue mass over time are much less significant for construction sites where mulch and erosion control products are much more uniform than the residue pieces associated with agricultural crops. However, the problem can be very significant on disturbed forest land where residue ranges from leaves to fine branches to coarse limbs.

Decomposition coefficient ϕ values for a particular residue are preferably location independent, but that objective is not always achieved. For example, the decomposition half-life is 28 days for soybeans grown in the Midwestern US while it is 53 days for soybeans grown in the Southern US. Differences in the vegetative properties of soybeans grown in the two regions partly contribute to the difference in decomposition half-life. The other contributor is climatic differences. The climate in the Southern US is warm and wet during the winter so that the leaves decompose very rapidly after harvest leaving residue in the spring that is primarily composed of stems that decay much more slowly than leaves. In contrast, the climate in the Midwestern US is cold so that little decomposition occurs after harvest during the winter, as illustrated in Figure 12.1. Thus, soybean residue has a higher ratio of leaves to stems in the spring in the Midwestern US than in the Southern US, which gives an apparent higher decomposition coefficient.

Another example where decomposition coefficient ϕ values differ between regions is for wheat residue. The decomposition half-life for wheat grown in the Northwest Wheat and Range Region (NWRR) is 40 days while it is 87 days for wheat grown in other parts of the US. Wheat residue seems to decompose much more rapidly in the NWRR than in other regions.[106] A contributing factor is the difference in climate between the NWRR where precipitation is very low immediately after harvest in comparison to the central Midwestern US. Although the reasons for this difference are not fully understood, the empirical data are more than sufficient to substantiate the difference.

The objective is to obtain the best average annual erosion estimate for conservation and erosion control planning.

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[106] The NWWR is a major portion of the region where the Req RUSLE2 relationships are used. **See Section 6.9.**

12.2.4. Decomposition coefficient ϕ values based on stage of growth

The organic properties that affect decomposition of plant materials vary with stage of growth. For example, the residue from a wheat cover crop killed well before maturity decomposes at a much faster rate than does the residue from a wheat crop harvested for grain. The decomposition half-life for wheat cover crop residue is 41 days while it is 87 days for residue from wheat harvested for grain. Therefore, two residue descriptions are created for wheat, one for wheat used as a cover crop that is killed well before maturity and one for wheat harvested for grain. The data inputs into RUSLE2 are always to create a description rather than to model a process. The residue description that best fits the situation is assigned to the vegetation description or selected for external residue.

12.2.5. Decomposition coefficient ϕ values for manure

Manure ranges widely from being almost entirely composed of straw used for bedding to liquid slurry. The important properties of manure include its dry matter biomass content and its decomposition properties. The residue descriptions for manure represent a composite of straw, wood shavings, manure, and other materials that may be present. The decomposition half-life assigned to a particular manure depends on the relative mass of individual components and the decomposition properties of each component, including the type of manure. Four classes of manure are recommended for use in RUSLE2. These classes are listed in Table 12.3.

Table 12.3. Recommended classes for residue descriptions for manure.

Class	Decomposition half-life (days)	Comment
Slow decomposition	87	Manure with high content of straw bedding
Moderately slow decomposition	41	Manure from open lots
Moderately rapid decomposition	23	Manure stored in settling basins
Rapid decomposition	14	Poultry litter

12.2.6. Decomposition coefficient ϕ values for erosion control products used on construction sites

Straw mulch is widely used on construction sites to control erosion. A decomposition half-life of 87 days is recommended for straw mulch. The decomposition half life for other erosion control materials used on construction sites can be determined by comparing their longevity with the longevity of wheat straw and adjusting the decomposition half life accordingly. For example, the decomposition half-life for native hay would be shorter than for wheat because of the greater proportion of leaves and fines in the native hay than in the wheat straw. Manufacturers' literature for roll products often includes information that can be used to estimate a decomposition half-life relative to that for wheat straw.

12.3. Mass-cover relationship

Although RUSLE2 tracks residue by mass, RUSLE2 computes the effect of surface (flat) residue on erosion using portion of the soil surface that the residue covers (see equation 9.6). RUSLE2 uses equation 9.9 to convert surface (flat) residue mass to portion of the soil surface cover by residue. User entered values in the residue description for data points (residue mass, cover) are used by RUSLE2 to determine values for the coefficient α in equation 9.9. These data points are the mass of residue that provides 30, 60, and 90 percent ground cover, respectively. RUSLE2 will use a single data point or an average of multiple data points to compute a value for α based on the data points for which values have been entered. Enter a mass value for 60 percent cover if only a single value is entered. The next best choice is a mass value for 30 percent cover. A single data point for 90 percent should be avoided because the mass-cover curve is very flat at high cover for many residue types, as Figure 9.5 illustrates. The best combination of two data points is 30 and 60 percent cover, and the poorest combination is one that involves a data point for 90 percent ground cover. Cover is very insensitive to a change in mass at high cover values where the curve is nearly flat. A value at this high cover is very poor for computing a value for α in equation 9.9 because residue mass value can vary over a wide range without affecting cover, which can result in great error when extrapolated to small cover values.

A RUSLE2 residue description is a composite that represents the net cover provided by the combined mass of the individual plant components of stems, leaves, pods and other plant parts. Leaves cover much more of the soil surface for a given mass per unit area than do stems, as illustrated in Figure 12.3. Thus, the mass-cover relationship for the composite residue depends on the relative mass of each plant component in the residue. A given residue mass covers much more of the soil surface immediately after harvest before the leaves decompose than later after the leaves have decomposed and only stems remain. For example, leaves decompose very rapidly and only stems are left soon after harvest for soybeans in the Southeastern US where fall and winter temperature and precipitation are high. In contrast, soybean leaves persist longer in the upper Midwestern US, and thus the leaves should be given greater consideration in selecting input values for the residue mass-cover relationship in the upper Midwestern US than in the Southeastern US.

RUSLE2 underestimates percent cover for a given mass per unit area immediately after harvest and overestimates percent cover late in the first year and beyond, as illustrated in

Figure 12.2. Refer to **Section 12.2.3** for information on how to best represent cover-mass for time periods that extend beyond one year after residue is added to the soil surface.
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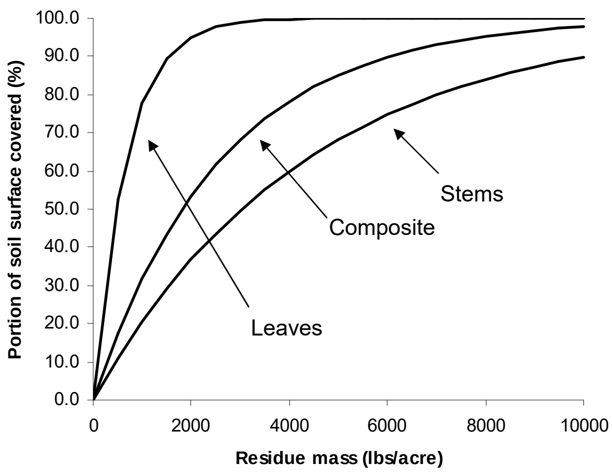

Figure 12.3. The relationship of cover to mass for leaves, stems, and the composite.

12.4. Non-organic residue

Non-organic materials, including stone, are used as mulch applied to the soil or incorporated into the soil. These materials are treated as **external residue** in RUSLE2. Input values in the residue descriptions for these materials must be carefully selected, especially if the materials are manipulated by operations.

12.4.1. Stones (rock fragments, gravel)

Stone, rock fragments, and gravel on the soil surface act as ground cover to reduce erosion (see **Sections 7.6, 9.2.2.1**). Values for rock cover can be entered in the **soil descriptions** in the **soil component** of the RUSLE2 database. RUSLE2 treats the rock cover value entered in a soil description as a constant that is not changed by operations.

Rock cover can also be added to the soil surface as an **external residue** by using an **operation description** that includes an **add other cover process** in a **cover-management description.** Rock cover added as an external residue is affected by soil disturbing operations (operation descriptions that include a **disturb soil process**). RUSLE2 treats rock added as an external residue as biomass that has the same effect on erosion as soil biomass described in **Section 9.2.2.1**. Adjustments should be made in the residue descriptions for rock added as external residue to prevent RUSLE2 from computing a soil biomass effect for rock.

Two special considerations are required to represent rock as external residue. The first step is to assign zero (0) for the decomposition coefficient value.[107] If the rock is not incorporated (buried) in the soil by a soil disturbing operation, no further adjustments are needed.

A second step is required if the rock is incorporated into the soil with a soil disturbing

[107] A very small value like 0.00001 should be entered rather than 0 to avoid a mathematical error in RUSLE2.

operation so that RUSLE2 does not treat rock as soil biomass. An index that has values less than 1 is used to represent the mass of the applied rock. For example, an index value of 0.2 could be used to represent 200,000 lbs/acre of applied rock cover. Values entered in the residue description to define the mass-cover relationship would be based on this index. The biomass subfactor equation (equation 9.12) in **Section 9.2.5.2** will use the index value as if the rock is biomass, but the equation will compute essentially no effect because the index indicates a very small biomass. Should you wish for RUSLE2 to compute an erosion reduction caused by rock incorporated into the soil, adjust the rock mass index until RUSLE2 computes the desired effect.

Be very careful in making these adjustments. See *Section 7.6.* The effect of rock in the soil on erosion is not well understood.

12.4.2. Non-organic erosion control materials that decay

Non-organic materials that decay by ultra-violet radiation are sometimes used at construction sites to control erosion. This decay process differs from the decomposition process assumed for **external residue**. Several special steps are required to develop **residue descriptions** for these materials.

Step 1 involves determining a decomposition coefficient value. RUSLE2 computes decomposition as a function of temperature and precipitation, whereas the decay of these materials is related to ultra-violent (u-v) radiation. Decomposition coefficient values must be determined by location or climatic region because the decomposition of these materials varies by location as u-v radiation, temperature and precipitation conditions that vary by location but are not internally represented in RUSLE2. Decomposition coefficient values are selected by running RUSLE2 and changing decomposition coefficient values until a value is determined that gives the desired loss of erosion control material over time.

Step 2 involves making adjustments for the fact that RUSLE2 adds a portion of the computed decomposed mass to the upper two inches of the soil (see **Section 9.2.5.3**). The decay products of these materials are assumed to have no effect on erosion. The adjustment for these non-organic materials that decay is like the one used for rock. An index is chosen for the erosion control product mass that numerically has values less than 1. The value entered in the **cover-management description** for the mass of the applied materials must be based on this index, and the values entered in the **residue description** for the cover-mass relationship must be consistent with the index definition.

Some erosion control materials are a combination of organic material and non-organic materials, such as compressed straw mulch between a plastic netting. The input values in the residue description should represent a composite of the material, much like residue with multiple plant components is represented as a composite. For example, the mass of the netting could be entirely ignored.

12.5. Selecting input values

The recommended approach for selecting input values for **residue descriptions** is to compare characteristics of the given residue with those in the residue descriptions in the RUSLE2 **core database.** The values in the core database are based on research data and have been evaluated to ensure that RUSLE2 computes erosion estimates appropriate for conservation and erosion control planning.

If the input values can not be selected based on a comparison with residue descriptions in the RUSLE2 core database, research literature may be a data source that can be used to derive RUSLE2 input values for residue descriptions. Otherwise field measurements may be required. Data used to determine RUSLE2 input values should meet certain conditions regardless of source. Data from multiple data sets, sources, locations, and measurements at a location are needed to deal with both spatial and temporal variability. Residue data, especially mass-cover values, are highly variable. The measurements should be made over at least a three year period at various times during the year. The objective is to capture main effects and trends rather than the details or differences between individual measurements. Differences often represent unexplained variability rather than characteristics of a particular residue.

The best measurements are from actual field conditions rather than from laboratory or specialized field experiments. This empirical approach also captures residue loss by other means besides decomposition such as by wind and worms. The purpose of RUSLE2 is not to be an accurate representation of processes but to be an easy-to-use conservation planning tool. Input values determined from measured data for residue descriptions should be compared among themselves and with those in the RUSLE2 core database for consistency. Such consistency is especially important for agencies implementing RUSLE2 on a national basis where fairness is an important requirement for those impacted by RUSLE2 estimates.

The input values in residue descriptions should reflect the most erosive period for the conditions where RUSLE2 is being applied. The values listed in the RUSLE2 core database were chosen to best fit the first year of the data, which is most important for agricultural cropping systems where annual harvest provides a relatively large biomass input. RUSLE2 tends to overestimate residue cover immediately after harvest and underestimate residue cover for periods longer than a year. Fitting the first year of data overall was considered more important than fitting the residue cover at end of the first year or fitting residue cover values beyond the first year. However, certain conditions exist where fitting over a longer period is important. Non-uniformity in the residue such as plant components that range from leaves to stems contributes significantly to RUSLE2 not fitting residue values beyond one year as well as during the first year. RUSLE2 fits residue data much better when residue pieces are uniform.

Surface residue cover values estimated by RUSLE2 are frequently used to judge the adequacy of RUSLE2. The first requirement in making these judgments is to ensure that the residue cover values being used to evaluate RUSLE2 values meet the requirements discussed above.

If RUSLE2 computed surface residue cover values do not match field measurements sufficiently well, do not immediately conclude that the residue decomposition coefficient value (half-life) should be modified. Numerous factors affect the surface residue cover values computed by RUSLE2. Changing the value for a single variable like the decomposition coefficient ϕ can have unexpected consequences that result in seriously erroneous erosion estimates even if the expected surface residue cover values are computed. That is, numerous other factors besides residue (ground) cover affect erosion. For example, changing the decomposition coefficient ϕ value, which affects residue cover, also affects buried residue and dead roots, which can significant affect computed erosion, especially for high yield, no-till corn cropping systems.

Several factors in addition to decomposition affect surface residue cover. These factors include the residue mass at harvest, the distribution between standing residue at harvest and surface (flat) residue, the rate that standing stubble falls, the relationship between residue cover to mass, and flattening, burial, and resurfacing of residue by operations. All of these factors should be systematically considered in correcting a surface residue cover problem.

13. OPERATION DATABASE COMPONENT

The **operation descriptions** in the **operation component** of the RUSLE2 database contain the information that RUSLE2 uses to compute how operations affect erosion. An **operation** is an event that affects the **soil**, **vegetation**, and/or **residue**. Operations play a major role in determining the values for variables used in the subfactor equations described in **Section 9**.

The variables used to describe an operation are given in Table 13.1. Speed of the operation is one of the variables used to describe an operation. Speed affects residue burial, much like disturbance depth. These two variables are discussed together in **Section 13.1.5.3**.

Table 13.1. Variables used to describe an operation

Variable	Comment
Recommended speed	The speed for which values in the operation description apply. The usual input value is the speed recommended by the manufacturer if the operation represents a machine
Minimum speed	RUSLE2 can adjust values in the operation description if the operation occurs at a speed that differs from the recommended speed. The minimum speed is the slowest speed that RUSLE2 will allow for the adjustment
Maximum speed	RUSLE2 can adjust values in the operation description if the operation occurs at a speed that differs from the recommended speed. The maximum speed is the fastest speed that RUSLE2 will allow for the adjustment
Sequence of processes	A set of processes is used to describe the operation. The processes must be listed in the proper order to have the desired effect. The variables used to describe processes are listed in Table 13.2.
List of processes that can be used to describe an operation	
No effect	Process has no effect. Typically used to cause RUSLE2 to display information on particular dates
Begin growth	Identifies the vegetation description that RUSLE2 is to begin using on the date of the operation description in the cover-management description. RUSLE2 references day zero in the vegetation description to the date of the operation
Kill vegetation	Converts live aboveground biomass and live root biomass to dead biomass that decomposes
Flatten standing residue	Transfer biomass from the standing residue pool to the surface (flat) residue pool. Does not affect live biomass
Disturb soil	Represents a mechanical disturbance of the soil. Creates roughness and ridges. Buries and resurfaces buried residue. Redistributes buried

	residue and dead roots in the soil. Does not affect live roots.
Live biomass removed	Takes a portion of above ground live biomass from the site. The removed biomass is no longer involved in RUSLE2's biomass accounting
Remove residue/cover	Removes residue (dead biomass) and other material from the soil surface.
Add other (external) cover	Adds external residue (e.g., mulch, manure, rolled erosion control materials) to soil surface. Also used to place materials like manure in the soil, which must be accompanied by a disturbed soil process in the operation description
Add non-erodible cover	Adds non-erodible cover including plastic used in vegetation production, water used to flood rice fields, and snow cover. RUSLE2 computes no erosion for portion of soil surface covered by non-erodible cover
Remove non-erodible cover	Removes non-erodible cover.

Some processes like **disturb soil** use additional variables to describe them. Those processes and variables and the variables used to describe them are listed in Tables 13.2.

Table 13.2. Variables used to describe particular operation processes

Process	Variables	Comment
Flatten standing residue	Flattening ratio	Portion of the standing residue mass (dry basis) that is flattened by the operation. Value entered for each residue type
Disturb soil	Tillage type	Describes where operation places buried material in soil and how it redistributes buried residue and dead roots in the soil
	Tillage intensity	Describes the degree that operation obliterates existing roughness
	Recommended depth	Typical depth of disturbance. Use value recommended by manufacturer if operation represents a machine
	Minimum disturbance depth	RUSLE2 adjusts values in operation description if disturbance depth differs from recommended depth. Minimum depth is the shallowest depth that RUSLE2 will use to make an adjustment.
	Maximum disturbance depth	RUSLE2 adjusts values in operation description if disturbance depth differs from recommended depth. Maximum depth is the deepest depth that RUSLE2 will make an adjustment.
	Ridge height	Height of ridges created by operation

	Initial roughness	Roughness left by operation when used on a smooth, silt loam soil when surface and soil biomass are very great
	Final roughness	Roughness after roughness has fully decayed
	Portion of surface area disturbed	Portion of the surface disturbed when disturbance occurs in strips.
	Burial ratios	Portion of surface (flat) residue (dry basis) that is buried. Value entered for each residue type
	Resurfacing ratios	Portion of buried residue in the disturbance depth brought to the soil surface and added to surface (flat) residue pool. Value entered for each residue type
Live biomass removed	Biomass affected	Portion of live aboveground biomass (dry basis) affected by operation
	Amount left on surface	Portion of the affected live biomass (dry basis) added to the surface (flat) residue pool by operation
	Amount left as standing residue	Portion of the affected live biomass (dry basis) added to the standing residue pool by operation
Remove residue/cover	All residue affected	Determines whether operation applies to all residue that is present or to the last residue added
	Flat residue removed	Portion of surface (flat) residue (dry basis) removed by operation
	Standing residue removed	Portion of standing residue (dry basis) that is removed by operation
Add other cover	Portion of external residue added to soil surface	Distributes added external residue between soil surface and placement in the soil over lower half of soil disturbance depth
Add non-erodible cover	Cover added	Portion of soil surface receiving non-erodible cover. Erosion is zero on the portion of the soil surface covered by the non-erodible cover
	Cover half life (days)	Time in days that half of the cover disappears by any process. Value entered must be appropriate for location because RUSLE2 does not consider environmental variables in computing loss of non-erodible cover.
	Cover permeability	Determines the degree that the non-erodible cover affects infiltration and runoff. 100% permeability means that the cover has no effect on infiltration. 0% permeability means that all precipitation on the non-

		erodible cover portion runs off
Remove non-erodible cover	Portion of non-erodible cover removed	Portion of current non-erodible cover removed by the operation.

13.1. Processes Used to Describe Operations

Operations are **discrete events** that change properties of **vegetation**, **residue**, and/or the **soil** that affect erosion. Examples of operations include tilling, planting, harvesting, grazing, burning, frost, ripping, blading, and applying mulch. Operations are described using a **sequence of processes**. Both the processes themselves and their sequence determine an operation's effect. Additional variables are used to describe some processes.

13.1.1. No Effect

The **no effect process** has no effect on RUSLE2 computations. It's main use is in a ***no operation*** **operation-description** to cause RUSLE2 to display output information on certain dates and for certain periods. **Section 10.2.1.3** discusses how to use a *no operation* operation-description to set the starting point for RUSLE2's tracking of time in an erosion computation. Also, users will sometimes place *no operation* operation-descriptions in a **cover-management description** where other users will later substitute other operation descriptions.

13.1.2. Begin growth

The **begin growth process** is used in an **operation description** to identify the **vegetation description** that RUSLE2 is to begin using on the date of the operation description in a **cover-management description**. RUSLE2 references day zero in the vegetation description to the date of the operation description containing the **begin growth process**. **Section 10.2.3** describes how a **begin growth process** is used in RUSLE2.

RUSLE2 uses only a single vegetation description at any time during its computations (i.e., only one vegetation description is **current** and being used at any time). RUSLE2 begins using a new vegetation description at each occurrence of an operation description with a **begin growth** process in a cover-management description. RUSLE2 does not combine information from multiple vegetation descriptions.

RUSLE2 uses certain rules regarding the **begin growth process** when an operation description with a begin growth process occurs where the previous vegetation description was not ended with a **kill vegetation process**. RUSLE2 adds the decrease between live root biomass on the last day the previous vegetation description was used and the live root biomass on day zero of the new vegetation description to the dead root biomass pool. RUSLE2 makes no change in the dead root biomass pool if live root biomass increases between vegetation descriptions.

RUSLE2 does not adjust residue pools as a result of differences in canopy cover or live aboveground biomass between vegetation descriptions. Any changes to these biomass pools must be explicitly represented using processes in operation descriptions. However, RUSLE2 DOES adjust the dead root biomass pool between vegetation descriptions. RUSLE2 assumes that a decrease in live root biomass between two vegetation descriptions is dead root biomass that is added to the dead root biomass pool on the date that the change in vegetation description occurs.

13.1.3. Kill vegetation

The **kill vegetation process** converts live aboveground biomass to standing residue and live roots to dead roots and sets values for live root biomass and live ground cover to zero. This process is used in most tillage and harvest **operation descriptions** that end vegetative growth. It is also used in frost killing operation descriptions and in burning operation descriptions if burning entirely kills the vegetation. If an operation such as burning or harvest kills only a portion of the vegetation, the procedure described below is used (see **Section 11.1.3.2**).

Because RUSLE2 uses a descriptive approach and is not a process model, an *operation description* using the *kill vegetation process* must be used to end vegetation growth.

The **kill vegetation process** "kills" all vegetation represented by the current vegetation description. A **kill vegetation process** also ends RUSLE2's use of information from the current vegetation description. If RUSLE2 computations extend beyond the last date represented in a vegetation description, RUSLE2 uses the values on the last date in the vegetation description until an operation description with either a **kill vegetation process** or a **begin growth process** occurs in the **cover-management description**.

Two processes are used in an operation description to represent a partial kill of vegetation. These processes transfer only a portion of the live aboveground biomass to the standing and surface (flat) residue pools and a portion of the live root biomass to the dead root biomass pool. The **first process** is **remove live biomass**, which determines how much of the live aboveground biomass that is affected by the operation and the portion of the affected biomass that is transferred to the standing and surface (flat) residue pools. The **next process** in this operation description is a **begin growth process** that identifies the vegetation description that follows the current vegetation description. RUSLE2 compares the live root biomass on day zero in the new vegetation description with the live root biomass in the current vegetation description on the transfer date. RUSLE2 transfers a **decrease** in live root biomass between the vegetation descriptions to the dead root biomass pool. An increase does not change the dead root biomass pool.

A *kill vegetation process* transfers all live aboveground biomass for the current vegetation to the standing residue pool and all live root biomass to the dead root biomass pool. Use *remove live biomass* and *begin growth processes* to transfer only a portion of live biomass to dead biomass.

13.1.4. Flatten standing residue

Biomass is transferred from the standing residue pool to the surface (flat) residue pool by natural and mechanical processes that flatten the standing residue (see **Section 9.2.2.3**).[108] Flattening of standing residue by natural processes is represented internally in RUSLE2 based on decomposition at the standing residue base. The **flatten standing residue process** is used in **operation descriptions** to represent mechanical flattening of standing residue. For example, this process is used in operation descriptions that describe flattening of standing residue by foot or vehicular traffic. Also, this process is used in operation descriptions for tillage operations that bury crop residue because standing residue must first be flattened before it can be buried according to RUSLE2 rules. This process is also used in harvest operation descriptions to describe the distribution between standing and flat residue after harvest. For example, about 50 percent of wheat residue is left standing after harvest, while only 5 percent of soybean residue is left standing. The difference is primarily related to combine cutter bar height. The amount of residue left standing for corn harvest can range from about 15 to 85 percent depending on combine snapper height or whether the corn was harvested by combine, picker, grazing, or hand. This process can be used in operation descriptions to represent wind flattening standing residue where the RUSLE2 internal procedures for natural processes do not compute sufficient fattening. To flatten live vegetation, a **begin growth process** is used to call a new vegetation description to describe characteristics of the live vegetation after flattening. **A flatten standing residue process** can not be used to descrbe flattening of live vegetation because a RUSLE2 rule is that only standing residue can be flattened..

Two rules apply in using the **flatten standing residue process** in an operation description. The **first rule** is only standing residue can be flattened. Live vegetation must first be converted to standing residue using a **kill vegetation process** or a **remove live biomass process** in an operation description. The **flatten standing residue process** has no effect on live vegetation. Live vegetation can be flattened and continue to live

[108] The companion values for burial and resurfacing ratios are entered in the **disturb soil process**.

(e.g., wheat blown over by wind before maturity). An operation description that includes a **begin growth process** and associated vegetation description that represents flattened live vegetation is used to describe this condition. The **second rule** is that standing residue can not be buried by an operation until the standing residue has been converted from standing residue to surface (flat) residue. Therefore, a tillage operation description that buries standing residue must include a **flatten standing residue process** before a **disturb soil process**. Sequence of processes is important.

Flattening ratio is the input used to describe the **flatten standing residue process**. This ratio is defined as the portion of mass (dry basis) of standing residue that is flattened to the mass (dry basis) of standing residue before flattening. A flattening ratio of 0 means that no standing residue was flattened, and a value of 1 means that the entire standing residue was flattened. The portion of standing residue flattened by a mechanical process depends on both residue type (e.g., the standing residue of some vegetation types resists flattening), type of mechanical process (e.g., vehicular traffic versus harvest, corn combine versus corn picker), and properties of the process (e.g., cutter bar height). A value for the flattening ratio in an operation description is entered for each residue type (see **Section 12.1**). The values must also represent the particular process (e.g., type of machine) and the properties of the process (e.g., how the machine is operated). Multiple operations are required for a particular machine operated in different ways (e.g., cutter bar set at different heights). Values for the flattening ratio are largest for residue types most easily flattened by mechanical action and cutter bar height close to the ground, such as for soybeans.

Values entered for flattening ratio in an operation description should be based on a comparison with operation descriptions in the RUSLE2 **core database**. If a selection can not be made on that basis, research literature may provide data that can be used to determine flattening ratio values. The third possibility is to make field measurements. Data used to determine flattening ratio values should be sufficient to deal with variability, and the emphasis should be on capturing main effects rather than details that may well be unexplained variability. Values determined from the literature or from actual measurements should be checked for consistency with values in the RUSLE2 core database.

13.1.5. Disturb Surface (Soil)

The **disturb surface (soil) process** represents a mechanical disturbance of the soil that, with one exception, resets the soil consolidation subfactor to 1 for the portion of the soil surface that is disturbed (see **Section 9.2.6**). RUSLE2 assumes that the soil must be disturbed to bury surface (flat) residue, to create soil surface roughness and ridges, to mechanically smooth the soil, and to place material in the soil. The exception is the compression tillage type that buries residue without loosening the soil (see **Table 13.3**).

Also, RUSLE2 assumes that a infinitely thin surface layer of soil can be cut away without disturbing the underlying soil. The **operation description** that describes this action would **not** include a **disturb soil process** but would include a **Remove residue/cover process** that removes all above ground and surface vegetation and cover. This operation description does not affect any soil biomass.

Input values for the variables listed in Table 13.2 are required to described the **disturb soil process** for a particular **operation description**.

13.1.5.1. Tillage type

Assigning a **tillage type** from the list in Table 13.3 for an **operation description** provides information to RUSLE2 how a **soil disturbing** operation vertically distributes surface residue when it is buried. This input also provides information on how the operation vertically redistributes existing buried residue and dead roots. The **disturb soil process** has no effect on the distributions of live roots. Live root biomass must be transferred to the dead root biomass pool before root biomass can be redistributed in the soil by a soil disturbing operation. The distribution and redistribution functions represented by the tillage types are described in **Sections 9.2.5.3.3 and 9.2.5.3.4.**

The **inversion+some mixing** tillage type is used to describe machines like moldboard plows and manual operations that bury residue by inverting the soil. These operations bury most of the residue in the lower one half of the disturbance depth as illustrated in Figure 9.15. One way to represent how a soil disturbing operation redistributes buried residue and dead roots is to describe the pattern that results after the operation is applied repeatedly. Repeated applications of the inversion+some mixing tillage type operation results in buried residue and dead roots being nearly uniformly distributed as illustrated in Figure 9.17.

The **mixing with some inversion** tillage type is used to describe machines like heavy offset disks, tandem disks, chisel plows, and field cultivators and manual operations that primarily bury residue by mixing but also bury some residue by soil inversion. These operations bury most of the residue in the upper one half of the disturbance depth as illustrated in Figure 9.15. The second application of an operation of this tillage type mixes the residue fairly uniformly in the upper one half of the disturbance depth as illustrated in Figure 9.18. Subsequence applications result in a moderate bulge of material that moves downward in the soil.

The **mixing only** tillage type is used to describe machines like rotary powered tillers and manual operations that incorporate residue by mixing with hardly any soil inversion. These operations tend to bury residue in the upper one third of the soil depth as illustrated in Figure 9.15 rather than uniformly over the disturbance depth as commonly assumed. Repeated applications of this tillage types results in a well defined bulge of material that moves downward in the soil.

The **lifting, fracturing** tillage type is used to describe machines like fertilizer and manure injectors, subsoilers, and sacrifiers and manual operations that have a similar effect on the soil and residue. This tillage type assumes almost no mixing or inversion, and an operation of this tillage type buries residue in the upper one third of the disturbance depth. The residue distribution and redistribution relationships for **mixing only** are used to describe this tillage type.

An **add other residue/cover process** is used to place external residue in the soil. This process must be followed by a **disturb soil process** in the **operation description**. The lifting, fracturing tillage type is selected for the operation. RUSLE2 places the inserted material in the lower one half of the disturbance depth as illustrated in Figure 9.16. This procedure assumes that the material is placed in the soil by injection. Material can be also placed in the soil by applying it to the soil surface and incorporating it using machines like disks, chisel plows, field cultivators, or rotary powered tillers or manual implements. The operation description for this method of incorporation includes an **add other residue/cover process** followed by a **disturb soil process**.

Table 13.3. Tillage types used in RUSLE2			
Tillage type	Burial pattern	Redistribution characteristics with repeated applications	Comment
Inversion + some mixing	Most of material is placed in lower 1/2 of disturbance depth	Material is nearly uniformly distributed	Used to represent soil disturbing machines like moldboard plows that invert soil
Mixing with some inversion	Most of material is placed in upper 1/2 of disturbance depth	2nd application results in a fairly uniform pattern in the upper ½ of soil disturbance depth after which a moderate bulge develops that moves downward in soil	Used to represent soil disturbing machines like chisel plows, field cultivators, and disks
Mixing only	Most of material placed in upper 1/3 of disturbance depth	A well defined bulge rapidly develops that moves downward in soil	Used to represent powered rotary tillers
Lifting, fracturing	Most of material placed in upper 1/3 of disturbance depth	A well defined bulge rapidly develops that moves downward in soil	Used to represent fertilizer injectors, manure injectors, subsoilers, and sacrifiers
Compression	Most of material placed in upper 1/3 of disturbance depth	No redistribution	Used to represent sheep's foot roller and animal traffic that presses residue into the soil. The soil consolidation subfactor is not reset to 1
Note: When external residue is placed in the soil, the **add other residue/cover process** must be followed with a **disturb soil process** in the operation description, which places the inserted material in the lower one half of the disturbance depth			

The **compression** tillage type is used to describe cattle trampling, a sheep foot's roller, and similar operations pressing residue into the soil without loosening the soil. The **mixing only** distribution relationship is used to vertically distribute the buried residue. Operations of this tillage type are assumed to not redistribute buried residue or dead roots. **An important difference between this tillage type and the other tillage types is that the soil consolidation subfactor is not reset to 1.**

The best way by far for assigning tillage types to soil disturbing operations is to base the selection on Table 13.3 in conjunction with comparisons with tillage types assigned in the RUSLE2 **core database**. Consistency between the assigned tillage type and those in the core database is essential.

A very important feature of the soil mixing relationships used in RUSLE2 is that material does not become uniformly mixed in the soil with repeated applications of the operation except for the *inversion+some mixing* tillage type. The distribution becomes more non-uniform with repeated applications of operations described with the other tillage types.

13.1.5.2. Tillage intensity

Tillage intensity refers to the degree that a soil disturbing operation obliterates existing roughness. Tillage intensity relates to the aggressiveness of the soil disturbance. A tillage intensity value of 1 means that existing soil roughness has no effect on the roughness created by the operation. A tillage intensity value of 0 means that roughness after the operation is the same as before the operation, unless the existing roughness is smoother than the roughness created by the operation on a smooth soil.

A moldboard plow and a rotary powered tiller are both assigned tillage intensity values of 1 because these aggressive machines totally eliminate any signs of existing roughness. In contrast, a spike tooth harrow, which is non-aggressive, is assigned a tillage intensity of 0.4 because the harrow hardly changes existing roughness. For example, soil surface roughness is greater when the harrow follows a moldboard plow than when it follows a tandem disk because of differences in existing roughness and the minimal effect that the harrow has on roughness. The harrow does some smoothing but does not totally work the soil to eliminate all existing soil surface roughness to create a totally new soil surface roughness. Tillage intensity values range from 0.5 to 0.9 machines like field cultivators, tandem disks, and chisel plows depending on the machine's "aggressiveness."

When the roughness immediately before an operation is smoother than the roughness created by the operation on a smooth soil, the tillage intensity variable has no effect on the roughness value estimated by RUSLE2. The roughness value for the operation is set to the **input (initial) roughness value** for the operation, adjusted for soil texture and soil biomass (see **Section 9.2.3**).

Tillage intensity is not necessarily related to the initial roughness created by an operation. For example, both a moldboard plow and a rotary powered tiller are assigned 1 for tillage intensity but the soil surface roughness left by the two machines is very different. The moldboard plow leaves a very rough surface and the powered rotary tiller leaves a very smooth surface. Both machines are very aggressive and completely disturb the soil. Machines that have low tillage intensity values also tend to leave a relatively smooth surface when used on a smooth soil.

Tillage intensity values should be assigned using values in the RUSLE2 **core database** as a guide. The selection is the operation's aggressiveness for obliterating signs of existing soil surface roughness, not the soil surface roughness left by the operation. The RUSLE2 assumption is that tillage intensity is not a function of soil properties. However, different intensity values can be assigned based on soil properties. The RUSLE2 user then chooses the operation description having the tillage intensity values most appropriate for the site-specific condition.

13.1.5.3. Recommended, minimum, and maximum speed and disturbance (tillage) depths

The portion of the surface (flat) residue mass buried by a **soil disturbing operation** (e.g., tillage) increases as disturbance depth and speed increase as illustrated in Figures 13.1 and 13.2. These relationships were derived from analysis of research data. The manufacturer of tillage implements and soil disturbing machines often specify a recommended disturbance depth and speed along with working ranges where the machine operates satisfactorily. The input burial ratio values are for the **recommended disturbance depth and speed**.[109] No other variable, including residue resurfacing, is affected by disturbance depth and speed in RUSLE2.

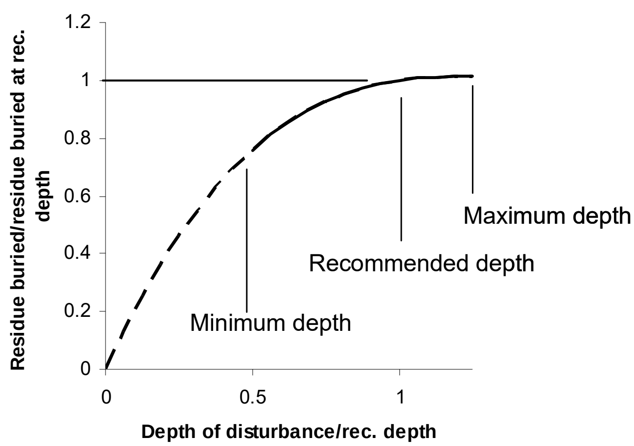

Figure 13.1. Effect of disturbance depth on residue burial (mass basis).

Increasing disturbance depth at shallow depths significantly increases residue burial, but increasing disturbance depth to depths deeper than the recommended depth does not greatly increase residue burial. Increasing speed does not significantly increase residue burial. The effect of speed on residue burial is generally less than the effect of disturbance depth.

[109] Disturbance depth in RUSLE2 is for the entire disturbance (tillage) depth, which differs from the incorporation depth used in RUSLE1. The RUSLE1 incorporation depth is the effective depth of residue burial assuming that residue is buried uniformly with depth. The RUSLE1 incorporation depth is shallower than the RUSLE2 disturbance depth.

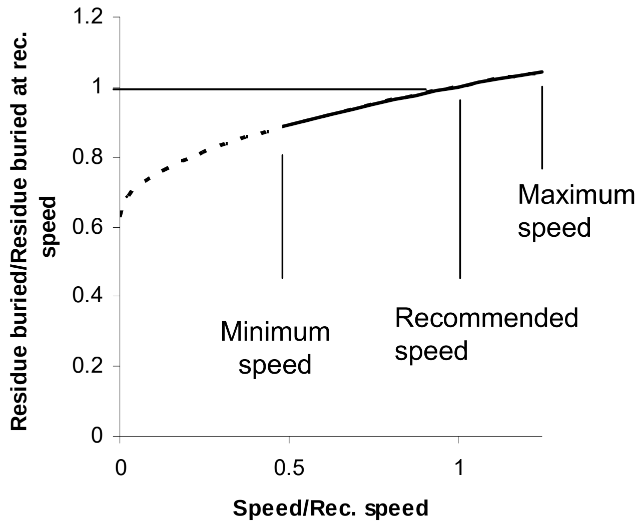

Figure 13.2. Effect of speed on residue burial (mass basis)

In most RUSLE2 applications, the recommended disturbance (tillage) depth and speed are accepted as default values.[110] Input values for disturbance depth and speed entered in **cover-management descriptions** must be within the minimum and maximum values entered in each **operation description.**

The common belief is that practically any surface residue cover can be achieved by varying how a machine is operated. Disturbance depth and speed are the two machine variables that can be changed easily. The assumption that a particular residue cover can be achieved by varying machine operation should be checked. The range in residue cover that can be achieved by varying disturbance depth and speed is determined by making RUSLE2 computations at the minimum and maximum disturbance depth and speed values. If RUSLE2 shows that the desired residue cover is not obtained by varying disturbance depth or speed, another change in the machine such as changing shovel type is required.

Input values for disturbance depth and speed can often be obtained from manufacturer's literature. Also, values given in the RUSLE2 **core database** can be used as a guide to selecting input values. The preferred approach is to select a tillage depth based on the implement type rather than selecting value specific to an individual machine or operator. The disturbance depth and speed values shown in the RUSLE2 core database were chosen to give the desired differentiation between implement types. Input values should be reviewed for consistency among themselves and with values in the RUSLE2 core database.

Input values for disturbance depth and speed should not deviate significantly from those in the RUSLE2 core database for a particular type of machine.

[110] Depth and speed of operations in a **cover-management description** may not be displayed by the RUSLE2 template used to configure your RUSLE2 screen. Choose an alternate RUSLE2 template that displays additional variables so that disturbance depth and speed can be entered for each operation in a **cover-management description**.

13.1.5.4. Ridge height

Ridge height has two effects in RUSLE2. One effect is that increased ridge height increases erosion when the ridges are oriented up and down hill perpendicular to the contour. This ridge effect is considered in the subfactors used to compute **cover-management** effects (see **Section 9.2.4**). The other effect is that increased ridge height decreases erosion when the ridges are on the contour (parallel to the contour). This ridge effect is considered in **support practice** relationships used to compute the **contouring** effect (see **Section 14.1**). The overall ridge height effect, which is the net between these effects, also varies with row grade (grade along the furrows between the ridges).

Operation descriptions that include a **disturb soil process** must be used in a **cover-management description** to create ridges for RUSLE2 to compute a contouring support practice effect. RUSLE2 assumes that ridges can not be created without disturbing the soil, which resets the soil consolidation subfactor to 1 for the portion of the soil surface that is disturbed by the operation that creates the ridges.

Input values for initial ridge height are entered in operation descriptions that include a **disturb soil process**. Ridge height created by an operation is not affected by ridge height that existed before the operation. In effect, an operation obliterates any ridge height that existed prior to the operation even when the operation minimally disturbs the soil. The ridge height entered for an operation should reflect the ridge height that exists when the operation is used in combination with other operations. RUSLE2 computes loss of ridge height over time as a function of precipitation amount and interrill erosion.

The best way, by far, to assign ridge height values is to use the values in the RUSLE2 **core database** as a guide. RUSLE2's estimate of the contouring effect on erosion is RUSLE2's most uncertain estimate. Too frequently, initial ridge height values are entered that are too low, which results in RUSLE2 not computing the expected contouring effect (see **Section 14.1**). Field measured ridge height values may be lower than the corresponding values in the RUSLE2 core database. Also, important ridges are also overlooked when field measurements are made.

If RUSLE2 is not computing as much contouring effect as expected, initial ridge height values in key operation descriptions may need to be increased.

13.1.5.5. Initial roughness

As described in **Section 9.2.3**, RUSLE2 computes decreased sediment production (i.e., detachment, see equations 5.4, 8.1, 9.1, 9.10) as soil surface roughness increases. RUSLE2 also computes decreased runoff rates as soil surface roughness increases (see **Section 5.4**). RUSLE2 uses runoff rate to compute how contouring affects erosion (see **Section 14.1**) and to compute sediment transport capacity (see equation 5.3). RUSLE2 uses sediment transport capacity to compute deposition, sediment yield, and enrichment of the sediment in fines on rough surfaces; on concave shaped slopes; upslope of strips of dense vegetation, rough soil surfaces, and heavy ground cover; and in low grade terrace/diversion channels (see **Section 14**).

RUSLE2 assumes that the soil must be disturbed to create roughness, which resets the soil consolidation subfactor to 1 for the disturbed portion of the soil surface, with one exception. The exception is a **compression tillage type** that creates soil surface roughness but does not reset the soil consolidation subfactor to 1 (see **Section 13.1.5.1**). Therefore, **operation descriptions** that include a **disturb (soil) surface process** must be included in **cover-management descriptions** to describe surface roughness. The input value for **initial roughness** in the disturb soil process in an operation description is an index for the roughness that the operation creates for a standard condition. **This standard condition is a smooth, silt loam soil, where the amount of soil biomass from buried residue and dead roots is very high in the soil disturbance depth after the operation** (see **Section 9.2.3.3**). RUSLE2 adjusts the input initial roughness value to obtain an **adjusted roughness** value for its erosion computations.

These adjustments are for:
soil texture (increased roughness for fine textured soils, decreased for coarse textured soils),

soil biomass in disturbance depth after operation (decreased roughness with decreased soil biomass), and

tillage intensity if the existing roughness is greater than the roughness created by operation on a smooth soil (resulting roughness is least affected by existing roughness as tillage intensity increases).

The initial roughness input value applies only to the **portion of the soil surface disturbed** and not to the entire soil surface. **The input value is not a net for the entire surface.**[111] RUSLE2 does not arithmetically average the roughness values for the disturbed and undisturbed portions of the soil surface. Instead, RUSLE2 computes a roughness subfactor value (see equation 9.10) for both the disturbed and undisturbed portions. These subfactor values are averaged based on the portion of the soil surface disturbed. This average roughness subfactor value is used to compute an **equivalent roughness** value for the entire surface that gives the proper net erosion for the entire surface.[112] This equivalent roughness value is decayed over time by precipitation amount and interrill erosion.

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[111] The roughness input is different from the inputs for residue burial and resurfacing in the **disturb (soil) surface process** description. Burial and resurfacing input values are net for the entire soil surface.
112 Proper erosion is the net erosion that is computed to occur based on the undisturbed and disturbed surfaces. An equivalent roughness is determined that gives this net erosion.

The best approach for selecting input values for initial roughness is to base them on values in the RUSLE2 **core database**. Like other variables, the values in the RUSLE2 core database were selected to represent operation classes and types to ensure that RUSLE2 computes main effect erosion differences among operations based on research data and professional judgment. User selected initial roughness input values should be reviewed for consistency among implements, machines, and manual types of soil disturbance and for consistency with RUSLE2 core database values. The requirement is that RUSLE2 estimate expected erosion rather than exactly reproducing a field roughness measurement.

The scientific literature is a source of initial roughness input values, but literature values require modification using equations in **Section 9.2.3.3** before using them in RUSLE2. For example, the RUSLE2 initial roughness input values are often higher than comparable values used in other erosion models because of the standard condition used to define RUSLE2 initial roughness. The internal RUSLE2 adjusted roughness values are often similar to input values used in other models.

The RUSLE2 standard condition used to define initial roughness is the same as the one used in RUSLE1 (AH703). However, the RUSLE2 initial roughness input values differ from the RUSLE1 values because of the RUSLE2 tillage intensity effect that is not used in RUSLE1. RUSLE2 initial roughness values are less than comparable RUSLE1 values where tillage intensity is less than 1.

RUSLE1 initial roughness values can not be used directly in RUSLE2 without adjusting for the tillage intensity effect

Field measurements can be made to determine RUSLE2 input initial roughness subfactor values (see **Section 9.2.3.2**). The measurements are on a 1 inch (25 mm) grid using pins lowered to the soil surface or elevations determined using a non-contact method. The chain method should not be used to determine roughness values for RUSLE2. Elevations related to ridges should be removed, and a plane should be fitted to the data to remove land slope effects. The roughness measure used in RUSLE2 is the standard deviation of elevations about this plane. Equations described in **Section 9.2.3.3** must be used to adjust measured values for a particular field condition to the RUSLE2 standard condition for initial roughness. Sufficient measurements are made to account for both temporal and spatial variability. The intent is to characterize main effects of roughness using a diverse data set rather than representing a single, specific site condition.

13.1.5.6. Final roughness

The RUSLE2 subfactors described in **Section 9**, including the roughness discussed in **Section 9.2.3**, are relative to the unit plot conditions used to determine soil erodibility factor values (see **Section 7.2**). The value for each subfactor is 1 for unit plot conditions. A roughness value of 0.24 inches (6 mm) is assumed to represent unit plot roughness. This roughness is similar to the roughness at harvest of a row crop where a moldboard plow, tandem disk, field cultivator, and row cultivator were used to till the soil. A 0.24-inch (6 mm) roughness is nearly but not completely smooth. A perfectly smooth soil surface has a roughness value of 0 inches (0 mm).

The 0.24-inch (6 mm) roughness represents the effect of a few erosion resistance clods on erosion. Even though **final roughness** represents the effect of a few erosion resistant clods, the input value for final roughness is not a function of soil texture. The effect of soil texture on final roughness is empirically represented in the soil erodibility factor values derived from unit plot conditions.

This empirical effect of soil texture on final roughness being included in the soil erodibility factor is but one reason why RUSLE2 definitions must be understood and followed.

A final roughness value of 0.24 inches (6 mm) is typically used in RUSLE2 for operation descriptions that create a roughness greater than 0.24 inches (6 mm) on a smooth soil. However, some operations leave a smoother surface than 0.24 inches (6 mm). A rotary powered tiller used to prepare a very fine seedbed is an example. This tiller creates almost uniform, small-sized soil aggregates (clods) and leaves almost no large clods in comparison to a moldboard plow, heavy offset disk, or chisel plow. Another example is a bulldozer or a road grader that cuts away soil leaving a very smooth surface. A 0.15-inch value is used for final roughness for these operations.

If the input value for final roughness is greater than or equal to 0.24 inches (6 mm), RUSLE2 decays roughness from a starting value to the final roughness value based on daily precipitation and daily erosion. If the input value for final roughness is less than 0.24 inches (6 mm), the input value for initial roughness should be the same as the input value for final roughness. RUSLE2 does not decay this roughness value.

Similarly, RUSLE2 does not decay roughness when the input values for both initial and final roughness are the same, even when the input value for final roughness is greater than 0.24 inches (6 mm). These inputs cause RUSLE2 to use a specific roughness value. An example of this application is representing roughness created by animal traffic, which also involves selecting compression for tillage type (see **Section 13.1.5.1**).

***Long term natural roughness*, discussed in *Section 10.2.7*, is the soil surface roughness that develops over time to soil consolidation after a soil disturbance. Final roughness and long term roughness are not the same, and the values entered for the two variables are not the same.**

13.1.5.7. Surface area disturbed

Some operations like planters disturb only a portion of the soil surface. The variable **portion of soil surface disturbed** directly affects the soil consolidation and soil surface roughness subfactors and indirectly affects the soil biomass subfactor, the effect of distance along an overland flow path on erosion, the effect of surface cover on erosion, and runoff (see **Section 9.2.6**).

Selecting proper values for the portion of the soil disturbed requires an understanding of the definition of soil disturbance, knowing the effect of soil disturbance on erosion, and recognizing indicators of soil disturbance. The definition of soil disturbance is given in **Section 9.2.6.3.**

Soil disturbance, as used in RUSLE2, occurs when an operation fractures and loosens the soil, displaces soil, mixes soil and surface residue so that the interface between the residue and the surface soil is no longer distinct, and disrupts a high organic matter layer at the soil surface.

The portion of the soil surface disturbed includes a **soil source area** and the **soil receiving area** that collects soil displaced from the soil source area. The soil source area is mechanically disturbed (disrupted) where the soil disturbing tool (e.g., disk blade, shank, or shovel) fractures, loosens, and displaces soil. This area is considered disturbed if the tool action penetrates below the residue (litter)-soil interface to mix underlying soil and residue (litter) and expose and displace mineral soil. The area disrupted by the tool should be considered to be disturbed if the disturbance depth exceeds an inch (25 mm) or two (50 mm).

Some tools run beneath the residue (litter)-soil interface and do little more than fracture and loosen the soil. This action is also soil disturbing even though mineral soil may not be exposed. However, the input value for the portion of the soil surface disturbed may be less that the actual field width of disturbance for conditions where the residue (litter)-soil interface remains largely intact and undisturbed. Selecting an input value for portion of the soil surface disturbed by undercutting involves comparing the surface high organic soil layer left after undercutting with this layer where no disturbance occurs.

The soil receiving area receives mineral soil displaced from the soil source area. The soil receiving area is considered disturbed if the residue (litter)-soil interface is disturbed and

Assigning input values for portion of the soil surface disturbed requires judgment. The effect being represented in RUSLE2 needs to be understood. A set of rules is highly useful to ensure that consistency is achieved in assigning input values among types of soil disturbances.

soil and residue (litter) are mixed. If the displaced soil is sufficiently deep that rill erosion does not penetrate the displaced soil layer, the buried residue (litter) has little direct effect on erosion and the entire receiving area should be considered disturbed. In this case, the portion of the soil surface disturbed includes the soil source area and all of the soil receiving area. A displaced soil depth of ½ inch (12 mm) or more is used as a guide in making this determination. The input value for the portion of the soil surface disturbed is reduced where rill erosion erodes through the displaced soil layer to the underlying intact reside (litter). The residue (litter) reduces erosion only after it becomes exposed.

Ridges are evidence of soil disturbance. Ridge creation requires a soil source area, and the receiving (ridge) area is soil of sufficient depth that erosion is unaffected by the underlying residue (litter). Ridges higher than ½ to 1 inch (12 to 50 mm) are considered to be disturbed areas.

The degree of soil disturbance is highly important considerations in determining the effectiveness of no-till cropping systems for controlling erosion. The two characteristics of these systems most responsible for their high erosion control effectiveness are the continuous presence of surface residue and a surface soil layer of high organic matter content, both of which are reduced by soil disturbance. **Both conditions must be present; high residue cover alone is not sufficient for the full no-till effect.** RUSLE2 uses **portion of the soil surface disturbed** along with the **soil consolidation subfactor** and **soil biomass** in the upper 2-inch (50 mm) soil layer to compute the effect of the upper high organic matter soil layer on erosion (see **Section 9.2.6**).

Portion of the soil surface disturbed by an operation and the **time since the last mechanical disturbance** are key variables. According to RUSLE2, surface residue cover is restored quickly in three years or less for much of the Eastern US after a single major disturbance such as moldboard plowing that buries almost the entire surface residue. About three to five years are required in much of the Eastern US to restore soil biomass in the upper 2-inch layer based on decomposition. This determination can be made by setting the **time to soil consolidation** to 1 year, which eliminates the effect of soil consolidation on the accumulation of soil biomass.

The accumulation of soil biomass in the upper 2-inch (50 mm) layer and the effect of this soil biomass on erosion are functions of the soil consolidation subfactor. Consequently, the total time for the no-till effect to be fully regained after a soil disturbance is about the same as the time entered in the **soil description** for the **time to soil consolidation**. The standard assumption for **time to soil consolidation** is seven years in most of the Eastern

US. RUSLE2 computes that most of the no-till effect is regained in about five years, as Table 13.4 illustrates for no-till 112 bu/ac corn **cover-management description** for Columbia, MO. This RUSLE2 estimate is consistent with the rule of thumb that five years is required for the full effect a no-till cropping system to be realized.

RUSLE2 computes a loss of the no-till effect that is almost as great with undercutting blade, chisel plow, field cultivator, and disk-type implements that disturb 100 percent of the soil as with soil inversion implements like moldboard plows. About one half of the no-till effect is lost directly through changes in the soil consolidation subfactor and the other half is lost through the effect of the soil consolidation subfactor being used as a variable in the soil biomass subfactor (see Figure 7.3 and equation 9.12).

Table 13.4. No-till effect after long term no-till is moldboard plowed in one year

Time (years) in no-till after moldboard year	Annual no-till effect (soil consolidation subfactor·soil biomass subfactor) weighted by erosivity distribution
1	0.61
2	0.49
3	0.39
4	0.32
5	0.28
6	0.25
7	0.24
8	0.23

All operations in a **cover-management description** are important in determining the degree of the no-till (lack of soil disturbance) effect. A single operation, such as a fertilizer/manure injector that disturbs as much as 50 percent of the soil surface causes RUSLE2 to compute a significantly reduced no-till effect (i.e., values closer to 1 for the product of the soil consolidation and soil biomass subfactors means a reduced no-till effect). The no-till effect is 0.54 where an injector that disturbs 50 percent of the surface is used with a planter that disturbs 15 percent of the surface for no-till 112 bu/acre corn at Columbia, MO. The no-till effect is 0.22 if the injector is not used for.

Multiple occurrences of an operation that minimally disturbs the soil surface in a cover-management description reduce the no-till effect. For example, the no-till effect is 0.22, 0.32, and 0.40 for one, two, and three occurrences, respectively, of a no-till planter on the same day in the Columbia, MO no-till corn example. **Section 9.2.6.4** describes the mathematical procedure that RUSLE2 uses where only a portion of the soil surface is disturbed by an operation. The net effect is similar to RUSLE2 assuming that most, but not all, of the soil disturbance is in an undisturbed area. RUSLE2 does not assume that a planter runs in the same place each year. However, the overlap effect was empirically considered by fitting RUSLE2 to no-till field data so that the expected erosion estimate is computed.

The large effect of the portion of the soil surface disturbed on estimated erosion is illustrated in Figure 9.19. This difference is significant when using RUSLE2 to estimate erosion for wide row (e.g., 30-inch width) no-till planters and narrow row no-till drills (e.g., 7-inch width). The no-till effect is 0.22, 0.30, 0.57, and 0.62 for 15, 25, 65, and 85 percent for portion of the soil surface disturbed, respectively, for a no-till 112/bu/acre corn cropping system at Columbia, MO. These values illustrated that a small change in portion of the soil surface disturbed has a greater effect on estimated erosion when little of the soil surface is disturbed in comparison to when most of the soil surface is disturbed. The soil disturbance characteristics for both wide row and narrow row seeding implements should be very carefully considered in assigning values for **portion of the soil surface disturbed**. The tendency is to assign values that are too low for wide row implements and values that are too high for narrow row implements.

The effect of no-till cropping on soil erosion was analyzed in depth during the development of RUSLE2. To achieve maximum benefits from no-till cropping, the portion of the soil surface disturbed must be minimized.

13.1.5.8. Burial and resurfacing ratios

RUSLE2 assumes that an **operation description** with a **disturb soil process** buries **surface residue** and resurfaces **buried residue** as described in **Sections 9.2.5.3.3 - 9.2.5.5**. RUSLE2 only buries surface residue because standing residue must be flattened before it can be buried. Therefore, if an operation is being used to bury **standing residue**, the operation description must include a **flatten standing residue process** followed by a **disturb soil process**. RUSLE2 only resurfaces buried residue; it does not resurface **live** or **dead roots**.

The processes in an operation description must be entered in the proper sequence. To bury standing residue, proper sequence is flatten standing residue and disturb soil. A reverse order of these processes in an operation description will give a very different result.

The residue mass left on the soil surface after a soil disturbing operation is the **net** between the residue that is buried and the residue that is resurfaced. Having both residue burial and resurfacing components allows RUSLE2 to compute an increase in surface residue after an operation in certain conditions. An example is a field cultivator following a tandem disk and a moldboard plow in a high yield corn **cover-management description**.[113]

Input values for burial and flattening ratios are on a **mass basis** rather than on the

[113] RUSLE1 does not include a resurfacing component in its residue equations. Consequently, RUSLE1 can not compute an increase in residue cover following an operation like a field cultivator. RUSLE1 can not duplicate the residue burial values computed by RUSLE2. The residue burial ratio values used in RUSLE2 differ from those used in RUSLE1 because of the resurfacing component in RUSLE2.

portion of the soil surface covered even though RUSLE2 uses portion of soil surface covered to estimate erosion. RUSLE2 displays values for portion of the soil surface covered (e.g., percent cover) that are useful in conservation and erosion control planning.

The best information for selecting input values for burial and resurfacing ratios is the RUSLE2 **core database**. The values in the RUSLE2 core database have been carefully selected based on research data and the validation of RUSLE2 to ensure that it computes good estimates of surface residue cover immediately after planting and that it computes good estimates of average annual erosion.

Values for net residue burial ratio are widely available in the technical literature. Unfortunately, much of this literature fails to specify whether the values are based on residue mass or portion of the soil surface covered by residue. In many cases, a mixture of the two was unknowingly included because original sources failed to describe the basis for the values. Consequently, many of the widely available and accepted burial ratio values are not appropriate for RUSLE2 use.

Residue burial values based on mass are very different from those based on percent cover because of the strong non-linear relationship between residue mass and the portion of the soil surface covered by a given residue mass.

Residue burial ratio values in the technical literature almost always represent net burial (net effect of burial and resurfacing combined) rather than burial alone as required by RUSLE2. Consequently, RUSLE2 residue burial ratio values are higher than the common values in technical literature.

The net residue burial ratio computed by RUSLE2 for an operation depends on the operations and their sequence in the cover-management description and the soil biomass in the operation's disturbance depth. For example, RUSLE2 computes 17 percent for the net burial ratio for a tandem disk for a 150 bu/acre corn cover-management description where the tandem disk follows a moldboard plow. In contrast, RUSLE2 computes 53 percent for the net burial ratio for the same tandem disk following a chisel plow with straight points. This illustrates a reason for variability in field observed residue net burial ratio values.

Residue burial and resurfacing ratio values must be assigned to operation descriptions not in the RUSLE2 core database. Sometimes adjustments to the values in the RUSLE2 core database may be desired. The value RUSLE2 computes for surface residue mass after a soil disturbing operation is very sensitive to the resurfacing ratio value. Unfortunately, very little research data are available for determining values for the resurfacing ratio. **The best approach is to accept the resurfacing ratio values in the RUSLE2 core database without adjustments.** Residue burial ratio values are adjusted until RUSLE2 computes the desired residue cover following a particular operation.

The proper field data required to determine RUSLE2 residue burial and resurfacing ratio values are where as operation has been repeated three or more times in the same area.[114] A value for the resurfacing ratio can not be determined from a single occurrence of an operation. Repeated occurrences of an operation establish the equilibrium surface residue mass as illustrated in Figure 13.3. The first occurrence of the operation can be used to estimate a residue burial ratio value provided soil biomass is insignificantly low in the operation's disturbance depth.

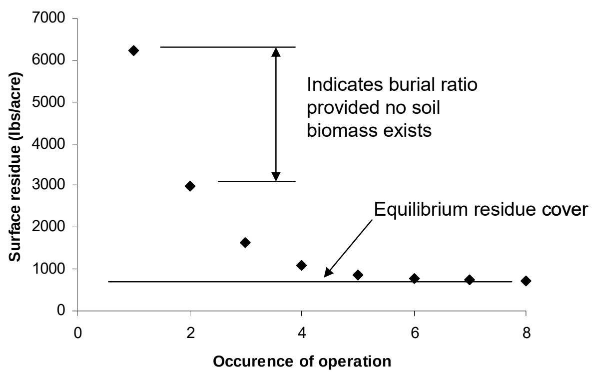

Figure 13.3. Residue burial by repeated occurrences of a field cultivator.

This residue burial ratio value along with the equilibrium surface residue mass can be used to estimate a resurfacing ratio value. The proper procedure for determining values for residue burial and resurfacing ratios is to fit RUSLE2's complete set of residue equations to field data.

Both residue burial and resurfacing ratios are a function of residue type discussed in **Section 12.1**. In general, residue burial ratio values are larger for residue that is in small, fragile pieces that break easily from the forces of a soil disturbing operation. Conversely, resurfacing ratio values are typically larger for residue composed of long, tough pieces. Therefore, size, shape, and fragility (inverse of toughness) all must be considered in selecting both burial and resurfacing ratio values. Rock/gravel is a special case where size and shape is a major factor.

The values in the RUSLE2 core database have been selected to represent the main classes of implements and machines that bury and resurface residue rather than describing specific machines operated in a specific way. The intent with RUSLE2 is to capture main effects within the overall accuracy of RUSLE2. The assigned burial and resurfacing ratio values, regardless of how they were obtained, should be consistent with values in the RUSLE2 core database and with values in the user's working database so that RUSLE2 computes the expected relative effects of the operation on erosion.

[114] Two excellent examples of the type of data needed to determine burial and resurfacing ratio values are: Brown, L.C., R.K. Wood, and J.M. Smith. 1992. Residue management, demonstration, and evaluation. Applied Engineering in Agriculture. 8:333-339.
Wagner, L.E. and R.G. Nelson. 1995. Mass reduction of standing and flat crop residues by selected tillage implements. Transactions of the ASAE. 38:419-427.

The common assumption is that machines can be adjusted to produce almost any desired residue cover. This assumption is often erroneous. RUSLE2 includes relationships discussed in **Section 13.1.5.3** that describe how speed and disturbance depth affect residue burial based on research data. **Input residue burial ratio values outside of the range computed by RUSLE2 on the basis of varying disturbance depth or speed are highly questionable.**

13.1.6. Live biomass removed

The **remove live biomass process** removes live aboveground biomass without **killing** the current vegetation. This process is used in **operation descriptions** used to represent such operations as silage harvest, hay harvest, and mowing permanent vegetation. It's most important use is where a portion, but not all, of the live aboveground biomass is converted to standing and/or surface (flat) residue without killing the current vegetation. Examples include intercropping where one crop is harvested and a second crop continues to grow, volunteer weeds and cover crops that continue to grow after a main crop is harvested, and vegetation that regrows after a mowing or hay harvest. In these cases, some or all of the live root biomass remains, and some or all of the live aboveground biomass remains. The **kill vegetation process** can not be used in **cover-management descriptions** for these vegetation systems because this process converts **all** live aboveground biomass to standing residue and **all** live roots to dead roots, rather than portions of these biomass pools.

RUSLE2 assumes that live aboveground biomass can not be removed without substantially affecting the vegetation. Therefore, RUSLE2 requires that a **begin growth process** or a **kill vegetation process** follow the **remove live biomass process** in an **operation description**. The **begin growth process** identifies the **vegetation description** that RUSLE2 is to use immediately after the operation. If the live root biomass on day zero of the new vegetation description is less than the live root biomass on the last day that the previous vegetation description was used, **the difference is added to the dead root biomass pool because the operation is assumed to have killed a portion, but not all, of the current vegetation.**

Changes in aboveground biomass caused by the operation are described using the input values for the variables that describe the remove live biomass process. These variables are portion of live aboveground biomass **affected** by the operation, portion of the affected biomass left as **surface (flat) residue**, and portion of the affected biomass left as **standing residue**. Although the biomass removed from the local area (field, site) is not important to RUSLE2, this variable is used for user input convenience. RUSLE2 needs a description of the biomass at the site at any particular time to compute erosion. Thus, the biomass left behind either as remaining live biomass and residue after the operation are key variables. The values in the vegetation description identified by the **begin growth process** in the operation description describe the vegetation variables that affect erosion after the operation. Therefore, the remove live biomass process tells RUSLE2 how much residue is left behind for an operation that affects the current vegetation but does not kill it.

Table 13.5 illustrates the input values for three typical operation descriptions where the **remove live aboveground biomass process** is used. The first example is mowing permanent vegetation where the biomass above the cutting height is left as surface residue and the vegetation regrows after the mowing. The amount of live biomass affected is the biomass above the cutting height. The affected biomass is assumed to be 50 percent of the total live aboveground biomass at the time of the mowing. All of the cut (affected) biomass is assumed to become surface residue. Thus, the input for portion of the affected biomass that becomes surface residue is 100 percent. The input is zero for the portion of affected biomass that is left as standing residue because the operation creates no standing residue. A **begin growth process** follows the **remove live biomass process** in the operation description to identify the vegetation description that RUSLE2 uses immediately after mowing. The canopy cover is reduced to reflect the mowing but the live root biomass remains the same between the current vegetation description and the new one.

Table 13.5. Input values for three operation descriptions that use the remove live aboveground biomass process (values on a dry matter basis)

Operation	Live aboveground biomass at time of operation (lbs/ac)	Live aboveground biomass affected (%)		Surface residue left by operation		Standing residue left by operation	
		Portion (%)	Mass (lbs/ac)	Portion (%)	Mass (lbs/ac)	Portion (%)	Mass (lbs/ac)
Mowing permanent vegetation that regrows	3,000	50	1,500	100	1,500	0	0
Legume hay harvest, hay regrows	2,000	95	1,900	5	95	0	0
Harvest small grain in a small grain-legume hay intercropping system	5,000	80	4,000	50	2,000	50	2,000

Note: Values for Portion are user entered input values. Mass values are computed by RUSLE2.

The second example is a legume hay harvest that removes live aboveground biomass and where the legume hay crop regrows after the hay harvest. In this example, 95 percent of the live aboveground biomass on the day of the operation is assumed to be affected. Only a small amount of stubble is left unaffected. The amount of the live aboveground biomass that is affected is 1,900 lbs/acre (= 2,000·95/100). All of the affected biomass is removed from the field except for five percent, which is 95 lbs/acre (= 1,900·5/100), that remains as surface residue. None of the affected biomass is left as standing residue. The surface residue left in the field is from leaf shatter and inefficiencies of the harvesting machines. The operation description includes a **begin growth process** immediately after the **remove live biomass process**. The **begin growth process** identifies the vegetation description that RUSLE2 is to use after the hay harvest. The canopy cover on day zero will be very low because the harvest left nothing but very short stubble. The root biomass does not change between the two vegetation descriptions because the hay harvest has no effect on live root biomass.

The third example is for an intercrop of small grain and legume hay. The small grain is seeded in the fall and the legume hay is seeded in late winter. The small grain is harvested in late spring, which kills that portion of the vegetation. The legume continues to grow after the small grain harvest to be killed by a hay harvest in late summer. The small grain harvest is represented with an operation description that includes a remove live biomass process followed by a **begin growth process**. The total live aboveground biomass at the time of the small grain harvest is 5,000 lbs/acre. Eighty percent (= 5,000·80/100 lbs/acre) of the total live aboveground biomass is affected by the small grain harvest. Half (50 percent) of the affected biomass is left as surface residue, which represents the straw discharged by the combine that harvested the small grain. The other half (50 percent) of the affected biomass is left as standing residue, which represents the standing small grain stubble left by the harvest. The **begin growth process** identifies the vegetation description that applies after the small grain harvest. Both the canopy cover and effective fall height values on day zero in the new vegetation description are reduced slightly from the values on the last day that the previous vegetation description was used. The legume already has a sufficient understory by the time of the small grain harvest that the legume is the major determinant of canopy cover and effective fall height (see **Section 9.2.1**). The live root biomass on day zero in the new vegetation description is significantly reduced from that on the last day for the previous vegetation description, which represents the combined small grain-legume hay vegetation. RUSLE2 assumes this difference to be dead root biomass created by the small grain harvest.

Relative (fractions, percents) rather than absolute variables are used to describe the remove live biomass process. Using an absolute variable like height above which the biomass is removed (e.g., cutting height) could be used for common machine operations like mowing and hay harvest. However, using an absolute height as an input variable also requires user entered values for vegetation height and user entered values or user selected relationships that describe the distribution of the vegetation's biomass within the plant height. The judgment of the RUSLE2 developers was that users could more easily estimate the portion of total plant biomass involved in a remove live aboveground biomass process than users could determine the distribution of biomass within the plant height. Furthermore, relative variables generalize RUSLE2, which gives RUSLE2 additional power and broadens its applicability. For example, RUSLE2 can be used to evaluate operations like hand picking of leaves over the entire canopy, which can not be described using an absolute height approach where all biomass above a given height is affected. Also, this approach gives the user direct control of aboveground biomass values that RUSLE2 uses in its computations.

Unfortunately the relative variable approach means that input values that describe the remove live biomass process are functions of the height above which the biomass is removed, vegetation type, and stage of growth. For example, a particular mower is operated at the same height regardless of the vegetation and its stage of growth. The portion of the biomass affected might be 90 percent for mature, tall weeds but less than 50 percent for early growth weeds and some grasses. Users should develop typical operations that use the remove live biomass process for several vegetation types and conditions.

Values in the RUSLE2 **core database** can be used as a guide for selecting input values for the remove live biomass process. Input values should be checked by making RUSLE2 computations to ensure that the values give expected standing and surface residue amounts. Input values should also be checked for consistency with values in the RUSLE2 core database and values in the user's working database.

Input values for the remove live biomass process are selected considering that the RUSLE2 objective is to describe a field condition rather than to model (simulate) the condition.

13.1.7. Remove residue/cover

The **remove residue/cover process** removes standing and surface (flat) residue. This process is used in **operation descriptions** such as burning and baling straw where a preceding operation description has created standing and/or surface (flat) residue. This process is also used in operation descriptions to represent silage and hay harvests where the current vegetation is live at the time of the operation. A **kill vegetation process** must precede the **remove residue/cover process** in a silage or hay harvest operation description to convert the live aboveground biomass to standing residue and/or surface (flat) residue. **The remove residue/cover process only removes standing and surface (flat) residue**; it does not remove live aboveground biomass. See **Section 13.1.6** for information on how to remove live aboveground biomass.

The three variables used to describe the remove residue cover process are: (1) are all residues affected, (2) portion of surface (flat) residue removed, and (3) portion of standing residue removed.

The first variable is related to how many residue applications on the surface that are to be removed. A **cover-management description** may involve several **residue descriptions** when multiple vegetation descriptions are involved. (e.g., corn, soybean, wheat). Multiple residue descriptions may also be involved when residue is added with the **add other cover process** (see **Section 13.1.8**). Added residues include manure spread on the soil surface and surface applied mulch, such as wheat straw, woodchips, erosion control blankets, and rock.

The input **yes** for the variable **are all residues affected** tells RUSLE2 to remove the same portion of all residues regardless of source, age, or how the residue was placed on the soil surface. An example operation description for this **yes** input is a burning operation that removes some of all residues that are present at the time of the operation.

An example of a **no** input is for a baling straw operation description in a cover-management description for a corn-soybean-wheat crop rotation. The baling straw operation description follows a wheat harvest operation description that kills the wheat to create standing and surface (flat) residue.[115] The **no** input tells RUSLE2 to only remove a portion of the wheat residue, which is the **last** residue description considered by RUSLE2 before the baling straw operation. Residue from previous crops of corn, soybeans, and wheat would not be removed. That is, the **no** input causes only the most recent residue application to be affected.

Inputs for the second and third variables are for the portions of the surface (flat) and standing residue that are removed by the remove residue/cover process. **These variables are on a dry mass basis**. In the baling straw operation description, a zero (0) is entered for the portion of the standing stubble removed because the baling operation has no effect on the standing straw stubble left after the wheat harvest other than to flatten it. If the **flatten standing residue process** occurs in the operation description before the remove residue/cover process, RUSLE2 will remove a portion of the surface (flat) residue created by the **flatten standing residue process** along with the same portion of the other surface (flat) residue.

In the burning operation description, a value of 90 percent is entered for the portion of the standing stubble removed by burning and 25 percent is entered for the portion of the

[115] The processes that describe the wheat harvest and the baling straw operations could be combined into a single operation description provided the harvest and straw baling operations occurred within a few days of each other before residue biomass decreases significantly by decomposition.

surface (flat) residue removed. The reason for the different input values is that the standing residue is assumed to be dry and to burn much more completely than the surface residue that is in contact with soil.

RUSLE2 can remove **buried residue**, but the residue must first be resurfaced with an operation description that includes a **disturb soil process** (see **Section 10.26**). Once the buried residue has been resurfaced as surface (flat) residue, it can be removed with an operation description that includes a remove residue/cover process. Dead roots can not be removed because RUSLE2 has no direct way to remove dead roots and dead roots can not be brought to the surface with a disturb soil process.

Values in the RUSLE2 **core database** can be used to guide the selection of input values for the remove residue/cover process. RUSLE2 computations should be made with the selected input values to ensure that RUSLE2 computes the expected residue cover left by the operation with a remove residue/cover process. Also, input values for the process should be checked for consistency with comparable values in the RUSLE2 core database and the user's working database.

13.1.8. Add other cover

The **add other cover process** is used in **operation descriptions** to place material that affects erosion on the soil surface and in the soil.[116] Typical operations descriptions using this process describe applying mulch on construction sites and in strawberry fields and manure and organic municipal and industrial waste (e.g., papermill waste) to crop and other lands.

The **add other cover process** involves three variables. Two variables are the description of the material added and the amount (dry mass basis) of the material added. These inputs are entered in the **cover-management description** that contains the operation description that uses the add other cover process (see **Section 10.6**). The entry for the type of material added, referred to as **external residue**, is selected from the list of **residue descriptions** in the **residue component** in the RUSLE2 database (see **Section 12**). The material added by this process has sufficient size to reduce the erosive forces of raindrop impact and runoff. Also, the material is generally assumed to be organic (biomass) that decomposes and affects erosion similarly to the decomposition of crop residue and plant litter. The procedure for handling non-organic material such as rock and synthetic erosion control blankets applied to the soil surface to control erosion is described in **Section 12.4**.

The third input, which describes the **add other cover process** itself, is the portion (dry

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[116] This process is **not** used to add irrigation water (e.g., see **Sections 6.3.4, 10.2.4**). Also, this process is **not** used to represent the addition of chemical compounds that affect soil erodibility. That effect must be represented by adjusting soil erodibility factor values (see **Section 7.3**)

mass basis) of the material that is added to the soil surface. RUSLE2 places the remainder of the added material in the soil. A 100 percent value is used to represent applying straw mulch at a construction site, for example, where none of the material is incorporated into the soil. A value less than 100 percent instructs RUSLE2 to place some of the material in the soil. A zero (0) value places all of the added material in the soil.

If the **add other cover process** places some of the added material within the soil, a companion **disturb soil process** must immediately follow the **add other cover process** in the operation description. RUSLE2 assumes that the soil must be disturbed for material to be placed in the soil, which resets the soil consolidation subfactor to 1 for the portion of the soil surface disturbed except when a **compression tillage type** is assumed.[117] Material placed in the soil using the **add other cover process** is placed in the lower one half of the disturbance depth as illustrated in Figure 9.16. The value for disturbance depth is entered in the **disturb soil process** that follows the **add other cover process** in the operation description.

13.1.9. Add non-erodible cover

RUSLE2 describes the effect of both erodible cover and non-erodible cover. **Erodible cover** is surface cover provided by residue and live ground cover. Residue includes material left by vegetation growth, applied mulch, erosion control blankets, and rock. These materials are referred to as erodible covers because RUSLE2 computes erosion even when these materials completely cover (100 percent cover) the soil surface.

> **The *add non-erodible cover process* can not be used to represent the application of erosion control blankets and similar materials. That effect is represented using the *add other cover process*.**

In contrast, RUSLE2 computes no erosion for **non-erodible cover** for the portion of the soil surface covered by these materials. Consequently, RUSLE2 computes no erosion when these materials completely cover the soil surface. Examples of non-erodible cover include plastic sheeting used in vegetable production, a water depth produced by flooding rice fields, and deep snow.

RUSLE2 assumes a linear relationship between erosion and non-erodible cover, in contrast to the non-linear relationship illustrated in Figure 9.4 for surface residue. Therefore, erosion varies linearly with non-erodible cover as it disappears over time.

[117] An exception is that a **compression tillage type** can be selected in the **disturb soil process** to place material in the soil without resetting the soil consolidation subfactor value to 1. However, this tillage type is specifically meant to describe the effects of animal traffic, sheep's foot soil compaction machines, and similar operations and not meant to describe injection of manure and fertilizer by typical machines used in these operations.

A non-erodible cover is also used to “shut off” RUSLE2’s erosion computations for certain periods. An example is turning off erosion computations during winter periods during frozen soils and/or snow cover. Another example is turning off erosion computations for periods when the RUSLE2 annual computational period does not correspond with the erosion control planning period. Some erosion control regulations for constructions sites require a certain level of erosion control between the date of final grading and the date that vegetation reaches a particular canopy cover. The assumption is that erosion control is adequate once the vegetation reaches a certain canopy cover. Thus, erosion computations are turned off for dates beyond the end date based on canopy cover.

13.1.9.1. Applications of add non-erodible cover process

The **add non-erodible cover process** is used in **operation descriptions** to cause RUSLE2 to compute no (zero) erosion for the portion of the soil surface covered by the non-erodible cover. Example applications include applying strips of plastic mulch in vegetable production, applying ponded water in rice production, representing no erosion during snow cover, and setting computed erosion to zero for computational purposes.[118] An operation description with a **remove non-erodible process** is used to remove non-erodible cover when the period of no erosion ends.

An example of using the **add non-erodible cover process** for computational purposes is a construction site where the overland flow path changes during construction and reclamation. The first analysis period represents the exposed hillslope from clearing and scalping until the topography is reshaped. The second analysis period represents the time after the hillslope is reshaped and erosion control practices are applied before permanent vegetation becomes established. The third analysis period is for mature, fully established vegetation.

Reshaping the hillslope creates a new overland flow path, which requires multiple sets of RUSLE2 computations because RUSLE2 can not change overland flow paths during a **cover-management description**. In this example, a cover-management description is created for each analysis period, and a RUSLE2 computation is made for each overland flow path using the corresponding **soil**, **cover-management**, and **support practice descriptions**. Table 13.6 outlines the three RUSLE2 computations for this example.

The date that RUSLE2 starts its computations must be set first. RUSLE2 operates and accounts for erosion on an annual basis. In this example, the 9/1/0 start date is set one year before the day that the hillslope is reshaped that creates a new overland flow path. The date that the hillslope is reshaped is the reference date in this example. **Section**

[118] This procedure is used in RUSLE2 to set erosion to zero. The comparable procedure used in RUSLE1 to set erosion to zero was to enter a 100 percent canopy cover at a zero fall height. This RUSLE1 technique can not be used in RUSLE2 (see **Section 9.2.1**).

10.2.1.3 describes procedures that can be used to cause RUSLE2 to start tracking time on a particular date.

The first RUSLE2 computation must end on the day before the new overland flow path is created. The erosion that RUSLE2 computes between 9/1/0 and 4/15/1 must be excluded from RUSLE2's accounting of erosion. This erosion is excluded by using an operation description that adds non-erodible cover on 9/1/0 and an operation description that removes the non-erodible cover on 4/15/1. The non-erodible cover causes RUSLE2 to set erosion to zero during this preliminary period. This approach starts RUSLE2's erosion accounting on 4/15/1 with the clearing and scalping of the hillslope.

Table 13.6. RUSLE2 computations for a construction site example where the overland flow path changes during construction and reclamation

RUSLE2 computation	Date	Event	Overland flow path	Cover-management description	Soil descriptio n
1	9/1/0	RUSLE2 starts tracking time	Natural topography	Non-erodible cover	Natural soil profile
	4/15/1	Cleared and scalped		Bare soil, freshly disturbed	
2	9/1/1	Reshaped, temporary erosion control, permanent vegetation seeded	Reshaped topography	Graded, temporary erosion control applied, permanent vegetation seeded	Highly disturbed
3	9/1/4	Permanent vegetation becomes established		Mature vegetation conditions	

Notes:

1. The first date is set so that RUSLE2's annual erosion accounting for the first period ends on the last day before the topography is reshaped that creates a new overland flow path.
2. NRCS soil survey data applies to the natural topography. Soil conditions after reshaping are highly disturbed, which requires use of the RUSLE2 modified soil erodibility nomograph.
3. Cover-management conditions after reshaping could be described with a single cover-management description rather than two as illustrated.

The second analysis period begins on the date (9/1/1) that the hillslope is reshaped and a new overland flow path is established. The third analysis period begins when the vegetation has become mature and fully established (see **Section 11.2.6**). The last two analysis periods can also be combined into a single period using a single cover-management description.

An alternative approach is to start RUSLE2's tracking time on the clearing and scalping date (4/15/1). However, because of RUSLE2's annual accounting, it will include erosion computed from 4/15/1 through 4/14/2 using the first overland flow path. The computed erosion from 9/1/1 through 4/14/2 must be excluded in RUSLE2's erosion accounting to obtain an erosion estimate for just the 4/15 to 9/1 period. This erosion can be excluded by using an operation description that adds non-erodible cover on 9/1/1.

The accounting date in RUSLE2 computations for the second analysis period can start on 9/1 by having the first date in the cover-management description be on 9/1 or it can start on 4/15 if an erosion estimate is needed for each year starting on 4/15. To start RUSLE2's accounting on 4/15/1 for the second analysis period, use an operation description that adds non-erodible cover on 4/15/1 and an operation description that removes the non-erodible cover on 9/1/1. RUSLE2 will set erosion to zero during this period when non-erodible cover is present. The estimated erosion for the period 4/15/1 to 4/14/2 can be obtained by adding the annual erosion from these two RUSLE2 computations.

13.1.9.2. Variables used to describe add non-erodible process

The variables used to describe the **add non-erodible cover process** are the portion of the soil surface covered by the non-erodible cover, half-life of the cover, and permeability of the cover. The value entered for the **portion of the soil surface covered** is the portion of the total area having zero erosion because of the non-erodible cover. This value is 100 percent for applying ponded water on rice fields or for the computational purpose described above where erosion is to set to zero for the entire area. Erosion is set to zero on the entire area. The value is less than 100 percent when strips of plastic are applied in a vegetable field resulting erosion being set to zero for only a portion of the total area.

Half-life is the time required for half of the non-erodible cover to disappear based on a simple exponential relationship involving time. RUSLE2 does not compute the loss of non-erodible material as a function of environmental conditions as it does for residue. The value entered for half-life must represent how local site conditions, such as ultraviolet radiation, temperature, or precipitation, affect loss of the non-erodible cover. Thus, input values for half-life for non-erodible cover can vary with location.

The loss of non-erodible cover is computed solely on an area basis, although mass per unit should be considered in assigning half-life input values. RUSLE2 does not use a mass-cover relationship for non-erodible cover like it does in residue descriptions.

A very large value, such as 1,000,000 days is input for half-life where non-erodible cover does not disappear over time. Refer to manufacture's literature for selecting input values for plastic and similar products. A half-life value can be used to approximate the loss of snow cover, but using RUSLE2 to compute erosion by snowmelt is questionable (see **Sections 6.9.1 and 6.11**). Selected input half-life values should be checked by making RUSLE2 computations to ensure that RUSLE2 computes the expected non-erodible cover over time for the conditions where RUSLE2 will be applied.

Although RUSLE2 computes no erosion for the portion of the soil surface covered by the non-erodible cover, RUSLE2 needs information on how non-erodible cover affects runoff. Deposition computed by RUSLE2 on concave-shaped overland flow paths, behind dense strips of vegetation, and in terrace channels is a function of runoff. If non-erodible cover significantly increases runoff, the computed deposition amount may be significantly reduced. RUSLE2 uses the value entered for non-erodible cover permeability and portion of the soil surface covered by the non-erodible cover to compute runoff.

The input value entered for **non-erodible cover permeability** is the portion of the precipitation that passes through the cover. Many non-erodible covers, such as plastic used in vegetable production and ponded water in rice fields, are impermeable. A value of zero (0) is entered for those materials. If all of the precipitation passes through the cover, 100 percent is entered. An input value less than 100 percent is entered when some but not all of the precipitation passes through the non-erodible cover. For example, 50 percent is entered if half of the precipitation passes through the non-erodible cover and the other half runs off the cover onto the soil surface.

Non-erodible cover such as plastic on the top of beds in vegetable fields completely eliminates both interrill and rill erosion. However, significant rill erosion can occur where runoff accumulates and flows onto the portion of the soil surface not covered. Also, runoff can accumulate under non-erodible cover to cause erosion. Therefore, the presence of non-erodible is not sufficient *alone* to completely eliminate erosion in all situations.

13.1.10. Remove non-erodible cover

The **remove non-erodible cover process** is used in **operation descriptions** to remove part or all existing non-erodible cover. The single variable used to describe this process is the portion of the non-erodible cover that is removed by the process. An input value of 100 percent completely removes non-erodible cover. An input value less than 100 percent removes that portion of the non-erodible cover. For example, assume that non-erodible cover is 62 percent and 50 percent is the input value for portion removed. The non-erodible cover after the removal operation will be $62\% \cdot 50\%/100 = 31\%$. The non-erodible cover may have covered 100 percent of the soil surface when it was initially applied, but it only covers 62 percent of the soil surface on the removal date because of loss by ultraviolet radiation or other processes.

14. SUPPORT PRACTICES DATABASE COMPONENTS

Support practices include contouring (ridges around the hillslope), filter and buffer strips (strips of dense vegetation on the contour), rotational strip cropping (a system of equal width cropping strips that are annually rotated with position along the overland flow path), terraces and diversions (ridges and channels that divide the overland flow path, collect runoff, and redirect it around the hillslope), and small impoundments (impoundment terraces and sediment traps). These practices are referred to as support practices because they are used to support primary cultural erosion control practices based on vegetation, crop residue, plant litter, and applied mulch. The effect of cultural erosion practices on erosion is described with the cover-management variables (see **Section 10**). Most support practices affect rill and interrill erosion and sediment delivery by reducing runoff's erosivity and transport capacity by redirecting the runoff around the hillslope; dividing the overland flow path that reduces the accumulation of runoff; slowing the runoff with strips of rough soil surface, heavy surface residue, or dense vegetation; and capturing and ponding runoff.

RUSLE2 computes how support practices affect **interrill** and **rill erosion** and **sediment yield** at the end of the flow path represented in a RUSLE2 computation (see **Sections 5.1, 5.3.1, 8.2.5**). Most properly designed, installed, and maintained support practices also reduce ephemeral gully erosion. However, RUSLE2 is not a conservation or erosion control planning tool for ephemeral gully erosion because RUSLE2 does not estimate ephemeral gully erosion.[119] RUSLE2 gives partial, indirect credit for reduction of ephemeral gully erosion by contouring and rotational strip cropping. Some of the data used to empirically derive RUSLE2's contouring relationships were measured on small watersheds, less than about 5 ac in size, where ephemeral gully erosion occurred on the non-contoured experimental watershed.

The benefits of support practices for controlling ephemeral gully can only be considered using a procedure other than RUSLE2.

Each support practice affects erosion and sediment delivery in a unique way. Therefore, each major support practice is discussed individually.

14.1. Contouring (ridge orientation relative to overland flow path)

14.1.1. Description of practice

[119] Conservation planners sometimes assume that the USLE and RUSLE1 describe all erosion that occurs within farm fields, which is not the case with these prediction technologies or with RUSLE2. Ephemeral gully erosion is not estimated with any of these technologies and can amount to one half or more of the total sediment production that occurs within field sized areas.

Contouring is the creation of ridges and furrows by tillage equipment, earth moving machines, and other soil disturbing operations to redirect runoff from a path directly downslope to a path around the hillslope.[120] Grade along the furrows is zero when contouring is “perfectly on the contour,” which results in runoff spilling uniformly over the ridges along their length. If furrow grade is not level, runoff flows along the furrows until it reaches low ridge heights or local low areas on the hillslope. The runoff break over ridges in these locations as illustrated in Figure 8.13.

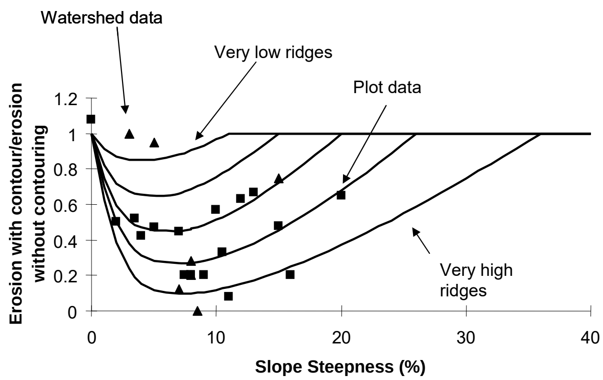

Figure 14.1. Experimental data on how contouring affects erosion.

Section 8.3.6 describes the three RUSLE2 methods that can be used to estimate how contouring affect erosion. The first two methods apply where the ridges are so high, well defined, and on a sufficiently uniform grade that runoff flows to major concentrated flow areas on a hillslope before overtopping the ridges. Application of these two methods is based on a detailed overland flow path description. The **third method** is for typical ridges left in farm fields by tillage equipment like tandem disks, chisel plows, and field cultivators and on reclaimed mined land and other highly disturbed lands by ridgers. This method uses the RUSLE2 relationships that describe contouring (ridging) as a support practice and a overland flow path description based on a flat soil surface.

14.1.2. Basic principles

RUSLE2 uses a daily value for the contouring factor p_c in equation 8.1 to compute the effect of contouring. This subfactor is the ratio of erosion with contouring to erosion without contouring. A value of 1 means that contouring has no effect on erosion. The value for the contouring subfactor is lowest when contouring has its greatest effect on erosion.

The effect of contouring on erosion that was measured on research plots and watersheds is illustrated in Figure 14.1. The effect of contouring varied greatly among the studies.

[120] Contouring in RUSLE2 refers to how orientation of ridges with respect to the overland flow path affects erosion. Standards for erosion control practices published by organizations like the USDA-Natural Resources Conservation Service require that ridging meet certain specifications to be considered the specific erosion control practice of contouring.

For example, contouring reduced erosion as much as 90 percent in one study but did not reduce erosion in another study also conducted on a 6 percent slope steepness.

Information from the research studies represented in Figure 14.1 and from other research studies was not sufficient to empirically derive RUSLE2 contouring relationships. The data were sufficient, however, to identify the main variables that determine how contouring affects erosion. That basic information, along with accepted erosion scientific knowledge and scientific and technical judgment were used to develop the mathematical relationships used in RUSLE2 to compute how contouring affects rill and interrill erosion.

14.1.2.1. Steepness

The first variable considered in developing the equations used to describe the contouring effect illustrated in Figure 14.1 was slope steepness. Contouring does not affect erosion at a flat slope because no preferred runoff path exists. Contouring also has no effect at very steep slopes because the ridge top is at a lower elevation than the ridge base (furrow) on the upper side of the ridge as illustrated in Figure 14.2. The ridge top elevation relative to the elevation of the upslope furrow is a function of both slope steepness and ridge height, which determine the slope steepness that contouring loses its effectiveness.

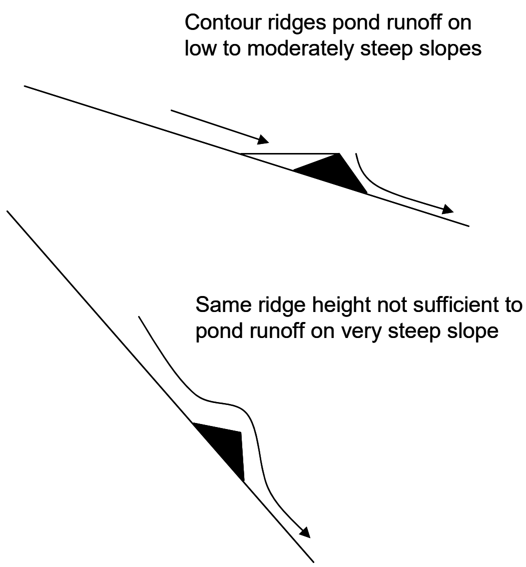

Figure 14.2.Effect of slope steepness and ridge height on contour ridges ponding runoff.

The general shape of the RUSLE2 relationship for contouring's effect on erosion is illustrated in Figure 14.1. The curve decreases from a value of 1, which means that contouring has no effect on erosion, for a flat slope (zero steepness) to a minimum value at a moderate slope steepness, which is the slope steepness that contouring has its greatest reduction on erosion. The curve increases from the minimum value to 1 (no effect) at a steep slope based on the concept that the steepness is so great that no runoff is ponded as illustrated in Figure 14.2 (see AH537, AH703).[121]

14.1.2.2. Ridge height

[121] The relative effect of slope steepness on contouring in RUSLE2 is the same as that in the USLE. The middle curve in Figure 14.1 is very similar to the contouring-slope steepness effect in the USLE (AH537).

The second variable considered was ridge height. The basic concept is that contouring's effect on runoff and erosion is a function of ridge height. Figure 14.2 illustrates the concept for steep slopes. Field data from research plots also showed that erosion decreased as ridge height increased. The ridges on these plots were perfectly on the contour on a moderate slope steepness. The overall variability illustrated in Figure 14.1 for the effect of contouring on erosion was interpreted as being caused by a variation in ridge height.

Contouring is assumed to lose its effectiveness over time as ridge height decays. In RUSLE2, ridge height decays after it is created because water from precipitation causes the soil to subside and as interrill erosion erodes the ridges (see **Section 9.2.4.3**).

Experimental data involving wheat and soybeans showed that closely spaced stems in rows on the contour affect erosion much like soil ridges on the contour. Therefore, RUSLE2 adds an effective vegetative ridge height to the soil ridge height to give an overall ridge height that is used by RUSLE2 to compute the effect of contouring on erosion. The effective vegetative ridge height increases as vegetative retardance increases, which is a function of the retardance class assigned in the vegetation description (see **Section 11.1.4**), yield (production) level, and growth stage.

14.1.2.3. Storm severity and runoff

Experimental plot data showed that contouring's effectiveness (p_c) is greater for small storms than for large storms (i.e., p_c values are less for small storms than for large storms). One reason for this difference in effectiveness is that a higher percentage of the excess rainfall (rainfall in excess of infiltration) is stored in ponded runoff behind the ridges for small storms than for large storms. Similarly, contouring reduces erosion more for low runoff amounts than for high runoff amounts. Therefore, RUSLE2 computes values for the contouring subfactor p_c that decrease as runoff depth decreases.

The minimum contouring factor value at the low point of each curve illustrated in Figure 14.1 is reduced linearly with runoff depth. Also, the slope steepness above which contouring has no effect on erosion is computed as a function of runoff depth raised to the 0.857 power. This power is based on the assumption that the maximum slope steepness at which contouring is effective for a given ridge height is a function of the shear stress that the runoff applies to the soil. The runoff variable used by RUSLE2 to compute contouring subfactor values is the ratio of runoff computed for the site specific condition to runoff computed for the base condition of a moldboard plowed, clean tilled, low yielding corn grown on a silt loam soil in Columbia, MO (see **Section 8.1.2**).

Field data from contouring on small watersheds (less than five acres) in the south central US showed that the effectiveness of contouring is related to storm severity. The data showed that erosion with contouring can be greater for very intense storms than for a comparable non-contoured situation. The intense storms caused much ridge breakovers, concentration of overland flow in a few rills which causes increased rill erosion, and a cascading effect similar to dam failures releasing water. These effects partially accounts for contouring subfactor values being greater than 1 in Figure 14.1. Also, moderate and large storms cause most of the erosion. The 24-hour precipitation amount with a 10-year return period rather than a precipitation amount based on an average annual return period is used in RUSLE2 to compute runoff depth. The 10-year return period captures how a more severe than average annual storm has a dominant effect on how much contouring reduces erosion.

The RUSLE2 computed contouring subfactor values vary daily as cover-management conditions change. The runoff curve number is a key variable in the NRCS runoff curve number method. RUSLE2 computes values for the curve number as a function of surface roughness, ground cover, soil biomass, and soil consolidation, which in turn means that runoff and contouring subfactor values vary daily in RUSLE2.

14.1.2.4. Relative row grade (ridge-furrow orientation relative to overland flow path)

In this RUSLE2 procedure for computing how contouring affects erosion, the overland flow path is determined assuming a flat soil surface without ridges. The contouring subfactor p_c value is 1 by definition for a ridge-furrow orientation directly **up and down hill** (parallel to the overland flow path). Contouring subfactor values are less than 1 when the ridge-furrow orientation is **perfectly on the contour** (perpendicular to the overland flow path).[122] **Relative row grade**, which is the ratio of absolute row (furrow) grade to the overland flow path steepness, is RUSLE2's measure of ridge-furrow orientation to the overland flow path.[123] A relative row grade of 1 means that the ridge-furrow orientation is up and down hill parallel to the overland flow path, and a relative row grade of zero (0) means that the ridge-furrow orientation is perfectly on the contour and perpendicular to the overland flow path. A 0.1 relative row grade means that the ridge-furrow orientation is slightly off contour, and a 0.5 relative row grade means that the ridge-furrow orientation is half way between being perfectly on the contour and up and down hill.

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[122] The **cover-management description** must include a **soil disturbing operation description** that creates ridges with a greater than zero height for RUSLE2 to compute a contouring subfactor value less than 1. That is, ridges with a height greater than zero must be present for RUSLE2 to compute a contouring effect.
[123] Even though absolute row grade can be entered into RUSLE2, RUSLE2 uses relative row grade to compute how ridge-furrow orientation to the overland flow path affects erosion.

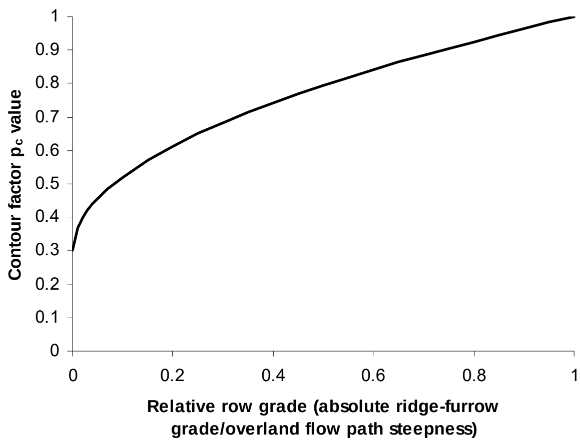

Figure 14.3. Effect of relative row grade on the contouring subfactor p_c.

RUSLE uses the empirical relationship illustrated in Figure 14.3 to compute contouring subfactor p_c values for ridge-furrow orientations between these two extremes. The assumption implicit in Figure 14.3 is that contouring rapidly loses effectiveness as ridge-furrow orientation deviates from being perfectly on the contour (i.e., as relative row grade increases from zero). This assumption is supported by the limited research data available for validation.

14.1.2.5. Contouring failure (critical slope length)

Contouring fails and totally loses its effectiveness when the combination of runoff rate and steepness along the overland flow path becomes too great for the given cover-management condition. The high contouring subfactor values in Figure 14.1 represent such failure based on the description of the field conditions in the research report. On simple uniform overland flow paths where soil, steepness, and cover-management do not vary spatially, a **critical slope length** is defined as the location along the path where contouring fails from that location through the end of the overland flow path. The contouring subfactor value for the upper portion of the overland flow path from its origin to the critical slope length location is the RUSLE2 computed values for contouring (i.e., contouring is fully effective). The contouring factor value is set to 1 for the portion of the overland flow path from the critical slope length location to the end of the path (i.e., contouring has completely failed). The contouring subfactor makes a step increase, rather than a gradual increase, at the critical slope length location as illustrated in Figure 14.4. Contouring subfactor values do not vary with distance along the overland flow path because RUSLE2 contouring subfactor values are based on runoff depth, not runoff rate.

RUSLE2 does not compute contouring failure and a critical slope length if the overland flow path length is sufficiently short. ***Also, contouring failure and critical slope length are not a function of ridge height or soil erodibility properties.***

RUSLE2 assumes contouring failure when the runoff applies a shear stress to the soil in the ridges that exceeds a critical shear stress related to ridge stability.[124] The shear stress

[124] Shear stress applied to the soil is a frictional type force per unit area much like the frictional force felt

applied to the soil by runoff **increases** as runoff rate and steepness of the overland flow path increase and **decreases** as total hydraulic roughness provided by cover-management increases.[125] Runoff rate is a function of both runoff depth and location along the overland flow path (see **Section 8.1.2**). Shear stress applied to the soil decreases as cover-management intensity increases because of the effect of cover-management on both runoff depth (hence, runoff rate) and the total hydraulic roughness (see **Section 14.2.3**).[126] Contouring failure increases and critical slope length decreases for a given cover-management condition as steepness of the overland flow path increases. Contouring failure increases with a change in location where storm erosivity represented by the 10-year, 24 hour precipitation amount increases. Conversely, contouring failure is reduced by increased soil surface cover, soil-surface roughness, and vegetation retardance and cover-management practices that reduce runoff, all of which reduce runoff's shear stress that causes contouring failure. Contouring failure on long overland flow paths is reduced by changing cover-management conditions that reduce runoff's shear stress and/or by dividing the overland flow path with terraces/diversions.

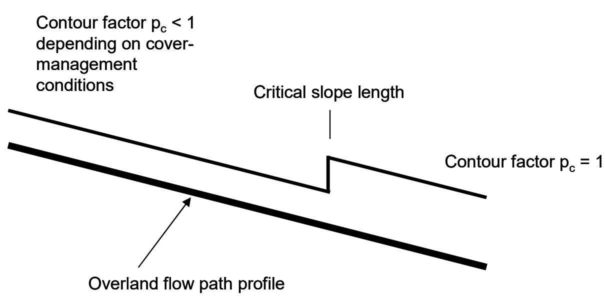

Figure 14.4. Illustration of critical slope length and contouring subfactor values for a uniform overland flow path.

Depending on conditions, RUSLE2 computes zones of contour failure along complex overland flow paths, like that illustrated in Figure14.5. Contouring failed in the mid-portion of the overland flow path because of the combination of runoff rate (represented by distance from the path origin) and steepness. Runoff's shear stress acting on the soil exceeds the soil's critical shear stress in this zone. Contouring does not fail on the upper portion of the overland flow path. The combination of runoff rate and steepness is low because distance is short even though steepness becomes large. Contouring failure ends on the lower portion of the overland flow path because the combination of runoff rate and steepness decrease so that the runoff's shear stress acting on the soil decreases below the soil's critical shear stress even though distance is large.

when your hand is rubbed by sandpaper.

[125] Total hydraulic roughness is composed of two parts, the part related to the shear stress that the flow exerts on the soil particles (referred in channel hydraulics as grain roughness) that causes erosion and sediment transport and the part related to the shear stress applied to hydraulic elements (referred to as form roughness) including soil surface roughness (e.g., clods), ground cover (e.g., surface residue and live ground cover), and plant stems.

[126] An increase in cover-management intensity refers to an overall increase in soil surface roughness, surface residue cover, aboveground biomass, soil biomass, vegetative retardance, and soil consolidation.

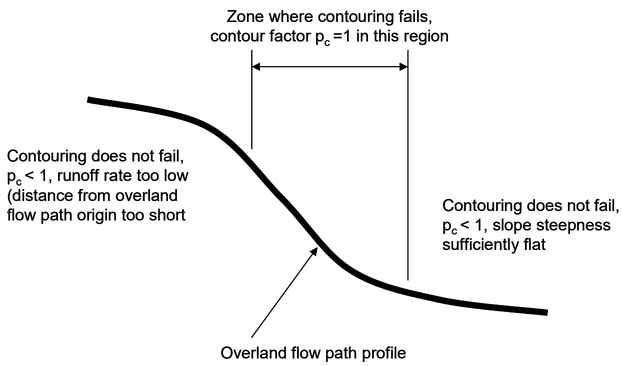

Figure 14.5. Zone on a complex shaped overland flow path where contouring fails because the combination of distance and steepness.

Figure 14.6 illustrates how RUSLE2 handles an overland flow path with an intense cover-management strip upslope from the end of the overland flow path. Several zones are identified in Figure 14.6. Contouring does not fail and the contouring subfactor value is less than 1 in Zone 1 because the combination of runoff rate (represented by distance from the path origin) and steepness is not sufficient for runoff's shear stress applied to the soil to exceed the soil's critical shear stress for the given cover-management condition. The applied shear stress equals the critical shear stress at the boundary between Zones 1 and 2 and exceeds the critical shear stress in Zone 2. Contouring fails and the contouring subfactor value equals 1 in Zone 2. The intense cover-management in Zone 3 greatly reduces the runoff's shear stress applied to the soil to less than the soil's critical shear stress. Contouring does not fail and contouring subfactor values are less than 1 in Zone 3.

Zone 4 is a special situation. The cover-management condition in Zone 4 is the same as in Zones 1, 2, and 5. Because contouring failed in Zone 2, the expectation is that contouring also fails in Zone 4 based on runoff rate, steepness, and cover-management condition. However, the difference is that the intense cover-management strip in Zone 3 is assumed to spread the runoff so that it leaves the strip in a very thin flow. The flow's shear stress applied to the soil is less than soil's critical shear stress in Zone 4. RUSLE2 assumes that the shear stress applied to the soil at the upper end of Zone 4 equals the shear stress applied to the soil at the lower end of Zone 3. The runoff's shear stress increases over Zone 4 and becomes equal to the soil's critical shear stress at the boundary between Zones 4 and 5. Contouring does not fail and the contouring subfactor value is less than 1 in Zone 4.

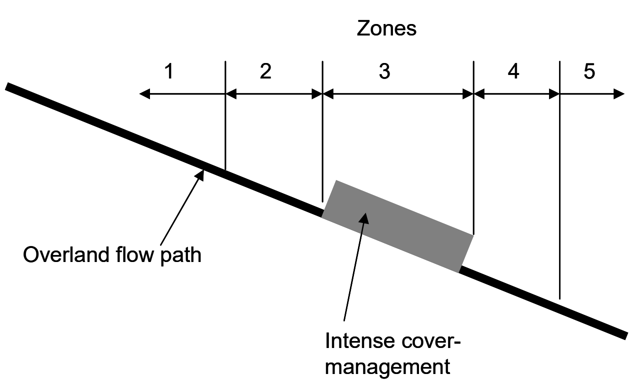

Figure 14.6. Zones along an overland flow part with an intense cover-management strip.

Runoff leaves the intense cover-management strip spread in a thin flow across the slope. The runoff becomes concentrated again in rill flow with distance in Zone 4.

This flow concentration increases the shear stress that the runoff applies to the soil and equals the soil's critical shear stress at the boundary between Zones 4 and 5. Contouring fails in Zone 5 because the runoff's shear stress applied to the soil exceeds the soil's critical shear stress and the contouring subfactor value equals 1 in Zone 5.[127]

14.1.2.6. Temporal changes in contouring subfactor values and contouring failure

RUSLE2 computes a daily value for the contouring subfactor p_c. The value changes daily because the soil ridge height decays daily and the effective vegetation ridge height changes as vegetative retardance changes daily. Cover-management conditions change daily to influence runoff depth that RUSLE2 uses to compute daily contouring subfactor p_c values. The daily contouring subfactor p_c value also changes on days that soil disturbing operations occur that creates ridges with a new height.

Runoff rate and shear stress applied to the soil by runoff change daily as cover-management conditions change. Runoff rate also changes as daily erosivity changes, which captures the likelihood of an intense storm occurring when the cover-management condition is vulnerable to contouring failure. The daily erosive precipitation amount used to compute runoff rate is the product of the 10 year, 24 hour precipitation amount and the ratio of daily erosivity to the maximum daily erosivity.[128]

This effect of combining a vulnerable cover-management condition for contouring failure with the likelihood of an intense storm is illustrated in Figure 14.7 for a conventionally tilled corn **cover-management description** at Lincoln, NE. This example is for a uniform overland flow path where the contouring fails beyond the critical slope length on the lower portion of the overland flow path. The most vulnerable period to contouring failure is from the first secondary tillage operation (tandem disk) on May 1 until harvest on October 15 because the soil surface is smooth with very little surface residue and the vegetation provides little retardance, even at maturity.

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[127] Equation 8.1 is used to compute detachment in each zone in Figure 14.6. The contouring subfactor p_c value for Zone 4 is computed based on runoff depth, steepness, cover-management condition, and relative row grade assuming no contouring failure. Even though runoff is spread in a thin sheet flow that has reduced erosivity, the values of no other factor are changed in equation 8.1 because the intense cover-management strip spreads runoff. That is, the only erosion reduction computed by RUSLE2 for Zone 4 is from the contouring subfactor value being less than 1 for Zone 4 because the intense cover-management strip spreads the runoff. The contouring subfactor value would equal 1 because of contouring failure if the intense cover-management was not on Zone 3.

[128] The daily erosive precipitation amount used to compute runoff rate is not the same as the daily precipitation amount determined by disaggreagtion of the monthly precipitation amounts in a location's **climate description**.

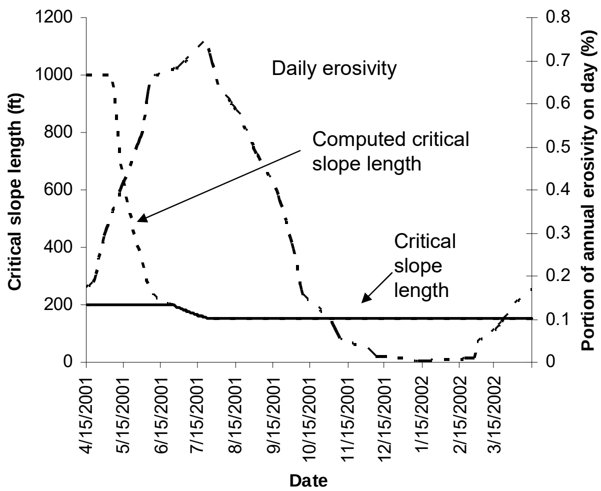

Figure 14.7. Daily critical slope length.

The critical slope length shown in Figure 14.7 is 200 ft, which is the overland flow path length, from April 15 to June 25.[129] A RUSLE2 displayed critical slope length that equals the overland flow path length means that the computed critical slope length is longer than the overland flow path length. A computed critical slope length longer than the overland path length has no consequence because contouring does not fail within the actual overland flow path length. The RUSLE2 computed critical slope length starts at 1000 ft, which is the longest overland flow path that RUSLE2 considers. The computed critical slope length becomes less than 1000 ft on May 7 and steadily decreases to 200 ft on June 25. The reason for the decrease is the increase in the daily erosive precipitation amount used to compute shear stress, which is indicated by the increase in the daily erosivity to July 22 in Figure 14.7. The vulnerability of the cover-management condition to contouring failure in this example does not change significantly during this period. However, in other cases, vulnerability to contouring failure can increase significantly over time as roughness and surface residue decay.

After June 25, the computed critical slope length decreases to a value less than 200 ft, which means that RUSLE2 has computed contouring failure and has set the contouring subfactor p_c value to 1 on the lower portion of the overland flow path. The critical slope length ultimately decreases to a minimum of 154 ft on July 22, the date of peak erosivity. Even though the site condition was slightly more vulnerable to contouring failure earlier, the shortest critical slope length did not occur until later when the combination of cover-management vulnerability and daily erosive precipitation was maximal.

The potential for contouring failure decreased significantly after July 22 because the daily erosivity decreased as illustrated in Figure 14.7. However, the critical slope length did not increase. Similarly, harvest on October 15 added a very heavy surface residue cover that greatly reduced the vulnerability for contouring failure, but the critical slope length did not increase at harvest. Once contouring fails, contouring effectiveness is not

[129] The actual critical slope length before June 25 is longer than 200 ft, but RUSLE2 does not display critical slope length value longer than the overland flow path length. The computed critical slope length can be seen by entering 1000 ft for the overland flow path length, which is the longest value that can be entered in RUSLE2.

restored until the next **operation description** that includes a **disturb soil process** to create new ridges. In RUSLE2, contouring failure is assumed to occur by runoff breaking through ridges; consequently ridges must be recreated to restore contouring effectiveness. Critical slope length is reset when new ridges are created. See **Section 14.1.2.5** for discussion on the importance of critical slope length in conservation planning.

In this example, the first soil disturbing operation after the critical slope length reached its minimum on July 22 is a moldboard plowing operation on April 15. This operation resets computed critical slope length, which is the reason for the increase in critical slope from 154 ft on April 14 to 1000 ft on April 15. The contouring subfactor p_c value remains at 1 for the portion of the slope beyond the critical slope length until new ridges are created to restore contouring effectiveness.

This example is for a uniform overland flow path. The same concepts apply to a non-uniform overland path. Contouring fails on portions of the overland flow path where runoff's shear stress applied to the soil exceeds the soil's critical shear stress for contour failure. That area expands as the combination of vulnerable cover-management and erosive conditions increase. Once contouring fails on an area, RUSLE2 sets the contouring subfactor value to 1, and contouring effectiveness is not restored until a soil disturbing operation occurs that creates new ridges.

Dates **for** ***operation descriptions*** **must be carefully selected for** ***no rotation cover-management descriptions*** **where critical slope length is important. Operations that occur together to create a particular field condition should be combined into a single operation, or the same date should be used for the operation descriptions. An example is creating ridging and applying mulch that occur together on a construction site. These two operation descriptions should either be combined into a single operation description or occur on the same date to prevent RUSLE2 from computing erroneous contouring failure (critical slope length) values.**

14.1.2.7. Use of critical slope length information in conservation planning

The usual conservation and erosion control planning objective is to avoid contouring failure anywhere along the overland flow path. In the case of uniform overland flow paths, this objective corresponds to the critical slope length not being less than the overland flow path length.

If contouring failure occurs, the two frequently used corrective measures are to change the cover-management practice or add terraces/diversions along the overland flow path. Reducing land steepness is a possible alternative on landfills, construction sites, reclaimed mine, and other similar highly disturbed lands where topography can be modified. An average erosion rate for the erodible portion of the overland flow path less than the planning criteria, such as soil loss tolerance, is usually not sufficient for adequate erosion control when contouring fails. Local erosion can be too high where contouring fails on an overland flow path even though the average erosion for the erodible portion of the overland flow path is sufficiently low.

14.1.3. Calibration

RUSLE2's contouring equations, which capture these contouring principles, were calibrated to the experimental field data illustrated in Figure 14.1.[130] The middle curve in Figure 14.1 was assumed to represent the overall, main effect of contouring on erosion. This curve is comparable to the contouring subfactor values in AH537. The calibration procedure required assuming a base condition to represent this overall, main effect curve in Figure 14.1.

Most of the experimental data illustrated in Figure 14.1, which includes the data that were the basis for the AH537 contouring subfactor values, are from research studies conducted from the early 1930's to the mid 1950's.[131] The base condition used in the RUSLE2 contouring calibration represented those conditions rather than modern conditions.[132] The assumed base condition was a conventionally tilled, low yield (60 bu/ac) corn cover-management description at Columbia, MO (see **Footnote 23**). The operations in this cover-management description included a moldboard plow in the spring for primary tillage, two secondary tillage operations to prepare the seedbed, row planter to seed the crop, row cultivation to control weeds, and harvest .

A second cover-management description used in the calibration was conventionally tilled soybeans and wheat added to the base corn cover-management description. This cover-

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[130] The data sources are listed in Tables 6-1 and 6-2, AH703.
[131] Using modern data to calibrate RUSLE2 contouring computations was preferred, but unfortunately adequate modern data do not exist. The important output from RUSLE2 for most conservation and erosion control planning is average annual erosion rather than erosion for individual storms. Also, erosion is highly variable and data over several years are needed to obtain good average annual erosion estimates. This requirement is especially important for calibrating RUSLE2 for contouring because the effectiveness of contouring is strongly related to major storms that occur at vulnerable times. The best data for calibrating RUSLE2 are from natural runoff events on small watersheds (less than 5 ac). Natural runoff plot data supplement these data. Rainfall simulator plot data are not especially useful for calibrating RUSLE2, although these data are extremely important for developing principles, concepts, and basic equations.

The calibration data should be from a wide range of climatic, soil, topographic, and cover-management conditions to capture main effects and to deal with the extreme variability in contouring data. Unfortunately, by the end of the 1970's, many studies involving natural runoff plots were discontinued and the emphasis shifted to rainfall simulator studies. Similarly the number of small watershed studies decreased and remaining studies did not have common study conditions needed to calibrate RUSLE2.
[132] The common assumption is that AH537 contouring subfactor values from the 1930's to 1950's data apply to modern cropping practices. That assumption is highly questionable, if not invalid, because of differences in cropping practices in the two eras. For example, row cultivation is used much less in modern practices than in older practices and yields for most crops have increased significantly since the 1930's.

management description was used to calibrate RUSLE2's effective vegetative ridge height. Research data from a location in Illinois and a location in Oklahoma were used in the calibration. Another important study in the RUSLE2 contouring calibration was a 1960's field study in Northern Mississippi on the effect of relative row grade.

Two very important calibration inputs were ridge height and relative row grade (ratio of row grade along furrows to average steepness of overland flow path). The calibration input values for these variables must be followed when RUSLE2 input values are selected for conservation and erosion control planning. A 3 inches (75 mm) ridge height was input for the row cultivation operation, which had the greatest contouring effect among the operation in the base cover-management description. The second important input was the 10 percent relative row grade used to represent contouring on the small research watersheds and farm fields, which is in contrast to a zero (0) relative row grade used to represent contouring on research plots.

Ridge heights assigned to operation descriptions must be consistent with the 3-inch (75 mm) ridge height assigned to the row cultivation used in the RUSLE2 contouring calibration.

The second major calibration of the RUSLE2 contouring computations was for critical slope length on uniform overland flow paths and contouring failure in general on complex overland flow paths. RUSLE2 was calibrated to AH537 critical slope length values for contouring alone without strip cropping using the base condition described above.[133] AH537 critical slope lengths values for strip cropping were doubled from those for contouring alone. Instead, RUSLE2 computes contouring failure as a function of cover-management conditions along the overland flow path rather than using a multiple of critical slope length values for contouring alone.[134] A cover-management description involving a conventionally tilled corn, alfalfa-timothy hay rotational strip cropping system was used to calibrate RUSLE2's computation of contouring failure, especially as it relates to a hydraulically rough strip spreading runoff. Research strip cropping data from the 1930's to mid 1950's for LaCrosse, Wisconsin were used to partially validate these RUSLE2 computations. The validation was based on the ratio of average sediment yield from the strip cropping system to sediment yield from the same rotational cropping system not in strips. Measured values for this ratio were compared to RUSLE2 computed values.

[133] No explicit research data exist for critical slope length. Contouring failure has been observed and described in research reports, especially at locations in Arkansas and Texas, where severe runoff events occurred. Critical slope length values given in AH282 and AH537 were based on these and other visual field evidence of contouring failure from the early 1930's to mid 1950's. The critical slope length concept and the assigned values based on scientific and technical judgments continue to be accepted by conservation and erosion control planners and were, therefore, used in the RUSLE2 calibration.

[134] RUSLE1 assumes that strip cropping and buffer strips have critical slope lengths that are 1 ½ times those for contouring alone.

14.1.4. Interpretation of RUSLE2 contouring relationships

Of all the variables that affect erosion, contouring is easily the most difficult one to accurately represent, especially at a specific site. Slight, non-obvious differences seem to greatly affect how contouring affects erosion. Consequently, RUSLE2 erosion estimates affected by contouring are more uncertain than erosion estimates influenced by any other RUSLE2 factor. **Therefore, special care should be exercised in interpreting RUSLE2 erosion estimates in relation to contouring.**

RUSLE2 describes the established main effects of contouring in relation to major variables. These effects are valid in general, but an effect at a specific site may be quite different from the general effect. For example, the statement that contouring reduces erosion by 50 percent for a given condition is true in general, but the reduction may be 10 percent at one site and 90 percent at another site. Contouring is a good conservation practice but its effectiveness at a specific site is more uncertain than for other erosion control practices. RUSLE2 is designed to capture broad trends related to contouring. For example, use of the 10 -year, 24-hour precipitation amount is intended to capture differences in general contouring effectiveness by geographic region. Similarly, the relationship of contouring to runoff is meant to capture general trends of how cover-management conditions affect runoff that in turn affect how contouring affects erosion. These RUSLE2 estimates are not meant to explicitly describe how cover-management affect runoff and contouring's effectiveness at a specific site. RUSLE2 is a tool to assist conservation and erosion control planning.

Although, research data are sufficient to identify the main variables that affect contouring, the amount and quality of the data are insufficient to empirically derive and calibrate mathematical relationships for the effect of contouring on erosion except in the general sense. In addition, the contouring data used to develop RUSLE2 do not represent modern agronomic conditions. The RUSLE2 developers significantly extended contouring relationships beyond the main effect of slope steepness normally represented in contouring subfactor values (see AH537). Because research data are not available to validate these extensions, RUSLE2 computations were very carefully examined to ensure that computed values reflect the current scientific knowledge, are acceptable based on modern scientific and technical judgment, and are reasonable for use in conservation and erosion control planning.

14.1.5. Contouring inputs

The **contour systems description** in the RUSLE2 database involves the two inputs of **how row grade is specified** and the **input value for row grade**. The other important input for contouring is the **ridge heights** for the **operation descriptions** in the **cover-management description.**

14.1.5.1. Method of specifying row grade

Row grade can be entered in a **contour system description** using the methods listed in Table 14.1. When a contour system description is used to represent to represent contouring, the assumption is that the overland flow path input represents the flow path perpendicular to contour lines, not a flow path along the ridges and furrows.

The first method of **up and down slope** represents a no-contouring effect. RUSLE2 gives the same result obtained with the other three methods by inputting an **absolute row grade** that equals the overland flow path steepness or inputting 1 for **relative row grade**. This selection tells RUSLE2 to compute erosion without considering any contouring effect.

The method **set absolute row grade** is where a value for the actual furrow (row) grade at the site is entered. This method should be used only where ridges and furrows are well defined and runoff flows to major concentrated flow areas before breaking over the ridges.

Using the *set absolute row grade* input method for ordinary contouring provided by most typical agricultural implements is a *misuse* of RUSLE2.

Table 14.1. Ways to specify row grade.

Row grade specification method	Comment
Up and down slope	Specifically sets relative row grade to 1, i.e., absolute row grade equals overland flow path steepness
Set absolute row grade	Value entered for absolute row grade as measured in the field. **Should only be used in special cases**.
Set relative row grade	Relative row grade is the ratio of the absolute row grade to steepness of overland flow path. Should be used to represent most ordinary contouring situations.
Use management relative row grade	RUSLE2 uses relative row grade input in the cover-management description used in the particular RUSLE2 application.

The **set relative row grade** is the appropriate way to enter row grade for ordinary contouring that affects runoff as illustrated in Figure 8.13 (see **Section 8.3.6**). Relative row grade is the ratio of absolute row grade to overland flow path steepness. As discussed in **Section 14.1.4**, RUSLE2's estimates of how contouring affect erosion are more uncertain than for any other variable. **Contouring system descriptions** based on relative row grade can be developed, stored in the RUSLE2 database, and used so that

RUSLE2 computes the proper relative differences in erosion in relation to contouring. The proper relative difference related to contouring between field situations is not achieved when the absolute row grade entry method is used. Contouring effectiveness is related to how closely the ridge forming operation follows the actual field contours. Equal values for relative row grade imply the same contouring quality in relation to following field contours regardless of land steepness.[135]

The following example illustrates how inputting absolute row grade gives too much credit for contouring on steep land. Assume that an absolute row grade of 1 percent is entered for both a 6% and a 30% overland flow path (land) steepness. The relative row grade is 1/6 = 0.17 for the 6% slope, which gives a contouring subfactor value of 0.70 if the contouring subfactor value is 0.50 for perfect contouring. The relative row grade is 0.033 for the 30% slope, which gives a contouring subfactor value of 0.59 if the contouring subfactor value for perfect contouring is also 0.50. Assuming the same row grade regardless of land steepness computes a much greater relative benefit for contouring on steep slopes than on moderately steep slopes. Achieving this increased contouring benefit requires extra care, which is unlikely, with the ridge forming operation to maintain the 1 percent row grade on steep slopes. Furthermore, such precision implied by varying absolute row grade on steep slopes is unwarranted given RUSLE2's accuracy and quality of the contouring data used to calibrate RUSLE2.

The entry method **use management relative row grade** requires the same inputs as the set relative row grade selection. When this selection is made, RUSLE2 uses the relative row grade entered in the **cover-management description** (see **Section 10.2.10**). The advantage of this method is that contouring and cultural erosion control can be combined into a single erosion control practice described by a cover-management description, which is useful in erosion inventory analysis. The relative row grade should be set to 10% in the cover-management description for ordinary contouring.

14.1.5.2. Row grade

The **set absolute row grade** entry method requires that the **absolute row grade** along the ridges-furrows be entered. As discussed in **Section 14.1.5.1**, this entry method should only be used where the ridges-furrows are so well defined that runoff travels in the furrows to major concentrated flow areas before breaking over the ridges. An alternative method for applying RUSLE2 to this condition is discussed in **Section 8.3.6.**

Absolute row grade is the value that is determined by measuring a decrease in elevation over distance along the furrows (rise/run). In many cases row grade varies along the ridges-furrows, particular on either side of concentrated flow areas to reduce sharp bends in the ridges and to facilitate the ridge forming operation. A representative row grade

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[135] Regardless of input method, RUSLE2 uses relative row in its computations.

must be selected because non-uniform row grades along the ridges-furrows can not be entered into RUSLE2.

Relative row grade is the ratio of row grade to overland flow path steepness. However, a more appropriate way to consider relative row grade is that values for relative row grade represent contouring classes, which are actually classes for ridge-furrow orientation with respect to the overland flow path. Five classes are listed in Table 14.2.[136] Additional classes are not warranted given RUSLE2's accuracy. The classes in Table 14.2 are **contour system descriptions** that have been created and placed in a RUSLE2 database.

Perfect contouring is where the ridges-furrows are oriented parallel to the contour. The row grade is perfectly flat and the ridge tops are level so that runoff spills over the ridge uniformly along the ridge. This condition is obtained in the field when a surveying instrument is used to lay out contour lines. This contouring class is used with high quality rotational strip cropping where row grade is level across concentrated flow areas. Strip cropping in the LaCrosse, Wisconsin area with its smooth sweeping curves with no evidence of ephemeral gully erosion is an example of perfect contouring.

Sometimes row grade associated with rotational strip cropping and buffer strips (see **Section 14.2**) is increased in the vicinity of concentrated flow areas to avoid sharp bends that hinder farming operations.[137] **Contouring with strips** (5% relative row grade) or **standard contouring** (10% relative row grade) should be selected for this situation. If the contouring subfactor value is 0.50 with perfect contouring, a 5% relative row grade gives a contouring subfactor value of 0.61.

Standard contouring (10% relative row grade) should be selected for contouring where no vegetative strips are present to guide ridge forming operations. Unless the topography is quite uniform, creating ridges and furrows perfectly on the contour is practically impossible. Also, row grade is often increased on either side of concentrated flow areas to facilitate ridge forming operations. If the contouring subfactor value is 0.5 with perfect contouring, a 10% relative row grade gives a contouring subfactor value of 0.66.

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[136] The classes listed in Table 14.2 are names used for **contour system descriptions** in the RUSLE2 database that is downloaded from the RUSLE2 Internet site at the USDA-Agricultural Research Service-National Sedimentation Laboratory, Oxford, MS (http://msa.ars.usda.gov/ms/oxford/nsl/rusle/index.html) ARS reviewer, check this). The values for relative row grades in Table 14.2 are the important information. Users may change the names of the contour system descriptions to other names for convenience.

[137] Row grade should remain level across concentrated flow areas. Increasing row grade from level on either side of concentrated flow areas ensures that concentrated areas will persist and may require a grassed waterway to control ephemeral gully erosion. Contour strip cropping that does not have level row grades across concentrated flow areas will not eliminate concentrated flow areas and ephemeral areas as occurred so effectively with level grade contour strip cropping in the LaCrosse, WI area.

RUSLE2 has two contouring (ridge-furrow orientation) classes to represent “cross slope” ridging. The two classes are **moderately off contour**, which is a relatively row grade of 25%, and **half off contour**, which is a relative row grade of 50%. If the contouring subfactor value is 0.50 for perfect contouring, the contouring subfactor values are 0.75 and 0.93, respectively, for these two ridge-furrow orientations.

The last class is **up and down slope** (hill) where the ridge-furrow orientation is parallel to the land slope. The relative row grade is 100% and the contouring subfactor value is 1 for this class.

Table 14.2. Classes of relative row grades to represent contouring (ridge-furrow orientation to land slope)

Contouring (ridge-furrow orientation) class	Relative row grade	Comment
Perfect contouring	0	Ridges-furrows are exactly on the contour (orientation is parallel to contour), use with strips that exactly follow the contour laid out with surveying instruments
Contouring with strips	5%	Use with strips laid out on the contour with survey instruments but with row grade adjustments when approaching concentrated flow areas
Standard contouring	10%	Typical contouring that was initially laid out with survey instruments. Row grade adjustments are made when approaching concentrated flow areas
Cross slope-moderately off contour	25%	Ridge-furrow orientation ¼ off contour. Sufficiently close to the contour to merit significant credit for reducing rill-interrill erosion
Cross slope-half off contour	50%	Ridge-furrow orientation is ½ off contour (half way between on-the-contour and up and down slope). Merits some but not much credit for reducing rill-interrill erosion
Up and down slope	100%	Ridge-furrow orientation is parallel to land steepness. Merits no credit for reducing rill-interrill erosion

Note: The effect of ridge-furrow orientation on ephemeral gully erosion, which RUSLE2 does not estimate, should be considered in developing a complete erosion control plan.

Being able to enter a non-zero row grade in RUSLE2 does not imply that use of such row grades is encouraged or even acceptable. It is recognition that contouring can not be perfect in most field situations and that some credit should be given for rill-interrill erosion reduction for ridge-furrow orientations that are not directly up and down hill. Ridge-furrow grades greater than flat (zero) should be avoided so runoff does not flow along the furrows to concentrated flow areas on the landscape, which promotes ephemeral gully erosion. In fact, a slight row grade may cause more ephemeral gully erosion because the ridges and furrows discharge runoff in a concentrated flow area much further upslope than with a steep relative row grade. RUSLE2 does not consider ephemeral gully erosion; RUSLE2 only deals with rill-interrill erosion.

Conversely, effective erosion control is to place ridges-furrows on a continuous grade with a sufficiently high ridge to ensure that runoff flows to a concentrated flow area protected by a grassed waterway.

A complete erosion control plan includes consideration of both rill-interrill and ephemeral gully erosion.

14.1.5.3. Input ridge heights in relation to contouring

At least one **operation description** that includes a **disturb soil process** to create ridges must be in the **cover-management** description for RUSLE2 to compute a contouring effect (see **Section 9.2.4**). The RUSLE2 assumption is that ridges oriented at an angle to the overland flow path must be present for a contouring effect on erosion. The degree that contouring (ridging) reduces rill-interrill erosion depends on ridge height and row grade.[138] Input ridge height values are entered in the operation descriptions (see **Section 13.1.5.4**).

Ridge height (along with row grade) is the single most important variable that determines the effectiveness of contouring (ridge-furrow orientation to the overland flow path) in RUSLE2. If RUSLE2 computes less contouring effect than expected, ridge heights may be too low.

Ridge height after an operation is totally determined by the operation description, and the ridge height that existed before the operation has no effect on ridge height left by an operation, even when the operation minimally disturbs the soil. The ridge height input in a particular operation description should reflect the ridge height that exists when that operation is used in combination with other operations.

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[138] The total effect of ridges on rill-interrill involves two parts. One part is the contouring effect which is related to the orientation of the ridge-furrows with respect to the overland flow path and the other part is the increased detachment caused by increased ridge height as described in **Section 9.2.4**.

After an operation description creates a ridge, ridge heights decay with precipitation amount and interrill erosion. RUSLE2 does not consider the loss of ridge height caused by deposition in the furrows. Daily ridge height used by RUSLE2 to compute the contouring effect can be much less than the input ridge height value.[139]

Ridge height values input in an operation description must be referenced to the initial 3-inch (75 mm) ridge height assigned to row cultivation used to calibrate the RUSLE2 contouring relationships for Columbia, MO (see **Section 14.1.3**). In assigning a ridge height to an operation description, ask the question of how the operation affects contouring in relation to row cultivation used for corn from the early 1930's to the mid 1950's? Measured ridge heights are a guide because RUSLE2 has been calibrated as much as possible to use ridge heights that are measured in the field. However, measured ridge heights may not always capture how RUSLE2 should compute contouring effectiveness for a particular operation description or for a cover-management description overall. Input ridge height values must be consistent with the ridge height values in the RUSLE2 **core database** because those values were selected to ensure that RUSLE2 computes the desired contouring effect.

Consequently, the best approach by far is to use ridge height values in the RUSLE2 **core database** as a guide in selecting an input value for an operation description. Consistency of ridge height values among operation descriptions is critically important so that RUSLE2 computes the expected relative erosion differences among contouring conditions. This requirement is especially important given the high variability and uncertainty in the research data used to develop RUSLE2 and the high variability in site specific contouring performance.

14.2. Porous Barriers

14.2.1. Description of practices

Porous barriers are support practices that do not terminate the overland flow path because runoff flows through these barriers. These practices must be placed on the contour or else their effectiveness is greatly reduced because runoff flows along them rather than through them. Examples include filter strips (dense vegetation strips at the end of overland flow paths), buffer strips (multiple narrow strips of dense permanent vegetation along the overland flow path), rotational strip cropping (equal width strips including some dense vegetation strips grown in a rotating and alternating fashion in time and space along the overland flow path), and fabric fences, gravel dams, and straw bales used on construction sites and similar lands.

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[139] The ridge height values used in RUSLE2's contouring computations do not correspond with those in RUSLE1 because ridge heights change daily in RUSLE2. The RUSLE2 input values for ridge height are similar to the ridge height values used in RUSLE1 computations.

14.2.2. Basic principles

The high flow retardance of the most effective porous barriers slows runoff and ponds water on the upper side of the barrier. Runoff leaves the barrier spread across the slope in a uniform thin depth, which significantly reduces the potential for contouring failure immediately downslope of the barrier (see **Section14.1.2.5**).

14.2.2.1. Description of actual processes

Ponding (**backwater**) immediately upslope of a barrier reduces runoff's transport capacity, which can cause deposition. As much as 90 percent of the incoming sediment load can be deposited in the backwater until deposited sediment accumulates so much that the lower edge of the sediment wedge reaches the upper edge of the barrier as illustrated in Figure 14.8. Narrow width, dense, high retardance barriers less than 18 inches (500 mm) wide produce wide backwater that causes much deposition. **However, vegetation type barriers must be sufficiently wide to protect against localized failure and short circuiting of the runoff through the barrier that are caused by poor non-uniform plant stands, for example.**

As deposited sediment accumulates during runoff events, the upper edge of the backwater and deposited sediment combined advance upslope as illustrated in Figure 14.8. The upslope advancement of the deposited sediment increases transport capacity in the backwater and fills the ponded area with sediment. Sediment is transported into the barrier itself where sediment is deposited because the barrier's high flow retardance greatly reduces runoff's sediment transport capacity. Eventually both the backwater and barrier, such as a grass strip, become filled with sediment. The barrier becomes almost ineffective because it no longer causes deposition and does little to reduce sediment load. Vegetation strips regain flow retardance during reduced erosion periods if vegetation growth is not overly hindered by sediment.

14.2.2.2. RUSLE2 description

RUSLE2's representation of these very complex processes is simplified as illustrated in Figure 14.9. **RUSLE2 bases its computations solely on the hydraulics within the effective width of the barrier itself.** RUSLE2 does not compute backwater hydraulics and deposition in the backwater. Instead RUSLE2 represents the backwater by computing an additional width that is added to the actual width to create a total effective width for the strip/barrier. **Temporal changes in the backwater effect are not considered. Section 8.1.4** describes the RUSLE2 computational procedures for porous barriers.

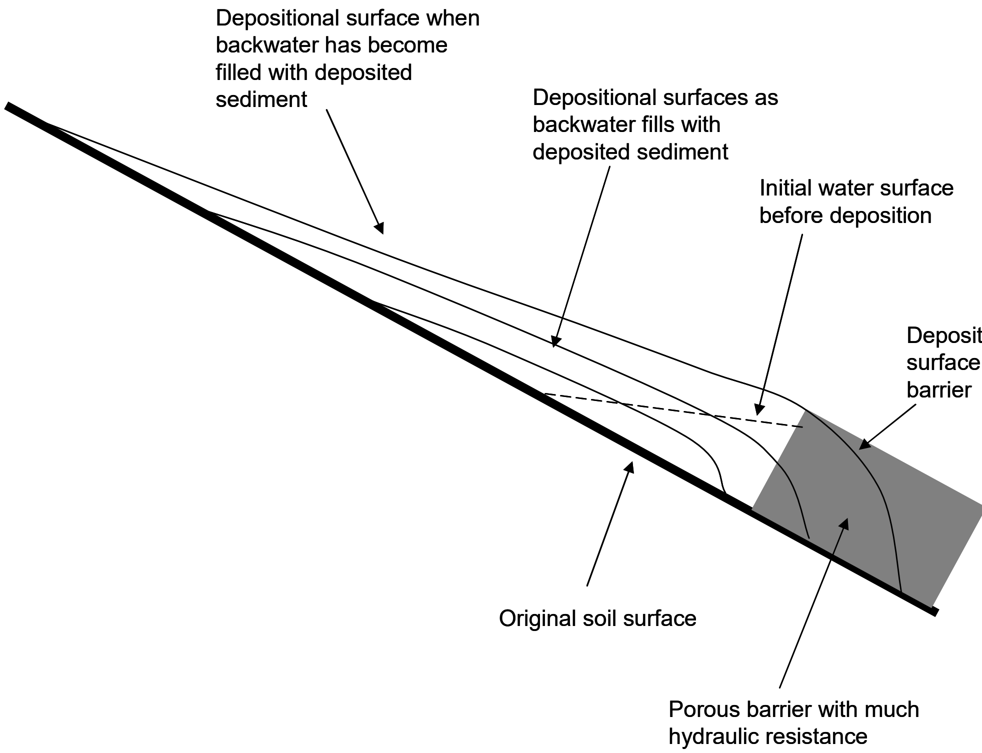

Figure 14.8. Deposition in backwater upslope of a porous barrier as deposition develops over time.

Neglecting deposition in the backwater and temporal changes is insignificant in most cases where barrier are wide such as with most grass buffer and filter strips.

The porous barrier's flow retardance must reduce runoff's sediment transport capacity to less than the incoming sediment load for RUSLE2 to compute deposition. If a barrier's retardance is low, the barrier will hardly slow runoff and transport capacity will not be sufficiently reduced at the barrier's upper edge for RUSLE2 to compute deposition. Also, RUSLE2 will not compute deposition by a barrier if the incoming sediment load is less than the transport capacity at the barrier's upper edge.

Deposition caused by a barrier reduces sediment load along the overland flow path, especially if a high retardance barrier is located at the end of the overland flow path. Detachment (sediment production) is typically low within high retardance barriers, but sediment production will not be greatly reduced if barriers are narrow with respect to the overland flow path length.

RUSLE2 computes deposition ending within a barrier as illustrated in Figure 14.9 where runoff's sediment transport capacity increases within the barrier, which is the usual case, and the barrier (e.g., grass buffer strip) is sufficiently wide. Increasing barrier width when RUSLE2 computes that deposition ends within a barrier does not significantly increase the fraction of the incoming sediment load that is trapped by the barrier. The decrease in sediment yield from the overland flow path that occurs as barrier width is increased results from the barrier occupying an increased portion of the overland flow path. Increasing barrier width reduces sediment yield more because of very low detachment (sediment production) within the barrier than sediment yield is reduced by increased sediment trapping.

However, increasing barrier width increases sediment trapping if RUSLE2 computes deposition over the entire barrier width (i.e., deposition does not end within the barrier). RUSLE2 computes reduced sediment yield because of both increased deposition and reduced sediment production in this case.

Figure 14.9 illustrates the usual case where transport capacity increases within the barrier after a step decrease at the upper edge of a barrier. This increase in transport capacity occurs where runoff rate increases within the barrier because rainfall rate exceeds infiltration rate (see **Sections 8.12 and 8.1.3**). Runoff rate and transport capacity decrease within a barrier where infiltration rate is greater than rainfall rate. RUSLE2 does not compute deposition ending within a barrier when transport capacity decreases within the barrier. Runoff ends within a barrier when infiltration rate exceeds rainfall rate if the barrier is sufficiently wide.

The width required for runoff to end within a barrier depends on discharge rate of the upslope runoff where it enters the barrier as well as rainfall rate and infiltration rate within the barrier. If runoff ends within a barrier, runoff begins at the next location on the overland flow path where infiltration rate is less than rainfall rate, which is often at the upper edge of the strip immediately downslope of the barrier as illustrated in Figure 14.10. An example of runoff ending within a barrier is a high residue strip, left rough by a moldboard plow throwing soil upslope in the Northwest Wheat and Range Region (NWRR, see **Section 6.9.1**). The rainfall rate and flow rate of upslope runoff entering the strip is very low, about 0.25 in/hr (6 mm/h) and infiltration rate in the strip is relatively high.

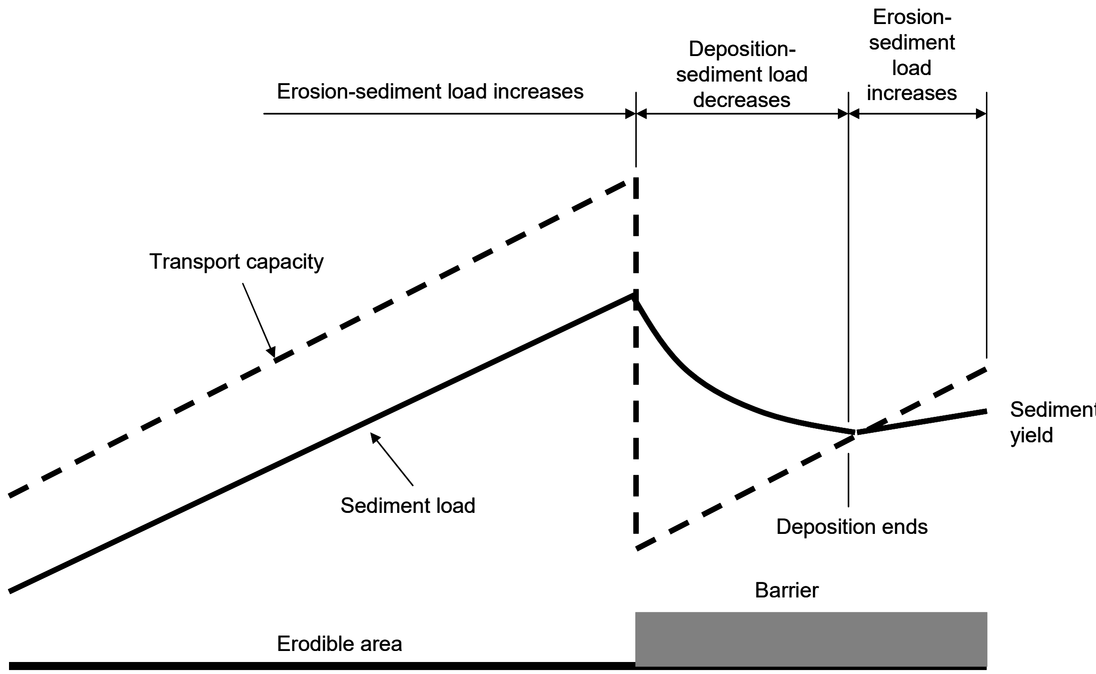

Figure 14.9. RUSLE2 hydraulic representation of a porous barrier.

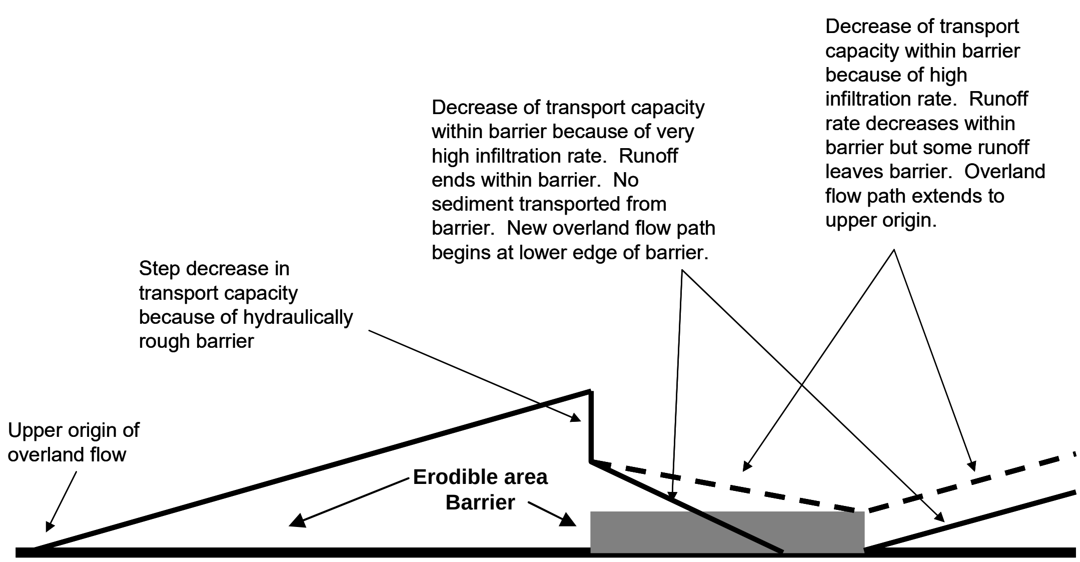

Figure 14.10. Effect of high infiltration rate within barrier that causes runoff date to decrease within barrier.

Most of the deposition caused by a porous barrier occurs in the backwater on the upper side of a strip/barrier. The length of this depositional area must be included with the actual physical width of the strip. Otherwise, RUSLE2 will overestimate sediment yield, especially if the strip is very narrow like a silt fence. RUSLE2 estimates a backwater width based on runoff rate and flow retardance of the strip. RUSLE2 computes the backwater/depositional length along the overland flow path and add this length to the input value for actual strip/barrier width. To simplify the computations, RUSLE2 adds the backwater/depositional width to the lower edge of the barrier/strip, which increases the overland flow path length by the same amount. RUSLE2 computes the backwater/depositional length by first computing flow depth at the upper edge of the strip/barrier using the total Manning's n for the barrier, discharge rate at the upper edge of the barrier, and steepness of the barrier segment. This computation was calibrated based on erosion plot studies involving 1.5 ft wide (0.46 m) stiff grass hedges at Holly Springs, Mississippi. The backwater/depositional length is computed from this flow depth and the steepness of the segment immediately upslope of the barrier assuming a level water surface.

RUSLE2 uses the retardance classes assigned to **vegetation descriptions** to compute the flow depth at the upper edge of the strip/barrier.[140] The maximum width that RUSLE2 adds for any retardance and hydraulic resistance is 15 ft (5.0 m). RUSLE2 only sets a minimum for the retardance class 7 condition, where the minimum backwater/deposition width that is added is 3 ft (1.0 m). Retardance class 7 represents stiff grass hedge, silt fence, or similar porous barrier that have an especially high retardance (see **Section 11.2.5**). If the retardance of these barriers is similar to the retardance of vegetation, an appropriate vegetation retardance class is assigned. The width added for the other retardance classes is computed value, except that it can not exceed 15 ft (5.0 m).

The backwater/depositional length increases as the hydraulic resistance (retardance, ground cover, surface roughness) of the strip/barrier increases. Also, the backwater/depositional length increases as discharge rate increases. RUSLE2 uses the same temporally varied discharge rate to compute backwater/depositional length that it uses to compute contouring failure (critical slope length). The backwater/depositional width decreases as steepness upslope of the strip/barrier and slope steepness of the segment that contains the barrier increases.

The RUSLE2 overland flow path begins at the origin of overland flow assuming that rainfall rate exceeds infiltration rate everywhere along the possible overland flow path based on topography. This choice of an overland flow path includes situations where discharge rate decreases within a barrier placed along the overland flow path, including situations where runoff ends within the barrier. RUSLE2 properly takes into account variations in infiltration and runoff along the overland flow path because of barriers and other changes in cover-management along the overland flow path. However, if the cover-management upslope of an erodible area is known not to produce runoff, the overland flow path can be started at the upper edge of the erodible area where runoff

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[140] A **vegetation description** is used to describe the retardance of mechanical porous barriers. The canopy cover should be 100 percent and the effective fall height should be set to 0 to minimize the detachment computed over the effective width for the strip/barrier. See **Section 14.2.5.1**.

begins. **Section 8.3.4** describes selecting RUSLE2 overland flow paths for porous barriers.

Barriers most effectively induce deposition and reduce sediment load when perfectly on the contour. Runoff may flow along but not through a barrier when the barrier's upper edge is on a grade. Runoff flows along the barrier until the runoff reaches a concentrated flow area where the runoff flows through and over the barrier. Porous barriers designed for overland flow generally perform very poorly in concentrated flow areas. The sediment trapping capacity of a barrier such as a grass strip is rapidly lost by becoming inundated with deposited sediment, or a barrier such as a fabric fence loses its sediment trapping capacity by structural failure. A ridge of soil can develop on the upper side of a barrier because of the combination of high rates of deposition and vegetation re-growing on top of the deposited sediment. Also, tillage in cropped fields and other soil disturbing operations can leave a ridge of soil at the upper edge of a barrier that causes runoff to flow along the barrier rather than entering it. Runoff may not reach a barrier when row grade is steep and ridges high on the inter-barrier area. The runoff flows along the ridges and furrows to concentrated flow area, where the concentrated flow causes the barriers to rapidly fail. [141]

Porous barriers should be analyzed as flow interceptors (e.g., terraces or diversions) when runoff flows along the upper edge of the barrier without entering the barrier.

When porous barriers are selected from the *strips-barriers component* of the *RUSLE2 database*, RUSLE2 requires that relative row grade (see *Section 14.1.5.2*) be 10 percent or less.

Sediment delivery ratio, which is the ratio of sediment leaving the overland path having porous barriers to sediment leaving the overland flow path without barriers is a measure of the degree that the barriers cause deposition. Values for the sediment delivery ratio determined from the RUSLE2 computed sediment yield values depend on the sediment load reaching a porous barrier relative to runoff's transport capacity within the barrier. That is, the sediment delivery ratio is near one, which means little deposition, when the incoming sediment load is only slightly greater than the transport capacity within the porous barrier. In contrast, deposition is much greater and the sediment delivery is much less than 1 when the incoming sediment load is much greater than the transport capacity

[141] RUSLE2 requires that a relative row grade of 10 percent or less be used when porous barriers are selected from the **strips-barriers RUSLE2 database component**. However, this restriction can be bypassed by selecting a **RUSLE2 template** that displays the three layer profile schematic (see **Section 8**), dividing the cover-management layer of the overland flow into segments, and selecting appropriate **cover-management descriptions** for each segment.

within the barrier. Therefore, the RUSLE2 sediment delivery ratio for a particular porous barrier depends on the erosion environment in which the porous barrier is placed as well as characteristics of the barrier itself.

The sediment delivery ratio based on RUSLE2 computations is not constant in general. For example, the sediment delivery ratio for a vegetation strip of moderate retardance is larger for no-till than for clean-till cropping on the inter-barrier area. The vegetation strip traps a smaller portion of the incoming sediment load from the no-till area than from the clean-till area because the incoming sediment load from the no-till area is only slightly higher than the transport capacity within the strip. Detachment and sediment production, which determine the incoming sediment load, is low with no-till cropping in comparison with clean-till cropping. Even though the sediment delivery ratio is higher for the clean-till cropping, overall erosion is less with the no-till cropping.

The RUSLE2 computed sediment delivery ratio for a porous barrier depends on the characteristics of the sediment that reaches the barrier. Sediment characteristics are determined by the properties of soil from which the sediment is eroded (see **Section 7.5**) and upslope deposition. For example, a high portion of sediment eroded from sandy soils is large, easily deposited particles. The RUSLE2 sediment delivery ratio for this sediment is much lower than for sediment eroded from high silt soils that produce a high portion of small, not easily deposited particles. A high portion of the sediment eroded from high clay soils is large, easily deposited aggregates. Clay is a bonding agent that contributes to sediment being eroded as aggregates. The RUSLE2 computed sediment delivery ratio is lower than is commonly assumed for sediment eroded from clay soils because of the high portion of large aggregates in the sediment eroded from these soils.

The RUSLE2 computed sediment delivery ratio for a porous barrier is high where much upslope deposition occurs. An example is a grass strip at the end of a concave-shaped overland flow path where much deposition occurred because of reduced steepness. This deposition removes a high portion of the coarse, easily deposited particles from the sediment load so that the sediment reaching the barrier is largely composed of fine, not easily deposited particles.

Sediment delivery ratio values for porous barriers do not depend very much on the erosion environment, except for sediment characteristics, where runoff's sediment transport capacity is near zero within the barriers. Dense grass strips are an example of this porous barrier.

Deposition is a selective process that enriches the sediment in fines because coarse, dense sediment like sand and large aggregates are more easily deposited than is fine sediment like clay, silt, and small aggregates (see **Sections 5.4 and 7.5**). RUSLE2 computes an **enrichment ratio** that is a measure of the degree that deposition enriches the sediment in fines. The enrichment ratio is the ratio of the specific surface area of the sediment leaving the RUSLE2 overland flow path to the specific surface area of the soil subject to erosion. The enrichment ratio for a porous barrier increases as portion of the incoming sediment load that is deposited increases. That is, enrichment ratio values increase as values for the sediment delivery ratio decrease.

A major question is the credit given to sediment deposited by porous barriers as **soil saved**. This deposition is referred to as **remote deposition** where the deposition is localized in contrast to **local deposition** that occurs over most of the overland flow area. As discussed in **Section 8.1.5.4**, the credit given to remote deposition as soil saved is a matter of scientific and technical judgment. Keeping the sediment on the overland flow path is clearly preferred to the sediment leaving the overland flow path. Furthermore, sediment deposited upslope is preferred to the sediment deposited near the end of the overland flow path. Also, sediment deposited in localized, semi-permanent locations, such as above grass buffer strips, is less desirable than sediment deposited where soil disturbing operations, such as tillage operations associated with rotational strip cropping, routinely spread the deposited sediment. An increased portion of the overland flow path (i.e., hillslope) benefits when the deposited sediment is spread.

The **conservation planning soil loss** discussed in **Section 8.1.5** gives partial credit for the deposition that occurs with porous barriers as soil saved that benefits the landscape. The credit taken for deposition reduces the soil loss used in conservation planning. The credit taken for this deposition depends on both the location and amount of deposition. For example, RUSLE2 takes little credit for deposition that occurs near the end of the overland flow path, but can take more than 80 percent credit for deposition that occurs on the upper one third of the overland flow path. Rotation strip cropping (see **Section 14.2**) is a special case where full credit is taken for deposition.[142]

Erosion on the inter-barrier area is not greatly affected by the barrier, except for the immediate area downslope of the barrier where erosion may be reduced. Even though the infiltration rate within a porous barrier may be substantially higher than on the inter-barrier area, RUSLE2 does not consider how erosion below a barrier is affected by reduced runoff exiting the barrier. RUSLE2 does compute how reduced runoff affects contouring failure and sediment transport capacity downslope of a porous barrer. High retardance porous barriers spread the exiting runoff so that rill erosion is reduced for a distance downslope before the runoff becomes concentrated once again in rills. This distance has not been defined in research studies. Based on field observations, rill erosion and runoff concentrated in rills occurs immediately downslope of the barrier if the soil is highly susceptible to rill erosion. In other cases, rill erosion and runoff

[142] A rotational strip cropping support practice must be selected through the **strips/barriers component** of the RUSLE2 database in order for RUSLE2 to give full credit (i.e., set **conservation planning soil loss** value to the **sediment yield** value) for deposition associated with rotational strip cropping. Rotational strip cropping can be represented in RUSLE2 by dividing the **management layer** of the **overland flow path schematic** (see **Section 8**), but this procedure takes only partial credit for deposition.

concentrated in rills has been observed not to occur until beyond 3 ft (1 m) on soils moderately resistant to rill erosion. A 10 ft (3m) and greater distance is required for visible evidence of rill erosion downslope of porous barriers on soils highly resistant to rill erosion. Runoff exiting a porous barrier has a very low sediment load and, therefore, has increased erosivity, which increases rill erosion. The RUSLE2 assumption is that these effects offset each other. Consequently, RUSLE2 computes the same erosion rate below a barrier regardless of the presence or absent of the barrier, except for conditions where RUSLE2 computes no contouring failure immediately downslope of a barrier as discussed in **Section 14.1.2.5**.

14.2.3. Calibration

Calibrating RUSLE2 for porous barriers required determining mathematical relationships and numerical values for the K_T coefficient in equation 5.3, which is RUSLE2's equation for runoff's sediment transport capacity (see **Section 8.1.3**). . Equation 5.3 is based on the concept that total overland flow shear stress is divided into the two components of shear stress applied to soil and sediment particles (grain roughness) and shear stress applied to ground cover, soil surface roughness, and standing vegetation (form roughness) (see **Section 14.1.2.5**). The shear stress applied to the soil and sediment particles is used to compute runoff's sediment transport capacity. The shear stress applied to the soil and sediment particles is related to the ratio of the hydraulic resistance of a smooth soil to total hydraulic resistance.

The K_T coefficient involves two parts. One part represents the combined effects of sediment transportability with the hydraulic resistance (grain roughness) of a smooth soil surface and the second part represents the effect of total hydraulic roughness (resistance). Although sediment transportability is related to diameter and density of sediment particles, RUSLE2 uses the same transportability value for all soils even though sediment characteristics vary. **However, RUSLE2 captures the main effects of sediment characteristics on deposition by using equation 5.2, which involves sediment fall velocity that is a function of sediment particle diameter and density (see Section 7.5).** A single Manning's n value is used for all smooth soil; it does not vary as a function of soil particle diameter.

The RUSLE2 developers judged that using constant representative values for sediment transportability and grain resistance improved RUSLE2's robustness as a conservation and erosion planning tool.

A combined base value for grain roughness (resistance) of a smooth soil and sediment's transportability was determined by calibrating RUSLE2 to measured sediment load on a concave overland flow path profile. The RUSLE2 assumption is that sediment transport capacity equals sediment load at the location where deposition begins on a concave profile. The calibration data were from a simulated rainfall field study on a concave plot

35 ft (10.7 m) long where slope steepness decreased continuously from 18 percent at the upper end to 0 percent at the lower end. The bare silt loam soil was smooth so that the only hydraulic resistance was grain roughness. The slope profile was cut from a deep soil profile so that soil characteristics were uniform along the overland flow path. Deposition began at the location where steepness equaled 6 percent. A base value for the K_T coefficient for grain roughness only was determined by adjusting its value until RUSLE2's sediment transport capacity equaled measured sediment load at the 6 percent steepness location. Additional evaluations of the calibrated K_T value were made by comparing RUSLE2 estimates with measured values in laboratory deposition studies, visual field evidence of deposition, and scientific and technical judgments.[143]

The second part of the K_T variable involves the mathematical equation that computes K_T values as a function of the ratio of grain hydraulic resistance to total hydraulic resistance. This equation was derived from sediment transport theory. The Manning's n, which is widely used in hydraulic analyses, is used in RUSLE2 as the measure of total hydraulic resistance. A RUSLE2 total Manning's n value is the sum of the Manning's n values for ground cover, soil surface roughness, and standing vegetation. Values for Manning's n for ground cover and surface roughness were developed from field overland flow velocity measurements.[144]

Manning's n for standing vegetation is based on a retardance concept where seven retardance classes are used to describe the hydraulic resistance provided by standing vegetation (see **Section 11.1.4**). RUSLE2 uses an equation that converts retardance values to Manning's n values. The retardance classes and the empirical equation that computes Manning's n as a function of retardance class were based on both field velocity measurements and scientific judgment of how standing vegetation affects overland flow velocity and hydraulic resistance.

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[143] Foster, G.R., W.H. Neibling, S.S. Davis, and E.E. Alberts. 1980. Modeling particle segregation during deposition by overland flow. *In:* Proceedings of Hydrologic Transport Modeling Symposium. American Society of Agricultural Engineers. St. Joseph, MI. pp. 184-195.

[144] e.g.,

Foster, G.R. and L.D. Meyer. 1975. Mathematical simulation of upland erosion by fundamental erosion mechanics. *In:* Present and Prospective Technology for Predicting Sediment Yields and Sources. ARS-S-40 USDA-Science and Education Administration. pp. 190-204.

Foster, G.R., L.J. Lane, and J.D. Nowlin. 1980. A model to estimate sediment yield from field sized areas: Selection of parameter values. *In:* CREAMS - a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. Vol. II: User Manual. USDA-Conservation Research Report No. 26. USDA-Science and Education Administration. pp. 193-281.

Foster, G.R. 1982. Modeling the erosion process. Chapter 8. *In:* Hydrologic Modeling of Small Watersheds. C.T. Haan, H.P. Johnson, D.L. Brakensiek, eds. American Society of Agricultural Engineers. St. Joseph, MI. pp. 297-382.

The next step was to calibrate the equations used to compute sediment characteristics as a function of deposition. The coefficient value involved in these equations was calibrated by comparing RUSLE2 computation of sediment yield and sediment class distributions for very dense grass strips of 3, 6, and 9 feet (0.9, 1.8, and 2.6 m) widths where sediment transport capacity within the grass strips can be considered to be zero (0).

The final step in the calibration was to validate the equations as a complete set. These equations involve complex interactions, which prevents calibration of coefficient values except for very special conditions. The equations and coefficient values, therefore, had to be validated as a set over the conditions where RUSLE2 would likely be applied in conservation and erosion control planning. RUSLE2 computed values for sediment load and sediment particle distributions along and at the end of concave shaped overland flow paths were compared to measured values for both field and laboratory studies. Similar comparisons were made for sediment yield from the end of slopes involving mulch strips of different hydraulic resistance and placement along the overland flow path and contour strip cropping at several locations.[145] In all cases, evaluations were made to ensure that RUSLE2 computed values for sediment load and sediment class distribution are reasonable and consistent with accepted scientific knowledge and available data.

14.2.4. Interpretation

RUSLE2's erosion, deposition, and sediment load computations for porous barriers are for conservation and erosion control planning purposes. Numerous assumptions were made in that context to derive simple, robust RUSLE2 equations that give reasonable values consistent with research data and accepted scientific and erosion control principles. With the possible exception of contouring, porous barrier erosion control varies more with site-specific condition than any other factor. For example, a barrier not perfectly on the contour can result in runoff flowing along the barrier, collecting in a concentrated flow area, breaking over the barrier, and causing the barrier to fail and trap almost no sediment. The effectiveness of vegetative strips depends on a ridge of soil not accumulating along the barrier's upper edge that prevents runoff from entering the barrier. Also, vegetation uniformity and a high quality and dense plant stand must be maintained for vegetative barriers to be fully effective. Installation and maintenance of fabric fences is more important than any other factor in determining their effectiveness.

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[145] e.g,

Foster, G.R., W.H. Neibling, S.S. Davis, and E.E. Alberts. 1980. Modeling particle segregation during deposition by overland flow. *In:* Proceedings of Hydrologic Transport Modeling Symposium. American Society of Agricultural Engineers. St. Joseph, MI. pp. 184-195.

Neibling, W.H. and G.R. Foster. 1983. Transport and deposition of soil particles by shallow flow. *In:* Proceedings of the D.G. Simons Symposium on Erosion and Sedimentation. Colorado State University, Ft. Collins. pp. 9.43-9.64.

Having and enforcing a good set of installation and maintenance specifications and standards is essential.

RUSLE2 **core database** values for porous barriers represent values that should be used in RUSLE2 applications in the judgment of RUSLE2 developers. RUSLE2 represents the general, overall main effects of these practices as they are judged to be commonly installed in the field. The effectiveness of porous barriers under ideal laboratory conditions is almost always much better than under typical field conditions. RUSLE2 input values for porous barriers values should reflect local conditions and the judgment of designers and regulatory officials for fabric fences, gravel dams, straw bales, and similar porous barriers typical of those used on construction sites.

14.2.5. Inputs

The inputs used to represent porous barriers in RUSLE2 include overland flow path description, a contouring description, and the specific inputs for the strip/barrier system. Porous barriers do not affect the overland flow path description because overland flow is assumed to pass through porous barriers. RUSLE2 accounts for infiltration variations along the overland flow path, including strips where infiltration is so high that runoff ends within the strip, to compute sediment transport capacity and contouring failure (critical slope length). The overland flow path length is selected as if runoff is produced along the entire overland flow path.

The upper edge of a strip/barrier system should be as close as possible to perfectly on the contour (zero row grade) for maximum effectiveness. Figures 14.11 and 14.12 illustrate the importance of a strip/barrier's upper edge being on the contour. If the upper edge is placed parallel to the site boundary as illustrated in Figure 14.11, a grade exists along the upper edge. This grade results in overland flow collecting and running along the upper edge of the strip/barrier to a concentrated flow area, where the flow can overwhelm the barrier. A much better layout is where the upper edge is on the contour as illustrated in Figure 14.12. Runoff enters the barrier uniformly along its length, and the barrier is much less likely to fail in concentrated flow areas. An advantage of having the upper edge of strips/barriers on the contour on cropland is that concentrated flow and ephemeral gully erosion can be greatly reduced.

Selecting a **strip/barrier description** from the RUSLE2 **strip/barrier database component** requires that relative row grade be 10 percent or less except for up and down slope (100 percent relative row grade) where runoff flows perpendicular into the strip/barrier. This restriction can be circumvented by using a RUSLE2 screen **template** that displays the three-layer profile schematic (see **Section 8**). In both input approaches, RUSLE2 assumes that the runoff flows into the porous barrier and that the only effect of the barrier being off grade is in the contouring effect described in **Section**

14.1. See **Section 14.1.5** for additional guidance on selecting contouring inputs for porous barriers.

Inputs specific to a strip/barrier system can be entered in one of two ways. Selecting a **strip/barrier description** from the RUSLE2 database is the intended approach for routine conservation planning. These descriptions involve simplifying assumptions such as uniform strip/barrier widths for convenience and consistency with RUSLE2's accuracy. However, the **three layer profile schematic** can be used to circumvent the 10 percent relative row grade rule when flexibility is needed to represent a complex field situation. The **management layer** in the profile schematic is divided into segments and **cover-management descriptions** are selected for each segment to represent the strips and barriers along the overland flow path.

The inputs for strip/barrier descriptions in the strip/barrier component of the RUSLE2 database are listed in Table 14.3.

Table 14.3. Input variables for strip/barrier descriptions

Input variable	Comment
Strip barrier type	Type refers to filter strip/barrier, buffer strip/barrier, or rotation strip cropping. A filter strip/barrier is permanent at end of overland flow path. Buffer strip/barrier type involves multiple permanent barriers along overland flow path. Rotational strip cropping involves multiple, equal width strips that alternate in time along the overland flow path
Number of strips/barriers crossing overland flow path	Assumption is that strips/barriers are equally spaced along overland flow path
How strip/barrier width is specified	Width can be specified in absolute units or as the portion of the overland flow path length
Absolute strip width	Strip/barrier width if input for width is specified in absolute units
Strip/barrier width relative to overland flow path length	Strip/barrier width if input for width is specified as the portion of the overland flow path length
Strip/barrier cover-management description	Select the cover-management description for the filter and buffer strip/barrier system. Cover-management description selected for profile is cover-management input for non-strip portion of the overland flow path. The cover-management description selected for the profile is the cover-management description that RUSLE2 uses for rotational strip cropping.
Strip/barrier at bottom of overland flow path	Selecting **yes** places a strip/barrier at the end of the overland flow path. Remaining strips are uniformly spaced along the overland flow path. Selecting **no** places the last strip/barrier

	the same distance above the end of the overland flow path that strips/barriers are spaced along the overland flow path.
Is strip/barrier used for water quality	For USDA-NRCS conservation planning. NRCS specifies require that last strip width be twice as wide as the other strips when explicit purpose is to improve water quality.

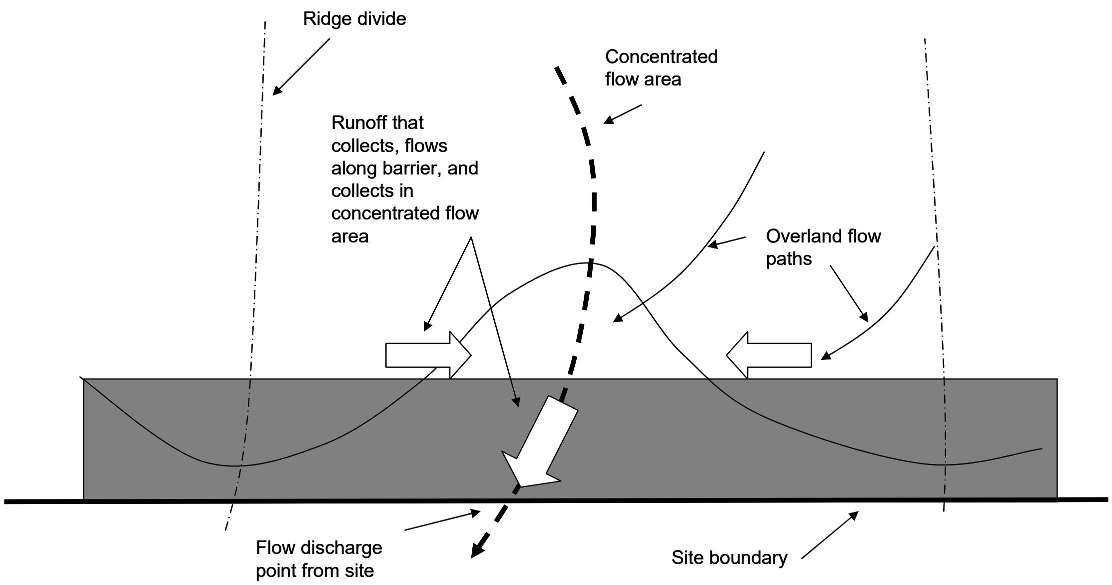

Figure 14.11. A strip where upper edge is parallel to site boundary.

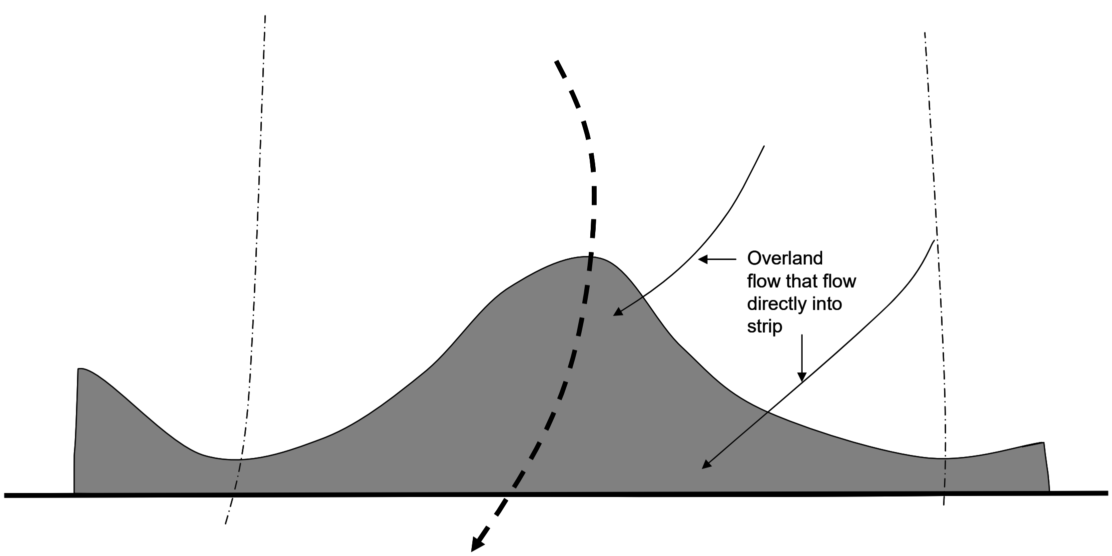

Figure 14.12. A strip where upper edge is perfectly on the contour.

14.2.5.1. Inputs for filter strip/barrier

A filter strip porous barrier is a single barrier at the end of the overland flow path. Four examples of a filter strip porous barrier are a wide strip of dense vegetation (e.g., grass strip) on cropland, a narrow strip of erect, stiff, dense grass (stiff grass hedge) on cropland, an undisturbed strip left along concentrated flow areas on disturbed forestland, and a fabric (silt) fence on a construction site. The specific inputs for a filter strip-type porous barrier are: strip/barrier type (select **filter strip**), how strip/barrier width is specified, strip/barrier width, and cover-management description for strip/barrier.

The general recommendation for conservation and erosion planning is to specify **strip/barrier width** as the portion of the overland flow path length. A strip width of 10 percent of the overland flow path length is commonly assumed for general conservation and erosion control planning. An alternate is to specify the actual widths in absolute units instead of a portion of the overland flow path length.

Figure 14.12 illustrates that the portion of the overland flow path occupied by a filter strip/barrier of a fixed width varies by overland flow path. This variation means that the relative filter strip/barrier width depends on the overland flow path assumed in applying RUSLE2 to a particular site. The recommended approach is to choose an overland flow path and a representative filter strip/barrier width that are consistent with the conservation and erosion control planning objectives for the site. For example, a typical RUSLE2 application is to protect the eroding portion of the hillslope from excessive erosion so that the soil resource is protected. The one third portion of the hillslope having the highest erosion potential is typically selected as the area where RUSLE2 will be applied when conservation planning objective is to protect the soil resource. An overland flow path is assumed through this hillslope area, and the filter strip/barrier width for that overland flow path is used as the input width. However, if this width is not representative of the filter strip/barrier as a whole, use a representative filter strip width even if it does not match the actual width for the selected overland flow path.[146]

Filter strips/barriers are often used to reduce sediment yield from a site. RUSLE2 computes sediment yield from the area represented in a RUSLE2 computation. This area can include the entire overland flow area, diversions/terrace channels having deposition, and small impoundments, but it does not include concentrated flow areas where additional deposition and ephemeral gully erosion can occur (see **Sections 5.1 and 5.2**).

RUSLE2 computations should be made for a collection of overland flow paths when computing sediment yield where conditions vary over the area of interest. The sediment yield value for each overland flow path is weighted by the area represented by that path to obtain a sediment yield estimate for the entire area represented by the RUSLE2 computations. The **plan component** of the **RUSLE2 database** can assist in this computation where the sediment yield values are weighted by the sub-area that each overland flow path represents relative to the total area.

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[146] RUSLE2 computes erosion and deposition values for porous barriers that are consistent with erosion science and research data. RUSLE2 is not meant to displace erosion control practice standards and specifications issued by agencies like the USDA-Natural Resources Conservation Service. However, such standards sometimes compromise erosion control performance for convenience of certain farming operations. RUSLE2 does not consider all factors important in conservation and erosion control planning. Use RUSLE2 values to guide developing an appropriate site-specific plan.

RUSLE2 only computes sediment yield from the overland flow area, diversion/terrace channels where deposition occurs, and small impoundments. RUSLE2 does not compute sediment yield from the site unless the flow paths represented by RUSLE2 end at the site boundary (see *Sections 5.1 and 5.2*).

RUSLE2 computes a backwater/deposition width and adds that value to the input width for the strip/barrier. This approach takes into account type and porosity of the barrier based on the retardance value assigned in the **vegetation description** used to represent the barrier (see **Sections 11.1.4 and 11.2.5**). This approach also takes into account how location, soil, and cover-management affect runoff and backwater/deposition width.

A **cover-management description** is selected to describe the filter strip/barrier, even for mechanical barriers like silt fences. The cover-management description for permanent vegetation strips should be a **no-rotation** type cover-management description (see **Section 10.2.8**). If the cover-management description on the upslope portion of the overland flow path is also a no-rotation type cover-management description, then consistency of the dates between the cover-management descriptions is not required. Similarly, consistency of dates between the cover-management descriptions is not important when cover-management description is a rotation type for the strip/barrier even though the upslope cover-management description is a no-rotation type. **However, if the cover-management descriptions are a no-rotation type for both the upslope area and the strip/barrier, then the dates in the two cover-management descriptions must be consistent.**

Strips/barriers can be added and removed at particular times over the computational period using operations in the cover-management description for the strip/barrier.[147] This RUSLE2 capability allows the use of a single cover-management description to describe a strip/barrier to compute erosion over the pre-construction, construction, and post construction phases.

A **vegetation description** is used to describe mechanical barriers such as fabric fences, gravel dams, straw bales, berms, and similar erosion control porous barriers used on construction sites. A selection is made from the **retardance classes** defined for vegetation plus the additional retardance class for silt fences and stiff grass hedges to describe the porosity of the barrier (see **Section 11.2.5**). Retardance class 7 for stiff grass hedges and silt fences is selected if the material provides extremely high retardance. Another retardance classes is used for more porous barriers. Also, the **production**

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[147] A **begin growth process** in an **operation description** is used to install (put in place) a mechanical barrier (e.g., silt fence) because a vegetation description is used to represent the barrier. A **kill vegetation** and a **remove residue processes** are used in an operation description to remove a mechanical barrier.

(yield) level can be changed to alter the retardance (porosity) of the strip/barrier unless the **extremely high retardance class** is selected for the strip/barrier.

The canopy cover should be set to 100 percent and the effective fall height should be set to zero in the vegetation description used to describe a mechanical barrier to minimize detachment that RUSLE2 computes for the portion of the overland flow path occupied by the barrier.

High quality filter strips/barriers can greatly reduce sediment yield, but they do not significantly reduce the conservation planning soil loss (see **Section 8.1.5.4**). The deposition caused by the strip/barrier is near the end of the overland flow path unless the strip is very wide such as a strip that occupyies more than 40 percent of the overland flow path.

Porous barriers must be perfectly on the contour for effective performance. RUSLE2 assumes well designed, installed, and maintained barriers.

14.2.5.2. Inputs for buffer strips/barriers

A **buffer strip/barrier** type porous barrier is a set of equal width strips/barriers spaced uniformly along the overland flow path and having the same cover-management description and width. The same base **cover-management description** applies to all of the inter-strip/barrier areas. Examples include permanent grass strips on cropland and silt fences on a construction site.

The specific inputs for a buffer strip type porous barrier are:

barrier type (select **buffer strip**),
number of strips/barriers crossing the overland flow path,
how strip/barrier width is specified,
strip/barrier width,
cover-management description for strip/barrier,
whether a strip/barrier is at the end of the overland flow path, and
is the buffer strip system for water quality.

The **buffer strip/barrier description** in the **strip/barrier component** of the RUSLE2 database is for routine conservation and erosion control planning. A RUSLE2 template (see **Section 8**) that displays the three layer profile schematic can be used to apply RUSLE2 to complex, non-uniform conditions.

Several inputs for a buffer strip/barrier system are the same as for a filter strip barrier description. See **Section 14.2.5.1** for a description of the common inputs. Only the additional inputs required to describe a buffer strip/barrier system are discussed in this section.

The number of strips/barriers is not the number of strips/barriers on the hillslope or in the field, but the number of strips/barriers that cross the overland flow path used in the RUSLE2 computation.

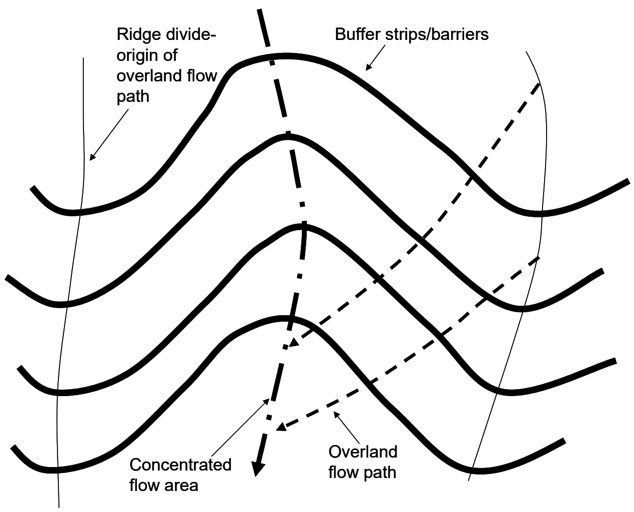

Figure 14.13. A buffer strip/barrier system on a typical hillslope illustrating various overland flow paths.

Enter a representative value for the number of strips/barriers that cross the overland flow path. The number will vary depending on the overland flow path that is chosen for the RUSLE2 computation as illustrated in Figure 14.13. Apply the guidelines described in **Section 14.2.5.1** regarding filter strip width for selecting a value for the number of strips/barriers that cross the overland flow path.

If a strip/barrier is placed at the end of the overland flow path, select **yes** for the input of **strip/barrier at the end of the overland flow path**. RUSLE2 divides the overland flow path into a number of barrier-interbarrier intervals equal to the number of strips/barriers crossing the overland flow path. This arrangement is illustrated in Figure 14.14.

The strip/barrier arrangement where a strip/barrier is not at the end of the overland flow path is also illustrated in Figure 14.14. In this case, the number of inter-strip/barrier intervals along the overland flow path is one greater than the number of strips/barriers. Consequently, the strips/barriers are more closely spaced than when a strip/barrier is at the end of the overland flow path. Sediment yield is increased when a strip/barrier is not at the end of the overland flow path to trap the sediment eroded on the last inter-strip/barrier area. Although sediment yield is reduced when a strip/barrier is at the end of the overland flow path, the conservation planning soil loss (see **Section 8.1.5.4**) may not differ greatly with strip/barrier placements.

As Figure 14.13 illustrates, the relationship of the last strip/barrier to the end of the overland flow path varies. Either chose the input that best represents the overall field situation or make RUSLE2 computations for both strip/barrier placements. The conservation or erosion control plan could be based on an average of the two computations or on the one where the erosion and sediment yield potential is greater.

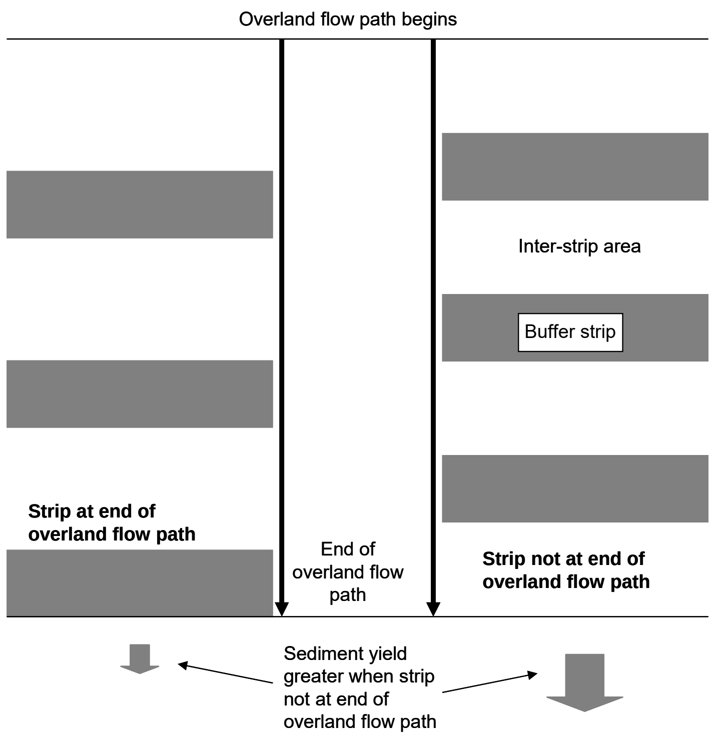

Figure 14.14. Illustration of a buffer strip systems where strip is at end of overland flow path and one where strip is not at end of overland flow path.

Select **yes** for the input **used for water quality** if the buffer strip/barrier description is being used for water quality purposes according to USDA-NRCS standards. Also, select **yes** for the input **to place a strip/barrier at the end of the overland flow path**. These selections cause the width of the strip at the end of the overland flow path to be twice the width of the other strips.

14.2.5.3. Inputs for rotational strip cropping

A rotational strip cropping system is a set of equal width strips that are annually rotated on the overland flow path in a sequence determined by a **cover-management description**. The cover-management description includes erodible periods and dense vegetations periods. Rotational strip cropping's effectiveness is from the deposition caused by the dense vegetation strips. The specific inputs for a rotational strip cropping type porous barrier are barrier type (select **rotational strip cropping**), number of strips/barriers crossing the overland flow path, the cover-management description, and the sequencing of the strips along the overland flow path.

Select a representative value for the number of strips that cross the overland flow path. The number of strips that cross the overland flow path varies with the overland flow path as described in **Section 14.2.5.2** for buffer strip systems. Also, the field overland flow path does not always begin and end on a strip boundary as assumed by RUSLE2. The idea is to a chose a number that best represents the overall field situation where RUSLE2 is being used as a conservation and erosion control planning tool. A RUSLE2 **template** that displays the three layer profile schematic can be used to estimate erosion on more complex situations that can be represented with the **rotation strip cropping description** in the **strip/barrier component** of the RUSLE2 database.[148] For example, this template

[148] If a RUSLE2 template with the three layer profile schematic is used to represent rotational strip cropping

is required to compute erosion for a rotational strip cropping system combined with a filter strip system because a filter strip description and a rotational strip cropping description from the RUSLE2 strip/barrier database component can not be combined.

The number of strips is not the number of strips on the hillslope or in the field, but the number of strips that cross the overland flow path used in the RUSLE2 computation.

Select a cover-management description that includes periods of dense vegetation that provide substantial flow retardance to cause deposition. The cover-management description, which is applied to all strips along the overland flow path, must include dense vegetation or other high hydraulic resistance conditions to cause deposition. The effectiveness of rotational strip cropping is achieved by having alternating strips of dense vegetation that cause deposition.

These alternating strips of dense vegetation are described by sequencing the cover-management description among the strips. The sequencing procedure used in RUSLE2 is to **offset** the starting date of the cover-management description by a particular number of years for each strip.

The following examples illustrate how to offset a cover-management description, which must be a rotation, to describe a rotational strip cropping system in RUSLE2. Assume a simple cover-management description of two years of corn followed by three years of hay represented by corn 1 - corn 2 - hay 1 – hay 2 – hay 3. Multiple years of each crop are grown together for convenience. Assume four strips along the overland flow path. The number of strips along an overland flow path need not match the years in the rotation as illustrated in this example. The number of strips will often be less than the number of years in the rotation.

Table 14.4 illustrates a rotation strip cropping description where the cover-management description is not offset for any strip. The result is that the same cover-management condition exists on all strips in any year. This system only reduces the conservation planning soil loss by reducing erosion that results from the three years of hay being much less erodible than is the corn. No deposition occurs among the strips because the hydraulic resistance does not increase between any two adjacent strips. This system is not rotational strip cropping because the dense vegetation (i.e., hay) are not alternated among the erodible (i.e., corn) strips.

Table 14.4. Example of no offset for a corn-corn-hay-hay-hay cropping rotation.

Strip	Years of	Year 1	Year 2	Year 3	Year 4	Year 5

and similar strip conditions where the strips must be sequenced along the overland flow path, the inputs to describe strip sequencing are entered in the **cover-management tab**.

Number	Offset					
1 (upper end of overland flow path	0	corn 1	corn 2	hay 1	hay 2	hay 3
2	0	corn 1	corn 2	hay 1	hay 2	hay 3
3	0	corn 1	corn 2	hay 1	hay 2	hay 3
4	0	corn 1	corn 2	hay 1	hay 2	hay 3

To achieve strip cropping, the cover-management description on some of the strips needs to be offset as illustrated in Table 14.5. The 2-year offset on strips 2 and 4 shifted the cover-management description by two years so that runoff from at least one corn strip runs through at least one hay strip. Sediment yield is reduced in the first two years because of a hay strip at the end of the overland flow path. However, sediment yield is increased in years 4 and 5 because the erodible corn strip is the last strip on the overland flow path. Both erosion and sediment yield are low in year 3 because the entire overland flow path is in the low erodible hay condition and only slight deposition occurs in this year.

Table 14.5. Example of a rotational strip cropping system where cover-management conditions are alternated by strip along the overland flow path.

Strip Number	Years of Offset	Year 1	Year 2	Year 3	Year 4	Year 5
1	0	corn 1	corn 2	hay 1	hay 2	hay 3
2	2	hay 1	hay 2	hay 3	corn 1	corn 2
3	0	corn 1	corn 2	hay 1	hay 2	hay 3
4	2	hay 1	hay 2	hay 3	corn 1	corn 2

Table 14.6 illustrates another possible strip cropping system described with a different set of offset years from the set illustrated in Table 14.5. The system illustrated in Table 14.6 is not as effective as the one illustrated in Table 14.5. In an example computation for Columbia, MO, the conservation planning soil loss for the system illustrated in Table 14.4 is 5.8 tons/acre. The conservation planning soil loss for the system illustrated in Table 14.5 is 2.6 ton/acre while it is 3.9 tons/acre for the system illustrated in Table 14.6. The major deficiency of the system illustrated in Table 14.6 is that it has fewer alternating strips of hay among corn strips than in the system illustrated in Table 14.5.

Table 14.6. Example of a rotational strip cropping system where the rotation is delayed a year on each subsequent strip.

Strip Number	Years of Offset	Year 1	Year 2	Year 3	Year 4	Year 5
1	0	corn 1	corn 2	hay 1	hay 2	hay 3
2	1	hay 3	corn 1	corn 2	hay 1	hay 2

3	2	hay 2	hay 3	corn 1	corn 2	hay 1
4	3	corn 2	hay 1	hay 2	hay 3	corn 1

RUSLE2 gives full credit to all deposition in the conservation planning soil loss for rotational strip cropping in contrast to the partial credit given for deposition caused by filter and buffer strip/barrier systems.

14.3. Flow Interceptors (diversions/terraces, sediment basins)

The conservation planning soil loss for rotational strip cropping is the same as the sediment yield when the *rotation strip cropping description* in the *strip/barrier component* of the RUSLE2 database is used. The two are not equal when the three layer profile schematic is used to represent rotational strip cropping by directing the overland flow path into segments.

14.3.1. Description of practices

Flow interceptors are topographic features that end the overland flow path (see **Sections 8.2 and 8.3**). Flow interceptors include diversions, terraces, and sediment basins. Diversions and terraces are constructed specifically to intercept overland flow and redirect the runoff around the hillslope in a low gradient channel. Terraces are constructed on a sufficiently low grade to cause deposition and even on a level grade with a closed outlet to conserve soil moisture in dry climates. Diversions are constructed on a sufficiently steep grade so that deposition does not occur but on a sufficiently flat grade so that erosion does not occur. Constructed terraces and diversions typically involve ridges and accompanying channels that convey the runoff to a protected open channel or an underground pipe that conveys the runoff downslope to a safe outlet. Disposal channels must be lined with vegetation, stone, or other material to prevent erosion because flow erosivity can be quite high in these channels.

The two major terrace types used on cropland are gradient and parallel tile outlet (PTO). Grade along a gradient terrace is nearly uniform, which requires plan curvature to fit the hillslope as illustrated in Figure 14.15. This curvature and the resulting non-uniform spacing between terraces along their length inconvenience farming operations. Gradient terraces generally divide the overland flow path length in shorter nearly uniform length overland flow paths between the terraces.

Parallel tile outlet terraces are relatively straight and are nearly uniformly spaced along their length. The terraces create small impoundments where they cross concentrated flow areas as illustrated in Figure 14.15. Impounded runoff drains through a vertical riser connected to an underground tile line (pipe). Grade along parallel terraces is typically non-uniform requiring that the grade be limited to prevent erosion. A variety of overland

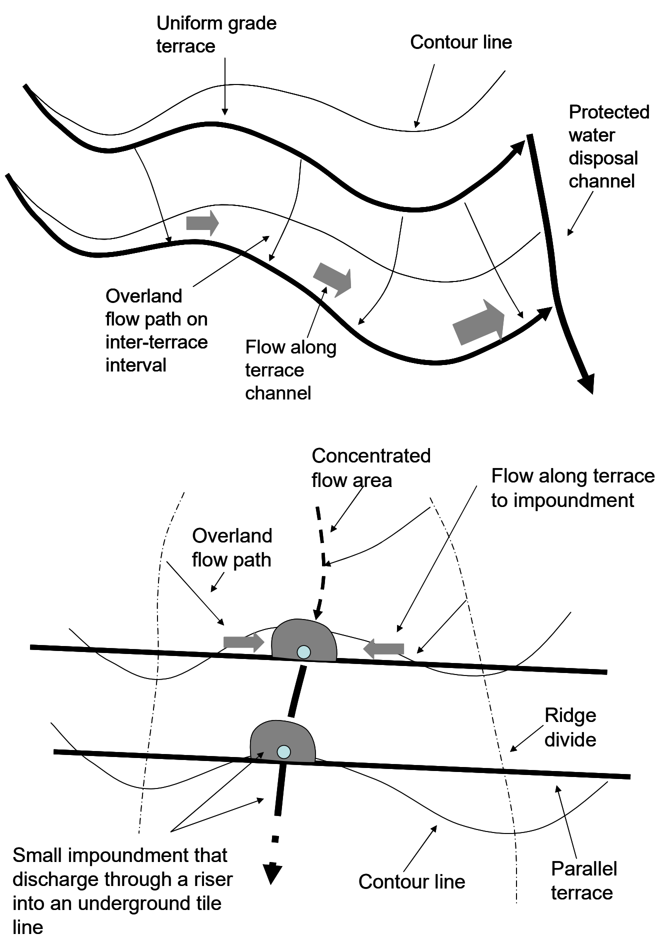

Figure 14.15. Illustration of a gradient terrace (top sketch) and parallel tile outlet (PTO) terrace systems (bottom sketch) and associated flow paths.

flow path lengths exist between parallel terraces. In contrast, to gradient terraces that almost always divide the overland flow path length, the longest overland flow path between parallel terraces may not be affected if the terraces are widely spaced. Sediment yield is low because of deposition in the small impoundment (sediment basin) in the concentrated flow areas.

Diversions, terraces, and sediment basins are also used on construction sites, reclaimed mine land, landfills, and other highly disturbed lands to shorten the overland flow path as illustrated in Figure 8.12 and reduce sediment yield, especially during periods when cover-management erosion control methods can not be used during soil disturbing operations.

Other features, including windrowed forest debris on disturbed forest land following site preparation for reseeding, act as diversion/terraces. Another example is a ridge of soil left by grading operations at the top of a cut or embankment on a construction site (see **Section 8.3.3**). Another example is an off-contour stiff grass hedge where tillage leaves a ridge of soil along the hedge that diverts the runoff rather than allowing it to flow through the hedge. A similar example is an off-contour silt fence on a construction site.

14.3.2. Basic principles

Flow interceptors involve two basic **hydraulic elements**, which are a **channel** and an **impoundment**. Diversions/terraces reduce rill and interrill erosion by shortening the overland flow path length, which is considered in the **topographic description** of the overland flow path (see **Section 8**).

Terraces also reduce sediment yield by causing deposition in the terrace channel. The basic principles described in **Section 5.4** for computing deposition on overland flow areas are used to compute deposition in diversion/terrace channels. The basic concept is that deposition occurs when the sediment load delivered to the diversion/terrace channel by overland flow on the inter-terrace interval exceeds transport capacity in the terrace channel. Deposition is computed with:

$$D = [\phi/(1+\phi)](dT_c/dx - D_o) \qquad [14.1]$$

where: D = deposition rate (mass/time·unit channel width), T_c = transport capacity in the diversion/terrace channel (mass/time), x = distance along the channel, dT_c/dx = change of transport capacity along the channel (mass/time·distance), and D_o = sediment delivered to the channel from the overland flow area (mass/time·unit distance along channel). The variable φ is given by:

$$\phi = aV_f / q_c \qquad [14.2]$$

where: α = a coefficient to be determined by calibration, V_f = fall velocity of the sediment particles, and q_c = discharge rate in channel per unit channel width, which is the discharge rate from the overland flow path that ends at the diversion/terrace channel. Transport capacity in the channel is computed by:

$$T_c = K_{Tc} Q_c s \qquad [14.3]$$

where: K_{Tc} = a coefficient to be determined by calibration, $Q_c = q_c x$ = discharge rate in the channel, and s = sine of the grade angle of the channel.

Simplifying assumptions consistent with RUSLE2's purpose to serve as a guide for conservation and erosion control planning were made in solving these equations. The equations are applied to each sediment particle class assuming no interaction among the particle classes. Grade along the channel is assumed to be uniform, which gives the mathematical result that deposition is uniform along the channel. Consequently, channel length is not a factor in the computations and, therefore, is not an input.

Transport capacity for a sediment particle class is assumed to be proportional to its portion in the sediment load that reaches the channel. Deposition among the particle classes varies according to the particle class's fall velocity. RUSLE2 computes the particle class distribution and the sediment load leaving the channel. RUSLE2 computes an enrichment ratio that is a measure of how deposition enriches the sediment load in fines (see **Section 7.5.1**). The enrichment ratio increases as deposition increases (i.e., as the sediment delivery ratio decreases).

RUSLE2 also assumes a smooth, bare soil surface in a diversion/terrace channel. Deposition in these channels is highly localized, typically along the channel edge where overland flow enters the channel flow. Deposition covers most soil surface roughness and crop residue to leave a bare, smooth soil surface. RUSLE2 does not accurately compute deposition where vegetation in the channel retards the flow to cause deposition. This limitation is not especially important because most erosion and deposition occur during the cropping season before vegetation develops.

RUSLE2 does not consider channel cross section shape in its computations.

Sediment delivery ratio is a measure of deposition. In RUSLE2, the sediment delivery ratio for a given diversion/terrace channel varies with several factors including channel grade and runoff, sediment load, and sediment characteristics entering the channel from the inter-diversion/terrace area. For example, very little or no deposition occurs when the channel grade is steep because transport capacity is high. Very little deposition occurs when sediment delivery is low and runoff is high from the overland flow area. Deposition is reduced when incoming sediment is mostly fine particles caused by the source soil properties or deposition on the overland flow path, particularly near its end (e.g., deposition by a grass strip or a flat concave overland flow path segment at the channel edge). Consequently, the sediment delivery ratio computed by RUSLE2 for a diversion/terrace is not constant for a particular channel grade, but depends on the conditions on the inter-diversion/terrace area as well.[149]

RUSLE2 computes deposition in a small impoundment (sediment basin) using:

$$g_{out} = g_{in} \exp(-\beta V_f) \quad [14.4]$$

where: g_{in} = sediment load coming into the sediment basin, g_{out} = sediment load leaving the sediment basin, and α = a coefficient determined by calibration. This equation is fundamentally for a simple settling tank where transport capacity is assumed to be zero and the effective length is determined by calibration. RUSLE2 computed deposition depends only on the characteristics of the incoming sediment. RUSLE2 typically computes large deposition amounts and fine sediment leaving the basin. RUSLE2 computes reduced deposition if the incoming sediment is fine, which is why RUSLE2 computes significantly less deposition by a second sediment basin than by the first basin in a series. RUSLE2 computes an enrichment ratio, which is a measure of deposition enriching the sediment in fines, for the outgoing sediment (see **Section 7.5.1)**.

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[149] The RUSLE1.06 computes deposition by diversions/terraces similar to RUSLE2. However, RUSLE1.05 computes sediment delivery ratio solely as a function of diversion/terrace grade.

RUSLE2 computed deposition is not a function of basin geometry, hydraulics, or remaining basin capacity. That is, RUSLE2 does not consider design or maintenance in its impoundment (sediment basin) computations.

RUSLE2 takes partial credit for the deposition caused by terraces and impoundments as soil saved in protecting the soil resource. The amount of deposition credited as soil saved in computing the conservation planning soil loss depends on diversion/terrace spacing and location of the diversion/terrace along the overland flow path. Deposition in a terrace located near the end of the overland flow path gets very little credit as soil saved. Deposition in a terrace located about half way along the overland flow path gets approximately half credit as soil saved when diversion/terrace spacing is less than 90 ft (30 m). The credit decreases as spacing increases beyond 90 ft (30 m) to essentially no credit for spacing greater than 300 ft (100 m).

RUSLE2 is a conservation and erosion control planning tool. It is not a hydraulic design tool. See *Haan et al. 1994. Design Hydrology and Sedimentology for Small Catchments. Academic Press* for a description of procedures that can be used to design channels and impoundments. Also, RUSLE2 is not meant to displace standards used by agencies such as the USDA-NRCS, although those standards sometime compromise practice performance for farming convenience and other reasons not considered by RUSLE2.

14.3.3. Calibration

Calibrating RUSLE2 for flow interceptors involves two sets of calibration, one for deposition in terrace channels and one for deposition in small impoundments (sediment basins). The erosion component of the CREAMS and the RUSLE1.05 equation that computes sediment delivery as a function of terrace grade were major tools used in this RUSLE2 calibration.[150] The CREAMS erosion component represents experimental field data involving gradient terraces on a range of grades at numerous locations, which were also used to derive the RUSLE1.05 equation. Another data set used in the RUSLE2 calibration was from a study of deposition in a ridge-furrow system.[151] The first step in

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[150] See:
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Foster, G. R., L. J. Lane, J. D. Nowlin, J. M. Laflen, and R. A. Young. 1980. A model to estimate sediment yield from field sized areas: Development of model. *In:* CREAMS - a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. Vol. I: Model Documentation. Conservation Research Report No. 26. USDA-Science and Education Administration. pp. 36-64.

Foster, G. R. and R. E. Highfill. 1983. Effect of terraces on soil loss: USLE P factor values for terraces. Journal of Soil and Water Conservation 38:48-51.

[151] Meyer, L.D. and W. C. Harmon. 1985. Sediment losses from cropland furrows of different gradients. Trans. ASAE. 28: 448-453, 461.

the calibration was to determine a value for the $\mathbf{K_{TC}}$ coefficient in the sediment transport capacity equation, equation 14.3, for a terrace channel. The value for this coefficient was adjusted until sediment transport capacity matched sediment load at the point that deposition was judged to begin based on field data as channel grade was reduced. Sediment transport capacity equals sediment load at the point that deposition begins according to RUSLE2 theory. The next step in the calibration was to determine a value for the coefficient $\boldsymbol{\beta}$ in equation 14.2. This equation determines the RUSLE2 computed particle class distribution in the sediment leaving the channel and determines deposition amount to a much lesser extent. Both the experimental field data and computed values from the CREAMS erosion component were used in this calibration.

The second set of calibrations was to determine a value for the coefficient **a** in equation 14.4 that RUSLE2 uses to compute deposition by particle class for a small impoundment. Once again, the CREAMS erosion component was used in the calibration because it had been calibrated using data from several field studies of impoundment, tile outlet terraces in Iowa. The primary calibration was to adjust values for the coefficient $\boldsymbol{\beta}$ until the RUSLE2 computed sediment delivery ratio matched experimental values. Also, the RUSLE2 computed values were evaluated against experimental values determined from sediment basins used on construction sites and mined land. The RUSLE2 computed sediment delivery ratio values matched the experimental values for sediment basins on highly disturbed land where the basins were well designed and constructed and were clear of sediment, i.e., functioning at optimum performance.[152]

14.3.4. Interpretation

RUSLE2 computations for **hydraulic elements** are for conservation and erosion control planning, **not for design**. RUSLE2 computes deposition in channels typical of diversions, terraces, and similar channels that intercept overland flow. RUSLE2 does not consider channel shape or hydraulic resistance in its computations. Although RUSLE2 computes average annual deposition, the computations represent an approximate 10 year return period. The channels are assumed to be in an environment, typically cropland and construction sites, where failure does not cause major damage and routine maintenance and repair are readily available.

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[152] See:

Foster, G. R., L. J. Lane, J. D. Nowlin, J. M. Laflen, and R. A. Young. 1980. A model to estimate sediment yield from field sized areas: Development of model. *In:* CREAMS - a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. Vol. I: Model Documentation. Conservation Research Report No. 26. USDA-Science and Education Administration. pp. 36-64.

Toy, T.J. and G.R. Foster (coeditors). 1998. Guidelines for the use of the Revised Universal Soil Loss equation (RUSLE1.06) on mined lands, construction sites, and reclaimed lands. USDI-Office of Surface Mining. Denver, CO.

However, a different environment exists in other RUSLE2 applications where a diversion failure causes major problems. Diversions are sometimes used on the steep side slopes of landfills and hazardous waste sites to reduce rill erosion. Deposition in the diversions should be avoided because it reduces flow capacity, which can cause overtopping, very serious gully erosion, and major failure of the diversion. Maintaining a uniform grade and avoiding adverse grades along these diversions is especially important to prevent overtopping. Also, differential settling on the overland flow area between diversions can cause overland flow to become concentrated flow that causes serious gully erosion and overwhelms downslope diversions. RUSLE2 provides no information on such localized failures.

Similarly, RUSLE2 computes average annual deposition by small impoundments (sediment basins) assuming optimum performance without considering basin geometry, hydraulics, or water and sediment chemistry. RUSLE2 computed values apply to small sediment basins similar in size and hydraulic performance to the impoundments created by parallel tile outlet terraces where impounded water is drained by a perforated riser pipe that discharges into an underground pipe. Retention time in these basins is about 24 hours and the maximum water depth is about 4 to 6 ft (1 to 2 m).

These sediment basins often have a life expectancy less than five years, which means that the probability of an extreme event occurring while they are in place is low. Therefore, RUSLE2's estimate of average annual deposition is reasonable for conservation and erosion control planning. Damages are likely to be minor if failure occurs. Construction cost is low and maintenance and repair are readily available. Cleaning the basin after major storms may be more cost effective than building a large basin based on an extreme event.

All hydraulic structures including channels and impoundments should be based on proper engineering design. *RUSLE2 IS NOT AN ENGINEERING DESIGN TOOL.* Good professional judgment should always be used in making final decisions rather than relying solely on RUSLE2. RUSLE2 is to be used as a guide to supplement other information.

14.3.5. Inputs

The **hydraulic element (open channel-impoundment) systems component** of the RUSLE2 database is used in routine conservation and erosion control planning to evaluate the effect of diversions/terraces and small impoundments (sediment basins) on erosion and sediment yield from the flow path represented in the RUSLE2 computation. The hydraulic element systems database component contains **diversions/terraces and sediment basin systems descriptions** that are applied to the overland flow path without the hydraulic elements in place. Each hydraulic element system description involves a **hydraulic element (channel/impoundment) flow path description** that is applied at one or more equally spaced intervals along the overland flow path. A channel/impoundment flow path description lists the **hydraulic elements** (i.e., channels, impoundments) in the channel/impoundment flow path. Each diversion/terrace and sediment basin is assumed to be thin and to take up no space on the hillslope. This approach does not take into account how back and front slope characteristics of a diversion/terrace or sediment basin affect erosion.

A RUSLE2 **template** having the **three layer profile schematic** should be used (1) for complex conditions where the channel/impoundment flow paths are not equally spaced along the overland flow path, (2) where the individual channel/impoundment flow path differ, (3) where the soil, topography, and cover-management conditions of the embankment/channel should be described because of their effect on erosion, and (4) where soil, steepness, or cover-management vary along the overland flow path.

An example where the hydraulic element flow paths are non-uniformly spaced along the overland flow path is illustrated in Figure 8.12 where a diversion is placed at the top of a landfill sideslope. Figure 8.11 illustrates a detailed description of embankment/channel topography. Grass is often used on steep backslope terraces to prevent excessive erosion. The detailed soil, topography, and cover-management of such embankment/channels can be represented as described in **Sections 8.3.3 and 8.3.4**.

14.3.5.1. Inputs for a hydraulic element (channel/impoundment) system description

The inputs for a **hydraulic element (channel/impoundment) system description** are (1) number of hydraulic element (channel/impoundment) flow paths that cross the overland flow path, (2) whether a channel/impoundment flow path is located at the end of the overland flow path, and (3) the **hydraulic element (channel/impoundment) flow path description**.

When a hydraulic element (channel/impoundment) system description is used in RUSLE2, the overland flow path length is described without the hydraulic elements present. RUSLE2 uses the input for number of channel/impoundment flow paths that cross the overland flow path to determine the overland flow path length between the hydraulic element flow paths. This overland flow path length is the overall overland flow path length divided by number of channel/impoundment flow paths (diversion/terraces) if a channel/impoundment path is located at the end of the overland flow path. If a channel impoundment path is not located at the end of the overland flow path, the overland flow path length between channel/impoundment paths is computed as the overall overland flow path length divided by the number of channel/impoundment paths plus one.

The number of channel/impoundment flow paths that cross the overall overland flow path varies with the overland flow path chosen for the RUSLE2 computation. A representative number should be chosen based on the conservation and erosion control planning objective, which is similar to choosing the number of porous barriers that cross the overland flow path (see **Sections 14.2.5.1 and 14.2.5.2**).

Extra consideration should be given to selecting the number of channel/impoundment flow paths that cross the overall overland flow path when representing parallel impoundment terraces. The overland flow path length between parallel impoundment terraces varies greatly as illustrated in Figure 14.15. The RUSLE2 computed overland flow path length should be checked to determine if this overland flow path length is appropriate. The RUSLE2 computed overland flow path length can sometimes be too short. An improvement in the erosion computation can be made by decreasing the number of channel/impoundment flow paths that cross the overall overland flow path. Also, the overall overland flow path can be lengthened for the hydraulic element computation but not for the computation when the hydraulic elements are not present. Another alternative is to apply RUSLE2 to a single inter-terrace interval.

The number of channel/impoundment paths is not the total number on the hillslope but the number that cross the selected overland flow path used in the RUSLE2 computation.

The input of whether a channel/impoundment (diversion/terrace) flow path is at the end of the overland flow path significantly affects computed sediment yield. A diversion/terrace at the end of the overland flow path is unnecessary when the sole purpose of the diversion/terrace system is to control rill-interrill erosion. In that case, a **no** input is selected for whether a channel/impoundment flow path is located at the end of the overland flow path. When **no** is selected, the sediment eroded on the last overland flow path interval leaves the RUSLE2 overall overland flow path without passing through the selected channel/impoundment flow path. If a channel/impoundment flow path is placed at the end of the overland flow path to trap sediment and control sediment yield from the site, select **yes** for whether a channel/impoundment flow path is located at the end of the overland flow path. This selection causes RUSLE2 to compute that sediment eroded on all overland flow path intervals passes through the selected channel/impoundment flow path.

The last input is to select a **hydraulic element (channel/impoundment) flow path description** from previously created entries in the RUSLE2 database.

14.3.5.2. Inputs for a hydraulic element (channel/impoundment) flow path description

A **hydraulic element (channel/impoundment) flow path description** gives the sequence of hydraulic elements (i.e., channel and impoundment) along the flow path.

Table 14.7 lists the possible sequences that can be used in RUSLE2.[153]

DO NOT ENTER SEQUENCES OTHER THAN THOSE LISTED IN TABLE 14.8.

Table 14.7. Possible sequences of channel and impoundment hydraulic elements used to represent hydraulic element (channel/impoundment) flow paths.	
Sequence	Comment
Impoundment	Overland flow drains directly into impoundment. Typical application is a sediment basin on a construction site.
Impoundment-impoundment	Overland flow drains directly into the first impoundment, which in turn drains directly into the second impoundment. Typical application is two sediment basins in series on a construction site where sediment yield leaving the site must be very low.
Channel	Overland flow drains uniformly into channel along its length. No inflow at upper end of the channel can occur. Typical application are gradient terraces on an agricultural field or a diversion on a construction site or landfill.
Channel-impoundment	Overland flow area drains uniformly into channel along its length. No inflow at upper end of the channel can occur. Discharge from channel flows directly into impoundment. Typical applications are impoundment parallel terraces on an agricultural field and a diversion used to divert overland flow into a sediment basin on a construction site.
Channel-impoundment-impoundment	Same as a channel-impoundment sequence except that discharge from the first impoundment flows directly into the second impoundment. An example application is a diversion channel discharging overland flow into a series of two sediment basins on a construction site.
Note: When a segment on the overland flow path is adjacent to a segment with an adverse (negative) steepness, RUSLE2 assumes a channel hydraulic element at the intersection of the segments (see **Section 8.3.3**). The default channel assumed by RUSLE2 is steep so that no deposition occurs. A hydraulic element (channel/impoundment) flow path description from the RUSLE2 database can be substituted for the default channel, which allows RUSLE2 to compute deposition in channels at the intersection of the backslope and frontslope of a bench terrace system (see Figure 14.16) and in furrows separating ridges (see Figure 8.14), for example.	

An impoundment element can be the single element in the sequence, which represents overland flow discharging directly into an impoundment without first flowing through a channel. This sequence represents a sediment basin on a construction site.

[153] Other sequences besides those listed in Table 14.8 can be entered, but RUSLE2 does not properly compute deposition for other sequences.

Outflow from an impoundment is assumed to be a point discharge that can only flow into another impoundment. It can not discharge into a channel because a channel can not accept inflow at its upper end. Two or more impoundments can be placed in series to represent sediment basins in series.

A RUSLE2 channel hydraulic element is a channel of uniform grade that receives runoff uniformly along its length from the adjacent overland flow area. No inflow occurs at the upper end of the channel (i.e., discharge is zero at the upper end of the channel). **Only a single channel can be in the sequence of hydraulic elements used to describe a hydraulic element (channel/impoundment) flow path. If a channel is in the sequence, it must be the first hydraulic element in the sequence.**

RUSLE2 does not compute erosion in a channel. Ensure that the channel's lining is sufficient to prevent erosion for the channel's field grade.

A single channel is used to represent gradient terraces, illustrated in Figure 14.15, on an agricultural field, a diversion on a construction site, and a diversion at the top of the landfill sideslope illustrated in Figure 8.12. The discharge from a channel is a point discharge that can only flow into an impoundment element because of the no inflow requirement for a channel. A channel-impoundment sequence is used to represent parallel impoundment terraces illustrated in Figure 14.15.

The no inflow requirement for channels means that a sequence of channels can not be used to describe a variable grade diversion or terrace system, for example. A single grade must be entered to represent a variable grade channel. If the profile along the channel is concave, enter the grade over the last one fourth to one third of the channel. If the profile along the channel is convex, enter the grade over the first one third to one half of the channel.

Notes:
Grade along a RUSLE2 channel is uniform.
No inflow can occur at the upper end of a RUSLE2 channel, i.e., channels can not be in series to represent non-uniform grade channels.
RUSLE2 does not compute erosion in channels.
RUSLE2 is not a hydraulic design procedure. Proper hydraulic procedures should be used to design channels and impoundments.
The impoundments considered by RUSLE2 are small impoundments like sediment basins and impoundments associated with parallel tile outlet terraces.
RUSLE2 does not consider the disposal channel system associated with diversions and gradient terraces.

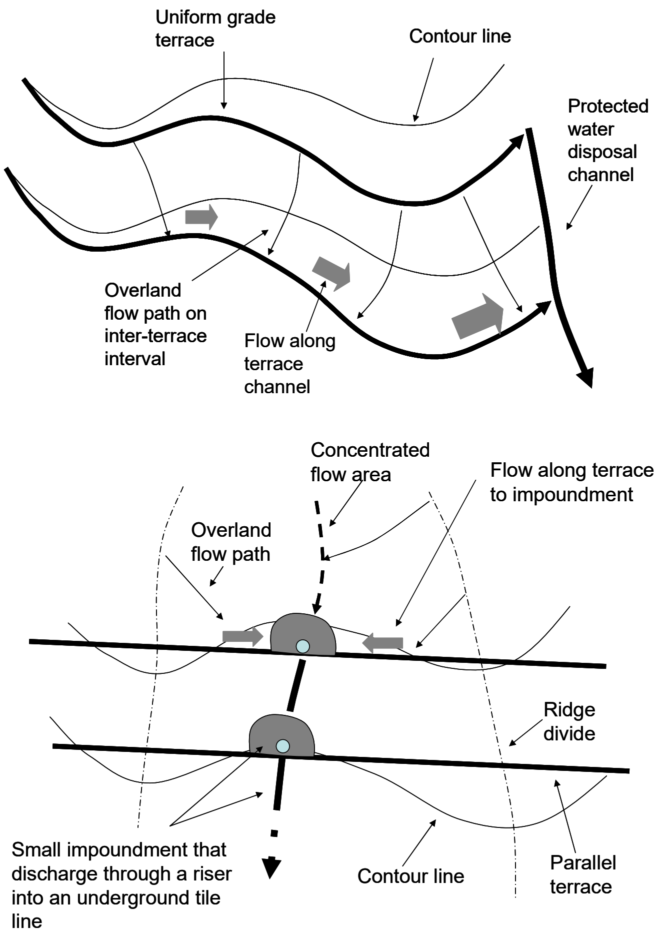

Figure 14.15. Illustration of a gradient terrace (top sketch) and parallel tile outlet (PTO) terrace systems (bottom sketch) and associated flow paths.

No inputs are required to describe an impoundment hydraulic element. Grade is the single input used to describe a channel hydraulic element. A typical RUSLE2 database contains channel descriptions over a range of grades from which selections can be made in describing channel/impoundment flow path systems.

RUSLE2 makes no distinction between a diversion or a terrace channel. Both are represented by the same channel hydraulic element. If a channel is intended to behave as a diversion where no deposition is expected, the RUSLE2 output should be reviewed for deposition. If deposition is computed in the diversion channel, a channel with an increased grade should be selected.

14.3.5.3. Inputs for the RUSLE2 default channel description

RUSLE2 automatically inserts a **default channel** when an overland flow path segment intersects with an overland flow path segment having an adverse (negative) steepness (see **Section 8.3.3**). Also, RUSLE2 may automatically assign a default channel at the end of the overland flow path. The grade of this default channel is already entered in the RUSLE2 database, and it can be changed. The grade is usually set at a very high steepness (e.g., 100 percent) so that RUSLE2 does not compute deposition in the default channel. Another channel that represents the field condition can be selected to replace the default channel in a particular RUSLE2 computation by selecting a channel/impoundment flow path description from the RUSLE2 database. By making this substitution, RUSLE2 can compute deposition in the channels that RUSLE2 assigns for inward sloping bench terraces illustrated in Figure 14.16, in the furrows between ridges illustrated in Figure 8.14, and in a concentrated flow areas that separates two overland flow areas, which are created by dividing an overland flow path into two segments and entering a negative steepness for the second segment.

14.3.5.4. Inputs for bench terraces

Figure 14.16 illustrates bench terraces that can be represented by RUSLE2. The hydraulic element system component of the RUSLE2 database is not used in this RUSLE2 application. A RUSLE2 template having the three layer profile schematic is used to describe bench terraces.

The first bench terrace system is an outward sloping bench terrace where the benches slope outward away from the hillslope. The overland flow path is divided into segments where steepness values are entered into appropriate segments to represent the steep backslope and the relative flat bench. Runoff as overland flow is assumed from the top of the benches across each bench through the last bench. Different cover-management descriptions are selected for the backslope and bench segments.

The same procedure is used to describe inward sloping bench terraces where the benches slope inward to the hillslope. A negative steepness is entered for the inward sloping bench segments. Using this information, RUSLE2 determines the overland flow path lengths for each segment. RUSLE2 treats each backslope-bench combination as a separate catchment. RUSLE2 also assigns a default channel at the intersection of the backslope and bench. A channel on a low grade can be selected from the RUSLE2 database to replace the default channel so that RUSLE2 can compute deposition in the runoff that flows around the hillslope at the base of each backslope. Appropriate cover-management descriptions are selected for the backslope and bench segments.

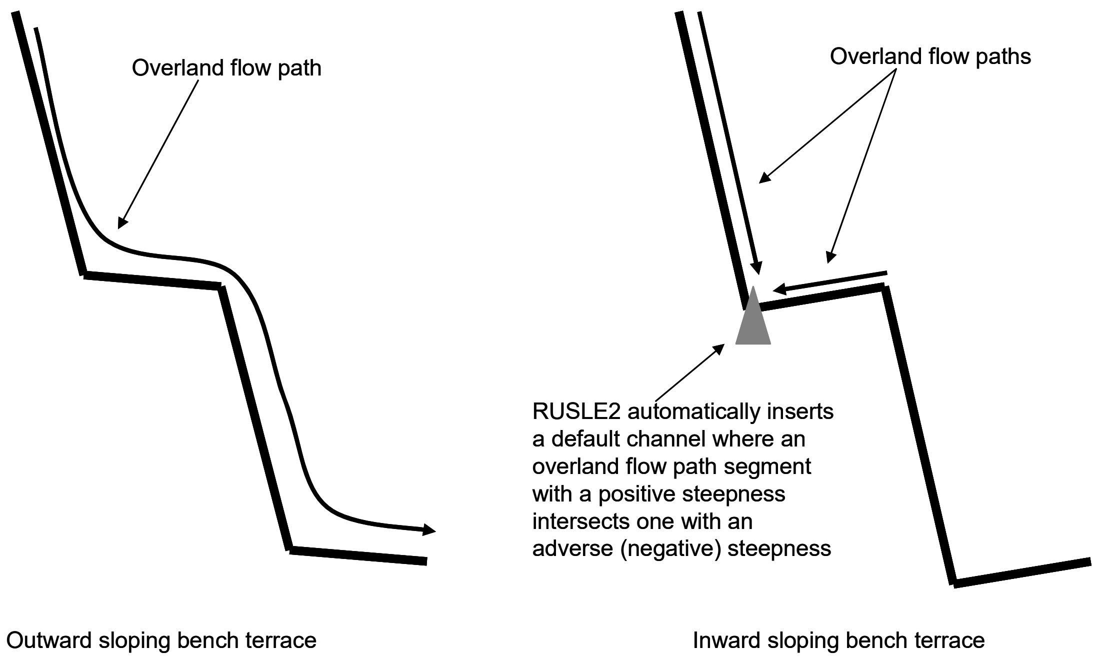

Figure 14.16. Overland flow paths for outward and inward sloping bench terraces.

14.4. Subsurface Drainage

14.4.1. Description of practice

Subsurface drainage is where lateral ditches or perforated pipe (tile line) placed about 2 to 3 ft (0.5 to 1 m) below the soil surface are used to reduce soil wetness to facilitate farming operations and improve crop yield. Subsurface drainage is most often used on relative flat slopes, less than 3 percent steepness, where the water table is near the soil surface over most of the site. Subsurface drainage lowers the water table and reduces soil water content, which in turn reduces runoff and erosion. Localized areas can also be subsurface drained. Examples include where a restricting layer causes a perched water table or in swales where the water table is high at the toe of hillslopes.

Installing tile drainage can be expensive, and therefore, a tile drainage system should be well designed based on site-specific conditions. The two major variables in a subsurface drainage system are depth and spacing of the tile lines and drainage ditches. Increasing depth and decreasing spacing improves subsurface drainage performance but also increases costs. Therefore, most subsurface drainage systems represent a balance between benefits and costs.

14.4.2. Basic principles

Subsurface drainage reduces rill-interrill erosion because it reduces surface runoff and increases vegetation production (crop yield) level. RUSLE2 uses the permeability subfactor equation in its soil erodibility nomographs to estimate how runoff potential reduced by subsurface drainage affects soil erodibility. The effect of increased production (yield) level is considered by inputting a production (yield) level value appropriate for the drained condition.

The two RUSLE2 soil erodibility nomographs include a permeability subfactor that adjusts soil erodibility based on the soil's runoff potential. The six permeability classes used in the nomographs describe runoff potential. Choice of a soil erodibility nomograph permeability class is based on texture and other surface soil properties, soil profile characteristics, presence of a naturally occurring restrictive layer, landscape position, location, and other factors that affect runoff potential under the unit plot condition (see **Sections 7.2 and 7.3.2**). Soil erodibility factor values increases as runoff potential increases.

Each **soil description** in the RUSLE2 database includes a hydrologic soil group designation, which is an index of runoff potential, for the undrained and drained conditions (see **Section 7.7**). RUSLE2 uses this index in the NRCS curve number method to estimate runoff (see **Section 8.1.2**).[154] A **D** hydrologic soil group represents the highest runoff potential while an **A** hydrologic soil group represents the lowest runoff potential. The same factors that determine a permeability class in a RUSLE2 soil erodibility nomograph also determine a hydrologic soil group.

The degree that subsurface drainage changes the hydrologic soil group depends on site specific conditions. A very fine texture undrained soil may be assigned a **D** hydrologic soil group. Subsurface drainage will decrease the soil's runoff potential, but not greatly, resulting in a change of hydrologic soil group from **D** to **C** or **B**. Soil texture is a limiting factor in being able to economically drain this soil.

A coarse texture soil may be assigned a **D** hydrologic soil group because of a restrictive subsoil layer or being in a low position on the landscape. Subsurface drainage can greatly improve internal drainage of this soil resulting in the hydrologic soil group changing from a **D** to an **A**. A coarse soil texture does not limit internal drainage nearly as much as does a fine texture.

Subsurface drainage does not always change the hydrologic soil group designation to an A hydrologic soil group. Internal soil properties, especially texture, also affect the assigned hydrologic soil group for the drained condition.

RUSLE2 uses the permeability subfactor in its soil erodibility nomographs to compute how subsurface drainage affects erosion. RUSLE2 computes permeability subfactor values for the soil erodibility factor based on the hydrologic soil group assigned for the undrained and the drained conditions. RUSLE2 uses the permeability subfactor values and the soil erodibility factor for the undrained condition to compute an **effective soil erodibility factor** value for the drained condition. The four hydrologic soil group classes are scaled to match the six permeability classes used in the permeability subfactor so that a hydrologic soil group can be converted to a soil erodibility nomograph permeability class. RUSLE2 computed values for the effect of subsurface drainage on rill-interrill erosion are illustrated in Table 14.8.

RUSLE2 computes the greatest effect of subsurface drainage when soil erodibility factor (K) values are low. For example, RUSLE2 computes a 60 percent reduction in erosion for subsurface drainage that reduces runoff potential from a **D** to **A** hydrologic soil group for a silty clay soil with a 0.20 US units soil erodibility factor (**K**) value. This runoff potential reduction is too high for a fine textured soil. A more likely runoff reduction potential would be either from a **D** to **C** or **B** hydrologic soil group. RUSLE2 computes

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[154] The permeability classes used in the RUSLE2 soil erodibility nomographs are essentially a runoff potential index in much way that the hydrologic soil group is a potential runoff index. The permeability class index is used in RUSLE2's soil erodibility nomograph to compute soil erodibility values and the hydrologic soil group index is used in RUSLE2 in the NRCS curve number runoff estimation method to estimate runoff in RUSLE2.

about a 20 percent reduction in erosion for this silty clay soil when runoff potential decreased from a **D** to **C** hydrologic soil group. RUSLE2 computes about a 25 percent reduction in erosion when the runoff potential decreases from **D** to **A** hydrologic soil group for a silt soil having a **K** value of 0.55 US units. These computations are based on the same crop yield for all cases.

The additive, rather than multiplicity, mathematical structure of the soil erodibility nomograph accounts for the much greater relative reduction in erosion by subsurface drainage at low soil erodibility factor values than at high soil erodibility factor values.

A lower limit of 0.2 is set in RUSLE2 for the ratio of erosion with subsurface drainage to erosion without subsurface drainage to prevent RUSLE2 from computing unreasonably low erosion estimates with subsurface drainage.

The RUSLE2 computed values for the effect of subsurface drainage on erosion is essentially not a function of location as illustrated in Table 14.8. Subsurface drainage should affect erosion more at a low precipitation location that at a high precipitation location, especially for coarse texture soils. Values for the hydrologic soil group for the drained condition entered in the **soil descriptions** in the RUSLE2 database can be selected to take this effect into account (see **Section 14.4.5**).

The runoff reduction provided by subsurface drainage depends on drain depth and spacing. This effect can be considered by the values entered in the soil descriptions for the drained condition (see **Section 14.4.5**).

Cover-management condition interacts with surface drainage to affect runoff. That effect is considered by the production (yield) level value for the drained condition entered in the **cover-management descriptions** in the RUSLE2 database (see **Section 10.2.4**). The production (yield) value in a RUSLE2 computation should be appropriate for the subsurface drainage condition.

The other effect of subsurface drainage that RUSLE2 considers is how reduced runoff affect contouring, contouring failure (critical slope length), and sediment transport capacity and deposition. A reduced runoff, which is used in these computations, is computed because of the reduced hydrologic soil group for subsurface drainage. Therefore, because of this reduced runoff, RUSLE2 computes less erosion and sediment yield for situations where contouring and deposition is involved.

If a subsurface drainage support practice is selected, the production (yield) level value should be changed accordingly from the undrained condition.

14.4.3. Calibration/validation

A rule of thumb is that tile drainage reduces rill-interrill erosion by about 40 percent.[155] RUSLE2 computations based on the principles described in **Section 14.2** were made for a wide range of soil textures and drainage intensities to ensure that RUSLE2 gives this result overall. Based on a review of the values listed in Table 14.8 and other values, RUSLE2 was judged to adequately capture the main effects of subsurface drainage on rill-interrill erosion for conservation and erosion control planning. The values shown in Table 14.8 do not consider how subsurface drainage affects yield and its consequent effect on erosion, which is an additional subsurface drainage effect.

14.4.4. Interpretation

Just as for other support practices, RUSLE2 erosion estimates for subsurface drainage represent broad, general effects more than site specific effects. RUSLE2 captures how factors related to site location, vegetation production (yield) level, soil properties, soil position on the landscape, and characteristics of the drainage system affect erosion. RUSLE2 results are much better than the rule of thumb that subsurface drainage reduces erosion by 40 percent. The accuracy of RUSLE2 erosion estimates for subsurface drainage is similar to that for other support practices, including contouring.

Sometimes subsurface drainage is given little consideration as an erosion control practice. It is seldom installed solely for erosion control because of its expense. However, research clearly shows that subsurface drainage significantly reduces erosion in certain conditions, and, therefore, erosion reduction should be recognized as an important benefit of subsurface drainage. Sometimes subsurface drainage is considered to be environmentally detrimental because it is used to drain wetlands, for example.

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[155] See:
AH703

Bengston, R.I. and G. Sabbage. 1988. USLE P-factor for subsurface drainage in a hot, humid climate. ASAE Paper 88-2122. American Society of Agricultural Engineers. St. Joseph, MI.

Formanek, G.E, E. Ross, and J. Istok. 1987. Subsurface drainage for erosion reduction on croplands of northwestern Oregon. In: Irrigation Systems of the 21st Century. Proceeding Irrigation and Drainage Division Specialty Conference. American Society of Civil Engineers. New York, NY. pp. 25-31.

Schwab, G.O. 1976. Tile or surface drainage for Ohio's heavy soils? Ohio Report. March-April. Ohio Agricultural Experiment Station. Columbus, OH.

Schwab, G.O. and J.L. Fouss. 1967. Tile flow and surface runoff from drainage systems with corn and grass cover. Transactions ASAE 10:492-493, 496.

Skaggs, R.W., A Nassehzadeh-Tabrizi, and G.R. Foster. 1982. Subsurface drainage effects on erosion. Journal of Soil and Water Conservation 37:167-172.

Table 14.8. RUSLE2 computed effect of subsurface drainage on erosion as a function of soil erodibility factor value (K) ad hydrologic soil group at three locations (does not consider any change in yield)

	Erosion drained/erosion undrained
silty clay soil (K = 0.20 US units), change in hydrologic soil group from D to A	
Ft Wayne, IN	0.38
Raleigh, NC	0.38
Jackson, MS	0.38
silty clay soil (K=0.20), hydrologic soil group D to C	
Ft Wayne, IN	0.83
Raleigh, NC	0.78
Jackson, MS	0.75
sandy loam soil (K = 0.30), hydrologic soil group D to A	
Ft Wayne, IN	0.58
Raleigh, NC	0.57
Jackson, MS	0.60
silt soil (K = 0.55), hydrologic soil group from D to A	
Ft Wayne, IN	0.77
Raleigh, NC	0.76
Jackson, MS	0.77

However, subsurface drainage should be recognized for its merits in appropriate situations.

Perhaps more than any other practice, the subsurface drainage component in RUSLE2 is subject to misuse. For example, subsurface drainage is most effective on relatively flat hillslope areas less than 3 percent steep and in localized areas of wet soils. RUSLE2 does not identify where subsurface drainage should not be used. Technical standards should be consulted for information on subsurface drainage applications.

14.4.5. Input

The **deep (subsurface) soil drainage system descriptions** in the RUSLE2 database have a single input of **portion of the hillslope that is well drained.** The other RUSLE2 inputs to represent subsurface drainage are the hydrologic soil groups in the **soil description** for the undrained and drained conditions (see **Section 7.7**) and the production (yield) level input in the **cover-management description**s used for the drained and undrained conditions (see **Section 10.2.4**).

The hydrologic soil group input represents the degree that subsurface drainage reduces runoff potential of the soil under the unit plot condition given the site location, the soil's position on the landscape, soil profile properties, naturally occurring soil restrictive layers, and subsurface drain depth and spacing. Multiple **soil descriptions** for the same soil profile can be created for various drain depths and spacings. The input for the hydrologic soil group for the drained condition should reflect the site's location. For example, subsurface drainage may have a greater effect on the reduction of runoff potential on a coarse texture soil at a low precipitation location when compared to a high precipitation location. The input for hydrologic soil group for the undrained and drained conditions reflects soil profile properties, especially texture. As discussed in **Section 14.2**, subsurface drainage does not automatically reduce the hydrologic soil group to **A** for all soils, especially fine textured soils.

The NRCS soil survey database and the NRCS RUSLE2 database may have a hydrologic soil group assigned for drained conditions. Check the criteria that NRCS used to select hydrologic soil groups to ensure consistency with RUSLE2 criteria.

Vegetation production (yield) level is usually increased by subsurface drainage because increasing crop production is the major reason for subsurface drainage. Use appropriate yield values for both the undrained and drained conditions.

Subsurface drainage was installed decades ago in many farm fields. When applying RUSLE2 to these fields, the easiest approach is to ignore subsurface drainage if no assessment is being made on how subsurface drainage affects erosion. Make sure that the hydrologic soil group input for the undrained condition and the input for vegetation production (yield) level represents the current field condition. RUSLE2 computes a subsurface drainage effect only if the hydrologic soil group input for the drained condition differs from the corresponding input for the undrained condition, and different vegetation production (yield) level inputs are not entered for the drained and undrained conditions.

The input for **portion of the hillslope that is well drained** is used to compute erosion for an overland flow path where only a portion of it is subsurface drained. An overland flow path having a complex:convex-concave profile is an example. The lower concave portion of this profile can have high soil wetness because of a low landscape position. Localized subsurface drainage is used to eliminate this soil wetness. Soil wetness is not a problem on the upper part of the overland flow path. An input value less than 100 percent for **portion of the hillslope that is well drained** represents this situation. RUSLE2 uses this input to weight its detachment (sediment production) computations and the curve numbers it uses to computes runoff for the undrained and drained conditions.

Also, this input can be used to reduce the effect that RUSLE2 computes for subsurface drainage. For example, if RUSLE2 is judged to compute too much erosion reduction, a value less than 100 percent can be input to reduce the subsurface drainage effect computed by RUSLE2. If the trivial input of zero (0) is entered, RUSLE2 computes no subsurface drainage effect on erosion, unless different yield values are used for the undrained and drained conditions.

RUSLE2 does not notify the user when it computes questionable erosion estimates for subsurface drainage. The RUSLE2 user must know where and how subsurface drainage is used and must make the proper inputs.

14.5. Irrigation

14.5.1. Description of practice

Irrigation adds water to the soil to increase vegetation (crop) production or to dispose of waste. The principal irrigation types are surface, sprinkler, and subsurface applied water. Surface irrigation discharges water in a line source at an upslope field edge and water infiltrates along the flow path, which results in discharge rate decreasing with downslope distance.[156] Although surface irrigation can cause high erosion, RUSLE2 does not estimate this erosion because RUSLE2 assumes an increasing discharge rate along its flow path.

RUSLE2 can not be used to estimate erosion directly caused by irrigation.

Sprinkler irrigation applies water through a system of pipes and overhead spray nozzles. Water is applied to only a portion of the area at a time. The water application is moved through time to cover the entire area. A two week cycle might be used, for example, to cover the entire area with multiple applications over a crop production season. Water is applied at a sufficiently low rate so that no runoff, and thus no erosion, occurs.

Subsurface (drip) irrigation applies water through a system of underground pipes and emitters. This type of irrigation does not cause rill-interrill erosion.

Although RUSLE2 is not used to estimate rill-interrill erosion caused by any type of irrigation, it can be used to estimate erosion caused by rainfall to reflect how irrigation changes the field conditions that affect rill-interrill erosion.

14.5.2. Basic principles

A main effect of irrigation captured by RUSLE2 is increased soil moisture that increases soil erodibility, increases biomass decomposition, and decreases soil surface roughness and soil ridge height. The main inputs to represent irrigation in RUSLE2 are the vegetation production (yield) level appropriate for the irrigation management, amount of water added by irrigation, and amount of biomass added in the irrigation water.

[156] The erosion mechanics of surface irrigation are described by Toy, T.J., G.R. Foster, and K.G. Renard. 2002. Soil Erosion: Processes, Prediction, Measurement, and Control. John Wiley and Son, New York, NY.
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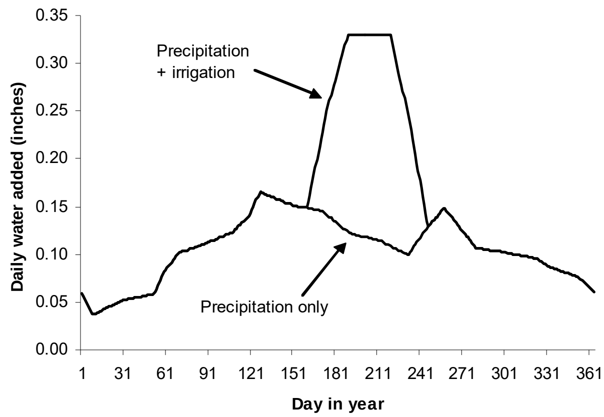

Figure 4.17. Precipitation and water added by irrigation for a 112 bu/ac corn crop at Columbia, Missouri.

RUSLE2 computations for the effect of irrigation were made for a 112 bu/ac conventionally tilled and a 112 bu/ac no-till corn crop at Columbia, Missouri. The results are summarized in Figure 14.17-14.20. In this example, irrigation water was added at the rate to just meet daily consumptive use, which is illustrated in Figure 14.17. The daily water added by irrigation is summed with daily precipitation, which is used to compute daily soil erodibility, daily decomposition, and daily loss of soil surface roughness and ridge height.

A major effect of irrigation computed by RUSLE2 is the increased soil erodibility during the irrigation period, which is illustrated in Figure 14.18. An upper limit is placed on how much added irrigation water can increase soil erodibility. No daily soil erodibility value can be greater than twice the soil erodibility value computed by a RUSLE2 nomograph.

The other major effect of irrigation is that it increases residue decomposition. Figure 10.19 shows the increase in decomposition computed by RUSLE2 for the 112 bu/ac no-till corn at Columbia, Missouri. The increase in decomposition was not great. The relative increase will be significantly greater in dry regions, such as Scotts Bluff, Nebraska. Very little of the decomposition effect continues beyond harvest because of the large amount of residue added by harvest.

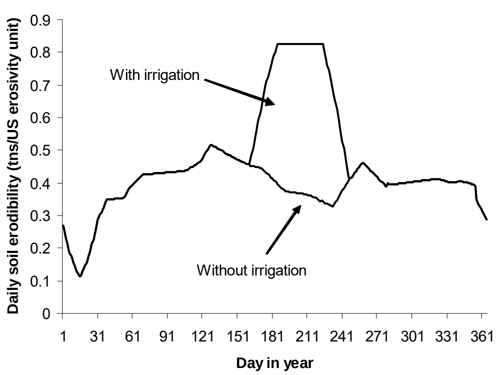

Figure 14.18. Effect of irrigation on daily soil erodibility at Columbia, Missouri.

Most of the effect of irrigation on erosion is during the irrigated period, as shown in Figure 10.20 by daily erosion rates computed for the 112 bu/ac conventionally tilled corn. The computed annual increase in erosion was from 24 to 30 tons/acre·year and 1.5 to 2.4 tons/acre·year, for the conventionally tilled and no-till crops, respectively. This difference in erosion is for the same yield. These computations illustrate how irrigation affects RUSLE2 computed erosion if nothing changes other than adding irrigation. The proper calculation would have been to input a yield value appropriate for the irrigated conditions. The RUSLE2 computed erosion is 26 tons/acre·year if the irrigation is assumed to increase yield from 112 bu/ac to 150 bu/ac. Further erosion reduction would have occurred if the applied irrigation had a significant content of bio-solids.

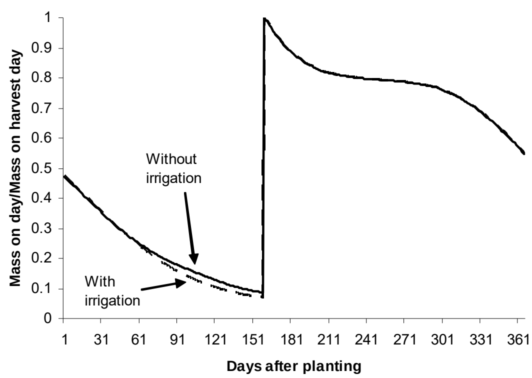

Figure 14.19. RUSLE2 computed decomposition for no-till corn at Columbia, Missouri.

14.5.3. Calibration

The RUSLE2 procedure that describes how irrigation affects erosion caused by natural precipitation (rainfall) and its associated runoff was not calibrated. Computed erosion values were not compared to measured values. However, erosion values were computed for a range of conditions and reviewed to ensure that RUSLE2 gives values acceptable for conservation planning.

14.5.5. Inputs

The input yield values should be appropriate for the irrigated management system (see **Section 10.2.4**). The effect of the increased yield that reduces erosion is just as important as the increased soil moisture that increases erosion. The best way to input yield values for irrigation is to create vegetation descriptions specifically for irrigated conditions. These vegetation descriptions include consumptive use values. A vegetation description is selected that is appropriate for the region, soil, and irrigation management system. Yield values in the cover-management descriptions using these vegetation descriptions can be varied to accommodate site-specific conditions. The RUSLE2 yield adjustment procedure for vegetation descriptions adjusts consumptive use values along with the other values.

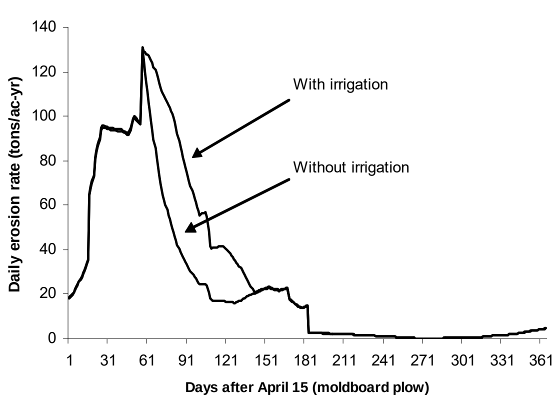

Figure 14.20. RUSLE2 computed effect of irrigation on daily erosion rate for 112 bu/ac conventionally corn at Columbia, Missouri.

The amount of water added by irrigation can be input using either of: (1) consumptive use through time, (2) dates and application rates on those dates, and (3) and period application depths. Irrigation systems are typically designed to supply water at the daily consumptive use of the crop being grown. Therefore, the consumptive use input method is preferred for inputting irrigation amount values in RUSLE2. Daily consumptive use values are entered in the vegetation description for the irrigated system, soil, and region. Consumptive use values depend on the crop and its yield, location, soil, and perhaps other factors.[157] If consumptive use is less than natural precipitation, such as for supplemental irrigation in the southeastern US, one of the other two input methods can be used to input irrigation amounts.

The other two input methods for irrigation amount are to enter application rates on particular days or to enter irrigation amounts (depths) by period. These periods are at the user's choice, which can be monthly, biweekly, or arbitrary non-uniform periods. Consideration should be given to reducing added water amounts for irrigation systems, such as drip irrigation, that do wet the surface soil.

The effect of added biomass that is applied by irrigation (e.g., for example waste disposal of bio-solids) is represented by including an **operation** that **adds external residue** in cover-management descriptions (see **Section 10.2.6**). Biomass added by irrigation is represented in a cover-management description having an **operation description** that applies **external residue** (see **Section 10.2.6**). This cover-management description involves the date of the operation that applies the biomass, biomass amount (dry matter basis) added by the operation (not the average annual mass applied), and the selection of a **residue description** that represents the applied biomass (see **Section 12**). RUSLE2 applies external residue by event rather than on a continuous daily rate. If biomass is applied by an irrigation system that operates on a cycle, the dates of the **add biomass** operation should be on the same frequency as the irrigation cycle. If the biomass is applied daily, the application can be approximated by applying a two week biomass amount once every two weeks. A sensitivity analysis (see **Section 17.3**) can be conducted to determine if the biomass can be applied in monthly intervals rather than in biweekly or other intervals. Decomposition characteristics of the biomass mainly determine the frequency of the biomass applications when approximating daily applications.

14.5.4. Interpretation

[157] Values for consumptive use and other information related to irrigation application rates can be obtained from local offices of the USDA-NRCS and Extension Service affiliated with Land Grant Universities in each state.

The RUSLE2 intent is to capture broad, main effects of increased soil moisture caused by the addition of water by irrigation. RUSLE2 does not capture hydrologic and hydraulic detail. The purpose of RSULE2 is to provide information useful for conservation and erosion control planning, not for irrigation system design. RUSLE2 estimated erosion for the effect of irrigation is comparable in accuracy to RUSLE2 computed values for other support practices, including contouring. Using RUSLE2 to evaluate the effect of irrigation on rill-interrill erosion by rainfall is much better than disregarding the effect.

15. APPLICATION OF RUSLE2 TO PARTICULAR LAND USES

RUSLE2 is **land use independent**, which means that RUSLE2 estimates rill-interrill erosion caused by rainfall and its associated Hortonian-type overland flow any where mineral soil is exposed (see **Section 5**). This capability is a major advantage when applying RUSLE2 to reclaimed mined land, waste disposal sites, disturbed forest land and mechanically disturbed military lands, and other lands where climate, soil, topography, and cover-management variables that affect erosion traverse the spectrum of conditions on common land use classifications such as cropland, rangelands, grazing lands, pasture lands, and disturbed forest lands. Erosion conditions on a common land use like cropland vary from a bare, highly erodible soil to a highly erosion resistant, well maintained pasture. Similarly, erosion conditions on rangeland vary from a highly erodible, recent mechanically disturbed pipeline construction site to a site never mechanically disturbed other than by wild animal presence. Well designed erosion prediction technology like RUSLE2 is based on a description of the fundamental variables that are land use independent. Erosion is a mechanical process where soil particles are detached and transported when the forces on them from raindrop impact and surface runoff become sufficiently strong.

Erosion prediction technologies designed for specific land uses like rangelands are much more limited than is RUSLE2, even when applied to that land use. RUSLE2's land-use independence allows it to be applied anywhere mineral soil is exposed to the erosive forces of raindrop impact and surface runoff produced by Hortonian overland flow.

However, many RUSLE2 users' applications will be limited to specific land uses such as construction sites. Easy-to-use RUSLE2 user guides targeted to specific land uses are needed. This RUSLE2 User's Reference Guide provides reference information on which to base user guides for specific land uses. Such RUSLE2 user guides will include input data and other land use specific information not available in this RUSLE2 User's Reference Guide. Also, user guides are needed that describe RUSLE2 computer program mechanics and operations for specific land uses.

An example of user guides for a specific land use includes a workbook and a user manual for construction sites and other highly disturbed lands. These documents are available from the International Erosion Control Association.

A primary source of RUSLE2 information is the USDA-ARS RUSLE2 Internet site http://www.ars.usda.gov/Research/docs.htm?docid=6010. The University of Tennessee and the USDA-Natural Resources Conservation Service, both of whom participated in the RUSLE2 development, also maintain RUSLE2 Internet sites.

Several RUSLE2 related documents are helpful for developing land use specific RUSLE2 user guides. Not all information in these and other RUSLE2 related documents applies to RUSLE2. Always check information from other sources to ensure that it is consistent with the RUSLE2 User's Reference Guide before using it in RUSLE2 applications.

15.1. Additional RUSLE2 Related Documents[158]

Dissmeyer, G.E. and G.R. Foster. 1980. A guide for predicting sheet and rill erosion on forest land. Technical Publication SA-TP-11. USDA-Forest Service-State and Private Forestry-Southeastern Area. 40 pp.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder. 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). U.S. Dept. of Agriculture, Agricultural Handbook 703, U.S. Govt Printing Office, Washington, D.C.

Toy, T.J. and G.R. Foster (coeditors). 1998. Guidelines for the use of the Revised Universal Soil Loss equation (RUSLE1.06) on mined lands, construction sites, and reclaimed lands. USDI-Office of Surface Mining. Denver. CO.

Wischmeier, W.H. and D.D. Smith. 1965. Predicting Rainfall-Erosion Losses from Cropland East of the Rocky Mountains: A guide to conservation planning. U.S. Dept. of Agriculture, Agriculture Handbook No. 282. U.S. Govt Printing Office, Washington, D.C.

Wischmeier, W.H. and D.D. Smith. 1978. Predicting Rainfall-Erosion Losses: A guide to conservation planning. U.S. Dept. of Agriculture, Agriculture Handbook No. 537. U.S. Govt Printing Office, Washington, D.C.

[158] See the USDA-ARS RUSLE2 Internet Site at http://msa.ars.usda.gov/ms/oxford/nsl/rusle/index.html (ARS reveiwer, check this) for information on how to obtain copies of these and other RUSLE2 related documents.

16. CORE DATABASE

A core database was used to develop, verify, and validate RUSLE2 for a base set of conditions. Values selected for new entries in a user's RUSLE2 working database should be selected based on information in this **RUSLE2 User's Reference Guide** and values in the **RUSLE2 core database**. Values for new entries must follow RUSLE2 definitions and be consistent with RUSLE2 core database values. Also, the **RUSLE2 core database** values must be used when RUSLE2 is being evaluated against the USLE, RUSLE1, and other erosion prediction technologies, against research data, and other analyses.

The **RUSLE2 core database** can be obtained from the official USDA-Agricultural Research Service Internet site http://www.ars.usda.gov/Research/docs.htm?docid=6010 maintained at the National Sedimentation Laboratory in Oxford, Mississippi. The **RUSLE2 core database** is named **RUSLE2 core data**.

17. EVALUATION OF RUSLE2

17.1. Verification/Validation

Verification is the process of ensuring that RUSLE2 makes its calculations as intended. Verification ensures that the equations, parameter values, and logic that links the equations have been programmed as designed and give the expected results. Verification involves running the model for the range of: research data used to derive the model, the RUSLE2 core database, and field conditions for which RUSLE2 might be used. Also, verification involves running the model for special conditions to make sure that every equation and every logic step in the model is exercised. The objective is to test every element of the model to find and fix all errors.[159] This verification process was extensively and fully followed in developing RUSLE2.

No guarantee is made that RUSLE2 contains no computational errors, only that an aggressive effort was made to find and fix errors.

Validation is the process of ensuring that RUSLE2 serves its intended purpose as described…"[160]

The stated purpose of RUSLE2 is to guide conservation and erosion control planning by users at the field office level, such as the field offices of the USDA-Natural Resources Conservation Service (NRCS). RUSLE2 was designed to be land use independent and is to apply to all conditions where rainfall and its associated Hortonian overland flow cause rill-interrill erosion of exposed mineral soil (see **Section 5**). RUSLE2 does not apply to erosion caused by runoff during irrigation (see **Section 14.5**) or snow melt (see **Section 6.3.3**). RUSLE2 is not a process representation of erosion, and RUSLE2 is not a tool for discovering new, original scientific knowledge about erosion. RUSLE2 represents its developers' interpretation of research data, accepted scientific and technical information, and judgments about use of erosion prediction technology in conservation and erosion control planning (see **Section 17.2**).

The most important part of RUSLE2's validation is whether RUSLE2 leads to the desired erosion control decision, not how well RUSLE2 estimates compare to measured data. Validation certainly involves evaluating RUSLE2's accuracy, but many other considerations are also important in judging how well RUSLE2 serves its stated purpose. For example, a model could perfectly compute erosion, but if the resources required to use the model exceed available resources, the model is invalid, (i.e., it does not serve its intended purpose).

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[159] Essentially a quote from Toy, T.J., G.R. Foster, and K.G. Renard. 2002. Soil Erosion: Processes, Prediction, Measurement, and Control. John Wiley and Son, New York, NY. p. 146.
[160] Essentially a quote from Toy et al., 2002. p. 146. Also, see pp. 146-149 regarding model validation.

RUSLE2 should be easy and convenient to use, including when it is used infrequently. RUSLE2 must not require excessive resources including: time required to learn the model; time to actually run the model in developing a conservation or erosion control plan; acquisition, assembly, and entry of input data; computer skills; and technical expertise required to run RUSLE2. Support documents, training, and assistance when problems arise must be available.

Are the benefits gained from using RUSLE2 worth its costs, especially in comparison to using alternative methods to develop conservation and erosion control plans? How does the quality of conservation and erosion control plans developed with RUSLE2 compare with those developed from use of other erosion prediction technologies? If two erosion prediction technologies result in the same conservation and erosion control plan, each technology performs equally well. The choice of a specific erosion prediction technology is, therefore, determined by preferences and resources required to use each technology.

RUSLE2 must accurately represents scientifically accepted trends of how major variables such as precipitation amount and intensity, soil texture, overland flow path length and steepness, ground cover, soil biomass, and contouring affect erosion. Research data available to develop erosion prediction technology are unavoidably incomplete and biased. The data do not represent all of the conditions where RUSLE2 will be applied, and consequently, numerous RUSLE2 applications will be extrapolations beyond the data used to derive RUSLE2. Therefore, whether RUSLE2 accurately represents scientifically accepted trends is a key factor in how well RUSLE2 performs when extrapolated. RUSLE2 was also developed to be robust so that extrapolations are conservative and conform to obvious, defined limits, (i.e., if RUSLE2 estimates are erroneous, the estimates will not be unreasonable).

Erosion data have a high degree of explained variability and bias. For example, regression fitting of an equation to a particular experimental data set gives the nonsensical results that the fitted equation computes increased erosion with increased ground cover. The data are obviously flawed or biased by incompleteness, measurements not based on RUSLE2 definitions, or measurement error. RUSLE2 describes accepted scientific trends even though the fit to particular observed data may be compromised.

RUSLE2 developers envisioned themselves in the position of land users impacted by RUSLE2. Given their knowledge of both erosion science and RUSLE2's representation of that science, RUSLE2 developers asked themselves the question, do they have sufficient confidence in RUSLE2 erosion estimates in particular situations to be willing to implement RUSLE2 based erosion control practices?

Users should assure for themselves the validity of RUSLE2. This RUSLE2 User's Reference Guide describes in detail how RUSLE2 was derived, what it represents, and how RUSLE2 represents accepted scientific and technical information.

17.2. Interpretations in the context of conservation and erosion control planning

The RUSLE2 developers followed several fundamental principles to interpret research data used to empirically derive and calibrate RUSLE2 equations and to validate RUSLE2. Whether or not RUSLE2 is considered valid depends on the acceptance of these principles.

17.2.1. Principle 1: Fit main effects

The first step in applying the **main effects principle** is to assemble the largest possible dataset for the erosion control practice or other condition being analyzed. These datasets are seldom ideal because of incomplete, non-uniform, and biased coverage, and much unexplained variability.[161] The second step is to identify the variables and equation form based on erosion theory and fundamental erosion process studies that will be used to describe the main effects. Analyzing erosion data for no-till cropping provides a case study for illustrating the main effects principle.

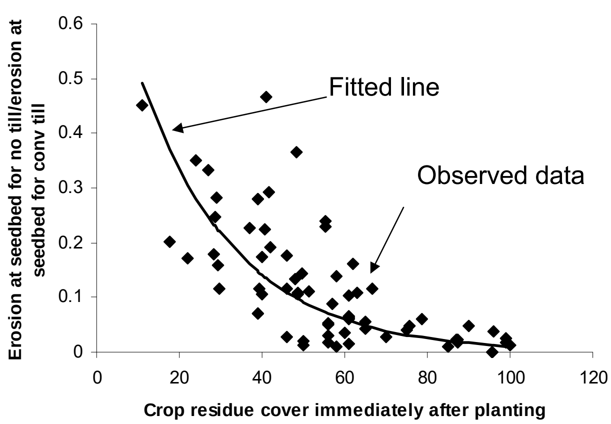

Figure 17.1. Relation of erosion with no-till cropping to erosion with conventional tillage for seedbed period.

Conservation tillage, including no-till, is widely used to control erosion on cropland. Experimental erosion data for no-till cropping are plotted in Figure 17.1 where the dependent variable is ratio of erosion with no-till to erosion with conventional till for the seedbed period. Results from many fundamental erosion studies involving applied mulch show that erosion decreases rapidly as ground cover increases as represented by Equation 9.6.[162]

[161] Nearing, M.A., G. Govers and L.D. Norton. 1999. Variability in soil erosion data from replicated plots. Soil Sci. Soc. Amer. J. 63: 1829-1835.

[162] See, for example,

Manering, J.V. and L.D. Meyer. 1963. Effects of various rates of surface mulches on infiltration and erosion. Soil Science Society of America Proceedings 27:84-86.

Therefore, ground cover is assumed to be a main effect variable for no-till's effect on erosion.

The deviation in erosion from the main effect is large in Figure 17.1. For example, the fitted value at 50 percent ground cover (crop residue cover) is 0.1 while the experimental values ranged from about 0.02 to 0.4. Other variables have a significant effect, which is captured in RUSLE2 by varying the coefficient **b** in equation 9.6.

Erosion theory and fundamental experimental erosion studies show that the coefficient **b** varies with the rill to interrill erosion ratio because of difference between rill erosion and interrill erosion mechanics. Ground cover reduces rill erosion more than it reduces interrill erosion.[163] Values for **b** are larger where rill erosion is dominant on bare soils, such as on relatively steep overland flow paths (greater than 12 %), than where interrill erosion is dominant, such as on relatively flat overland flow paths (less than 3%).

Fundamental erosion studies show that **b** values are increased when added ground cover increases infiltration, which in turn reduces runoff and rill erosion. Increased biomass in the upper soil layer accompanies increased ground cover in long term no-till cropping but not in short term no-till cropping or in mulch applied to freshly graded construction sites. Consequently, **b** values are a function of land use. Rather than making **b** values a function of land use classification, RUSLE2 computes **b** values as a function of cover-management variables.[164] For example, RUSLE2 detects the difference between a construction site and a no-till cropped field using the soil consolidation factor and the amount of soil biomass in the upper soil layer.

This approach of using equations to represent main effects of major universal climate, soil, topographic, and cover-management variables rather associating equations and coefficient values with a land use classification gives RUSLE2 its land use independence.

The concept in RUSLE2 is to describe the main effect that major variables have on erosion and then compute deviations about the main effect using secondary variables. RUSLE2 properly represents trends apparent from an overall analysis of the experimental data and erosion science even though RUSLE2 may not faithfully reproduce individual

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Meyer, L.D., W.H. Wischmeier, and G.R. Foster. 1970. Mulch rates required for erosion control on steep slopes. Soil Science Society of American Proceedings 34:928-931.

[163] Foster, G.R. and L.D. Meyer. 1975. Mathematical simulation of upland erosion by fundamental erosion mechanics. *In:* Present and Prospective Technology for Predicting Sediment Yields and Sources. ARS-S-40 USDA-Science and Education Administration. pp. 190-204.

[164] RUSLE1.06 assigns **b** values as a function of land use classification. RUSLE1.05 assigns b_g values according to a user selected classification for rill to interrill erosion ratio.

data values in an experimental dataset. The RUSLE2 approach increases robustness, which means that RUSLE2 can be more confidently extrapolated beyond the data used to derive it than can regression equations involving a large set of variables fitted to the data.

Selecting equations and coefficient values based on best statistical fits to experimental field data can produce very flawed results for conservation and erosion control planning. The results can be especially flawed if the experimental data have a high degree of unexplained variability and are non-uniform in coverage, incomplete, and biased, problems impossible to avoid in erosion data. For example, the regression approach can result in nonsensical results where erosion is computed to increase as ground cover increases. RUSLE2 faithfully reproduces trends proven by erosion science rather than simply providing the best fit to experimental data that are almost always flawed.

17.2.2. Principle 2: Don't custom fit to local data or to specific data

Some users adjust RUSLE2 parameter and input values to fit a particular data point because that data point is considered more valid that other data points. Increased value is placed on that data point because the data came from a particular locale or because of familiarity with the investigator who collected the data. RUSLE2 adjustments and evaluations based on how well RUSLE2 fits a single data point are generally improper.

RUSLE2 is designed to fit main effects as described in **Section 17.2.1**. Erosion data are highly variable and have a high degree of uncertainty for unknown reasons, especially if the measured erosion rates are low (less than 1 ton/acre per year). The validity of any single data point is, therefore, highly questionable. The validity of a single data point must be judged against the dataset as a whole.

If a particular data point is judged to be valid, fitting RUSLE2 to the single data point should still be avoided. Calibrating RUSLE2 to a data point could well result in RUSLE2 estimates that are seriously erroneous because RUSLE2 no longer will fit the main effect. Either RUSLE2's fit of this single data point should be considered in a particular RUSLE2 application, or another erosion prediction procedure should be used instead of RUSLE2.

17.2.3. Principle 3: Follow RUSLE2 definitions, rules, procedures, guidelines, and core database values

RUSLE2 uses specific definitions, rules, procedures, and core database values that must be followed. RUSLE2 definitions, rules, and procedures were chosen for specific reasons that are sometimes not obvious. For example, adjusting RUSLE2 soil erodibility K factor values to account for increased organic matter resulting from organic farming or applying manure is improper and gives erroneous results. Similarly, soil erodibility factor values adjusted for surface rock fragments should not be used. RUSLE2 considers the effect of rock cover and increased soil biomass in its cover-management computations. The soil erodibility factor applies specifically and only to unit plot conditions.

Similarly, RUSLE2 core database values must be followed because RUSLE2 was calibrated based on those values. The core database values were selected to represent main effects adequately supported by research data and erosion science. The values were selected to be consistent with accuracy of RUSLE2 and the data used to derive RUSLE2. Input values for database entries not represented in the RUSLE2 core database must be consistent with core database values for similar conditions.

While you as a user may not agree with the RUSLE2 definitions, rules, procedures, and core database values, they must be observed. Do not assume that USLE and RUSLE1 definitions, rules, procedures, and input values apply to RUSLE2, because many do not.

17.2.4. Principle 4: Don't evaluate RUSLE2 based on how well it fits secondary variables

RUSLE2 was developed, calibrated, and validated to ensure that it gives good average annual erosion estimates, even if the fit of RUSLE2 computed values for secondary variables (e.g., crop residue) is less than expected. For example, RUSLE2 typically under estimates residue cover for periods longer than about 1 year, but this underestimate does not mean that the average annual erosion estimate is erroneous, especially in rotation-type cover-management descriptions where a large amount of residue is added annually. The adequacy of RUSLE2 computed values for secondary variables is based on RUSLE2 computing the expected erosion estimate, not on how RUSLE2 computed values for secondary variables are used for non-RUSLE2 purposes.

RUSLE2 estimates of crop residue cover immediately after planting can be used in routine conservation planning and compliance activities.

However, situations arise where the RUSLE2 accuracy of a secondary variable is insufficient in a particular RUSLE2 application. An example is applying RUSLE2 to a construction site two or more years after only a single mulch application. Separate RUSLE2 computations using different input residue values for each year may be required to accurately compute erosion in particular years.

Users should use this RUSLE2 User's Reference Guide to determine where RUSLE2 erosion estimates may need special interpretations or RUSLE2 inputs may need adjustment.

17.2.5. Principle 5: Avoid fine tuning parameter and input values

If you must adjust parameter and input values, be sure that you understand the variable being adjusted and how it is used in RUSLE2. Carefully read and follow this RUSLE2 User's Reference Guide to avoid unintended consequences.

Adjusting input values so that RUSLE2 computes an expected residue cover is an example where adjustments are sometimes made. Because RUSLE2 has many interacting variables, changing the value for a single variable may affect several computations. For example, changing the value for the residue decomposition coefficient affects surface residue cover and soil biomass as well. Soil biomass affects computed values for the soil biomass subfactor, surface roughness, and runoff. If the change is only to affect surface residue cover, the residue decomposition coefficient value is not the input variable that should be changed.

Another example where changing the value of a single variable can have unexpected results is the width of soil disturbance. Changing the value for this variable affects more than the soil consolidation subfactor value because several RUSLE2 computations are a function of the soil consolidation subfactor.

Section 12.5 describes a procedure for adjusting input values to obtain an expected residue cover. This procedure is a guide for changing input values for other variables to achieve a particular result.

Make sure that the proper variables are being changed to achieve the desired result.

17.2.6. Principle 6: Make sufficient temporal and spatial field measurements according to RUSLE2 requirements

Canopy, surface cover, surface roughness, and yield are variables that are sometimes field measured as a part of evaluating RUSLE2 and collecting field data for RUSLE2 input. Measuring root biomass should not be attempted except in a very carefully managed research environment, and even then the results are questionable. Soil biomass as used in RUSLE2 should be back calculated from other variables because it is almost impossible to measure.

Field measured values vary randomly and systematically (e.g., a combine leaving residue in strips) in both space and time. Field measurements must be proper and in sufficient number to account for variability keeping in mind that RUSLE2 is designed to represent main effects. Canopy cover, surface cover, fall height, and other RUSLE2 variables must be measured based on RUSLE2 definitions, rules, and procedures to accurately evaluate

RUSLE2 and properly selected input values. Also, many RUSLE2 relationships are nonlinear, which affects how field measurements are made, analyzed, and interpreted. Follow this RUSLE2 User's Reference Guide closely in making field measurements.

Field measurements of residue surface cover are often made and used in the conservation planning and compliance determination on cropland. Given the importance of residue surface cover, special precautions should be observed in making residue cover

Field measurements must be made in accordance with RUSLE2 definitions, rules, and procedures.

measurements.

Both high residue and low residue cover is difficult to measure and convert to residue mass values, partly because of the non-linear residue mass-cover relationship (see **Section 12.3**). Residue samples must be carefully collected and processed (e.g., soil particles carefully removed). The residue mass to cover relationship varies within the field and during the year as the relative composition of plant parts (leaves, stems, and other components) vary in the residue. The relationship also varies from year to year as weather, yield, and field operations vary. Residue measurements should be made over a minimum of three years to obtain values that can be compared to RUSLE2 estimates. Experience also shows that when residue surface cover is accurately measured, cover is often less than assumed based on visual observations.

Soil surface roughness values used in RUSLE2 computations are not the input values because RUSLE2 adjusts the input values for soil texture and soil biomass (see **Section 9.2.3.2**). Also, field measured values for soil surface roughness only match input values when roughness is measured for the base condition used to define RUSLE2 soil surface roughness input values.

The terminology and definitions of plant cover used in vegetation surveys may be quite different from the very specific definitions of canopy cover, ground cover, live ground cover, and fall height used in RUSLE2. Also, the definitions of vegetation production (yield) level may be quite difference from RUSLE2 definitions and input values in the RUSLE2 core database.

Before using information from vegetation surveys, ensure that the values taken from these survey are proper when using them for RUSLE2 input.

17.2.7. Principle 7. Avoid too much detail

Difference between RUSLE2 computed erosion estimates may not be significant. Significance in this context is not the same as statistical significance discussed in **Section 17.4**. In this context, significance refers to a sufficient difference resulting in a conservation planning or compliance decision being altered.

The general guideline is that difference in estimated erosion values should exceed 10 percent because the difference is considered practically significant.

RUSLE2 is not designed to capture the difference between machine adjustments on particular tillage machines, unless the effect of the adjustment is sufficiently great. RUSLE2 is designed to distinguish between machine classes such as straight, sweep, and twisted shovel type chisel plows. Some of the differences in residue burial that are often claimed to be achievable by machine adjustment are questionable (see **Section 13.1.5.3**). Input values should be for machine classes and not varied to reflect individual machine configuration or operation.

Similarly, RUSLE2 is not designed to capture differences between crop varieties other than major differences such as between popcorn and field corn, for example. When differences between crop varieties grown in different regions are sufficiently great to give erosion estimates that differ by more that 10 percent (i.e., the 10 percent rule), differences in crop varieties should be represented. Likewise, dates in cover-management descriptions should be selected to represent major differences such as early, mid, and late season planting and/or harvest, not to represent operations on particular dates. Also, RUSLE2 is not intended to capture how annual variation in operation dates within a cover-management description affects erosion.

RUSLE2 users, especially those who prepare RUSLE2 databases, have the responsibility of determining when difference are sufficiently great to warrant creating new entries in the RUSLE2 database with different input values. Differences in erosion estimates because of difference in inputs values for similar conditions are a partial measure of uncertainty and precision in RUSLE2 erosion estimates.

17.2.8. Principle 8. Computing erosion with RUSLE2 for historical events and individual storm events is an advanced application

RUSLE2 is a conservation planning tool, not a model that reproduces historical erosion events. RUSLE2 is not designed to be evaluated or calibrated by inputting historical data to compute erosion values that are compared to values measured at a particular site. Also, RUSLE2 is not designed to evaluate how historical events such as an unusually dry or wet season or year affected erosion. The uncertainty in RUSLE2 erosion estimates for these applications is much greater than in average annual erosion estimates.

RUSLE2 is not structured to readily accommodate input of historical data, especially weather data for multiple years. Also, RUSLE2 does not represent temporal variations in soil moisture that can greatly affect runoff from individual storm events. RUSLE2 does not conveniently represent residual effects from a previous year, although expert RUSLE2 users can capture much of the effects of these initial conditions. RUSLE2 does not model how vegetation responds to environmental conditions, but values that represent the vegetation and operations for a specific historical period can be input into RUSLE2.

The adequacy of the historical experimental data against which RUSLE2 is being evaluated must be considered. Are the historical, experimental data comparable to the data used to develop RUSLE2 parameter and input values? If not, RUSLE2 computed erosion may not compare well with the measured erosion. A poor fit does not necessarily indicate that RUSLE2 performs poorly, but that the historical experimental data are not representative of the main effects represented by RUSLE2.

A short record, such as three years, often produces data that differ significantly from average annual erosion values measured over an extended period or estimated by RUSLE2. The cover-management data used to develop RUSLE2 were analyzed to compute ratios of erosion values for a given cover-management condition to erosion values for a base condition. The advantage of the RUSLE2 approach is that these ratio values varied much less year to year than did absolute erosion values. RUSLE2 does not reflect how year to year variation in soil moisture, runoff, plant yield, and other variables affects erosion.

RUSLE2 has similar limitations when used to estimate how an especially dry or wet season or year affects erosion. In these extremes, the ratio of runoff to precipitation usually differs significantly from average annual values. Extreme storm events sometimes occur in dry years. Although annual rainfall may be quite low in a dry year, a few very intense rainfall events can cause exceedingly high erosion per unit precipitation. Conversely, a wet year can involve many relatively low intensity storms that cause reduced erosion per unit precipitation. Although RUSLE2 captures some but not all of these effects, RUSLE2 is limited because it does not compute runoff by individual storm event.

Input data for the climate, operation, vegetation, residue, and cover-management descriptions can be entered to represent a particular year. RUSLE2 computes erosion estimates that partially reflect how departure of these input values from average annual conditions affects erosion. Also, expert users can set up RUSLE2 to capture most residual effects from a previous year where conditions differed greatly from those for the year being analyzed. The RUSLE2 computed erosion is likely to be less than it should be for a wet year and greater than it should be for a dry year.

RUSLE2 can be configured to estimate erosion for a single storm by inputting values to represent conditions on the day of the storm. However, RUSLE2 does not estimate soil moisture and how runoff is affected by soil moisture on the day of the rainfall event. Thus, RUSLE2 erosion estimates will be low or high depending on how soil moisture departs from its average annual value for the particular event. Although RUSLE2 is not intended to estimate erosion from individual storms, its accuracy for individual storm event erosion estimates may be comparable to estimates from complex, process-based models.[165] **RUSLE2 is better for estimating individual event erosion than is commonly assumed.**

These RUSLE2 applications are quite advanced. Proper procedures must be followed. For example, no-rotation type cover-management descriptions should be used in most cases rather than using standard rotation-type cover-management descriptions, even when representing crop rotations. This RUSLE2 User's Reference Guide should be carefully studied and followed in applying RUSLE2 in these special applications.

If users understand how RUSLE2 works regarding individual storms and representing historical events and they have the expertise and other resources to apply RUSLE2, then RUSLE2 is valid in these applications if these RUSLE2 users consider RUSLE2 estimates to be useful.

17.2.9. Principle 9. Always evaluate the adequacy of the data

17.2.9.1. An ideal dataset

All measured erosion data available for developing and evaluating RUSLE2 are questionable in some way.[166] An ideal dataset represents modern climatic and land use conditions, soils and topography as they occur on actual hillslopes, and the full range of conditions where RUSLE2 is applied. Record length is sufficient to provide accurate average annual estimates and probability distributions. The dataset is complete, un-biased, and without measurement error. Replications and treatments are sufficient to define RUSLE2 relationships with a high degree of statistical accuracy. Measurements must be made according to RUSLE2 definitions, rules, and procedures.

17.2.9.2. Natural rainfall versus simulated rainfall

[165] Although RUSLE2 is not intended for estimating erosion for specific storm events, RUSLE2 is fundamentally an event-based procedure. The linearity between storm erosivity and storm erosion simplifies the RUSLE2 mathematical integration for estimating average annual erosion. See **Sections 5.4 and 7.2**.

[166] Toy, T.J., G.R. Foster, and K.G. Renard. 2002. Soil Erosion: Processes, Prediction, Measurement, and Control. John Wiley and Son, New York, NY.

Data from natural rainfall events are much preferred over data from simulated rainfall because simulated rainfall does not perfectly match natural rainfall. Most erosion data collected with rainfall simulators are for standard, uniform intensity storms in comparison with natural rainstorms having greatly varying intensities and amounts. Measured infiltration, runoff, and erosion are functions of temporal rainfall intensity pattern and its interaction with spatially varied soil conditions.[167] Energy for some rainfall simulators is much less than that of natural rainfall. **Data were not used in the development of RUSLE2 that were collected using simulated rainfall where energy was less than about 75 percent of that in natural rainfall.** Rainfall simulators having energies approaching natural rainfall typically apply water intermittently on a cycle ranging from about 5 seconds to 30 seconds, which affects infiltration, runoff, erosion, sediment transport, deposition, and sediment characteristics.

The standard storm set is typically applied only at a few times during the year, usually when the study condition is most vulnerable to erosion condition. In some erosion studies on rangelands involving rainfall simulators, the applied erosivity was much greater than typical annual rainfall erosivity at some locations.[168]

These differences between natural and simulated rainfall raise questions about the advisability of using simulated rainfall erosion data to develop and evaluate RUSLE2. The RUSLE2 developers judged that these data were useful in the context of RUSLE2 being a conservation and erosion control planning tool. Erosion data from simulated rainfall would be interpreted against erosion data from natural rainfall. Erosion data from simulated rainfall were primarily analyzed, except for the soil erodibility nomographs, by forming ratios of erosion for a given condition to erosion for a base condition, realizing that these ratios vary with storm characteristics and other factors (see Figure 17.1).

17.2.9.3. Measurement area size

Erosion plots that are either 35 ft long or 72.6 ft long and 6, 10, or 12 ft wide were widely used to measure the effect of climate, soil, land steepness, and cover-management on erosion. Plots of about 36, 72.6, and 150 ft long (plots as long as 370 ft were used in one study and 650 ft in another study) were used in multiple studies to determine the effect of overland flow path length on erosion. Small watersheds ranging in size from about 2 ac to 5 ac were used to measure the effect of contouring, rotational strip cropping, and terracing on erosion.

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[167] Flanagan, D.C., G.R. Foster, and W.C. Moldenhauer. 1988. Storm pattern effect on infiltration, runoff, and erosion. Trans. ASAE 31:414-420.

[168] See:
Simanton, J.R., L.T. West, M.A. Weltz, and G.D. Wingate. 1987. Rangeland experiments for Water Erosion Prediction Project. Paper No. 87-2545. American Society of Agricultural Engineers. St. Joseph, MI.
Spaeth, Jr., K.E., F.B. Pierson, M.A. Weltz, and W.H. Blackburn. 2003. Evaluation of USLE and RUSLE estimated soil loss on rangelands. J. Range Management 56:234-246.

Do these erosion plots tilled manually or with small equipment adequately represent typical land use practices and non-uniform overland flow paths having lengths that range from 1 ft to 1,000 ft.? Do these small watersheds with their spatial variability of soil, topography, and cover-management conditions provide data suitable for developing RUSLE2?

Even though these and other questions can be raised about these measurement areas, the RUSLE2 developers judged that these measurement areas were appropriate for developing RUSLE2 as a conservation and erosion control planning tool. RUSLE2 users must interpret RUSLE2 erosion estimates in terms of how well these plots and small watersheds represent erosion on the field area where RUSLE2 is being applied (see **Sections 5.1, 5.2, and 5.3**). RUSLE2 developers judged that erosion data from small measurement areas about 3 ft by 3 ft (1 m by 1m) where essentially only interrill erosion occurs are not suitable for developing RUSLE2 or evaluating its estimates of rill and interrill erosion combined for typical overland flow paths.[169] This small measurement area is not suitable for determining RUSLE2 soil erodibility factor values or making relative comparisons of soil erodibility and erosion control practices. Erosion data from plots shorter than 35 ft were not used in the development of RUSLE2 where both interrill and rill erosion were being considered. However, data from interrill erosion type areas were used to develop RUSLE2 interrill erosion relationships.

Finding a suitable area on a natural hillslope for a set of erosion plots having uniform soil and steepness is difficult. A minimum of three replications along with a base treatment, and three treatments are needed, for example, in a simple study to evaluate mulch application rate for a particular mulch type. A set of 12 rainfall simulator plots are needed for this study, which requires a total width of about 220 ft. Finding a uniform area that wide is difficult on natural landscapes. The problem is especially acute on rangelands where erosion rates are low and spatial variability is great. The scale of the variability is on the order of the plot width and length. A slight shift in the placement of a plot can result in significantly different measured erosion rates.

17.2.9.4. Modern data

Modern data representative of current land use practices and climate conditions should be used to develop and evaluate RUSLE2. Modern climate data were used to develop RUSLE2 input erosivity, precipitation, and temperature values. However, the underlying natural rainfall erosion data used to calibrate the soil biomass subfactor equation (equation 9.12) were from the mid 1930's to the mid 1950's. Few natural rainfall erosion

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[169] Foster, G.R., J.R. Simanton, K.G. Renard, L.J. Lane, and H.B. Osborn. 1981. Discussion of "Application of the Universal Soil Loss Equation to Rangelands on a Pre-Storm Basis." Journal of Range Management 34:161-165.

plot data were collected after the 1970's. Most modern erosion data were collected using simulated rainfall.

Therefore, a question is how well does RUSLE2 estimate erosion for modern conditions? Applying RUSLE2 to modern conditions represents an extrapolation from conditions quite different from current ones. RUSLE2 developers addressed this question and judged that RUSLE2 performs satisfactorily for modern conditions. They also judged that the cover-management subfactor procedure allows RUSLE2 to be extrapolated to conditions significantly beyond those represented in the underlying data.

17.2.9.5. Data record length

About 10 years are usually required to obtain representative average annual values for erosion data measured from natural rainfall for one- and two-year crop rotations. Erosion data for cropped conditions are available from only two locations where the record length exceeded a decade. However, interpretation of a long term data is difficult because of temporal weather variability and changes in farming practices over time. None of the data available for analyzing rotational strip cropping involving five-year and longer crop rotations are fully adequate because of short record length even though record length is about 10 years. A five-year rotation requires 20 or more years to obtain reasonable average annual data and even longer when the crop rotation is used in strip cropping. Collecting such data is often not feasible, which is the reason that these data do not exist.

Data having record lengths as short as three years for natural rainfall events were used in the development of RUSLE2. These data were primarily analyzed to determine ratios, which vary less temporally than do absolute values (see Figure 17.1). Data having a short record length are more susceptible to interpretation problems caused by extreme events occurring during the measurement period and to measurement equipment failure than data having a long record length.

Missing data can be a serious problem. An example is the high erosion rates that can occur during late winter and early spring thaws when soil erodibility is significantly increased. Too few events were measured to adequately represent them in the temporal erodibility equation (see **Section 7.3**). Few locations were adequately equipped to measure runoff and erosion in these environmental conditions, and the need to make those measurements was probably not recognized at the time.

17.2.9.6. Dividing the data into development and evaluation parts

Developers of models sometimes divide data into two parts, one part is used to develop the model and the other part is used to evaluate the model. The entire dataset was used to develop RUSLE2 rather than dividing the data. The best approach is to use the largest dataset possible to develop erosion models given the variability, incompleteness, bias, and other shortcomings in erosion data.

Reports are sometimes published where measured data at a single location for a small, specific set of conditions are compared with RUSLE2 estimates. Such data should first be evaluated to determine how they fit with the RUSLE2 dataset as a whole to ensure that the specific study data are not outliers. Given the unexplained variability in erosion data (e.g., see Figure 17.1), either a good or poor fit of RUSLE2 to a single data point is by chance. Evaluations involving essentially a single data point usually provide very little information about RUSLE2's adequacy.

A main criterion in developing RUSLE2 is that it describes well established main effects. Fitting an erosion prediction equation to incomplete and biased data can produce nonsensical results such as erosion increasing as ground cover increases. The fit of RUSLE2 to experimental data as determined by statistical goodness of fit measures was sometimes compromised so that RUSLE2 accurately represents established main effects. Getting the best statistical fit to reduced quality data may not produce the best result for conservation and erosion control planning.

17.2.9.7. Users must make their own judgments

All developers of erosion prediction technology make judgments about erosion data used to derive equations, parameter values, and input values. Different people reach different conclusions when evaluating a particular dataset and in evaluating RUSLE2's adequacy relative to the dataset. The RUSLE2 developers' judgments are described in this RUSLE2 User's Reference Guide.

Users must make their own judgments about RUSLE2. Users should only use RUSLE2 when they are satisfied that RUSLE2 is suitable for their purposes.

17.2.10. Principle 10. Make sure that the inputs are proper

When RUSLE2 users obtain poor results, they often suspect a problem with RUSLE2, while RUSLE2 developers often suspect improper inputs. Always double check input values when evaluating and applying RUSLE2, and especially ensure that input values are consistent with the core database values. Do not use input values from other erosion models. RUSLE2 input values sometimes differ from values used for similar variables in other erosion prediction technologies, including the USLE and RUSLE1.

Ensure that RUSLE2 rules and procedures are followed. Errors in the sequence of processes used in an **operation description** can easily occur, for example. If a **flatten standing residue process** is used in a soil disturbing operation description, the results will differ significantly depending on whether the flattening process is placed in the operation description before or after the **disturb soil process**. Another example of an input error is where the live root biomass value on day zero in a **vegetation description** is much less than the live root biomass on the last day in this vegetation description when it is used to represent mature vegetation. RUSLE2 adds the difference in the live root biomass between the ending and beginning dates to the dead root biomass pool when none should be added in this situation.

RUSLE2 results can be no better than the inputs.

17.2.11. Principle 11. Be alert for RUSLE2 users who believe RUSLE2

RUSLE2 estimates contain error and uncertainty. All RUSLE2 estimates should be examined, interpreted, and carefully considered before using them. Conservation and erosion control planners should always make planning decisions using RUSLE2 estimates as a guide.

17.2.12. Principle 12. RUSLE2 is only in error when it leads to a poor conservation or erosion control plan

RUSLE2's accuracy (see **Section 17.4**) should be evaluated in the context of conservation and erosion control planning.[170] Does RUSLE2 result in the desired conservation and erosion control planning decision? For example, RUSLE2 could compute annual erosion estimates of 50, 200, and 400 tons/acre for a particular highly erodible site given the uncertainty in RUSLE2 estimates. The range in these values represents significant numerical error. However, RUSLE2 leads to the correct conservation decision with each estimate; that is; erosion is excessive and needs to be significantly reduced. In fact, RUSLE2 probably is not needed in this situation because the erosion hazard is easily recognized from general erosion knowledge.

Similarly, RUSLE2 could compute an annual erosion estimate between 0.001 and 0.1 tons/acre for a rangeland site given the uncertainty in RUSLE2 estimates. Nevertheless, RUSLE2 leads to the desired conservation planning decision; erosion is low. Making erosion measures using plots that are 35 ft long and 12 ft wide to determine the "correct" value is difficult for low erosion rates, especially on rangelands. The 0.001 tons/acre value could have been 0.05 tons/acre if a gopher hole had been near the plot end or the soil had been slightly disturbed and exposed when placing a plot border or installing a plot end. The 0.1 tons/acre value could have been 0.01 tons/acre had the plot had been located differently because of non-uniform spatial variability within the plot and on the hillslope.

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[170] For additional discussion, see Toy, T.J., G.R. Foster, and K.G. Renard. 2002. Soil Erosion: Processes, Prediction, Measurement, and Control. John Wiley and Son, New York, NY.

RUSLE2's accuracy is most important when erosion estimates are sufficiently close to the erosion control criteria such that errors result in substantial expense to apply unnecessary erosion control. RUSLE2 is typically used in conservation planning to compute a soil loss value that is compared against a soil loss tolerance value **T** or another erosion control criteria value. If the computed soil loss value is less than the erosion control criteria, erosion control is assumed to be adequate.

Assume that the erosion control criterion is an annual 5 tons/acre. If the RUSLE2 annual erosion estimate is 10 tons/acre, the RUSLE2 based conservation planning decision is that erosion is excessive and additional erosion control is needed. However, if the "correct" erosion estimate is an annual 5 tons/acre, the proper conservation planning decision is that erosion control is acceptable and no further erosion reduction is needed. The significance of the error is determined by the expense of additional erosion control when none was needed.

Fortunately RUSLE2 is most accurate in the critical range of annual estimates between about 2 to 20 tons/acre. Annual erosion greater than 20 tons/acre is usually considered excessive and annual erosion less than 1 ton/acre is generally considered to be acceptable. If RUSLE2 computes an annual erosion of 10 tons/acre with one practice and 20 tons/acre with a second practice, the erosion control planner can be confident that erosion with the first practice will be substantially less than with the second practice. However, if RUSLE2 computes 1 and 2 tons/acre annual erosion estimates for two practices, especially on pasture land, the difference between the two practices is not great, and the most that can be said is that erosion will likely be less with one practice than with the other practice and that erosion will be low with both practices.

RUSLE2 erosion estimates for support erosion control practices, especially contouring, are much more uncertain than those for cultural erosion control practices based on cover-management variables. RUSLE2 accurately represents the global effects of support practices but not their performance on specific sites. The uncertainty in the estimated erosion reduction by support practices on a specific site is much greater than the uncertainty in estimated erosion reduction by cultural erosion control practices.

17.3. Sensitivity analysis

A RUSLE2 sensitivity analysis is very helpful in understanding how RUSLE2 computes erosion, determining how a particular practice or condition affects erosion, determining the effect of a particular variable on erosion, and detecting input errors. The general procedure for conducting a sensitivity analysis is to change a single input while holding other inputs constant. For example, a sensitivity analysis can be conducted on how location affects erosion by making RUSLE2 computations for a set of locations using a single set of inputs for soil, topography, cover-management, and support practices. Likewise, a sensitivity analysis can be conducted on cover-management practices by making erosion computations for a set of practices for a given location, soil, topography, and support practices.

A sensitivity analysis can also be conducted on a single variable such as overland flow path length. Changing input values from 10 to 1000 ft for the overland flow path length has little effect on RUSLE2 computed erosion where steepness is 1 percent or less. Therefore, carefully selecting a precise input value for overland flow path length on very flat slopes is not critical.

A sensitivity analysis for the single variable overland flow path length can be easily conducted by changing input values on the main RUSLE2 **profile** screen. Sensitivity analyses conducted on other individual variables usually requires changing values in the **RUSLE2 database description** that contains the values for that variable. For example, conducting a sensitivity analysis on canopy cover requires changing values in a **vegetation description**.

The effect of a single variable or a set of variables, such as those in cover-management descriptions, on erosion varies with the situation. For example, overland flow path length has little effect on erosion on very flat slopes. However, it has a moderate effect on steep slopes. Therefore, more care is needed in selecting input values for overland flow path lengths on moderate and steep slopes than on very flat slopes. Furthermore, the effect of overland flow path length also depends on soil and cover-management conditions. Similarly, the effect of a particular cover-management practice depends on location, soil, and topography.

Some variables are used in multiple RUSLE2 equations, which results in complex interactions that complicate sensitivity analyses. Surface biomass, soil biomass and the soil consolidation subfactor are examples of such variables. Each variable has a primary effect and several secondary effects. Surface (flat) cover is often assumed to be the most important RUSLE2 variable, which is true for many but not all conditions. Soil biomass can have a much greater effect on erosion than surface biomass in certain conditions. Surface biomass, soil biomass, and soil consolidation strongly interact so that the combined effect is more than expected based on the primary effect of each variable. Special inputs must be used in sensitivity analyses to isolate the primary effect of individual variables separate from their interactive effects.

Be very careful about generalizing results from a sensitivity analysis. Sensitivity analyses should be conducted over a wide range of conditions before drawing conclusions about the effect of a particular variable on erosion.

Inputs must be changed carefully to conduct sensitivity analyses on surface (flat) cover, which is an important variable in conservation planning on cropland. An input must be selected to change surface cover to conduct a sensitivity analysis on surface cover. An obvious input is vegetation production (yield) level. Changing yield does change surface biomass, but it also changes soil biomass and canopy values. Changing yield is an important sensitivity analysis but not for conducting a sensitivity analysis on surface cover. Is the surface cover analysis to study the effect of surface biomass or is it to study the effect of the portion of the soil surface covered? If the purpose of the sensitivity analysis is to study the effect of surface biomass, inputs for the relationship of aboveground biomass to yield in a vegetation description can be changed. If the sensitivity analysis is to study the effect of how the portion of the soil covered affects erosion, inputs in a **residue description** that relate portion of the soil surface covered to the surface biomass can be changed.

An important sensitivity analysis is the effect of soil disturbance width on erosion (see **Section 9.2.6**). The soil disturbance width effect of a particular soil disturbing operation depends greatly on whether the operation is the only soil disturbing operation in the **cover-management description**. The soil disturbance width effect can be great if only one **soil disturbing operation** is in a cover-management description. The soil disturbance width effect for a particular operation is much less if other soil disturbing operations, especially ones that disturb the full soil width, are included in the cover-management description.

Although soil disturbance width has a minor effect on surface roughness, its major effect is on the soil consolidation subfactor and its secondary effects. The soil consolidation primary effect is illustrated in Figure 7.3. Its secondary effects are from being a variable in several other computations including the soil biomass subfactor, decomposition's transfer of surface biomass to soil biomass, runoff, and the rill-interrill erosion ratio that affects the slope length exponent in equation 8.1 and **b** value in equation 9.6 used to compute ground cover effect. A sensitivity analysis on soil disturbance width and on the soil consolidation effect requires sorting through an array of complex, interacting variables.

Care must also be taken in sensitivity analyses to ensure that the effect of a variable being studied is not being masked by another variable. An example is disturbance depth of secondary tillage. A primary tillage operation with a deep disturbance depth typically precedes secondary tillage operations in many cropland cover-management descriptions. Disturbance depth of secondary tillage operations has very little effect on erosion because primary tillage buries most of the residue below the disturbance depth of the secondary tillage operation. The effect of disturbance depth of the same secondary tillage operation can be significant when no primary tillage operations are in the cover-management description.

RUSLE2 uses a description of field conditions to compute erosion. Most variables in a RUSLE2 description are not automatically changed when input values for key variables are changed. For example, RUSLE2 does not change vegetation production (yield) level when a new location (which changes precipitation and temperature), soil, or management is selected that affects yield. Therefore, a sensitivity analysis that involves changes in variables that affect yield requires changing the yield input value in the cover-management descriptions used in the analysis.

The value entered for yield must be consistent with the selected location's climatic, soil, and management.

17.4. RUSLE2 Accuracy

The assumption in developing RUSLE2 was that the widely accepted and used USLE and RUSLE1 were valid models for conservation and erosion control planning. RUSLE2 was developed to improve these technologies by significantly extending their applicability to practically every field situation where rill and interrill erosion occurs, increasing their power, and improving their underlying supporting science. Therefore, one assessment of RUSLE2's accuracy is to compare RUSLE2 and USLE computed erosion values. A second assessment is the fit of the USLE, and thus RUSLE2, to the research data from which the USLE was derived. A third assessment is identifying where RUSLE2 is most, (and least) accurate.

17.4.1. Comparison of RUSLE2 erosion estimates with USLE erosion estimates

Determining the accuracy of RUSLE2 for estimating how cover-management affects erosion is perhaps the most important assessment of RUSLE2 because of the major role of cover-management in conservation and erosion control planning. The soil loss ratio values in Table 5, AH537 represent measured values.[171] These values are a summary of a large mass of research data, 10,000 plot-years, as analyzed and interpreted by Wischmeier and Smith (AH537). The fully empirical USLE directly uses measured values to compute cover-management's effect on erosion. In contrast, RUSLE2 uses a set of equations that were fitted to the soil loss ratio values in Table 5, AH537 and other data (see **Section 9**). Therefore, one part of the assessment is how well the RUSLE2 subfactor equations fit measured soil loss ratio values.

17.4.1.1. Average annual erosion values for cropland

Table 17.1 shows erosion values computed with the USLE and RUSLE2 for a wide range of cover-management practices for Columbia, MO and for two cotton cover-management practices for Holly Springs, MS.[172] The values in AH537 represent a summary of

[171] Soil loss ratio values in AH537 are the ratio of soil loss with a given cover-management condition at a particular crop stage period to soil loss from the unit plot for the same crop stage.
[172] Columbia, MO is used as a base location in RUSLE2. AH537 values for slope length and steepness, soil loss ratio, and support practice factors are assumed to apply at Columbia, MO. RUSLE2 adjusts its values for these factors about the Columbia, MO base values. The weather at Columbia, MO is near the "middle"

measured values for the eastern US. Measured soil loss ratio values varied greatly among

Table 17.1. Estimated average annual erosion values (tons/acre) for the USLE and RUSLE2 (overland flow path length = 150 ft, steepness = 6%)

Management	USLE	RUSLE2
conv. cont corn, 112 bu/ac spring plow	16	17
conv. cont corn, 112 bu/ac fall plow	19	19
conv. cont. corn 50 bu/ac spring plow	23	28
conv. cont. corn 50 bu/ac fall plow	27	31
conv cont corn silage 112 bu/ac spring plow	28	28
conv cont corn silage 112 bu/ac fall plow	31	29
conv cont corn silage 50 bu/ac spring plow	34	37
conv cont corn silage 50 bu/ac fall plow	37	38
conv 112 bu/ac corn-25 bu/ac soybeans	20	22
conv 112 bu/ac **corn**-25 bu/ac soybeans	21	23
conv 112 bu/ac corn-25 bu/ac **soybeans**	18	21
conv 112 bu/ac corn-25 bu/ac soybeans fall plow	22	25
conv 112 bu/ac **corn**-25 bu/ac soybeans fall plow	23	25
conv 112 bu/ac corn-25 bu/ac **soybeans** fall plow	22	27
conv cont soybeans 25 bu/ac		27
conv cont winter wheat 30 bu/ac	9.4	13
conv 112 bu/ac corn - 25 bu/ac soybeans-30 bu/ac winter wheat	14	19
no till 112 bu/ac corn		1
mulch till 112 bu/ac corn		10
ridge till 112 bu/ac corn		10
conv. cont corn, 112 bu/ac spring plow manure 8000 lbs/ac (dry basis)		9
corn-corn-meadow-meadow-meadow (high production)	7	6
corn-**corn**-meadow-meadow-meadow (high production)	14	17
established meadow, 4 tons/acre	0.2	0.2
established alfalfa	1.1	0.9
conv cotton "flat" planted	32	37
cotton hipped	44	47

Notes:
1. conv - conventional
2. cont - continuous
3. erosion value is erosion in year for crop in bold
4. erosion values computed for Columbia, MO except for two cotton management where values are for Holly Springs, MS
5. meadow refers to hay production
6. Same R value and K value used in USLE and RUSLE2 comptuations
7. LS = 0.824 for USLE while "net" LS value for RUSLE2 varied from 0.73 for no-till corn to 1.01 for conv cont 50 bu/ac silage corn

locations. For example, the soil loss ratio value for the seedbed crop stage for conventionally tilled corn varied from about 0.2 to 0.8 in data collected in the 1970's at several locations.[173] The reasons for this variation could not be empirically determined

of the data for the Eastern US. Holly Springs, MS was used in RUSLE2 as the base location for cotton cover-management because research at that location and other nearby locations provided most of the data used to derive AH537soil loss ratio values for cotton.

[173] The seedbed crop stage is when the soil is finely tilled in preparation for crop seeding. No vegetation

because of unexplained variability in the data. However, fundamental research conclusively shows that erosion decreases as soil biomass increases. Therefore, the seedbed soil loss ratio value for conventionally tilled continuous corn at a particular yield should be higher in the southern US than in the northern US because increased precipitation and temperature significantly increase decomposition, which reduces soil biomass. RUSLE2 captures this and other effects in its cover-management subfactor equations that are not captured by the USLE.

The soil loss ratio values computed by RUSLE2 vary by location, soil, and topography in contrast to the USLE soil loss ratio values that do not vary with these factors. Therefore, a comparison between RUSLE2 and USLE estimated erosion values must be for a representative condition. Columbia, MO (a central location), a silt loam soil, and a uniform overland flow path 150 ft (50 m) long, 6 percent steep were chosen to compute the estimates shown in Table 17.1. Differences in RUSLE2 and USLE erosion estimates vary with location, generally becoming greater with distance from Columbia, MO as climatic conditions differ from those at Columbia, MO.

Even at Columbia, MO, RUSLE2 and the USLE do not compute the same erosion estimates because of differences in equation structure. The daily topographic length factor in RUSLE2 varies with cover-management, while the corresponding USLE L factor does not vary. RUSLE2 computes a “net” LS value that is a temporal integration of daily values weighted by the temporal distribution of erosivity. Values for the RUSLE2 “net” LS factor vary from a low of 0.73 for the 112 bu/ac no-till corn to 1.01 for the 50 bu/ac corn silage whereas the USLE LS value is 0.82 for all conditions in Table 17.1.

Even when the RUSLE2 “net” LS value is the same as the USLE LS factor value, RUSLE2 and the USLE likely will not compute the same erosion values because of differences in temporal integration. RUSLE2 multiplies its daily factors values to determine a daily erosion estimate and sums these values for an annual erosion estimate. The only temporal integration in the USLE is by crop stage period where the soil loss ratio values are weighted by the temporal erosivity distribution to compute a cover-management factor value, which is multiplied by the other factor values to determine an annual erosion estimate.

RUSLE2 does not use “net” factor values to compute annual erosion. These values are only for comparison with USLE factor values and for use in the USLE for conditions where empirical erosion data are not available to determine USLE factor values. **Multiplication of the RUSLE2 computed “net” factor values according to the USLE equation structure does not compute the same erosion estimate as that computed by RUSLE2 (see *Section 5.4*)**.

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and very little surface residue cover are present in conventional moldboard plowed cropping systems that bury almost the entire residue from the previous year’s crop.

An assessment of RUSLE2 based on a comparison of estimated erosion values with USLE estimates must consider differences in equation structure and the additional effects represented by RUSLE2 (see *Section 17.2*).

As illustrated in Table 17.1, RUSLE2 computed erosion values compare well with USLE values. Biomass is the principal factor that affects erosion for the conditions listed in Table 17.1. Biomass differences primarily account for the difference in erosion values from the high biomass meadow (hay) to the low biomass in 50 bu/ac corn silage. Biomass differences also principally account for the differences in erosion between the 50 and 112 bu/ac corn practices. A land use residual effect results from soil biomass loss over time after large amounts of biomass are buried in the soil and a large amount of roots are killed. Erosion increases over two years of corn following a high production meadow (hay) as soil biomass is lost.

Vegetation characteristics and vegetation management affect erosion (e.g., corn, wheat, and hay and hay versus grain production). As the values in Table 17.1 show, RUSLE2 captures the effect of these variables on erosion.

Other factors besides cover-management must be considered when evaluating the RUSLE2 values in Table 17.1. The topographic length factor discussed above is one of those factors. RUSLE2 does not vary the topographic steepness factor; it is constant just as in the USLE. However, the RUSLE2 topographic steepness factor differs from the USLE one. The RUSLE2 steepness factor value for a 6 percent steepness is 18 percent greater than the corresponding USLE value. Consequently, all RUSLE2 erosion estimates in Table 17.1 are systematically increased by 18 percent larger relative to the corresponding USLE values. The difference between the RUSLE2 and USLE steepness factors decreases for steepness less than 6 percent except for very flat steepness where the RUSLE2 values are greater than the USLE values. The RUSLE2 and USLE steepness factor values are equal at 9 percent steepness. Above 9 percent, the USLE values become progressively greater than the RUSLE2 values.[174]

Even when the RUSLE2 “net” soil erodibility value equals the USLE soil erodibility factor value and all other factors are the same, the erosion estimates computed by RUSLE2 and the USLE can differ. The daily RUSLE2 soil erodibility values temporally vary, which affects estimated erosion, especially when comparisons are made for

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[174] See:
AH703

McCool, D.K., L.C. Brown, G.R. Foster, C.K. Mutchler, and L.D. Meyer. 1987. Revised slope steepness factor for the Universal Soil Loss Equation. Transactions of American Society of Agricultural Engineers 30:1387-1396.

multiple locations and soils. Also, the rill erodibility to interrill soil erodibility ratio

Therefore, differences in RUSLE2 and USLE erosion estimates can not be generalized on the basis of computations for a single location, soil, or topography.

varies among soils, which also affects results.

Conservation tillage, including no-till, mulch till, and ridge till, is a major erosion control practice used on cropland. However, no USLE erosion estimates are given in Table 17.1 for conservation tillage because AH537 soil loss ratio values for conservation tillage are considered unreliable. The AH537 values were based on research conducted early when conservation tillage was beginning to be adopted and do not represent modern conservation tillage. Other data on conservation tillage besides the AH537 values were used to develop the RUSLE2 cover-management subfactor equations. Data from a large number of references were reviewed and analyzed to give special attention to no-till because the USLE and RUSLE1 were highly criticized for not accurately computing erosion for no-till. As Figure 17.1 shows, the effectiveness of no-till varies greatly, even more than erosion with conventional tillage. A very detailed analysis of the empirical data did not provide the information required to describe the variability in the no-till data. RUSLE2 captures the main effect illustrated in Figure 17.1 and computes values about this line as a function of location, slope steepness, soil, crop, and yield.

The cover-management subfactor approach used in RUSLE2 computes erosion values that compare well with values computed by the USLE and, therefore, with the experimental data on which the USLE is based.

17.4.1.2. Soil loss values by crop stage for cropland

An additional assessment of RUSLE2's accuracy is how well it reproduces the soil loss ratio values in Table 5, AH537 for crop stage periods.[175] Tables 17.2, 17.3, and 17.4 show RUSLE2 computed soil loss ratio values for corn and cotton. The soil loss ratio values for the fallow crop stage period shows that RUSLE2 captures the effects of surface roughness and the values for crop stages 1, 2, and 3 shows that RUSLE2 captures the effect of a developing and mature crop. Differences between values in Tables 17.3 and 17.4 confirm that RUSLE2 captures the effect of ridges where repeated tillage operations bury almost the entire residue for a low residue cotton crop.

Comparisons for soil loss ratios were made for the other cover-management conditions listed in Table 17.1. The values in Tables 17.2, 17.3, and 17.4 and from the other comparison between RUSLE2 soil loss ratio estimates and the AH537 values indicate that RUSLE2 accurately computes the temporal variation in soil loss ratio values.

RUSLE2 is judged to accurately compute temporal cover-management effects during the year.

Table 17.2. Soil loss ratios for 112 bu/ac conv cont corn from AH537 and values computed with RUSLE2		
Crop stage (defined in AH537)	AH537 Soil loss ratio	RUSLE2 Soil loss ratio
Fallow	31	28
Seedbed	55	54
1 -- 10% < canopy < 50%	48	52
2 – 50% < canopy < 75%	38	30
3 – to maturity	23	18
4 after harvest (stalks spread)	6	6

Table 17.3. Soil loss ratio values for 750 lbs/acre cotton flat planted at Holly Springs, MS. Values from AH537 and computed by RUSLE2		
Crop stage (defined in AH537)	AH537 Soil loss ratio	RUSLE2 Soil loss ratio
Fallow	0.39	0.54
Seedbed	0.64	0.74
1--10% canopy < 35%	0.59	0.74
2--35% < canopy < 60%	0.46	0.49
3--to maturity	0.32	0.23
Defoliation to Dec 31	0.26	0.24
Jan 1 to Feb. tillage	0.32	0.32

Table 17.4. Soil loss ratio values for 750 lbs/acre cotton hipped (ridged) at Holly Springs, MS. Values from AH537 and computed by RUSLE2		
Crop stage (defined in AH537)	AH537 Soil loss ratio	RUSLE2 Soil loss ratio
1st hip, no prior tillage	84	88
Split ridges with a “do-all”	54	52
Hip after 2 prior tillages	108	101
Split ridges with a “do all”	62	58
Hip after 3 or more tillages	110	112
Split ridges with a “do all”	64	64
Seedbed	64	64
1--10% canopy < 35%	59	64
2--35% < canopy < 60%	46	45
3--to maturity	32	21
Defoliation to Dec 31	22	23
Jan 1 to Feb. tillage	32	27

17.4.1.3. Crop residue cover immediately after planting

Crop residue cover immediately after planting is an important variable used in conservation planning and compliance determination on cropland. RUSLE2 is expected to accurately estimate this cover, which it does as illustrated in Table 17.5 for a wide range of conservation tillage systems and the major crops of corn and soybeans.

RUSLE2 accurately estimates crop residue cover immediately after planting for a wide range of tillage systems.

17.4.1.4. Erosion values for range, pasture, and similar lands

Both RUSLE1 and RUSLE2 apply to range and similar lands, although the USLE poorly estimates erosion for these lands.[176] The major problem is with Table 10, AH537, entitled "Factor C for permanent pasture, range, and idle land" used to apply the USLE to these lands. This table does not include a soil surface roughness effect, and it improperly links below ground biomass to ground cover. Table 10, AH537 does not allow rock cover to be considered separately from biomass ground cover, it does not properly account for production (yield) level, and the **b** value in equation 9.6 for the ground cover effect is about 0.026 rather than a much more preferred value of 0.035. Also, values for the USLE slope steepness are too large for steepness greater than 25 percent.

Differences between the RUSLE2 and RUSLE1.06 soil biomass subfactor equations required that new RUSLE2 values for the ratio of effective root biomass to annual above ground production be developed. Two major datasets known as the WEPP rangeland data[177] and the USDA Rangeland Study Team data[178] are available for determining these RUSLE2 ratio values and evaluating RUSLE2 for rangelands.

Only the WEPP data set was used because of problems with the USDA Range Study Team data. The USDA Range Study Team dataset was carefully analyzed to compute effective root biomass values or to evaluate RUSLE2. When the data were divided into plant type categories of sagebrush, bunch, sod, and tall grass, the relationship between surface cover and erosion empirically derived from the data showed that erosion increased as surface cover increased for some of the

[176] Spaeth, Jr., K.E., F.B. Pierson, M.A. Weltz, and W.H. Blackburn. 2003. Evaluation of USLE and RUSLE estimated soil loss on rangelands. J. Range Management 56:234-246.
[177] Simanton, J.R., L.T. West, M.A. Weltz, and G.D. Wingate. 1987. Rangeland experiments for Water Erosion Prediction Project. Paper No. 87-2545. American Society of Agricultural Engineers. St. Joseph, MI.
[178] Spaeth, Jr., K.E., F.B. Pierson, M.A. Weltz, and W.H. Blackburn. 2003. Evaluation of USLE and RUSLE estimated soil loss on rangelands. J. Range Management 56:234-246.

Table 17.5. Measured and RUSLE2 estimated residue cover (percent) immediately after planting

Crop	Tillage system	Observed cover	Estimated cover	Reference
corn	spring disk	15	21	1
corn	fall chisel, spring disk	13	12	1
corn	spring disk, spring disk	27	18	2
corn	spring chisel, spring disk	22	11	2
corn	spring disk	15	21	2
corn	fall chisel, spring disk	13	12	2
soybeans	spring disk, spring disk	27	18	2
soybeans	spring chisel, spring disk	22	11	2
corn	spring disk	8	20	2
corn	spring disk, spring disk	5	7	2
corn	spring chisel, spring disk	7	3	2
corn	field cultivator	24	20	2
soybeans	spring disk, spring disk	11	8	2
soybeans	spring disk	15	22	2
soybeans	spring chisel, spring disk	11	4	2
corn	fall chisel, spring disk	33	26	3
corn	spring chisel, spring disk	19	19	4
corn	spring disk, spring disk	30	27	4
corn	fall chisel, spring disk, spring field cultivator	9	14	5
soybeans	fall chisel, spring field cultivator, spring field cultivator	9	5	5
corn	fall chisel, spring disk, spring field cultivator	16	14	6
soybeans	fall chisel, spring field cultivator, spring field cultivator	3	5	6
soybeans	spring disk, spring disk	9	7	7
soybeans	spring disk, spring disk	9	7	8
soybeans	spring disk	13	18	8

Table 17.5 (continued). Measured and RUSLE2 estimated residue cover (percent) immediately after planting			
References:			
1. Siemens, J. C., W. R. Oschwald.1976. Erosion from corn tillage systems. Trans. ASAE 19:69-72.			
2. Dickey, E. C., D. P. Shelton, P. J. Jasa, T. R. Peterson. 1985. Soil erosion from tillage systems used in soybeans and corn resides. Trans. ASAE 28:1124-1129, 1140.			
3. Lindstrom, M. J. and C. A. Onstad. 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. J. of Soil and Water Cons. 39:149-152.			
4. Laflen, J. M., J. L. Baker, R. O. Hartwig, W. F. Buchele, and H. P. Johnson. 1978. Soil and water losses from conservation tillage systems. Trans. ASAE 21:881-885.			
5. McIsacc, G. F., J. K. Mitchell, and M. C. Hirschi. 1990. Contour and conservation tillage for corn and soybeans in the Tama Silt Loam Soil:hydraulics and sediment concentration.Trans. ASAE 33:1541-1550.			
6. McIsaac, G. F., J. K. Mitchell, M. C. Hirschi, and L. K. Ewing. 1991. Conservation and contour tillage for corn and soybeans in the Tama silt loam soil:the hydrologic response. Soil and Tillage Research 19:29-46.			
7. Shelton, D. P., P. J. Jasa, and E. C. Dickey. 1986. Soil erosion from tillage and planting systems used in soybean residue:Part I-influences of row spacing. Trans. ASAE 29:756-760.			
8. Jasa, P. J., E. C. Dickey, and D. P. Shelton. 1986. Soil erosion from tillage and planting systems used in soybean residue:Part II-influences of row direction. Trans. ASAE 29:761-766.			

plant types, which is unacceptable based on well accepted fundamental research. Measurements were taken at too few sites for the number of variables affecting erosion, and perhaps measurements of input variables were not made according to RUSLE definitions. In several cases, the plant litter cover was inconsistent with the production level (e.g., far too much litter cover for the annual production). Also, in the few cases when experimental sites for the WEPP and Range Study Team studies coincided or were close together much of the data for the basic cover-management variables from these common sites values did not agree. Some of these differences may have been caused by temporal differences because the experiments were conducted in different years.

The first step in determining these ratio values was to classify the WEPP data by plant community. The standard RUSLE2 soil erodibility, topographic, canopy, ground cover, surface roughness, and soil consolidation factor values were assumed to apply to these data, which reflects RUSLE2 land use independence. Measured erosion values were divided by the product of these factor values to compute a soil biomass subfactor value for each experimental site. A value for effective root biomass was next obtained by substituting the soil biomass subfactor value computed from the experimental data in equation 9.12, where a zero buried residue biomass was assumed. The effective root biomass value computed by solving equation 9.12 was divided by the annual aboveground biomass production (yield) level to determine a value for the ratio of effective root biomass in the upper 4 inch (100 mm) soil depth to annual aboveground production. A non-linear procedure that fitted predicted erosion to measured (observed) erosion was used to determine ratio values for plant communities that occurred at multiple sites. The resulting values are shown in Table 17.6.

Table 17.6. Values for ratio of effective root biomass to annual above ground biomass production for vegetation typical of range, pasture, and similar lands.

Plant community	ratio effective root biomass in upper 4 inches (100 mm)/annual above ground production
N mixgrass	2.5
S mixgrass	3.1
tallgrass prairie	1.0
shortgrass prairie	3.0
desert grassland	6.1
southern grasses	6.4
CA annual grass	2.6
cold desert shrub	5.9
southern desert shrub	6.6
shinnery oak w/herb interspace	2.6
chaparral	1.3
pasture, sod grasses	6.0
pasture, bunchgrasses	3.7
pasture, weeds	2.3

The values shown in Table 17.6 may not be consistent with known rooting and other characteristics of these plant communities. One reason for the lack of expected trends is variability in the measured data, too few measurement sites for each plant community, and too few replications. A sufficient number of sites to obtain a reasonably accurate overall effective root biomass ratio value for a plant community were available for only the southern desert shrub and southern mixed grass prairie plant communities. With these two exceptions, the Table 17.6 values for each plant community were derived from data for a single site. The Table 17.6 value for a plant community could differ from the expected value by a factor of two based on data for the two plant communities that occurred at multiple sites.

The Table 17.6 values are also affected by applying the standard RUSLE2 soil erodibility factor and the soil consolidation factor values to rangeland conditions. Tilling coarse texture rangeland soils in the southwestern US to create unit plot conditions greatly increases infiltration and reduces runoff and erosion (see **Section 7.2**). The low erosion immediately after tillage is related to land use residual effects (see **Section 9.2.5**). For example, soil plowed out of high production meadow is only one fourth as erodible immediately after tillage as it is after two years of tillage for row crop production (AH537). This land use residual effect disappears over time as a soil is continuously maintained in a unit plot condition. Research on these southwestern US rangeland soils showed that erosion increased over about three years after an initial tillage but no subsequent tillage, which indicates a strong land use residual effect in these soils.[179] The RUSLE2 assumption that standard erodibility values apply to rangeland conditions seem reasonable.

The soil consolidation effect assumes that tillage increases erosion by about 55 percent (see **Section 7.8**). This effect seems to have been masked in the land use residual effect in the research described above. The soil consolidation effect surely varies with soil properties and climate. However, research has not defined the relationship between the soil consolidation effect with these variables, even for cropland conditions and certainly not for rangeland conditions. The RUSLE2 soil consolidation relationship was empirically derived from data collected on a single soil at Zanesville, Ohio.

In any case, discrepancies between RUSLE2 soil erodibility and soil consolidation relationships and those for rangeland conditions were empirically incorporated in the Table 17.6 values. These soil and climate effects, along with data variability, account for any inconsistency in Table 17.6 values with vegetation characteristics.

Until research provides improved information, the values in Table 17.6 should be used even if they do not seem consistent with vegetation characteristics.

The Table 17.6 values were derived assuming the time invariant cover-management (C factor) procedure (AH703). Therefore, these values represent buried residue and dead roots as well as live roots. Vegetation, residue, and cover-management descriptions can be created so that RUSLE2 computes erosion using a time invariant C factor procedure similar to that in RUSLE1.06c. The **vegetation description** has a single entry in the **growth chart** on day zero. The entered value for live root biomass is the product of the site average annual production level and the ratio value in Table 17.6 for the plant community. Entered values for canopy cover, effective fall height, and live ground cover are representative values chosen to compute average annual erosion. The **cover-management description** includes an **operation description** having a **begin growth process** that tells RUSLE2 to use the single entry vegetation description and an **add other residue/cover process** that applies an **external residue** to give the desire ground cover. The **residue description** uses a zero value for the **decomposition coefficient** so

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[179] See:

Simanton, J.R. and K.G. Renard. 1982. Seasonal change in infiltration and erosion from USLE plots in southeastern. Hydrol. Water Resources in Arizona and Southwest 12:p. 37-46.

Simanton, J.R., Johnson, C W., Nyhan, J.W., Romney, E.M. 1986. Rainfall simulation on rangeland erosion plots. Proc. Rainfall Simulator Workshop, Jan. 1985, Tucson, AZ, pp. 11-17.

Simanton, J.R., Renard, K.G. 1986. Time related changes in rangeland erosion. Proc. Rainfall Simulator Workshop, Jan. 1985, Tucson, AZ, pp. 18-22.

that the residue does not decompose to properly represent the time invariant approach. The cover-management description is a **no-rotation type** with one year **duration**.

Rather than use this time invariant approach, the recommended procedure is to use RUSLE2's full temporal capability when applying it to range and similar lands. Two options are available for determining input values for live root biomass in the vegetation descriptions. One option is to use literature values or to make field measurements. The literature values are highly variable. For example, the reported ratio for root biomass to aboveground biomass ranged from 0.6 to 120 for the northern mixed grass prairie plant community (AH537). A problem with literature values and with field measuring roots, which are very difficult to measure, is knowing the root size above which to discard roots because large roots have little effect on erosion. The most important roots are the fine ones near the soil surface. Even if roots are accurately measured, research has not established the relationship of erosion to root characteristics.

The best option for determining live root biomass input values is to use the RUSLE2 **long-term vegetation tool** to construct vegetation descriptions (see **Section 11.2.6**). This tool uses Table 17.6 values to estimate live root biomass values. A major advantage of using Table 17.6 values is that they have been empirically determined directly from measured erosion data using RUSLE2 definitions and equations.

Although the Table 17.6 values include a buried residue and dead root effect when used in the time invariant C factor procedure, these values give good results when they are used to estimate live root biomass values for temporal vegetation descriptions. The RUSLE2 full temporal method using live root biomass developed from Table 17.6 values gave comparable erosion estimates to those from the RUSLE1.06c time invariant C factor procedure.

The RUSLE2's temporal procedures should be used when applying RUSLE2 to range, pasture, and similar lands rather than the time invariant C factor method.

WEPP data collected for plant communities that occurred at multiple sites provided a limited indication of the uncertainty in RUSLE2 erosion estimates. The south desert shrub plant community occurred at six sites and the southern mixed grass prairie plant community occurred at five sites.[180] Estimated (predicted) and measured (observed) erosion values are shown in Figures 17.2 and 17.3. RUSLE2 estimated erosion values compare reasonably well with measured erosion values for the south desert shrub plant community except for one data point in Figure 17.2 where the predicted erosion was

[180] Data from two additional sites for the south desert shrub plant community and from an additional site for the southern mixed grass prairie plant community were not used in the analysis because these data points were judged to be outliers.

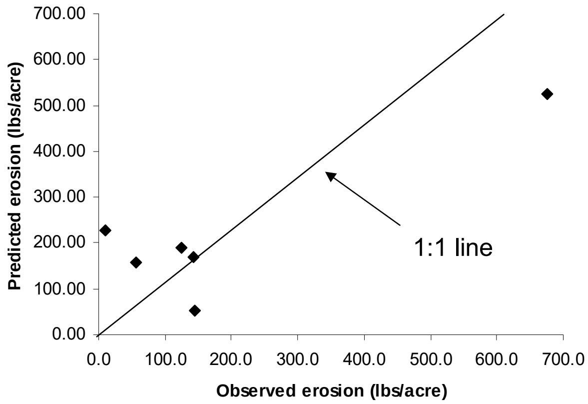

Figure 17.2. Predicted and observed erosion for south desert shrub plant community.

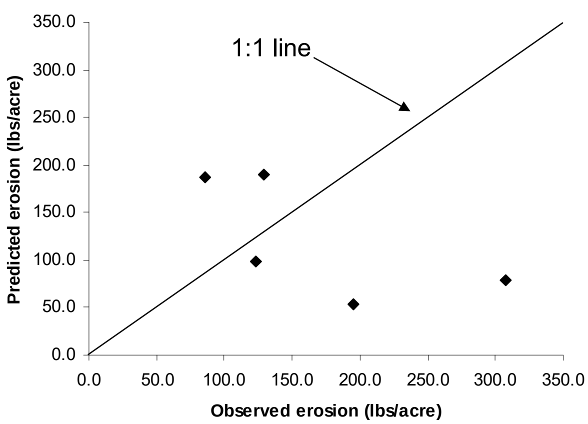

Figure 17.3. Predicted and observed erosion for southern mixed grass plant community.

about 220 lbs/acre while observed erosion was about 10 lbs/acre. However, other than this data point, the data are comparable to scatter in erosion data for cropland at such low erosion rates. Data for the southern mixed grass prairie plant community are shown in Figure 17.3. The error is large for two data points. Based on these results, a RUSLE2 erosion estimate for a particular rangeland site could be in error by a factor of five.

Even a modest evaluation of RUSLE2's accuracy for range and similar lands is essentially impossible because of limited research data (See **Section 17.2)**. The WEPP and Range Study Team datasets are the best available, but these data were produced using rainfall simulators and involved rainfall application at a single point in time rather than at several times during the year and over several years. The WEPP and Range Study Team data do not account for average annual seasonal changes or year to year changes. Even though above and surface ground cover can be measured, below ground measurements can not be easily made to determine the land use residue effect at the time of the experiments. Weather, vegetation, and soil conditions over several years preceding the experiments can greatly affect erosion measured at a single point in time.

The similarity of erosion generated by simulated rainfall and that produced by natural rainfall on western US rangelands is highly questionable. For example, the erosivity of single simulated storm in both the WEPP and Range Study Team experiments was about 50 US erosivity units whereas the average annual erosivity in much of the western US, where most rangeland occurs, is less than 20 US erosivity units. The data used to determine the Table 17.6 values were from a single simulated storm applied to dry soil conditions. These experiments also involved a second simulated storm applied to moist conditions. Table 17.6 values and results of RUSLE2 evaluations depend greatly on whether one or two storms are used in the analysis. Also, the simulated rainfall was applied in a uniform intensity that can give significantly different erosion when infiltration rates are high and spatially varied than erosion from temporally varied intensity.[181] Applying multiple simulated rainfall multiple times during the year affects the conditions being studied because of the additional rainfall. This effect is very important in the dry climates where most rangeland occurs where the simulated rainfall is a significant portion of the annual rainfall.

Table 17.7. Erosion values from two side by side replicates for WEPP study

Erosion (lbs/ac)		
Low rep	High rep	ratio
8	20	0.42
55	85	0.64
0	56	0.00
34	91	0.37
4	100	0.04
14	27	0.54
0	3	0.00
0	0	-
0	330	0.00
0	0	0.00
26	68	0.38
213	375	0.57
145	194	0.75
0	10	0.00
0	0	-
0	0	-
22	79	0.28
0	20	0.00
350	464	0.75
244	300	0.81
50	203	0.24
0	23	0.00
302	581	0.52
3	48	0.06
7	44	0.16
0	0	-
0	0	-
5	69	0.07
15	43	0.36
0	4	0.00

Accurately measuring the low erosion rates typical of rangeland conditions (e.g., 50 lbs/ac in Figure 17.3) and having small differences, especially on a percentage basis, between replications is almost impossible. Table 17.7 shows a range of the ratio of measured erosion for the two replications in the WEPP study. These ratio values are not particularly meaningful given the low erosion rates. A slight soil disturbance near the end of a plot or a slight shift in the placement of plots could have easily produced significantly different measured erosion values. Expecting RUSLE2 or any other model to precisely fit data for individual sites is unrealistic and unreasonable because of the low erosion rates, spatial and temporal variability, and the difficulty of measuring low erosion rates. These data issues must be considered when evaluating RUSLE2 for its applicability to range and similar lands. RUSLE2 may perform better than the experimental data used to evaluate it.

Is RUSLE2 adequate for conservation and erosion control planning for range, pasture, idle, and similar lands? VERY DEFINITIVELY. RUSLE2 describes the main effects of how the major physical, biological, and ecological variables, affect erosion as conclusively proven by fundamental erosion research. RUSLE2 computes the low erosion rates that have been measured on range, pasture, idle, and similar lands. RUSLE2 accurately represents how changing major variables such as plant community, production level, removal of biomass, and mechanical soil disturbance affects erosion.

[181] Flanagan, D.C., G.R. Foster, and W.C. Moldenhauer. 1988. Storm pattern effect on infiltration, runoff, and erosion. Transactions of American Society of Agricultural Engineers 31(2):414-420.

RUSLE2 can be used as a conservation and erosion control planning tool for rangelands, pasturelands, idle, and other similar lands.

17.4.1.5. Erosion values for construction sites

Published data related to erosion control on construction sites using straw and other mulch types were extensively reviewed during the development of RUSLE1.06.[182] New RUSLE1.06 relationships were developed to describe the reduced effectiveness of mulch on construction sites relative to cropland. These new relationships also describe how mulch conformance to soil surface roughness affects erosion control on construction sites. Also, the effectiveness of simple sediment basins, surface roughness, ridging, and porous barriers on reducing erosion and trapping sediment was also extensively reviewed during the RUSLE1.06 development. Equations, input values, and other information developed for RUSLE1.06, along with information developed since the RUSLE1.06 release were used in the development and evaluation of RUSLE2 for its applicability to construction sites and similar conditions. RUSLE2 works significantly better for construction site conditions than does RUSLE1.06.

17.4.1.6. Erosion values for disturbed forestland

The Dissmeyer-Foster subfactor method used to estimate erosion on disturbed forestland is widely recognized and accepted.[183] The basic subfactor relationships used in that method are used in the RUSLE2. Therefore, RUSLE2 estimates erosion with comparable accuracy as does the Dissmeyer-Foster method. RUSLE2 is substantially better than the USLE with the Dissmeyer-Foster method because of RUSLE2's increased power and capability, such as applying to non-uniform overland flow profiles and improved relationships for computing revegetation of disturbed forestland following mechanical disturbance. RUSLE2 can also be applied to road construction in forested areas and can estimate erosion on logging roads where the runoff occurs as overland flow. RUSLE2 can also be used to evaluate how alternative burning treatments and forest fire affects erosion. Burning removes surface biomass and some buried biomass and roots. RUSLE2 represents burning removing surface and buried biomass, but it does not represent the removal of either live or dead root biomass by burning.

17.4.2. Accuracy of RUSLE2 by statistical measures

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[182] Toy, T.J. and G.R. Foster (coeditors). 1998. Guidelines for the use of the Revised Universal Soil Loss equation (RUSLE1.06) on mined lands, construction sites, and reclaimed lands. USDI-Office of Surface Mining. Denver. CO.

[183] Dissmeyer, G.E. and G.R. Foster. 1980. A guide for predicting sheet and rill erosion on forest land. Technical Publication SA-TP-11. USDA-Forest Service-State and Private Forestry-Southeastern Area. 40 pp.

An analysis of the statistical fit of the USLE to the experimental natural runoff plot data used to develop the USLE showed that the USLE computes average annual erosion within 25 percent for average annual erosion between 4 and 30 tons/acre and within 50 percent for average annual erosion between about 0.5 and 4 tons/acre.[184] The uncertainty increases rapidly for average annual erosion less than 1 ton/acre and can exceed 500 percent for average annual soil loss less than 0.1 tons/acre (see **Section 17.4.1.4**). The uncertainty also increases, but not greatly, for average annual erosion greater than 30 tons/acre. The uncertainty in RUSLE2's estimates erosion are slightly greater than that for the USLE based on an evaluation of RUSLE1 using the same data and the similarities between RUSLE1 and RUSLE2.[185]

RUSLE2 (and RUSLE1) not fitting the data as well as the USLE is expected. The AH537 soil loss ratio values used in the USLE are essentially direct summaries of the experimental data whereas the soil loss ratio values used by RUSLE2 (and RUSLE) are computed with equations fitted to the AH537 values. As expected, the fitted equations do not exactly fit the data (see **Section 17.4.1.1)**.

Even though the fit of RUSLE2 to the experimental data is slightly less than the USLE fit, RUSLE2 is superior to the USLE because of RUSLE2's increased power and capability. In contrast to the USLE, RUSLE2 can be applied to conditions where experimental data have not been collected to empirically determine soil loss ratio values. Although the USLE has a cover-management subfactor procedure for "undisturbed, pasture, and idle lands," the procedure is deficient and should not be used. The RUSLE2 subfactor procedure is much better than the USLE procedure.

A statistical analysis of the fit of the USLE to the experimental data is not particularly robust because the natural runoff plot data have a high degree of unexplained variability.[186] A difference of 30 percent in measured erosion between adjacent plots is common for conditions where little difference would be expected. The difference in measured erosion between replicate plots can not be explained by measured differences in soil, topography plot preparation, or plot condition. Data quality must often be compromised in finding a hillslope where an adequate number of replications can be installed without excessive variation in soil or topographic properties that affect erosion

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[184] Risse, L.M., M.A. Nearing, A.D. Nicks, and J.M. Laflen. 1993. Error assessment in the Universal Soil Loss Equation. Soil Sci. Soc. Am. J. 57: 825-833.
[185] See:
Rapp, J.F. 1994. Error assessment of the Revised Universal Soil Loss Equation using natural runoff plot data. M.S. Thesis. University of Arizona, Tucson.

Tiwari, A.K., L.M. Risse, and M.A. 2000. Evaluation of Wepp and its comparison with USLE and RUSLE. Trans. ASAE 43:1129-11135. (Based on this paper, RUSLE is slightly better than the process-based model WEPP.)
[186] Nearing, M.A., G. Govers. and L.D. Norton. 1999. Variability in soil erosion data from replicated plots. Soil Sci. Soc. Amer. J. 63: 1829-1835.

(see **Section 17.2**). Too few replications at individual locations, non-uniform coverage of the major variables that affect erosion and differences in statistical designs between locations in numerous studies prevent the use of common statistical methods to evaluate RUSLE2's statistical accuracy. The number of variables affecting erosion is very large, which in turn requires a large and high quality database to statistically evaluate RUSLE2. If the database is too small and does not uniformly cover the range of variables affecting erosion, erroneous conclusions are drawn. For example, Risse et al.[187] concluded that contouring does not affect erosion. However, when a proper dataset on contouring is assembled and analyzed, the analysis shows that contouring has a major effect on erosion although its effect is highly variable (see **Section 14.1**).[188]

Because RUSLE2 is, for the most part, empirically derived, RUSLE2's adequacy is determined by the data used to derive it. Therefore, RUSLE2's adequacy for a particular application is largely determined by how well the plots and small watersheds (<5 acres) used to derive RUSLE2 represent actual field conditions.

RUSLE2 provides an accurate representation of how major variables affect erosion as measured by plots and small watersheds (<5 acres).

17.4.3. Qualitative assessments of RUSLE2's accuracy

Qualitative assessments of RUSLE2's accuracy are useful in guiding conservation planning decisions. The following sections provide qualitative assessments of where RUSLE2 works best and where it is less well suited.

17.4.3.1 Temporal values

RUSLE2 is designed to estimate average annual erosion. It is not designed to estimate erosion from individual storms, specific time periods, probability distributions of erosion by storm, season, or year. Also, it is not designed to estimate erosion for a storm with a given recurrence interval. Information in AH537 can be used to construct probability

[187] Risse, L.M., M.A. Nearing, A.D. Nicks, and J.M. Laflen. 1993. Error assessment in the Universal Soil Loss Equation. Soil Sci. Soc. Am. J. 57: 825-833.

[188] The Risse et al. and Tiwari et al. papers are considered definitive papers on statistical evaluations of the USLE and RUSLE. However, these papers' shortcomings affect interpretation of their results. The evaluations described in both papers used only a portion of the available data (e.g., Tiwari et al. used only 1600 plot-years of data for 20 locations while Risse et al. used only 1700 plot-years of data at 23 locations out of more than 10,000 plot-years of data at 43 locations used to develop the USLE and RUSLE). The natural runoff plot data used to develop the USLE are not uniformly distributed for the main variables that affect rill-interrill erosion. Choosing an unbiased 20 percent sample from the entire dataset is difficult. For example, the evaluation dataset chosen by Risse et al. was biased. The dataset included 2 plots from Morris, MN, 13 plots at Guthrie, OK, and 18 plots from LaCrosse, WI. Neither paper provides information to show that the evaluation results were unbiased. Such statistical evaluations are not robust and their validity is questionable.

distributions for annual erosivity at individual locations that can be used in RUSLE2 to compute probability distributions of annual erosion for average soil and cover-management conditions. **RUSLE2** can not consider deviations in cover-management conditions by day, season, or year from the average condition.

An advanced user can compute erosion with RUSLE2 for a single storm. The erosion computed for this storm represents the average erosion produced by the storm occurring in many years on the storm's date.[189] Although RUSLE2 is not recommended for estimating erosion for individual storms, RUSLE2's accuracy for individual storms is comparable to that for process-based models like WEPP.[190] Other research has also shown that simple empirical models fitted to observed data perform as well as or better than process-based hydrologic models.

The USLE equation structure, which is used in RUSLE2, is said to underestimate erosion when average annual erosion and erosion from individual storms is large.[191] However, this statement does not accurately represent this equation structure. The USLE equation structure is fitted to estimate average annual erosion values. Consequently, it is self evident that this equation structure, when properly fitted to the data, both underestimates and overestimates large erosion. This equation structure underestimates erosion when a large storm produces an unusually high runoff relative to storm amount because the storm occurred on very moist soil. RUSLE2 has no explicit runoff term to represent increased runoff for a given rainstorm. Conversely, the equation structure overestimates erosion when the same storm occurs on very dry soil that produces low runoff. Estimating runoff is more difficult than estimating erosion based on W.H. Wischmeier's experience.[192] Process-based models' equation structure should give them an inherent advantage over RUSLE2 for estimating erosion for single storms, but that capability is barely realized in practical applications. The advantage of process-based models is lost because of

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[189] The RUSLE2 is designed for conservation and erosion control planning where average annual erosion is used in the planning process. As a consequence, the RUSLE2 computer program is not designed to accept inputs for specific storms and, therefore, is inconvenient for computing erosion for individual storms.

[190] See:

Tiwari, A.K., L.M. Risse, and M.A. Nearing. 2000. Evaluation of Wepp and its comparison with USLE and RUSLE. Trans. ASAE 43:1129-11135.

Nearing, M.A. 1998. Personal communication.

[191] Risse, L.M., M.A. Nearing, A.D. Nicks, and J.M. Laflen. 1993. Error assessment in the Universal Soil Loss Equation. Soil Sci. Soc. Am. J. 57: 825-833. (In fact, Figure 1 in this paper shows that the USLE does not underestimate erosion for measured high erosion relative to moderate erosion. Figure 1 does show that the USLE overestimates erosion for low measured erosion. The overestimation occurs for annual erosion less than 1 ton/acre.)

[192] **Wischmeier**, W.H. 1966. Relation of field plot runoff to management and physical factors. Soil Sci. Amer. Proc. 30:272-277.

Wischmeier, W.H. mid 1970's. personal communication.

estimation errors in runoff and the many variables that are functions of environmental variables in these models.[193] The cumulative effect of having many more variables to calibrate in process-based models than in the USLE equation structure diminishes process-based model performance. Too often calibration of process-based models results in fitting unexplained variability rather than main effects.

17.4.3.2. Soils

Difficulty in estimating runoff from input climate data is the major reason why an explicit runoff term is not used in RUSLE2 except for computing the effect of support practices on erosion where an index-based approach is used to capture main effects.

RUSLE2 is most applicable to medium textured soils. It works moderately well for fine textured soils and acceptably for coarse textured soils and least well for high sand soils. Errors can be large when applied to rangeland coarse textured soils in the Southwestern US and to soils on reclaimed mined land having a very high content of large rock fragments. Technical judgment can be used in assigning soil erodibility factor values to overcome some of these difficulties (see **Section 7**).

RUSLE2 should not be applied to organic soils, such as peat.

17.4.3.3. Topography

RUSLE2 works best for overland flow path lengths between 50 (15 m) and 300 ft (100 m) long. It works moderately well for overland flow path lengths less than 20 ft long, including overland flow path lengths as short as 1 inch (25 mm), and for overland flow path lengths between 300 and 600 ft (100 and 200 m). It works acceptably for overland flow path lengths between 600 and 1000 ft long (200 and 300 m).

RUSLE2 should not be applied to overland flow path lengths greater than 1000 ft (300 m). The RUSLE2 program will not accept input values greater than 1000 ft (305 m).

RUSLE2 works best for overland flow path steepness between 3 and 20 percent. It works moderately well for steepness less than 3 percent and between 20 and 35 percent. It works acceptably for steepness between 35 and 100 percent. It should not be applied to steepness greater than 100 percent.

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[193] Tiwari, A.K., L.M. Risse, and M.A. Nearing. 2000. Evaluation of Wepp and its comparison with USLE and RUSLE. Trans. ASAE 43:1129-11135.

RUSLE2 should not be used for overland flow path steepness greater than 100 percent. The RUSLE2 program does not accept input values greater than 100 percent

RUSLE2 can be applied to all overland flow path profile shapes, including those where deposition occurs (see **Section 5.2**). Its erosion estimates for the eroding portions of overland flow paths are significantly more accurate than deposition estimates for the depositional portions. Accurately estimating deposition by overland flow is very difficult because a slight change in overland flow hydraulics can greatly affect deposition. RUSLE2 estimates are most accurate for uniform cover-management along an overland flow path. RUSLE2 is less accurate where cover-management varies enough along the overland flow path to significantly affect runoff because RUSLE2 does not explicitly consider runoff in its detachment computations. Overland flow path segment lengths can be adjusted to partially to account for this RUSLE2 limitation (see **Section 8.4**).

17.4.3.4. Geographic Region

RUSLE2 works best where rainfall occurs regularly, rainfall is the dominant precipitation, and average annual rainfall exceeds 20 inches. **RUSLE2** works acceptably in low rainfall regions like the western US. In these areas, RUSLE2 results should be interpreted as representing average erosion for sites having conditions like the field site rather than representing erosion on the actual field site. RUSLE2 erosion estimates are more accurate for actual field sites in high than in low rainfall regions. RUSLE2's accuracy is significantly reduced in low rainfall regions where annual erosion is low, especially if it is less than 1 ton/acre. **RUSLE2** can be used to estimate erosion in the special winter condition represented by the Northwest Wheat and Range Region. Special adjustments are needed for other regions where Req-type effects occur (see **Section 6.3.3**).

RUSLE2 does not explicitly estimate erosion caused by snowmelt.

17.4.3.5. Land Use

RUSLE2 is land use independent. It applies to all land uses where mineral soil is exposed to the erosive forces of raindrop impact and Hortonian overland flow. RUSLE2 works best for all land uses where annual erosion exceeds 1 ton/acre. **RUSLE2** works best for cropland, construction sites, land fills, and moderate to highly disturbed military training sites. It works moderately well on pastureland, mine spoil and disturbed forestland. It works acceptably on rangeland, abandoned crop and pastureland, and similar wildlife lands with few trees.

RUSLE2 should not be used for undisturbed forestland.

17.4.3.6. Irrigation

RUSLE2 can be used to estimate erosion by rainfall on lands where irrigation is used.

RUSLE2 cannot estimate erosion by furrow, flood, or similar types of surface irrigation.

17.4.3.7. Processes

RUSLE2 estimates rill and interrill erosion from rainfall and its associated runoff produced as Hortonian overland flow. It estimates sediment yield from overland flow paths, from diversion/terrace type channels where deposition occurs, and from impoundments like small sediment basins and impoundment terraces (see **Section 5.2**).

RUSLE2 does not estimate erosion or deposition in concentrated flow areas like within-field ephemeral gullies, incised gullies, and stream channels. RUSLE2 does not estimate erosion by mass wasting or by piping (i.e., water flowing through "pipes" in the soil).

17.5. Relation of RUSLE2 to other USLE/RUSLE erosion prediction technologies

The USLE was first used for local field office conservation planning by the USDA-Soil Conservation Service in the early 1960's. AH282, published in 1965, documented this USLE version. The next version of the USLE was documented in AH537, and it remains the standard USLE version. RUSLE1 was first released in 1992. The NRCS officially adopted RUSLE1.05 for local field office conservation planning in the mid 1990's. RUSLE1.05 is documented in AH703. RUSLE1.06, intended to replace RUSLE1.05, was released in 1998 and documented in the OSM manual for applying RUSLE1.06 to construction, mine, and reclaimed lands.[194] An erroneous impression is that RUSLE1.05 should be applied to cropland and RUSLE1.06 to disturbed lands. All versions of RUSLE1.06 apply to all lands. RUSLE1.06c was released in 2003. Changes were made so that RUSLE1.06c erosion estimates more closely correspond with RUSLE2's estimates than those from previous RUSLE1.06 versions.

[194] Toy, T.J. and G.R. Foster (coeditors). 1998. Guidelines for the use of the Revised Universal Soil Loss equation (RUSLE1.06) on mined lands, construction sites, and reclaimed lands. USDI-Office of Surface Mining. Denver. CO.

Foster et al. describe major differences in these technologies.[195]

17.5.1. Erosivity

The erosivity values given in AH282, AH537, and AH703 were determined from precipitation data collected from the mid 1930's to mid 1950's for the eastern US. The RUSLE2 erosivity values were determined from precipitation data collected from 1960 through 1999 for the entire continental US (see **Section 6.2**). Overall, the erosivity values from the recent data are about 10 percent higher in the Eastern US than erosivity values from the early data. The RUSLE2 erosivity values for the western US are much better than the erosivity values in AH537 or AH703.

RUSLE2 erosivity values should be used in all USLE/RUSLE versions.

Erosivity values in AH537 were reduced along the US Gulf Coast to account for high intensity rainfall ponding water that creates a water depth and reduces raindrop impact erosivity. Erosivity values in AH703 were not reduced to account for this effect. Instead, a ponding subfactor that is a function of the 10 year EI value and slope steepness was used in all RUSLE1 versions, but the ponding subfactor was used only with ridges. RUSLE2 uses a similar ponding subfactor (see **Section 9.2.7**) that is applied regardless of the presence of ridges.

The AH703 10 yr EI values were also based on the 1930's to 1950's precipitation data. The 10 yr EI values were contoured in great detail, which resulted in a 10 yr EI map with long narrow ridges-valleys in the equal value lines. A 10 yr EI map was developed for RUSLE1.06c that eliminated these ridges-valleys to represents main trends across the US appropriate for computing how support practices affect erosion.

The new RUSLE1.06c 10 yr EI map should be used in all RUSLE1 versions.

RUSLE2 uses 10 yr-24 hr precipitation values, which are based on data collected from before the 1960's, rather than 10 yr EI values. Smoothed 10 yr-24 hr precipitation values used in RUSLE2 are shown in Figure 6.18. These values capture the main trends across the Eastern US, much like the new 10 yr EI map developed for RUSLE1.06c.

RUSLE2 uses modern precipitation and temperature data that should also be used in all RUSLE1versions.

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[195] Foster, G.R., T.J. Toy, and K.G. Renard. 2003. Comparison of the USLE, RUSLE1.06c, and RUSLE2, for application to highly disturbed land. In: First Interagency Conference on Research on Research in the Watersheds. USDA-Agricultural Research Service. Washington, D.C. pp. 154-160.

Use the smoothed 10 year EI map developed for RUSLE1.06c for all RUSLE1 versions.

17.5.2. Soil erodibility

All USLE/RUSLE versions use the same base soil erodibility factor value. RUSLE1.05 and RUSLE1.06b temporally vary the soil erodibility factor value while RUSLE1.06c does not. The resulting erosion difference can be 20 percent in some Midwestern US and Northeastern US location. RUSLE2 uses a new procedure to temporally vary soil erodibility factor values that is much better than the old RUSLE1 procedure, especially in the western US outside of Req type regions. The net soil erodibility factor value computed by RUSLE2 can also differ from RUSLE1.05 and RUSLE1.06 net erodibility factor value by 20 percent. The net soil erodibility value computed by RUSLE2 is close to the base soil erodibility value used by RUSLE1.06c for most of the Eastern US.

The RSULE2 temporal soil erodibility equation also computes average annual soil erodibility values that vary with location, even when soil properties are the same between locations. This effect is greatest in the Western US where soil erodibility values can vary as much as 50 percent from base soil erodibility values.

Do not temporally vary soil erodibility factor values in any RUSLE1 version.

RUSLE2 includes the standard USLE soil erodibility nomograph (AH537, AH703) widely used to estimate soil erodibility values. RUSLE2 also includes a modified version of the USLE soil erodibility nomograph that computes a greater effect of soil structure on soil erodibility than does the standard USLE nomograph (see **Section 7.3.2**). The trend of soil erodibility with soil structure in the standard USLE nomograph is not consistent with the trend identified by fundamental research.

The RUSLE2 modified soil erodibility nomograph should be used in all USLE/RUSLE versions when applied to highly disturbed lands. The standard USLE soil erodibility nomograph can be used on cropland.

The USLE does not consider sediment characteristics. RUSLE1.05 uses a single value deposition coefficient that does not vary with soil properties or upslope deposition. RUSLE1.06b and c use a deposition coefficient that is computed as a function of soil texture, but it does not change with upslope deposition. RUSLE2 computes sediment characteristics values for five sediment classes at the point of detachment as a function of soil texture. RUSLE2 computes how deposition changes the distribution among the sediment classes as deposition occurs. RUSLE2 computed deposition depends on how much upslope deposition has enriched the sediment in fines. RUSLE2 computes an enrichment ratio based on specific surface area, which is a function of soil texture and the portion of the detached sediment that is deposited.

17.5.3. Topography

The USLE slope length exponent varies only with slope steepness for steepness less than 5 percent. The RUSLE1.05 slope length exponent varies with slope steepness over the full range of steepness from zero to 100 percent. Also, the RUSLE1.05 slope length exponent is a function of the rill to interrill erosion ratio where the user selects from one three classes. In RUSLE1.06b and c, the slope length exponent is computed from the rill to interrill erosion ratio where the user selects from land use classes. Also, the RUSLE1.06 slope length exponent is a function of the rill soil erodibility to interrill soil erodibility ratio computed from soil texture. RUSLE2 computes the slope length exponent as a function of soil, steepness, and cover-management variables that affect the rill to interrill erosion ratio (see **Section 8.1.1**).

The slope length exponent used in the USLE and all RUSLE1 versions is constant over the computational period (i.e., duration in cover-management description). In contrast, RUSLE2 computes a slope length exponent value that varies daily as cover-management conditions change daily.

As a minimum, the RUSLE1.05 slope length relationship (AH703) should be used in the USLE.

The slope steepness relationship in the USLE has a quadratic form empirically derived from data collected at La Crosse, WI. This equation does not apply well to slope steepness less than about 2 percent or to slope steepness greater than about 25 percent. The RUSLE1 and RUSLE2 slope steepness relationship is based on a wide ranging dataset and is much more linear than the USLE quadratic relationship. No USLE, RUSLE, or RUSLE2 version varies the slope steepness relationship with any variable including time, soil, or cover-management.

The RUSLE slope steepness relationship (AH703) should be used in the USLE.

The USLE irregular slope procedure works well for determining how overland flow path profile shape affects erosion on the eroding portion of the flow path. It is not easily used where cover-management varies along the flow path. **The USLE does not compute deposition on concave flow path profiles.** RUSLE1.05, 1.06b, and 1.06c compute deposition on concave overland flow path profiles but do not vary the deposition coefficient along the overland flow path as deposition changes sediment characteristics. These models are not easily used where cover-management varies along the overland flow path except for rotational strip cropping. RUSLE2 computes how deposition changes sediment properties along the overland flow path that in turn affect downslope deposition. RUSLE2 is easily applied where cover-management varies along the overland flow path in any pattern (see **Section 17.4.3.3**)

17.5.4. Cover-management

RUSLE2 computes soil loss ratio values that can be compared to AH537 values. Also, RUSLE2 can be used to compute soil loss ratio values to use where experimental research has not determined values for the USLE. However, a much better approach is to use RUSLE1.06c rather than the USLE. The cover-management relationships in RUSLE1.06c are comparable to those in RUSLE2 and an error in the RUSLE1.05 and RUSLE1.06b computer programs in the soil biomass subfactor was corrected in RUSLE1.06c. The erosion reduction computed for no-till was reduced between RUSLE1.06b and RUSLE1.06c to be consistent with analysis conducted during the RUSLE2 development. Also, the interaction between canopy cover and ground cover used in the USLE and RUSLE2 is used in RUSLE1.06c but not in other RUSLE1 versions.

The AH537 soil loss ratio values for "conventional tillage" were used to calibrate **RUSLE2** so that the soil loss ratio values computed by **RUSLE2** match, as closely as possible, AH537 values.[196] The AH537 values for conservation tillage were not used in the **RUSLE** calibration because the AH537 values were based on research data collected in the late 1960's and early 1970's that do not represent modern conservation tillage. An extensive set of data from a literature survey was assembled and used to validate **RUSLE2** for no-till and other conservation tillage types.

Several considerations are important to ensure proper comparisons of RUSLE2 computed soil loss ratio values with AH537 and other soil loss ratio values.

RUSLE2 uses a ridge subfactor that is not used by RUSLE1. The effect of ridges is not represented in the AH537 soil loss ratio values except in Table 5-A. for cotton. Daily values of the RUSLE2 C and the ridge subfactors must be multiplied and integrated using the temporal erosivity distribution to compute a RUSLE2 soil loss ratio that can be compared to AH537 soil loss ratios.

The AH537 soil loss ratio values for crop stage four, the period following harvest, were not used to calibrate RUSLE2. Most of the data used to develop AH537 soil loss ratio

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[196] Soil loss ratio is the ratio of erosion in a given period, like a crop stage, to erosion from the "unit plot" for the same period where all other conditions are the same. A crop stage is a period where cover-management conditions can be assumed to be constant. Equation 5.9 shows how soil loss ratios and crop stage periods are used to compute a cover-management factor value in the USLE.

values for cropland, except for conservation tillage and cotton, were from about 1935 to 1955. Farming practices in this period left corn stalks standing more erect after harvest than do modern combines that shred and spread the stalks. Also, AH537 soil loss ratio values for flat residue are based on a surface cover effect (mulch subfactor) having a b_f value of 0.026 (see equation 9.6), much lower than the now accepted value of 0.035. The data used to determine and evaluate **b** values in **RUSLE2** included the data used to develop the AH537 mulch subfactor curve plus additional data.

Many of the AH537 soil loss ratio values are for yields lower than modern yields, especially for corn. For example, the AH537 yield for high production corn is 112 bu/ac, whereas a modern corn yield is easily 150 bu/ac or more.

Soil loss ratios in AH537 are independent of location, whereas **RUSLE2** computed soil loss ratio values vary with location. For example, **RUSLE2** soil loss ratio values for corn are significantly lower in the upper Midwestern US than in the lower part of the Mid-South US because of the low soil biomass in the Mid-South where a humid, warm climate greatly increases biomass decomposition in comparison with the climate of the upper Midwest. Climate data at Columbia, Missouri were used to calibrate **RUSLE** and to represent typical conditions that would produce soil loss ratio values to compare with AH537 values, except for cotton where climate data from Holly Springs, MS were used.

To make comparisons between RUSLE2 soil loss ratio values and AH537 values, use Columbia, MO climate to compute RUSLE2 soil loss values for all AH537 conditions, except for cotton where the Holly Springs, MS location should be used. Climate data from Pullman, WA or Pendleton, OR should be used to compute RUSLE2 soil loss ratio values and other values to compare with research determined values in the Northwest Wheat and Range Region.

RUSLE2 was calibrated with the RUSLE2 core database. RUSLE2 soil loss ratio values should be computed using the RUSLE2 core database when making comparisons with AH537 values. Also, the RUSLE2 production (yield) level adjustment procedure should be used when comparing RUSLE2 computed soil loss ratio values with AH537 values for different production levels.

Table 10, AH537 is widely used in the USLE to compute erosion on range, pasture, idle, and undisturbed lands. **This procedure should not be used because it has major shortcomings (see Section *17.4.1.4*).** RUSLE2 and RUSLE1.06c provide much better estimates than the USLE for these conditions.[197] Also, RUSLE1.06c is much improved over RUSLE1.05 and earlier RUSLE1.06 versions for these conditions.

[197] Spaeth, Jr., K.E., F.B. Pierson, M.A. Weltz, and W.H. Blackburn. 2003. Evaluation of USLE and RUSLE estimated soil loss on rangelands. J. Range Management 56:234-246.

A major advantage of RUSLE2 and RUSLE1.06c is their land use independence that allows them to be applied to conditions that vary from highly disturbed to undisturbed over the period of interest. Examples include construction sites, reclaimed mine land, disturbed forestland, and landfills from the time of the last disturbance through recovery and stabilization. Also, RUSLE2 and RUSLE1.06c work well for military training sites and similar areas where conditions at the site range from highly disturbed to undisturbed and for rangeland sites that move back and forth with cropland depending on farming economics. If different models are applied to different time periods or to different land use conditions, the likelihood is almost 100 percent that erosion estimates from the different models will differ significantly at common point in time when common estimates are expected. These erosion estimate differences complicate interpretation of the values and raise questions about the validity of one or more of the models. Users may not know the correct erosion estimate, but they can easily recognize that differences are being computed where values should not be different.

RUSLE2 can be used to compute soil loss ratio values for any land use where RUSLE2 applies. These values can be used in the USLE for conditions where experimentally derived soil loss ratio values are not available. *RUSLE1.06c should be used rather than the USLE.*

17.5.5. Support practices

17.5.5.1. Contouring

The AH537 contouring subfactor values typically used in the USLE vary only with steepness of the overland flow path. All RUSLE1 versions compute contouring subfactor values that vary with the major variables that affect the relation between erosion and contouring. RUSLE1 uses input values for cover-management condition and ridge height that represent the entire computational period. These inputs are selected to compute average annual erosion. RUSLE2 uses equations similar to those in RUSLE1 to compute daily contouring subfactor values (**see Section 14.1**). A relative row grade of 10 percent and climate data for Columbia, MO should be used when comparing RUSLE2 and RUSLE1 contouring subfactor values with AH537 values. Also, cover-management conditions, including yield, used in RUSLE2 and RUSLE1 should be chosen to represent farming practices in the 1930' to mid 1950's to compute contouring subfactor values to compare with AH537 values.

RUSLE2 computes a net contouring subfactor value by integrating daily contouring factor values with the temporal erosivity distribution values. However, RUSLE2 net contour values are not the proper values to compare with AH537 values. The proper RUSLE2 contouring subfactor value to compare with an AH537 value is the ratio of RUSLE2 computed average annual erosion for a 10 percent relative row grade to average annual erosion for an up and downhill (100 percent) relative row grade. This RUSLE2 contouring subfactor is comparable to AH537 contouring subfactor values computed as the ratio of measured average annual erosion with contouring to measured average annual erosion with up and downhill tillage. Values for this RUSLE2 contouring subfactor value differs from the RUSLE2 net contouring subfactor (see **Section 17.5.6** for a discussion of the reason for this difference).

A difficulty with RUSLE1 is that representative input values for the entire computational period must be chosen. RUSLE2 computes daily contouring subfactor values based on the daily values for cover-management variables. RUSLE2 and RUSLE1 should give similar contouring subfactor values but the values will not compare exactly.

All RUSLE versions describe how major variables affect contouring failure (critical slope length). AH537 values only vary with slope steepness and whether or not strip cropping is used. AH537 gives a single adjustment for conservation tillage conditions. All RUSLE versions were calibrated to give AH537 critical slope lengths for the base Columbia, MO condition (see **Section 14.1.2.5**).

RUSLE2 can be used to compute contouring subfactor values for use in the USLE. The value should be computed as a ratio of average annual erosion values with and without contouring computed by RUSLE2. Actually, RUSLE1.06c should be used rather than the USLE.

17.5.5.2. Strips/barriers

Although Table 14, AH537 list factor values for several rotational strip cropping conditions, AH537 provides no factor values for narrow strips of permanent vegetation or mechanical barriers like fabric (silt) fences. To compare RUSLE2 and RUSLE1 factor values with AH537 values, make RUSLE2 and RUSLE1 computations with and without rotational strip cropping for Columbia, MO using input values that represent farming practices, including yield, in the 1930' to mid 1950's. Compute ratio values using RUSLE2 estimated average annual sediment yield, not detachment or erosion, to compare with AH537 values that were computed as measured sediment yield with strip cropping to measured sediment yield without strip cropping. Similarly, RUSLE1 sediment yield values should be used rather than the P factor values. The RUSLE1 P factor values do not give full credit for deposition as soil saved, whereas the AH537 and RUSLE2 values give full credit for deposition as soil saved for rotational strip cropping.

The AH537 strip cropping factor values do not apply to modern farming practices, including conservation tillage, that leave rough soil surfaces and high residue cover that induce deposition much like dense vegetation strips. The effectiveness of strips is related to sediment production on the more erodible strips relative to transport capacity in the strips having a high hydraulic resistance (see *Section 14.2*).

All RUSLE versions capture how major variables affect the relationship between sediment yield and strips/barriers. RUSLE1 uses inputs for cover-management condition for each strip that represents each year of the computational period. RUSLE2 computes daily factor values as a function of daily cover-management variables. Just as with contouring, RUSLE2 and RUSLE1 factor values for strips/barriers will not agree because of this difference in input even though similar equations are used in both models. Another reason for differences is that RUSLE1.05 uses a single deposition coefficient value, RUSLE1.06 uses a deposition coefficient that is a function of soil texture, and RUSLE2 uses sediment characteristics that are a function of soil texture and upslope deposition.

See **Sections 14.2 and 17.5.5.3** for a discussion of RUSLE2's conservation planning soil loss that gives credit for deposition as soil saved.

RUSLE2 can compute factor values for strips/barriers that can be used in the USLE, but a better approach is to use RUSLE1.06c rather than the USLE.

17.5.5.3. Diversions/terraces/sediment basins

Factor values for diversions, terraces, and small sediment basins reported by Foster and Highfill and the RUSLE1.06 OSM manual are the best values for comparing with RUSLE values.[198] The value of terraces as a soil conservation practice has been debated for several years. The benefit of terraces for shortening the overland flow path length to reduce sediment production and deposition in terrace channels and small sediment basins reducing sediment yield reduction is universally accepted. However, the value of deposition as soil saved is debated. For example, credit was given to deposition in 1965 in AH282 as soil saved but no credit was given in 1978 in AH537. The credit given is a matter of judgment. USDA-NRCS agronomists tend to claim no credit for deposition with terraces but prefer to claim credit for deposition caused by narrow permanent vegetation strips, while USDA-NRCS engineers prefer to claim credit for deposition caused by terraces.[199]

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[198] See:
Foster, G. R. and R. E. Highfill. 1983. Effect of terraces on soil loss: USLE P factor values for terraces. Journal of Soil and Water Conservation 38:48-51.

Toy, T.J. and G.R. Foster (coeditors). 1998. Guidelines for the use of the Revised Universal Soil Loss equation (RUSLE1.06) on mined lands, construction sites, and reclaimed lands. USDI-Office of Surface Mining. Denver. CO.

[199] This debate among these NRCS disciplines involves a certain amount of self-interest. NRCS agronomists have technical oversight for permanent vegetation strips while NRCS engineers have technical oversight for terraces.

The RUSLE2 developers consider deposition in terrace channels and above permanent vegetation strips to have a similar benefit as soil saved. In fact deposition in terrace channels could perhaps merit increased credit because tillage redistributes this deposited sediment over a larger landscape area than tillage redistributes sediment deposited by permanent vegetation strips. RUSLE2 gives consistent credit to deposition as soil saved between terraces and permanent vegetation strips based on location along the overland flow path, except for rotational strip cropping where full credit is given to deposition. Also, the credit given to deposition as soil saved with terraces decreases as terrace spacing increases (see **Section 14.3**). Giving full credit to deposition associated with rotational strip cropping is consistent with AH282 and AH537 values. The RUSLE2 soil conservation planning soil loss value is the RUSLE2 output that reflects credit for deposition as soil saved (see **Section 8.1.5.4**).

RUSLE1.05 computes sediment yield from diversion/terrace channels as a function of channel grade only. That is, the fraction of the sediment load that is deposited in a diversion/terrace channel is independent of the sediment load coming into the channel or transport capacity in the channel. RUSLE2 and RUSLE1.06 compute deposition as a function of sediment characteristics, sediment transport capacity in the channel, and sediment load reaching the channel. If incoming sediment load is less than transport capacity, no deposition is computed. RUSLE1.05 assumes that 95 percent of the sediment that reaches a small sediment basin is deposited. RUSLE2 and RUSLE1.06c compute deposition in small sediment basins as a function of characteristics of the incoming sediment.

RUSLE2 can be used to compute diversion/terrace/sediment basin P factor values for use in the USLE. However, a better approach than using the USLE is to use RUSLE1.06c, which computes diversion/terrace/sediment basin P factors using equations that are similar to those used in RUSLE2.

17.5.6. Computing erosion

RUSLE2 computes net values for the soil erodibility factor K, topographic factor LS, cover-management factor C without the ridging effect, ridge subfactor, ponding subfactor, and contouring subfactor by weighting daily values with the temporal erosivity distribution, exactly in the same way that these computations are made in the USLE for the C factor and in RUSLE1 for the K and C factors.

These RUSLE2 computed factor values can be compared with those for the USLE and RUSLE1. These comparisons give insight into differences among RUSLE2, RUSLE1, and the USLE. The comparisons should be properly made. For example, the RUSLE2 net factor values for cover-management and ridging should be multiplied to obtain a C factor that can be compared with the USLE and RUSLE1 C factor values. Also, the proper RUSLE2 values for the contour and strip cropping factors is to divide the average annual sediment yield for contouring and contouring/contouring/strip cropping on a uniform overland flow path by estimated sediment yield without contouring or strip cropping. The RUSLE2 net contouring subfactor value differs from this RUSLE2 factor value for contouring because the net contouring subfactor only involves the temporal integration of the erosivity distribution while the ratio values involves the temporal integration of the product of all the RUSLE2 factors.

The RUSLE2 computed values for these factors can be multiplied as the USLE and RUSLE1 factor values are multiplied to estimate average annual erosion. However, this erosion value differs from the value computed by RUSLE2 because of differences in the mathematic integration among these models (see **Section 5.4**). RUSLE2 does not compute erosion by multiplying average annual values for individual factors; RUSLE2 computes average annual erosion by computing daily erosion as the product of the daily factor values and summing the daily erosion values. The difference in these mathematical procedures for computing average annual erosion can be as much as 15 percent, depending on cropping-management system and location.

Even if RUSLE2 were to produce net factor values that equaled USLE and RUSLE1 factor values, RUSLE2's computed average annual erosion would not match USLE and RUSLE1's computed average annual erosion. RUSLE2's mathematics properly integrate the temporally and spatially varying governing equations. The USLE and RUSLE1 procedures are approximations.

18. HOW RUSLE2 CAME TO BE

The Universal Soil Loss Equation (USLE) was developed in the late 1950s and became widely used in conservation planning on cropland in the 1960s. Beginning in the 1970s, the USLE was applied to many other land uses in addition to cropland and to other applications besides conservation planning.

The USLE was updated in 1978, but by 1985 the USLE needed another update with passage of the Farm Bill and to incorporate new research information. A project led by USDA-Agricultural Research Service was initiated at a workshop in Lafayette, Indiana in 1985 to update the USLE. This workshop attended by leading U.S. erosion research scientists and USLE users from the USDA-Natural Resources Conservation Service (formerly, Soil Conservation Service) and Forest Service, USDI-Bureau of Land Management, and U.S. Army Corps of Engineers set objectives and approaches for the update.

By 1987, much of the background work on updating the USLE was well underway and some had been completed. The project evolved into much more than an updating of the USLE. The USLE was undergoing a major revision, and hence the updated USLE became what is now referred to as **RUSLE1**, the **R**evised **USLE**. Also, another major addition to the project was the development of a computer program to implement RUSLE1.

Development of **RUSLE2** began in 1993 using RUSLE1 as the starting point. RUSLE2 uses the basic USLE equation structure to compute sediment detachment but differs greatly from the USLE in almost every other way. RUSLE2 is similar to RUSLE1, but RUSLE2 uses new equations, a new mathematical integration procedure, new database values, and is implemented in a modern graphical user interface computer program. Almost all of the mathematical relationships in RUSLE2 have been revised from corresponding relationships in RUSLE1.

RUSLE2 is much more powerful than either the USLE or RUSLE1. The interface for the RUSLE2 computer program, the underlying modeling engine of this computer program, its computational routines, and RUSLE2's mathematical equations make RUSLE2 the most modern, powerful, and easy-to-use erosion prediction technology available for use in conservation and erosion control planning at the local field office level.

RUSLE2 was developed by a group of experienced and nationally recognized erosion scientists, erosion control specialists, and soil conservationists. Data needed to develop and validate RUSLE were incomplete in some cases, which necessitated scientists and users using judgment to fill gaps. USDA-Agriculture Handbook 703 and other RUSLE1 publications, which was the starting point for RUSLE2, have been reviewed by peer scientists in a process typical of the reporting of rigorous research. Erosion scientists, NRCS technical specialists, and many others have made many computations with RUSLE2 to ensure that RUSLE2 works well for every imaginable situation where RUSLE2 will be applied. The scientific documentation for RUSLE2 has been peer reviewed according to standard procedures of the USDA-Agricultural Research Service.

RUSLE2 can be used with full confidence that it meets high scientific standards and produces reliable results for conservation and erosion control planning for all lands where rill and interrill erosion occur by rainfall and Hortonian overland flow.

A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

Prepared by Pamela C. Dodds, Ph.D., Licensed Professional Geologist
Prepared for The Wilderness Society - January 24, 2023

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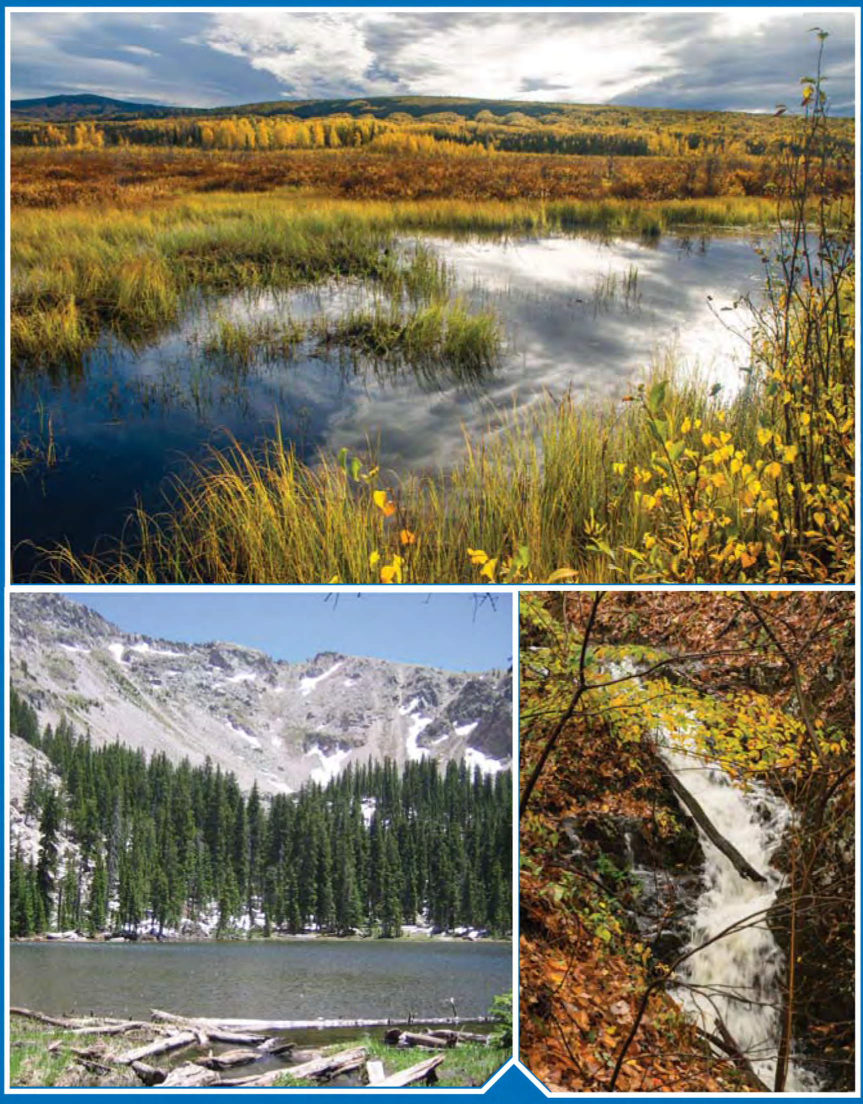
Connectivity of Streams & Wetlands to Downstream Waters:
A Review & Synthesis of the Scientific Evidence



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CONNECTIVITY OF STREAMS AND WETLANDS TO DOWNSTREAM WATERS: A REVIEW AND SYNTHESIS OF THE SCIENTIFIC EVIDENCE

Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC

DISCLAIMER

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LIST OF ABBREVIATIONS AND ACRONYMS

CWA	Clean Water Act
DEM	digital elevation model
DOC	dissolved organic carbon
FPOM	fine particulate organic matter
GW	groundwater flowpath
HUC	Hydrologic Unit Code
NHD	National Hydrography Dataset
PPR	prairie pothole region
USDA-ARS	United States Department of Agriculture, Agricultural Research Services
U.S. ACE	United States Army Corps of Engineers
U.S. EPA	United States Environmental Protection Agency
USGS	United States Geological Survey

LIST OF UNITS AND VARIABLES

A	drainage area
C	Celsius
c	scaling power constant
cm	centimeter
d	day
g	gram
ha	hectare
hr	hour
kg	kilogram
km	kilometer
L	liter
m	meter
mg	milligram
Mg	megagram
mm	millimeter
μM	micromolar
N	metric normal temperature and pressure
ng	nanogram
Pg	petagram
Q	discharge
s	second
t	metric ton
τ_o	shear stress
V	velocity
yr	year

PREFACE

This report was prepared by the National Center for Environmental Assessment, the National Health and Environmental Effects Research Laboratory, and the National Exposure Research Laboratory, in the U.S. Environmental Protection Agency's (U.S. EPA's) Office of Research and Development. It reviews and evaluates evidence from peer-reviewed sources that were published or in press by December 2014. Throughout this document, terms are used with their generally recognized scientific meaning. We have provided definitions of technical terms in the Glossary (Appendix A). Two previous drafts prepared on 1 February 2011 and 12 July 2011 were reviewed by U.S. EPA and U.S. Army Corps of Engineers staff. Additional comments were received from scientists in government, academic, nonprofit, and private industry organizations listed in the **Reviewers** section who reviewed all or part of the 1 February 2011 preliminary draft. A draft prepared on 11 October 2011 was independently peer reviewed by a panel of 11 topic experts, listed in the **Reviewers** section, on 30 January 2012. An external review draft released in September 2013 (600/R-11/098B) was reviewed by U.S. EPA staff and a panel of the U.S. EPA's Science Advisory Board (SAB) that convened 16−18 December 2013 (SAB report number EPA-SAB-15-001, available online at www.epa.gov/sab). The 27 topic experts comprising the SAB panel are listed in the **Reviewers** section. In addition, comments from the public were received through the docket or at the SAB panel meeting. Comments from these sources were considered and used to improve the clarity and scientific rigor of the document.

AUTHORS AND REVIEWERS

AUTHORS

Laurie C. Alexander, PhD
U.S. Environmental Protection Agency
Office of Research and Development, National Center for Environmental Assessment
Washington, DC

Bradley Autrey, MS, JD
U.S. Environmental Protection Agency
Office of Research and Development, National Exposure Research Laboratory
Cincinnati, OH

Julie DeMeester, PhD
American Association for the Advancement of Science Fellow
U.S. Environmental Protection Agency
Office of Research and Development, National Center for Environmental Assessment
Washington, DC

Ken M. Fritz, PhD
U.S. Environmental Protection Agency
Office of Research and Development, National Exposure Research Laboratory
Cincinnati, OH

Heather E. Golden, PhD
U.S. Environmental Protection Agency
Office of Research and Development, National Exposure Research Laboratory
Cincinnati, OH

David C. Goodrich, PhD
U.S. Department of Agriculture
Agricultural Research Service
Tucson, AZ

William G. Kepner, MS, MPA
U.S. Environmental Protection Agency
Office of Research and Development, National Exposure Research Laboratory,
Environmental Sciences Division
Las Vegas, NV

AUTHORS (continued)

Charles R. Lane, PhD
U.S. Environmental Protection Agency
Office of Research and Development, National Exposure Research Laboratory
Cincinnati, OH

Stephen D. LeDuc, PhD
U.S. Environmental Protection Agency
Office of Research and Development, National Center for Environmental Assessment
Washington, DC

Scott G. Leibowitz, PhD
U.S. Environmental Protection Agency
Office of Research and Development, National Health and Environmental Effects Research Laboratory
Corvallis, OR

Michael G. McManus, PhD
U.S. Environmental Protection Agency
Office of Research and Development, National Center for Environmental Assessment
Cincinnati, OH

Amina I. Pollard, PhD
U.S. Environmental Protection Agency
Office of Water, Office of Wetlands, Oceans, and Watersheds
Washington, DC

Hadas Raanan Kiperwas, PhD
Oak Ridge Institute for Science and Education Fellow, U.S. Environmental Protection Agency
Office of Water, Office of Wetlands, Oceans, and Watersheds
Washington, DC

Caroline E. Ridley, PhD
U.S. Environmental Protection Agency
Office of Research and Development, National Center for Environmental Assessment
Washington, DC

Kate Schofield, PhD
U.S. Environmental Protection Agency
Office of Research and Development, National Center for Environmental Assessment
Washington, DC

AUTHORS (continued)

Melanie Vanderhoof, PhD
Oak Ridge Institute for Science and Education Fellow, U.S. Environmental Protection Agency
Office of Research and Development, National Center for Environmental Assessment
Washington, DC

Parker J. Wigington, PhD
U.S. Environmental Protection Agency
Office of Research and Development, National Health and Environmental Effects Research Laboratory
Corvallis, OR

PEER CONSULTATION REVIEWERS

Robert T. Brooks, PhD
U.S. Department of Agriculture Forest Service, Amherst, MA

William H. Eldridge, PhD
Stroud Water Research Center, Avondale, PA

Keith B. Gido, PhD
Kansas State University, Manhattan, KS

Arthur J. Gold, PhD
University of Rhode Island, Kingston, RI

Tracie-Lynn Nadeau, PhD
U.S. Environmental Protection Agency, Portland, OR

Denis Newbold, PhD
Stroud Water Research Center, Avondale, PA

Michael J. Paul, PhD
TetraTech Inc., Owings Mills, MD

Donald Rosenberry, PhD
U.S. Geological Survey, Lakewood, CO

Doug Samson, PhD
The Nature Conservancy, Bethesda, MD

Rebecca Sharitz, PhD
Savannah River Ecology Laboratory, Aiken, GA

Kirk O. Winemiller, PhD
Texas A&M University, College Station, TX

EXTERNAL PEER REVIEW PANEL

David J. Cooper, PhD
Colorado State University, Fort Collins, CO

William G. Crumpton, PhD
Iowa State University, Ames, IA

Kenneth W. Cummins, PhD
Humboldt State University, Arcata, CA

Walter K. Dodds, PhD (Chair)
Kansas State University, Manhattan, KS

James W. La Baugh, PhD
U.S. Geological Survey, Reston, VA

Mark C. Rains, PhD
University of South Florida, Tampa, FL

John S. Richardson, PhD
University of British Columbia, Vancouver, BC

Joel W. Snodgrass, PhD
Towson University, Towson, MD

Arnold van der Valk, PhD
Iowa State University, Ames, IA

Mark S. Wipfli, PhD
U.S. Geological Survey, Fairbanks, AK

William R. Wise, PhD
University of Florida, Gainesville, FL

U.S. ENVIRONMENTAL PROTECTION AGENCY SCIENCE ADVISORY BOARD PANEL FOR THE REVIEW OF THE EPA WATER BODY CONNECTIVITY REPORT

Amanda D. Rodewald, PhD (Chair)
Cornell University, Ithaca, NY

Allison Aldous, PhD
The Nature Conservancy, Portland, OR

Genevieve Ali, PhD
University of Manitoba, Winnipeg, MB, Canada

U.S. ENVIRONMENTAL PROTECTION AGENCY SCIENCE ADVISORY BOARD
PANEL FOR THE REVIEW OF THE EPA WATER BODY CONNECTIVITY REPORT (continued)

J. David Allan, PhD
University of Michigan, Ann Arbor, MI

Lee Benda, PhD
Earth Systems Institute, Mt. Shasta, CA

Emily S. Bernhardt, PhD
Duke University, Durham, NC

Robert P. Brooks, PhD
Pennsylvania State University, University Park, PA

Kurt Fausch, PhD
Colorado State University, Fort Collins, CO

Siobhan Fennessy, PhD
Kenyon College, Gambier, OH

Michael Gooseff, PhD
Colorado State University, Fort Collins, CO

Judson Harvey, PhD
U.S. Geological Survey, Reston, VA

Charles Hawkins, PhD
Utah State University, Logan, UT

Lucinda B. Johnson, PhD
University of Minnesota Duluth, Duluth, MN

Michael Josselyn, PhD
Wetlands Research Associates, Inc., San Rafael, CA

Latif Kalin, PhD
Auburn University, Auburn, AL

Kenneth Kolm, PhD
Hydrologic Systems Analysis, LLC, Golden, CO

Judith L. Meyer, PhD
University of Georgia, Lopez Island, WA

U.S. ENVIRONMENTAL PROTECTION AGENCY SCIENCE ADVISORY BOARD
PANEL FOR THE REVIEW OF THE EPA WATER BODY CONNECTIVITY REPORT (continued)

Mark Murphy, PhD
Hassayampa Associates, Tucson, AZ

Duncan Patten, PhD
Arizona State University, Bozeman, MT

Mark Rains, PhD
University of South Florida, Tampa, FL

Ramesh Reddy, PhD
University of Florida, Gainesville, FL

Emma Rosi-Marshall, PhD
Cary Institute of Ecosystem Studies, Millbrook, NY

Jack Stanford, PhD
University of Montana, Polson, MT

Mazeika Sullivan, PhD
The Ohio State University, Columbus, OH

Jennifer Tank, PhD
University of Notre Dame, Notre Dame, IN

Maurice Valett, PhD
University of Montana, Missoula, MT

Ellen Wohl, PhD
Colorado State University, Fort Collins, CO

PHOTO CREDITS

Front cover, Executive Summary, Chapter 5, and References	Nambe Lake, New Mexico (L.C. Alexander, U.S. EPA)
Back cover, Executive Summary, and References	Children in Delaware inland wetland (Hennis H. Bartow, Delaware Center for the Inland Bays)
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EXECUTIVE SUMMARY

BACKGROUND

The objective of the Clean Water Act is to restore and maintain the chemical, physical, and biological integrity of the nation's waters. The U.S. Environmental Protection Agency's (U.S. EPA's) Office of Research and Development developed this report to inform rulemaking by the U.S. EPA and U.S. Army Corps of Engineers (U.S. ACE) on the definition of "waters of the United States" under the Clean Water Act (CWA). Its purpose is to summarize current scientific understanding about the connectivity and mechanisms by which streams and wetlands, singly or in aggregate, affect the physical, chemical, and biological integrity of downstream waters. The focus of the review is on surface and shallow subsurface connections of small or temporary streams, nontidal wetlands, and certain open waters. Because this report is a technical review of peer-reviewed scientific literature, it neither considers nor sets forth legal standards for CWA jurisdiction, nor does it establish EPA policy.

The report is organized into six chapters. Chapter 1 outlines the purpose, scientific context, and approach of the report. Chapter 2 describes the components of a river system and watershed; the types of physical, chemical, and biological connections that link those components; the factors that influence connectivity at various temporal and spatial scales; and methods for quantifying connectivity. Chapter 3 reviews literature on connectivity in stream networks in terms of physical, chemical, and biological connections and their resulting effects on downstream waters. Chapter 4 reviews literature on the connectivity and effects of nontidal wetlands and certain open waters on downstream waters. Chapter 5 applies concepts and evidence from previous chapters to six case studies from published literature on Carolina and Delmarva bays, oxbow lakes, prairie potholes, prairie streams, southwestern streams, and vernal pools. Chapter 6 summarizes key findings and conclusions, identifies data gaps, and briefly discusses research approaches that could fill those gaps. A glossary of scientific terms used in the report and detailed case studies of selected systems (summarized in Chapter 5) are included in Appendix A and Appendix B, respectively.

SUMMARY OF MAJOR CONCLUSIONS

Based on the review and synthesis of more than 1,200 publications from the peer reviewed scientific literature, the evidence supports five major conclusions. Citations have been omitted from the text to improve readability; please refer to individual chapters for supporting publications and additional information.

Conclusion 1: Streams

The scientific literature unequivocally demonstrates that streams, individually or cumulatively, exert a strong influence on the integrity of downstream waters. All tributary streams, including perennial, intermittent, and ephemeral streams, are physically, chemically, and biologically connected to downstream rivers via channels and associated alluvial deposits where water and other materials are concentrated, mixed, transformed, and transported. Streams are the dominant source of water in most rivers, and the majority of tributaries are perennial, intermittent, or ephemeral headwater streams. Headwater streams also convey water into local storage compartments such as ponds, shallow aquifers, or stream banks, and into regional and alluvial aquifers; these local storage compartments are important sources of water for maintaining baseflow in rivers. In addition to water, streams transport sediment, wood, organic matter, nutrients, chemical contaminants, and many of the organisms found in rivers. The literature provides robust evidence that streams are biologically connected to downstream waters by the dispersal and migration of aquatic and semiaquatic organisms, including fish, amphibians, plants, microorganisms, and invertebrates, that use both upstream and downstream habitats during one or more stages of their life cycles, or provide food resources to downstream communities. In addition to material transport and biological connectivity, ephemeral, intermittent, and perennial flows influence fundamental biogeochemical processes by connecting channels and shallow ground water with other landscape elements. Physical, chemical, and biological connections between streams and downstream waters interact via integrative processes such as nutrient spiraling, in which stream communities assimilate and chemically transform large quantities of nitrogen and other nutrients that otherwise would be transported directly downstream, increasing nutrient loads and associated impairments due to excess nutrients in downstream waters.

Conclusion 2: Riparian/Floodplain Wetlands and Open Waters

The literature clearly shows that wetlands and open waters in riparian areas and floodplains are physically, chemically, and biologically integrated with rivers via functions that improve downstream water quality, including the temporary storage and deposition of channel-forming sediment and woody debris, temporary storage of local ground water that supports baseflow in rivers, and transformation and transport of stored organic matter. Riparian/floodplain wetlands and open waters improve water quality through the assimilation, transformation, or sequestration of pollutants, including excess nutrients and chemical contaminants such as pesticides and metals, that can degrade downstream water integrity. In addition to providing effective buffers to protect downstream waters from point source and nonpoint source pollution, these systems form integral components of river food webs, providing nursery habitat for breeding fish and amphibians, colonization opportunities for stream invertebrates, and maturation habitat for stream insects. Lateral expansion and contraction of the river in its floodplain result in an exchange of organic matter and organisms, including fish populations that are adapted to use floodplain habitats for feeding and spawning during high water, that are critical to river ecosystem function. Riparian/floodplain wetlands and open waters also affect the integrity of downstream waters by subsequently releasing (desynchronizing) floodwaters and retaining large volumes of stormwater, sediment, and contaminants in runoff that could otherwise negatively affect the condition or function of downstream waters.

Conclusion 3: Non-floodplain Wetlands and Open Waters

Wetlands and open waters in non-floodplain landscape settings (hereafter called "non-floodplain wetlands") provide numerous functions that benefit downstream water integrity. These functions include storage of floodwater; recharge of ground water that sustains river baseflow; retention and transformation of nutrients, metals, and pesticides; export of organisms or reproductive propagules to downstream waters; and habitats needed for stream species. This diverse group of wetlands (e.g., many prairie potholes, vernal pools, playa lakes) can be connected to downstream waters through surface-water, shallow subsurface-water, and ground-water flows and through biological and chemical connections.

In general, connectivity of non-floodplain wetlands occurs along a gradient (Conclusion 4), and can be described in terms of the frequency, duration, magnitude, timing, and rate of change of water, material, and biotic fluxes to downstream waters. These descriptors are influenced by climate, geology, and terrain, which interact with factors such as the magnitudes of the various functions within wetlands (e.g., amount of water storage or carbon export) and their proximity to downstream waters to determine where wetlands occur along the connectivity gradient. At one end of this gradient, the functions of non-floodplain wetlands clearly affect the condition of downstream waters if a visible (e.g., channelized) surface-water or a regular shallow subsurface-water connection to the river network is present. For non-floodplain wetlands lacking a channelized surface or regular shallow subsurface connection (i.e., those at intermediate points along the gradient of connectivity), generalizations about their specific effects on downstream waters from the available literature are difficult because information on both function and connectivity is needed. Although there is ample evidence that non-floodplain wetlands provide hydrologic, chemical, and biological functions that affect material fluxes, to date, few scientific studies explicitly addressing connections between non-floodplain wetlands and river networks have been published in the peer-reviewed literature. Even fewer publications specifically focus on the frequency, duration, magnitude, timing, or rate of change of these connections. In addition, although areas that are closer to rivers and streams have a higher probability of being connected than areas farther away when conditions governing the type and quantity of flows—including soil infiltration rate, wetland storage capacity, hydraulic gradient, etc.—are similar, information to determine if this similarity holds is generally not provided in the studies we reviewed. Thus, current science does not support evaluations of the degree of connectivity for specific groups or classes of wetlands (e.g., prairie potholes or vernal pools). Evaluations of individual wetlands or groups of wetlands, however, could be possible through case-by-case analysis.

Some effects of non-floodplain wetlands on downstream waters are due to their isolation, rather than their connectivity. Wetland "sink" functions that trap materials and prevent their export to downstream waters (e.g., sediment and entrained pollutant removal, water storage) result because of the wetland's ability to isolate material fluxes. To establish that such functions influence downstream waters, we also need to know that the wetland intercepts materials that otherwise would reach the downstream water. The literature we reviewed does provide limited examples of direct effects of wetland isolation on downstream waters, but not for classes of wetlands (e.g., vernal pools). Nevertheless, the literature we reviewed enables us to conclude that sink functions of non-floodplain wetlands, which result in part from their relative isolation, will affect a downstream water when these wetlands are situated between the downstream water and known point or nonpoint sources of pollution, and thus intersect flowpaths between the pollutant source and downstream waters.

Conclusion 4: Degrees and Determinants of Connectivity

Watersheds are integrated at multiple spatial and temporal scales by flows of surface water and ground water, transport and transformation of physical and chemical materials, and movements of organisms. Although all parts of a watershed are connected to some degree—by the hydrologic cycle or dispersal of organisms, for example—the degree and downstream effects of those connections vary spatially and temporally, and are determined by characteristics of the physical, chemical, and biological environments and by human activities.

Stream and wetland connections have particularly important consequences for downstream water integrity. Most of the materials—broadly defined as any physical, chemical, or biological entity—in rivers, for example, originate from aquatic ecosystems located upstream or elsewhere in the watershed. Longitudinal flows through ephemeral, intermittent, and perennial stream channels are much more efficient for transport of water, materials, and organisms than diffuse overland flows, and areas that concentrate water provide mechanisms for the storage and transformation, as well as transport, of materials.

Connectivity of streams and wetlands to downstream waters occurs along a continuum that can be described in terms of the frequency, duration, magnitude, timing, and rate of change of water, material, and biotic fluxes to downstream waters. These terms, which we refer to collectively as connectivity descriptors, characterize the range over which streams and wetlands vary and shift along the connectivity gradient in response to changes in natural and anthropogenic factors and, when considered in a watershed context, can be used to predict probable effects of different degrees of connectivity over time. The evidence unequivocally demonstrates that the stream channels and riparian/floodplain wetlands or open waters that together form river networks are clearly connected to downstream waters in ways that profoundly influence downstream water integrity. The connectivity and effects of non-floodplain wetlands and open waters are more variable and thus more difficult to address solely from evidence available in peer-reviewed studies.

Variations in the degree of connectivity influence the range of functions provided by streams and wetlands, and are critical to the integrity and sustainability of downstream waters. Connections with low values of one or more descriptors (e.g., low-frequency, low-duration streamflows caused by flash floods) can have important downstream effects when considered in the context of other descriptors (e.g., large magnitude of water transfer). At the other end of the frequency range, high-frequency, low-magnitude vertical (surface-subsurface) and lateral flows contribute to aquatic biogeochemical processes, including nutrient and contaminant transformation and organic matter accumulation. The timing of an event can alter both connectivity and the magnitude of its downstream effect. For example, when soils become saturated by previous rainfall events, even low or moderate rainfall can cause streams or wetlands to overflow, transporting water and materials to downstream waters. Fish that use nonperennial or perennial headwater stream habitats to spawn or rear young, and invertebrates that move into seasonally inundated floodplain wetlands prior to emergence, have life cycles that are synchronized with the timing of flows, temperature thresholds, and food resource availability in those habitats.

Conclusion 5: Cumulative Effects

The incremental effects of individual streams and wetlands are cumulative across entire watersheds and therefore must be evaluated in context with other streams and wetlands. Downstream waters are the time-integrated result of all waters contributing to them. For example, the amount of water or biomass contributed by a specific ephemeral stream in a given year might be small, but the aggregate contribution of that stream over multiple years, or by all ephemeral streams draining that watershed in a given year or over multiple years, can have substantial consequences on the integrity of the downstream waters. Similarly, the downstream effect of a single event, such as pollutant discharge into a single stream or wetland, might be negligible but the cumulative effect of multiple discharges could degrade the integrity of downstream waters.

In addition, when considering the effect of an individual stream or wetland, all contributions and functions of that stream or wetland should be evaluated cumulatively. For example, the same stream transports water, removes excess nutrients, mitigates flooding, and provides refuge for fish when conditions downstream are unfavorable; if any of these functions is ignored, the overall effect of that stream would be underestimated.

SUPPORT FOR MAJOR CONCLUSIONS

This report synthesizes a large body of scientific literature on the connectivity and mechanisms by which streams, wetlands, and open waters, singly or in aggregate, affect the physical, chemical, and biological integrity of downstream waters. The major conclusions reflect the strength of evidence currently available in the peer-reviewed scientific literature for assessing the connectivity and downstream effects of water bodies identified in Chapter 1 of this report.

The conclusions of this report were corroborated by two independent peer reviews by scientists identified in the front matter of this report.

The term connectivity is defined in this report as the degree to which components of a watershed are joined and interact by transport mechanisms that function across multiple spatial and temporal scales. Connectivity is determined by the characteristics of both the physical landscape and the biota of the specific system. Our review found strong evidence supporting the central roles of the physical, chemical, and biological connectivity of streams, wetlands, and open waters—encompassing varying degrees of both connection and isolation—in maintaining the structure and function of downstream waters, including rivers, lakes, estuaries, and oceans. Our review also found strong evidence demonstrating the various mechanisms by which material and biological linkages from streams, wetlands, and open waters affect downstream waters, classified here into five functional categories (source, sink, refuge, lag, and transformation; discussed below), and modify the timing of transport and the quantity and quality of resources available to downstream ecosystems and communities. Thus, the currently available literature provided a large body of evidence for assessing the types of connections and functions by which streams and wetlands produce the range of observed effects on the integrity of downstream waters.

We identified five categories of functions by which streams, wetlands, and open waters influence the timing, quantity, and quality of resources available to downstream waters:

- Source: the net export of materials, such as water and food resources;
- Sink: the net removal or storage of materials, such as sediment and contaminants;
- Refuge: the protection of materials, especially organisms;
- Transformation: the transformation of materials, especially nutrients and chemical contaminants, into different physical or chemical forms; and
- Lag: the delayed or regulated release of materials, such as stormwater.

These functions are not mutually exclusive; for example, the same stream or wetland can be both a source of organic matter and a sink for nitrogen. The presence or absence of these functions, which depend on the biota, hydrology, and environmental conditions in a watershed, can change over time; for example, the same wetland can attenuate runoff during storm events and provide ground-water recharge following storms. Further, some functions work in conjunction with others; a lag function can include transformation of materials prior to their delayed release. Finally, effects on downstream waters should consider both actual function and potential function. A potential function represents the capacity of an ecosystem to perform that function under suitable conditions. For example, a wetland with high capacity for denitrification is a potential sink for nitrogen, a nutrient that becomes a contaminant when present in excessive concentrations. In the absence of nitrogen, this capacity represents the wetland's potential function. If nitrogen enters the wetland (e.g., from fertilizer in runoff), it is removed from the water; this removal represents the wetland's actual function. Both potential and actual functions play critical roles in protecting and restoring downstream waters as environmental conditions change.

The evidence unequivocally demonstrates that the stream channels and riparian/floodplain wetlands or open waters that together form river networks are clearly connected to downstream waters in ways that profoundly influence downstream water integrity. The body of literature documenting connectivity and downstream effects was most abundant for perennial and intermittent streams, and for riparian/floodplain wetlands. Although less abundant, the evidence for connectivity and downstream effects of ephemeral streams was strong and compelling, particularly in context with the large body of evidence supporting the physical connectivity and cumulative effects of channelized flows that form and maintain stream networks.

As stated in Conclusion 3, the connectivity and effects of wetlands and open waters that lack visible surface connections to other water bodies are more difficult to address solely from evidence available in the peer-reviewed literature. The limited evidence currently available shows that these systems have important hydrologic, water-quality, and habitat functions that can affect downstream waters where connections to them exist; the literature also provides limited examples of direct effects of non-floodplain wetland isolation on downstream water integrity. Currently available peer-reviewed literature, however, does not identify which types or classes of non-floodplain wetlands have or lack the types of connections needed to convey the effects on downstream waters of functions, materials, or biota provided by those wetlands.

KEY FINDINGS FOR MAJOR CONCLUSIONS

This section summarizes key findings for each of the five major conclusions, above and in Chapter 6 of the report. Citations have been omitted from the text to improve readability; please refer to individual chapters for supporting publications and additional information.

Conclusion 1, Streams: Key Findings

- Streams are hydrologically connected to downstream waters via channels that convey surface and subsurface water either year-round (i.e., perennial flow), weekly to seasonally (i.e., intermittent flow), or only in direct response to precipitation (i.e., ephemeral flow). Streams are the dominant source of water in most rivers, and the majority of tributaries are perennial, intermittent, or ephemeral headwater streams. For example, headwater streams, which are the smallest channels where streamflows begin, are the cumulative source of approximately 60% of the total mean annual flow to all northeastern U.S. streams and rivers.

- In addition to downstream transport, headwaters convey water into local storage compartments such as ponds, shallow aquifers, or stream banks, and into regional and alluvial aquifers. These local storage compartments are important sources of water for maintaining baseflow in rivers. Streamflow typically depends on the delayed (i.e., lagged) release of shallow ground water from local storage, especially during dry periods and in areas with shallow ground-water tables and pervious subsurfaces. For example, in the southwestern United States, short-term shallow ground-water storage in alluvial floodplain aquifers, with gradual release into stream channels, is a major source of annual flow in rivers.
- Infrequent, high-magnitude events are especially important for transmitting materials from headwater streams in most river networks. For example, headwater streams, including ephemeral and intermittent streams, shape river channels by accumulating and gradually or episodically releasing stored materials such as sediment and large woody debris. These materials help structure stream and river channels by slowing the flow of water through channels and providing substrate and habitat for aquatic organisms.
- There is strong evidence that headwater streams function as nitrogen sources (via export) and sinks (via uptake and transformation) for river networks. For example, one study estimated that rapid nutrient cycling in small streams with no agricultural or urban impacts removed 20–40% of the nitrogen that otherwise would be delivered to downstream waters. Nutrients are necessary to support aquatic life, but excess nutrients lead to eutrophication and hypoxia, in which over-enrichment causes dissolved oxygen concentrations to fall below the level necessary to sustain most aquatic animal life in the stream and streambed. Thus, the influence of streams on nutrient loads can have significant repercussions for hypoxia in downstream waters.
- Headwaters provide habitat that is critical for completion of one or more life-cycle stages of many aquatic and semiaquatic species capable of moving throughout river networks. Evidence is strong that headwaters provide habitat for complex life-cycle completion; refuge from predators, competitors, parasites, or adverse physical conditions in rivers (e.g., temperature or flow extremes, low dissolved oxygen, high sediment); and reservoirs of genetic- and species-level diversity. Use of headwater streams as habitat is especially critical for the many species that migrate between small streams and marine environments during their life cycles (e.g., Pacific and Atlantic salmon, American eels, certain lamprey species). The presence of these species within river networks provides robust evidence of biological connections between headwaters and larger rivers; because these organisms also transport nutrients and other materials as they migrate, their presence also provides evidence of biologically mediated chemical connections. In prairie streams, many fishes swim upstream into tributaries to release eggs, which develop as they are transported downstream.

- Human alterations affect the frequency, duration, magnitude, timing, and rate of change of connections between headwater streams, including ephemeral and intermittent streams, and downstream waters. Human activities and built structures (e.g., channelization, dams, groundwater withdrawals) can either enhance or fragment longitudinal connections between headwater streams and downstream waters, while also constraining lateral and vertical exchanges and tightly controlling the temporal dimension of connectivity. In many cases, research on human alterations has enhanced our understanding of the headwater stream-downstream water connections and their consequences. Recognition of these connections and effects has encouraged the development of more sustainable practices and infrastructure to reestablish and manage connections, and ultimately to protect and restore the integrity of downstream waters.

Conclusion 2, Riparian/Floodplain Wetlands and Open Waters: Key Findings

- Riparian areas and floodplains connect upland and aquatic environments through both surface and subsurface hydrologic flowpaths. These areas are therefore uniquely situated in watersheds to receive and process waters that pass over densely vegetated areas and through subsurface zones before the waters reach streams and rivers. When pollutants reach a riparian or floodplain wetland, they can be sequestered in sediments, assimilated into wetland plants and animals, transformed into less harmful or mobile forms or compounds, or lost to the atmosphere. Wetland potential for biogeochemical transformations (e.g., denitrification) that can improve downstream water quality is influenced by local factors, including anoxic conditions and slow organic matter decomposition, shallow water tables, wetland plant communities, permeable soils, and complex topography.
- Riparian/floodplain wetlands can reduce flood peaks by storing and desynchronizing floodwaters. They can also maintain river baseflows by recharging alluvial aquifers. Many studies have documented the ability of riparian/floodplain wetlands to reduce flood pulses by storing excess water from streams and rivers. One review of wetland studies reported that riparian wetlands reduced or delayed floods in 23 of 28 studies. For example, peak discharges between upstream and downstream gaging stations on the Cache River in Arkansas were reduced 10−20% primarily due to floodplain water storage.
- Riparian areas and floodplains store large amounts of sediment and organic matter from upstream and from upland areas. For example, riparian areas have been shown to remove 80−90% of sediments leaving agricultural fields in North Carolina.
- Ecosystem function within a river system is driven in part by biological connectivity that links diverse biological communities with the river system. Movements of organisms that connect aquatic habitats and their populations, even across different watersheds, are important for the survival of individuals, populations, and species, and for the functioning of the river ecosystem. For example, lateral expansion and contraction of the river in its floodplain result in an exchange of matter and organisms, including fish populations that are adapted to use floodplain habitats

for feeding and spawning during high water. Wetland and aquatic plants in floodplains can become important seed sources for the river network, especially if catastrophic flooding scours vegetation and seed banks in other parts of the channel. Many invertebrates exploit temporary hydrologic connections between rivers and floodplain wetland habitats, moving into these wetlands to feed, reproduce, or avoid harsh environmental conditions and then returning to the river network. Amphibians and aquatic reptiles commonly use both streams and riparian/floodplain wetlands to hunt, forage, overwinter, rest, or hide from predators. Birds can spatially integrate the watershed landscape through biological connectivity.

Conclusion 3, Non-floodplain Wetlands and Open Waters: Key Findings

- Water storage by wetlands well outside of riparian or floodplain areas can affect streamflow. Hydrologic models of prairie potholes in the Starkweather Coulee subbasin (North Dakota) that drains to Devils Lake indicate that increasing the volume of pothole storage across the subbasin by approximately 60% caused simulated total annual streamflow to decrease 50% during a series of dry years and 20% during wet years. Similar simulation studies of watersheds that feed the Red River of the North in North Dakota and Minnesota demonstrated qualitatively comparable results, suggesting that the ability of potholes to modulate streamflow could be widespread across eastern portions of the prairie pothole region. This work also indicates that reducing water storage capacity of wetlands by connecting formerly isolated potholes through ditching or drainage to the Devils Lake and Red River basins could increase stormflow and contribute to downstream flooding. In many agricultural areas already crisscrossed by extensive drainage systems, total streamflow and baseflow are increased by directly connecting potholes to stream networks. The impacts of changing streamflow are numerous, including altered flow regime, stream geomorphology, habitat, and ecology. The presence or absence of an effect of prairie pothole water storage on streamflow depends on many factors, including patterns of precipitation, topography, and degree of human alteration. For example, in parts of the prairie pothole region with low precipitation, low stream density, and little human alteration, hydrologic connectivity between prairie potholes and streams or rivers is likely to be low.
- Non-floodplain wetlands act as sinks and transformers for various pollutants, especially nutrients, which at excess levels can adversely impact human and ecosystem health and pose a serious pollution problem in the United States. In one study, sewage wastewaters were applied to forested wetlands in Florida for 4.5 years; more than 95% of the phosphorus, nitrate, ammonium, and total nitrogen were removed by the wetlands during the study period, and 66−86% of the nitrate removed was attributed to the process of denitrification. In another study, sizeable phosphorus retention (0.3 to 8.0 mg soluble reactive P m^{-2} d^{-1}) occurred in marshes that comprised only 7% of the lower Lake Okeechobee basin area in Florida. A non-floodplain bog in Massachusetts was reported to sequester nearly 80% of nitrogen inputs from various sources, including atmospheric deposition, and prairie pothole wetlands in the upper Midwest were found to remove >80% of the nitrate load via denitrification. A large prairie marsh was found to remove 86% of nitrate, 78% of ammonium, and 20% of phosphate through

assimilation and sedimentation, sorption, and other mechanisms. Together, these and other studies indicate that onsite nutrient removal by non-floodplain wetlands is substantial and geographically widespread. The effects of this removal on rivers are generally not reported in the literature.

- Non-floodplain wetlands provide unique and important habitats for many species, both common and rare. Some of these species require multiple types of waters to complete their full life cycles, including downstream waters. Abundant or highly mobile species play important roles in transferring energy and materials between non-floodplain wetlands and downstream waters.
- Biological connections are likely to occur between most non-floodplain wetlands and downstream waters through either direct or stepping stone movement of amphibians, invertebrates, reptiles, mammals, and seeds of aquatic plants, including colonization by invasive species. Many species in those groups that use both stream and wetland habitats are capable of dispersal distances equal to or greater than distances between many wetlands and river networks. Migratory birds can be an important vector of long-distance dispersal of plants and invertebrates between non-floodplain wetlands and the river network, although their influence has not been quantified. Whether those connections are of sufficient magnitude to impact downstream waters will either require estimation of the magnitude of material fluxes or evidence that these movements of organisms are required for the survival and persistence of biota that contribute to the integrity of downstream waters.
- Spatial proximity is one important determinant of the magnitude, frequency and duration of connections between wetlands and streams that will ultimately influence the fluxes of water, materials and biota between wetlands and downstream waters. However, proximity alone is not sufficient to determine connectivity, due to local variation in factors such as slope and permeability.
- The cumulative influence of many individual wetlands within watersheds can strongly affect the spatial scale, magnitude, frequency, and duration of hydrologic, biological and chemical fluxes or transfers of water and materials to downstream waters. Because of their aggregated influence, any evaluation of changes to individual wetlands should be considered in the context of past and predicted changes (e.g., from climate change) to other wetlands within the same watershed.
- Non-floodplain wetlands can be hydrologically connected directly to river networks through natural or constructed channels, nonchannelized surface flows, or subsurface flows, the latter of which can travel long distances to affect downstream waters. A wetland surrounded by uplands is defined as "geographically isolated." Our review found that, in some cases, wetland types such as vernal pools and coastal depressional wetlands are collectively—and incorrectly—referred to as geographically isolated. Technically, the term "geographically isolated" should be applied only to the particular wetlands within a type or class that are completely surrounded by uplands. Furthermore, "geographic isolation" should not be confused with functional isolation, because

geographically isolated wetlands can still have hydrologic, chemical, and biological connections to downstream waters.

- Non-floodplain wetlands occur along a gradient of hydrologic connectivity-isolation with respect to river networks, lakes, or marine/estuarine water bodies. This gradient includes, for example, wetlands that serve as origins for stream channels that have permanent surface-water connections to the river network; wetlands with outlets to stream channels that discharge to deep ground-water aquifers; geographically isolated wetlands that have local ground-water or occasional surface-water connections to downstream waters; and geographically isolated wetlands that have minimal hydrologic connection to other water bodies (but which could include surface and subsurface connections to other wetlands). This gradient can exist among wetlands of the same type or in the same geographic region.
- Caution should be used in interpreting connectivity for wetlands that have been designated as "geographically isolated" because (1) the term can be applied broadly to a heterogeneous group of wetlands, which can include wetlands that are not actually geographically isolated; (2) wetlands with permanent channels could be miscategorized as geographically isolated if the designation is based on maps or imagery with inadequate spatial resolution, obscured views, etc.; and (3) wetland complexes could have connections to downstream waters through stream channels even if individual wetlands within the complex are geographically isolated. For example, a recent study examined hydrologic connectivity in a complex of wetlands on the Texas Coastal Plain. The wetlands in this complex have been considered to be a type of geographically isolated wetland; however, collectively they are connected both geographically and hydrologically to downstream waters in the area: During an almost 4-year study period, nearly 20% of the precipitation that fell on the wetland complex flowed out through an intermittent stream into downstream waters. Thus, wetland complexes could have connections to downstream waters through stream channels even when the individual wetland components are geographically isolated.

Conclusion 4, Degrees and Determinants of Connectivity: Key Findings

- The surface-water and ground-water flowpaths (hereafter, hydrologic flowpaths), along which water and materials are transported and transformed, determine variations in the degree of physical and chemical connectivity. These flowpaths are controlled primarily by variations in climate, geology, and terrain within and among watersheds and over time. Climate, geology, and terrain are reflected locally in factors such as rainfall and snowfall intensity, soil infiltration rates, and the direction of ground-water flows. These local factors interact with the landscape positions of streams and wetlands relative to downstream waters, and with functions (such as the removal or transformation of pollutants) performed by those streams and wetlands to determine connectivity gradients.
- Gradients of biological connectivity (i.e., the active or passive movements of organisms through water or air and over land that connect populations) are determined primarily by species

assemblages, and by features of the landscape (e.g., climate, geology, terrain) that facilitate or impede the movement of organisms. The temporal and spatial scales at which biological pathways connect aquatic habitats depend on characteristics of both the landscape and species, and overland transport or movement can occur across watershed boundaries. Dispersal is essential for population persistence, maintenance of genetic diversity, and evolution of aquatic species. Consequently, dispersal strategies reflect aquatic species' responses and adaptations to biotic and abiotic environments, including spatial and temporal variation in resource availability and quality. Species' traits and behaviors encompass species-environment relationships over time, and provide an ecological and evolutionary context for evaluating biological connectivity in a particular watershed or group of watersheds.

- Pathways for chemical transport and transformation largely follow hydrologic flowpaths, but sometimes follow biological pathways (e.g., nutrient transport from wetlands to coastal waters by migrating waterfowl, upstream transport of marine-derived nutrients by spawning of anadromous fish, uptake and removal of nutrients by emerging stream insects).
- Human activities alter naturally occurring gradients of physical, chemical, and biological connectivity by modifying the frequency, duration, magnitude, timing, and rate of change of fluxes, exchanges, and transformations. For example, connectivity can be reduced by dams, levees, culverts, water withdrawals, and habitat destruction, and can be increased by effluent discharges, channelization, drainage ditches and tiles, and impervious surfaces.

Conclusion 5, Cumulative Effects: Key Findings

- Structurally and functionally, stream-channel networks and the watersheds they drain are fundamentally cumulative in how they are formed and maintained. Excess water from precipitation that is not evaporated, taken up by organisms, or stored in soils and geologic layers moves downgradient by gravity as overland flow or through channels carrying sediment, chemical constituents, and organisms. These channels concentrate surface-water flows and are more efficient than overland (i.e., diffuse) flows in transporting water and materials, and are reinforced over time by recurrent flows.
- Connectivity between streams and rivers provides opportunities for materials, including nutrients and chemical contaminants, to be transformed chemically as they are transported downstream. Although highly efficient at the transport of water and other physical materials, streams are dynamic ecosystems with permeable beds and banks that interact with other ecosystems above and below the surface. The exchange of materials between surface and subsurface areas involves a series of complex physical, chemical, and biological alterations that occur as materials move through different parts of the river system. The amount and quality of such materials that eventually reach a river are determined by the aggregate effect of these sequential alterations that begin at the source waters, which can be at some distance from the river. The opportunity for transformation of material (e.g., biological uptake, assimilation, or beneficial transformation) in intervening stream reaches increases with distance to the river.

Nutrient spiraling, the process by which nutrients entering headwater streams are transformed by various aquatic organisms and chemical reactions as they are transported downstream, is one example of an instream alteration that exhibits significant beneficial effects on downstream waters. Nutrients (in their inorganic form) that enter a headwater stream (e.g., via overland flow) are first removed from the water column by streambed algal and microbial populations. Fish or insects feeding on algae and microbes take up some of those nutrients, which are subsequently released back into the stream via excretion and decomposition (i.e., in their organic form), and the cycle is repeated. In each phase of the cycling process—from dissolved inorganic nutrients in the water column, through microbial uptake, subsequent transformations through the food web, and back to dissolved nutrients in the water column—nutrients are subject to downstream transport. Stream and wetland capacities for nutrient cycling have important implications for the form and concentration of nutrients exported to downstream waters.

- Cumulative effects across a watershed must be considered when quantifying the frequency, duration, and magnitude of connectivity, to evaluate the downstream effects of streams and wetlands. For example, although the probability of a large-magnitude transfer of organisms from any given headwater stream in a given year might be low (i.e., a low-frequency connection when each stream is considered individually), headwater streams are the most abundant type of stream in most watersheds. Thus, the overall probability of a large-magnitude transfer of organisms is higher when considered for all headwater streams in a watershed—that is, a high-frequency connection is present when headwaters are considered cumulatively at the watershed scale, compared with probabilities of transport for streams individually. Similarly, a single pollutant discharge might be negligible but the cumulative effect of multiple discharges could degrade the integrity of downstream waters. Riparian open waters (e.g., oxbow lakes), wetlands, and vegetated areas cumulatively can retain up to 90% of eroded clays, silts, and sands that otherwise would enter stream channels. The larger amounts of snowmelt and precipitation cumulatively held by many wetlands can reduce the potential for flooding at downstream locations. For example, wetlands in the prairie pothole region cumulatively stored about 11−20% of the precipitation in one watershed.
- The combination of diverse habitat types and abundant food resources cumulatively makes floodplains important foraging, hunting, and breeding sites for fish, aquatic life stages of amphibians, and aquatic invertebrates. The scale of these cumulative effects can be extensive; for example, coastal ibises travel up to 40 km to obtain food from freshwater floodplain wetlands for nesting chicks, which cannot tolerate salt levels in local food resources until they fledge.

CLOSING COMMENTS

The structure and function of downstream waters highly depend on materials—broadly defined as any physical, chemical, or biological entity—that originate outside of the downstream waters. Most of the constituent materials in rivers, for example, originate from aquatic ecosystems located upstream in the drainage network or elsewhere in the drainage basin, and are transported to the river through flowpaths illustrated in the introduction to this report. Thus, the effects of streams, wetlands, and open waters on rivers are determined by the presence of (1) physical, chemical, or biological pathways that enable (or inhibit) the transport of materials and organisms to downstream waters; and (2) functions within the streams, wetlands, and open waters that alter the quantity and quality of materials and organisms transported along those pathways to downstream waters.

The strong hydrologic connectivity of river networks is apparent in the existence of stream channels that form the physical structure of the network itself. Given the evidence reviewed in this report, it is clear that streams and rivers are much more than a system of physical channels for efficiently conveying water and other materials downstream. The presence of physical channels, however, is a compelling line of evidence for surface-water connections from tributaries, or water bodies of other types, to downstream waters. Physical channels are defined by continuous bed-and-bank structures, which can include apparent disruptions (such as by bedrock outcrops, braided channels, flow-through wetlands) associated with changes in the material and gradient over and through which water flows. The continuation of bed and banks downgradient from such disruptions is evidence of the surface connection with the channel that is upgradient of the perceived disruption.

Although currently available peer-reviewed literature does not identify which types of non-floodplain wetlands have or lack the types of connections needed to convey functional effects to downstream waters, additional information (e.g., field assessments, analysis of existing or new data, reports from local resource agencies) could be used in case-by-case analysis of non-floodplain wetlands. Importantly, information from emerging research into the connectivity of non-floodplain wetlands, including studies of the types identified in Section 4.5.2 of this report, could close some of the current data gaps in the near future. Recent scientific advances in the fields of mapping, assessment, modeling, and landscape classification indicate that increasing availability of high-resolution data sets, promising new technologies for watershed-scale analyses, and methods for classifying landscape units by hydrologic behavior can facilitate and improve the accuracy of connectivity assessments. Emerging research that expands our ability to detect and monitor ecologically relevant connections at appropriate scales, metrics to accurately measure effects on downstream integrity, and management practices that apply what we already know about ecosystem function will contribute to our ability to identify waters of national importance and maintain the long-term sustainability and resiliency of valued water resources.



CHAPTER 1. INTRODUCTION

1.1 Purpose

The objective of the Clean Water Act is to restore and maintain the chemical, physical, and biological integrity of the nation's waters. The U.S. Environmental Protection Agency's (U.S. EPA's) Office of Research and Development developed this report to inform rulemaking by the U.S. EPA and U.S. ACE on the definition of "waters of the United States" under the Clean Water Act (CWA). Its purpose is to summarize current scientific understanding about the connectivity and mechanisms by which streams and wetlands, singly or in aggregate, affect the physical, chemical, and biological integrity of downstream waters. Because this report is a technical review of peer-reviewed scientific literature, it does not consider or set forth legal standards for CWA jurisdiction. Rather, the report evaluates, summarizes, and synthesizes the available peer-reviewed scientific literature to address three questions:

1. What are the physical, chemical, and biological connections to and effects of ephemeral, intermittent, and perennial streams on downstream waters (e.g., rivers, lakes, reservoirs, estuaries)?
2. What are the physical, chemical, and biological connections to and effects of riparian or floodplain wetlands and open waters (e.g., riverine wetlands, oxbow lakes) on downstream waters?
3. What are the physical, chemical, and biological connections to and effects of wetlands and open waters in non-floodplain settings (e.g., most prairie potholes, vernal pools) on downstream waters?

These questions were developed in collaboration with the U.S. EPA's Office of Water to translate regulatory questions and terminology into more scientifically relevant questions and terms (Table 1-1).

This report focuses on the physical, chemical, and biological connections (or lack thereof) by which small or temporary streams, nontidal wetlands, and certain open waters can affect the integrity of downstream waters.

In addition to a broad survey of literature responding to the three questions above, the U.S. EPA's Office of Water asked the Office of Research and Development to create six case studies with more detailed reviews of published literature on Carolina and Delmarva bays, oxbow lakes, prairie potholes, prairie streams, southwestern streams, and vernal pools.

Table 1-1. Translating connectivity-related questions between policy and science. This table presents a crosswalk of regulatory and scientific questions this report addresses. Policy questions use regulatory terms (shown in quotation marks) that lack scientific definitions or are defined differently in scientific usage. All terms used in this report reflect scientific definitions and usage.

Policy question	Science question
What tributaries have a "significant* nexus" to "traditional navigable waters"?	What are the connections to and effects of ephemeral, intermittent, and perennial streams on downstream waters?
What "adjacent" waters have a "significant* nexus" to "traditional navigable waters"?	What are the connections to and effects of riparian or floodplain wetlands and open waters on downstream waters?
What categories of "other waters" have a "significant* nexus" to "traditional navigable waters"?	What are the connections to and effects of wetlands and open waters in non-floodplain settings on downstream waters?

* "Significant," as used here, is a policy determination informed by science; it does not refer to statistical significance.

1.2 Scientific Context

1.2.1 Concepts of Connectivity in Hydrology and Ecology

Streams, wetlands, and other surface waters interact with ground water and terrestrial environments throughout the landscape, from the mountains to the oceans. Thus, an integrated perspective of the landscape, described in this section, provides the appropriate scientific context for evaluating and interpreting evidence about the physical, chemical, and biological connectivity of streams, wetlands, and open waters to downstream waters.

Connectivity has long been a central tenet for the study of aquatic ecosystems. The River Continuum Concept (Vannote et al., 1980) viewed the entire length of rivers, from source to mouth, as a complex hydrologic gradient with predictable longitudinal patterns of ecological structure and function. The key pattern is that downstream communities are organized, in large part, by upstream communities and processes (Vannote et al., 1980; Battin et al., 2009). The Serial Discontinuity Concept (Ward and Stanford, 1983) built on the River Continuum Concept to improve our understanding of how dams and impoundments disrupt the longitudinal patterns of flowing waters with predictable downstream effects.

The Spiraling Concept (Webster and Patten, 1979; Newbold et al., 1981; Elwood et al., 1983) described how river network connectivity can be evaluated and quantified as materials cycle from dissolved forms to transiently stored forms taken up by living organisms, then back to dissolved forms, as they are transported downstream (Section 3.4.1). These three conceptual frameworks focused on the longitudinal connections of river ecosystems, whereas the subsequent flood pulse concept (Junk et al., 1989) examined the importance of lateral connectivity of river channels to floodplains, including wetlands and open waters, through seasonal expansion and contraction of river networks. Ward (1989) summarized the importance of connectivity to lotic ecosystems along four dimensions: longitudinal, lateral, vertical (surface-subsurface), and temporal connections; he concluded that running water ecosystems are open systems that are highly interactive with both contiguous habitats and other ecosystems in the surrounding landscape. As these conceptual frameworks illustrate, scientists have long recognized the hydrologic connectivity that the physical structure of river networks represents.

More recently, scientists have incorporated this connected network structure into conceptual frameworks describing ecological patterns in river ecosystems and the processes linking them to other watershed components, including wetlands and open waters (Power and Dietrich, 2002; Benda et al., 2004; Nadeau and Rains, 2007; Rodriguez-Iturbe et al., 2009). The Network Dynamic Hypothesis (Benda et al., 2004) is a physically based framework for predicting patterns of habitat heterogeneity observed along a river, based on dynamics that generate potential biological "hotspots" at tributary confluences. It essentially reexamines earlier, linearly driven frameworks given the patchy and stochastic nature of lotic ecosystems (e.g., Resh et al., 1988; Townsend, 1989; Rice et al., 2001), and thus reflects a more realistic river network perspective. Bunn and Arthington (2002) identified natural flow variability and associated lateral and longitudinal connectivity of stream channels and floodplains as two principal mechanisms linking hydrology to aquatic biodiversity of riverine species (also Leigh et al., 2010). In addition, application of metapopulation theory and population genetic theory to natural populations has greatly improved our understanding of the role of dispersal and migration in the demographic persistence, community assembly, and evolution of aquatic species (Hastings and Harrison, 1994; Moilanen and Hanski, 1998; Hanski, 1999; Pannell and Charlesworth, 2000; Fagan, 2002; Bohonak and Jenkins, 2003; Waples, 2010; Fronhofer et al., 2012). Sheaves (2009) emphasized the key ecological connections—which include process-based connections that maintain habitat function (e.g., nutrient dynamics, trophic function) and movements of individual organisms—throughout a complex of interlinked freshwater, tidal wetland, and estuarine habitats as critical for the persistence of aquatic species, populations, and communities over the full range of time scales.

1.2.2 Connectivity Gradients and Descriptors

The landscape and flowpath perspectives illustrated in Figure 1-1 draw heavily from the connectivity frameworks described in Section 1.2.1. These perspectives are essential to understanding connections from streams, wetlands, and open waters that affect the integrity of downstream waters. **Connectivity** is defined here as the degree to which components of a watershed are joined and interact by **transport mechanisms** that function across multiple spatial and temporal scales (Section 2.3.2.1). The primary transport mechanisms considered in this report are surface-water and shallow ground-water flows,

Table 1-2. Dimensions of watershed connectivity.	
Dimension	**Examples and flowpaths in Figure 1-1 or Figure 1-2**
Longitudinal	Streamflow and downstream transport of materials, organisms (1-1A); hyporheic flow (1-1A); ground-water flow through local and larger scale aquifers (1-1A), aquatic or overland movement of organisms in or along stream channels (1-1B); biogeochemical transport and transformation (1-1B) (Alexander et al., 2007; Freeman et al., 2007)
Lateral	Overbank flow and transport from channels into banks, floodplains, and riparian areas (1-1A); spillage and transport from wetlands and open waters into streams (1-1A); overland flow and interflow (1-1A); ground-water recharge from streams and wetlands (1-1A); bank storage (1-1A); transport or movement of organisms between streams and wetlands or open waters (1-1B) (Ward, 1989; Stanford and Ward, 1993)
Vertical	Surface-subsurface exchange of water, materials, organisms (1-1A and 1-1B); ground-water recharge from streams and wetlands (1-1A); atmospheric losses (1-1A) (Amoros and Bornette, 2002; Banks et al., 2011)
Temporal	Variable source area (1-2); seasonal cycles of wetland inundation and outflow to streams (1-1A); migration or diapause of aquatic organisms (1-1B) (Hewlett and Hibbert, 1967; Bohonak and Jenkins, 2003; Zedler, 2003)

transport and transformation of physical and chemical materials, and movements of aquatic and semiaquatic organisms, all of which connect watersheds in four dimensions (Table 1-2). Figure 1-1 illustrates the continuous hydrologic flowpaths (Figure 1-1A) and biological pathways (Figure 1-1B) that connect watershed components spatially; Figure 1-2 illustrates the temporal dynamics of hydrologic flowpaths (Sections 2.2.3 and 2.3.2.2).

Although all parts of a watershed are connected to some degree—by the hydrologic cycle or dispersal of organisms, for example—the degree of connectivity among aquatic components varies along a continuum from highly connected to highly isolated. This continuum can be described in terms of the **frequency, duration, magnitude, timing,** and **rate of change** (Poff et al., 2007) of physical and chemical fluxes to and biological exchanges with downstream waters. These terms, which we refer to collectively as **connectivity descriptors**, characterize the range over which streams and wetlands vary and shift along the connectivity gradient in response to changes in natural and anthropogenic factors and, when considered in a watershed context, can be used to predict probable effects of different degrees of connectivity over time. These and similar descriptors are used in hydrology and disturbance ecology to characterize the variability and alteration of natural flow regimes (Resh et al., 1988; Poff, 1992; Poff et al., 1997; Lake, 2000; Leibowitz et al., 2008). For example, in hydrology, magnitude is the amount of water moving past a fixed location per unit time, frequency is how often a particular flow magnitude occurs, duration is a measure of how long a particular flow magnitude persists, and rate of change is how quickly one type of flow changes to another. Because the presence of water determines hydrologic connectivity, these descriptors also can be used to describe the timing and magnitude of hydrologic connections. Further, they can describe other types of connections. The number of individuals immigrating or emigrating during a dispersal event, for example, could be used to determine

Figure 1-1A. Hydrologic flowpaths. Arrows are representative of surface-water and ground-water flows occurring throughout the watershed. Subsurface flows are shown within the cross section, and by faded arrows outside the cross section.

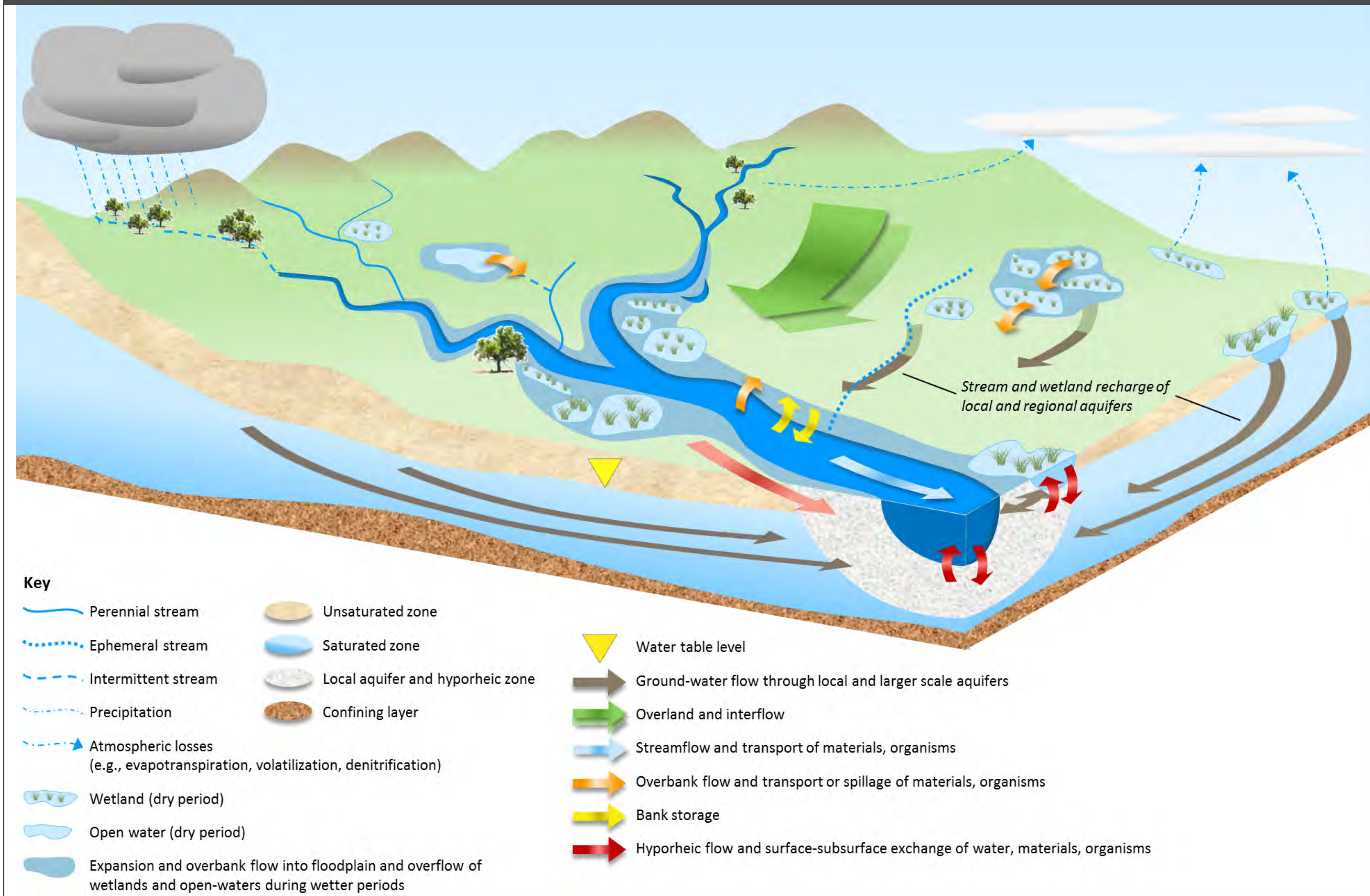


Figure 1-1B. Biological flowpaths. Arrows are representative of biological pathways occurring throughout the watershed. This figure also includes representative biogeochemical pathways occurring in streams and floodplains.

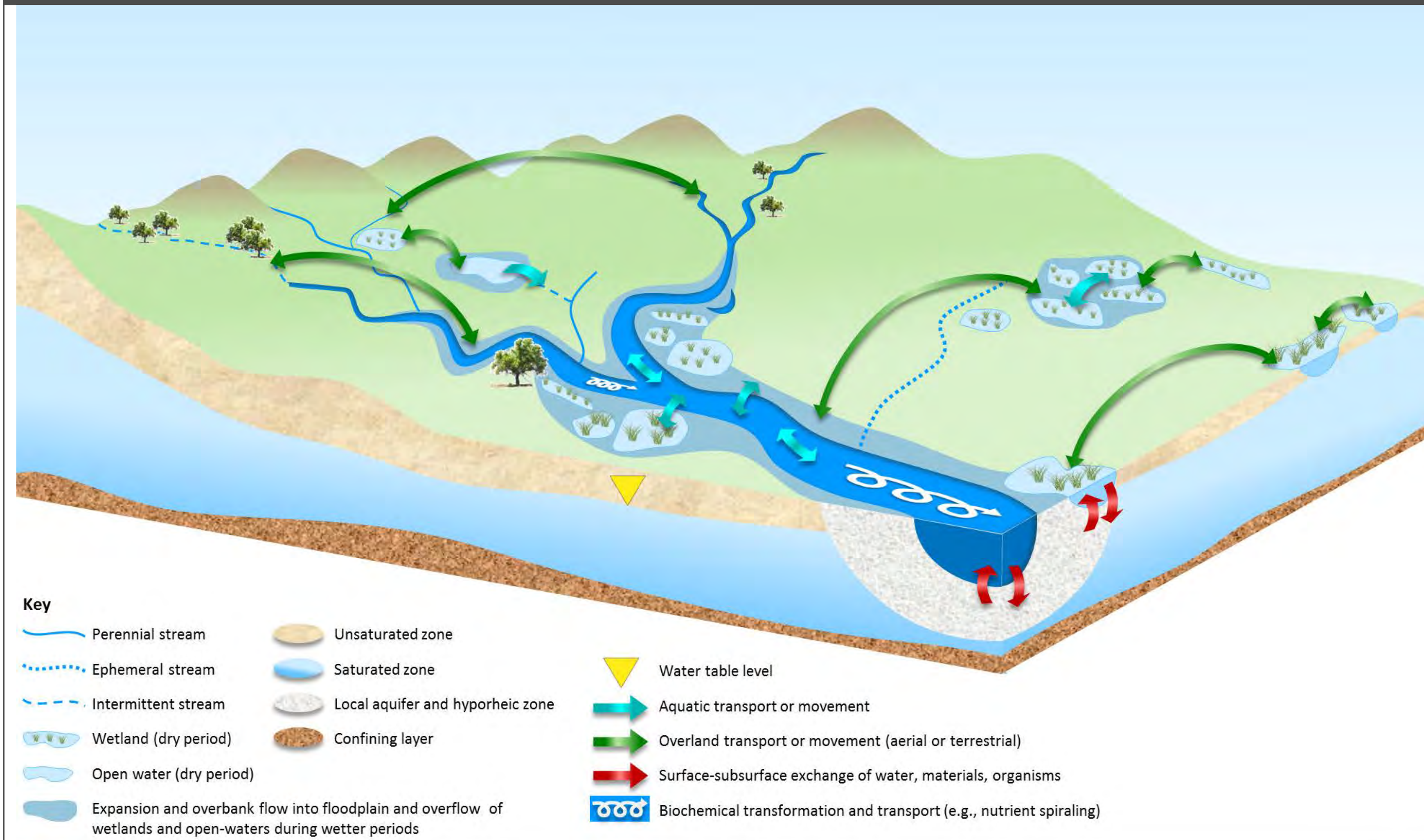
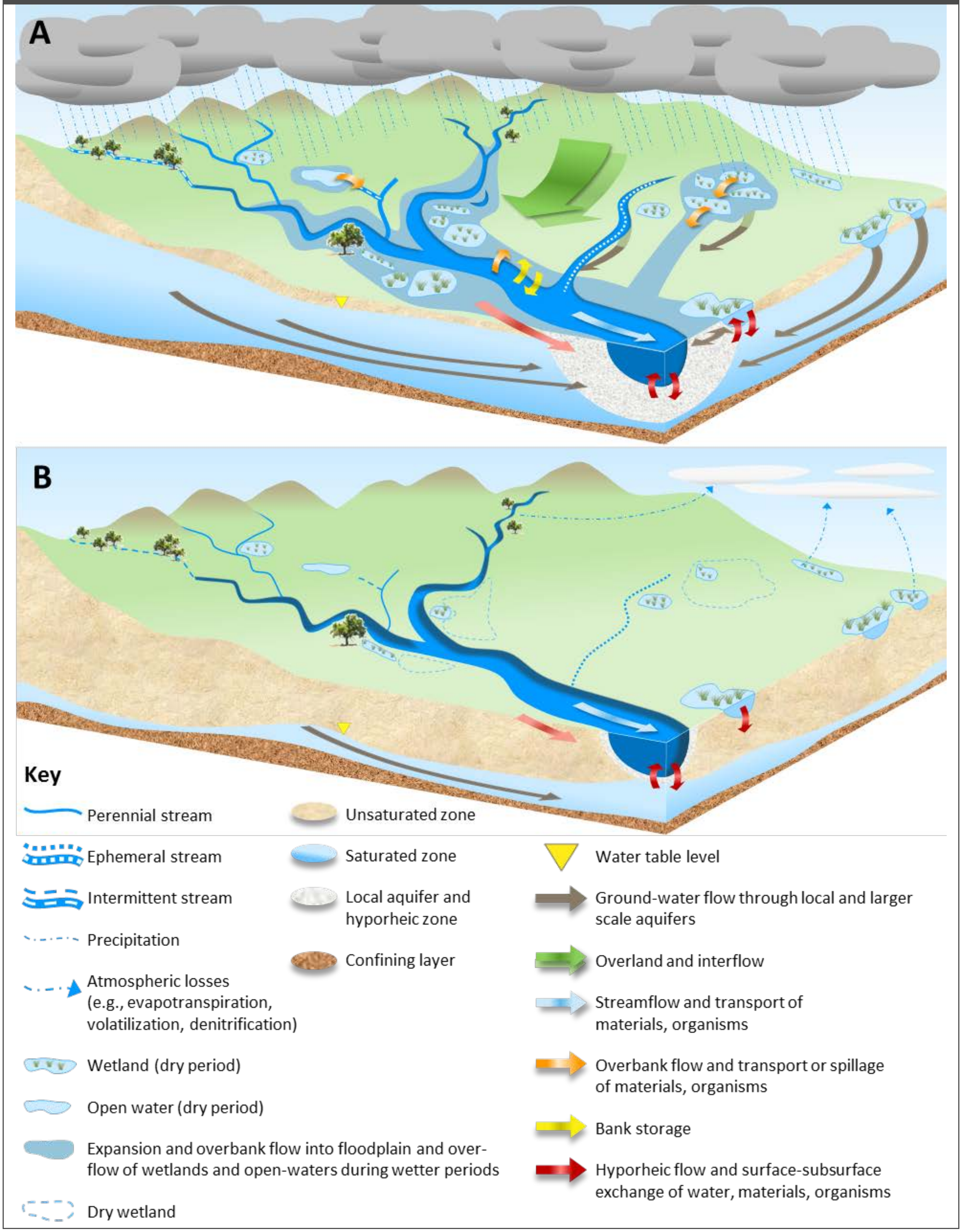


Figure 1-2. Temporal dynamics of hydrologic flowpaths. (A) A riverscape at peak hydrologic expression. (B) The same riverscape in a dry period. Intermittent and ephemeral streams, and some wetlands, are dry.



the magnitude of the event; the probability, length, and predictability of similar events could be expressed in terms of their frequency, duration, and timing; and fluctuations in dispersal could be described as the rate of change through time (e.g., across seasons or years).

Stream and wetland connections have particularly important consequences for downstream water integrity. Longitudinal flows through ephemeral, intermittent, and perennial stream channels (Figure 1-1A, blue lines and arrows) are much more efficient for transport of water, materials, and organisms than diffuse overland flows and interflows (Figure 1-1A, green arrows). Over time, stream transport pathways are reinforced by recurrent flows that maintain channel form. Areas that concentrate water also provide mechanisms for storage, transformation, and transport of materials. Differences in flow frequency, duration, magnitude, timing, and rate of change (e.g., rapid flow in mountain streams, slow flow through glacial ice or bedrock, intermittent flow in seasonal streams, ephemeral flow in arid rivers) create conditions needed for a range of ecosystem functions that affect downstream waters. Such functions include short- and long-term storage of water and sediment, transformation or sequestration of contaminants, recycling of excess nutrients, provision of habitat for aquatic and semiaquatic species, recharge of river baseflow, and provision of drinking water for humans and wildlife. For example, areas that are prone to wetting and drying cycles in response to seasonal conditions (e.g., stream and wetland perimeters shown in Figure 1-1A) are "hotspots" for chemical transformations (Vidon et al., 2010).

Ultimately, differences in the frequency, duration, magnitude, timing, and rate of change of physical, chemical, and biological connections describe different positions along the connectivity gradient and produce different types of downstream effects. For example, highly connected stream channels convey water and channel-forming sediment to rivers, whereas highly isolated wetlands can reduce flooding and store excess sediment. Connections with low values of one or more descriptors (e.g., low-frequency, short-duration flooding) can have important downstream effects when values for other descriptors are high (e.g., large-magnitude downstream transfer of floodwaters, sediment, large woody debris, and organisms). At the other end of the frequency gradient, high-frequency, low-magnitude vertical and lateral flows (Table 1-2) contribute to aquatic biogeochemical processes, including nutrient and contaminant transformation and organic matter accumulation (e.g., Brunke and Gonser, 1997; Karwan and Saiers, 2012; Lawrence et al., 2013).

In addition, timing is a key connectivity descriptor that can influence downstream waters. For example, when soils are saturated by previous rainfall events, even low or moderate rainfall can cause streams or wetlands to overflow, transporting water and materials to downstream waters. The same wetland or wetland type can attenuate floods or generate floods, depending on hydrologic conditions (Acreman and Holden, 2013). Predictable events also can profoundly influence the effects of connections. Wetlands and river networks expand and contract in response to seasonal and decadal cycles and longer term changes in environmental conditions. In wet conditions (Figure 1-2A), streams and rivers expand longitudinally into headwaters and laterally into floodplains or riparian areas, wetlands inundate and connect via surface water and ground water to other wetlands and the stream network, the water table rises, and local aquifers are recharged. In dry conditions (Figure 1-2B), the river network is limited to perennial streams, wetlands dry down, and the water table level lowers. Seasonal flooding and drying events over an annual cycle are formative processes of physical, chemical, and biological attributes of streams in the western United States (Gasith and Resh, 1999). Large seasonal waterfowl migrations can move nutrients, plants (seeds), and invertebrates between wetlands and downgradient waters (Figuerola and Green, 2002; Green and Figuerola, 2005; Frisch et al., 2007). Fish that use nonperennial or perennial headwater stream habitats to spawn or rear young, and invertebrates that move into seasonally inundated floodplain wetlands prior to emergence, have life cycles that are synchronized with the timing of flows and flood pulses, temperature thresholds, and food resource availability in those habitats (Junk et al., 1989; Falke et al., 2010).

The surface-water and ground-water flowpaths along which water and materials are transported and transformed (Sections 2.2.2, 3.3, 3.4, 4.3.2, 4.3.3, 4.4.2, and 4.4.3; Figure 1-1A) determine variations in the degrees of physical and chemical connectivity. These flowpaths are controlled primarily by variation in climate, geology, and terrain within and among watersheds and over time. These factors have been used to group watersheds into hydrologic landscapes units that, although not necessarily spatially contiguous, are predicted to exhibit similar hydrologic function (Wolock et al., 2004; Wigington et al., 2013). Climate, geology, and terrain are reflected locally in factors such as rain and snowfall intensity, soil infiltration rates, and the direction of ground-water flows. These local factors interact with stream and wetland function and landscape position to influence degrees of connectivity through time and across space. When considered together with these local factors, hydrologic landscapes could provide a regional context for evaluating the physical and chemical connectivity of streams and wetlands in a particular watershed or group of watersheds (Section 2.4.1).

Gradients of biological connectivity (i.e., the active or passive movements of organisms through water and air and over land that connect populations of aquatic species; Sections 3.5, 4.3.4, and 4.4.4; Figure 1-1B) are determined primarily by species assemblages and by landscape features, including the factors discussed above, that facilitate or impede the movement of organisms. Organisms move across the landscape to colonize new habitats, avoid inbreeding, escape predation or competition, locate mates, and acquire resources needed to survive and reproduce. The temporal and spatial scales at which biological pathways connect aquatic habitats depend on characteristics of both the landscape and species, and overland transport or movement can occur across watershed boundaries. Dispersal is essential at higher levels of biological organization for population persistence, maintenance of genetic diversity, and evolution of aquatic species (Labbe and Fausch, 2000; Fagan, 2002; Malmqvist, 2002; Bohonak and Jenkins, 2003; Armsworth and Roughgarden, 2005). Consequently, dispersal strategies reflect aquatic species' responses and adaptations to biotic and abiotic environments, including spatial and temporal variation in resource availability and quality (e.g., Clobert et al., 2009). Dispersal-related traits and behaviors (e.g., habitat specialization, dispersal mode, behavioral response to environmental cues) therefore encompass species-environment relationships over time and provide an ecological and evolutionary context for evaluating biological connectivity in a particular watershed or group of watersheds.

Pathways for chemical transport and transformation largely follow hydrologic flowpaths (Figure 1-1A), but sometimes follow biological pathways (e.g., nutrient transport from wetlands to coastal waters by migrating waterfowl, upstream transport of marine-derived nutrients by anadromous fish, uptake and removal of nutrients by emerging stream insects; Figure 1-1B). The transport and transformation of nutrients (e.g., sequential transformations, Section 2.3.2.1; and nutrient spiraling in streams, Section 3.4.1) and other chemicals associated with water integrate physical, chemical, and biological connectivity of streams and wetlands to downstream waters (Figure 1-1B).

1.2.3 Cumulative Effects of Streams and Wetlands on Downstream Waters

Stream and wetland connectivity to downstream waters, and the resulting effects on downstream water integrity, must be considered cumulatively. First, when considering the effect of an individual stream or wetland, including the cumulative effect of all the contributions and functions that a stream or wetland provides is essential. For example, the same stream transports water, removes excess nutrients, mitigates flooding, and provides refuge for fish when conditions downstream are unfavorable; ignoring any of these functions would underestimate the overall effect of that stream.

Secondly, stream channel networks and the watersheds they drain are fundamentally cumulative in how they are formed and maintained. Excess precipitation that is not evaporated, taken up by organisms, or stored in soils and geologic layers moves downgradient as overland flow or through channels, which concentrate flows and carry sediment, chemical constituents, and organisms (Sections 3.3, 3.4, and 3.5). As flows from numerous headwater channels combine in larger channels, the volume and effects of those flows accumulate as they move through the river network. As a result, the incremental contributions of individual streams and wetlands accumulate in the downstream waters. Important cumulative effects are exemplified by ephemeral flows in arid landscapes, which are key sources of baseflow for downgradient waters (Sections 5.6 and B.5; Schlesinger and Jones, 1984; Baillie et al., 2007; Izbicki, 2007), and by the high rates of denitrification in headwater streams (Section 3.4.1). The amount of nutrients removed by any one stream over multiple years or by all headwater streams in a watershed in a given year can have substantial consequences for downstream waters (Alexander et al., 2007; Alexander et al., 2009; Böhlke et al., 2009; Helton et al., 2011). Similar cumulative effects on downstream waters have been documented for other material contributions from headwater streams (Chapter 3). For example, although the probability of a large-magnitude transfer of organisms from any given headwater stream in a given year might be low (i.e., a low-frequency connection when each stream is considered individually), headwater streams are the most abundant type of stream in most watersheds (Section 3.2). Thus, the overall probability of a large-magnitude transfer of organisms is higher when considered for all headwater streams in a watershed—that is, there is a high-frequency connection when considered cumulatively at the watershed scale, compared with probabilities of transport for streams individually. Similarly, a single pollutant discharge might be negligible but the cumulative effect of multiple discharges could degrade the integrity of downstream waters.

Evaluating cumulative contributions over time is critical in streams and wetlands with variable degrees of connectivity. For example, denitrification in a single headwater stream in any given year might not affect downstream waters; over multiple years, however, this effect could accumulate. Western vernal pools provide another example of cumulative effects over time. These pools typically occur as complexes in which the hydrology and ecology are tightly coupled with the local and regional geological processes that formed them (Section B.6). When seasonal precipitation exceeds wetland storage capacity and wetlands overflow into the river network and generate stream discharge, the vernal pool basins, swales, and seasonal streams function as a single surface-water and shallow ground-water system connected to the river network.

1.2.4 Effects of Human Activities on Connectivity

Human activities alter naturally occurring gradients of physical, chemical, and biological connectivity by modifying the frequency, duration, magnitude, timing, and rate of change of fluxes, exchanges, and transformations. For example, all dimensions of connectivity (Table 1-2) can be reduced by dams and levees (Ward and Stanford, 1983; Ligon et al., 1995; Collier et al., 1996; Wohl, 2005; Franklin et al., 2009), water withdrawals (Haag and Pfeiffer, 2012), and habitat destruction. Alternatively, connectivity can be increased by point source discharges (Brooks et al., 2006); channelization, drainage ditches, and tiles (Randall et al., 1997; Min et al., 2010); and storm drains and impervious surfaces (Booth, 1990; Paul and Meyer, 2001; Elmore and Kaushal, 2008; Walsh et al., 2012). The effects of human activities on connectivity are often complex. For example, a levee will decrease connectivity between a river channel and its floodplain at the levee site, but might increase connectivity of the channel and floodplain farther downstream, due to increased flow. Similarly, drainage ditches that increase hydrologic connectivity between isolated aquatic systems also can decrease biological connectivity through habitat loss and fragmentation.

Human activities modify the natural biological processes, material fluxes, and energy fluxes that link watershed components, resulting in a suite of stressors with measurable effects on downstream ecosystems. Some of these activities are illustrated in a hypothetical watershed (Figure 1-3). In Figure 1-3 (A), buried and ditched streams have eliminated aquatic habitat, increased downstream export of runoff and contaminants, and eliminated stream functions that could benefit downstream water quality. Figure 1-3 (B) shows a dam and reservoir that have constrained natural river expansion and contraction cycles by increasing water storage, trapping sediment, and regulating the volume and timing of river discharge. Dams and reservoirs also block upstream movement of migrating fish and other organisms, alter riparian areas, and impair riparian and floodplain wetland functions. In Figure 1-3 (C), levees and channelization have disconnected the river from its floodplain; decreased exchange of water, materials, and biota between the channel bed and hyporheic zone; and eliminated stream and wetland habitats. In addition, levees decrease the volume of river discharge at the levee site, but increase discharge downstream of the levee site. In Figure 1-3 (D), urban stormwater drainage has increased export of runoff and contaminants from impervious surface areas, altered stream temperature, and impaired instream habitats. In Figure 1-3 (E), drained and ditched wetlands have impaired wetland habitat and functions; increased downstream export of excess nutrients and

Figure 1-3. Effects of human alterations on watershed connectivity. See Section 1.2.4 for description of alterations illustrated in A-G.

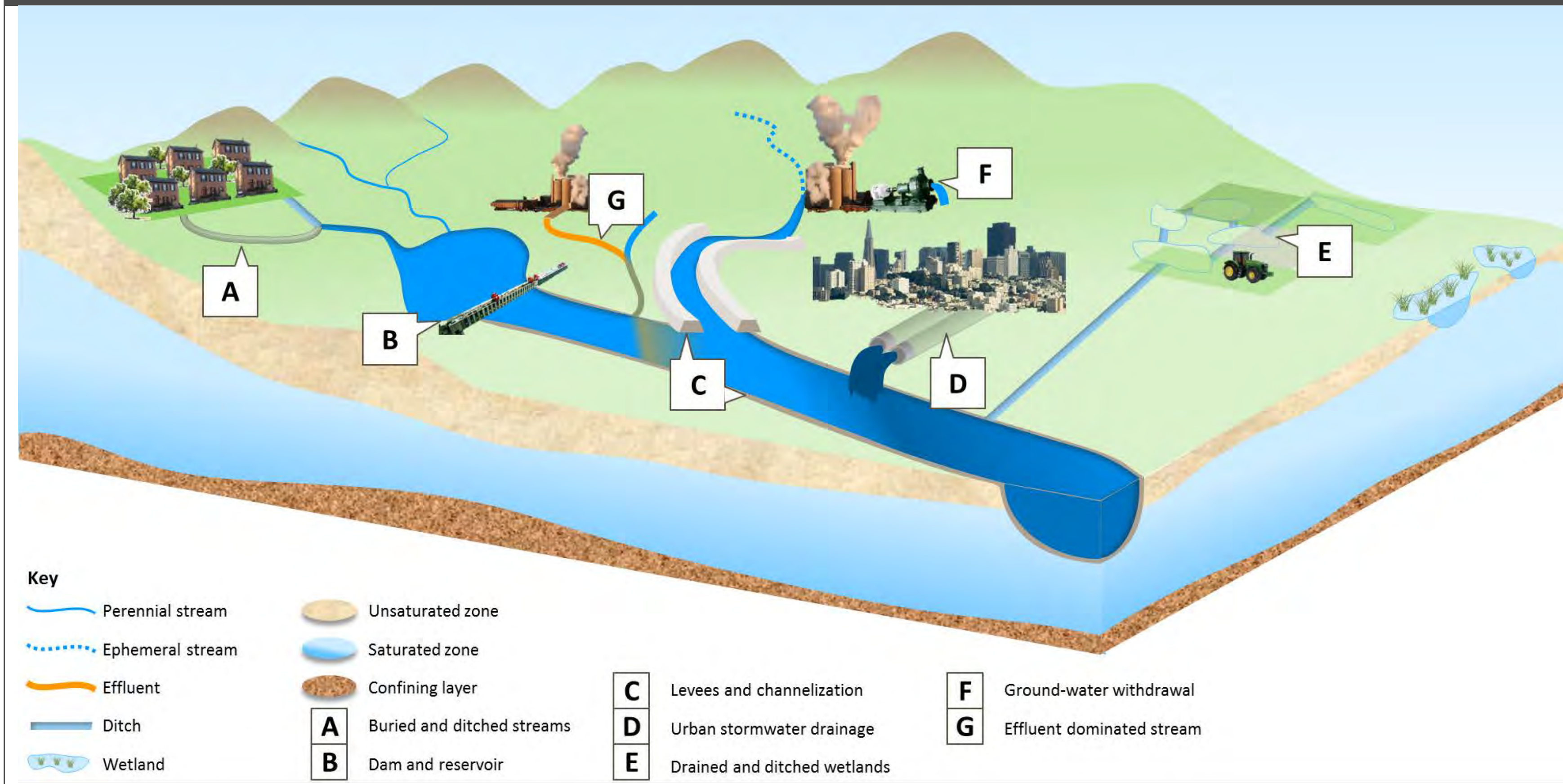
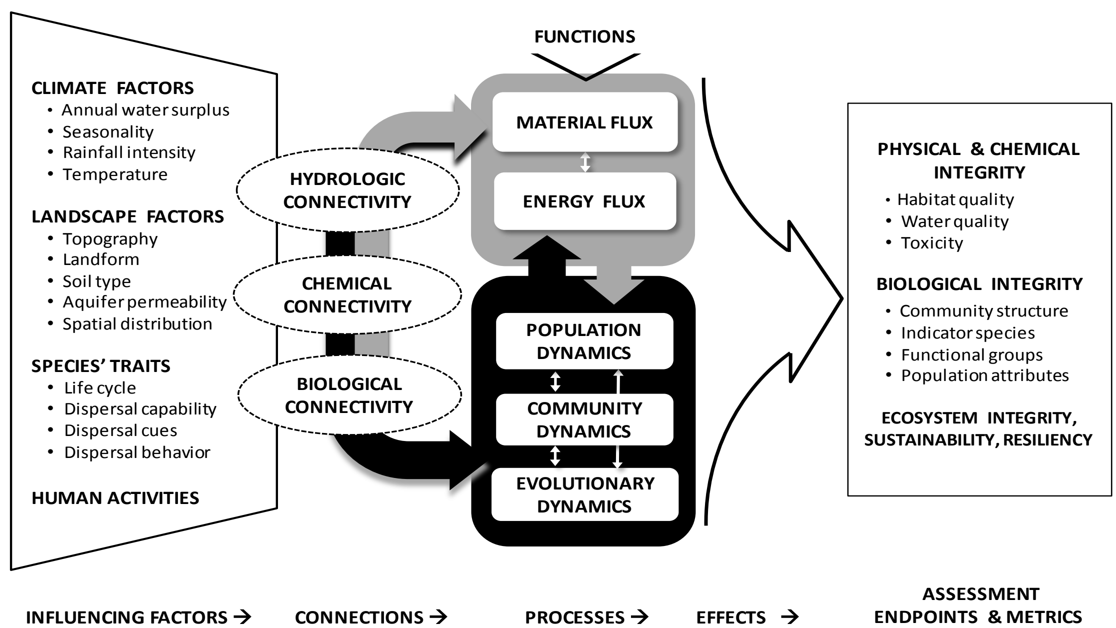


Figure 1-4. The role of connectivity in maintaining the physical, chemical, and biological integrity of water. Climate, landscape, and species' traits (Influencing Factors) interact to form Connections (hydrologic, chemical, and biological) that control the frequency, duration, magnitude, timing, and rate of change of material and energy fluxes, and biological dynamics (Processes) linking watershed components. The Functions by which these connections affect downstream waters modify the timing of transport and the quantity and quality of resources available to downstream communities. Biomonitoring programs have developed structural metrics for assessing physical habitat, water quality, and biological assemblages as indicators of the physical, chemical, and biological integrity of downstream waters (Assessment Endpoints and Metrics).



other contaminants; and decreased recharge of local and regional aquifers. In Figure 1-3 (F), groundwater withdrawal has lowered the water table, disconnecting surface water and ground water, thereby causing local streams and wetlands to dry. Finally, in Figure 1-3 (G), pollutant discharges into effluent-dominated streams have altered the volume and timing of streamflow, and increased the export of contaminants into streams. Because watersheds typically experience multiple covarying stressors, determining the cause of a specific downstream effect can be difficult. Relating observed effects to probable causes requires not only reliable measures of candidate stressors and observed effects, but also a clear understanding of the intermediate processes that link them mechanistically (U.S. EPA, 2010; Farrar et al., 2014).

Multiple indicators and measures have been proposed for detecting and quantifying changes in connectivity associated with human activities (With et al., 1997; Tischendorf and Fahrig, 2000; Moilanen and Nieminen, 2002; Calabrese and Fagan, 2004; Martin and Soranno, 2006; Fullerton et al., 2010; Hermoso et al., 2012). Impairments that result from structural alteration of landscape attributes (e.g., dam construction, channel incision, loss of overland dispersal corridors) are relatively easier to detect and quantify than impairments of functional processes (e.g., altered nutrient dynamics, reduced gene flow), but both have important consequences for the short- and long-term integrity of freshwater ecosystems. Palmer and Febria (2012) proposed that ecosystem impairment can be better identified and diagnosed by a combination of structural and functional metrics than by either type alone. Because connectivity can be defined in both structural and functional terms and is an integral component of aquatic ecosystem integrity, this approach is more appropriate for detecting and assessing effects of altered connectivity. To this end, systematic approaches that are rooted in landscape analysis and which incorporate hydroecological dynamics present in streams and wetland complexes (Section 2.4.6) are likely to provide useful information for inferring when and where altered connectivity is a cause of impairment to water resources.

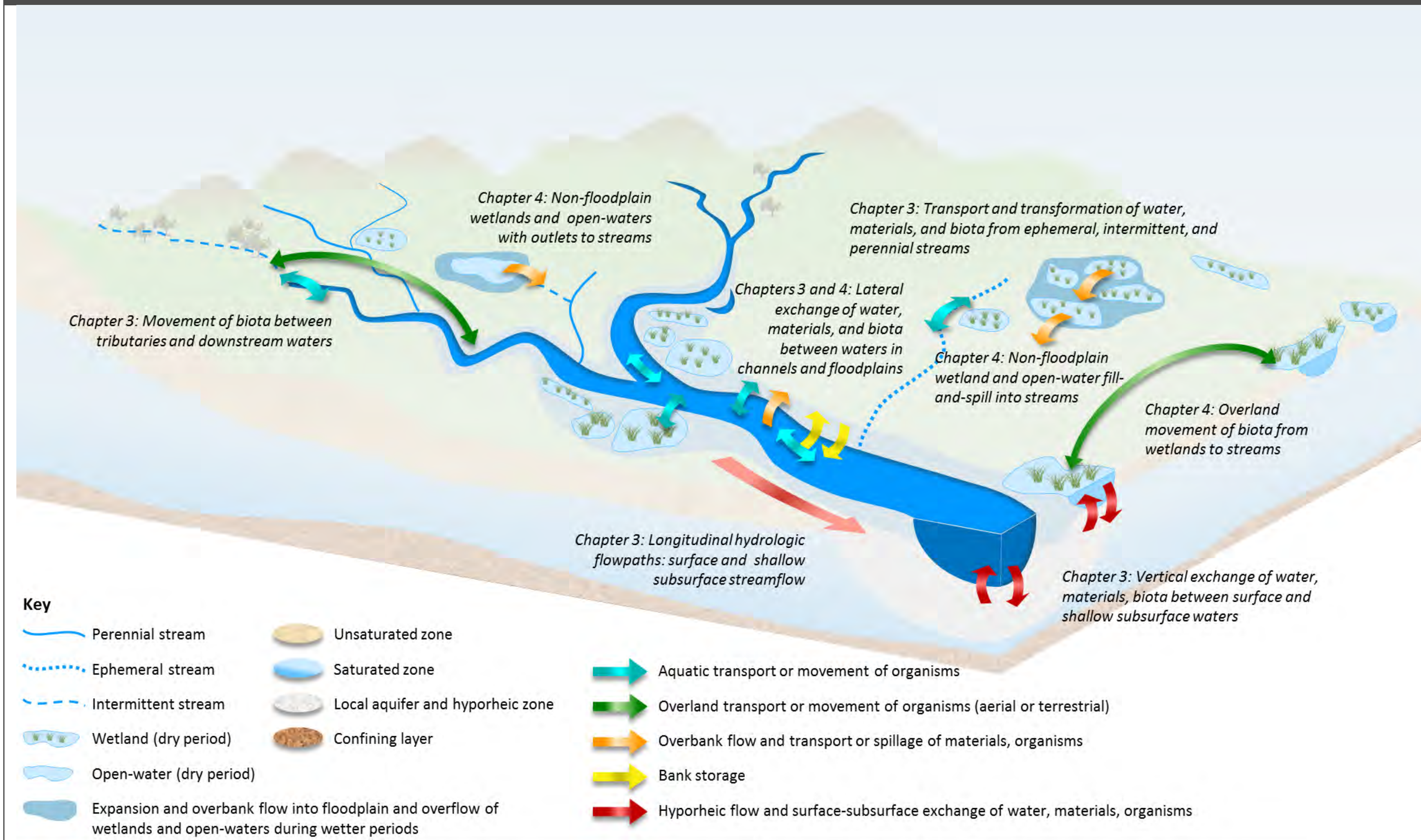
1.3 Report Approach

In this report, we focus entirely on peer-reviewed, publicly accessible sources of information about surface-water and ground-water (particularly shallow ground-water) connections and interactions from streams, wetlands, and open waters that influence the function and condition of downstream surface waters (Figure 1-5). Information about connections among water bodies of the same type (e.g., wetland-to-wetland or headwater stream-to-headwater stream connections) and connections from terrestrial systems to downstream waters are considered out of scope (Figure 1-5).

The topical scope of this report was chosen to consider waters that often fall under the purview of the CWA. As a scientific review, however, this report does not consider or make judgments regarding legal standards for CWA jurisdiction. Our review of subsurface flows emphasizes shallow (local) ground water, because flows in this category have the greatest interchange with surface waters (Winter et al., 1998) although relevant surface-subsurface exchanges occur at depths ranging from centimeters to tens of meters, depending on geographic location, stream channel geometry, and other factors (Woessner, 2000). As with any literature review, readers should refer to the cited publications for quantitative information, such as flow distance, depth, duration, timing, and magnitude, about specific surface-water and ground-water connections, and for other details about the systems and studies discussed in this report.

To identify connections and effects of streams, wetlands, and other water bodies on downstream waters, we used two types of evidence from peer-reviewed, published literature: (1) direct evidence that demonstrated a connection or effect (e.g., observed transport of materials or movement of organisms from streams or wetlands to downstream waters) and (2) indirect evidence that suggested a connection or effect (e.g., presence of environmental factors known to influence connectivity, a gradient of impairment associated with cumulative loss of streams or wetlands). In some cases, an individual line of evidence demonstrated connections along the entire river network (e.g., from headwaters to large rivers). In most cases, multiple sources of evidence were gathered and conclusions drawn via logical inference—for example, when one body of evidence shows that headwater streams are connected to downstream segments, another body of evidence shows those downstream segments are linked to other

Figure 1-5. Waters and connections considered to be within scope for this report.



segments farther downstream, and so on. This approach, which borrows from weight-of-evidence approaches in causal analysis (Suter et al., 2002; Suter and Cormier, 2011), is an effective way to synthesize the diversity of evidence needed to address questions at larger spatial and longer temporal scales than are often considered in individual scientific studies.

1.3.1 Selection and Screening of Scientific Materials

We searched the scientific literature for information on the types of waters, connections, and downstream effects identified in the report objectives and scope (Section 1.1; Figure 1-5). We conducted keyword searches using terms inclusive of the types of waters, connections, and downstream effects of interest (e.g., [wetland* AND [river* OR stream*] AND [connect* OR isolat*]]). Because simple keyword searches would have omitted relevant publications, we also searched for literature on related topics. Topics included conceptual frameworks of watershed and landscape connectivity; hydrologic flowpaths among watershed components; biogeochemical transformation and cycling in streams and wetlands; natural or artificial tracers of difficult-to-observe flows (e.g., ground-water flow, gene flow); chemical and biological processes associated with aquatic habitat fragmentation and spatial isolation; and climate or landscape factors that influence connectivity or isolation. We also reviewed citations provided by peer-review panels and in public comments on drafts of the report. We then screened those results and selected the most relevant publications for review and synthesis in this report, based on the criteria in Figure 1-6.

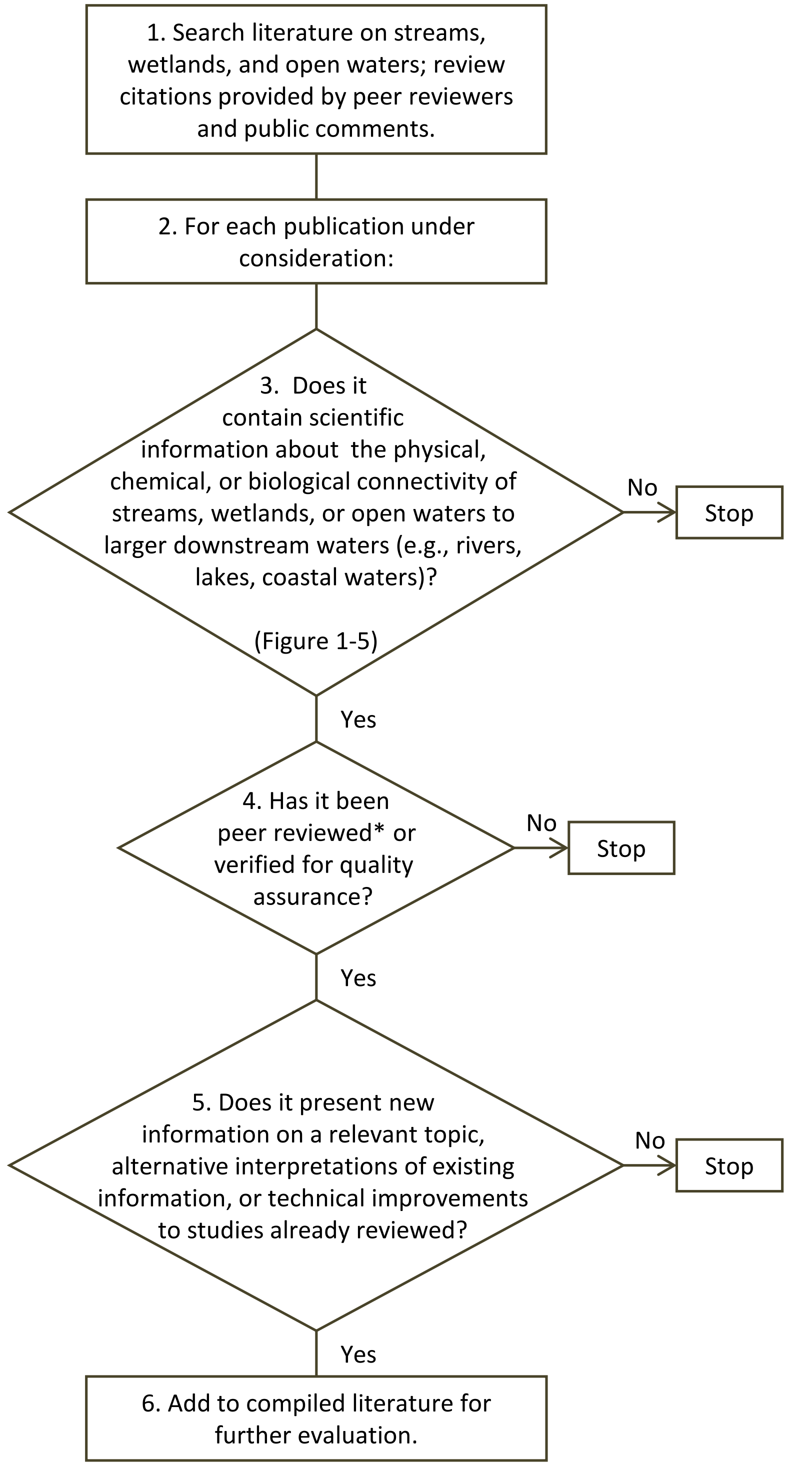
We used science citation databases and search engines available through Web of Science™ and Google Scholar™ to search primary (original research) and secondary (review) literature. These searches included examination of references citing or cited in relevant publications obtained through specific searches.

Because the breadth and depth of topics covered in this report made an exhaustive literature review impractical, we emphasized highly influential papers on relevant topics, review papers that summarized multiple studies in narrative form, meta-analyses that used statistical methods to combine results from multiple independent studies into a single evaluation of evidence, and superseding editions or versions of published research. Publications that did not provide new information, an alternative perspective or interpretation of evidence, or a technical improvement (e.g., improved accuracy or better study design) were not summarized in the report to avoid redundancy and excessive length and detail.

We summarized the relevant literature in narrative form and organized each chapter into lines of evidence pertaining to different types of connections (physical, chemical, biological) for different types of systems (streams, riparian/floodplain wetlands, non-floodplain wetlands). Lines of evidence were evaluated for strength, consistency, mechanistic plausibility, and relevance to the endpoints identified in the report objectives. Finally, conclusions for each of the report's three questions were derived from the key findings, and placed in context with concepts and evidence provided in each chapter.

Cited in this report are 1,353 references. Most were published in refereed scientific journals (86%), as scientific reports by federal agencies that follow peer-review guidelines of the Office of Management and

Figure 1-6. Flow chart for screening and compiling literature.



* Peer review is the formal evaluation of scientific information by independent experts who were not involved in the work but have equivalent scientific and technical expertise. Its purpose is to ensure that materials accepted for publication have been critically reviewed and revised as needed to meet the documented standards of scientific integrity and quality for specific journals or organizations. All reports published by the U.S. EPA Office of Research and Development meet or exceed peer-review requirements established by the Office of Management and Budget (OMB, 2004).

Budget (4%), or scientific books (~9%). The remaining citations refer to photographs, maps, non-federal reports, or websites (<1%) that provide supplemental information.

1.3.2 Report Structure

The report is organized into six chapters. Chapter 1 outlines the purpose, scientific context, and approach of the report. Chapter 2 describes the components of a river system and watershed; the types of physical, chemical, and biological connections that link those components; the factors that influence connectivity at various temporal and spatial scales; and methods for quantifying connectivity. Chapter 3 reviews literature on connectivity in stream networks in terms of physical, chemical, and biological connections and their resulting effects on downstream waters. Chapter 4 reviews literature on the connectivity and effects of nontidal wetlands and certain open waters on downstream waters. Chapter 5 applies concepts and evidence from previous chapters to the case studies detailed in Appendix B. Chapter 6 presents the five major conclusions of this report, with a summary of key findings from the literature synthesized to develop these conclusions. It also discusses the relative abundance of literature on topics reviewed in this report, and briefly discusses emerging research that can close some current data gaps identified in the report. A glossary of scientific terms used in the report and detailed case studies of selected systems (summarized in Chapter 5) are included in Appendix A and Appendix B, respectively.

1.4 Summary

This report evaluates, summarizes, and synthesizes available peer-reviewed scientific literature on the connectivity and mechanisms by which streams, wetlands, and open waters, singly or in aggregate, affect the physical, chemical, and biological integrity of downstream waters.

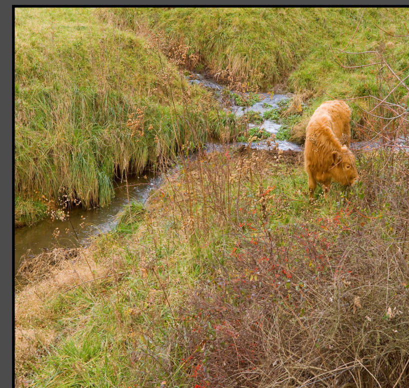
Connectivity has long been a central tenet for the study of aquatic ecosystems. Watersheds are integrated at multiple spatial and temporal scales by flows of surface water and ground water, transport and transformation of physical and chemical materials, and movements of organisms. Although all parts of a watershed are connected, the degrees and downstream effects of those connections vary; the effects also are influenced by characteristics of the physical environment, the biological environment, and by human activities in the watershed.

Variation in the degree of connectivity is critical to the integrity and sustainability of downstream waters, and can be described in terms of the frequency, duration, magnitude, timing, and rate of change of fluxes to and biological exchanges with downstream waters. These descriptors characterize the range over which streams and wetlands vary and shift along connectivity gradients and the probable effects of different types (hydrologic, chemical, biological) and degrees of connectivity over time. Gradients of physical, chemical, and biological connectivity are controlled primarily by variation in climate, geology, terrain, aquatic organisms, and human activities within and among watersheds, and over time.

Ultimately, differences in the frequency, duration, magnitude, timing, and rate of change of physical, chemical, and biological connections describe different positions along the connectivity gradient and produce different types of downstream effects. Connections with low values of one or more descriptors (e.g., low-frequency, short-duration floods) can have important downstream effects when values for other descriptors are high (e.g., large-magnitude transfers of floodwaters, sediment, large woody debris, and organisms downstream). At the other end of the frequency gradient, the effects of high-frequency, low-magnitude vertical and lateral flows strongly contribute to biogeochemical functions, including nutrient and contaminant transformation and organic matter accumulation.

Stream channel networks and the watersheds they drain are fundamentally cumulative in how they are formed and maintained. The downstream consequences (e.g., the amount and quality of materials that eventually reach a river) are determined by the aggregate effect of contributions and sequential alterations that begin at the source waters and function along continuous flowpaths to the watershed outlet. Cumulative effects across a watershed must therefore be considered when quantifying the frequency, duration, and magnitude of connectivity, to evaluate the downstream effects of streams, wetlands, and open waters.





CHAPTER 2. AN INTEGRATED SYSTEMS PERSPECTIVE ON INTERACTIONS OF WATERSHEDS, STREAMS, WETLANDS, AND DOWNSTREAM WATERS

2.1 Introduction

A river is the time-integrated result of all waters contributing to it, and connectivity is the property that spatially integrates the individual components of the watershed. In discussions of connectivity, the watershed scale is the appropriate context for interpreting technical evidence about individual watershed components (Newbold et al., 1982b; Stanford and Ward, 1993; Bunn and Arthington, 2002; Power and Dietrich, 2002; Benda et al., 2004; Naiman et al., 2005; Nadeau and Rains, 2007; Rodriguez-Iturbe et al., 2009). Such interpretation requires that freshwater resources be viewed within a landscape—or systems—context (Baron et al., 2002). Addressing the questions asked in this report (Section 1.1), therefore, requires an integrated systems perspective that considers both the components contributing to the river and the connections between those components and the river. This chapter describes this integrated systems perspective. Section 2.2 outlines the basic hydrologic foundation of river systems. Section 2.3 provides a general overview of how streams and wetlands affect downstream waters, focusing on functions within streams and wetlands and how they are connected to downstream waters. Finally, Section 2.4 examines key factors that affect connectivity between streams and wetlands and rivers. Although we focus our discussion here on interactions between streams, wetlands, and rivers, similar exchanges of water, influenced by many of the same factors, also occur between rivers, lakes, estuaries, and marine waters.

2.2 An Introduction to River Systems

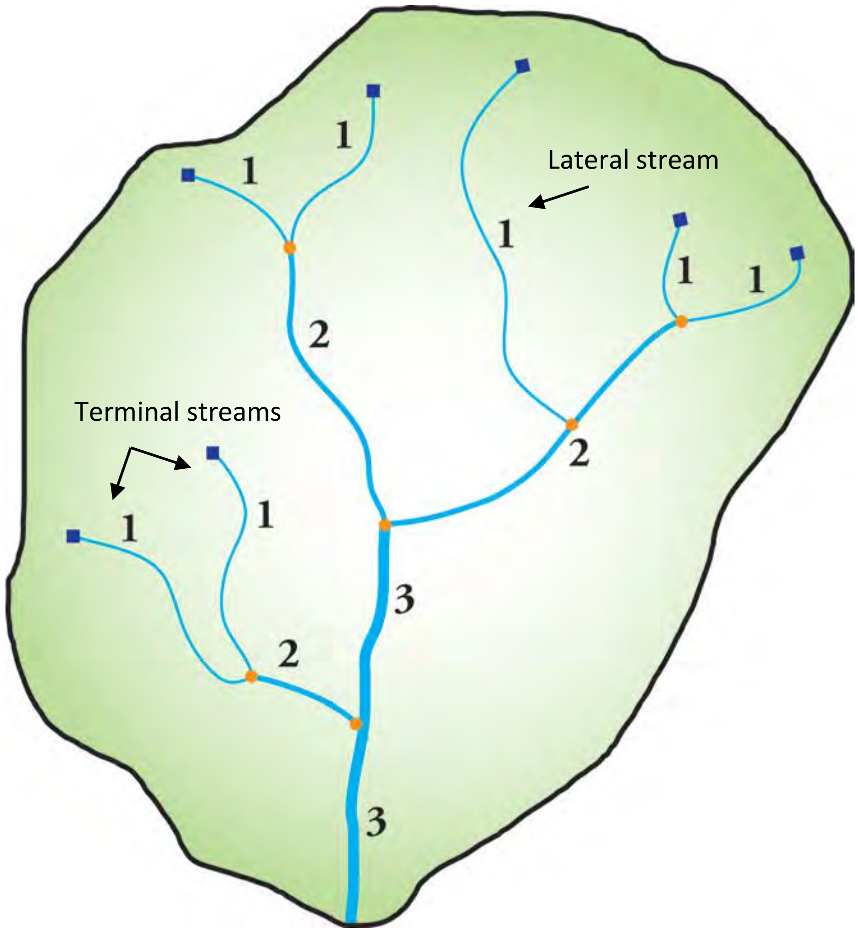
2.2.1 River System Components

In this report, the term **river** refers to a relatively large volume of flowing water within a visible channel, including subsurface water moving in the same direction as the surface water and lateral flows exchanged with associated floodplain and riparian areas (Naiman and Bilby, 1998). **Channels** are natural or constructed passageways or depressions of perceptible linear extent that convey water and associated materials downgradient. They are defined by the presence of continuous bed and bank structures, or uninterrupted (but permeable) bottom and lateral boundaries. Although bed and bank structures might in places appear to be disrupted (e.g., bedrock outcrops, braided channels, flow-through wetlands), the continuation of the bed and bank downgradient from such disruptions is evidence of the surface connection with the channel that is upgradient of the perceived disruption. Such disruptions are associated with changes in the gradient and in the material over and through which the water flows. If a disruption in the bed and bank structure prevented connection, the area downgradient would lack a bed and bank, be colonized with terrestrial vegetation, and be indiscernible from the nearby land. The concentrated longitudinal movement of water and sediment through these channels lowers local elevation, prevents soil development, selectively transports and stores sediment, and hampers the colonization and persistence of terrestrial vegetation. **Streams** are defined in a similar manner as rivers: a relatively small volume of flowing water within a visible channel, including subsurface water moving in the same direction as the surface water and lateral flows exchanged with associated floodplain and riparian areas (Naiman and Bilby, 1998).

A **river network** is a hierarchical, interconnected population of channels that drains surface and subsurface water (Sections 2.2.2 and 2.2.3) from a watershed to a river and includes the river itself. Watershed boundaries traditionally are defined topographically, such as by ridges, but ground-water sources and losses can occur outside of topographic boundaries (Winter et al., 2003). These channels can convey water year-round, weekly to seasonally, or only in direct response to rainfall and snowmelt (Frissell et al., 1986; Benda et al., 2004). The smallest of these channels, where streamflows begin, are considered **headwater streams**. Headwater streams are first- to third-order streams (Vannote et al., 1980; Meyer and Wallace, 2001; Gomi et al., 2002; Fritz et al., 2006b; Nadeau and Rains, 2007), where stream order is a classification system based on the position of the stream in the river network (Figure 2-1; Strahler, 1957). The point at which stream or river channels intersect within a river network is called a **confluence** (Figure 2-1). The confluence of two streams with the same order results in an increase of stream order (i.e., two first-order streams join to form a second-order stream, two second-order streams join to form a third-order stream, and so on); when streams of different order join, the order of the larger stream is retained.

One weakness of classification based on stream order is that it disregards the contributions of lower order streams where they join a higher order stream. Link magnitude, an alternative method for classifying streams, resolves this issue. Link magnitude is the sum of all source streams draining into a given stream segment (Scheidegger, 1965; Shreve, 1967). Therefore, unlike stream order, the link

Figure 2-1. A generalized example of a river network within its watershed. Blue lines illustrate the river network, within the light green area of its watershed. Numbers represent Strahler stream order, with streams increasing in order when two streams of equal order join. Blue squares indicate channel heads, and orange dots depict confluences.



magnitude of a segment accounts for all contributing lower order streams regardless of their position in river networks. For some properties, link magnitude might better reflect the aggregate upstream contributions to downstream waters.

Mock (1971) presented a classification of the streams comprising stream or river networks. He designated first-order streams that intersect other first-order streams as sources. We refer to these as **terminal source streams**. Mock defined first-order streams that flow into higher order streams as tributary sources, and we refer to this class of streams as **lateral source streams** (Figure 2-1)**.**

Terminal and lateral source streams typically originate at channel heads (Dietrich and Dunne, 1993), which occur where surface-water runoff is sufficient to erode a definable channel. The channel head denotes the upstream extent of a stream's continuous bed and bank structure (Figure 2-1). Channel heads are relatively dynamic zones in river networks, as their position can advance upslope by overland or subsurface flow-driven erosion, or retreat downslope by colluvial infilling. Source streams also can originate at seeps or springs and associated wetlands.

When two streams join at a confluence, the smaller stream (i.e., that with the smaller drainage area or lower mean annual discharge) is called a **tributary** of the larger stream, which is referred to as the **mainstem**. A basic way of classifying tributary contributions to a mainstem is the **symmetry ratio**, which describes the size of a tributary relative to the mainstem at their confluence, in terms of their respective discharges, drainage areas, or channel widths (Roy and Woldenberg, 1986; Rhoads, 1987; Benda, 2008).

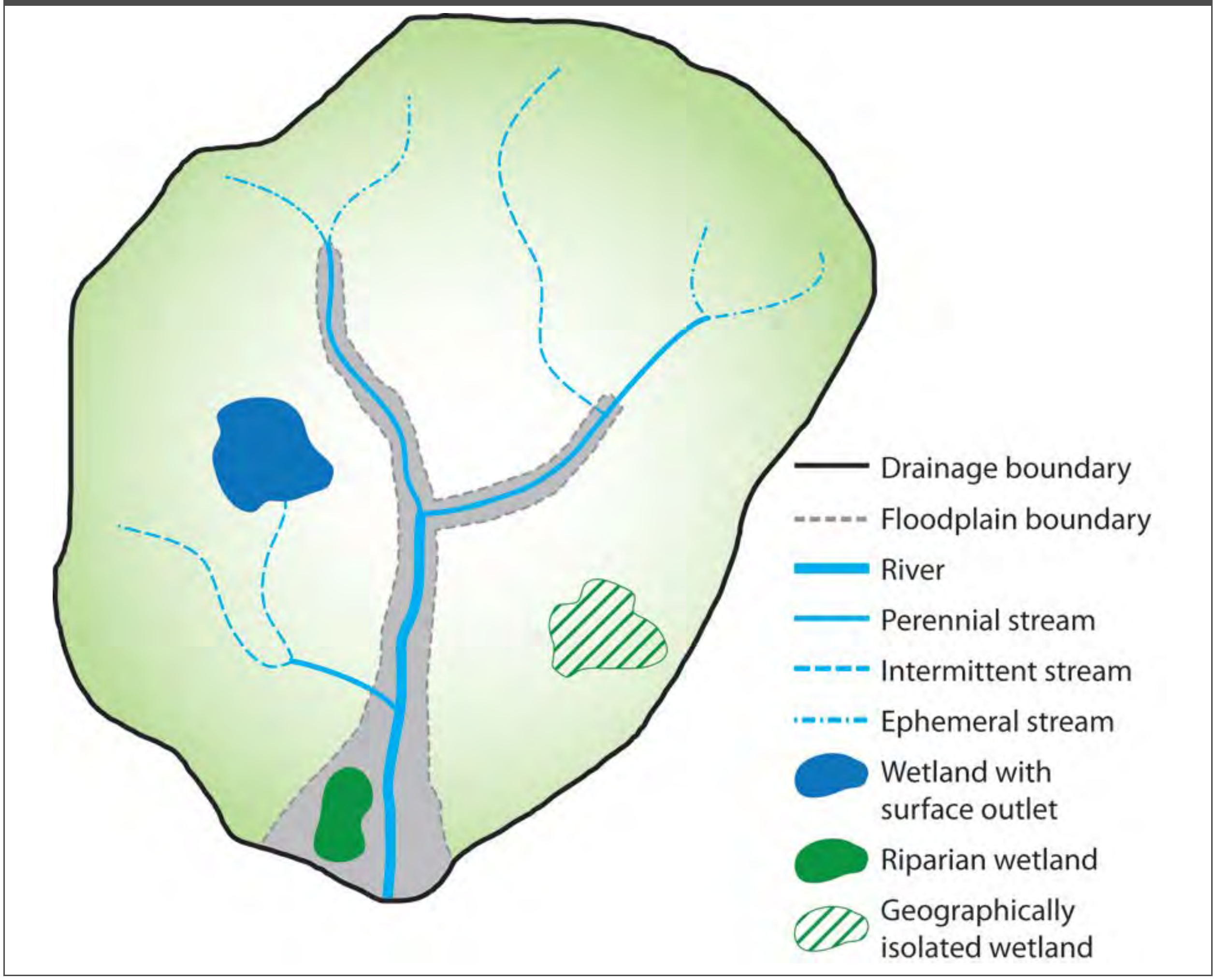
Surface-water hydrologic connectivity within river network channels occurs, in part, through the unidirectional movement of water from channels at higher elevations to ones at lower elevations—that is, hydrologic connectivity exists because water flows downhill. In essence, the river network represents the aboveground flow route and associated subsurface-water interactions, transporting water, energy, and materials from the surrounding watershed to downstream rivers, lakes, estuaries, and oceans (the River Continuum Concept; Vannote et al., 1980).

A **river system** (Figure 2-2) consists of a river network and its entire watershed. It includes all connected or isolated surface-water bodies (e.g., lakes and wetlands), any ground-water flow systems connecting the drainage basin with the river network and surface-water bodies, and terrestrial ecosystems (Stanford and Ward, 1993; Naiman et al., 2005).

Streamflow and the quantity and character of sediment—interacting with watershed geology, terrain, soils and vegetation—shape morphological changes in the stream channel that occur from river network headwaters to lower rivers (Montgomery, 1999; Church, 2002). Headwater streams are typically erosion zones in which sediment from the base of adjoining hillslopes moves directly into stream channels and is transported downstream. As stream channels increase in size and decrease in slope, a mixture of erosion and deposition processes usually is at work. At some point in the lower portions of river networks, sediment deposition becomes the dominant process and floodplains form. **Floodplains** are level areas bordering stream or river channels that are formed by sediment deposition from those channels under present climatic conditions (Figure 2-3). These natural geomorphic features are inundated during moderate to high water events (Leopold, 1994; Osterkamp, 2008). Floodplain and associated river channel forms (e.g., meandering, braided, anastomosing) are determined by interacting fluvial factors, including sediment size and supply, channel gradient, and streamflow (Church, 2002, 2006). **Terraces** are historical floodplains, formed under different climatic conditions, that are no longer connected to the river or stream channel that formed them (Figure 2-3).

Both riparian areas and floodplains are important components of river systems (Figure 2-3). **Riparian areas** are transition zones between terrestrial and aquatic ecosystems that are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect water bodies with their adjoining uplands, and they include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (National Research Council, 2002). Riparian areas often have high biodiversity (Naiman et al., 2005). They occur near lakes and estuarine-marine shorelines and along river networks,

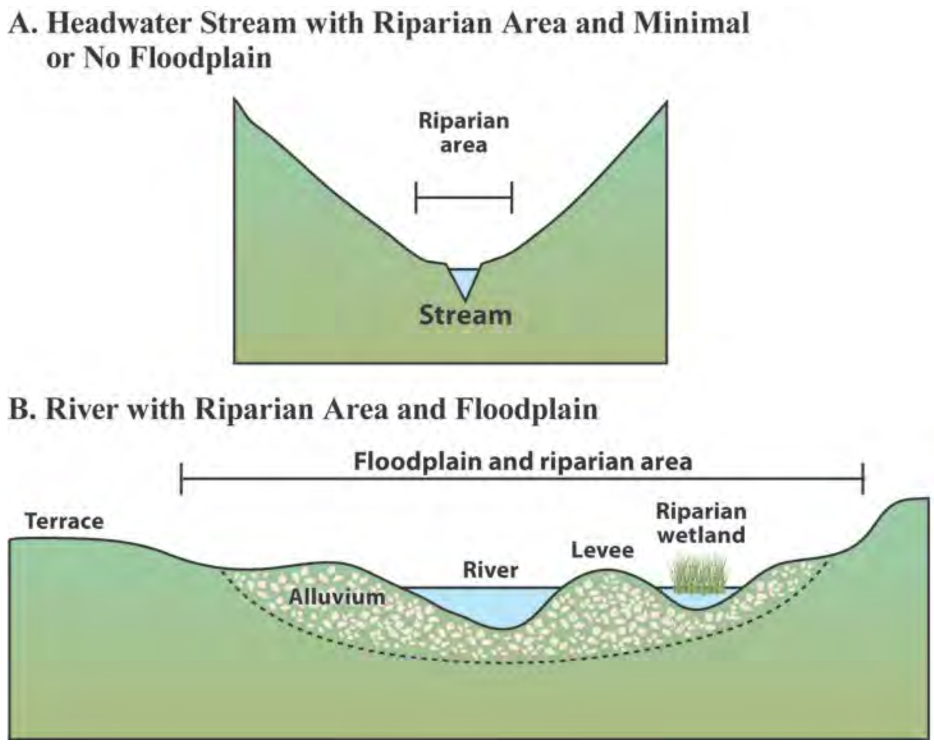
Figure 2-2. Elements of a river system. These elements include: the drainage basin (light green area), river network (rivers and streams), and other water bodies (riparian/floodplain wetlands, lakes, and wetlands in non-floodplain settings). Note that the non-floodplain wetland that lacks a stream outlet also would be considered "geographically isolated" *sensu* Tiner (2003b).



where their width can vary from narrow bands along headwater streams (Figure 2-3A) to broad zones that encompass the floodplains of large rivers (Figure 2-3B).

Floodplains are also considered riparian areas, but not all riparian areas have floodplains. All rivers and streams within river networks have riparian areas, but small streams in constrained valleys are less likely to have floodplains than larger streams and rivers in unconstrained valleys (Figures 2-2 and 2-3). The Federal Emergency Management Agency defines the area that will be inundated by the flood event having a 1% chance of being equaled or exceeded in any given year as the "Special Flood Hazard Area," also referred to as the "100-year floodplain" (https://www.fema.gov/floodplain-management/flood-zones). The 100-year floodplain can but need not coincide with the geomorphic floodplain. Like riparian areas, wetlands are transitional areas between terrestrial and aquatic ecosystems. According to Cowardin et al. (1979), an area is classified as a wetland if it has one or more of the following three

Figure 2-3. Hypothetical cross-sections of (A) a headwater stream and (B) a large river within a river network. The headwater stream in (A) is a constrained reach with a narrow riparian area and no floodplain; the river in (B) has both a riparian area and a floodplain with the same spatial extent. Examples of other common natural floodplain features are shown in (B). The lateral extent of riparian areas varies depending on the criteria used for delineation.



attributes: (1) the area supports predominantly hydrophytes (i.e., water-loving plants) at least periodically; (2) the land has substrate that is predominantly undrained hydric soil; or (3) the land has nonsoil substrate that is saturated with water or covered by shallow water at some time during the growing season of each year. Note that the Cowardin et al. (1979) definition requires only one of these characteristics, in contrast to the federal regulatory definition, which requires all three (33 Code of Federal Regulations 328.3(b); see also USACE, 1987). Thus, as used in this report, a wetland need not meet the federal regulatory definition. Wetlands include areas such as swamps, bogs, fens, marshes, ponds, and pools (Mitsch et al., 2009).

Many classification systems have been developed for wetlands (Mitsch and Gosselink, 2007). These classifications can focus on vegetation, hydrology, hydrogeomorphic characteristics, or other factors (Cowardin et al., 1979; Brinson, 1993; Tiner, 2003a; Comer et al., 2005). Because this report focuses on downstream connectivity (Section 1.3), we consider two landscape settings in which wetlands occur based on directionality of hydrologic flows. Directionality of flow also is included as a component of hydrodynamic setting in the hydrogeomorphic approach (Brinson, 1993; Smith et al., 1995) and as an element of water flowpath in an enhancement of National Wetlands Inventory data (Tiner, 2011). This emphasis on directionality of flow is necessary because hydrologic connectivity plays a dominant role in determining the types of effects wetlands have on downstream waters (Section 2.3.2).

A **non-floodplain wetland setting** is a landscape setting where the potential exists for unidirectional, lateral hydrologic flows from wetlands to the river network through surface water or ground water. Such a setting would include upgradient areas such as hillslopes or upland areas outside of the floodplain. Any wetland setting where water could only flow from the wetland toward a river network would be considered a non-floodplain setting, regardless of the magnitude and duration of flows and of travel times. In this document, we therefore refer to wetlands that occur in these settings as **non-floodplain wetlands**.

A **riparian or floodplain wetland setting** is a landscape setting (e.g., floodplains, most riparian areas, lake and estuarine fringes) that is subject to bidirectional, lateral hydrologic flows. Wetlands in riparian/floodplain settings can have some of the same types of hydrologic connections as those in non-floodplain settings. In addition, wetlands in these settings also have bidirectional flows. For example, wetlands within a riparian area are connected to the river network through lateral movement of water between the channel and riparian area (e.g., through overbank flooding, hyporheic flow). Given our interest in addressing the effects of wetlands on downstream waters (Section 1.1), we have focused in particular on the subset of these wetlands that occur in riparian areas with and without floodplains (collectively referred to hereafter as **riparian/floodplain wetlands**); we generally do not address wetlands at lake and estuarine fringes. **Riparian wetlands** are portions of riparian areas that meet the Cowardin et al. (1979) three-attribute wetland criteria (i.e., having wetland hydrology, hydrophytic vegetation, or hydric soils); **floodplain wetlands** are portions of the floodplain that meet these same criteria.

Our use of landscape setting to define riparian/floodplain wetlands and non-floodplain wetlands is similar to the use of landscape position by Tiner (2011) to supplement the Cowardin et al. (1979) classification. Our use of riparian/floodplain wetland setting is generally consistent with Tiner's estuarine, lotic, and lentic landscape positions, whereas our non-floodplain setting is similar to his terrene category (Tiner, 2011). One important difference is that Tiner (2011) would consider a wetland to be terrene if it were located along a river but not subject to frequent overflow. Given that even infrequent flooding can have profound effects on wetland development and function, we would consider such a wetland to be in a riparian/floodplain setting.

The terms "riparian/floodplain" and "non-floodplain" are meant to describe the landscape setting in which wetlands occur and do not refer to wetland type or class. Many wetland types occur in both settings. For example, a palustrine emergent wetland (Cowardin et al., 1979) could be located outside a floodplain, or it could be located within a floodplain and subject to bidirectional flows. A wetland that is classified as depressional in the hydrogeomorphic approach could have any combination of inlets and outlets or none at all (Smith et al., 1995). The setting for such a wetland would be riparian/floodplain if it had both an input and output channel because water from the stream flows into and affects the wetland. A depressional wetland with a surface outlet and no inlet or with no outlets and inlets, however, would be considered non-floodplain because water could flow downgradient only from the wetland to the river network, and not from a stream to the wetland. Similarly, a riverine wetland (Smith et al., 1995) that is the origin for a stream would be considered non-floodplain if it had no input channel, even though it occurs in a riparian area. In most cases, however, riverine wetlands would be considered riparian/floodplain. Thus, directionality of hydrologic flow is a function of landscape setting and cannot necessarily be determined from wetland class.

A major consequence of the two different landscape settings is that waterborne materials can be transported only from the wetland to the river network for a non-floodplain wetland, whereas waterborne materials can be transported from the wetland to the river network and from the river network to the wetland for a riparian/floodplain wetland. In the latter case, there is a mutual, interacting effect on the structure and function of both the wetland and river network. In contrast, a non-floodplain wetland can affect a river through the transport of waterborne material, but the opposite is not true. Note that we limit our use of riparian/floodplain and non-floodplain landscape settings to describe the direction of hydrologic flow; the terms cannot be used to describe directionality of geochemical or biological flows. For example, mobile organisms can move from a stream to a non-floodplain wetland (e.g., Subalusky et al., 2009a; Subalusky et al., 2009b). In Alaska, transport of live salmon or their carcasses from streams to riparian areas by brown bears (*Ursus arctos*) account for more than 20% of riparian nitrogen budgets (Helfield and Naiman, 2006). Although this example is in a riparian/floodplain setting, it shows how geochemical fluxes can be decoupled from hydrologic flows.

Both non-floodplain and riparian/floodplain wetlands can include **geographically isolated wetlands**, or wetlands completely surrounded by uplands (Tiner, 2003b). These wetlands have no apparent surface-water outlets, but can hydrologically connect to downstream waters through spillage or ground water. We define an **upland** as any area not meeting the Cowardin et al. (1979) three-attribute wetland criteria, meaning that uplands can occur in both terrestrial and riparian areas. Thus, a wetland that is located on a floodplain but is surrounded by upland would be considered a geographically isolated, riparian/floodplain wetland that is subject to periodic inundation from the river network. Although the term "geographically isolated" could be misconstrued as implying functional isolation, the term has been defined in the peer-reviewed literature to refer specifically to wetlands surrounded by uplands. Furthermore, the literature explicitly notes that geographic isolation does not imply functional isolation (Leibowitz, 2003; Tiner, 2003b). Discussion of geographically isolated wetlands is essential because hydrologic connectivity (an element of connectivity, which is the focus of this document) is generally difficult to characterize for these wetlands. The difficulty arises because hydrologic monitoring or additional information and analyses would be necessary to determine whether surface or subsurface hydrologic connections occur for such wetlands.

2.2.2 River System Hydrology

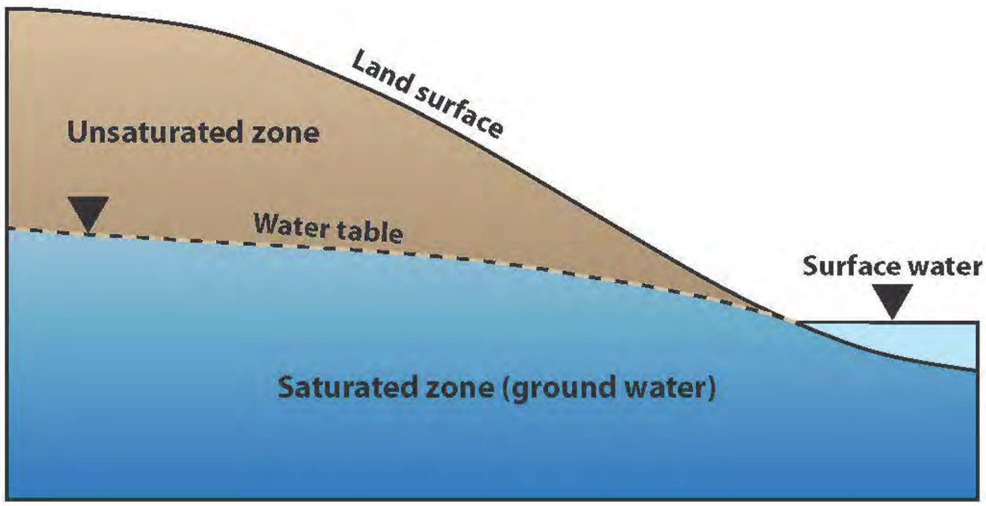
River system hydrology is controlled by hierarchical factors that result in a broad continuum of belowground and aboveground hydrologic flowpaths connecting river basins and river networks (Winter, 2001; Wolock et al., 2004; Devito et al., 2005; Poole et al., 2006; Wagener et al., 2007; Poole, 2010; Bencala et al., 2011; Jencso and McGlynn, 2011). At the broadest scale, regional climate interacts with river-basin terrain and geology to shape inherent hydrologic infrastructure that bounds the nature of basin hydrologic flowpaths. Different climate-basin combinations form identifiable hydrologic landscape units with distinct hydrologic characteristics (Winter, 2001; Wigington et al., 2013). Buttle (2006) posited three first-order controls of watershed streamflow generated under specific hydroclimatic conditions: (1) the ability of different landscape elements to generate runoff by surface or subsurface lateral flow of water; (2) the degree of hydrologic linkage among landscapes by which surface and subsurface runoff can reach river networks; and (3) the capacity of the river network itself to convey runoff downstream to the river-basin outlet. River and stream waters are influenced by not only basin-scale or larger ground-water systems, but also local-scale, vertical and lateral hydrologic exchanges between water in channels and sediments beneath and contiguous with river network channels (Ward, 1989; Woessner, 2000; Malard et al., 2002; Bencala, 2011). The magnitude and importance of river-system hydrologic flowpaths at all spatial scales can radically change over time at hourly to yearly temporal scales (Junk et al., 1989; Ward, 1989; Malard et al., 1999; Poole et al., 2006).

Because interactions between ground waters and surface waters are essential processes in rivers, knowledge of basic ground-water hydrology is necessary to understand the interactions between surface and subsurface water and their relationship to connectivity within river systems. Subsurface water occurs in two principal zones: the unsaturated zone and the saturated zone (Figure 2-4; Winter et al., 1998). In the **unsaturated zone**, the spaces between soil, gravel, and other particles contain both air and water. In the **saturated zone**, these spaces are completely filled with water. **Ground water** refers to any water that occurs and flows (**saturated ground-water flow**) in the saturated zone beneath a watershed surface (Winter et al., 1998). Rapid flow (**interflow**) of water can occur through large pore spaces in the unsaturated zone (Beven and Germann, 1982).

Traditionally, geologic formations in which ground water occurs are divided into two major categories: (1) **aquifers**, which are saturated geologic units capable of transmitting significant amounts of water under ordinary hydraulic gradients; and (2) **aquicludes**, which are saturated geologic units that are *not* capable of transmitting significant quantities of water (aquicludes are also referred to as confining layers or confining units; Freeze and Cherry, 1979). Water flow in an aquifer can take various forms: Water can flow in small voids and pores between the aquifer strata (porous media aquifers), in large voids (karst), or in fractures and cracks within the aquifer formation (fractured flow aquifers). Flow differs in its characteristics between the various aquifer types mentioned, yet follows the same basic rule, by which flow occurs from regions of high hydraulic pressure to regions of lower hydraulic pressure, down the pressure gradient (Jones and Mulholland, 2000).

There are two main types of aquifers (Freeze and Cherry, 1979). **Unconfined aquifers** are underlain by a confining unit but remain open to the atmosphere at their top and exchange gases with the environment. The upper saturated horizon in unconfined aquifers is known as the **water table** (Figure 2-4). Complex geologic conditions can lead to more complex distributions of saturated and unsaturated zones. Discontinuous saturated lenses creating **perched water tables** can occur where low permeability layers (e.g., clay) are present in the midst of highly permeable materials such as sand (Freeze, 1971). **Confined aquifers** are bounded by an underlying confining unit and an overlying confining unit and typically lack a direct connection with current surface and atmospheric conditions (Figure 2-5). Water in confined aquifers is often pressurized, and, consequently, water levels in wells

Figure 2-4. Water below the land surface occurs in either the unsaturated or the saturated zone. The upper surface of the saturated zone is the water table. Ground water and ground-water flow occur in the saturated zone. If a surface-water body is connected to the ground-water system, the water table intersects the water body at or near the surface of its shoreline. Modified from Winter et al. (1998).

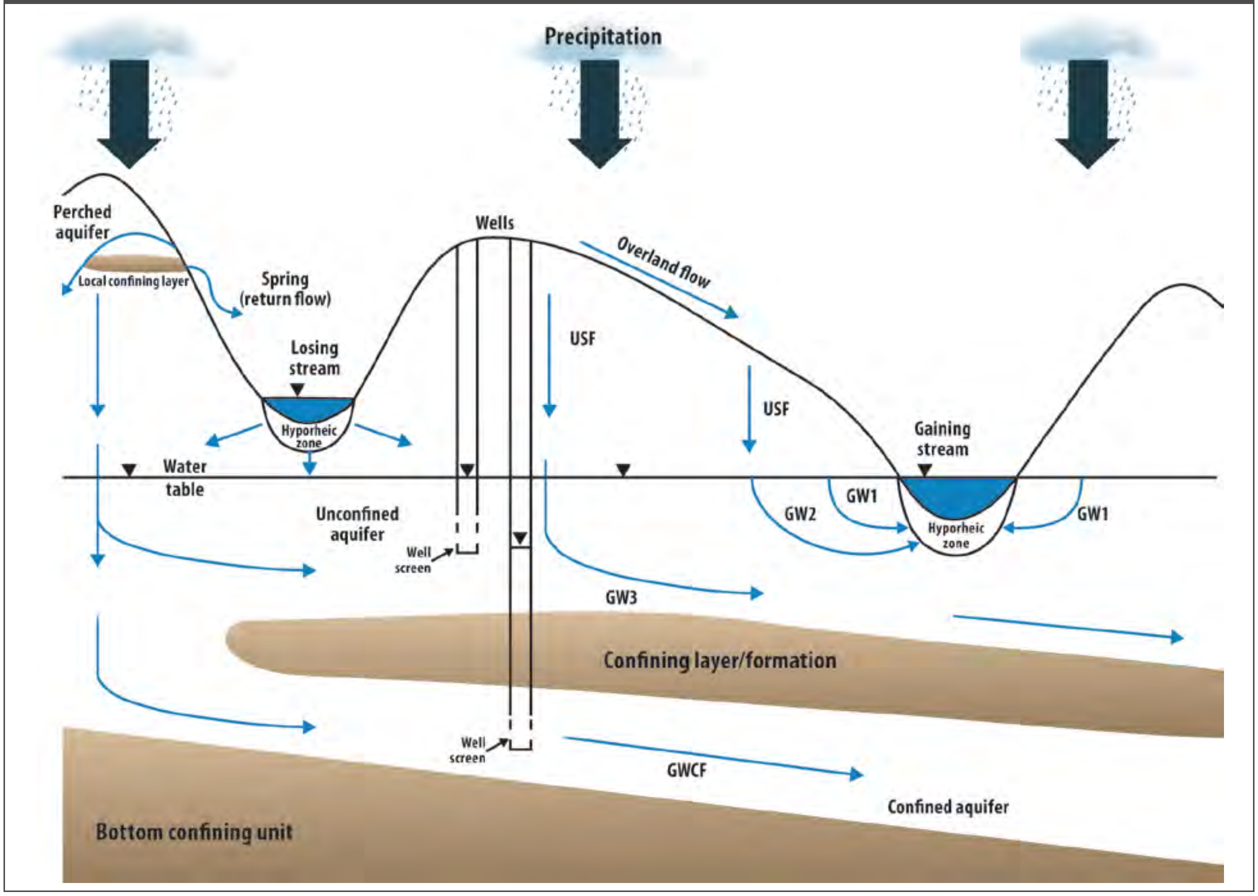


penetrating confined aquifers occur at elevations above the upper confining unit. The surface of the water levels in wells penetrating a confined aquifer is called the **potentiometric surface**. Confined aquifers typically occur deeper below the land surface than unconfined aquifers and generally have less frequent influence on surface waters than unconfined aquifers.

Traditionally, aquifers were identified based solely on their ability to support wells for water production, but in recent years hydrologists studying ground water-surface water interactions have recognized the need for a broader definition that recognizes the importance of low-flow geologic formations to aquatic ecosystems. Payne and Woessner (2010) highlighted the importance of aquifers with varying flow rates on streams and proposed a classification of aquifer flow systems that ranged from high flow to low flow, with low flow aquifers having limited ground-water discharge potential except for small streams and wetlands. Winter et al. (1998) simply defined aquifers as the permeable materials (e.g., soil, rock) through which ground water flows. In this report, we have adopted the Winter et al. (1998) aquifer definition. Unless otherwise noted, our discussion of ground water and aquifers is limited to unconfined systems.

Ground-water **recharge areas** occur where water from land surfaces or surface-water bodies infiltrates and moves into saturated zones. **Discharge areas** occur where water flows from saturated zones into a river network, other water bodies, or onto land surfaces. A **gaining stream (**or **wetland**; also referred to as a **discharge wetland**) within a river network receives inflow of ground water. In this situation, the water table elevation near the stream (or wetland) must be higher than the elevation of the stream water surface. In a **losing stream (**or **wetland**; i.e., **recharge wetland**), water flows from the stream (wetland) to ground water. In this situation, the water table elevation near the stream or wetland is

Figure 2-5. Cross-section showing major hydrologic flowpaths in a regional-scale stream-watershed system. USF = unsaturated flow, GW = ground-water flowpath (saturated flow); GW1, GW2, and GW3 = ground-water flowpaths of varying depth and length. GW1 represents local ground water and GW3 represents regional ground water. GWCF = ground-water flowpath in confined aquifer.



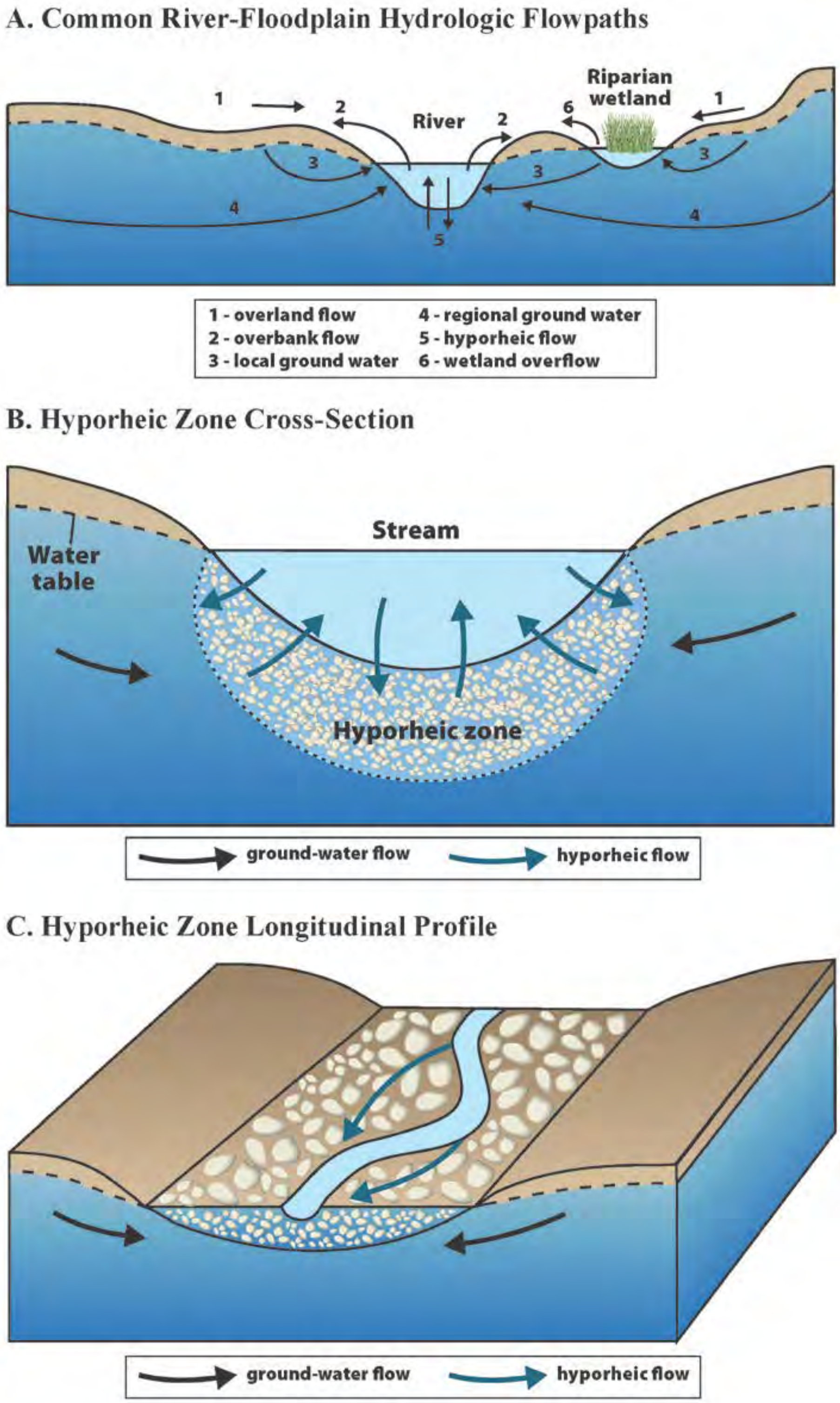
lower than the stream or wetland water surface. Conditions that determine whether streams and wetlands are gaining or losing can change over short periods of time and over short distances within river networks and river basins (Winter et al., 1998; Harrington et al., 2002; Wilson and Guan, 2004; Coes and Pool, 2005; Scanlon et al., 2006; Vivoni et al., 2006; Larned et al., 2008). Overall, however, the volume and sustainability of streamflow within river networks typically depend on contributions from ground water (Winter, 2007), especially in areas with shallow ground-water tables and pervious subsurfaces (de Vries, 1995; Kish et al., 2010).

Ground-water flow systems within river basins can be complex, of varying sizes and depths, and overlie one another (Tóth, 1963; Winter et al., 1998; Haitjema and Mitchell-Bruker, 2005). Although in reality there is a continuum of flowpath lengths that occur within river basins (Bencala et al., 2011), they are commonly grouped into three categories (Figure 2-5). In **local ground-water** flow systems (also referred to as shallow ground-water flow systems), ground water flows from the highest elevations of water tables (water table highs) to nearby lowlands or surface waters (Winter and LaBaugh, 2003). Local ground-water flow is the most dynamic of ground-water flow systems, having the greatest interchange with surface waters. If the depth-to-width ratios of aquifers are sufficiently large, regional flow systems (deepest ground-water flowpaths) also might be present. **Regional ground water** (also referred to as deep ground water) originates from precipitation in distant upland recharge areas and moves long distances, through deep regional-scale aquifers, to river networks (Figure 2-5). The contact times between ground water and subsurface materials are longer for these deep and long flow systems than for local systems. Eventually, deep regional flow systems also discharge to surface waters in the lower portions of river networks where they influence surface-water conditions. An **intermediate ground-water** flow system is one in which ground water flows from a water table high to a lowland that is not immediately adjoining the water table high. Intermediate ground-water flow systems are representative of the wide range of flowpath lengths and depths that occur between local and regional ground-water systems.

Other hydrologic flowpaths are also significant in determining the characteristics of river systems. The most obvious is the downstream water movement within stream or river channels, or **open-channel flow**. River water in stream and river channels can reach riparian areas and floodplains via **overbank flow** (Figure 2-6A), which occurs when floodwaters flow over stream and river channels (Mertes, 1997). **Overland flow** is the portion of streamflow derived from net precipitation that flows over the land surface to the nearest stream channel with (Figure 2-6A; Hewlett, 1982). Overland flow can be generated by several mechanisms. **Infiltration-excess overland flow** occurs when the rainfall rates exceed the infiltration rates of land surfaces (Horton, 1945). **Saturation-excess overland flow** occurs when precipitation inputs cause water tables to rise to land surfaces so that precipitation inputs to the land surfaces cannot infiltrate and flow overland (Dunne and Black, 1970). **Return flow** occurs when water infiltrates, percolates through the unsaturated zones, enters saturated zones, and then returns to and flows over watershed surfaces, commonly at hillslope-floodplain transitions (Dunne and Black, 1970).

Alluvium (Figure 2-3B) comprises deposits of clay, silt, sand, gravel, or other particulate materials that running water has deposited in a streambed, on a floodplain, on a delta, or in a fan at the base of a mountain. These deposits occur near active river systems but also can be found in buried river valleys—the remnants of relict river systems (Lloyd and Lyke, 1995). In this report, we are concerned primarily with alluvium deposited along active river networks. Commonly, alluvium is highly permeable, creating an environment conducive to ground-water flow. **Alluvial ground water** (typically a mixture of river water and local, intermediate, and regional ground water) moves through the alluvium. Together, the alluvium and alluvial ground water comprise **alluvial aquifers**. Alluvial aquifers are closely associated with floodplains and have high levels of **hyporheic exchange** (Stanford and Ward, 1993; Amoros and Bornette, 2002; Poole et al., 2006). Hyporheic exchange occurs when water moves from stream or river into alluvial deposits and then returns to the channels (Figures 2-6B and 2-6C; Bencala, 2005; Leibowitz et al., 2008). Hyporheic exchange allows for the mixing of surface water and ground water. It occurs during both high- and low-flow periods, and typically has relatively horizontal flowpaths at scales of meters to tens of meters (Bencala, 2005) and vertical flowpaths with depths ranging from centimeters to tens of meters (Stanford and Ward, 1988; Woessner, 2000 and references therein).

Figure 2-6. Hyporheic zone flows. (A) Common hydrologic flowpaths by which water flows between watersheds and river networks. (B) and (C) The three-dimensional process of hyporheic flow, or the movement of water from a river or stream to nearby alluvium and then back to the river or stream. Modified from Winter et al. (1998).



Riparian areas and floodplains can have a diverse array of hydrologic inputs and outputs, which, in turn influence riparian/floodplain wetlands. Riparian areas and floodplains receive water from precipitation; overland flow from upland areas; local, intermediate, regional ground water; and hyporheic flows (Figure 2-6A; National Research Council, 2002; Richardson et al., 2005; Vidon et al., 2010). Water flowing over the land surface in many situations can infiltrate soils in riparian areas. If low permeability subsoils or impervious clay layers are present, water contact with the plant root zone is increased and materials in the water are subject to ecological functions such as denitrification before it reaches the stream channel (Section 4.3.2; National Research Council, 2002; Naiman et al., 2005; Vidon et al., 2010).

The relative importance of the continuum of hydrologic flowpaths among river systems varies, creating streams and rivers with different flow duration (or hydrologic permanence) classes (Figures 2-2 and 2-7). **Perennial streams** or stream reaches (Figure 2-7A) typically flow year-round. They are maintained by local or regional ground-water discharge or streamflow from higher in the stream or river network. **Intermittent streams** or stream reaches (Figure 2-7B) flow continuously at certain times of the year (e.g., during certain seasons such as spring snowmelt); drying occurs when the water table falls below the channel bed elevation. **Ephemeral streams** or stream reaches (Figure 2-7C) flow briefly (typically hours to days) during and immediately following precipitation; these channels are above the water table at all times. Streams in these flow duration classes often transition longitudinally, from ephemeral to intermittent to perennial, as drainage area increases and elevation decreases along river networks. Many headwater streams, however, originate from permanent springs and flow into intermittent downstream reaches. At low flows, intermittent streams can contain dry segments alternating with flowing segments. Transitions between flow duration classes can coincide with confluences or with geomorphic discontinuities within the network (May and Lee, 2004; Hunter et al., 2005). Variation of streamflow within river systems occurs in response to **hydrologic events** resulting from rainfall or snowmelt. **Stormflow** is streamflow that occurs in direct response to rainfall or snowmelt (Figure 2-8A), which might stem from multiple ground-water and surface-water sources (Dunne and Leopold, 1978). **Baseflow** is streamflow originating from ground-water discharge or seepage (locally or from higher in the river network), which sustains water flow through the channel between hydrologic events (Figure 2-8A). Perennial streams have baseflow year-round; intermittent streams have baseflow seasonally; ephemeral streams have no baseflow. All three stream types convey stormflow. Thus, perennial streams are more common in areas receiving high precipitation, whereas intermittent and ephemeral streams are more common in the more arid portions of the United States (Figure 2-9; NHD, 2008). The distribution of headwater streams (perennial, intermittent, or ephemeral) as a proportion of total stream length is similar across geographic regions and climates (Figure 2-9C).

Similar to streams, the occurrence and persistence of riparian/floodplain wetland and non-floodplain wetland hydrologic connections with river networks, via surface water (both channelized and nonchannelized) or ground water, can be continuous, seasonal, or ephemeral, depending on the overall hydrologic conditions in the watershed. For example, a non-floodplain wetland might have a direct ground-water connection with a river network during wet conditions but an indirect regional ground-water connection (via ground-water recharge) under dry conditions. Geographically isolated wetlands can be hydrologically connected to the river network via nonchannelized surface flow (e.g., swales or overland flow) or ground water.

Figure 2-7. Hypothetical hydrographs illustrating maximum duration of flow ($D_{max,q}$) for (A) perennial, (B) intermittent, and (C) ephemeral streams. Source: Reprinted from Non-navigable streams and adjacent wetlands: Addressing science needs following the Supreme Court's Rapanos decision, (2008) by Leibowitz et al. with permission of Ecological Society of America.

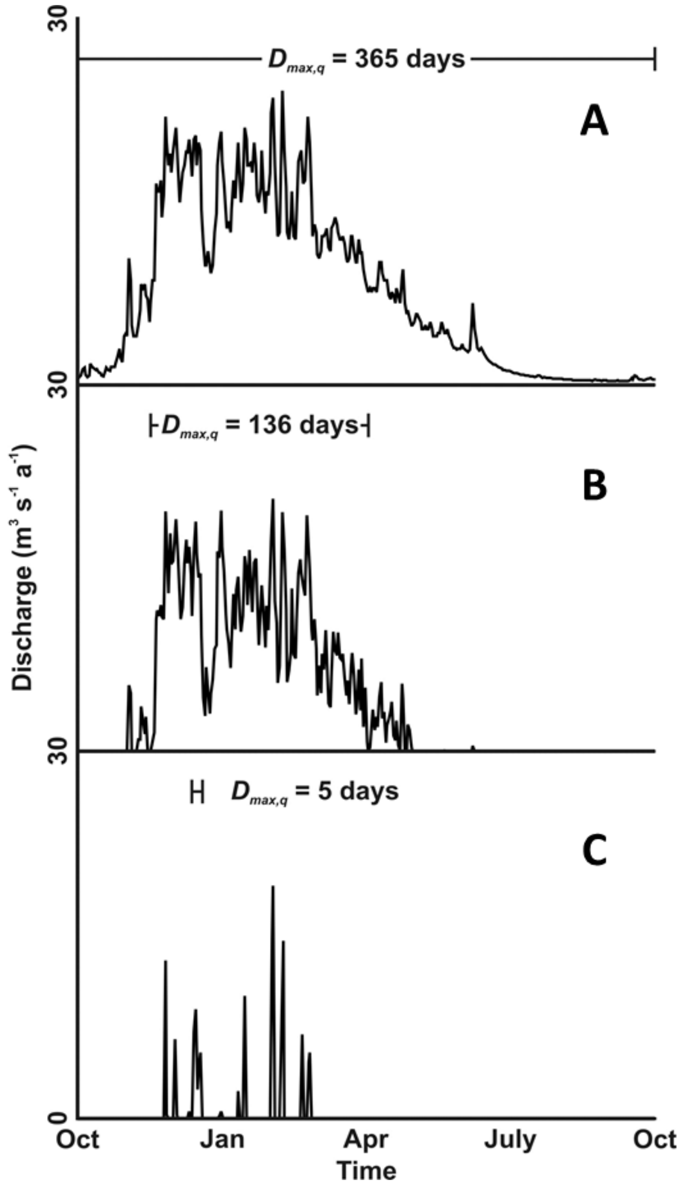


Figure 2-8. (A) Hypothetical hydrograph showing stormflow and baseflow responses to a rainfall event. (B) Expansion and contraction of flowing water in a stream network following a rainfall event. Panel B Source: Reprinted from Subsurface stormflows in the highly permeable forested watersheds of southwestern British Columbia, (1988) by Cheng et al. with permission of Elsevier.

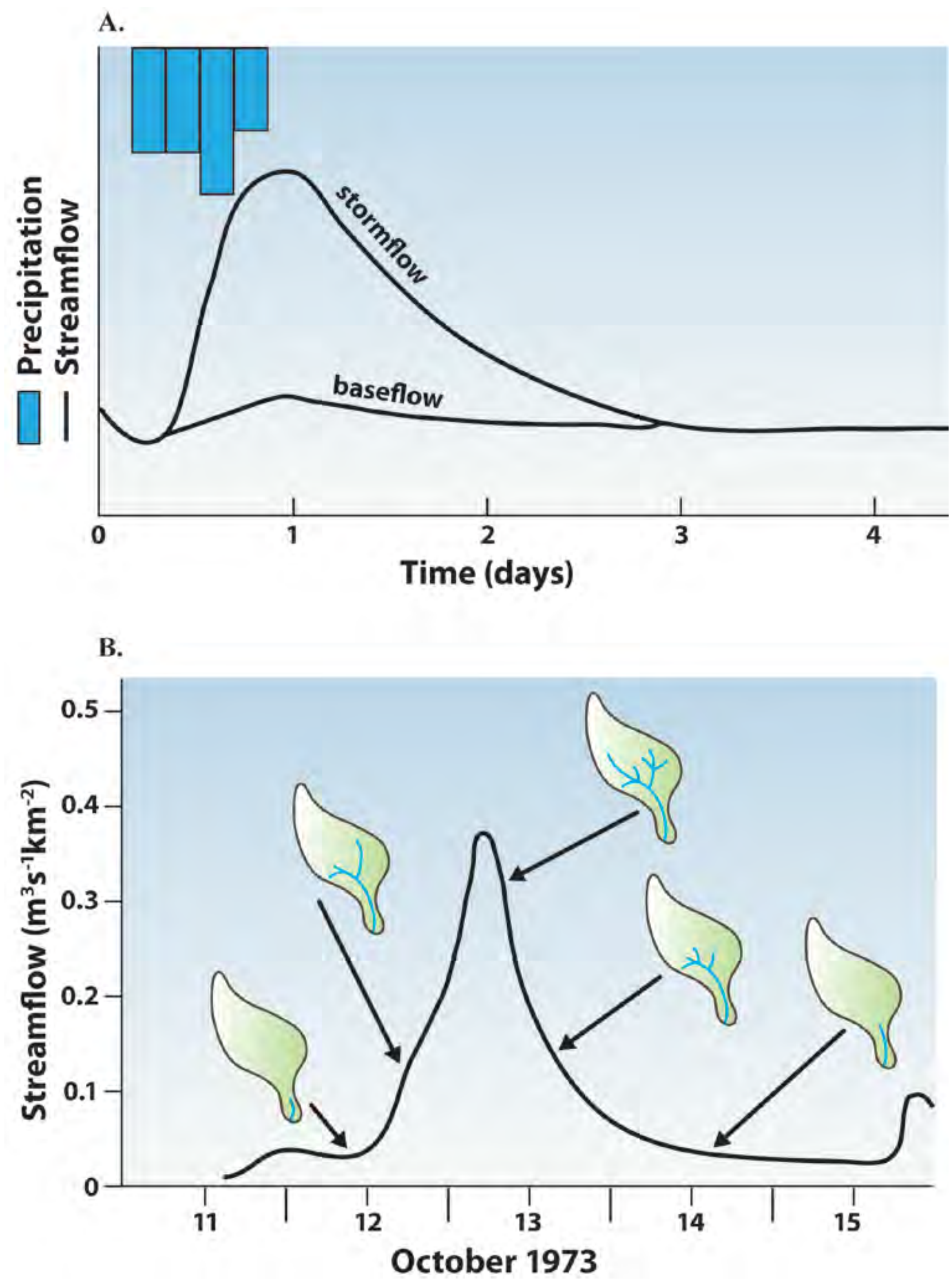
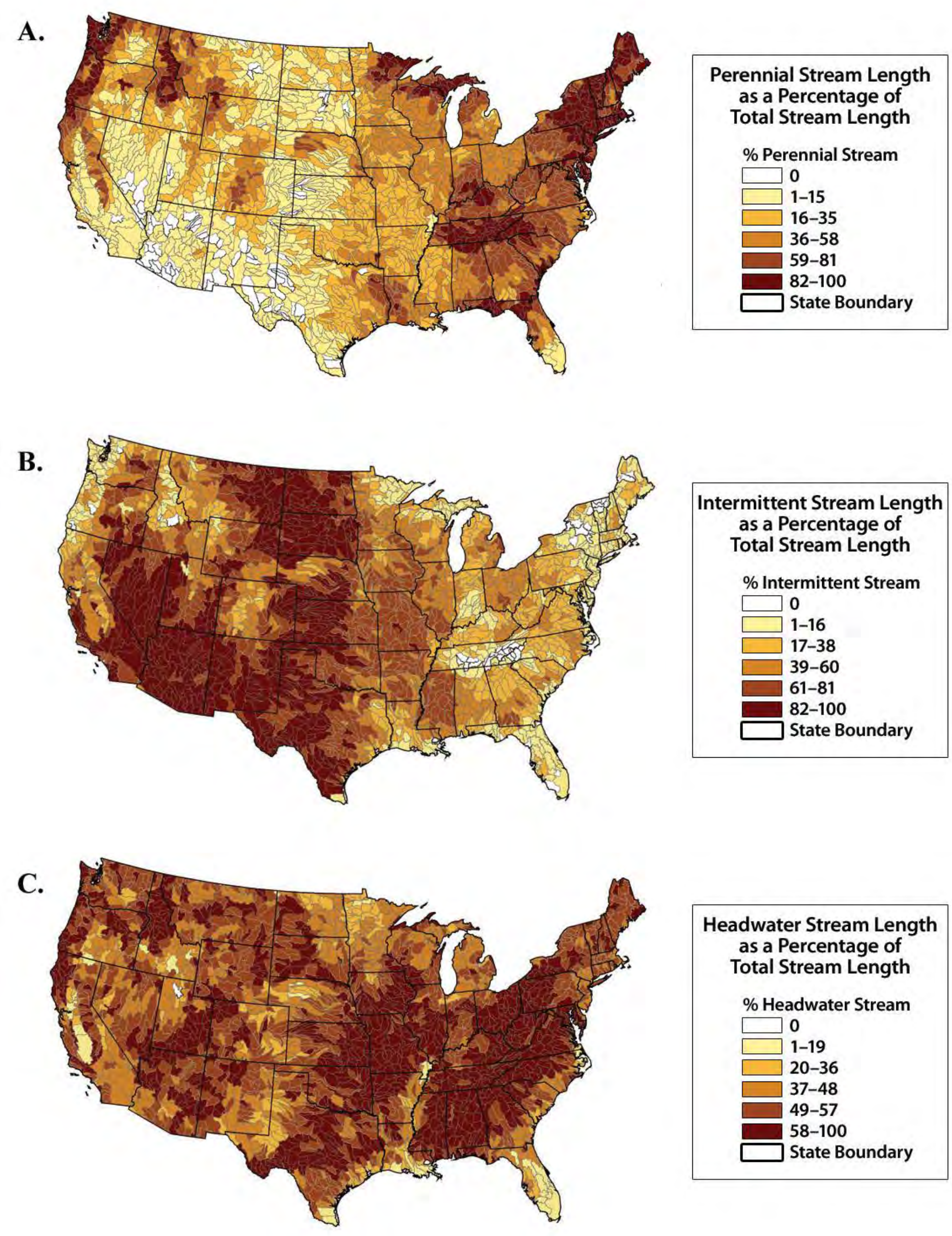


Figure 2-9. Characteristics of U.S. streams by watershed, in terms of percent of total stream length as (A) perennial, (B) intermittent, and (C) headwater streams. Data from the National Hydrography Dataset (NHD) Reach Address Database (RAD) v2.0 at 1:100,000 scale using 8-digit HUC (Hydrologic Unit Code) watersheds. Here, “intermittent” includes streams having intermittent or ephemeral flow. Note that NHD data generally do not capture streams <1.6 km (1 mile) in length, and ranges of color categories are not consistent across maps.



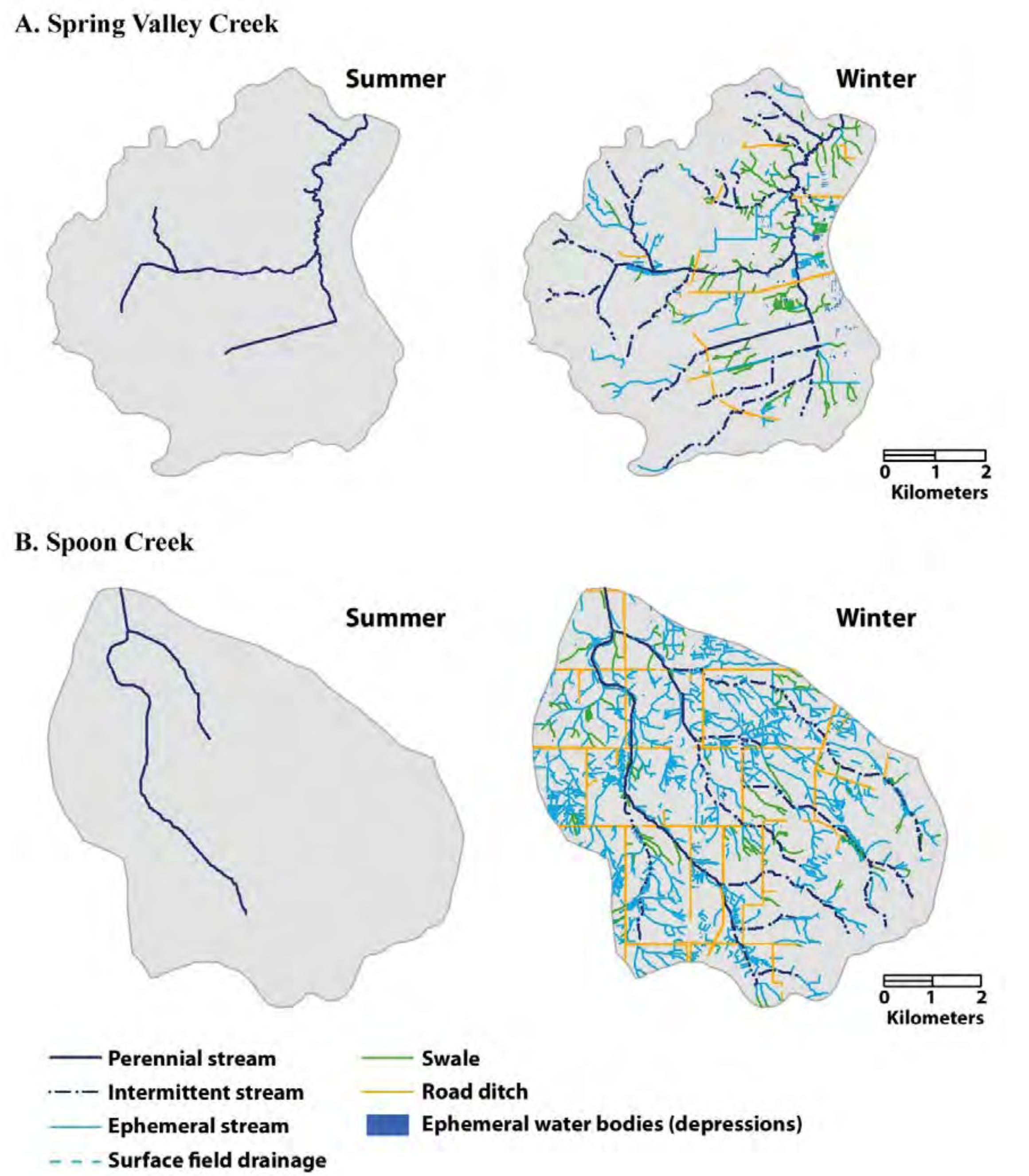
2.2.3 River Network Expansion and Contraction

The portions of river networks with flowing water expand and contract longitudinally (in an upstream-downstream direction) and laterally (in a stream channel-floodplain direction) in response to seasonal environmental conditions and precipitation events (Hewlett and Hibbert, 1967; Gregory and Walling, 1968; Dunne and Black, 1970; Day, 1978; Junk et al., 1989; Hunter et al., 2005; Wigington et al., 2005; Rains et al., 2006; Rains et al., 2008). The longitudinal expansion of channels with flowing water in response to major precipitation events represents a transient increase in the extent of headwater streams. Figure 2-10 shows the expansion of the flowing portion of two stream networks in western Oregon between dry, summer and wet, winter seasons. Intermittent and perennial streams flow during wet seasons, whereas ephemeral streams flow only in response to rainfall or snowmelt. During dry periods, flowing portions of river networks are limited to perennial streams; these perennial portions of the river network can be discontinuous (Stanley et al., 1997; Hunter et al., 2005; Larned et al., 2010) or interspersed with intermittently flowing stream reaches.

The dominant sources of water to a stream can shift during river network expansion and contraction (Malard et al., 1999; McGlynn and McDonnell, 2003; McGlynn et al., 2004; Malard et al., 2006). Rainfall and snowmelt cause a river network to expand in two ways. First, local aquifers expand and water moves into dry channels, which increases the total length of the wet channel (Winter et al., 1998); the resulting intermittent streams will contain water during the entire wet season. Second, stormflow can cause water to enter ephemeral and intermittent streams (Figure 2-8). The larger the rainfall or snowmelt event, the greater the number of ephemeral streams and total length of flowing channels that occur within the river network. Ephemeral flows cease within days after rainfall or snowmelt ends (Figure 2-8B), causing the length of wet channels to decrease and river networks to contract. The flowing portion of river networks further shrinks as the spatial extent of aquifers with ground water in contact with streams contract and intermittent streams dry. In many river systems across the United States, stormflow comprises a major portion of annual streamflow (Hewlett et al., 1977; Miller et al., 1988; Turton et al., 1992; Goodrich et al., 1997; Vivoni et al., 2006). In these systems, intermittent and ephemeral streams are major sources of river water (Section B.5). When rainfall or snowmelt induces stormflow in headwater streams or other portions of the river network, water flows downgradient through the network to its lower reaches. As water moves downstream through a river network, the hydrograph for a typical event broadens with a lower peak (Figure 2-11). This broadening of the hydrograph shape (Figure 2-11A) results from transient storage of water in river network channels and nearby alluvial aquifers (Fernald et al., 2001).

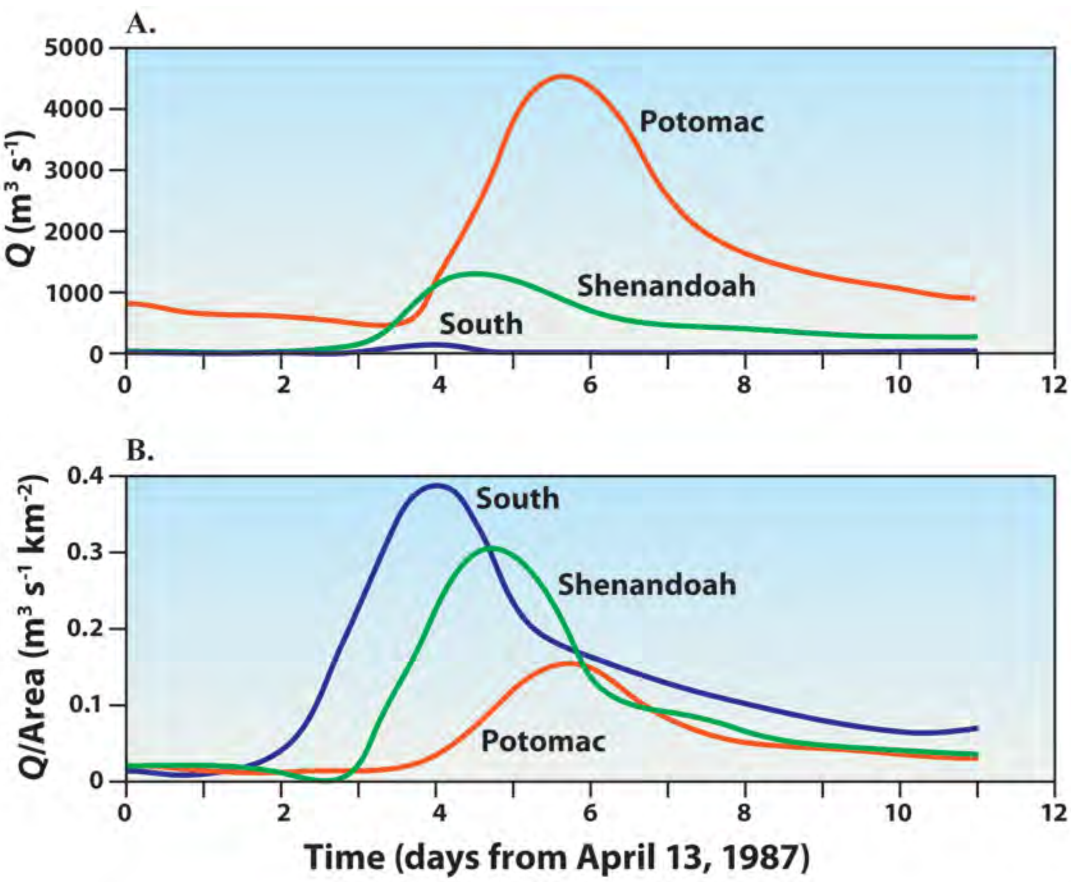
Floodplains and riparian areas can be locations with significant ground-water recharge and discharge (National Research Council, 2002; Naiman et al., 2005). During very large hydrologic events, aggregate flows from headwaters and other tributary streams can result in overbank flooding in river reaches with floodplains; this occurrence represents lateral expansion (Figure 2-12) of the river network (Mertes, 1997). Water from overbank flows can recharge alluvial aquifers, supply water to floodplain wetlands, surficially connect floodplain wetlands to rivers, and shape the geomorphic features of the floodplain

Figure 2-10. Extent and connectivity of streams with flowing water, wetlands, and other water bodies in (A) Spring Valley Creek, OR and (B) Spoon Creek, OR during dry summer (left) and wet winter (right) conditions. Source: Reprinted from Stream network expansion: A riparian water quality factor, (2005) by Wigington et al. with permission of John Wiley & Sons.



(Wolman and Miller, 1960; Hammersmark et al., 2008). Depending on the nature of the hydraulic gradients, ground water within floodplain alluvium can move both parallel and perpendicularly to streams or rivers (National Research Council, 2002) and enter river networks at various discharge points. Bidirectional exchanges of water between ground water and river networks, including hyporheic

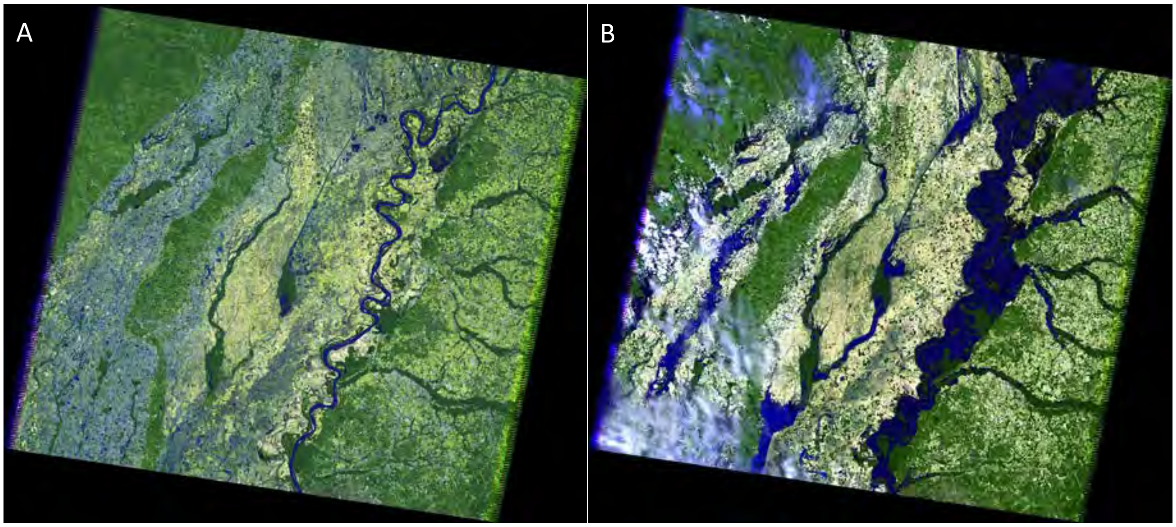
Figure 2-11. Stormflow moves downstream through the river network and interacts with lower stream reaches, floodplains, and alluvial aquifers. (A) Hydrographs for three nested rivers in the Potomac River watershed (drainage area Potomac > Shenandoah > South). (B) Hydrographs for the same three rivers with streamflow normalized by drainage area. Source: Reprinted from Elements of physical hydrology, (1998) by Hornberger et al., with permission of Johns Hopkins University Press.



flow, can occur under a wide range of streamflows, from flood flows to low flows (National Research Council, 2002; Naiman et al., 2005; Vivoni et al., 2006).

The hydrologic connections with river networks fundamentally differ for riparian/floodplain wetlands and non-floodplain wetlands. Riparian/floodplain wetlands can have bidirectional, lateral hydrologic connections to the river network, either through overbank flooding (i.e., lateral expansion of the network) or hyporheic flow, in addition to unidirectional flows from upland and ground-water sources (Figure 2-6A). In contrast, hydrologic connections between non-floodplain wetlands and river networks originate via surface-water spillage or ground-water flow when water inputs exceed evapotranspiration and available storage. Although wetlands that serve as origins for streams are riparian, we group them with non-floodplain wetlands because they also have unidirectional flow through their outlet streams. In both cases, the degree of hydrologic connectivity between riparian/floodplain and non-floodplain wetlands and the river network varies with lateral expansion and subsequent contraction.

Figure 2-12. Landsat 5 satellite images of the Mississippi River along the borders of Tennessee, Kentucky, Missouri, and Arkansas on (A) May 12, 2006 and (B) May 10, 2011. Images courtesy of U.S. Geological Survey/National Aeronautics Space Administration.



One factor affecting the lateral distance that overbank flow spreads is preexisting moisture conditions on the floodplain (Mertes, 1997; Naiman et al., 2005). River overbank flow that enters a dry floodplain will spread and then infiltrate the soil (Naiman et al., 2005). If inflows from streams, rainfall, or ground water have water tables elevated to the floodplain surface, water entering the riparian area from overbank flow cannot infiltrate soils. The result is standing water on the floodplain and subsequent movement of water to lower elevations of the floodplain. This water can alter the geomorphology of the floodplain (Hupp and Osterkamp, 1996), be biogeochemically transformed (Section 4.3.2; Naiman et al., 2005), be lost by evaporation, or be transpired by vegetation (Meyboom, 1964). As the river and floodplain water table elevations decrease, surface water on the floodplain can flow back into the river, infiltrate floodplain soils, or evapotranspire.

Many studies have documented the fact that riparian/floodplain wetlands can attenuate flood pulses of streams and rivers by storing excess water from streams and rivers. Bullock and Acreman (2003) reviewed wetland studies and reported that wetlands reduced or delayed floods in 23 of 28 studies. For example, Walton et al. (1996) found that peak discharges between upstream and downstream gaging stations on the Cache River in Arkansas were reduced 10–20% primarily due to floodplain water storage. Locations within floodplains and riparian areas with higher elevations likely provide flood storage less frequently than lower elevation areas.

The interactions of high flows with floodplains and associated alluvial aquifers of river networks are important determinants of hydrologic and biogeochemical conditions of rivers (Ward, 1989; Stanford and Ward, 1993; Boulton et al., 1998; Burkart et al., 1999; Malard et al., 1999; Amoros and Bornette, 2002; Malard et al., 2006; Poole, 2010). Bencala (1993; 2011) noted that streams and rivers are not pipes: They interact with the alluvium and geologic materials adjoining and under channels. In streams or river reaches constrained by topography, significant floodplain and near-channel alluvial aquifer interactions are limited (Figure 2-3A). In reaches with floodplains, however, stormflow commonly supplies water to alluvial aquifers during high-flow periods through the process of **bank storage** (Figure 2-13; Whiting and Pomeranets, 1997; Winter et al., 1998; Chen and Chen, 2003). As streamflow decreases after hydrologic events, the water stored in these alluvial aquifers can serve as another source of baseflow in rivers (Figure 2-13C).

In summary, the extent of wetted channels is dynamic because interactions between surface water in the channel and alluvial ground water, via hyporheic exchange, determine open-channel flow. The flowing portion of river networks expands and contracts in two primary dimensions: (1) longitudinally, as intermittent and ephemeral streams wet up and dry; and (2) laterally, as floodplains and associated alluvial aquifers gain (via overbank flooding, bank storage, and hyporheic exchange) and lose (via draining of alluvial aquifers and evapotranspiration) water. Vertical ground-water exchanges between streams and rivers and underlying alluvium are also key connections, and variations in these vertical exchanges contribute to the expansion and contraction of the portions of river networks with open-channel flow. Numerous studies have documented expansion and contraction of river systems (e.g., Gregory and Walling, 1968); the temporal and spatial pattern of this expansion and contraction varies in response to many factors, including interannual and long-term dry cycles, climatic conditions, and watershed characteristics (Cayan and Peterson, 1989; Fleming et al., 2007).

2.3 Influence of Streams and Wetlands on Downstream Waters

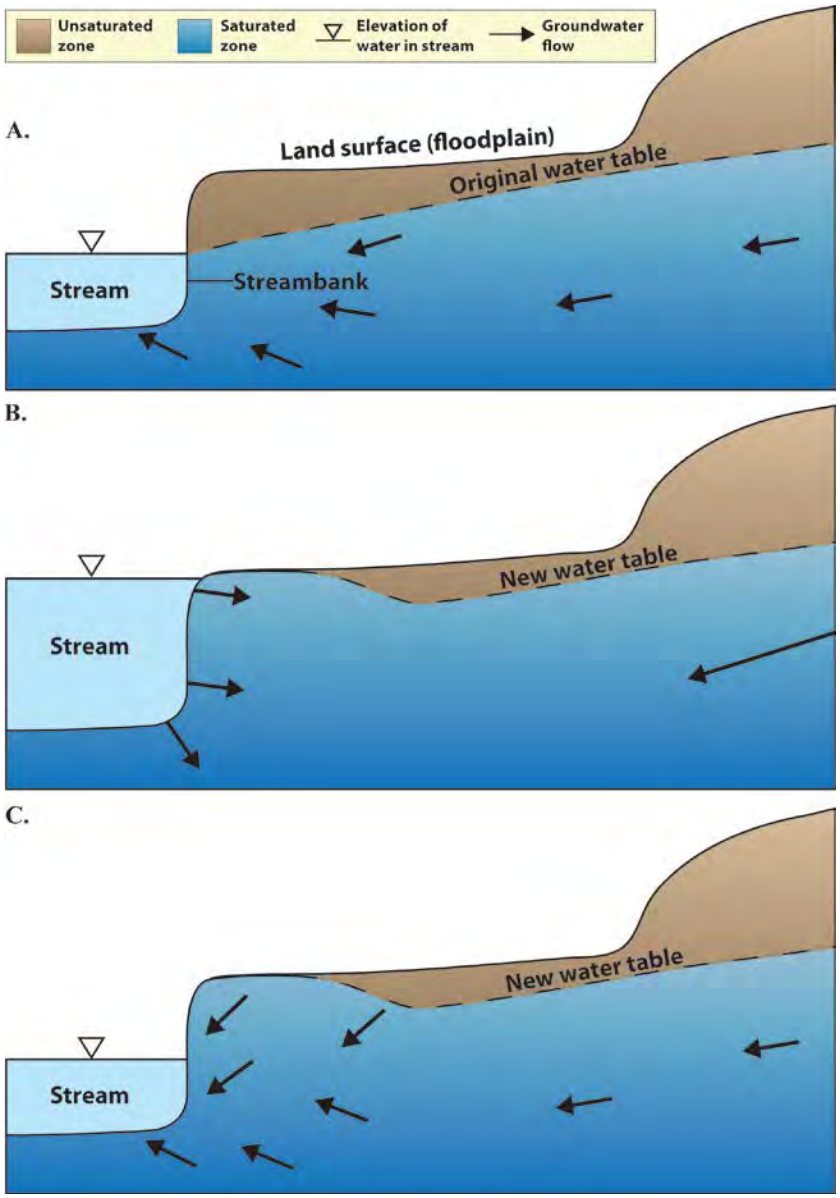
The previous section provided background on river system hydrology. In this section, we present a general overview of how streams and wetlands affect downstream waters, focusing on functions within streams and wetlands and their connectivity to rivers.

The structure and function of rivers are highly dependent on the constituent materials stored in and transported through them. Most of these materials, broadly defined here as any physical, chemical, or biological entity, including water, heat energy, sediment, wood, organic matter, nutrients, chemical contaminants, and organisms, originate outside of the river: They originate from either the upstream river network or other components of the river system, and then are transported to the river by water movement or other mechanisms. Thus, the fundamental way in which streams and wetlands affect river structure and function is by altering fluxes of materials to the river. This alteration of material fluxes depends on two key factors: (1) functions within streams and wetlands that affect material fluxes, and (2) connectivity (or isolation) between streams and wetlands and rivers that allows (or prevents) transport of materials between the systems.

2.3.1 Effects of Streams and Wetlands on Material Fluxes

Streams and wetlands affect the amounts and types of materials that are or are not delivered to downstream waters, ultimately contributing to the structure and function of those waters. Leibowitz et al. (2008) identify three functions, or general mechanisms of action, by which streams and wetlands

Figure 2-13. The direction and magnitude of interactions between surface water and ground water can dramatically change during large hydrologic events, including floods. (A) In a hypothetical stream-floodplain cross-section, ground water flows from the alluvial aquifer to the stream before a major hydrologic event. (B) During the bank-full hydrologic event, surface water moves from the stream and becomes ground water in the alluvial aquifer. (C) After recession of the event, ground water that was stored in the alluvial aquifer during the hydrologic event flows back to the stream. This process is called bank storage, which can sustain baseflow in streams and rivers after the hydrologic event has ended. Modified from Winter et al. (1998).



influence material fluxes into downstream waters: **source**, **sink**, and **refuge**. We have expanded on this framework to include two additional functions: **lag** and **transformation**. These five functions (summarized in Table 2-1) provide a framework for understanding how physical, chemical, and biological connections between streams and wetlands and downstream waters influence river systems.

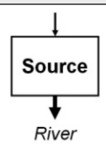
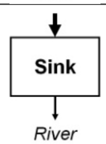
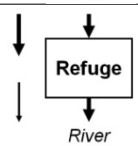
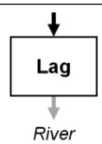
These five functions (Table 2-1) are neither static nor mutually exclusive, and often the distinctions between them are not sharp. A stream or wetland can provide different functions at the same time. These functions can vary with the material considered (e.g., acting as a source of organic matter and a sink for nitrogen) and can change over time (e.g., acting as a water sink when evapotranspiration is high and a water source when evapotranspiration is low). The magnitude of a given function also is likely to vary temporally: For example, streams generally are greater sources of organic matter and contaminants during high flows.

Leibowitz et al. (2008) explicitly focused on functions that benefit downstream waters, but these functions also can have negative effects—for example, when streams and wetlands serve as sources of chemical contamination (Sections 3.4.4, 4.3.3.5, 4.3.3.6; Table 2-1). In fact, benefits need not be linear with respect to concentration; a beneficial material could be harmful at higher concentrations due to nonlinear and threshold effects. For example, nitrogen can be beneficial at lower concentrations but can reduce water quality at higher concentrations. Although here we focus primarily on the effects of streams and wetlands on downstream waters, these same functions can describe effects of downstream waters on streams and wetlands (e.g., downstream rivers can serve as sources of colonists for upstream tributaries).

Because many of these functions depend on import of materials and energy into streams and wetlands, distinguishing between *actual function* and *potential function* is instructive. For example, a wetland with appropriate conditions (e.g., a reducing environment and denitrifying bacteria) is a potential sink for nitrogen (Sections 4.3.3.2 and 4.4.3.2): If nitrogen is imported into the wetland, the wetland can remove it by denitrification. The wetland will not serve this function, however, if nitrogen is not imported. Thus, even if a stream or wetland does not currently serve a function, it has the potential to provide that function under appropriate conditions (e.g., when material imports or environmental conditions change). Although potential functions do not actively affect downstream waters, they can be instrumental in protecting those waters from future impacts. Ignoring potential function also can lead to the paradox that degraded streams and wetlands (e.g., those receiving nonpoint-source nitrogen inputs) receive more protection than less degraded systems (Leibowitz et al., 2008).

Three factors influence the effect that material and energy fluxes from streams and wetlands have on downstream waters: (1) proportion of the material originating from (or reduced by) streams and wetlands relative to the importance of other system components, such as the river itself; (2) residence time of the material in the downstream water; and (3) relative importance of the material. In many cases, the effects on downstream waters need to be considered in aggregate. For example, the contribution of material by a particular stream or wetland (e.g., a specific ephemeral stream) might be small, but the aggregate contribution by an entire class of streams or wetlands (e.g., all ephemeral streams in the river network) might be substantial. Integrating contributions over time also might be necessary, taking into account the frequency, duration, and timing of material export and delivery.

Table 2-1. Functions by which streams and wetlands affect material and energy fluxes to downstream waters. Arrows indicate material and energy imports to and exports from a stream or wetland, in terms of mass or energy; arrow widths represent relative material mass or energy and differences in arrow shades represent timing (lag) or composition (transformation) changes. Imports to streams and wetlands can come from upland terrestrial areas, other streams and wetlands, or from the river itself. Arrows are meant to be illustrative, and do not necessarily represent upstream/downstream relationships. For example, materials and energy can move downstream, upstream, or laterally into streams and wetlands. Examples of commonly exchanged materials and energy include water, heat energy, nutrients, contaminants, sediment, particulate organic matter, organisms, and reproductive propagules; note that exchange of materials and energy between streams and wetlands and downstream systems can result in positive or negative effects on downstream waters.

Function	Definition	Examples
	Net increase in a material or energy flux (exports > imports)	*Streams*: invertebrate production (Wipfli and Gregovich, 2002) *Wetlands*: phytoplankton production from floodplain (Schemel et al., 2004; Lehman et al., 2008)
	Net decrease in a material or energy flux (exports < imports)	*Streams*: upstream fish populations that are not sustainable without net immigration from downstream areas (Woodford and McIntosh, 2010) *Wetlands*: sediment deposition, denitrification (Johnston, 1991)
	Avoidance of a nearby sink function, thereby preventing a net decrease in material or energy flux (exports = imports)	*Streams*: headwaters as summer coldwater refuges (Curry et al., 1997) *Wetlands*: riparian wetlands as aquatic refuges in dryland rivers (Leigh et al., 2010)
	Temporary storage and subsequent release of materials or energy without affecting cumulative flux (exports = imports); delivery is delayed and can be prolonged	*Streams*: delay of downstream peak flows due to bank storage (Burt, 1997); temporary heat storage within the alluvial aquifer (Arrigoni et al., 2008) *Wetlands*: flood attenuation (Bullock and Acreman, 2003)
	Conversion of a material or energy into a different form; the amount of the base material or energy is unchanged (base exports = base imports), but its composition (e.g., mass of the different forms) can vary	*Streams*: conversion of coarse to fine particulate organic matter (Wallace et al., 1995) *Wetlands*: mercury methylation (Galloway and Branfireun, 2004; Selvendiran et al., 2008)

Considering the cumulative material fluxes that originate from a specific stream or wetland, rather than the individual materials separately, is essential in understanding the effects of material fluxes on downstream waters (Section 1.2.3).

In general, the more frequently a material is delivered to a river, the greater its effect. The effect of an infrequently supplied material, however, can be large if the material has a long residence time in the river (Leibowitz et al., 2008). For example, woody debris might be exported to downstream waters infrequently but it can persist in downstream channels. In addition, some materials are more important in defining the structure and function of a river. Using the same example, woody debris can have a large effect on river structure and function because it affects water flow, sediment and organic matter transport, and habitat (Harmon et al., 1986; Gurnell et al., 1995). Another example is salmon migrating to a river: They can serve as a keystone species to regulate other populations and as a source of marine-derived nutrients (Schindler et al., 2005).

2.3.2 Connectivity and Transport of Materials to and from Streams and Wetlands

2.3.2.1 Connectivity and Isolation

The functions discussed above represent general mechanisms by which streams and wetlands influence downstream waters. For these altered material and energy fluxes to affect a river, however, transport mechanisms that deliver (or could deliver) these materials to the river are necessary. **Connectivity** describes the degree to which components of a system are connected and interact through various transport mechanisms; connectivity is determined by the characteristics of both the physical landscape and the biota of the specific system. This definition is related to, but is distinct from, definitions of connectivity based on the actual flow of materials between system components (e.g., Pringle, 2001). That connectivity among river-system components, including streams and wetlands, plays a significant role in the structure and function of these systems is not a new concept. In fact, much of the theory developed to explain how these systems work focuses on connectivity and linkages between system components (e.g., Section 1.2; Vannote et al., 1980; Newbold et al., 1982a; Newbold et al., 1982b; Junk et al., 1989; Ward, 1989; Benda et al., 2004; Thorp et al., 2006).

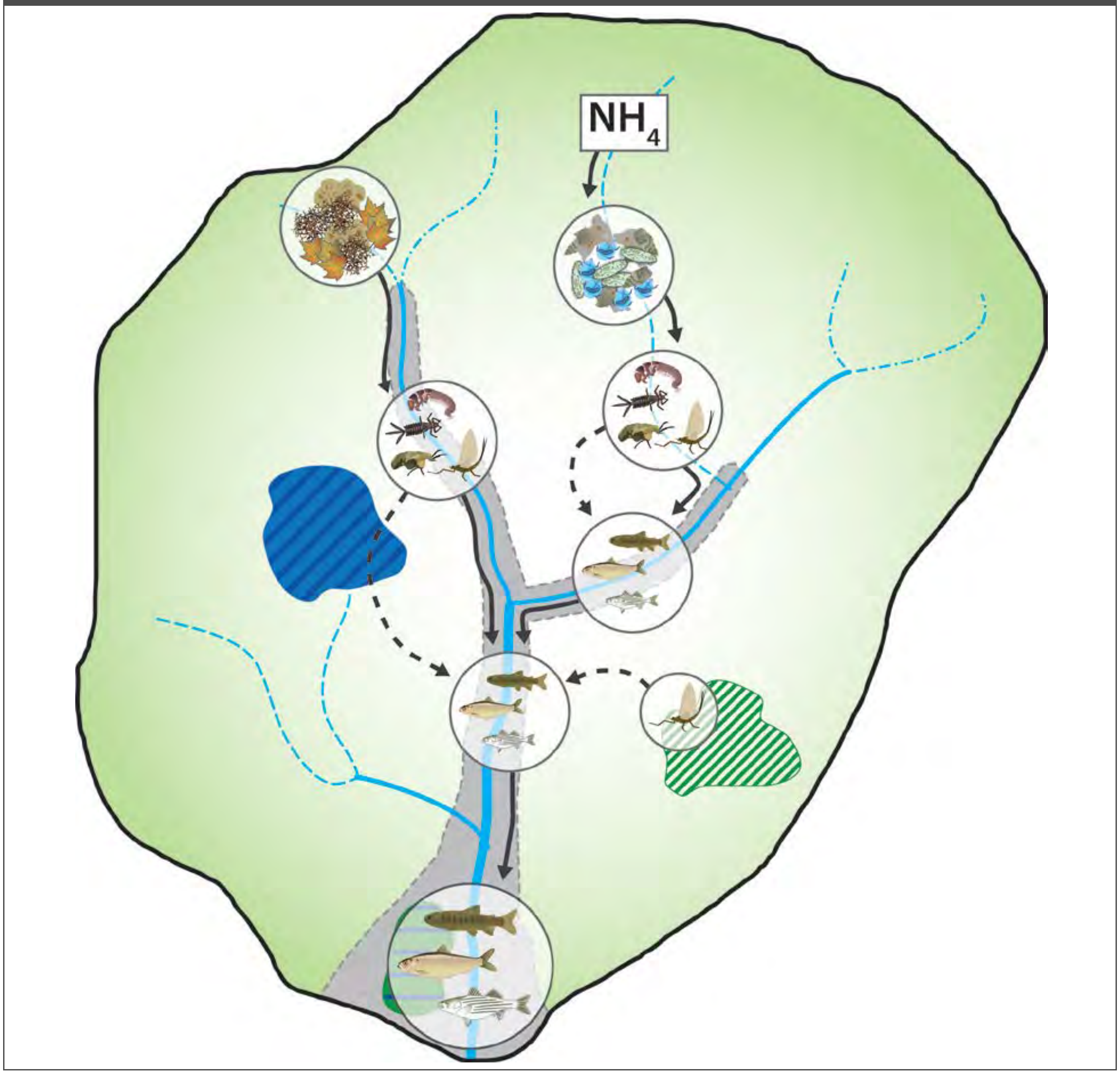
In addition to its central role in defining river systems (Section 2.2.1), water movement through the river system (Figure 2-6) is the primary mechanism providing physical connectivity both within river networks and between those networks and the surrounding landscape (Fullerton et al., 2010). Hydrologic connectivity results from the flow of water, which provides a "hydraulic highway" (Fausch et al., 2002) along which physical, chemical, and biological materials associated with the water are transported (e.g., sediment, woody debris, contaminants, organisms).

Ecosystem function within a river system is driven by interactions between the river system's physical environment and the diverse biological communities living within it (Wiens, 2002; Schroder, 2006). Thus, river system structure and function also depend on biological connectivity among the system's populations of aquatic and semiaquatic organisms. Biological connectivity refers to the movement of organisms, including transport of reproductive materials (e.g., seeds, eggs, genes) and dormant stages, through river systems. These movements link aquatic habitats and populations in different locations through several processes important for the survival of individuals, populations, and species (Sections 3.5, 4.3.4, and 4.4.4). Movements include dispersal, or movement away from an existing population or parent organism; migration, or long-distance movements occurring seasonally; localized movement over an organism's home range to find food, mates, or refuge from predators or adverse conditions; and movement to different habitats to complete life-cycle requirements. At the population and species levels, dispersal and migration contribute to persistence at local and regional scales via colonization of new habitats (e.g., Hecnar and McLoskey, 1996; Tronstad et al., 2007); location of mates and breeding habitats (Semlitsch, 2008); rescue of small populations threatened with local extinction (Brown and Kodric-Brown, 1977); and maintenance of genetic diversity (e.g., Waples, 2010). These movements can result from passive transport by water, wind, or other organisms (e.g., birds, terrestrial mammals); active movement with or against water flow (e.g., upstream fish migration); or active movement over land (for organisms capable of terrestrial dispersal) or through the air (for birds or insects capable of flight; Figure 1-1B). Thus, biological connectivity can occur within aquatic ecosystems or across ecosystem or watershed boundaries, and it can be multidirectional. For example, organisms can move downstream from perennial, intermittent, and ephemeral headwaters to rivers; upstream from estuaries to rivers to headwaters; and laterally between floodplain wetlands, geographically isolated wetlands, rivers, lakes, or other water bodies. Significant biological connectivity can also exist between aquatic and terrestrial habitats (Nakano et al., 1999; Gibbons, 2003; Baxter et al., 2004), but our focus is on connections among components of aquatic systems (Section 1.3).

As noted in Section 2.2.3, streams and rivers are not pipes (Bencala, 1993; Bencala et al., 2011); they provide opportunities for water to interact with internal components (e.g., alluvium, organisms) through the five functions by which streams and wetlands alter material fluxes (Table 2-1). Connectivity between streams and wetlands provides opportunities for material and energy fluxes to be altered sequentially by multiple streams and wetlands as the materials are transported downstream. The aggregate effect of these sequential fluxes determines the proportion of material that ultimately reaches the river. The form of the exported material can change as it moves down the river network (Figure 2-14), however, making quantitative assessments of the importance of individual stream and wetland resources within the entire river system difficult. For example, organic matter can be exported from headwater streams and consumed by downstream macroinvertebrates (Figure 2-14). Those invertebrates can drift farther downstream and be eaten by juvenile fish that eventually move into the mainstem of the river, where they continue to feed and grow.

The assessment of stream and wetland influence on rivers also is complicated by the cumulative time lag resulting from these sequential transformations and transportations. For example, removal of nutrients by streambed algal and microbial populations, subsequent feeding by fish and insects, and release by excretion or decomposition delays the export of nutrients downstream (Figure 2-14).

Figure 2-14. Illustration of the sequential transformation of materials as they move through the river network, via either downstream transport with water flow (solid black arrows) or via aerial or terrestrial movements (dashed black arrows). Here, an ephemeral headwater stream exports organic matter (at left) and an intermittent headwater stream exports ammonium, which is incorporated into algal biomass (at right). Macroinvertebrates consume these basal food resources and transform them into biomass, which in turn is eaten and transformed into fish biomass in both local and downstream reaches.



The opposite of connectivity is **isolation**, or the degree to which transport mechanisms (i.e., pathways between system components) are lacking; isolation acts to reduce material fluxes between system components. Although here we primarily focus on the benefits that connectivity can have on downstream systems, isolation also can have important positive effects on the condition and function of downstream waters. For example, waterborne contaminants that enter a wetland cannot be transported to a river if the wetland is hydrologically isolated from the river, except by nonhydrologic pathways. Increased isolation can decrease the spread of pathogens (Hess, 1996) and invasive species (e.g., Bodamer and Bossenbroek, 2008), and increase the rate of local adaptation (e.g., Fraser et al., 2011). Thus, both connectivity and isolation should be considered when examining material fluxes from streams and wetlands, and biological interactions should be viewed in light of the natural balance between these two factors.

When assessing the effects of connectivity or isolation and the five general functions (sources, sinks, refuges, lags, and transformations; Table 2-1) on downstream waters, dimensions of time and space must be considered. Water or organisms transported from distant headwater streams or wetlands generally will take longer to travel to a larger river than materials transported from streams or wetlands near the river (Section 2.4.2). This can introduce a lag between the time the function occurs and the time the material arrives at the river. In addition, the distribution of streams and wetlands can be a function of their distance from the mainstem channel. For example, in a classic dendritic network, there is an inverse geometric relationship between number of streams and stream order. In such a case, the aggregate level of function could be greater for terminal source streams, compared to higher order or lateral source streams. This is one reason why watersheds of terminal source streams often provide the greatest proportion of water for major rivers. Connectivity, however, results from many interacting factors (Section 2.4.5). For example, the relationship between stream number and order can vary with the shape of the watershed and the configuration of the network (Section 2.4.2). Thus, caution must be exercised when generalizing about these spatial and temporal relationships. Spatial and temporal variability of connectivity is discussed below, and the factors influencing them are considered in Section 2.4.

2.3.2.2 Spatial and Temporal Variability of Connectivity

Connectivity is not a fixed characteristic of a system, but varies over space and time (Ward, 1989; Leibowitz, 2003; Leibowitz and Vining, 2003). Variability in hydrologic connectivity results primarily from the longitudinal (Figures 2-8 and 2-10) and lateral (Figure 2-12) expansion and contraction of the river network and transient connection with other components of the river system (Section 2.2.3). The variability of connectivity can be described in terms of frequency, duration, magnitude, timing, and rate of change (Section 1.2.2).

The expansion and contraction of river networks affect the extent, magnitude, timing, and type of hydrologic connectivity. For example, intermittent and ephemeral streams (Figure 2-7) flow only during wetter seasons (Section 2.4) or during and immediately following precipitation events. Thus, the spatial extent of connectivity between streams and wetlands and rivers increases greatly during these high-flow events because intermittent and ephemeral streams are estimated to account for 59% of the total length of streams in the contiguous United States (Nadeau and Rains, 2007). Changes in the spatial extent of connectivity due to expansion and contraction are even more pronounced in the arid and semiarid Southwest, where more than 80% of all streams are intermittent or ephemeral (Figures 2-9B and B-5; Levick et al., 2008). Expansion and contraction also affect the magnitude of connectivity because larger flows provide greater potential for material transport (e.g., Section 3.3.2).

Besides affecting the spatial extent and magnitude of hydrologic connectivity, expansion and contraction of the stream network also affect the duration and timing of flow in different portions of the network. Perennial streams have year-round connectivity with a downstream river, whereas intermittent streams have seasonal connectivity. The temporal characteristics of connectivity for ephemeral streams depend on the duration and timing of storm events (Figure B-10). Similarly, connectivity between wetlands and downstream waters can range from permanent to seasonal to episodic.

The expansion and contraction of river systems also affect the type of connectivity. For example, during wet periods when input from precipitation can exceed evapotranspiration and available storage, non-floodplain wetlands could have connectivity with other wetlands or streams through surface spillage (Leibowitz and Vining, 2003; Rains et al., 2008). When spillage ceases due to drier conditions, hydrologic connectivity could only occur through ground water (Rains et al., 2006; Rains et al., 2008).

When the flow of water mediates dispersal, migration, and other forms of biotic movement, biological and hydrologic connectivity can be tightly coupled. For example, seasonal flooding of riparian/floodplain wetlands creates temporary habitat that fish, aquatic insects, and other organisms use (Junk et al., 1989; Smock, 1994; Tockner et al., 2000; Robinson et al., 2002; Tronstad et al., 2007). Factors other than hydrologic dynamics also can affect the temporal and spatial dynamics of biological connectivity. Such factors include movement associated with seasonal habitat use (Moll, 1990; Lamoureux and Madison, 1999) and shifts in habitat use due to life-history changes (Huryn and Gibbs, 1999; Gibbons et al., 2006; Subalusky et al., 2009a), quality or quantity of food resources (Smock, 1994), presence or absence of favorable dispersal conditions (Schalk and Luhring, 2010), physical differences in aquatic habitat structure (Grant et al., 2007), or the number and sizes of nearby populations (Gamble et al., 2007). For a specific river system with a given spatial configuration, variability in biological connectivity also occurs due to variation in the dispersal distance of organisms and reproductive propagules (Section 2.4.4; Semlitsch and Bodie, 2003).

Finally, just as connectivity from temporary or seasonal wetting of channels can affect downstream waters, temporary or seasonal drying also can affect river networks. Riverbeds or streambeds that temporarily dry up are used by aquatic organisms that are specially adapted to wet and dry conditions, and can serve as egg and seed banks for several organisms, including aquatic invertebrates and plants (Steward et al., 2012). These temporary dry areas also can affect nutrient dynamics due to reduced microbial activity, increased oxygen availability, and inputs of terrestrial sources of organic matter and nutrients (Steward et al., 2012).

2.4 Factors Influencing Connectivity

Numerous factors affect physical, chemical, and biological connectivity within river systems. These factors operate at multiple spatial and temporal scales, and interact with each other in complex ways to determine where components of a system fall on the connectivity-isolation gradient at a given time. In this section, we focus on four key factors—climate-watershed characteristics, spatial distribution patterns, biota, human activities and alterations. These are by no means the only factors influencing connectivity, but they illustrate how many different variables shape physical, chemical, and biological connectivity. We also examine how interactions among different factors influence connectivity, using as an example wetlands in the prairie pothole region.

2.4.1 Climate-Watershed Characteristics

The movement and storage of water in watersheds varies with climatic, geologic, physiographic, and edaphic characteristics of river systems (Winter, 2001; Wigington et al., 2013). At the largest spatial scale, climate determines the amount, timing, and duration of water available to watersheds and river basins. Key characteristics of water availability that influence connectivity include annual water surplus (precipitation minus evapotranspiration), timing (seasonality) of water surplus during the year that is heavily influenced by precipitation timing and form (e.g., rain, snow), and rainfall intensity.

Annual runoff generally reflects water surplus and varies widely across the United States (Figure 2-15). Seasonality of water surplus during the year determines when and for how long runoff and ground-water recharge occur. Precipitation and water surplus in the eastern United States is less seasonal than in the West (Finkelstein and Truppi, 1991). The Southwest experiences summer monsoonal rains (Section B.5), whereas the West Coast and Pacific Northwest receive most precipitation during the winter season (Wigington et al., 2013). Throughout the West, winter precipitation in the mountains occurs as snowfall, where it accumulates in seasonal snowpack and is released during the spring and summer melt seasons to sustain streamflow during late spring and summer months (Brooks et al., 2012). The flowing portions of river networks tend to have their maximum extent during seasons with the highest water surplus (Section 2.2.3; Figure 2-10), when conditions for flooding are most likely. Typically, the occurrence of ephemeral and intermittent streams is greatest in watersheds with low annual runoff and high water surplus seasonality but also is influenced by watershed geologic and edaphic features (Gleeson et al., 2011).

Rainfall intensity can affect hydrologic connectivity in localities where watershed surfaces have low infiltration capacities relative to rainfall intensities. Infiltration-excess overland flow occurs when rainfall intensity exceeds watershed surface infiltration, and it can be an important mechanism in providing water to wetlands and river networks (Goodrich et al., 1997; Levick et al., 2008). Overland flow is common at low elevations in the Southwest, due to the presence of desert soils with low infiltration capacities combined with relatively high rainfall intensities (Section B.5). The Pacific Northwest has low rainfall intensities, whereas many locations in the Mid-Atlantic, Southeast, and Great Plains have higher rainfall intensities. The prevalence of impermeable surfaces in urban areas can generate overland flow in virtually any setting (Booth et al., 2002).

River system topography and landscape form can profoundly influence river network drainage patterns, distribution of wetlands, and ground-water and surface-water flowpaths. Winter (2001) described six generalized hydrologic landscape forms (Figure 2-16) common throughout the United States. Mountain

Figure 2-15. Map of annual runoff in contiguous United States showing locations of five example streams that illustrate daily runoff patterns and total annual runoff depths. (A) Rapidan River, VA; (B) Noyo River, CA; (C) Crystal River, CO; (D) San Pedro River, AZ; and (E) Metolius River, OR. All data are from http://waterdata.usgs.gov/usa/nwis/sw (downloaded June 27, 2011). Runoff can be conceived as the difference between precipitation and evapotranspiration at the watershed scale. The varied runoff patterns in the five rivers result from divergent climate, geology, and topography.

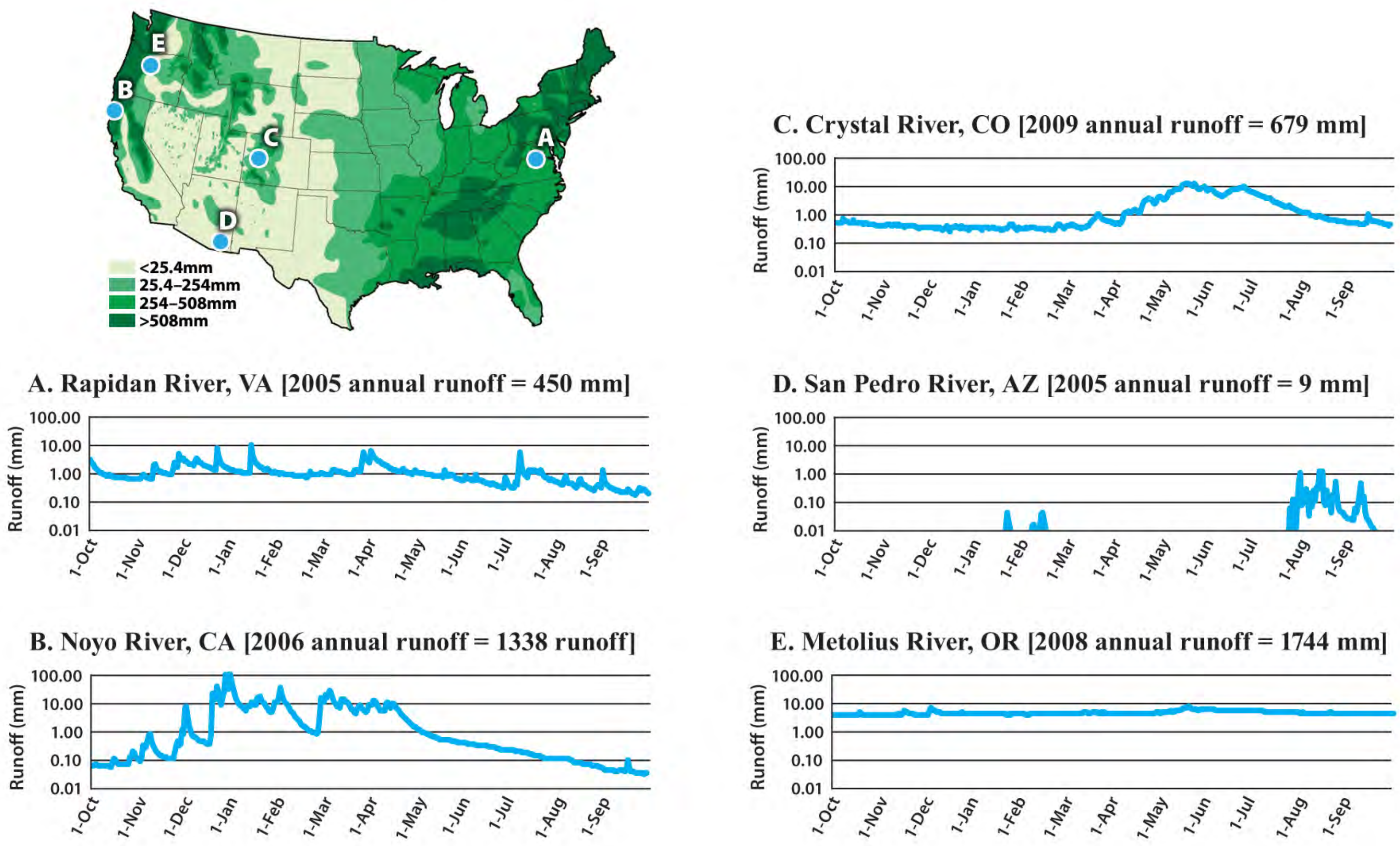
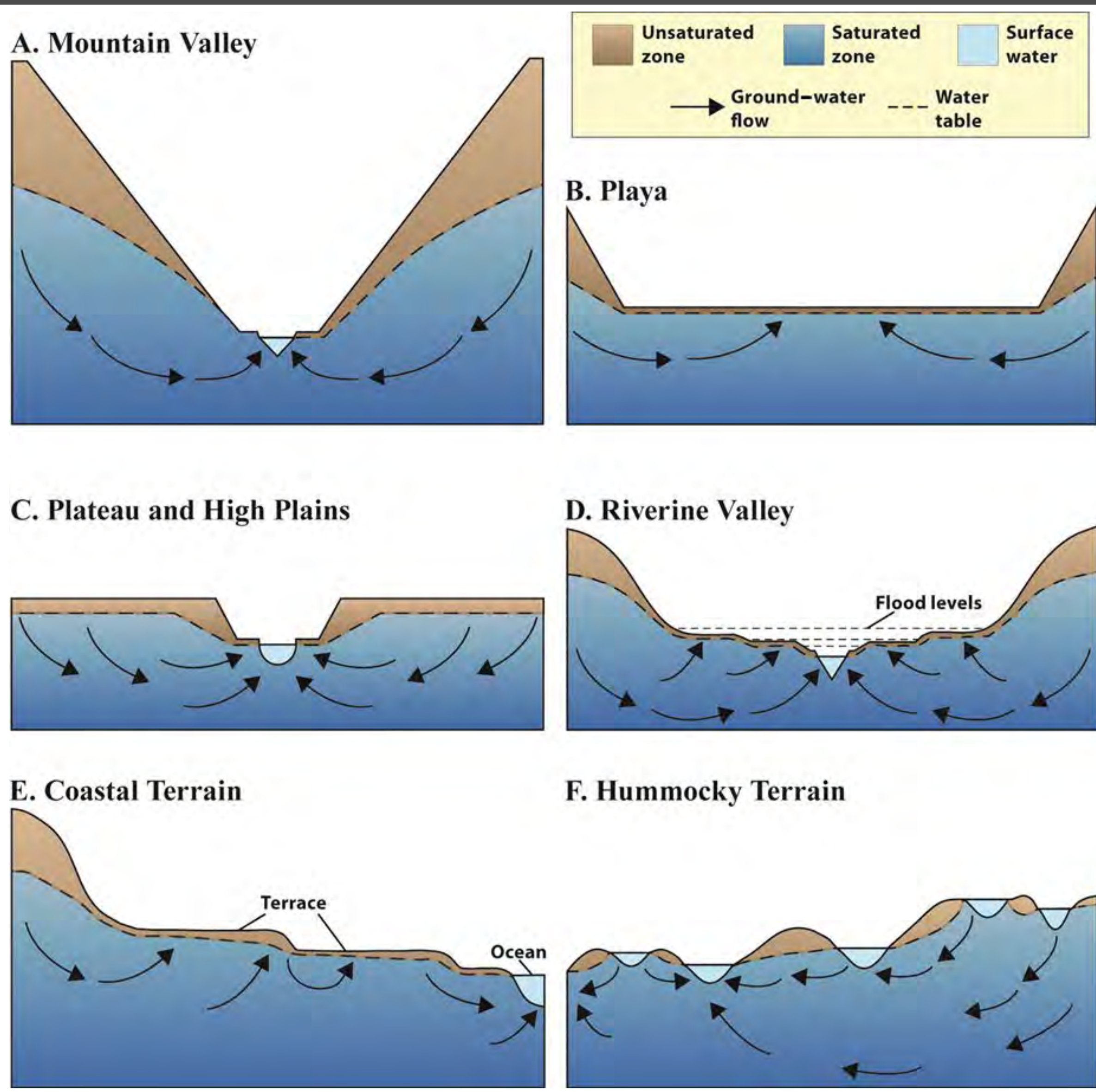


Figure 2-16. Generalized hydrologic landscape forms. (A) Mountain Valley: narrow uplands and lowlands separated by large steep valley sides; (B) Playa: large broad lowland separated from narrow uplands by steeper valley sides (playas and basins of interior drainage); (C) Plateau and High Plains: small narrow lowlands separated from broad uplands by steeper valley sides; (D) Riverine Valley: small fundamental landscape units nested inside broader fundamental landscape unit; (E) Coastal Terrain: small fundamental landscape units nested inside broader fundamental landscape unit (coastal plain with terraces and scarps); and (F) Hummocky Terrain: small fundamental landscape units superimposed randomly on larger fundamental landscape unit. A fundamental hydrologic landscape unit is defined by land-surface form, geology, and climate. Modified from Winter (2001).

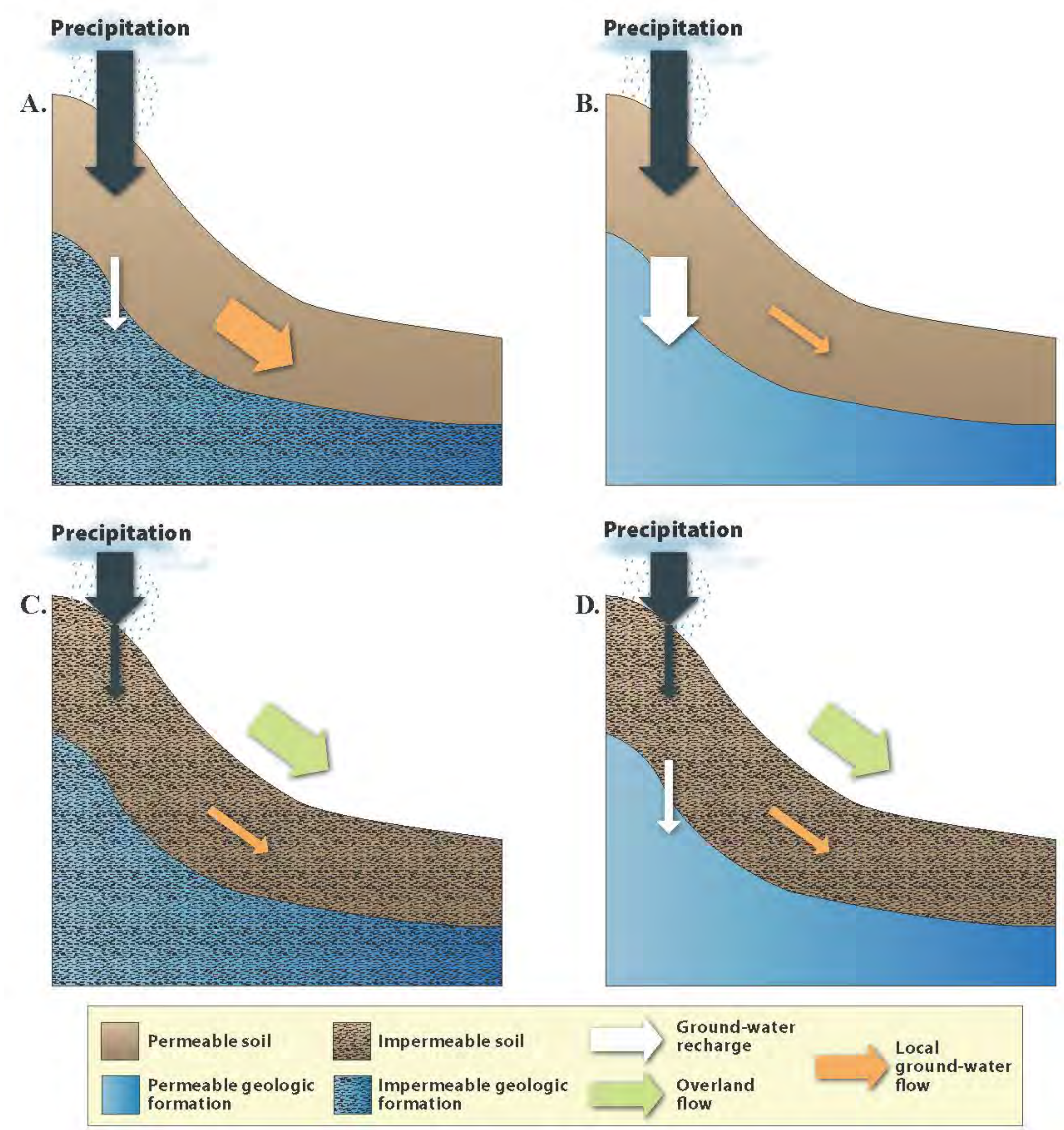


Valleys (Figure 2-16A) and Plateaus and High Plains (Figure 2-16C) have constrained valleys through which streams and rivers flow. The Mountain Valleys form has proportionally long, steep sides with narrow to nonexistent floodplains resulting in the rapid movement of water downslope. In contrast, Riverine Valleys (Figure 2-16D) have extensive floodplains that promote strong surface-water, hyporheic water, and alluvial ground-water connections between wetlands and rivers. Small changes in water table elevations can influence the water levels and hydrologic connectivity of wetlands over extensive areas in this landscape form (Figure 2-16D). Local ground-water flowpaths are especially important in Hummocky Terrain (Figure 2-16F). Constrained valleys, such as the Mountain Valley landform (Figure 2-16A), have limited opportunities for the development of floodplains and alluvial aquifers, whereas unconstrained valleys, such as the Riverine Valley landform (Figure 2-16D), provide opportunities for the establishment of floodplains. Some river basins can be contained within a single hydrologic landscape form, but larger river basins commonly comprise complexes of hydrologic landscape forms. For example, the James River in Virginia, which flows from mountains through the Piedmont to the Coastal Plain, is an example of a Mountain Valley-High Plateaus and Plains-Coastal Terrain-Riverine Valley complex.

Floodplain hydrologic connectivity to rivers and streams occurs primarily through overbank flooding, shallow ground-water flow, and hyporheic flow (Section 2.2). Water-table depth can influence connectivity across a range of hydrologic landscape forms, but especially in floodplains. Rivers and wetlands can shift from losing reaches (or recharge wetlands) during dry conditions to gaining reaches (or discharge wetlands) during wet conditions. Wet, high water-table conditions influence both ground-water and surface-water connectivity. When water tables are near the watershed surface, they create conditions in which swales and small stream channels fill with water and flow to nearby water bodies (Wigington et al., 2003; Wigington et al., 2005). Nanson and Croke (1992) noted that a complex interaction of fluvial processes forms floodplains, but their character and evolution are essentially a product of stream power (the rate of energy dissipation against the bed and banks of a river or stream) and sediment characteristics. They proposed three floodplain classes based on the stream power-sediment characteristic paradigm: (1) high-energy noncohesive, (2) medium-energy noncohesive, and (3) low-energy cohesive. The energy term describes stream power during floodplain formation, and the cohesiveness term depicts the nature of material deposited in the floodplain. The cohesiveness term is also related to the hydraulic properties of alluvial aquifers. Alluvium for Class 1 and 2 floodplains tends to have higher hydraulic conductivity, or a higher rate at which water moves through a saturated, permeable soil or rock layer, than Class 3 floodplains. The higher the hydraulic conductivity of an alluvial aquifer, the greater the exchange rate between the alluvial aquifer and river waters (Whiting and Pomeranets, 1997). In addition, hyporheic and alluvial aquifer exchanges are more responsive to seasonal discharge changes in floodplains with complex topography (Poole et al., 2006).

Within hydrologic landscape forms, soil and geologic formation permeabilities are important determinants of hydrologic flowpaths (Figure 2-17). Permeable soils promote infiltration that results in ground-water hydrologic flowpaths (Figures 2-17A and 2-17B), whereas the presence of impermeable soils with low infiltration capacities is conducive to overland flow (Figures 2-17C and 2-17D). In situations in which ground-water outflows from watersheds or landscapes dominate, the fate of water depends in part on the permeability of deeper geologic strata. The presence of an aquiclude near the watershed surface leads to shallow subsurface flows through soil or geologic materials (Figure 2-17A).

Figure 2-17. Major hydrologic flowpaths for hillslopes with combinations of permeable and impermeable soils and geologic formations. (A) Permeable soil and impermeable underlying geologic formation; (B) permeable soil and permeable underlying geologic formation; (C) impermeable soil and impermeable underlying geologic formation; and (D) impermeable soil and permeable underlying geologic formation. Width of arrow indicates relative magnitude of flow. Note that pavement can be another source of impermeable surfaces and subsequent overland flow in anthropogenically influenced settings.



These local ground-water flowpaths connect portions of watersheds to nearby wetlands or streams (Figure 2-3). Alternatively, if a deep permeable geologic material (an aquifer) is present, water is likely to move farther downward within watersheds and recharge deeper aquifers (Figure 2-17B). The permeability of soils and geologic formations both can influence the range of hydrologic connectivity between non-floodplain wetlands and river networks. For example, a wetland that is the origin of a stream can have a permanent or temporary surface-water connection with downstream waters through a channelized outlet (Figure 2-18A); a wetland can be connected to downstream waters by transient surface-water flows through swales (Figure 2-18B) or by shallow ground-water flows (Figure 2-18C); or a wetland can be hydrologically isolated from downstream waters (Figure 2-18D) because it recharges a deep ground-water aquifer that does not feed surface waters, or it is located in a basin where evapotranspiration is the dominant form of water loss.

The importance of climate-watershed interactions in determining the amount and seasonality of water surpluses, the timing and duration of streamflow, and thus the timing and extent of hydrologic connectivity, is illustrated by annual hydrographs for five rivers in different regions of the United States (Figure 2-15).

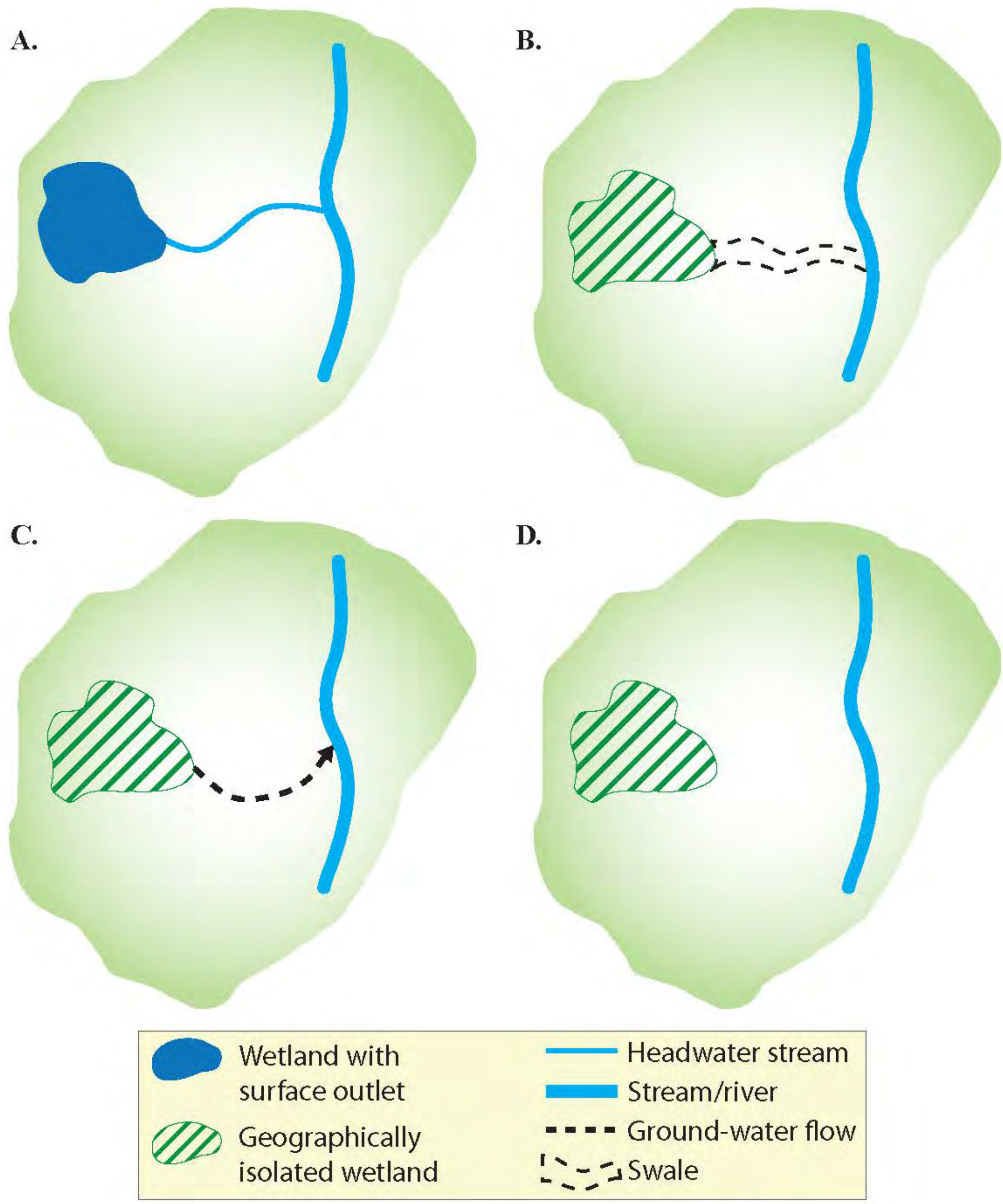
The hydrograph for the Rapidan River in Virginia (Figure 2-15A) illustrates the uniform annual precipitation pattern of the East (with small variations due to increased evapotranspiration in the summer months) interacting with a steep Blue Ridge Mountain watershed comprising metamorphic bedrock with alluvial and colluvial fill in the lower riparian areas (Castro and Hornberger, 1991). Hydrologic events driven by rainfall can occur anytime during the year, but are especially common in winter and spring months; these events result in expansion of the river network as ephemeral streams flow. Baseflow sustains perennial flow over a large part of the network.

Located in a region of steep slopes and impermeable bedrock (Mayer and Naman, 2011), the Noyo River watershed in California (Figure 2-15B) has highly seasonal water surplus because rainfall occurs primarily from November through May and the impermeable bedrock prevents precipitation water from moving to deep ground water. Consequently, runoff timing is similar to precipitation temporal patterns. Total runoff for the basin is high, and baseflow levels are high during the winter and low during the dry summer season. These low baseflow periods create conditions favorable for intermittent flows in streams with significant channel alluvium (Wigington et al., 2006).

The Crystal River of Colorado (Figure 2-15C) drains a glaciated landscape in the upper portion of the Gunnison River in the Colorado Rocky Mountains. It has protracted high flow during the spring that is controlled by the accumulation and melting of snow in the basin's higher elevations during the winter and subsequent melting during spring and summer. This streamflow pattern also promotes the occurrence of intermittently flowing streams due to large water surplus differences between the high-flow and low-flow periods.

Total runoff in the San Pedro River, Arizona is low (Figure 2-15D), and short, intense rainstorms during the summer monsoons commonly drive hydrologic events (Levick et al., 2008). Because a major proportion of water reaching the San Pedro River originates as overland flow to ephemeral streams that ultimately flow to the mainstem river, baseflow is limited (Section B-5). In other San Pedro River

Figure 2-18. Types of hydrologic connections between non-floodplain wetlands and streams or rivers. (A) A wetland connected to a river by surface flow through a headwater stream channel. (B) A wetland connected to a river by surface flow through a nonchannelized swale. Such a wetland would be considered geographically isolated if the swale did not meet the Cowardin et al. (1979) three-attribute wetland criteria. (C) A geographically isolated wetland connected to a river by ground-water flow (flowpath can be local, intermediate, or regional). (D) A geographically isolated wetland that is hydrologically isolated from a river. Note that in A–C, flows connecting the wetland and river may be perennial, intermittent, or ephemeral.



mainstem reaches, ground-water flow from regional and alluvial aquifers supports baseflow (Dickinson et al., 2010). Like the Crystal River, the Metolius River in Oregon (Figure 2-15E) also has snowpack in its higher elevations, but geologic conditions in the watershed alter the climate signal. Meltwaters in the Metolius River flow through long flowpaths in porous bedrock to springs in or near the river (James et al., 2000; Gannett et al., 2001). Although intermittent and ephemeral streams occur in the Metolius basin, most streams are spring-fed and perennial.

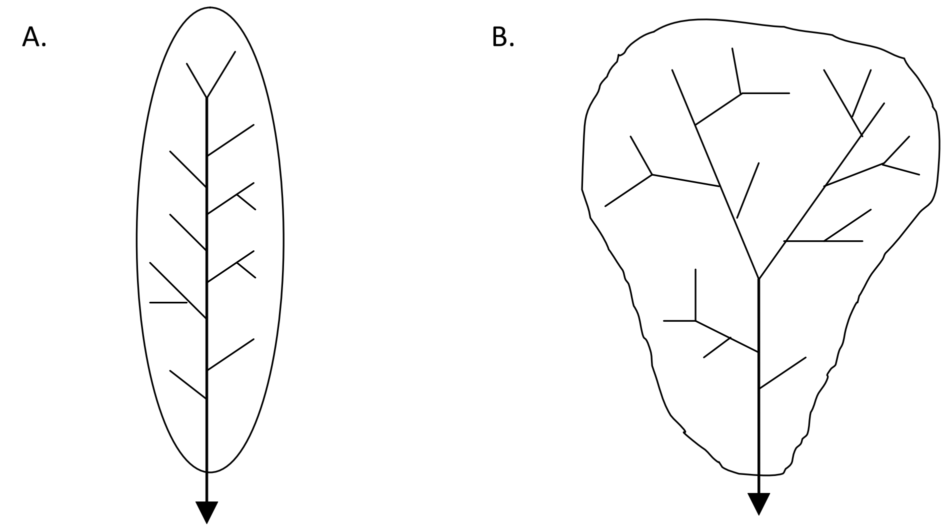
2.4.2 Spatial Distribution Patterns

Climate and watershed characteristics directly affect spatial and temporal patterns of connectivity between streams and wetlands and rivers by influencing the timing and extent of river network expansion and contraction. They also influence the spatial distribution of water bodies within a watershed (e.g., Tihansky, 1999), and in particular, the spatial relationship between those water bodies and the river.

Hydrologic connectivity between streams and rivers can be a function of the distance between the two water bodies (Bracken and Croke, 2007; Peterson et al., 2007). If channels functioned as pipes, this would not be the case, and any water and its constituent materials exported from a stream eventually would reach the river. Because streams and rivers are not pipes (Section 2.2.3; Bencala, 1993), water can be lost from the channel through evapotranspiration and bank storage and diluted through downstream inputs. Thus, material from a headwater stream that flowed directly into the river would be subject to less transformation or dilution. On the other hand, the greater the distance a material travels between a particular stream reach and the river, the greater the opportunity for that material to be altered (e.g., taken up, transformed, or assimilated) in intervening stream reaches; this alteration could reduce the material's direct effect on the river, but it could also allow for beneficial transformations. For example, organic matter exported from a headwater stream located high in a drainage network might never reach the river in its original form, instead becoming reworked and incorporated into the food web (Figure 2-14). Similarly, higher order streams generally are located closer to rivers and, therefore, can have higher connectivity than upstream reaches of lower order. Note that although an individual low-order stream can have less connectivity than a high-order stream, a river network has many more low-order streams, which can represent a large portion of the watershed (Section 3.2); thus, the magnitude of the cumulative effect of these low-order streams can be significant.

The relationship between streams and the river network is a function of basin shape and network configuration. Elongated basins tend to have trellis networks where relatively small streams join a larger mainstem (Figure 2-19A); compact basins tend to have dendritic networks with tree-like branching, where streams gradually increase in size before joining the mainstem (Figure 2-19B). This network configuration describes the incremental accumulation of drainage area along rivers, and therefore provides information about the relative contributions of streams to downstream waters. Streams in a trellis network are more likely to connect directly to a mainstem, compared with a dendritic network. The relationship between basin shape, network configuration, and connectivity, however, is complex. A mainstem in a trellis network also is more likely to have a lower stream order

Figure 2-19. Major types of basin shapes and network configurations. (A) A rectangular basin with trellis network, and (B) a compact basin with a dendritic network.



than one in a dendritic network. For example, the lowest reach in the trellis network in Figure 2-19A is a third-order stream, while that of the dendritic network (Figure 2-19B) is a fourth-order stream.

Distance also affects connectivity between non-floodplain and riparian/floodplain wetlands and downstream waters. Riverine wetlands that serve as origins for lateral source streams that connect directly to a mainstem river have a more direct connection to that river than wetlands that serve as origins for terminal source streams high in a drainage network. This also applies to riparian/floodplain wetlands that have direct surface-water connections to streams or rivers. If geographically isolated non-floodplain wetlands have surface-water outputs (e.g., depressions that experience surface-water spillage or ground-water seeps; Figure 2-18B), the probability that surface water will infiltrate or be lost through evapotranspiration increases with distance. For non-floodplain wetlands connected through ground-water flows, less distant areas are generally connected through shallower flowpaths (Figure 2-5), assuming similar soil and geologic properties. These shallower ground-water flows have the greatest interchange with surface waters (Section 2.2.2) and travel between points in the shortest amount of time. Although elevation is the primary factor determining areas that are inundated through overbank flooding, connectivity with the river generally will be higher for riparian/floodplain wetlands located near the river's edge compared with riparian/floodplain wetlands occurring near the floodplain edge.

Distance from the river network also influences biological connectivity among streams and wetlands. For example, mortality of an organism due to predators and natural hazards generally increases with the distance it has to travel to reach the river network. The likelihood that organisms or propagules traveling randomly or by diffusive mechanisms such as wind will arrive at the river network generally decreases as distance increases.

The distribution of distances between wetlands and river networks depends on both the drainage density of the river network (the total length of stream channels per unit area) and the density of wetlands. Climate and watershed characteristics influence these spatial patterns, which can vary widely. For example, a subset of fens in New York State was located closer to each other, on average, than a subset of Carolina bays at the Savannah River Site: The proportion of wetlands located at distances of 0–100, 100–500, and >500 m was 27, 39, and 35%, respectively, for the fens and 12, 44, and 44% for the Carolina bays, respectively (Bedford and Godwin, 2003; Sharitz, 2003). When interpreting such distributions, however, other factors that affect connectivity (e.g., differences in soils or slope) should be considered.

Figure 2-20 compares the spatial distribution of wetlands and streams to the river network in six different landscape settings. The figure shows landscape settings ranging from no nearby streams and dense small wetlands (Figure 2-20A), to a few nearby streams with high wetland density (Figures 2-20B and 2-20C), to less spatially uniform wetlands (Figure 2-20D), to areas with higher drainage densities and riparian (Figure 2-20E) or larger, more extensive (Figure 2-20F) wetlands. The maps in Figure 2-20 are single examples of these various settings, so they might not be representative. They are useful, however, for illustrating the degree to which landscape setting can affect the interspersion—and thus average distance—between wetlands and the river network, and the large variability that can result. In settings having many wetlands and relatively low drainage density (Figures 2-20B, 2-20C, and 2-20D), the distances between individual wetlands and the stream can vary greatly. In contrast, the distances in areas having a higher drainage density (Figure 2-20E and 2-20F) are shorter and vary less. All factors being equal, wetlands closer to the stream network will have greater hydrologic and biological connectivity than wetlands located farther from the same network.

2.4.3 Biota

Biological connectivity results from the interaction of physical characteristics of the environment—especially those facilitating or restricting dispersal—and species' traits or behaviors, such as life-cycle requirements, dispersal ability, or responses to environmental cues (Section 1.2.2). Thus, the types of biota within a river system are integral in determining the river system's connectivity, and landscape features or species traits that necessitate or facilitate movement of organisms tend to increase biological connectivity among water bodies.

Diadromous fauna (e.g., Pacific and Atlantic salmon, certain freshwater shrimps and snails, American eels), which require both freshwater and marine habitats over their life cycles and therefore migrate along river networks, provide one of the clearest illustrations of biological connectivity. Many of these taxa are either obligate or facultative users of headwater streams (Erman and Hawthorne, 1976; Wigington et al., 2006), meaning that they either require (obligate) or can take advantage of (facultative) these habitats; these taxa thereby create a biological connection along the entire length of the river network. For example, many Pacific salmon species spawn in headwater streams, where their young grow for a year or more before migrating downstream, living their adult life stages in the ocean, and then migrating back upstream to spawn. Many taxa also can exploit temporary hydrologic connections

Figure 2-20. Examples of different landscapes showing interspersion of wetlands and streams or rivers. (A) Prairie potholes within the Missouri Coteau in North Dakota; (B) prairie potholes within the Drift Prairie in North Dakota; (C) playas in Texas; (D) vernal pools in California; (E) bottomland hardwood wetlands in Illinois; and (F) Carolina bays in North Carolina. Note all maps are at the same scale. Wetlands smaller than the minimum mapping unit (currently 0.4 ha) might not appear on maps. Source: National Wetlands Inventory Wetlands Mapper (http://www.fws.gov/wetlands/Data/Mapper.html).

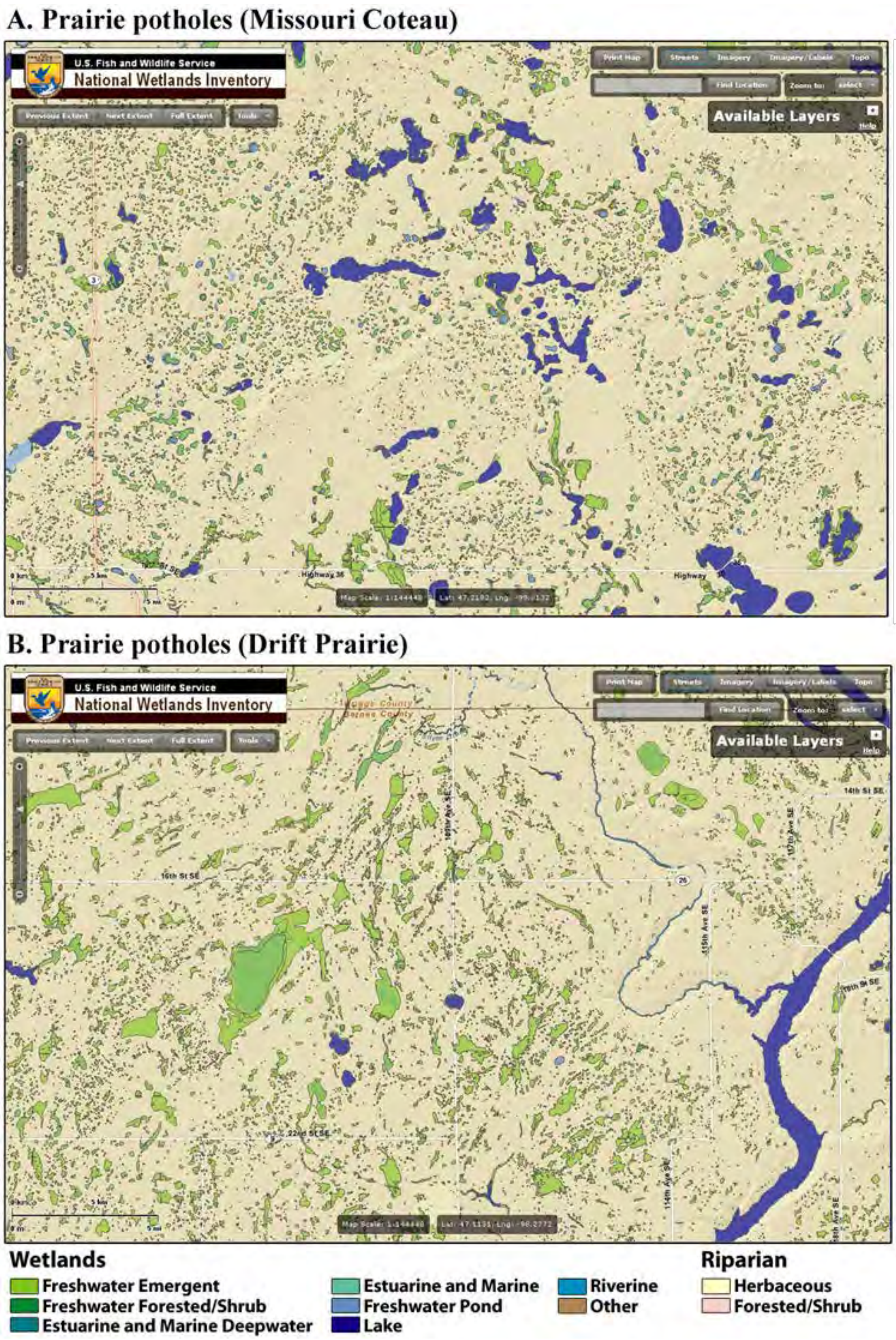
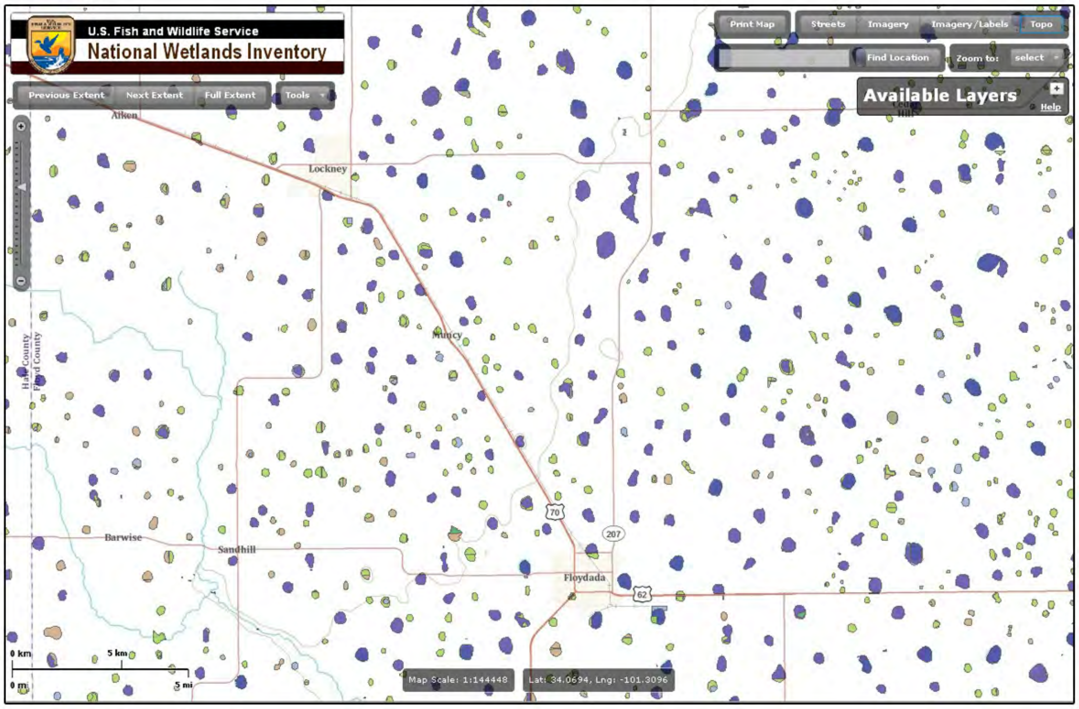


Figure 2–20. Examples of different landscapes showing interspersion of wetlands and streams or rivers (continued).

C. Playa



D. Vernal pools

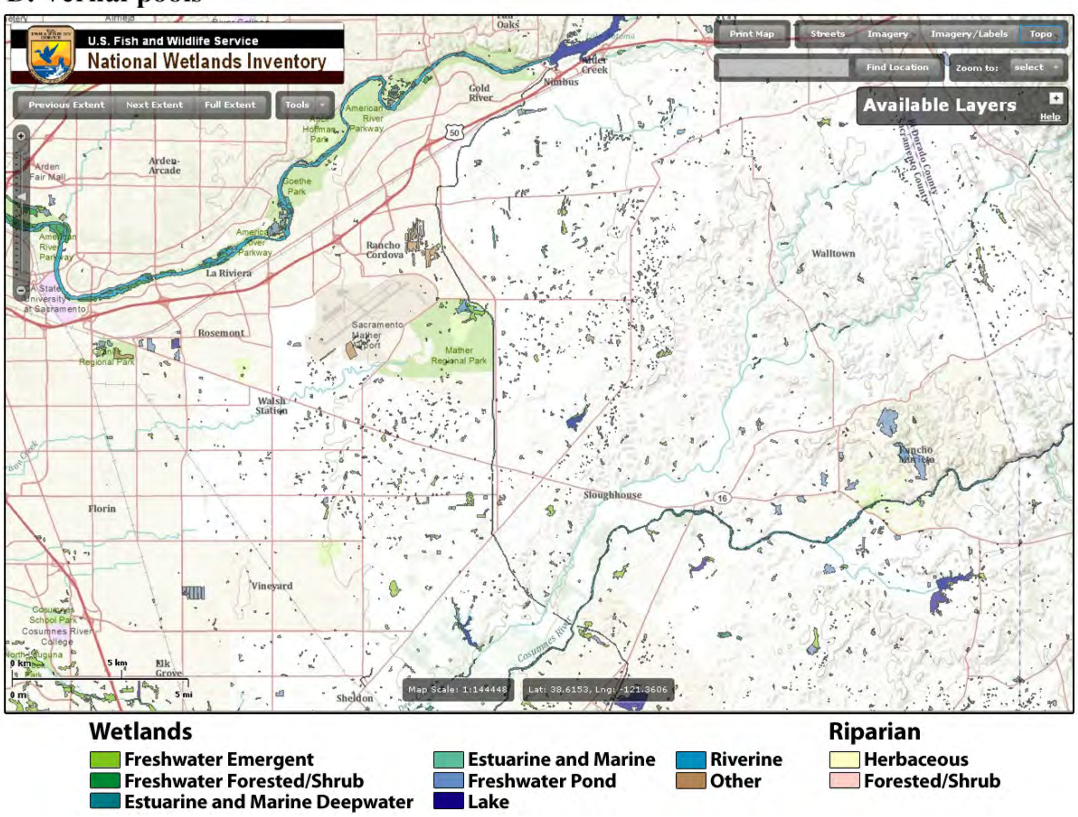
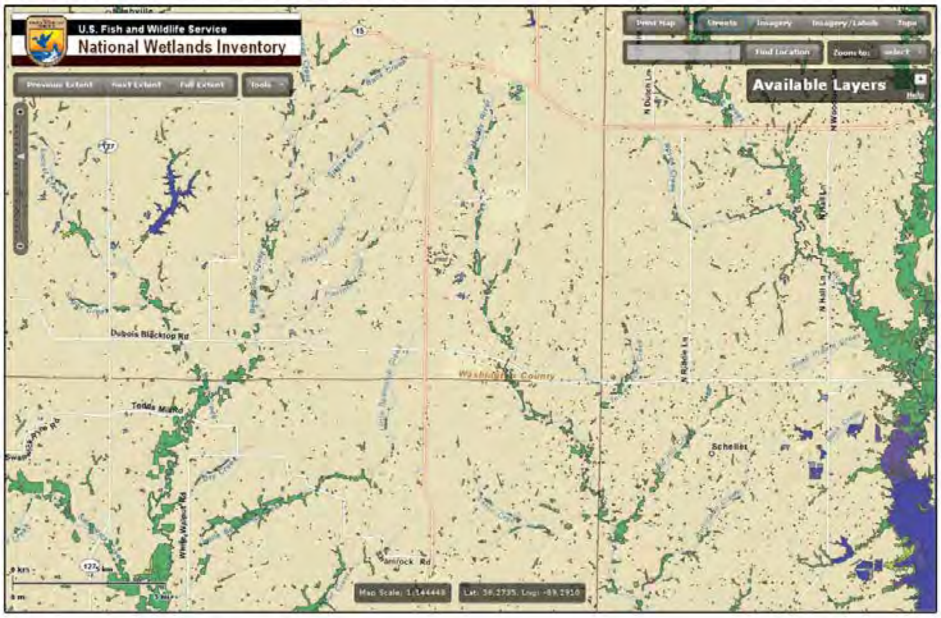
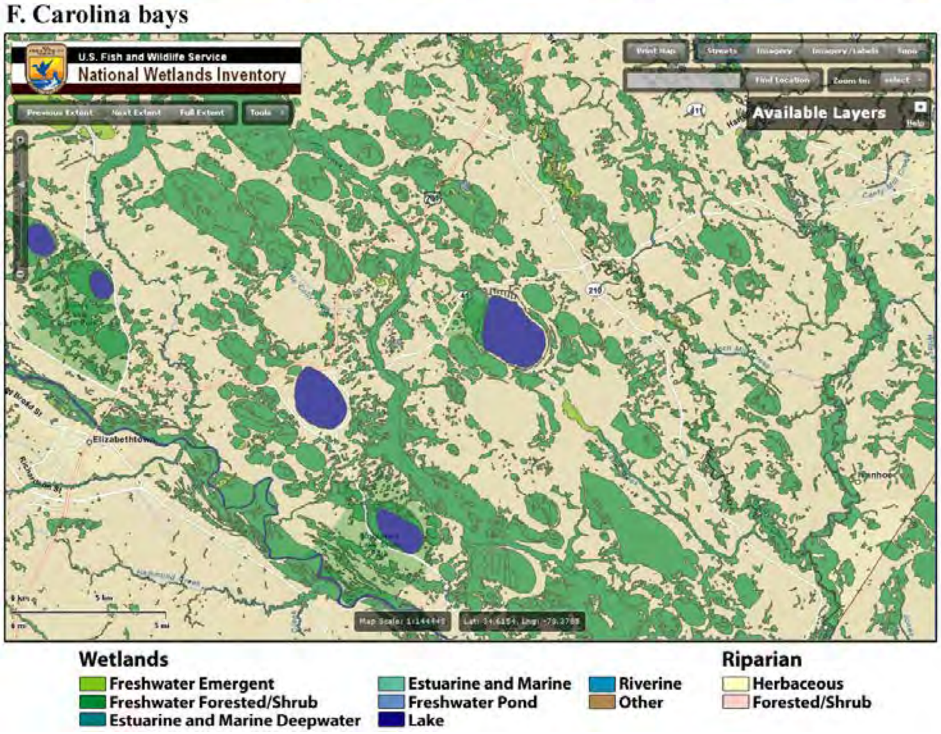


Figure 2−20. Examples of different landscapes showing interspersion of wetlands and streams or rivers (continued).

E. Bottomland hardwood wetlands



F. Carolina bays



between rivers and floodplain wetland habitats caused by flood pulses (Section 1.2.1; Junk et al., 1989; Tockner et al., 2000), moving into these wetlands to feed, reproduce, or avoid harsh environmental conditions and then returning to the river network (Copp, 1989; Smock, 1994; Richardson et al., 2005).

Biological connectivity does not solely depend on diadromy, however, as many nondiadromous organisms are capable of significant movement within river networks (Section 1.2.2). For example, organisms such as pelagic-spawning fish and mussels release eggs or larvae that disperse downstream with water flow (e.g., Platania and Altenbach, 1998; Schwalb et al., 2010); many fish swim significant distances both upstream and downstream (e.g., Gorman, 1986; Hitt and Angermeier, 2008); and many aquatic macroinvertebrates move or drift downstream (e.g., Elliott, 1971; Müller, 1982; Brittain and Eikeland, 1988; Elliott, 2003). Taxa capable of movement over land, via either passive transport (e.g., wind dispersal or attachment to animals capable of terrestrial dispersal) or active movement (e.g., terrestrial dispersal or aerial dispersal of winged adult stages), can establish biotic linkages between river networks and wetlands, as well as linkages across neighboring river systems (Hughes et al., 2009).

The fundamental influence that biological connectivity has on species distributions can last long after a system is disconnected. In a global analysis of freshwater fish diversity, Dias et al. (2014) found that paleoconnected drainage basins (basins that had hydrologic connections during the most recent glacial maximum) currently have greater species richness and lower endemism and beta diversity than paleodisconnected basins. This study indicates that hydrologic connectivity, by allowing dispersal of aquatic organisms, can have a long-lasting legacy effect on the geographic distribution of species.

The examples discussed above illustrate how environmental characteristics provide the physical structure through which biological connectivity occurs, as mediated by biological traits and behavior. The physical structure of the environment is not static, however, and also can be altered by biological behavior. The beaver (*Castor canadensis*) is a keystone species that builds dams that can alter connectivity in several ways. Most obviously, beaver dams reduce hydrologic connectivity by impounding streams and modifying conditions above the dam from lotic to lentic. The area impounded by beaver dams can be large: In the Kabetogama Peninsula of Minnesota, impounded area accounted for up to 13% of the landscape, with an average pond area of about 4 ha (Johnston and Naiman, 1990a, b). In a review of the effects of beaver on stream ecosystems, Collen and Gibson (2001) noted that, although the hydrologic effects of a single beaver dam can be small, the impact of a series of dams on streams can be significant; for example, up to 30% of the water in an Oregon catchment was impounded by beaver dams. Such dams can directly affect material transport (e.g., the ability of the stream to carry sediment is reduced) and alter biogeochemical characteristics (Naiman et al., 1994; Collen and Gibson, 2001). Beaver dams also can affect biological connectivity, for example, by obstructing upstream migration, and cause changes in fish distributions (Collen and Gibson, 2001).

2.4.4 Human Activities and Alterations

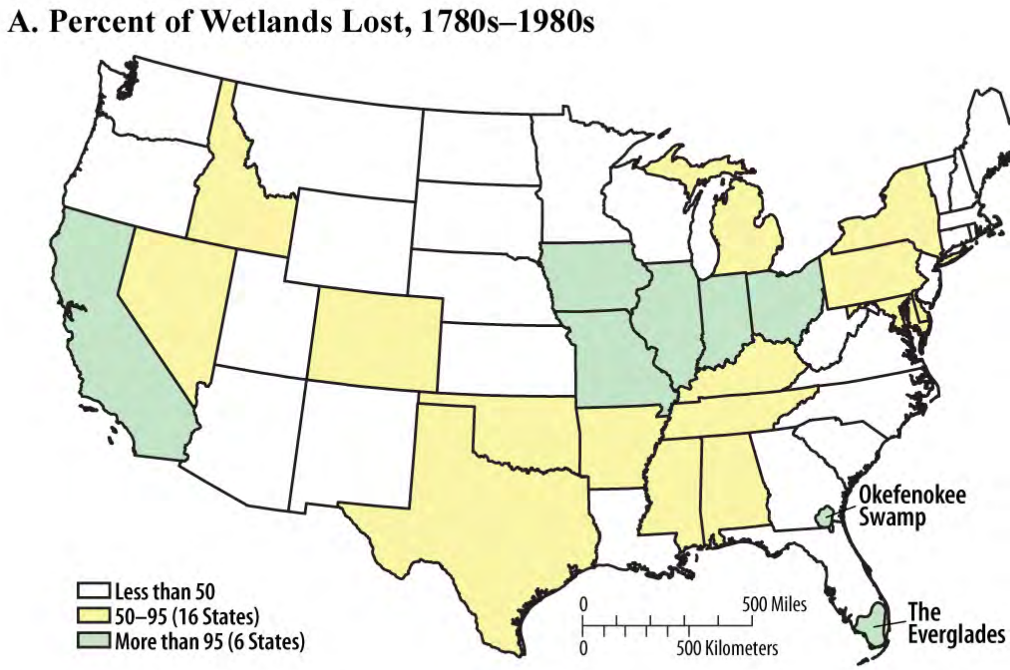
Human activities frequently alter connectivity between headwater streams, riparian/floodplain wetlands, non-floodplain wetlands, and downgradient river networks (Sections 1.2.4, 3.2, 4.3, and 4.4). In doing so, they alter the transfer and movement of materials and energy between river system components. In fact, the individual or cumulative effects of headwater streams and wetlands on river networks often become discernible only following human-mediated changes in degree of connectivity. These human-mediated changes can increase or decrease hydrologic and biological connectivity (or, alternatively, decrease or increase hydrologic and biological isolation). For example, activities and alterations such as dams, levees, water abstraction, piping, channelization, and burial can reduce hydrologic connectivity between streams and wetlands and rivers, whereas activities and alterations such as wetland drainage, irrigation, impervious surfaces, interbasin transfers, and channelization can increase hydrologic connections. Biological connectivity can be affected similarly: For example, dams and impoundments might impede biotic movement, whereas nonnative species introductions artificially increase biotic movement. Further complicating the issue is that a given activity or alteration might simultaneously increase and decrease connectivity, depending on which part of the river network is considered. For example, channelization and levee construction reduce lateral expansion of the river network (thereby reducing hydrologic connections with floodplains), but might increase this connectivity downstream due to increased frequency and magnitude of high flows.

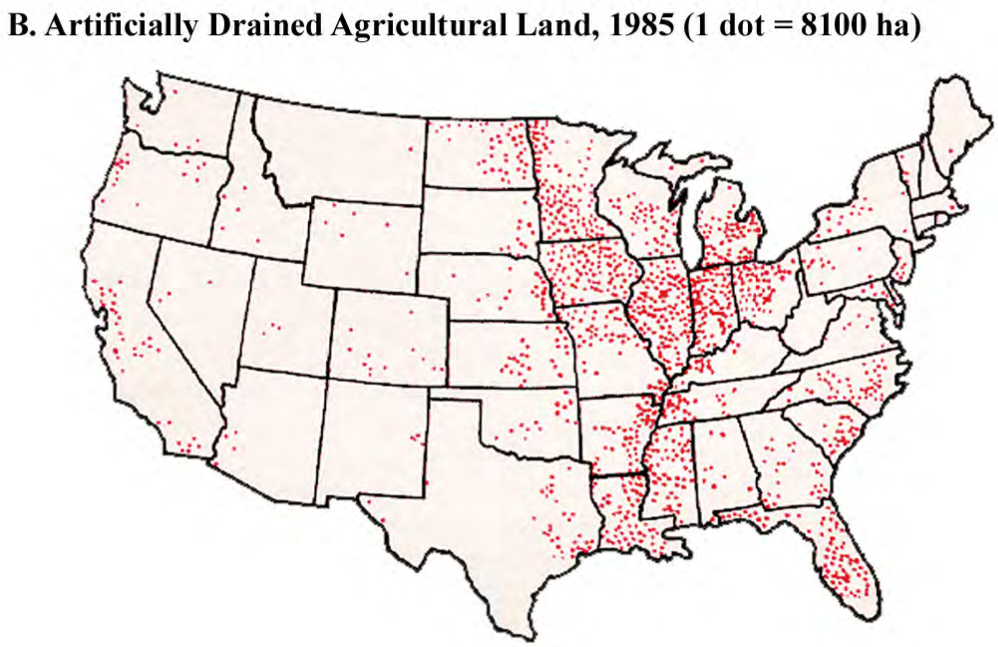
To illustrate, we describe two notable alterations that affect river system connectivity: dams (and their associated impoundments) and wetland drainage. The United States has more than 80,000 dams, over 6,000 of which exceed 15 m in height (USACE, 2009). Numerous studies have shown that dams impede biotic movements, reduce biological connectivity between upstream and downstream locations (e.g., Greathouse et al., 2006; Hall et al., 2011), and form a discontinuity in the normal stream-order-related progression in stream ecosystem structure and function (Stanford and Ward, 1984). Dams, however, can have the opposite effect with respect to natural lakes: increasing their biological connectivity with respect to invasive species by adding impoundments that decrease average distances between lakes and serving as stepping stone habitat (Johnson et al., 2008). Upstream of large dams, riparian areas are permanently inundated, increasing lateral hydrologic connectivity. Downstream, dams decrease peak stream volumes during the normal high-runoff seasons, while increasing minimum flows during normal low-flow seasons—an overall dampening of stream-flow variability (Poff et al., 2007). Because many riverine organisms are adapted (via life history, behavioral, and morphological characteristics) to the seasonality of natural flow regimes, dampening flow variability can have deleterious effects on species persistence where dams have been built (Lytle and Poff, 2004). This reduction in high flows also decreases the connectivity of riparian wetlands with the stream by reducing the potential for overbank lateral flow. Reducing overbank lateral flow can affect downstream water quality, because overbank flow deposits sediment and nutrients that otherwise remain entrained in the river (Hupp et al., 2009).

The greatest human impact on riparian/floodplain wetlands and non-floodplain wetlands has been through wetland drainage (Figure 2-21), primarily for agricultural purposes. Estimates show that, in the conterminous United States, states have lost more than half their original wetlands, with some losing more than 90%; wetland surface areas also have declined significantly (Dahl, 1990).

Drainage causes a direct loss of function and connectivity in cases where wetland characteristics are completely lost. In the Des Moines lobe of the prairie pothole region, where more than 90% of the wetlands have been drained, a disproportionate loss of smaller and larger wetlands has occurred. Accompanying this loss have been significant decreases in perimeter-area ratios—which are associated with greater biogeochemical processing and ground-water recharge rates—and increased

Figure 2-21. Comparison of percent wetland loss between (A) the 1780s and mid-1980s with (B) the distribution of artificially drained agricultural land in 1985. One dot equals 8100 ha. From Blann et al. (2009), as modified from Dahl (1990).





mean distances between wetlands, which reduces biological connectivity (Van Meter and Basu, In press). Wetland drainage also increases hydrologic connectivity between the landscape—including drained areas that retain wetland characteristics—and downstream waters. Effects of this enhanced hydrologic connectivity include (1) reduced water storage and more rapid conveyance of water to the network, with subsequent increases in total runoff, baseflows, stormflows, and flooding risk (Wiskow and van der Ploeg, 2003; Blann et al., 2009); (2) increased delivery of sediment and pollutants to downstream waters; and (3) increased transport of water-dispersing organisms (Babbitt and Tanner, 2000; Baber et al., 2002; Mulhouse and Galatowitsch, 2003). Biological connectivity, however, also can decrease with drainage and ditching, as average distances between wetlands increase and limit the ability of organisms to disperse between systems aerially or terrestrially (Leibowitz, 2003). Ground-water withdrawal can have an effect similar to drainage on some wetlands, which can affect wetland connectivity by reducing the number of wetlands. Of particular concern in the arid Southwest is that ground-water withdrawal can decrease regional and local water tables, reducing or altogether eliminating ground-water-dependent wetlands (Patten et al., 2008). Ground-water withdrawal, however, also can increase connectivity in areas where that ground water is applied or consumed.

Particularly noteworthy is that restoration of hydrologic connectivity, especially in systems with widespread human alterations, also might adversely affect downstream waters (Jackson and Pringle, 2010). For example, dam removal can result in the downstream transport of previously sequestered pollutants (Jackson and Pringle, 2010); dam releases to restore flows, without simultaneous restoration of sediment supplies, can result in downstream channel degradation (Germanoski and Ritter, 1988; Schmidt and Wilcock, 2008). Hammersmark et al. (2008) used a modeling study to show how the restoration of incised stream channels can improve connectivity between streams and floodplains and thus restore predisturbance hydrology (i.e., increased floodplain water storage, reduced peak stormflow, and reduced baseflow).

2.4.5 Interactions Among Factors

Interactions among the factors discussed above can be complex. Here we provide an example of temporary surface-water connections between wetlands in the prairie pothole region (PPR) to illustrate these complex interactions (Leibowitz and Vining, 2003). Further details on wetlands in the PPR are provided in Sections 5.4 and B.3.

During high-water conditions in 1995, a temporary surface-water connection was observed between two geographically isolated prairie potholes in the region’s Drift Prairie. Based on a spatial analysis during similarly wet conditions in 1996, 28% of the wetlands in a 40 km^2 area containing the sites had a temporary surface-water connection to at least one other wetland, including a complex (defined in the study as a group of wetlands interconnected through temporary surface-water connections) of 14 wetlands.

In considering these findings, Leibowitz and Vining (2003) suggested that precipitation and local relief are the primary factors controlling the spatial distribution of these temporary surface connections. Precipitation is the ultimate source of water that fills these wetlands, whereas relief controls how much the water level in a wetland must rise before spillage occurs (water level is also influenced by evapotranspiration and ground water, but ground-water dynamics are difficult to predict for individual wetlands). Relief also controls mixing—which could occur in flatter areas when the boundaries of expanding wetlands overlap—by determining the change in surface area per change in water level. Thus, for a given level of precipitation, the number of surface connections occurring between wetlands should be inversely proportional to local relief. Within the PPR, precipitation generally decreases from east to west, while relief generally increases. The easternmost physiographic region in the PPR is the Red River Valley, a relatively flat ancient lakebed (Lake Agassiz) having deep deposits of silt and clay. Water can pond easily on these deposits, producing shallow wetlands and integrated drainage (i.e., the presence of stream networks). The Missouri Coteau, which forms the western boundary of the PPR, consists of dead-ice glacial moraine. This area has hummocky terrain, and local relief can be as great as 15–45 m in steeper areas (Winter et al., 1998). As a result, the Coteau has deeper wetlands and little to no integrated drainage. The Drift Prairie, located between the Red River Valley and the Missouri Coteau, is an undulating plain formed on ground moraine. Relief, wetland depth, and the level of integrated drainage in the Drift Prairie are intermediate in comparison with the other two regions.

Leibowitz and Vining (2003) hypothesized that the combined effect of these patterns in precipitation and relief should produce a strong east-west gradient across the PPR in the occurrence of intermittent surface-water connections. Both the absolute number of connections and complex size (the number of wetlands contained in a complex) should be highest in the Red River Valley. Given the relative flatness of this area, mixing should be the more common mechanism for temporary connections. The number of temporary connections and complex size should be lower in the Drift Prairie, and spillage might dominate in this hillier terrain. In the Missouri Coteau, where relief is greatest, the occurrence of these temporary connections should be rare and limited to small complex sizes. Human impacts, however, could affect these trends (Section 2.4.4).

Beyond these regional trends in relief and precipitation, local variation in the occurrence of intermittent surface-water connections should be influenced strongly by ground-water dynamics. The ground-water hydrology of prairie potholes has been well investigated at several sites (e.g., Winter et al., 1998; Winter and Rosenberry, 1998). The specific ground-water interactions—and hence the effects of ground-water movement on spillage or mixing, however, are unknown for most prairie potholes. All else being equal, ground-water discharge wetlands should receive more water, and so should have a higher probability of spillage, than ground-water recharge wetlands because recharge should reduce the amount of water available for spillage.

A major factor influencing the temporal distribution of intermittent connections within the PPR is wet-dry cycles. Climatic changes that have occurred throughout the Holocene drive these cycles. Evidence, for example, exists for 20-, 22-, 50-, 100-, and 200-year climatic cycles (Ashworth, 1999). Wetland hydrology responds dramatically to these wet-dry cycles as ground-water levels and precipitation patterns fluctuate. In 1996, the average monthly Palmer Hydrological Drought Index for central North Dakota was 4.02 (88th percentile), compared with a median of 1.00 for annually calculated monthly averages between 1895 and 2001. Moisture levels of this magnitude—and consequently the degree of connectivity observed (Leibowitz and Vining, 2003)—would be expected to occur during wetter portions of wet-dry cycles.

2.4.6 Quantifying Connectivity

As previously discussed, watershed connectivity is a dynamic and scalable quantity that occurs along a gradient from highly connected to highly isolated (Ward, 1989; Euliss et al., 2004). Connectivity can be quantified using *structural* metrics of physical landscape features (e.g., watershed topography, the spatial arrangement of habitat patches), or *functional* metrics of system dynamics, which integrate information about processes and interactions that influence hydrologic flows or biological dispersal. Selection of specific metrics for quantifying connectivity depends on the purpose of the assessment, the environmental context (e.g., humid versus arid), type of connection (e.g., hydrologic, chemical, biological), spatial and temporal scale of interest, and available data (Calabrese and Fagan, 2004; Lexartza-Artza and Wainwright, 2009).

2.4.6.1 Hydrologic and Chemical Connectivity

In hydrology, connectivity research has aimed to understand how and when water volume inputs (e.g., precipitation minus water loss through infiltration, evaporation and transpiration) and moisture thresholds trigger surface and subsurface flow, thereby influencing streamflows in a given watershed (Western et al., 2001; Ali and Roy, 2010; Bracken et al., 2013). Because movement of water is the primary mechanism by which chemical substances are transported downstream, quantifying chemical connectivity is closely related to quantifying hydrologic connectivity (Michalzik et al., 2001; Borselli et al., 2008). Hydrologic connectivity research has focused on relating patterns of soil moisture following precipitation events to stream discharge (Western et al., 2001; James and Roulet, 2007; Ali and Roy, 2010) or measuring flow-process connectivity at the hillslope scale (Knudby and Carrera, 2005; Reaney, 2008; Smith et al., 2010). Although this research provides a critical understanding of how water moves through a watershed, it is only indirectly related to connectivity between small streams and rivers, or between wetlands and streams. Metrics for quantifying hydrologic connections between upstream and downstream waters have started to be explored through research characterizing the hydrologic permanence of streams (Fritz et al., 2008; Fritz et al., 2009) or mapping temporal variation in surface connections between wetlands and streams using field (McDonough et al., 2015) or remotely sensed data (Sass and Creed, 2008; Lang et al., 2012; Huang et al., 2014). More commonly, research efforts have focused on data collection methods that could inform measurement of connectivity (e.g., deriving relationships between connectivity and topography or water quality; hydrologic tracers; geostatistical modeling; and watershed, ground-water, or coupled surface water-ground water modeling).

Structural indices derived from topography can be used to predict patterns of watershed wetness. Examples include the Topographic Wetness Index (Quinn et al., 1995), which is quantified using the upslope contributing area and local slope, as well as quasi-dynamic indices that calculate the effective contributing area (**variable source area**) in a watershed (e.g., Barling et al., 1994; Tarboton, 1997; Creed and Beall, 2009). These indices could be used to predict the location of hydrologic flowpaths and areas of a watershed that might be efficient exporters of nutrients, sediment, or pollutants following heavy rainfall or snowmelt periods (Creed and Beall, 2009; Lane et al., 2009). In flatter landscapes, a more dynamic contributing area model is typically required (Shaw et al., 2013). One example is the fill-and-spill model in which the watershed contributing area expands when wetland storage reaches capacity (fill) and wetlands overflow (spill) onto the land surface and into other surface-water bodies (Tromp-van Meerveld and McDonnell, 2006; Shaw et al., 2013; McCauley and Anteau, 2014). Other researchers have quantified basin-scale hydrologic connectivity as the ratio of flowing stream reaches connected to the outlet to the total potentially flowing stream reaches (Phillips et al., 2011; Spence and Phillips, 2015), or as transport potential in a given direction quantified by a directional connectivity index (Larsen et al., 2012). Similar to this, the volume-to-breakthrough concept quantifies connectivity as actual runoff relative to water inputs, where connectivity decreases with increased infiltration, depression storage, slope length, barriers, or other factors (Bracken and Croke, 2007).

Several other lines of research are contributing to a general understanding of connectivity between water features. Water quality indicators have been used to identify connectivity between wetlands and streams (Johnston et al., 1990; Leibowitz and Vining, 2003). Tracer experiments using ^{15}N, bromide, salt solutions, fluorescing particles, or other conservative compounds have been conducted that can inform flowpaths in aquatic systems (Mulholland et al., 2004; Bencala et al., 2011; O'Brien et al., 2012). Modeling and measuring the mass transfer efficiency of a watershed using a parameter such as the sediment delivery ratio, which describes and predicts the relationship between erosion and sediment yield in a watershed, can indicate the degree of connectivity within a watershed (Atkinson, 1995; Hooke, 2003; Bracken and Croke, 2007). Geostatistical approaches are being developed to consider how connectivity would be quantified within a branched stream network (Fagan, 2002; Ganio et al., 2005; Peterson et al., 2007). In addition, numerous mechanistic modeling and simulation tools can be modified and applied to investigate connectivity dynamics from geographically isolated wetland systems (Golden et al., 2014) and headwaters (e.g., TOPMODEL; Beven and Kirkby, 1979) to downstream surface-water systems.

Although the research community has not reached a consensus regarding the best methods or metrics to quantify or predict hydrologic or chemical connectivity (Lexartza-Artza and Wainwright, 2009; Ali and Roy, 2010; Bracken et al., 2013), future efforts to quantify connectivity using the descriptors discussed in Chapter 1 (frequency, magnitude, duration, timing, and rate of change) or other connectivity metrics will help to further refine and quantify the lines of research summarized above.

2.4.6.2 Biological Connectivity

In the quantification of biological connectivity, species traits (e.g., dispersal mode, habitat requirements, behavior) also must be considered (Calabrese and Fagan, 2004). Structural connectivity can be quantified from the physical landscape (e.g., the size, shape, and arrangement of habitat patches) assuming that the spatial configuration of habitats reflects species' ability to move between them. Functional connectivity directly incorporates information about species' movement obtained from field studies or from models to inform estimates of connectivity (Calabrese and Fagan, 2004; Wainwright et al., 2011).

Indices based on graph theory calculate connectivity using a graph to represent the landscape as a network of nodes (e.g., habitat patches) connected by edges (pathways of movement; Urban and Keitt, 2001). Such connectivity indices include the Minimum Spanning Tree (Urban and Keitt, 2001), Correlation Length (Keitt et al., 1997; Rae et al., 2007), the Integral Index of Connectivity (Pascual-Hortal and Saura, 2006), and the Probability of Connectivity (Saura and Pascual-Hortal, 2007). Graph-theory approaches can be used to assess structural or functional connectivity at multiple spatial scales (Eros et al., 2012). Specific information about habitats and focal species is incorporated by applying node weights (e.g., habitat area or quality, population abundance), edge weights (e.g., Euclidean distance, landscape resistance), or edge characteristics (e.g., direction of movement; Galpern et al., 2011). Indices derived from such graphs seek to characterize connectivity in terms of habitat (e.g., total connected habitat area), dispersal pathways (e.g., relative abundance of individuals using a pathway, path redundancy or vulnerability), or both (Rayfield et al., 2010). The Integral Index of Connectivity, for instance, incorporates patch area, the topological distance between patches and the proportion of connected patches (Pascual-Hortal and Saura, 2006), and has been successfully used to quantify connectivity within a river network at varying spatial scales for otters (Van Looy et al., 2013).

The dendritic nature of stream networks also can be explicitly integrated when considering the biological connectivity for obligate aquatic species, such as fish. The branching structure of a dendritic network (Figure 2-19B), which has a single pathway (the stream channel) between habitat patches (e.g., stream reaches), influences individual movement and population distribution and abundance, and thus the impact of disturbances and fragmentation on connectivity (Fagan, 2002; Grant et al., 2007); this can be reflected in graph-theoretic connectivity indices (Malvadkar et al., 2015). An example of a dendritic metric is the Dendritic Connectivity Index, which uses the number of barriers (e.g., culverts) and the passability of these barriers to quantify the probability that fish can move between two points in a river network (Cote et al., 2009).

2.4.6.3 Summary

This section briefly reviews the growing body of research into testable indices and metrics that represent hydrologic and biological connectivity of functional importance to downstream waters. Data availability is a critical issue, as the information content that connectivity indices provide often is related directly to their data requirements (Calabrese and Fagan, 2004; Bergsten and Zetterberg, 2013). Additionally, the many proposed connectivity indices and approaches discussed in the literature suggest that different metrics are needed to quantify different types of connectivity across diverse environments, scales, and ecosystem functionalities (Rayfield et al., 2010; Galpern et al., 2011; Bracken et al., 2013). With further development and refinement, the utilization of connectivity indices can provide graphical, quantitative assessments of connectivity.



CHAPTER 3. STREAMS: PHYSICAL, CHEMICAL, AND BIOLOGICAL CONNECTIONS TO RIVERS

3.1 Abstract

The physical structure of a river network inherently demonstrates cumulative connectivity (Section 1.2.3) between all streams and their downstream rivers. Substantial evidence supports physical, chemical, and biological connections from headwater streams—including those with ephemeral, intermittent, and perennial flows—to waters immediately downstream through transport of water and associated materials, movement of organisms and their products, and bidirectional geomorphic adjustments. Among the most compelling evidence for the effects of headwater streams on rivers is as sources of water, nitrogen, organic carbon, and sediment (clean and contaminated); as transformers of and sinks for nitrogen, carbon, and contaminants; and as providers of essential habitat for migratory animals such as anadromous salmon. Headwater streams as a class provide substantial quantities of water to larger water bodies. For example, first-order streams cumulatively contribute approximately 60% of the total mean annual flow to all northeastern U.S. streams and rivers. Infrequent, high-magnitude events are especially important for transmitting materials from headwater streams in most river networks. The strongest lines of evidence supporting the effects of headwater streams are from watersheds where headwater streams drain a unique portion of the basin (e.g., hydrology, geology, human alteration). Investigation of connections among river network components continues to be an active area of scientific research, with progress occurring in the development of river network models and connectivity metrics for quantifying connections and their downstream effects. Physical, chemical, and biological connections between headwater streams and downstream waters are fundamental to the structure and function of river networks, and additional empirical data and further breakthroughs that quantify linkages across large spatiotemporal scales will continue to enhance our understanding of river network complexity.

3.2 Introduction

In this chapter, we describe the state of knowledge of stream connectivity and its effects on the physical, chemical, and biological condition of downstream waters. Although we recognize that streams also are important sources of water and other materials to nearby terrestrial systems and deep ground-water systems via lateral and vertical connections (e.g., Gray, 1993; Shentsis and Rosenthal, 2003; Walters et al., 2008), we focus here on longitudinal surface-water connections between streams and rivers, and on shallow subsurface-water interactions integral to surface-water connections and downstream water condition. The evidence primarily focuses on the connections between headwater streams and downstream waters, but we draw some evidence from connections of larger streams to rivers, reservoirs, lakes, and coastal waters. We consider the peer-reviewed evidence for connectivity and its consequent effects on downstream rivers in terms of physical (Section 3.3), chemical (Section 3.4), and biological (Section 3.5) connections between upstream and downstream habitats. Although we recognize that many linkages between streams and downstream waters cross physical, chemical, and biological boundaries, we have chosen this format for ease of presentation. In each section we also consider how human alteration of streams affects their connectivity and resulting effects on downstream rivers (Sections 1.2.4 and 2.4.4). In some cases, connectivity and its effects on downstream waters become more discernable with human alteration (e.g., Chin and Gregory, 2001; Wigmosta and Perkins, 2001); however, when human alterations are widespread and relatively uniform (e.g., Blann et al., 2009) attributing downstream effects to particular tributaries or parts of the river network can be more complex. Coupled human-natural systems are an area of active research (Box 3-1). Section 3.6 closes this general section with a discussion on stream-river connections by synthesizing evidence in terms of the conceptual framework (Chapter 2) and viewing streams in a connectivity gradient context (Section 1.2.2). In addition, two case studies on specific types of stream systems are in Appendix B: prairie streams (Section B.4) and southwestern intermittent and ephemeral streams (Section B.5).

Streams range greatly in size in terms of both drainage area and discharge. In general, their abundance is inversely related to their size. First-order streams typically are most abundant, although individually they have the smallest drainage areas and shortest average stream lengths (Horton, 1945; Schumm, 1956; Ijjasz-Vasquez et al., 1993). When considering drainage area and stream length of headwater streams together, however, they can represent most of the river watershed and network. Thus, despite their small individual size, these headwater streams cumulatively can have a large influence on downstream waters (Section 1.2.3).

Some headwater streams lack channel connections to large downstream water bodies because they drain closed or endorheic basins. Endorheic basins have no surface outflows to oceans, but terminate as inland lakes, seas, playas, or pans (Shaw and Bryant, 2011). Although endorheic streams are common in some areas (Section B.5), endorheic basins represent only approximately 2% of the North American continent (Vörösmarty et al., 2000) and generate 0.15% (9 of 5,892 $km^3\ yr^{-1}$) of its annual discharge (Fekete et al., 2002).

Box 3-1. Urban Streams

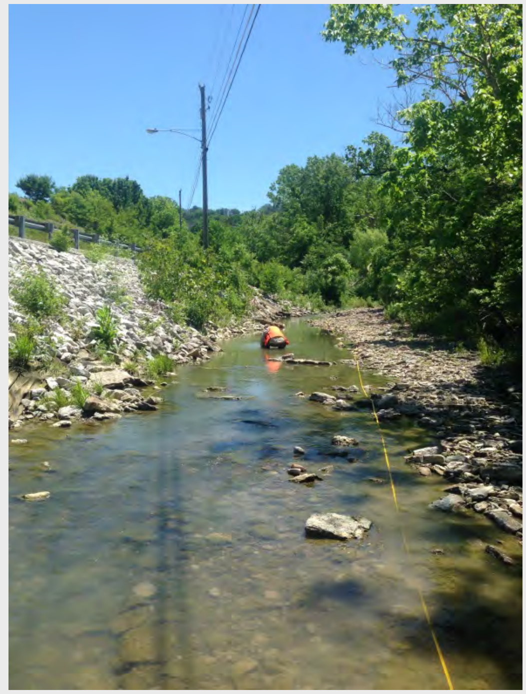
Urban development alters the structure and function of stream ecosystems in numerous ways (Paul and Meyer, 2001; Walsh et al., 2005). Although the specific symptoms of what Walsh et al. (2005) referred to as the “urban stream syndrome” depend on numerous factors, including the location, density, type, and age of urban development, common patterns have emerged. For example, urban streams typically experience increased stormflows (from direct runoff to channels), flashier hydrographs, altered baseflows, increased nutrient and contaminant concentrations, and decreased organic matter retention. Many of these attributes are related to changes in connectivity—that is, alteration of the longitudinal, lateral, and vertical connections between the landscape, headwater streams, and downstream waters.

Connectivity and consequences on downstream waters. One pervasive effect of urban development is the alteration of hydrologic connectivity along river networks. The frequency, duration, magnitude, timing, and rate of change of both stormflows and baseflows are altered via multiple pathways. The highly connected, engineered network of impervious surfaces, pipes, and storm drains increases the volume and rapidity of stormwater runoff into urban streams, resulting in increased frequency, magnitude, and rate of change of stormflows within the river network. This quick delivery of stormwater runoff to streams also means that stormflows tend to recede quickly, shortening stormflow duration. Because impervious surfaces reduce infiltration and watershed storage of water, urban development also can reduce baseflow magnitudes. Together, these patterns result in the typical flashy hydrographs of urban streams and altered hydrologic connections throughout urban river networks. Higher stormflow magnitudes and frequencies also can scour sediments from urban channels, which, in combination with engineered channel straightening, can cause urban channels to enlarge via incision and expansion. Direct wastewater discharges to urban streams (e.g., from wastewater treatment plants, industrial facilities, or combined sewer overflows) and water withdrawals for municipal and industrial uses also can affect the frequency, duration, and magnitude of hydrologic connections in urban streams. Vertical hydrologic connections can be augmented by leaky subsurface sewer and water pipes, or diminished by reduced infiltration due to increased impervious surface area and channel incision, straightening, hardening, and simplification.

Stream burial, or the diversion of streams into pipes, culverts, and other conveyances, is common in urban watersheds, and provides another illustration of how urban development alters connections. For example, more than 60% of all streams in Baltimore City, particularly small headwater streams, have been buried (Elmore and Kaushal, 2008). As a result, most lateral and longitudinal connections along urban river networks have been replaced by urban infrastructure, resulting in greatly expanded headwater drainage areas (Kaushal and Belt, 2012).

These changes in hydrologic connectivity have significant consequences for downstream waters in urban areas. Between rain events, urban landscapes accumulate materials such as organic material, nutrients, and contaminants, which then are delivered quickly to urban streams with surface runoff. As natural stream channels are converted to simplified engineered structures, they lose their ability to retain and transform these materials, resulting in reduced storage and lag time before transport to downstream waters (Nedeau et al., 2003; Carey and Migliaccio, 2009; Kaushal and Belt, 2012).

Box 3-1. Urban Streams (continued)



Longitudinal connectivity in urban streams also influences the movement and distribution of organisms in these systems. Urban stream habitats frequently become fragmented and homogenized, as connectivity is disrupted by road crossings, channel incision, and other impacts associated with urban development. Habitat homogenization reduces complexity, which limits the availability of habitats needed throughout species' life cycles (for reproduction, rearing, refuge from disturbance and predation). Fragmentation can result in reduced movement of mobile organisms, most notably fish, through the river network (Perkin and Gido, 2012). Urban streams also can benefit, however, from connectivity with intact, upstream habitats. For example, Waits et al. (2008) found that immigration from less disturbed upstream areas serving as source habitats maintained central stoneroller populations in an urban stream.

Connectivity and restoration of urban streams. Because so many of the adverse effects associated with urban development are related to changes in lateral, longitudinal, and vertical connections along urban riverscapes, restoration of these systems often involves re-establishing connections that existed before urbanization. For example, detention ponds and green infrastructure (rain gardens, bioswales, permeable pavements, green roofs) are designed to slow stormwater runoff into urban streams, thereby increasing retention and processing of water, nutrients, sediment, and contaminants. Ultimately, the slowing of stormwater runoff can re-establish lateral and longitudinal connections as retention and transformation pathways, rather than the primarily export pathway these connections traditionally served in urban river networks.

The contribution of headwater streams to river networks in terms of stream number, length, or drainage area over large geographic regions has been difficult to determine, even with advances in remote sensing and geographic information systems. The small size of headwater streams makes distinguishing them from surrounding areas and overlying tree canopies difficult in most regions (Gilvear and Bryant, 2003). Numerous studies have shown that existing U.S. hydrographic databases and topographic maps underestimate the extent of headwater streams (Morisawa, 1957; Gregory, 1976; Hansen, 2001; Heine et al., 2004; Stoddard et al., 2005; Roy et al., 2009). Therefore, most streams portrayed on databases and maps as first-order streams are, when ground-truthed, second- or third-order streams. For example, more than 80% of mapped (1:25,000-scale topographic maps) stream terminuses in a Massachusetts watershed underestimated the upstream extent of the channels (Brooks and Colburn, 2011). On average, these unmapped upstream segments were nearly 0.5 km in length, and 40% had one or more upstream tributaries (Brooks and Colburn, 2011). Even with this widely known underestimation by databases and maps, first-order streams recognized in the U.S. Geological Survey (USGS) medium-resolution (1:100,000-scale) National Hydrography Dataset (NHD) represent 53% (2,900,000 km) of total stream length (Nadeau and Rains, 2007). Moreover, approximately 50% of these first-order streams were classified as not having year-round flow (i.e., nonperennial; Section 2.2.2; Nadeau and Rains, 2007). Southwestern and prairie streams are predominantly ephemeral and intermittent

(Sections 5.5, 5.6, B.4, and B.5). Thus, despite the shortcomings of existing national maps and hydrographic databases, it is still clear that headwater streams—including ephemeral and intermittent streams—represent a large fraction of river networks in the United States. Combining their overwhelming extent with their high biogeochemical activity (Section 3.4) means that headwater streams, including ephemeral and intermittent channels, have a large cumulative or aggregate effect on the river network (Benstead and Leigh, 2012).

In the following sections, we consider longitudinal connectivity between streams and downstream waters in terms of the physical, chemical, and biological connections between them.

3.3 Physical Connections

Physical connections result from the transport of nonliving materials that do not chemically change (or change slowly) enroute from streams to downstream rivers. In this section, we discuss factors controlling water, temperature (heat energy), sediment, and wood in streams; how these materials are transported downstream; and evidence that these connections affect the condition of downstream rivers.

3.3.1 Water

The recurrent, concentrated surface flow of water from surface runoff and ground water develops and maintains river networks, and water is the primary medium carrying other materials from streams to rivers (Section 2.3). The temporal dynamics of flow (its frequency, duration, magnitude, timing, and rate of change) within and among river networks vary in space and time and influence the physical, chemical, and biological connectivity between streams and downstream waters (Sections 2.2.2, 2.2.3, and 2.3.2.2). Thus, the physical connection of water flow through river networks largely forms the foundation for chemical and biological connections and where along the dynamic connectivity gradient streams are positioned (Section 1.2.2).

Most rivers receive the majority of their water from tributaries rather than from direct precipitation on or ground-water input to river segments (Winter, 2007; Bukaveckas, 2009). Alexander et al. (2007) modeled flow through river networks in the northeastern United States and estimated that first-order streams (designated on the 1:100,000-scale NHD river network) provide approximately 70% of the mean annual water volume in second-order streams and about 55% and 40% of the mean water volume in fourth- and higher order rivers, respectively. Overall, first-order streams cumulatively contribute about 60% of the total volume of mean annual flow to all northeastern streams (Alexander et al., 2007).

Headwater stream contributions to downstream baseflow vary among river networks, based on several large-scale factors (Section 2.4). For example, headwater streams that have stronger connections to ground water or that consistently receive more precipitation relative to downstream reaches have a larger effect on downstream river baseflows. Hydrologic data from 11 nested gages distributed throughout a watershed (176 km^2) in the Catskill Mountains, NY were used to assess the extent of spatial correlation in baseflow discharge (Shaman et al., 2004). Baseflow discharge in smaller streams (i.e., with watersheds <8 km^2) was more weakly correlated with mainstem discharge than discharge in larger streams; the authors concluded that this pattern reflected greater contributions by deep ground water as drainage area increased (Shaman et al., 2004). Using geochemical tracers and hydrologic data from 32 nested stations in a watershed (1,849 km^2) of the River Dee in Scotland, Tetzlaff and Soulsby (2008) determined that streams draining the upper 54% of the watershed contributed 71% of baseflow. However, the upper watershed received only 58% of the total annual precipitation, indicating that long residence time ground-water flowpaths from the headwater watersheds were also important in maintaining downstream baseflows (Tetzlaff and Soulsby, 2008). In contrast, headwater streams (0.11−3.5 km^2) making up 33% of the total area in a northern Sweden watershed (78 km^2) contributed only 18% of the summer baseflow at the basin outlet (Temnerud et al., 2007). The specific discharge contribution (L s^{-1} km^{-2}) for headwater streams, however, varied by an order of magnitude (~0.5−8.0), reflecting the heterogeneity (i.e., mires, lakes, forest) of the study watershed (Temnerud et al., 2007). Jencso et al. (2009) monitored 24 transects with a total of 84 wells along lower hillslopes, toe-slope, and riparian areas in a northern Rocky Mountains watershed (22.8 km^2) and found that the duration of connectivity from hillslopes to streams was positively correlated (r^2 = 0.95) with the duration of higher than normal downgradient watershed streamflow. This finding demonstrates the strong link between downstream flow conditions and the connectivity of ephemeral and intermittent streamflow from nearby hillslopes, and that the cumulative downstream effect of the hydrologic connections between the hillslope and stream channel is time varying. Hydrologic connections to downstream rivers are often complex, involving longitudinal, lateral, and vertical exchanges that vary over space and time. This means that the flowpath by which headwater streams contribute to downstream waters will vary according to climatic, topographic, and geologic context.

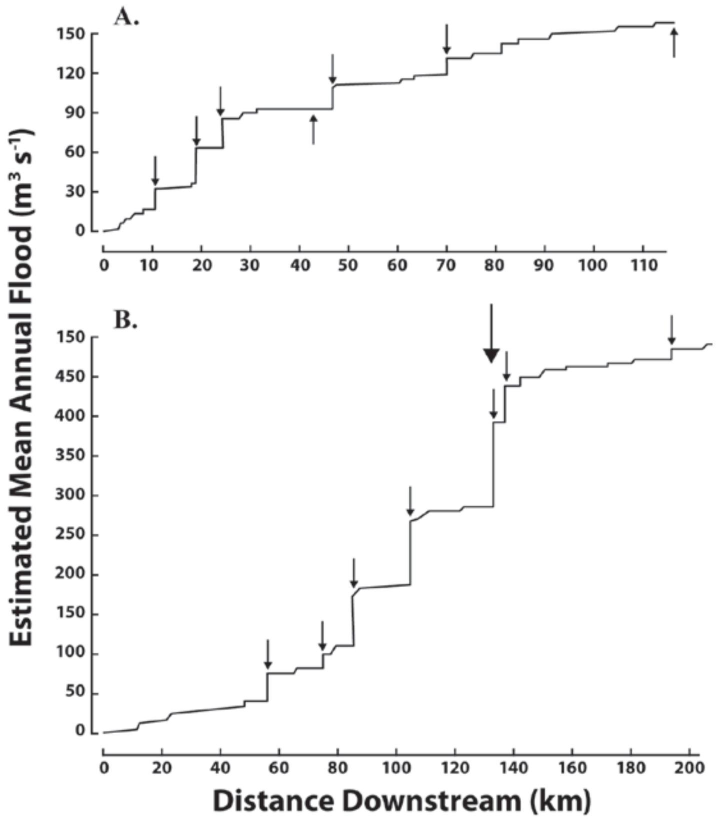
We can also infer the importance of headwater streams from variation in river hydrologic responses over space. Discharge increases with drainage area, and the general assumption, particularly for mesic environments, is that drainage area can be used as a proxy for discharge. The relationship can be written as $Q = kA^c$, where Q is discharge (m^3 s^{-1}), k is a constant representing hydrologic factors such as antecedent moisture and precipitation, A is drainage area (km^2), and c is the scaling power constant. This scaling power reflects how the rate of discharge increases with drainage area, and can be useful for qualitatively assessing headwater contributions to downstream discharge. Where $c \approx 1$, discharge is generated proportionally with increasing drainage area. Where $c < 1$, upstream portions of the watershed (where headwater streams tend to be most abundant) generate more discharge per unit area than downstream portions, suggesting that rivers with $c < 1$ derive a higher proportion of their flow from headwater streams. Where $c > 1$, downstream portions generate more discharge per area than upstream reaches, suggesting that rivers with $c > 1$ might store more water per unit area in upstream vs. downstream areas. Alternatively, urbanization in the lower portions of the watershed can lead to a similar relationship (Galster et al., 2006). Data from multiple USGS gages along large, unregulated rivers showed that mean and peak annual discharge do not always increase proportionally with drainage area (Galster, 2007, 2009). Of the 40 rivers examined, only 16 had linear peak annual discharge-area relationships ($c \approx 1$) throughout their period of record (Galster, 2009). Eleven rivers had relationships where $c < 1$, three rivers had relationships where $c > 1$, and ten showed changes in the relationship over their period of record.

Despite variability in area-discharge relationships, most mesic watersheds have a value of *c* between 0.8 and 1 (Galster, 2007), suggesting that drainage area can be used to roughly estimate the proportion of flow that arises from headwater streams. For example, Alexander et al. (2007) found that the watersheds of first-order streams cumulatively accounted for 57% of the total drainage area and 55% of the total annual river flow of the New England states. In more xeric arid and semiarid watersheds where the ground-water table can be below the stream channel and thunderstorms of limited spatial extent dominate runoff, however, *c* is generally < 1. For instance, in the highly instrumented Walnut Gulch Experimental Watershed (operated by the U.S. Department of Agriculture, Agricultural Research Services [USDA-ARS]) in southeastern Arizona, discharge becomes more nonlinear (*c* decreases) with increasing watershed area, and a critical transition threshold area occurs roughly within 37–60 ha (Goodrich et al., 1997). The primary causes of increasingly nonlinear response are (1) the increasing role of ephemeral channel infiltration losses to the subsurface, unconsolidated alluvium, and (2) the continual decline of fractional storm area coverage as watershed area increases. Caruso and Haynes (2011) reported that first-order watersheds made up 61% of total drainage area of the Upper Colorado River basin. In this case, the first-order streams produced a lower proportion (41%) of the total annual river flow than suggested by their total drainage area, in part because 84% of the streams were intermittent. Both studies used the 1:100,000-scale NHD, in which first-order watersheds generally correspond to second-order watersheds at the 1:24,000 scale (Alexander et al., 2007). These results, representing two very different parts of the United States, strongly suggest that headwater streams, even where seasonally dry, cumulatively generate a large fraction of the nation's stream and river flows.

The propagation of stormflow through river networks provides clear evidence of hydrologic connectivity between headwater streams and rivers, particularly when an intense storm occurs over only the headwater portions of a river network. In these cases, the hydrograph peaks sharply in the headwater streams, indicating a quick response to precipitation (Figures 2-8 and 2-11). Timing of the storm and onset of the peak are increasingly delayed with increasing distance down the network (Figure 2-11; see below for further discussion of hydrologic dispersion). Typically, discharge magnitude increases as stormflow accumulates incrementally over the river network (Allan, 1995). The contribution of tributaries to rivers during widespread floods manifests as stepped increases in discharge immediately below confluences, as water flows accumulate through a river network (Figure 3-1).

Such propagation was recorded following a monsoonal storm event through an arid network of ephemeral channels in the Río Grande, NM (Figure 3-2). The high-intensity storm dropped approximately 18–25% of annual rainfall on the stream's approximately 16,000 km^2 drainage area over a 2-day period. Discharge recorded at two gages on the stream and three gages on the Río Grande downstream of the confluence illustrated lag (residence) time and peak hydrograph broadening at least 127 km downstream (Vivoni et al., 2006). Stormflow contributions from the ephemeral stream

Figure 3-1. Longitudinal pattern of flow along (A) River Derwent and (B) River Trent, illustrating stepped increases in flow associated with tributary inflows. Small arrows indicate location of tributary confluences along the mainstem; bold arrow in (B) indicates the confluence of the two rivers. Source: Reprinted from Fluvial Forms and Processes: A New Perspective, (1998) by Knighton with permission of Routledge.

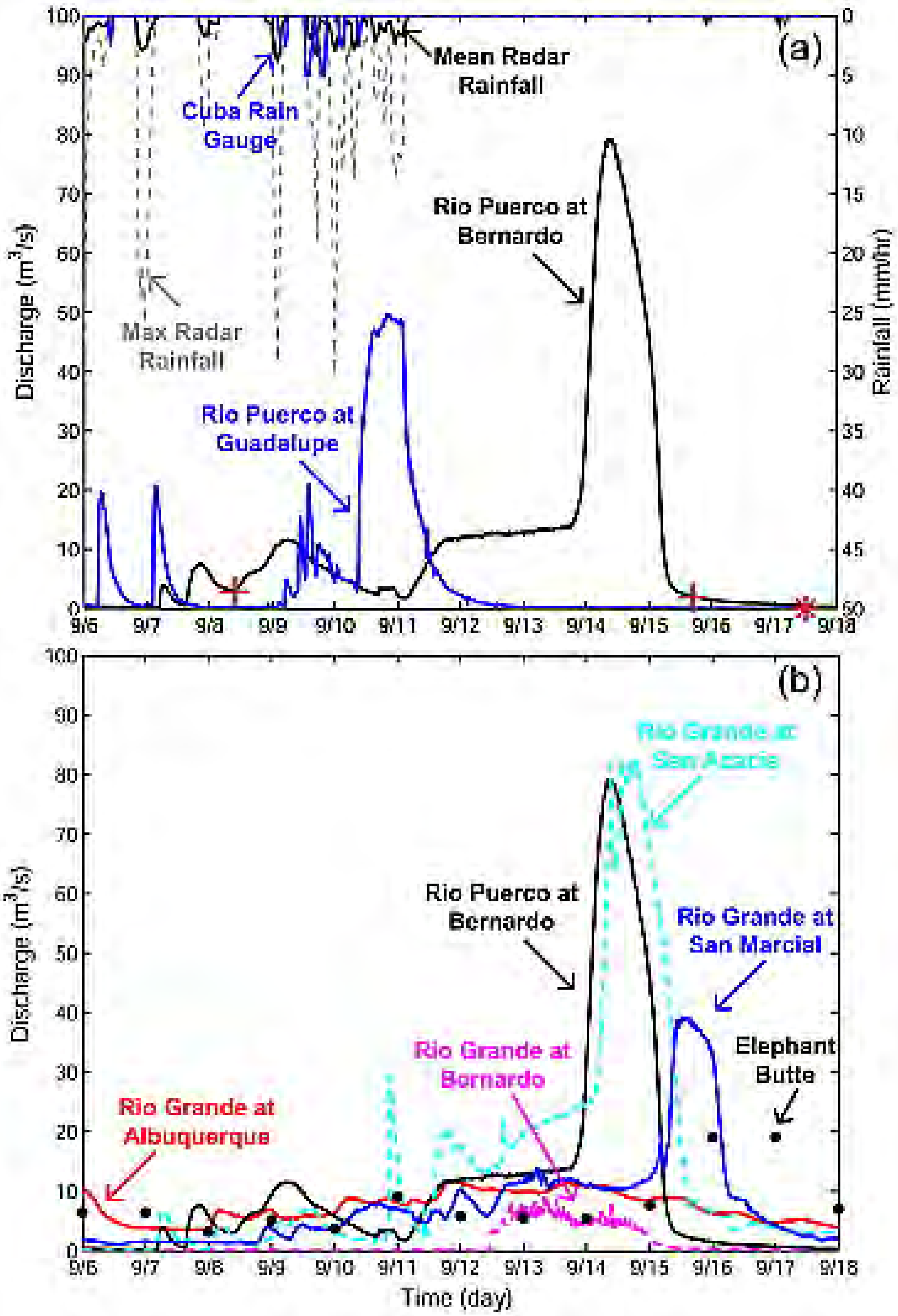


accounted for 76% of flow at the Río Grande, even though these channels were considered to have a flood return interval of 1.11 to 1.84 years across the USGS gages in the network (Vivoni et al., 2006).

How water flows through the streams in river networks shapes hydrologic responses (time to peak flow, peak-flow magnitude, and recession of peak flow) in downstream rivers (also see Sections 2.2, 4.3.2.1, and B.2 for discussion of hydrologic exchange between main channels and floodplains and associated water bodies). A key effect streams in a network structure have on hydrologic responses is dispersion, or the spreading of water output from a drainage basin over time. Hydrologic dispersion is the combined effect of several mechanisms operating across different spatial scales that influence the travel time (or residence time) and volume of water reaching a river network outlet (Saco and Kumar, 2002).

The components of hydrologic dispersion most relevant to river networks include hydrodynamic dispersion, geomorphologic dispersion, and kinematic dispersion. At the scale of individual channels within the network, hydrodynamic dispersion represents storage, turbulence, and shear stress processes that make portions of a channel's water volume move downstream faster than others, rather than as a single, discrete pulse. Hydrodynamic dispersion, which can be visualized by placing a volume

Figure 3-2. Time series of rainfall and streamflow observations in the Rio Puerco and Rio Grande, 6−18 September 2003. Source: Reprinted from Analysis of a monsoon flood event in an ephemeral tributary and its downstream hydrologic effects, (2006) by Vivoni et al. with permission of John Wiley & Sons.



of dye tracer in an upstream location and watching how the dye disperses longitudinally as it moves downstream, takes into account water flowing into and out of recirculating eddies at channel margins, off-channel sloughs, the streambed, and nearby bank sediments (see hyporheic exchange, Section 2.2.2).

These areas, which mix with the main channel flows at relatively slow rates, are collectively part of the stream's transient storage. As streamflow decreases after a storm, water that was temporarily stored in the banks, the floodplain, and other off-channel habitats flows back into the channel and supports stream baseflow (Sections 2.2.3 and 4.3.2.1; Whiting and Pomeranets, 1997; Chen and Chen, 2003; Baillie et al., 2007). Hydrodynamic dispersion is also readily apparent when flow resumes in ephemeral channels. The velocity at the front of flow moving down the dry channel is much slower than upgradient of the front because of higher turbulence and infiltration losses at the front. Flow in these situations, piles up at the front and is reflected as rapid rises in the hydrographs (Figures B-6 and B-10).

Hyporheic flowpaths have been characterized for a variety of situations that affect streambed topography and impede flow across a range of spatial scales (e.g., gravel bars, channel meanders, pool-riffle sequences, and large woody debris; Buffington and Tonina, 2009; Stonedahl et al., 2010; Sawyer et al., 2011) and in varying flow conditions that shift streambed topography (Harvey et al., 2012). The residence time that water spends in the subsurface alluvium before upwelling into streams—that is, the hyporheic residence time—is defined locally by the pressure head, alluvial volume, hydraulic conductivity, bed stability, and near-bed turbulence. For example, because 90% of the stream length in mountainous drainage basins is composed of steep channels with associated bed-form sequencing and limited alluvial volumes, most hyporheic exchange in these systems is expected to be rapid, shallow, and occur over small spatial scales (Buffington and Tonina, 2009). Slower, deeper, and longer hyporheic flowpaths occur in streams in unconfined valleys, with moderate hydraulic gradients and extensive alluvial volumes. In streams of both regions, hydrologic connections exist between shallow ground-water sources and stream channels, but the characteristics of these connections differ. These differences in hydrologic residence time are important, given that residence time reduces downstream flooding, controls various biogeochemical processes, and influences the distribution of stream organisms (Sections 3.4 and 3.5).

Geomorphologic dispersion is the cumulative effect of different travel distances over the larger spatial scale of entire river networks (Rodríguez-Iturbe and Valdes, 1979; Gupta et al., 1980; Rinaldo et al., 1991; Snell and Sivapalan, 1994). Not all points along the river network (or even headwater streams) are equidistant from the network outlet, so water simultaneously entering different parts of the network will not simultaneously arrive at the outlet.

Geomorphologic dispersion assumes water flowing through the network moves at a constant velocity or has varying resistance to downgradient transport. Within river networks, however, water velocity and related hydrodynamics change over space and time (e.g., channel slope and dimensions are not uniform across all pathways through the river network; Saco and Kumar, 2002; Paik and Kumar, 2004). Kinematic dispersion is the cumulative effect of spatially variable water velocity as it moves through river networks (Saco and Kumar, 2002). The physical configuration and variable channel form of streams within a river network, which influence components of hydrologic dispersion at varying scales, are the primary controls dispersing flow from streams to rivers over time and thereby cumulatively mediate the arrival time of stormwater pulses in rivers following rainstorms (Saco and Kumar, 2008).

Another factor that influences hydrologic response is channel transmission loss, or the loss of surface-flow volume due to infiltration into unconsolidated alluvium (Section 2.2). Transmission is another process by which streams, particularly in arid and semiarid regions, can slow or divert from the longitudinal flow of water to downstream rivers and thus minimize downstream flooding. Channel transmission losses are readily apparent from a series of hydrographs recorded in the USDA-ARS Walnut Gulch Experimental Watershed (Figure B-10). These hydrographs are the result of several high-intensity thunderstorms in the upper and lower portions of the watershed. As little or no lateral overland or tributary inflow occurs between the two upstream flumes, the decrease in both peak runoff rate and runoff volume is the result of channel transmission losses and dispersion only. As illustrated in this figure, however, even though runoff transmission losses are large there is sufficient runoff to increase flow in the San Pedro River at the downstream Tombstone USGS gaging station. Over relatively short time frames, infiltration or seepage through channel bed and banks typically dominates transmission losses, although evapotranspiration losses can be significant in stream reaches with prolonged surface flows (Hamilton et al., 2005; Costelloe et al., 2007). In many arid areas, precipitation and the potential for runoff are highest in mountainous regions, where small, ephemeral streams are most abundant (Section B.5). Because streams represent the topographic low points in watersheds that collect and concentrate surface water, they tend to have more water available for infiltration, be more permeable (have coarser sediment) than upland soils, have fewer plants, have higher antecedent moisture, and be closer to shallow ground water—all of which are factors that increase the potential for infiltration. In fact, evidence is mounting that ground-water recharge in hot arid and semiarid areas will occur only where water is concentrated and focused, such as in channels, depressions, or areas of high infiltration (e.g., karst; Brahana and Hollyday, 1988; Hughes and Sami, 1992; Sharma and Murthy, 1995; Scanlon et al., 1997; Scott et al., 2000; Constantz et al., 2002; Coes and Pool, 2005). Infiltrated precipitation in upland portions of alluvial drainage basins rarely reaches the ground-water table as recharge due to high potential evapotranspiration, the adaptation of xeric plants to use available soil moisture efficiently, and upward temperature gradients that transport water vapor upward in thick vadose zones. Relative to their cumulative surface area, an inordinate amount of ground-water recharge occurs in headwater ephemeral and intermittent channels within arid drainage basins (Osterkamp et al., 1994; Goodrich et al., 2004).

Channel bed and bank permeability also governs the degree to which infiltration is an important pathway between streams and ground-water aquifers. Fine bed and bank sediments slow infiltration. In many semiarid and arid streams, bed sediments become finer in the downstream direction because flow competence declines (Dunkerley, 1992), suggesting that lateral and vertical hydrologic connections might be especially important in headwater streams. Sand and gravel mining in ephemeral and intermittent channels and other human alterations that increase fine sediment loading and deposition can further slow percolation (Bull and Scott, 1974). Because fine sediments can concentrate in channels following moderate flows, higher flows that scour fine sediments or submerge more permeable floodplains have higher infiltration rates (Lange, 2005). In the Walnut Gulch Experimental Watershed, cumulative transmission losses over 54 km of channel resulted in a 57% decrease in flow volume associated with a storm (Renard and Keppel, 1966). Infiltration losses accounted for up to half the flow volume along three ephemeral channels in the southwestern United States (Constantz et al., 2002). Chemical and isotopic tracers have confirmed that ephemeral streams are cumulatively important areas for floodwaters to recharge ground-water aquifers in desert regions (Tang et al., 2001). Although transmission losses represent disruptions of surface connectivity between streams and downstream waters, such losses indicate vertical hydrologic connections that reduce downstream flooding and recharge the ground-water aquifers that eventually contribute to flow in downstream waters (Izbicki, 2007).

Human alterations designed to control the spatial and temporal distribution of water have affected the longitudinal, lateral, vertical, and temporal dimensions of hydrologic connectivity in river networks. Structures such as dams, weirs, levees, culverts, and pipes alter longitudinal transport, restrict lateral expansion, and alter vertical exchange (e.g., Gregory, 2006; Hester and Doyle, 2008; Park et al., 2008). Surface-water and ground-water abstraction and diversion can cause tributary segments to dry, thereby severing longitudinal and vertical connectivity and reducing or eliminating lateral connectivity during low-flow periods (e.g., Colvin and Moffitt, 2009; Scanlon et al., 2012). Human alterations that increase fine sediment deposition or microbial biofilm in streambeds also can hamper vertical exchange (Battin and Sengschmitt, 1999; Rehg et al., 2005), causing conditions that can become chronic without periodic floods to flush out deposited sediments and biofilms (Box 3-1).

Human alterations also can affect the temporal dynamics of hydrologic connectivity in river networks. In a predominantly rural river network in central Illinois, the total dispersion of the flow was controlled primarily by geomorphological (~60%) and kinematic dispersion (~35%; Saco and Kumar, 2002). In contrast, hydrodynamic dispersion cumulatively contributed to 72–86% of the total dispersion in highly urbanized watersheds in the Chicago metropolitan area (Cantone and Schmidt, 2011). The rapid hydrologic travel times associated with impervious surface runoff and rapid flow through the sewer and storm drain networks contributed to the predominant influence of hydrodynamic dispersion (Cantone and Schmidt, 2011).

Interbasin water transfer also affects the temporal and spatial dynamics of flow in human-dominated river networks (Meador, 1996). Water is fundamental to human societies for drinking, food production, industry, waste transport and processing, recreation, and aesthetics. Engineered infrastructure moves water (and associated waste products) where and when it is needed (or removes it from where it is unwanted). Many streams in human-dominated watersheds, particularly streams that historically have ephemeral and intermittent flows, receive a significant proportion of their baseflow from municipal and industrial wastewater effluent discharges (Box 3-1). Streams that would be dry in the absence of these discharges are called effluent-dependent streams, whereas those that receive most, but not all, of their flow from effluent are called effluent-dominated streams (Brooks et al., 2006). About 25% of permitted effluent discharges in the United States enter streams with mean annual flows incapable of diluting effluents by more than 10-fold. This percentage of permitted effluent discharges entering streams incapable of diluting effluents by more than 10-fold increases to 60% when low-flow discharge is considered (Brooks et al., 2006). Streams draining human-dominated areas also can derive baseflow from ground water recharged by over-irrigation and leaky infrastructure (Lerner, 1986; Roach et al., 2008; Townsend-Small et al., 2013).

Ultimately, these alterations can increase the frequency, duration, magnitude, and predictability of baseflows when tributaries might otherwise contain little or no water. Because dry periods in intermittent and ephemeral streams contribute to the key transformation, lag, and refuge functions these systems perform (Sections 3.4 and 3.5), loss of these dry periods has consequences for downstream waters. In addition, when water is stored or imported for human use, it is essentially being "borrowed" from another period or location, which then must contend with reduced water availability. Without careful water management and reuse (e.g., Bischel et al., 2013), any benefits of baseflow augmentation can be overshadowed by potential risks, such as increased contaminant and pathogen exposures (Section 3.4.4) and increased success of introduced species (Jackson and Pringle, 2010).

3.3.2 Sediment

Sediment carried with water flow from streams to downstream waters is critical for maintaining the river network. Fluvial sediments scour channels, deposit to form channel features, and influence channel hydrodynamics (Church, 2006). Although sediment is essential to river systems, excess sediment can impair ecological integrity by filling interstitial spaces, reducing channel capacity, blocking sunlight transmission through the water column, and increasing contaminant and nutrient concentrations (Wood and Armitage, 1997).

Sediment in headwater streams originates from nearby hillslopes and enters these streams via overland flow, bank erosion (Grimshaw and Lewin, 1980), and infrequent disturbances such as landslides and debris flows (e.g., Benda and Dunne, 1987; Swanson et al., 1998; Eaton et al., 2003). Sediment transported within river networks can be divided into two major categories: suspended and bedload. Suspended sediment is fine sediment (clay, silt, fine sand) that requires slow velocities and little turbulence to remain entrained in the water column; bedload sediment is coarser particles that slide, roll, and bounce along the streambed during faster, more turbulent flows (Church, 2006; Wilcock et al., 2009).

The dynamic balance between sediment supply and transport capacity (Lane, 1955; Bull, 1991; Trimble, 2010)—with the variables of sediment flux and sediment grain size on one side, and discharge and channel slope on the other—is a principal paradigm of fluvial geomorphology. If one of these variables changes, a compensatory change occurs in at least one of the other variables. For example, if discharge increases, a lower channel slope is needed to transport the same amount of similarly sized sediment; alternatively, less discharge or lower channel slope is needed to move a load of fine sediment than the same load of coarse sediment. Associated with this balance is the relationship between channel geometry (width and depth) and discharge (Leopold and Maddock, 1953), and adjustments to maintain a dynamic balance also can include changes in channel dimensions.

The sediment supply-transport capacity balance is particularly relevant to geomorphologic connectivity in river networks, because these variables typically differ as one moves from headwater streams to downstream rivers (Ferguson et al., 2006; Ferguson and Hoey, 2008). For example, slope and grain size typically decrease, whereas discharge and channel size typically increase, in downstream reaches (Church, 2002). Thus, streams cumulatively and aggregatively affect rivers in part by changing sediment supply or transport capacity locally at confluences over time. Relatively small, local contributions in sediment and discharge from a tributary stream might elicit no detectable change or only a short-lived spike in downstream sediment characteristics, discharge, or channel geometry. In contrast, tributary streams making large relative contributions at mainstem confluences elicit strong, stepped changes in mainstem characteristics. Because headwater streams can make large contributions during infrequent disturbances (e.g., floods, debris flows), the influence of headwater streams on downstream waters can vary significantly over time, and even headwater streams can have long-lasting effects on rivers.

Human alterations can exert considerable influence on the structure and distribution of a watershed's river network, thereby affecting sediment-based connections between headwater streams and downstream waters. For example, road building in steep forested areas in the U.S. Pacific Northwest can cause soil erosion, create concentrated discharge, and increase stream channel network lengths, all of which affect the spatial distribution, intensity, and timing of erosional processes and cumulative sediment delivery to downstream waters (Montgomery, 1994; Wemple et al., 1996; Wemple et al., 2001).

Dams also modify sediment dynamics within river networks. Sediment concentrations and suspended loads can be reduced for hundreds of kilometers downstream of dams, as is especially apparent in the semiarid and arid western U.S. river networks (Williams and Wolman, 1984). The disruption of downstream sediment supply by dams alters the balance between sediment supply and transport capacity (Williams and Wolman, 1984; Kondolf, 1997). Water released from dams lacks sediment load and thus has excess energy. This energy often downcuts channels downstream of dams, causing channel incision and streambed coarsening as finer gravels and sands are transported downstream over time (Williams and Wolman, 1984; Kondolf, 1997). The elimination of floods enables the encroachment of terrestrial vegetation, resulting in channel narrowing and the conversion of complex, multithreaded channels into simple, single-thread channels.

Other human activities also can affect sediment dynamics. Gravel and sand mining locally removes bed sediment and lowers streambed elevation, creating a steep gradient change. Erosion of the streambed can occur both upstream and downstream of the mine. The steep gradient change increases stream power locally, which increases sediment demand and causes the streambed to erode in the upstream direction via headcutting, which often extends far up into tributary channels (e.g., Florsheim et al., 2001; Rinaldi et al., 2005; Rieke-Zapp and Nichols, 2011). Erosion in the downstream direction occurs because most of the sediment being carried by water is deposited in the mining pit, leaving the water that passes over the pit with excess energy that subsequently leads to downstream channel downcutting (Bull and Scott, 1974; Kondolf, 1997). These examples show that the dynamic balance between sediment supply and transport capacity represents a fundamental longitudinal connection along the river network that must be considered to determine the potential repercussions of human alterations.

Streams transport and store sediment. Headwater streams tend to have low competence to transport sediment during baseflow (Gooderham et al., 2007), but they have structures (boulders, woody debris) that entrain and store colluvial sediments between infrequent disturbances (e.g., stormflows) that are the dominant means for downstream sediment transport (e.g., Gomi and Sidle, 2003). Because of their abundance and distribution, headwater streams can have a substantial cumulative effect on downstream waters via sediment storage and transport. Poor soil conservation, drainage of wetlands, deforestation, and tributary channelization associated with the development of agricultural land has long been recognized as being detrimental to downstream waters via their connections with headwater streams (Person et al., 1936). To stem further degradation, government agencies encouraged and funded various soil conservation practices and the construction of small impoundments on headwater streams to trap sediment and provide stable water supplies for livestock, irrigation, and recreation (Person et al., 1936; Renwick et al., 2005). Although most such ponds are small (≤1 ha or 2.5 acre) and represent only ~20% of the total impounded area (or 0.4% of the total watershed area), they can cumulatively have a significant effect. For example, Smith and Kraft (2005) estimated that the approximately 2.3 million ponds distributed primarily on headwater streams of the Mississippi River network cumulatively captured 25–50% of the eroded soil from the landscape.

Ephemeral desert streams are another example of sediment connections between headwater streams and downstream waters. These ephemeral streams can exhibit high sediment export efficiency by having higher bedload per unit stream power than that of forested perennial streams (Laronne and Reid, 1993). Despite infrequent flows of short duration, flood waves (bores) in ephemeral desert streams can carry substantial amounts of sediment downstream (Hassan, 1990). The transport distance associated with these floods, however, often is insufficient to link them directly to perennial rivers. For example, a reach-scale study in the Walnut Gulch Experimental Watershed in Arizona estimated sand transport distances of only 401 and 734 m in nine floods over two consecutive years (Powell et al., 2007). Over longer times spans the episodic nature of flow in ephemeral and intermittent channels transfers sediment in a stepwise manner, depositing sediment some distance downstream and then moving it farther downstream by subsequent events. The frequency, timing, and predictability of stream runoff and therefore sediment transport vary widely with significant seasonal, annual, and interannual variations that depend on elevation, climate, channel substrate, geology and the presence of shallow ground water. Over longer time spans, however, sediment will continue to move downstream and affect downstream waters (Brooks and Lemon, 2007).

Despite increasing bank erosion rates with increasing channel size and discharge, sediment yield from watersheds typically decreases with increasing drainage area, due to increased sediment deposition within channels and on nearby floodplains (Walling, 1983). This storage of sediment contributes to the temporal attenuation or lag in the sediment delivery to downstream waters; it also illustrates that headwater streams are important sediment sources for maintaining channels and floodplains.

Streams also can store substantial amounts of sediment that are released only during rare export events. A series of experimental sediment introductions into steep, ephemeral, second-order streams in southwestern Washington showed that between 30 and 45% of the added sediment (ranging from clay to coarse sand) was exported to the mainstem 95−125 m downstream, during stormflows of 66−69% of bank full discharge (Duncan et al., 1987). Virtually all the added fine clay particles were exported from the ephemeral streams to the mainstem, presumably because this fraction remained suspended at even moderate flows (Duncan et al., 1987). Headwater streams within an Oregon Coastal Range watershed (2.5 km^2 area) stored 23% of total stored sediment within the watershed's river and valley network, compared with only 9% storage within the mainstem channel (May and Gresswell, 2003). Trimble (1999) constructed a long-term sediment budget for the Coon Creek watershed (360 km^2), a Wisconsin stream in the Mississippi River drainage, over periods coinciding with major land-use changes. When agricultural practices caused major soil erosion (1853–1938), streams acted as net sources of sediment (42×10^3 Mg yr^{-1}); after erosion control, streambank stabilization, and revegetation (1975–1993), streams became net sediment sinks (9×10^3 Mg yr^{-1}) (Trimble, 1999).

Several studies identify abrupt changes in sediment size and channel morphology that coincide with stream confluences having sufficiently high symmetry ratios (Knighton, 1980; Rhoads, 1987; Rice and Church, 1998; Rice et al., 2001). Reviews of tributary confluence data have identified that symmetry ratios ranging from 0.2 to 0.7 are needed to create a discernible sediment or channel morphology discontinuity along a mainstem (Rhoads, 1987; Benda, 2008). Suspended particulate matter (inorganic + organic) and bed particle size were measured above and below eight confluences on the Acheron River in Australia to determine stream contributions (Wallis et al., 2008; Wallis et al., 2009). Suspended particulate matter downstream of confluences approximated the sum of mainstem and stream exports during high flows, but stream contributions were negligible during low flows (Wallis et al., 2009). Four of the eight confluences showed expected changes in bed particle size below confluences with streams, but bed particle sizes were similar in the mainstem and stream for the remaining confluences (Wallis et al., 2008).

Streams, through their connections to rivers at confluences, can disrupt longitudinal trends in discharge of water and sediment in rivers (Best, 1988; Benda et al., 2004; Ribeiro et al., 2012). For example, dams often remove much of the sediment from transport, whereas most streams naturally are sediment sources. The objective of a study on the Agigawa River in Japan was to examine contrasting disruptions associated with a dam (sediment removal) and a stream confluence (sediment discharge) downstream of the dam (Katano et al., 2009). Stream sediment contributions to the river reversed many of the dam-related changes to downstream waters, including restoration of turbidity levels and the proportion of sand and gravel substrate in the river bed (Katano et al., 2009). Other upstream land uses can also have an effect on downstream sediment transport. Numerous modeling studies have shown how land use can affect sediment export from headwater streams to downstream waters. For example, Howarth et al. (1991) used the Generalized Watershed Loading Function model in the Hudson River estuary and its associated watershed and demonstrated that urban, suburban, and agricultural land uses in headwater watersheds produced the highest proportion of downstream sediment and organic carbon delivery to the estuary. More recently, Wilson and Weng (2011) applied the Soil and Water Assessment Tool in the Des Plaines River watershed in Illinois to simulate the cumulative effects of headwater streams on downstream total suspended solids concentrations. Their calibrated model projected that expansion of medium- and high-density residential development in place of low-density residential development in headwater subwatersheds would decrease downstream total suspended solid concentrations.

3.3.3 Wood

Large woody debris (typically considered >10 cm diameter and >1 m long) has a strong influence on hydrodynamics, sediment transport and storage, and channel morphology (e.g., Harmon et al., 1986; Nakamura and Swanson, 1993; Abbe and Montgomery, 1996; Naiman and Decamps, 1997; Montgomery et al., 2003). Woody debris dissipates energy, traps moving material, and forms habitat for aquatic plants and animals (Anderson and Sedell, 1979; Harmon et al., 1986; Abbe and Montgomery, 1996; Naiman and Decamps, 1997; Gurnell et al., 2002). In-channel wood can redirect water movements, create pools, and slow water movement through a channel (Nakamura and Swanson, 1993; Abbe and Montgomery, 1996; Naiman and Decamps, 1997). Wood recruitment to forested streams occurs because of chronic tree mortality; episodic disturbances such as fire, debris flows, landslides, and windthrow; and bank erosion. The steeper topography associated with hillslopes along many headwater streams increases the likelihood that trees will fall toward the channel (Sobota et al., 2006), relative to streams in flatter terrain. Environmental setting, including valley slope, influences the supply of wood to streams and therefore the degree of connectivity between streams and downstream waters.

Wood tends to accumulate in, rather than be exported from, most forested headwater streams, due to their low discharge and relatively narrow channel widths (Keller and Swanson, 1979; Bilby and Ward, 1989; Gurnell, 2003). For example, wood was determined to have entered the channel more than 60 years earlier in a North Carolina headwater stream (Wallace et al., 2001); in some Pacific Northwest streams, wood entered the channel more than a century earlier (Swanson and Bachmann, 1976; Keller et al., 1981). Because of the large occurrence of wood and small size of streams, wood has a stronger influence on hydrologic and geomorphic processes in headwater streams than in most larger rivers (Bilby and Bisson, 1998).

Large, infrequent disturbance events are the primary drivers for wood movement from headwater streams (Benda and Cundy, 1990; Benda et al., 2005; Bigelow et al., 2007). Reeves et al. (2003) determined that 65% of the wood pieces and 46% of the wood volume in a fourth-order stream in Oregon's Coastal Range were delivered downstream from headwater streams by debris flows, rather than originating from the riparian zone next to the fourth-order channel. Using data from 131 reservoirs in Japan, investigators identified a curvilinear relationship between watershed area and large woody debris export (Seo et al., 2008); wood export per unit area increased with stream size for headwater streams (6–20 km^2), peaked at intermediate-sized streams (20–100 km^2), and then decreased with stream size for large streams (100–2,370 km^2). The amount of wood in low-gradient midwestern streams was determined to be supply limited mainly because human alteration both depletes large wood sources and results in altered hydrology and channel structure enhancing downstream transport of small wood (Johnson et al., 2006). Topography and topology also govern wood delivery from headwater streams. Downstream segments draining steep, finely dendritic networks receive a greater proportion of wood from headwater streams than networks that are low gradient and weakly dissected (Benda and Cundy, 1990; Reeves et al., 2003).

Additional evidence on wood-mediated connections along the river network comes from studies of wood upstream and downstream of tributary confluences. Several studies have assessed the distribution of wood associated with confluences. Wood volumes were measured upstream and downstream of 13 confluences (symmetry ratios ranged from 0.05 to 0.49) in the Cascade Range of western Washington (Kiffney et al., 2006). Wood volumes tended to peak at or immediately downstream of stream confluences (Kiffney et al., 2006), suggesting that streams are either important sources of wood to mainstems or alter channel form to enhance wood storage at confluences. Elevated wood density, however, was not associated with confluences of eight streams to the Acheron River in Australia (Wallis et al., 2009). The authors concluded that the study streams had insufficient capacity to transport wood to the mainstem, because streams had similar slope to the mainstem but lower discharges (Wallis et al., 2009).

Large wood can shorten sediment transport distances and debris flow runout by entrainment (Lancaster et al., 2003). Woody debris in 13 Coastal Range streams in Oregon had accumulation rates ranging from 0.003 to 0.03 $m^3\ m^{-1}\ yr^{-1}$, largely based on time since the last debris flow (May and Gresswell, 2003). The volume of instream wood was strongly related to the volume of sediment stored. On average, 73% of stream sediment, prone to debris flow transport, was stored behind instream wood (May and Gresswell, 2003). Unlike most human-built dams, natural logjams and beaver dams are temporary structures that do not completely restrict transport of water, sediment, and biology across all discharge levels. Although natural wood accumulations act to restrict longitudinal connectivity by slowing the downstream transport, these features enhance lateral and vertical connectivity with the floodplain and hyporheic zone, respectively (Burchsted et al., 2010; Sawyer et al., 2011). The importance of wood in decreasing longitudinal connectivity, while enhancing lateral connectivity, temporary storage, and habitat diversity has been documented not only locally at unit and reach spatial scales (1–100 m stream length) but along entire networks where valley confinement is an important predictor for wood storage (Wohl and Beckman, 2014). Past and ongoing human activities (timber harvest, beaver trapping, road building along streams, placer mining, log floating, desnagging) have so completely removed in-channel wood and availability of near-channel old-growth wood recruitment, that retention of new wood in channels is unlikely (Wohl and Beckman, 2014). Wood (and associated sediment) movement from headwater streams to downstream segments occurs through infrequent, high-magnitude events (e.g., debris flows, fire). Once in larger streams, wood and sediment can be stored in alluvial fans and floodplains between stormflows that trigger additional downstream movement through the network (Benda et al., 2005). Because of the long distances and infrequent triggers associated with wood transport from most headwater streams to rivers, the relevant periods for governing transport aggregate over decades to centuries (Benda et al., 1998). Wood entering headwater streams can affect the downstream transport of water and materials in headwater streams, but also can be transported downstream from headwater streams where it is important habitat for aquatic life, a source of dissolved and particulate organic matter, and influential in controlling hydrodynamics and channel morphology of rivers.

3.3.4 Temperature (Heat Energy)

Connections between streams and downstream waters can affect heat transfer, and thus water temperature, throughout river networks (Knispel and Castella, 2003; Rice et al., 2008). Heat is thermal energy transferred across a boundary, whereas temperature is the amount of thermal energy per unit volume (Coutant, 1999; Poole and Berman, 2001). Therefore, the amount of heat and the size of the water body (i.e., volume, discharge) are fundamental controls of water temperature. Because water temperature is such a fundamental property that drives physical (e.g., viscosity and density of water), biological (e.g., organism behavior and physiology), and biogeochemical (e.g., nutrient assimilation and mineralization) characteristics of stream ecosystems, it can cumulatively have significant indirect effects on downstream waters via its effects on other forms of connectivity. This influence can occur over even relatively small spatial scales or patches (Sections 3.4 and 4.5; Allan, 1995). For example, water temperature strongly regulates stream ecosystem respiration, which then drives nutrient uptake (Section 3.4.1; Demars et al., 2011). Warmer temperatures exacerbates eutrophication problems such as fish kills, and heat stress can interact with chemicals synergistically or antagonistically making them more or less toxic to organisms, respectively (e.g., Holmstrup et al., 2010).

The total net heat exchange for a stream has several components, including heat flux from solar radiation, evaporation, convection with air, conduction with the streambed sediments, and advection with direct inputs from precipitation, ground water, tributaries, and effluents (Webb, 1996; Coutant, 1999). Given these diverse thermal energy fluxes, numerous direct and indirect factors can change stream temperature. For instance, riparian vegetation directly affects stream temperature by insulation (shading incoming solar radiation and trapping air, reducing wind; Moore et al., 2005) and indirectly affects stream temperature via its influence on channel morphology (e.g., Trimble, 1997) and degree of hyporheic exchange through input of woody debris (e.g., Sawyer et al., 2012). Channel morphology can directly influence stream temperature by affecting bank shading and altering channel width-to-depth ratio, and indirectly influence stream temperature by affecting hyporheic exchange. Hyporheic exchange influences stream temperature via buffering (reducing the diel temperature range) and lagging (offsetting daily temperature patterns relative to surface-water patterns) effects, due to the extended alluvial flowpath and by the advection or conduction of thermal energy or both (Arrigoni et al., 2008).

Over coarse spatial scales, a nonlinear increase in mean daily water temperature typically occurs from headwater streams to large rivers (Caissie, 2006). A unimodal trend occurs in daily variation (i.e., daily maximum-minimum) of water temperature, as stable ground-water temperatures (in headwater streams) and greater depth and volume of water (in large rivers) buffer water temperatures from the daily changes typical in intermediate-sized streams (Caissie, 2006). The steep increase in water temperature immediately downstream of headwater streams is associated with more rapid flux of heat into headwater streams, as shallow water contacts the surrounding air and receives direct radiation (Caissie, 2006). This longitudinal pattern, however, does not hold for all river networks: Some river networks receive substantial deep ground-water contributions at lower reaches or advective inputs from tributaries along the mainstem. Channel network configurations can influence the length, dominant aspect relative to the sun, and distribution of tributaries, which influence the thermal heterogeneity along a stream that might be associated with inflowing surface and hyporheic water. Callahan et al. (2015) illustrated how topographic, geomorphic, riparian, and hyporheic exchange can interact to influence stream temperature in the Kenai Peninsula, AK. Ground-water inputs played important moderating roles in determining stream temperatures in both low-gradient versus steep headwater streams, despite these streams having different channel morphologies, draining contrasting topographies, and having different riparian canopies (Callahan et al., 2015). Although low-gradient headwater streams had fewer channel margin seeps and lower hyporheic exchange than the steep headwater streams, the subsurface-water temperature entering the low-gradient streams was lower during summer than that entering the steep streams (Callahan et al., 2015).

Although many studies have determined that several direct and indirect factors can alter stream temperature, including those listed above, these effects typically have been documented to carry for only short distances downstream. This is in part because most studies measuring stream temperature changes are conducted over reach or subreach scales (<100 m) and because stream-water temperature equilibrates rapidly (~4 hr) to immediate surrounding conditions (e.g., Zwieniecki and Newton, 1999; Rutherford et al., 2004; Hester et al., 2009). Some studies, however, do provide evidence of thermal connections along river networks. The empirical evidence supporting thermal connections between headwater streams and downstream waters includes studies that have gauged the spatial relationship of water temperature over river networks and studies that have detected discontinuities in river temperature associated with stream confluences. Geospatial analyses are used to assess the degree of spatial dependence of a variable across a river network, and are particularly well suited for studying connectivity within these systems. Studies of this type have shown that upstream water temperature is significantly related to downstream water temperature, even over relatively long distances. For example, water temperature data collected at 72 locations throughout a Catskill Mountain, NY watershed were used to predict daily mean summer water temperatures spatially throughout approximately 160 km of channel (Gardner and Sullivan, 2004). Results showed that water temperatures at points along the river network separated by up to nearly 20 km were related. Johnson et al. (2010) similarly used geostatistical analyses to determine the influence of headwater streams on downstream physicochemistry, including water temperature. Water temperature within the eastern Kentucky watershed was correlated across the river network over an average distance of approximately 5 km (Johnson et al., 2010).

Studies that have detected discontinuities in river temperature associated with stream confluences also provide evidence of thermal connections along river networks. Ebersole et al. (2003) identified and characterized cold patches along a river network in northeastern Oregon that largely had summer water temperatures exceeding the tolerance limit of native salmonids. Floodplain springbrook streams were among the cold patches identified and were determined to contribute the coldest water to the river network (Ebersole et al., 2003). A subsequent study in northeastern Oregon determined that tributary confluences typically provided coldwater (≥3 °C colder than mainstem temperatures) patches during the summer (Ebersole et al., 2015). In addition, 39% of these tributary confluences were with streams that contributed cold hyporheic water even when they lacked surface water—that is, they were ephemeral and intermittent streams that were significantly connected to downstream waters even when the streambed surfaces were dry (Ebersole et al., 2015). Unexpectedly, factors such as tributary size, flow presence, and flowpath length were not important in predicting whether a tributary's confluence would be a cold patch. Rather, the probability of a confluence's being a cold patch was largely explained by amount of available water at the end of the snowmelt season (Ebersole et al., 2015).

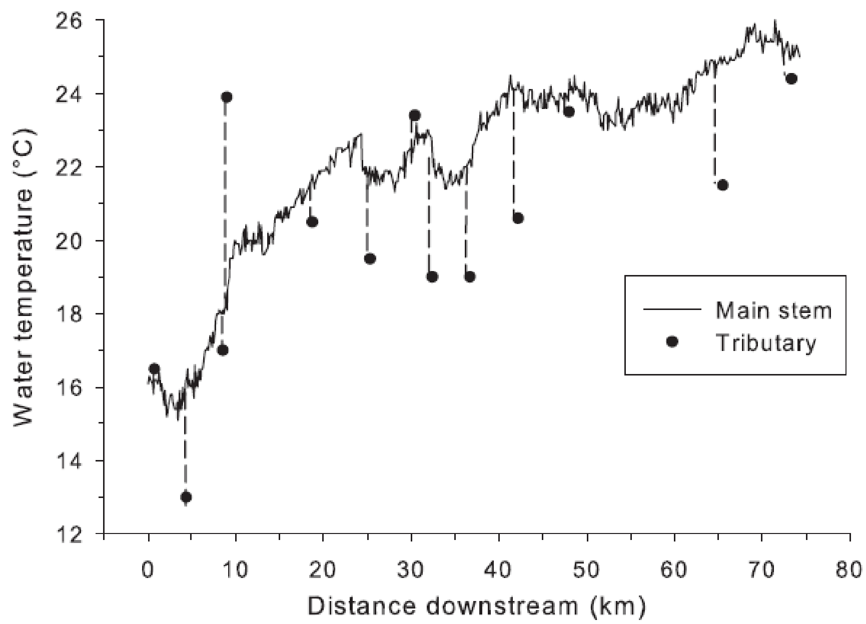
Thermal infrared sensors are a recent remote-sensing tool that can provide snapshots of thermal heterogeneity along river corridors (Torgersen et al., 2001; Torgersen et al., 2008; Cristea and Burges, 2009). Thermal maps and plots of longitudinal profiles overlaid by stream locations show that confluences coincide with distinct peaks and troughs in river temperature (Figure 3-3). The effects of streams were discernible when temperature differences of streams and the mainstem exceeded 1 °C and streams had large symmetry ratios (Cristea and Burges, 2009). In most cases, the effect of the stream on river-water temperature was minor relative to longitudinal changes over the course of the river (Torgersen et al., 2001; Cristea and Burges, 2009). Despite having a relatively minor effect on temperature over the length of entire rivers, however, streams provide persistent coldwater habitats that are less susceptible to meteorological variation than other classes of thermal refuges and therefore are particularly important for aquatic life (Section 3.5.2; Dugdale et al., 2013).

Although headwater stream temperatures are highly responsive to local conditions, they still can have a cumulative effect on downstream waters. The fact that large-scale alteration of headwater streams has been documented to affect downstream water temperature illustrates this point. For example, reductions in baseflow (ground-water inputs) resulting from increased surface runoff from impervious surfaces (Leopold, 1968) and reduced hyporheic exchange through the engineered piping, straightening, and hardening of streambeds contribute to increased average and maximum summer water temperatures and decreased average and minimum winter temperatures in downstream waters. The combination of riparian vegetation removal, increased urban runoff, and storm sewer inputs results in larger temperature swings associated with increased channel width-to-depth ratios and thus air-water surface area available for radiant, evaporative, and convective fluxes (LeBlanc et al., 1997).

3.4 Chemical Connections

Chemical connections are linkages between headwater and other tributary streams and their downstream waters based on the transport of chemical elements and compounds (e.g., nutrients, dissolved and particulate organic matter, ions, and contaminants). Chemical connectivity between streams and rivers involves the transformation, removal, and transport of these substances throughout the river network; these processes, in turn, influence water quality, sediment deposition, nutrient availability, and biotic functions in rivers.

Figure 3-3. Airborne thermal infrared remotely sensed water temperature in the mainstem and at tributary confluences of the North Fork John Day River, OR, on 4 August 1998. Line indicates mainstem, black dots indicate tributary confluences, and dashed vertical lines indicate location of tributary confluences along the mainstem. Reprinted with permission from Torgersen et al. (2008).



Because water flow is the primary mechanism for downstream transport of chemical substances, chemical connectivity is closely related to hydrologic connectivity (Sections 2.2 and 3.3.1). The movement of water across and through landscapes and into river networks integrates potential solute sources and sinks throughout the watershed. Thus, solute concentrations are an integration of upstream mixing processes and transport processes in the stream channel. In simplest terms, streams generally operate in two modes: a high-discharge throughput mode in which solutes and particles entering the stream channel are quickly transported downstream, and a low-discharge processing mode whereby solutes and particles are processed or stored near where they entered the river network (Meyer and Likens, 1979).

Factors that affect hydrologic connectivity (including precipitation patterns and human alterations) modify these upstream-downstream chemical linkages. For example, the spatial and temporal variability of rainfall affects chemical connectivity between streams and rivers. Many headwater streams receive pulsed inputs of water, sediment, organic matter, and other materials during rain events. Periodic flows in ephemeral or intermittent streams can have a strong influence on biogeochemistry by connecting the channel to other landscape elements (Valett et al., 2005), and this episodic connection can transmit substantial amounts of material into downstream rivers (Nadeau and Rains, 2007).

The alternation of dry and flowing periods largely drives the temporal dynamics of chemical connections between ephemeral and intermittent streams and downstream waters. The frequency, duration, magnitude, timing, and rate of change of flow further account for the variable connectivity observed within and across river networks over space and time (Section 1.2.2). Materials accumulate on and within dry streambeds where they are temporarily stored and can undergo transformations (Acuña et al., 2005; Fritz et al., 2006a; Ademollo et al., 2011; Arce et al., 2014). Transmission losses, tributary confluences, various channel forms, and retention structures also can contribute to the spatial distribution of materials and processes in dry streambeds (Marcus, 1987; Graf et al., 1991; Reneau et al., 2004; Taylor and Little, 2013). The onset of flows in ephemeral and intermittent stream channels, particularly those following long dry periods and initiated by floods (i.e., first flushes), are important in transporting and transforming large amounts of unique materials for long distances downstream, which then can have significant effects (e.g., Obermann et al., 2009; Hladyz et al., 2011; David et al., 2012). Human alteration of channel characteristics (e.g., channel shape and depth) and organic matter inputs also affect the ability of streams to temporarily store and cycle materials before transport to downstream waters.

Biogeochemical transformations control the mobility of different chemicals by altering chemical properties, such as form (e.g., dissolved, colloidal, gravitoidal), bioavailability, and toxicity. Thus, transformation is a key process influencing the downstream transport and attenuation of chemicals. Physicochemical (e.g., pH, redox potential, chelator concentration, light, hydrologic residence time) and biological (e.g., extracellular enzymes, physiology, lipid content) conditions control the location, rate, and timing of chemical transformations in streams and downstream rivers. For example, the introduction of stream restoration structures (e.g., small log dams) can affect the spatial distribution of oxic and anoxic zones in streambeds and thus biogeochemical cycling and reaction rates for instream biogeochemical processes throughout the river network (Lautz and Fanelli, 2008). These types of human alterations, in turn, affect the form of chemical substances and the timing of their transport downstream (Box 3-1). Data from the Baltimore Ecosystem Study Long-Term Ecological Research site suggest that increased hydrologic connectivity from urban infrastructure (e.g., pipes, storm drains, ditches) in headwaters increases the frequencies of occurrence and transport rates of nutrients, carbon, and metals to downstream surface waters (Kaushal and Belt, 2012). Urbanization can cause complex downstream responses, however, and sometimes creates longer travel times (i.e., reduced downstream connections). For example, aging infrastructure can leak water and pollutants into ground water rather than transporting these materials directly downstream.

3.4.1 Nutrients

Studies have documented nutrient-based chemical connections along river networks. Alexander et al. (2007) investigated how stream size affected nitrogen transport in a northeastern U.S. river network. First-order headwater streams contributed approximately 65% of the nitrogen mass in second-order streams, and approximately 40% of that mass in fourth-order and higher order streams (Alexander et al., 2007). Alexander et al. (2000) conducted a study of major regional watersheds of the Mississippi River basin, which showed that instream nitrogen loss was inversely related to mean stream depth. This finding most likely resulted from the reduced occurrence of denitrification and settling of particulate nitrogen in deeper channels, due to reduced contact and exchange between stream water and benthic sediments (Alexander et al., 2000). Böhlke et al. (2009) used laboratory-, local-, and reach-scale studies to describe the effect of seasonal and event-based variation of instream properties (e.g., stream depth, flow rates, temperature) on denitrification rates in headwater streams, which can cause interannual variations in rates of nitrate export to downstream waters. A dynamic transport model using a one-dimensional version of the advection-dispersion equation was developed to estimate progressive instream nitrate removal from first- to fourth-order streams (Alexander et al., 2009). Model simulations indicated that denitrification rate constants in headwater tributaries varied strongly by season, based on biogeochemical and hydrologic factors. This in turn had a cumulative effect on downstream nitrate export (Alexander et al., 2009). These studies highlight how stream size affects nitrogen-based chemical connections, with headwater streams within the network affecting downstream water quality.

Phosphorus-based chemical connections also have been documented. Doyle et al. (2003) modeled the relative influence of hydrogeomorphic and uptake processes on longitudinal phosphorus retention through a river network of first- through sixth-order streams. The model revealed greater variation in uptake relative to hydrogeomorphic processes, and the authors concluded that uptake processes influence downstream variation in phosphorus retention at the watershed scale more than hydrogeomorphology.

Research on hydrologic control and seasonality of nutrient export from streams in the Mississippi River basin similarly provides evidence of downstream connectivity (Section B.4.3.2.1). Export of dissolved reactive phosphorus from second- and fourth-order streams in agricultural watersheds occurred mainly during high-discharge conditions, with discharges equal to and greater than the 90th percentile exporting 84% of the dissolved reactive phosphorus, primarily during January and June (Royer et al., 2006). Similar patterns have been documented in total phosphorus concentrations of first- through fourth-order streams from another Mississippi River basin (Bayless et al., 2003). In another study, researchers modeled riverine dissolved reactive phosphorus yield of 73 watersheds within the Mississippi River basin during the January to June period, as a function of nutrient sources and precipitation (Jacobson et al., 2011). Riverine dissolved reactive phosphorus yield was positively related to fertilizer phosphorus inputs, human sources of phosphorus (e.g., sewage effluent), and precipitation, which generates surface runoff that moves fertilizer applied to the landscape into streams and rivers that then transport it downstream (Jacobson et al., 2011). These studies demonstrate the connections and processes by which nutrients exported from streams in the Mississippi River basin contribute to anoxia in the Gulf of Mexico (Rabalais et al., 2002).

Other environmental and biological processes also can affect nutrient-based chemical connections. The underlying geology of the Mokelumne River in California's central Sierra Nevada Mountains affected the spatial and temporal variability in chemical connections. Holloway et al. (1998) examined water quality in that watershed to identify primary sources of nitrate entering downstream reservoirs. They conducted a paired watershed comparison with two ephemeral streams in nearby watersheds that were underlain with different rock types (diorite vs. biotite schist) but had similar land-use, vegetation, topography, and watershed area. Many samples from the diorite watershed had nitrate concentrations below detection limits (<4 μM), with a median concentration of 3.3 μM; concentrations were not strongly associated with the start or end of the high precipitation period. In the biotite schist watershed, maximum stream concentrations of nitrate (>300 μM) occurred at the start of the high precipitation period, and concentrations decreased over time. A nearby perennial stream, also in a biotite schist watershed, displayed this same temporal trend, with highest nitrate concentrations at the beginning of the rainy season and decreasing concentrations during the spring. Holloway et al. (1998) concluded that biotite schist streams contributed a disproportionately large amount of total nitrate to downstream reservoirs, despite draining only a small area of the entire watershed.

In another study, nitrate concentrations were measured at 50 sites across the West Fork watershed of the Gallatin River in southwestern Montana's northern Rocky Mountains under different hydrologic conditions and across two seasons, growing and dormant (Gardner and McGlynn, 2009). Streams ranged from first-order mountain streams to fourth-order streams near the West Fork-Gallatin River confluence. In the dormant season, the distance over which nitrate concentrations were spatially correlated ranged from 3.2 to 5.5 km. In the growing season, this range decreased to 1.9 to 2.7 km. This seasonal difference likely resulted from greater biological uptake and use of nitrate during the growing season, which then limited its downstream transport; during the dormant season, downstream transport increased, resulting in greater spatial dependence in nitrate concentrations (Gardner and McGlynn, 2009).

Seasonal variability in chemical connectivity also was observed in Arizona's San Pedro River. Differences in dissolved organic nitrogen concentration were detected among three segments of the river during the dry season, but stream water was well mixed, the system was hydrologically connected, and no differences in dissolved organic nitrogen concentration were detected during the wet season (Brooks and Lemon, 2007). These seasonal differences occur because nitrogen accumulates locally at varying levels during drier periods but is mixed and transported downstream during large, infrequent storm events, making nitrogen concentrations more longitudinally uniform (Fisher et al., 2001).

Peterson et al. (2001) examined chemical connectivity by studying similar network components across different types of river networks. After measuring nitrogen export from 12 headwater streams distributed throughout the contiguous United States, Alaska, and Puerto Rico, they found that uptake and transformation of inorganic nitrogen were most rapid in the smallest headwater streams (Peterson et al., 2001). Given the prevalence of headwater streams on the landscape (Section 3.2) and their hydrologic connectivity to other river network components (Sections 2.2 and 3.3.1), headwater stream nitrogen processing can improve water quality in downstream waters. Many other studies also highlight the importance of nitrogen processing in headwater streams (e.g., Hill et al., 1998; Hill and Lymburner, 1998; Triska et al., 2007). Mulholland et al. (2008) measured in situ rates of nitrate removal by denitrification in 72 streams across different biomes and used those rates to model how headwater and larger streams in a river network respond to simulated nitrate loading increases. At low loading rates, the biotic removal of dissolved nitrogen from water is high and occurs primarily in headwater streams, which reduces loading to larger streams and rivers downstream. At moderate loading rates, the ability of headwater streams to remove nitrogen is reduced, but larger streams can remove the excess nitrogen. At high loading rates, removal by headwater streams and larger streams in the river network is ineffective, resulting in high nitrogen export to rivers (Mulholland et al., 2008). Similar results were obtained by Wollheim et al. (2008) in the Ipswich River, MA.

Helton et al. (2011) conducted simulation experiments that illustrated the effects of connectivity in the Ispwich River (MA) and Flat Creek (WY) networks, via the use of river-network models of nitrate dynamics. The nitrate models underpredicted nitrogen removal in many reaches, which was attributed to connections between the river channels and neighboring wetlands that were not characterized by the model and that functioned as nitrogen sinks (Section 4.3.3.2). By not representing the fine-scale variability in nitrogen uptake in river-network models and assuming that nitrogen uptake decreases with depth along a river network, simulations can potentially misrepresent the export of nitrogen from headwater streams to downstream waters (Darracq and Destouni, 2005, 2007). The potential for this misrepresentation, however, depends on the spatial scale of the study and the specific characteristics of the river network.

The influences of headwater and other tributary streams on nutrient concentrations in larger downstream waters, as detailed in the numerous examples above, reflect the combined processes of nutrient cycling and downstream transport that occur throughout river networks, albeit most intensively in headwater streams. The concept of nutrient spiraling provides an approach to quantifying these cycling and transport processes and a relatively simple framework for understanding their implications. As nutrients cycle through various forms or ecosystem compartments, being consumed and regenerated for reuse, they complete a “cycle” only after having been displaced some distance downstream, which stretches the cycle into a helix or “spiral” (Webster and Patten, 1979). The stretch of the spiral, or the openness between its loops, is primarily determined by flow, whereas the diameter of the loops is mainly determined by biological activity (Cummins et al., 2006). Nutrients such as dissolved phosphorus and nitrogen, which enter the stream via ground-water or overland flow, are removed from the water column by algae and microbial organisms. These nutrients are then consumed by organisms at higher trophic levels, transported farther downstream as suspended particles, or returned to the dissolved pool through cell death and lysis. Nutrients flowing through the food web also are regenerated to the dissolved pool via excretion and microbial decomposition. Nutrients in the dissolved, particulate, and living tissue phases of the cycling process are subject to downstream transport, such that each phase transition moves some distance downstream. The average downstream distance associated with one complete cycle—from a dissolved inorganic form in the water column, through microbial uptake, subsequent transformations through the food web, and back to a dissolved available form—is termed the “spiraling length.”

Although measurement of total spiraling length requires detailed study of tracer dynamics through multiple compartments of the stream ecosystem, Newbold et al. (1981; 1983a) have shown that it can be approximated by “uptake length” or the distance traveled in the water column before algal and microbial assimilation occurs. Uptake lengths for phosphorus and nitrogen can be estimated precisely only from tracer additions of radioactive or stable isotopes, but they can be roughly estimated from experimental additions that briefly raise the concentration of the natural form of the nutrient. Ensign and Doyle (2006) compiled results of 404 measurements of uptake length of phosphate, ammonium, and nitrate in streams and rivers ranging from first- to fifth-order. For a given stream order, they estimated the number of cycles that each nutrient had undergone as the ratio of median uptake length to the average length of stream for that stream order (from Leopold et al., 1964). They found that the three nutrient forms cycle between roughly 8 (nitrate) and 40 (ammonium) times within the length of a first-order stream, and between roughly 8 and 90 times within the respective lengths of first- to fourth-order streams.

Withers and Jarvie (2008) also compared phosphorus uptake lengths among different streams. Shorter uptake lengths are indicative of more rapid phosphorus cycling and greater efficiency of phosphorus retention. The shortest uptake lengths (2–580 m) were in first-order streams that drained “pristine” watersheds. Uptake lengths were longer (26–3,460 m) in second- to fourth-order streams that drained agricultural watersheds, and longest (4,140–367,000 m) in fifth-order rivers that drained a mixture of urban and agricultural land use (Withers and Jarvie, 2008).

These studies highlight the high nutrient-processing potential of headwater streams. This potential results from their low water volume-to-bed sediment area ratio, which enhances conditions for key nutrient uptake processes (e.g., adsorption, precipitation, assimilation) not only at the water-bed interface but within the streambed sediments (Withers and Jarvie, 2008). Downstream ecosystems depend on processes that occur in headwater streams. Given that roughly half the water reaching larger tributaries and rivers originates from headwater streams (Section 3.3.1), the results of Ensign and Doyle (2006) make clear that phosphorus and nitrogen arrive at downstream waters having already been cycled many times in headwater and smaller tributaries. This cycling is, fundamentally, a complex of ecosystem processes that intensively uses nutrients and then regenerates them for delivery to downstream waters much in their original form. Because nutrients undergo transformations across various forms (e.g., dissolved, particulate, inorganic, or in living organisms) while being transported downstream (i.e., spiraling), explicitly identifying their exact origin in the network can be difficult.

Although headwater nutrient cycling, or spiraling, functions largely to deliver regenerated nutrients downstream, headwater stream processes measurably alter the delivery of nutrients to downstream waters in many ways. For example, if cycling has been seriously impaired such that nutrient regeneration is inhibited or nutrients are generated in biologically unavailable or toxic forms, the downstream effects could be large. Nutrients taken up as readily available inorganic forms can be released back to the water column as organic forms (Mulholland et al., 1988) that are less available for biotic uptake (Seitzinger et al., 2002). Similarly, nutrients incorporated into particles are not entirely regenerated (Merriam et al., 2002; Hall et al., 2009), but rather accumulate and contribute to longitudinally increasing particulate loads (Whiles and Dodds, 2002). The amount of phosphorus and nitrogen delivered downstream by headwater streams cycles seasonally due to the accumulation of nutrients in temporarily growing streambed biomass (Mulholland and Hill, 1997; Mulholland et al., 2004). Such variations affect downstream productivity (Mulholland et al., 1995) and help explain the seasonality in the spatial correlations of nutrient concentrations described above.

Microbially mediated transformations affect the forms of nitrogen transported from headwater streams to downstream waters, and these transformations can influence—and be influenced by—human alterations of the landscape. Nitrification, or the transformation of ammonium to nitrate, occurs naturally in undisturbed headwater streams (e.g., Bernhardt et al., 2002) but increases sharply in response to ammonium inputs (e.g., Newbold et al., 1983b), thereby reducing potential ammonium toxicity from pollutant inputs (Chapra, 1996). Denitrification, which removes nitrate from stream-water through transformation to atmospheric nitrogen, is also widespread among headwater streams, as demonstrated by stable isotope tracer additions to 72 streams in the conterminous United States and Puerto Rico (Mulholland et al., 2008). Mulholland et al. (2008) estimated that headwater streams (<100 L s^{-1}, about third order or less) free from agricultural or urban impacts reduce downstream delivery of nitrogen by 20–40%. Alexander et al. (2007) and Wollheim et al. (2008), using earlier and less extensive measurements of denitrification rates, estimated nitrogen removal of 8 and 16% by stream networks of first to third order and first to fifth order, respectively. In headwater agricultural streams, denitrification in stream sediments might not be effective at removing nitrate from stream water because of altered hydrology. In watersheds with tile drains and channelized headwaters, stream nitrate concentration is positively correlated with stream discharge, suggesting that these altered streams are in throughput mode, whereby nitrate inputs are rapidly transported downstream with little retention or processing (Royer et al., 2004).

Small tributaries also affect the downstream delivery of nutrients through abiotic processes. Meyer and Likens (1979) showed that phosphorus concentrations in a forested first-order New Hampshire stream were reduced by sorption to stream sediments. A much stronger sorption of phosphorus by stream sediments was observed by Simmons (2010) in first- to third-order West Virginia streams impacted by acid mine drainage, where phosphorus sorbed to metal hydroxide precipitates introduced by mine drainage. These examples further illustrate the potential for headwater streams to absorb nutrient impacts to the benefit of downstream waters.

3.4.2 Dissolved and Particulate Organic Matter

Headwater streams supply downstream waters with dissolved and particulate organic carbon, which support biological activity throughout the river network. Organic carbon enters headwater streams from the surrounding landscape, including wetlands (Section 4.3.3.4 and 4.4.3.1), in the form of terrestrial leaf litter and other seasonal inputs, dissolved organic carbon (DOC) in subsurface and surface runoff, and fine particulate organic matter (including eroded soil) in surface runoff. Headwater reaches also export organic carbon produced within the stream by photosynthesis, both as DOC (Kaplan and Bott, 1982) and suspended particles (Marker and Gunn, 1977; Lamberti and Resh, 1987).

Ågren et al. (2007) determined that headwater streams exported the largest amount of terrestrial DOC on a per unit basis in the Krycklan watershed in Sweden. The amount of organic matter exported from headwater streams to downstream waters varies with multiple factors, including surrounding land use. For example, Schelker et al. (2014) developed a mixing-model approach and quantified that forest harvesting at areal proportions of 11% and 23–25% of a northern Sweden watershed induced stepped increases in DOC delivery, due to disturbance of shallow forest soils and subsequent transport from headwaters to downstream locations. Similarly, a 20% increase in downstream DOC concentrations was predicted following forest harvesting in the headwater areas of the H.J. Andrews Long Term Ecological Research site, using the VELMA (Visualizing Ecosystems for Land Management Assessments) model (Abdelnour et al., 2013). In southeast Arizona, Meixner et al. (2007) found that DOC consistently doubled to tripled in the San Pedro River during storm events from a flush of terrestrial organic matter and nutrients. This is comparable to the flush response observed by others (Fisher et al., 1982; Brooks et al., 2007) during monsoon precipitation events in the southwestern United States. These examples further demonstrate connectivity of headwater streams and their cumulative effects on downstream water quality.

Fisher and Likens (1973) followed the fate of these inputs in a forested headwater stream in New Hampshire. They concluded that 34% of inputs were mineralized through respiration by consumers and microbes within the headwater stream, which represented the "ecosystem efficiency" of the reach. The remaining 66% was exported downstream and constituted, as Fisher and Likens (1973) observed, "… inputs to the next stream section where they are assimilated, or passed on (throughput) or both." Other studies have reported similar amounts of export. Webster and Meyer (1997) compiled organic matter budgets from 13 North American first- and second-order streams. The median ecosystem efficiency was 31%, implying a median export of 69% of organic matter inputs. A large body of literature has demonstrated that headwater streams modify and export organic carbon that significantly affects ecosystem processes throughout the river network.

Vannote et al. (1980) recognized that exported carbon was not simply the unutilized fraction but was also greatly modified in character. A basic tenet of their River Continuum Concept is that longitudinal variations in the structure of stream ecosystems reflect, in part, the cumulative effects of upstream organic matter processing. Much or most of the organic carbon exported from headwater streams has been altered either physically or chemically by ecosystem processes within the headwater reaches. Leaf litter contributes an average of 50% of the organic matter inputs to forested headwater streams (Benfield, 1997), but leaves and leaf fragments (>1 mm) account for only 2% or less of organic matter exports (Naiman and Sedell, 1979; Wallace et al., 1982; Minshall et al., 1983). The conversion of whole leaves to fine particles (<1 mm) involves physical abrasion, microbial decomposition, and invertebrate feeding and egestion (Kaushik and Hynes, 1971; Cummins et al., 1973; Petersen and Cummins, 1974). The rate of that conversion is affected by whether the leaves are in an aerobic environment, such as riffles, or an anaerobic environment, such as depositional pools (Cummins et al., 1980). Feeding activities of aquatic invertebrates called "shredders" break down leaves that have entered streams (Cummins and Klug, 1979; Cummins et al., 1989). Invertebrate activity is particularly important, as demonstrated by large reductions of fine particle export following experimental removal of invertebrates from a headwater stream (Cuffney et al., 1990; Wallace et al., 1991). Strong invertebrate influence on fine particle export also has been inferred from analysis of seasonal (Webster, 1983) and daily (Richardson et al., 2009) variations.

Downstream organisms consume organic carbon exported from headwater streams, supporting metabolism throughout the river network. In part, this results from direct consumption of detrital organic matter (Wallace et al., 1997; Hall et al., 2000), but much of the metabolic consumption of organic matter in streams occurs via microbial decomposition (Fisher and Likens, 1973). The microbes themselves are then consumed by other organisms (Hall and Meyer, 1998; Augspurger et al., 2008), whose energy in turn supports the food web through what is known as the "microbial loop" (Meyer, 1994). In addition to transformations associated with microbial and invertebrate activity, organic matter in streams can be transformed through other processes such as immersion (Corti et al., 2011) and abrasion (Paul et al., 2006); photodegradation also can be important in ephemeral and intermittent streams where leaves accumulate in dry channels exposed to sunlight (Dieter et al., 2011; Fellman et al., 2013).

The organic carbon turnover length, derived from the nutrient spiraling concept (Section 3.4.1; Newbold et al., 1982b), is a measure of the downstream fate of exported carbon. Carbon turnover length is the ratio of the downstream flux of organic carbon to ecosystem respiration per length of stream. It approximates the average distance that organic carbon would travel before being consumed and mineralized by aquatic organisms. Carbon turnover length for first-order streams is on the order of 1 to 10 km (Newbold et al., 1982b; Minshall et al., 1983), suggesting that organic carbon exported from headwater streams is likely to be used primarily in the somewhat larger streams to which they are direct tributaries (i.e., second- or third-order streams). The carbon turnover length, however, actually represents a weighted average of widely varying turnover lengths associated with the diverse array of particulate and dissolved forms of organic carbon in stream and river ecosystems (Newbold, 1992). Turnover lengths of specific organic carbon forms can be estimated if their rates of downstream transport and mineralization (or assimilation) are known. For example, Webster et al. (1999) estimated a turnover length of 108 m for whole leaves in a North Carolina second-order stream, but a much longer turnover length of 40 km for fine (<1 mm) organic particles. Newbold et al. (2005) obtained similar estimates of 38 and 59 km for the turnover lengths of two different size fractions of fine organic particles in a second-order Idaho stream. Kaplan et al. (2008) concluded that DOC in a third-order southeastern Pennsylvania stream consisted of a rapidly assimilated "labile" fraction with a turnover length of 240 m, a more slowly assimilated "semilabile" fraction with a turnover length of 4,500 m, and a "refractory" fraction with immeasurably slow assimilation, implying an indefinitely long turnover length sufficient to carry the carbon to coastal waters.

Because turnover length increases with stream size, organic carbon that travels to a larger order stream is likely to travel farther than its original turnover length predicts (Minshall et al., 1983; Webster and Meyer, 1997). For example, the organic carbon turnover length of the Salmon River, ID increased from 3.7 km in a second-order headwater stream to 1,200 km in the eighth-order reach, about 600 km downstream (Minshall et al., 1992). In a modeling study, Webster (2007) estimated that turnover length increased from several hundred meters in the headwater streams to greater than 100 km in a large downstream river. This progression of increasing turnover length from headwater streams to increasingly larger streams and rivers implies that organic carbon exported from headwaters supports metabolism throughout the river network.

Although turnover length reflects the spatial scale over which upstream exports of organic carbon are likely to support downstream metabolism, it does not provide direct evidence for or quantify the actual use of organic carbon in downstream reaches. Studies of transport and mass balance throughout the river network provide such evidence. Shih et al. (2010) applied the SPARROW (SPAtially Referenced Regressions On Watershed attributes) model to organic carbon data from 1,125 monitoring sites throughout the conterminous United States. They estimated that all river reaches (large and small) delivered an annual average of 72 kg C ha^{-1} of incremental drainage area, whereas the river systems as a whole exported 30 kg C ha^{-1}. Thus, 58% of carbon inputs were respired within the river networks, while the rest (42%) were transported downstream. Shih et al. (2010) did not specify the proportion of inputs originating from headwater streams, but using their results (with certain assumptions), we can estimate the amount of organic carbon in river networks that originates from headwater streams. We begin with the proportion of carbon originating from allochthonous sources as 0.78 (Shih et al., 2010). If we assume that the proportion of headwater streams in a drainage area is 0.50 (Section 3.2; Alexander et al., 2007; Caruso and Haynes, 2011), headwater streams then provide 0.39 (= 0.78 × 0.50) of the total organic carbon supply, with the input from the larger downstream network being 0.61 (i.e., 61%) of the carbon supply. Using the ecosystem efficiency for headwater streams of 31% (Webster and Meyer, 1997), the proportion of carbon originating from headwater streams that is delivered downstream is 0.39 × (1 − 0.31) = 0.27. The proportion of carbon exported from headwater streams (0.27), plus the proportion of carbon input directly to the downstream network (0.61), equals the total carbon input to the downstream network (0.88). Thus, 31% (= 0.27/0.88 × 100) of the total carbon supplied to downstream reaches originates from headwater streams.

Most terrestrial organic matter that enters headwater streams is transported downstream (Gomi et al., 2002; MacDonald and Coe, 2007), typically as fine particulate or dissolved organic matter (Bilby and Likens, 1980; Naiman, 1982; Wallace et al., 1995; Kiffney et al., 2000). These headwater streams also can export significant amounts of autochthonous organic matter via the downstream transport of benthic algae (Swanson and Bachmann, 1976). Both allochthonous and autochthonous organic matter can be transported significant distances downstream (Webster et al., 1999), especially during high flows (Bormann and Likens, 1979; Naiman, 1982; Wallace et al., 1995). The importance of discharge in determining organic matter transport dynamics highlights the interdependence of physical and biological connections within the river network. For example, Wallace et al. (1995) examined coarse particulate organic matter export in three headwater streams in North Carolina and found that 63–77% of export over a 9-year period occurred during the 20 largest floods. This finding suggests that headwater streams (including ephemeral and intermittent streams) can provide temporary storage for organic matter (Gomi et al., 2002), which is then transported downstream during storms or snowmelt. Exports also can vary seasonally, increasing in autumn and winter when deciduous trees drop their leaves (Wipfli et al., 2007) and in the spring when flowers and catkins are shed.

The amount of organic matter exported from headwater streams can be large, and often depends on factors such as discharge, abiotic retention mechanisms within the channel (Bilby and Likens, 1980), biological communities (Cuffney et al., 1990), and the quality and quantity of riparian vegetation in headwater watersheds (Wipfli and Musslewhite, 2004). For example, Wipfli and Gregovich (2002) found that organic matter export ranged from <1 to 286 g of detritus (dead organic matter) per stream per day in 52 coastal headwater streams in Alaska. When debris dams were removed from a New Hampshire headwater stream, export of fine particulate organic carbon increased by 632% (Bilby and Likens, 1980). The longitudinal discontinuities created by logjams and beaver dams slow the downstream transport of organic matter, enabling instream organisms to process the carbon and slowly leak material downstream (Wohl and Beckman, 2014). The strong links among organic matter storage, processing, and downstream transport in ephemeral streams of the southwestern United States can be seen in the distribution of organic matter of varying quality and mobility over periods with varying rainfall intensities (Norton et al., 2007). Arroyos or ephemeral channels in northeastern New Mexico are important in transporting and transforming organic matter that enhances the fertility of agricultural areas along downstream alluvial fans. More frequent but low-intensity rainfall was important in driving biochemical transformations that altered organic matter mobility and quality, which was subsequently transported downstream by larger storms (Norton et al., 2007). Traditional farming practices in the region relied on the temporary storage, transformation, and transport of organic matter from ephemeral streams (Norton et al., 2007; Sandor et al., 2007).

Although organic matter clearly is exported from headwater streams, effects on downstream organisms, and the distance over which these effects propagate are difficult to quantify (Wipfli et al., 2007). Many downstream organisms rely on organic matter and its associated microbes for food, but demonstrating where in the river network such material originates presents a challenge. Similarly, the conversion of organic matter to other forms (e.g., invertebrate or fish biomass via consumption), each with its own transport dynamics, makes tracking sources of downstream contributions difficult. Given the prevalence of headwater streams in both the landscape and the river network (Leopold et al., 1964), and their primacy in organic matter collection and processing, a logical conclusion is that headwater streams exert a strong influence on downstream organic matter dynamics. Benstead and Leigh (2012) estimated that headwater streams, including intermittent and ephemeral channels, result in a global carbon efflux of 1.6 Pg C yr^{-1}, making the overall contributions of rivers and streams about equivalent to all inland lakes and wetlands combined. In addition, headwater streams also serve as a source of colonists for downstream habitats (Section 3.5). For example, headwater springs can provide algae a winter refuge from freezing, then serve as a source of propagules for downstream reaches upon spring thaws (Huryn et al., 2005).

3.4.3 Ions

Measurements of ions and conductivity from nested study designs provide additional evidence for connectivity by various transport mechanisms. Rose (2007) collected data at 52 sampling stations in Georgia's Chattahoochee River basin, which includes the heavily urbanized region of Atlanta, over a 2-year period. The study sought to characterize baseflow hydrochemistry across a rural-to-urban land-use gradient. A plot of the major ion (sodium, bicarbonate alkalinity, chloride, and sulfate) concentrations versus downstream river distance showed distinct peaks relative to baseflow measurements, with elevated concentrations persisting downstream.

In a study of mined and unmined streams in the Buckhorn Creek basin in Kentucky, water measurements taken at several locations within the same tributary had similar conductivity values (Johnson et al., 2010). As expected, confluences disrupted this spatial similarity along the river network. Conductivity values along the mainstem decreased at confluences with unmined streams and increased at confluences with mined streams, demonstrating that headwater streams were transporting ions downstream and affecting downstream conductivity. This spatial pattern in conductivity was consistent between spring and summer surveys of the river network.

In a study in Sweden, measurements of pH from the outlets of seven watersheds were statistically related to headwater pH measurements in those watersheds (Temnerud et al., 2010). As pH at outlets increased under low-flow conditions, so did median pH of the headwater streams. This study illustrates the connectivity between the headwater components of the river network and the outlets of the watersheds and the cumulative effects of headwater streams to downstream waters.

3.4.4 Contaminants and Pathogens

The movement of contaminants—that is, substances that adversely affect organisms when present at sufficient concentrations—and waterborne pathogens provides another line of evidence for chemical connectivity between tributaries and the river network. Existing information typically has been derived from either empirical experiments that release tracer substances into streams to monitor movement along a longitudinal gradient or the use of modeled projections and characterization of contaminants. Studies also have examined trace metal data collected at multiple sites throughout a specific watershed, relative to a point source or a complex mixture of point-source inflows (e.g., active mining areas, wastewater treatment plant discharges). These studies provide a way to understand sediment transport in streams and rivers and to determine how metals are spatially and temporally dispersed in the watershed (Rowan et al., 1995).

The degree of surface-water and ground-water mixing or exchange in the hyporheic zone influences the transport and uptake of trace metals. In a 7 km perennial stream segment contaminated by copper mining in Arizona, 20% of the dissolved manganese load was removed by microbial activity that was likely stimulated by the physicochemical conditions and increased residence time (compared with surface channel residence time) associated with hyporheic exchange (Harvey and Fuller, 1998). That oxidation of manganese enhanced the uptake of other trace metals and thereby decreased cobalt, nickel, and zinc loads 12–68% over the 7 km reach (Fuller and Harvey, 2000). Modeling the contributions of hyporheic exchange on contaminant dynamics over entire river networks requires further research.

Another example of chemical connections along the river network is how inputs of water associated with natural gas (coalbed methane) extraction and hardrock mining can influence trace element and dissolved solute concentrations in perennial rivers. Patz et al. (2006) examined trace elements and other water quality parameters in ephemeral streams resulting from coalbed methane extraction activities that are connected to the perennial Powder River, WY. Iron, manganese, arsenic, fluoride, dissolved oxygen, pH, and turbidity differed across sample locations, demonstrating connectivity between wellhead discharge and ephemeral streams. The contribution of ephemeral streams was detected in the Powder River, where pH was consistently elevated downstream of the confluence with a high-pH stream (Patz et al., 2006).

In a broader study, Wang et al. (2007) used retrospective USGS data (1946−2002) to investigate spatial patterns in major cation and anion concentrations related to coalbed methane development in the Powder River basin (33,785 km^2) in Wyoming and Montana. The study indicated that coalbed methane development could have detrimental effects on the Powder River, especially in terms of sodium adsorption ratio (sodicity). Although the authors indicated connectivity and adverse effects in stream quality with increased sodium and stream sodicity, data also revealed inconsistent patterns associated with complex spatial variability within the drainage basin due to the geographic distribution of the coalbed methane wells.

The spatial extent of metal transport has been demonstrated in the upper Arkansas River of Colorado, where the headwaters have been affected by past mining activities (Kimball et al., 1995). Bed sediments sampled from the headwaters to approximately 250 km downstream showed an inverse relationship between sediment cadmium, lead, and zinc concentrations and downstream distance. That same spatial distribution pattern in bed sediment metal concentrations was observed from headwater streams to the downstream Clark Fork River in Montana, which has been impacted by mining and smelting activities in its headwaters (Axtmann and Luoma, 1991). Based on regression models, bed sediment metal concentrations from river sites were inversely related to downstream distance, and predictions from those models indicated that sediments with metals originating from headwater mining and smelting areas were reaching Lake Pend Oreille, more than 550 km downstream. Hornberger et al. (2009) used a 19−year data set from the Clark Fork River, with sites from the headwater streams to 190 km downstream, and found that bed sediment copper concentrations at downstream sites were positively correlated with concentrations at upstream sites.

Lewis and Burraychak (1979) examined the downstream transport of heavy metals from ephemeral and intermittent streams to a downstream perennial stream, due to the impacts of active and abandoned copper mines. Water chemistry in Pinto Creek was monitored biweekly for 2 years at four stations, one above and three below a point discharge associated with the Pinto Valley Mine in east-central Arizona (Lewis and Burraychak, 1979). Surveys of fish, aquatic macroinvertebrates, and vegetation were conducted during the same period at 13 sampling stations along the total stream length. Contaminants from the Pinto Valley Mine entered Pinto Creek via accidental discharge of waste from tailings ponds (Lewis, 1977). Monitoring revealed that mine wastes comprised up to 90% of total flow in Pinto Creek, and that most chemical parameters increased in concentration below the discharge point, then decreased progressively downstream (Lewis and Burraychak, 1979). Increases in sulfate, conductivity, and total hardness between above-mine and below-mine locations were most apparent, although increases in heavy metals and suspended solids were considered most detrimental to organisms.

Suspended solids settled in and buried intermittent channels, which contained up to 50 cm of mine-waste sediment; these sediments were present all the way to the stream terminus. Increased heavy metal concentrations in the food web and sediments also were detected below the discharge point (Lewis and Burraychak, 1979).

Lampkin and Sommerfeld (1986) similarly showed that intermittent streams can contribute highly mineralized, acidic waters to a downstream perennial reach, in a study that characterized acid mine drainage impacts on water and sediment chemistry (particularly major cations, silica, sulfate, selected heavy metals, and acidity) in Lynx Creek, a small intermittent stream in east-central Arizona. Six stations, two above and four below an abandoned copper mine, were monitored (water and sediment samples) monthly for 1 year. Specific conductance, pH, and dissolved ion concentrations varied with proximity to the mining complex. Concentrations of most constituents were higher near the mine and progressively decreased downstream toward the terminus of Lynx Creek, due to precipitation and dilution by headwater streams. All heavy metal and sulfate concentrations were higher at the immediate discharge location versus the above-mine stations; sulfate concentrations downstream of mine-drainage inputs also significantly differed from the rest of the creek. Sediments throughout the creek were high in metals, suggesting downstream transport of contaminated sediments. Acid-mine drainage from the mine had a major but mostly localized impact on Lynx Creek.

As discussed in previous sections, headwater streams are connected to downstream waters through the transport of chemicals but also through transformation processes. Boreal river networks, in which headwater streams are sources of DOC and pH increases downstream, provide these transformations. Iron exported from the acidic headwater tributaries is bound to DOC (mobile form). As pH increases, iron-rich ground water enters the channel, and iron transforms to iron (oxy) hydroxides that aggregate and precipitate out of solution (Neubauer et al., 2013). These iron (oxy) hydroxides can function as carriers of toxic metals and metalloids (e.g., arsenic), thereby removing them from solution and temporarily storing them in and along the river network (Neubauer et al., 2013).

Several studies also have projected the cumulative effect of headwater systems on downstream mercury concentrations and loads in response to land use, climate, and atmospheric deposition. The Water Quality Analysis Simulation Program and the Bioaccumulation and Aquatic System Simulator models were used to predict changes in water, sediment, and fish-tissue mercury concentrations across water bodies with varying upstream headwater drainage areas (Knightes et al., 2009). Simulations predicted that watersheds with high headwater drainage densities would exhibit longer lag times for mercury delivery downstream compared to those with low headwater drainage densities. This work suggests that headwater streams can serve a mercury storage function, and that temporally varying connectivity contributes to the transport of mercury from headwater streams to downstream waters.

The cumulative effects of land-cover change on total and methylmercury fluxes from a North Carolina headwater watershed to the Cape Fear River were simulated using the Grid Based Mercury Model (Golden and Knightes, 2011). The simulations estimated a 95% increase in total mercury fluxes from the landscape to downstream waters in response to new suburbanization and a 7% decrease in total and methylmercury export in response to reforestation. Predicted changes in total mercury fluxes from the landscape to the downstream assessment point resulted primarily from changes in landscape land cover, rather than changes in connections within the river network.

The effects of climate change on total mercury export from headwater tributaries draining a Coastal Plain watershed (79 km^2) in South Carolina were simulated using multiple watershed models (Golden et al., 2014). Results indicated increased total mercury export under the high-precipitation scenario and decreased total mercury export under the low-precipitation scenario, showing that precipitation, and thus hydrologic connections, drive mercury transport from headwater streams to downstream waters.

Contaminants are commonly transported from tributaries to downstream rivers bound to sediments. Using isotopic fingerprinting, Gehrke et al. (2011) identified different tributaries as contributing to downstream mercury contamination of surface sediments in San Francisco Bay. Historic gold mining in the tributary watersheds of the San Joaquin and Sacramento Rivers contributed to contaminated mercury sediments in the northern part of San Francisco Bay, whereas wastes from mercury mine operations were delivered to the southern part of the bay via the Guadalupe River (Gehrke et al., 2011).

Studies of radionuclide (e.g., plutonium, thorium, uranium) distribution, transport, and storage provide convincing evidence for long-distance chemical connections in river networks. Although the natural occurrence of radionuclides is extremely rare, their production, use, and release for military and energy applications have been monitored for more than 50 years. Like metals, radionuclides adsorb readily to fine sediment; thus, the fate and transport of radionuclides in sediment generally mirrors that of fine sediment. From 1942 to 1952, plutonium dissolved in acid was discharged untreated into several intermittent headwater streams that flow into the Rio Grande at the Los Alamos National Laboratory, NM (Graf, 1994; Reneau et al., 2004). These intermittent headwaters drain into Los Alamos Canyon (152 km^2 drainage area), which joins the Rio Grande approximately 160 km upriver from Albuquerque. Also during this time, nuclear weapons testing occurred west of the upper Rio Grande near Socorro, NM (Trinity blast site) and in Nevada. The San Juan Mountains in the northwestern portion of the upper Rio Grande basin (farther upstream from the site where Los Alamos Canyon enters the Rio Grande) is the first mountain range greater than 300 m in elevation east of these test locations. The mountains therefore have higher plutonium concentrations than the latitudinal and global averages because of their geographic proximity to the test sites. The mountain areas are steep with thin soils, so plutonium from testing fallout was readily transported to headwater streams in the upper Rio Grande basin via erosion and subsequent overland movement. The distribution of plutonium within the Rio Grande illustrates how headwater streams transport and store contaminated sediment that has entered the basin through both fallout and direct discharge. Although Los Alamos Canyon represented only 0.4% of the drainage area at its confluence with the Rio Grande, its mean annual bedload contribution of plutonium was almost seven times that of the mainstem (Graf, 1994). Much of this contribution occurred sporadically during intense storms that were out of phase with flooding on the upper Rio Grande. Total estimated contributions of plutonium to the Rio Grande are approximately 90% from fallout to the landscape and 10% from direct effluent at Los Alamos National Laboratory (Graf, 1994). Based on plutonium budget calculations, only about 10% of the plutonium directly discharged into Los Alamos

Canyon and less than 2% of the fallout over the upper Rio Grande basin have been exported to the Rio Grande. Much of the plutonium is adsorbed to sediment and soil that has either not yet been transported to the river network or is stored on floodplains or in tributary channels (Graf, 1994). Approximately 50% of the plutonium that entered the Rio Grande from 1948 to 1985 is stored in the river and its floodplain; the remaining amount is stored in a downriver reservoir. Similar export of radionuclides through a river network has been traced following the Fukushima Dai-ichi Nuclear Power Plant accident in Japan (Chartin et al., 2013). The highest levels of radionuclide fallout were in areas drained by headwater tributaries. Isotopic analysis of sediment-bound radionuclides collected from throughout the river network over time documented the downstream transfer of contaminated sediment during a succession of summer typhoons and spring snowmelt (Chartin et al., 2013).

Waterborne pathogens (bacteria, viruses, protozoa) are another class of contaminants of concern because of the associated risks to human health and well-being. The principal origins of waterborne pathogens to downstream waters are as point and diffuse sources from livestock and municipal wastes via tributaries (Ferguson et al., 2003). Rainfall events and waterborne disease outbreaks in the United States are strongly correlated, pointing to hydrologic connectivity through tributaries and stormwater drains as a key link in transporting pathogens downstream, where they can overwhelm treatment plants and eventually contaminate drinking water sources (Curriero et al., 2001). Ephemeral and intermittent tributaries also transport waterborne pathogens downstream from livestock and human waste (e.g., Parker et al., 2010; Wilkes et al., 2013). Moist sediments in and near ephemeral and intermittent streams can act as temporary pathogen reservoirs (Chase et al., 2012). Survival of fecal indicator bacteria in dry sediments of an intermittent stream was high and remained constant over 1 month, but declined to unculturable levels after 51 days at 20 °C and 163 days at 5 °C (Chahinian et al., 2012). As for contaminants, various physicochemical (e.g., discharge, nutrient concentrations, temperature, humic acids) and biological (predation, competition) conditions in tributaries can mediate the transport or inactivation of pathogens (Ferguson et al., 2003).

3.5 Biological Connections

Biological connections are linkages throughout the river network, from headwater streams (including those with intermittent and ephemeral flow) to their downstream waters, that are mediated by living organisms or their products (e.g., seeds, exudates, or excreta; Lamberti and Resh, 1987).

Because biological connections often result from passive transport of organisms or their products with water flow, biological connectivity often depends on hydrologic connectivity (Section 3.3.1). Many living organisms, however, also can actively move with or against water flow; others disperse actively or passively over land by walking, flying, drifting, or "hitchhiking." All of these organism-mediated connections form the basis of biological connectivity between headwater streams and downstream waters.

Biological connections between upstream and downstream reaches can affect downstream waters via multiple pathways or functions. For organisms capable of significant upstream movement, headwater streams, including ephemeral and intermittent streams, can increase both the amount and quality of habitat available to those organisms. Many organisms require different habitats for different resources (e.g., food, spawning habitat, overwintering habitat), and thus move throughout the river network—both longitudinally and laterally—over their life cycles (Schlosser, 1991; Fausch et al., 2002). For example, headwater streams can provide refuge habitat under adverse conditions, enabling organisms to persist and recolonize downstream areas once adverse conditions have abated (Meyer and Wallace, 2001; Meyer et al., 2004; Huryn et al., 2005). Headwater streams also provide food resources to downstream waters: as Progar and Moldenke (2002) state, "…headwater streams are the vertex for a network of trophic arteries flowing from the forest upland to the ocean."

In this section, we consider longitudinal biological connections in terms of both the aquatic organisms—specifically invertebrates and fishes—that move along river networks and their consequent effects on downstream waters (see Section 3.4.2 for discussion of particulate organic matter dynamics and Section 3.4.4 for discussion of waterborne pathogens). We then discuss the importance of organism movement throughout the river network for genetic connectivity in a separate section. We also recognize the many important biological connections between river networks and terrestrial systems (Lamberti and Resh, 1987), but as discussed in Chapter 1, these connections are outside the scope of this document. Lateral biological connections between the river network and riparian and floodplain habitats are considered in Chapter 4.

3.5.1 Invertebrates

Headwater streams provide habitat for diverse and abundant stream invertebrates (Meyer et al., 2007) and serve as collection areas for terrestrial and riparian invertebrates that fall into them (Edwards and Huryn, 1995; Kawaguchi and Nakano, 2001). These aquatic and terrestrial invertebrates can be transported downstream with water flow and ultimately serve as food resources for downstream organisms. Many fish feed on drifting insects (Nakano and Murakami, 2001; Wipfli and Gregovich, 2002), and these organisms can also settle out of the water column and become part of the local benthic invertebrate assemblage in downstream waters. Drift, however, has been shown to increase invertebrate mortality significantly (Wilzbach and Cummins, 1989), suggesting that most drifting organisms are exported downstream in the suspended detrital load (Section 3.4.2).

The downstream drift of stream invertebrates (Müller, 1982; Brittain and Eikeland, 1988) and the contribution of terrestrial and riparian invertebrates to overall drift (Edwards and Huryn, 1995; Kawaguchi and Nakano, 2001; Eberle and Stanford, 2010) have been well documented. For example, drift estimates in 52 small coastal streams in Alaska ranged from 5 to 6,000 individuals per stream per day (Wipfli and Gregovich, 2002). This export of invertebrates can be especially high in intermittent and ephemeral streams, as terrestrial invertebrates accumulate in these channels during dry periods and are then transported downstream upon channel rewetting (Corti and Datry, 2012; Rosado et al., 2015). The amount of invertebrate drift often is closely related to stream discharge (e.g., Harvey et al., 2006), as well as diel invertebrate behavioral patterns that are independent of flow (Rader, 1997). To compensate for loss of individuals to downstream drift, invertebrate populations in headwater streams are maintained and replenished through a combination of high productivity and upstream dispersal (Hershey et al., 1993; Humphries and Ruxton, 2002). This dispersal creates downstream to upstream biological connections along the river network; for organisms capable of directed movement over long distances (e.g., winged adult forms of aquatic invertebrate larvae), these connections can occur over significant network distances.

Given this evidence, that headwater streams are biologically connected to downstream waters via the active and passive export of invertebrates is clear, and the cumulative export of invertebrates from numerous headwater streams to downstream waters can be substantial. As with organic matter, however, assessing the effect of headwater invertebrate production and export on downstream waters is difficult, given that these resources enter downstream waters at multiple points and times throughout the river network. Nevertheless, some studies have documented the importance of drifting invertebrates for downstream organisms. Wipfli and Gregovich (2002) estimated that drifting insects and detritus (i.e., particulate organic matter; Section 3.4.2) from fishless headwater streams in Alaska supported between 100 and 2,000 young-of-year salmonids per km in a large, salmon-bearing stream. This estimate of headwater importance in systems where juvenile salmonids move into headwater streams to feed and grow is likely conservative (Section 3.5.2). Other studies have shown increased fish growth with increased invertebrate drift (Wilzbach et al., 1986; Nielsen, 1992; Rosenfeld and Raeburn, 2009), indicating that drift does provide a valuable food resource, especially when food is limiting (Boss and Richardson, 2002).

Headwater streams also serve as habitat for invertebrates. Many invertebrate species are well adapted to seasonal or episodic periods of drying (Feminella, 1996; Williams, 1996; Bogan and Lytle, 2007) or freezing temperatures (Danks, 2007) and can be found throughout a range of stream sizes (e.g., Hall et al., 2001b) and flow regimes (intermittent and perennial, e.g., Feminella, 1996). Intermittent streams also can provide refuge from adverse biotic conditions. For example, Meyer et al. (2004) found that native amphipods can persist in intermittent reaches but are replaced by nonnative amphipods in perennial reaches. After disturbance, these upstream habitats can provide colonists to downstream reaches. This phenomenon can be especially important in intermittent streams, where permanent upstream pools can serve as refuges during drying. For example, Fritz and Dodds (2002, 2004) examined invertebrate assemblages before and after drying in intermittent prairie streams and found that initial recovery of invertebrate richness, richness of invertebrate drift, and richness of aerially colonizing insects were negatively related to distance from upstream perennial water. Dry stream channels also can facilitate dispersal of aquatic invertebrates by serving as dispersal corridors for terrestrial adult forms (Bogan and Boersma, 2012; Steward et al., 2012).

Headwater stream invertebrates also provide critical functional roles in maintaining physical and chemical connectivity to downstream waters (Covich et al., 1999). Invertebrates accelerate the breakdown of coarse particulate organic matter (e.g., leaves) to more mobile fine and dissolved forms (Section 3.4.2; Wallace and Webster, 1996); promote algal productivity and microbial activity (and nutrient uptake) by biofilm grazing (Feminella and Hawkins, 1995); and temporarily store and transfer sediments, nutrients, and contaminants through their trophic and physical activity (e.g., via bioconsolidation and bioturbation; Pringle et al., 1993; Walters et al., 2008; Statzner, 2012). The contribution of invertebrates in controlling sediment mobilization can be substantial. For example, Statzner (2012) estimated that the discharge necessary to move approximately 0.4 kg of sediment s^{-1} in the Colorado River would increase by an order of magnitude in response to bioconsolidation by net-spinning caddisflies and would decrease by an order of magnitude in response to bioturbation by crayfish.

Diverse and abundant invertebrate assemblages also inhabit the hyporheic zone of river networks (Stanford and Ward, 1988; Boulton, 2000). Hyporheic assemblages are composed of invertebrate species that inhabit shallow subsurface sediments within streambeds to various degrees. Some taxa spend their entire lives in the hyporheic zone (Boulton, 2000). Other taxa spend only part of their life cycles, typically their earliest larval stages or periods of disturbances, in the hyporheic zone, and others spend their entire aquatic stages in the hyporheic zone then migrate out for their aerial adult stages (Boulton, 2000). These hyporheic assemblages make similar contributions to physical and chemical connectivity with downstream waters as benthic invertebrates do, while also enhancing hyporheic exchange (Section 3.3.1) through movements and migration within the hyporheic zone (Boulton, 2000).

3.5.2 Fishes

Although some fish species maintain resident headwater populations, many species move into and out of headwater streams at some point in their life cycles (Ebersole et al., 2006; Meyer et al., 2007). Some fish species occur only in headwater streams, contributing to regional aquatic biodiversity (e.g., Paller, 1994). As with invertebrates, however, certain fish species can be found throughout a range of stream sizes (Freeman et al., 2007) and flow durations (Schlosser, 1987; Labbe and Fausch, 2000), and the fish species found in headwater streams often are a subset of species found in downstream habitats (Horwitz, 1978). Use of headwater streams as habitat is especially evident for the many diadromous species that migrate between headwater streams and marine environments during their life cycles (e.g., Pacific and Atlantic salmon, American eels, certain lamprey species), and the presence of these species within river networks provides robust evidence of biological connections between headwater streams and larger rivers.

Through their activities, migratory fish can be important in modifying habitat, and transforming and transporting materials (e.g., Taylor et al., 2006; Hassan et al., 2008). Return migration of diadromous fishes provides a feedback loop in which marine-derived nutrients are transported upstream to headwater streams, for subsequent processing and export (Section 3.4.1). This example illustrates how biological connections also can create chemical connections throughout the river network. Migratory fish also can bioaccumulate and transport contaminants long distances between headwater streams and downstream waters (e.g., Krümmel et al., 2003; Morrissey et al., 2011). Fish also can act as transport vectors of other organisms (e.g., seeds, pathogens, glochidia), moving other organisms against flow or extending their dispersal distances (e.g., Chick et al., 2003; Senderovich et al., 2010; Schwalb et al., 2013). Even nonmigratory taxa can travel substantial distances within river networks throughout their life cycles (Gorman, 1986; Sheldon, 1988; Hitt and Angermeier, 2008). As a result, the distribution and movement of fish throughout river networks can be highly variable, both spatially and temporally (Schlosser, 1991; Labbe and Fausch, 2000; Fausch et al., 2002).

The importance of connectivity in structuring fish assemblages provides further evidence of biological connections along river networks. Fish assemblages among connected streams tend to be more similar, in that assemblages in reaches located closer together tend to have more species in common than assemblages in distantly separated reaches (Matthews and Robinson, 1998; Hitt et al., 2003; Grenouillet et al., 2004). Measures of river network structure also can explain fish assemblage structure, with studies showing that metrics such as link magnitude (the sum of all first-order streams draining into a given stream segment) and confluence link (the number of confluences downstream of a given stream segment) are significant predictors of fish assemblages (e.g., Osborne and Wiley, 1992; Smith and Kraft, 2005).

The importance of biological connections along river networks is often highlighted by human alterations that affect these connections. For example, fish assemblages within highly connected river networks were more homogeneous, whereas fragmentation by road crossings resulted in greater dissimilarity of fish assemblages between upstream and downstream habitats (Perkin and Gido, 2012). Many studies have documented statistically significant associations between impoundment of prairie streams and loss of native fishes (e.g., Winston et al., 1991; Luttrell et al., 1999; Schrank et al., 2001; Falke and Gido, 2006; Matthews and Marsh-Matthews, 2007), and fragmentation of river networks has been consistently related to local extinction of salmonid populations (Morita and Yamamoto, 2002; Letcher et al., 2007).

For certain taxa, headwater streams—including intermittent and ephemeral streams— provide critical habitat for specific portions of their life cycles. Many fish, both salmonids and nonsalmonids, spawn in headwater streams, including those with intermittent flow (Erman and Hawthorne, 1976; Schrank and Rahel, 2004; Ebersole et al., 2006; Wigington et al., 2006; Colvin et al., 2009). Kanno et al. (2014) found that many brook trout moved between mainstem and tributary habitats over their life cycles. Because reproductive success varied across these habitats, this movement resulted in substantial gene movement into tributary habitats (Section 3.5.3).

After spawning, fish using headwater streams return downstream for feeding and overwintering. For example, Bonneville cutthroat trout moved from less than 1 km to more than 80 km downstream postspawning, typically within 30 days (Schrank and Rahel, 2004). Many salmonids also grow in headwater streams (Brown and Hartman, 1988; Curry et al., 1997; Bramblett et al., 2002). In some cases, these headwater streams, including intermittent streams, can provide higher quality habitat for juvenile fish, as evidenced by increased growth, size, and overwinter survival in these habitats (Ebersole et al., 2006; Ebersole et al., 2009), perhaps due to warmer temperatures and higher prey and lower predator densities (Limm and Marchetti, 2009).

In prairie streams (Section B.4), the importance of hydrologic connectivity for biological connectivity is especially evident, as many fishes broadcast spawn, or release eggs into the water column, which then develop as they are transported downstream (Cross and Moss, 1987; Fausch and Bestgen, 1997). Platania and Altenbach (1998) estimated that unimpeded eggs could travel as far as 144 km before hatching, and another 216 km as developing protolarvae (i.e., the swim-up stage), illustrating that downstream transport of these drifting organisms can be extensive. Adult fish then migrate upstream prior to egg release (Fausch and Bestgen, 1997). Thus, these fishes require hydrologic connectivity to maintain both upstream and downstream populations (Fausch and Bestgen, 1997).

When abiotic or biotic conditions farther downstream in the river network are adverse, upstream reaches can provide refuge habitat for downstream fishes. Examples of adverse abiotic conditions include temperature (Curry et al., 1997; Cairns et al., 2005) and flow (Pires et al., 1999; Wigington et al., 2006) extremes, low dissolved oxygen concentrations (Bradford et al., 2001), and high sediment levels (Scrivener et al., 1994). Examples of adverse biotic conditions include the presence of predators, parasites, and competitors (Fraser et al., 1995; Cairns et al., 2005; Woodford and McIntosh, 2010).

Because headwater streams often depend on ground-water inputs, temperatures in these ecosystems tend to be warmer in winter (when ground water is warmer than ambient temperatures) and colder in summer (when ground water is colder than ambient temperatures), relative to reaches farther downstream (Section 3.3.4; Power et al., 1999). Thus, these headwater streams can provide organisms with both warmwater and coldwater refuges at different times of the year (Curry et al., 1997; Baxter and Hauer, 2000; Labbe and Fausch, 2000; Bradford et al., 2001), again highlighting the spatial and temporal variability of these fish-based biological connections. In some cases, loss of coolwater refuges can facilitate invasion by species more tolerant of warmwater conditions (Karr et al., 1985).

Headwater streams also can provide refuge from flow extremes. Fish can move into headwater streams, including intermittent streams, to avoid high flows downstream (Wigington et al., 2006); fish also can move downstream during peak flows (Sedell et al., 1990), highlighting the bidirectionality of biological connections within these systems. Low flows can cause adverse conditions for organisms, as well, and residual pools that are often fed by hyporheic flow can enable organisms to survive dry periods within intermittent streams (Pires et al., 1999; May and Lee, 2004; Wigington et al., 2006).

Biotic conditions within the river network—that is, the taxa found in the system—also can create an adverse environment, as the presence of invasive species or other predators and competitors can negatively affect native taxa. In some cases, headwater streams can provide these taxa refuge from other species and enable populations to persist. For example, Fraser et al. (1995) found that prey fish moved downstream when piscivores (fish-eating fish) were excluded, but moved upstream into headwater streams when they were present. The role of headwater streams as refuges from adverse biotic conditions can be closely related to where along the connectivity-isolation continuum these habitats fall, with isolation allowing for persistence of native populations (Letcher et al., 2007). Physical barriers (which reduce connectivity and increase isolation) have been used to protect headwater streams from invasion (Middleton and Liittschwager, 1994; Freeman et al., 2007); similarly, most genetically pure cutthroat trout populations are confined to small, high-elevation streams that are naturally or anthropogenically isolated (Cook et al., 2010).

When adverse conditions have abated and these organisms move back down the river network, they can serve as colonists of downstream reaches (Meyer and Wallace, 2001). For example, Hanfling and

Weetman (2006) examined the genetic structure of river sculpin and found that upstream populations were emigration biased (i.e., predominant movements were out of these reaches), whereas downstream populations were immigration biased (i.e., predominant movements were into these reaches).

3.5.3 Genes

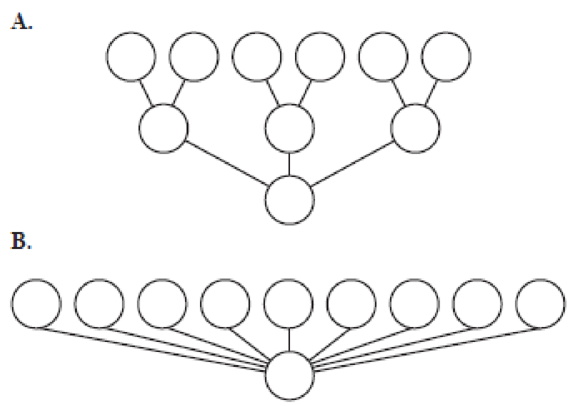
Genetic connectivity results from biotic dispersal and subsequent reproduction and gene flow, or the transfer of genetic material within and among spatially subdivided populations. Populations connected by gene flow have a larger breeding population size, making them less prone to inbreeding and more likely to retain genetic diversity or variation—a basic requirement for adaptation to environmental change (Lande and Shannon, 1996). Genetic connectivity exists at multiple spatial and temporal scales. It can extend beyond a single river watershed (Hughes et al., 2009; Anderson et al., 2010), and in diapausing organisms, can provide a direct link between distant generations (dispersal through time; Bohonak and Jenkins, 2003).

Although physical barriers can protect headwater habitats and populations by isolating them from colonization by and hybridization with invasive species (Section 2.3.2.1), isolation also can have serious adverse effects on native species via reductions in genetic connectivity. For example, Hanfling and Weetman (2006) found that artificial weirs intensified natural patterns of limited headwater immigration, such that headwater (above-barrier) sculpin populations diverged genetically from downstream (below-barrier) populations and lost significant amounts of genetic diversity. This pattern of strong genetic divergence accompanied by loss of headwater genetic diversity above natural and artificial barriers has been documented in multiple fish species and regions (Yamamoto et al., 2004; Wofford et al., 2005; Deiner et al., 2007; Guy et al., 2008; Gomez-Uchida et al., 2009; Whiteley et al., 2010). Loss of headwater-river genetic connectivity might be exerting selection pressure against migrant forms in fish with life cycles requiring movement along the entire river corridor (Morita and Yamamoto, 2002). Ultimately, tradeoffs exist between the risks associated with headwater-river genetic connectivity (e.g., hybridization with nonnative species and hatchery fish) and those associated with genetic isolation (e.g., reduced reproductive fitness, increased risk of local extinction, deterioration of overall genetic variation, and selection against migratory traits; Fausch et al., 2009).

In general, genetic connectivity decreases with increasing spatial distance (Wright, 1943). Genetic connectivity in river networks is also strongly influenced by the hierarchical structure of a river network (Section 2.4.2), the direction of dispersal (upstream, downstream, or both), dispersal modes and pathways used (e.g., swimming, flying), and species' life histories (Hudy et al., 2010).

Computer simulation approaches examine the spatial and temporal processes of genetic connectivity for realistic behaviors and life histories of species inhabiting complex, dynamic landscapes and riverscapes (Epperson et al., 2010). For example, Morrissey and de Kerckhove (2009) demonstrated that downstream-biased dispersal in dendritic river networks (which by definition have more tributaries than mainstems) can promote higher levels of genetic diversity than other geographical habitat structures. Under these conditions, low-dispersing headwater stream populations can act as reservoirs of unique genetic alleles (units of genetic variation) that occasionally flow into and mix with highly dispersing downstream populations. Although the number of headwater streams (i.e., potentially unique genetic reservoirs) is important in maintaining genetic diversity, networks with more complex hierarchical structures (Figure 3-4) are more efficient at maintaining genetic diversity than networks in which all tributaries flow directly into the mainstem (Morrissey and de Kerckhove, 2009). In another simulation, Chaput-Bardy et al. (2009) demonstrated that out-of-network gene flow (e.g., terrestrial dispersal by insects or amphibians) or very high levels of within-network gene flow (e.g., fish that move and reproduce throughout the network) can counteract the effects of network structure; thus, individual species behavior can profoundly affect observed genetic patterns.

Figure 3-4. (A) A dendritic network with multilevel hierarchical structure, and (B) a uninodal network with all headwater streams feeding directly into a river mainstem. Source: Reprinted from The maintenance of genetic variation due to asymmetric gene flow in dendritic metapopulations, (2009) by Morrissey and de Kerckhove with permission of The Univ of Chicago Press.



Most empirical evidence for the role of headwater streams in maintaining genetic connectivity and diversity comes from studies of economically important fish species, but correlations of river network structure or landscape alteration with genetic patterns have been reported for other species. Consistent with the model of Morrissey and de Kerckhove (2009), Fer and Hroudova (2008) found higher genetic diversity in downstream populations of yellow pond-lily (*Nuphar lutea*), which disperses over long distances via water-mediated dispersal of detached rhizomes. Frequent dispersal and high gene flow among headwater and downstream populations of the giant Idaho salamander (*Dicamptodon aterrimus*; Mullen et al., 2010) are expected to contribute to genetic diversity of upstream and downstream populations.

Headwater populations contribute to the maintenance of genetic diversity even in animals capable of overland dispersal. In a field study of the common stream mayfly *Ephemerella invaria*, which emerges into streamside forests to mate and disperse, Alexander et al. (2011) found that regional genetic diversity was strongly correlated with tree cover in first-order (headwater) stream watersheds. Observed loss of genetic diversity in this species could be related to degradation of stream habitats, degradation of out-of-network dispersal pathways, or both (Chaput-Bardy et al., 2009; Grant et al., 2010; Alexander et al., 2011).

In summary, genetic connectivity in river systems reflects the breeding potential of a metapopulation. The maintenance of genetic diversity is directly related to genetic connectivity, and thus is critical to a species' regional persistence. Genetic connectivity is influenced by the landscape, riverscape, and biology of the organisms involved; spatially subdivided stream and river populations can maintain genetic diversity, provided they remain connected by at least low levels of gene flow (Waples, 2010).

3.6 Streams: Synthesis and Implications

Despite widespread human alterations, rivers are not simple conduits draining watersheds. A river, including the water and material it carries and the organisms living in it, represents the cumulative longitudinal, lateral, and vertical connections of its network of channels integrated over time (Section 1.2.3). Although we recognize that streams also exchange water and other materials with nearby terrestrial and deep ground-water systems via lateral and vertical connections, this chapter focused on longitudinal surface-water connections between streams and rivers, as well as shallow subsurface-water interactions integral to surface-water connections and downstream water condition.

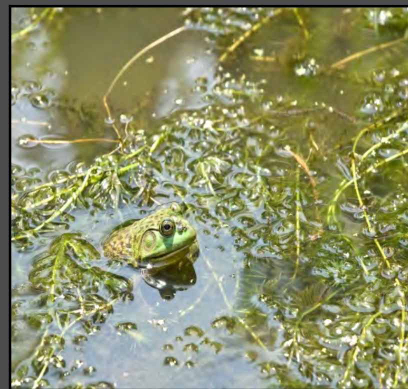
A substantial body of evidence unequivocally demonstrates connectivity between streams and downstream rivers via both structural and functional connectivity (as defined in Wainwright et al., 2011). Streams are structurally connected to rivers through the network of continuous channels (beds and banks) that make these systems physically contiguous, and the very existence of a continuous bed and bank structure provides strong geomorphologic evidence for connectivity (Section 2.2.1). A stream must be linked to a larger, downstream water body by a channel for the two to have a surface-water (hydrologic) connection. Although some streams lack a channel connection to larger water bodies (i.e., small endorheic basins), they are the exception. Streams that link larger water bodies through networks of continuous bed and bank are the rule. The network structure reflects the aggregate and cumulative nature of the connections between distant headwater streams and the downstream river.

Although not comprehensive or equally studied among all stream types, the existing science indicates that connectivity with downstream waters varies among streams and over time. This variation in connectivity to downstream waters can be described as a connectivity gradient, ranging from highly connected to highly isolated (Section 1.2.2). A stream's position on the gradient is influenced not only by distance to downstream waters but also by the frequency, magnitude, duration, timing, and rate of change of fluxes to downstream waters. Connectivity is dynamic: It changes with immediate, seasonal, and interannual or interdecadal (e.g., climate oscillations) conditions that affect the availability and distribution of water, materials, and biota. Because connectivity is dynamic, a complete understanding of a stream's connections and consequences to downstream waters should aggregate connections over relatively long time scales (multiple years to decades; Section 1.2.3). Although distance between streams and downstream waters vary, other factors such as intervening resistance, relative size or chemical load, and species assemblage also influence the degree of connectivity with and level of consequence on downstream waters. Despite being distant from downstream waters, headwater streams make up the majority of stream channels in most river networks and cumulatively supply most of the water in rivers.

Streams are functionally connected to rivers by the movement of water and other materials through this network of channels (Table 3–1). The longitudinal, vertical, and lateral connections within river networks are inextricably tied. Even losing-stream reaches that at times lack sufficient flow for hydrologic connection can still influence downstream waters by functioning as sinks for water and materials carried by water. The river network and its flow of materials represent the integration of its streams' cumulative contributions to downstream waters. Existing evidence indicates that headwater streams (including intermittent and ephemeral streams) transform, store, and export significant amounts of material (e.g., water, organic matter, organisms) to downstream waters. The most compelling evidence linking headwater streams to downstream habitats supports source, sink (or lag), and transformation functions (Section 2.3.1; Table 2-1). For example, studies that involved sampling throughout river networks have documented headwater streams as sources of water (via floods and baseflow) to rivers (Section 3.3.1). Nitrogen and carbon transported from headwater streams cumulatively contribute to nitrogen and carbon levels in downstream rivers, and headwater streams can function as nitrogen and carbon sinks for river networks (Sections 3.4.1 and 3.4.2). Studies documenting the fate and transport of contaminants through headwater streams to downstream waters also represent clear lines of evidence for headwater streams as sources and sinks (Section 3.4.4). Many organisms, such as anadromous salmon, have complex life cycles that involve migration through the river network, from headwater streams to downstream rivers and oceans, over the course of their lives (Section 3.5). In fact, the importance of headwater streams (including intermittent and ephemeral streams) in the life cycles of many organisms capable of moving throughout river networks provides strong evidence for connectivity among these systems.

Most of the evidence relevant to issues of connectivity between headwater streams and large rivers is based on data collected either in the upper (i.e., from headwater streams to intermediate tributaries) or lower (i.e., from large tributaries to mainstem rivers) portions of the river network. Although few studies have explicitly examined the movement of materials along entire river networks, the exchange of materials among closely located stream reaches—which numerous studies have documented, for a variety of materials—can be extended over large spatial scales.

Table 3-1. Examples of mechanisms by which streams are connected to and influence downstream waters, by functional type. See relevant section and appendix numbers in parentheses for greater detail. Note that the distinction between types of functions is not always clear. For example, denitrification can be considered a sink or transformation function. Bold letters represent the primary type of connection (B = biological; C = chemical; and P = physical).
Source Function
• Streams supply water downstream through baseflow and floods that influence discharge and habitat (3.3.1, B.4.2.5, B.4.3.1.1, B.5.3, B.5.4.2, B.5.5.1). **P** • Streams supply downstream waters with sediment (3.3.2, 3.4.4, B.4.3.1.3, B.5.3, B.5.4.2). **P** • Streams supply downstream waters with nutrients and other ions (3.4.1, 3.4.3, B. 4.3.2.1, B.5.4.2). **C** • Streams can transport to downstream waters contaminants and pathogens that adversely affect organisms and human health (3.4.4, B.4.3.1.3). **C** • Streams supply dissolved and particulate organic matter that can fuel heterotrophy in downstream waters and influence physicochemical conditions (3.3.3, 3.4.2, B.4.3.2.2, B.5.4.2). **C** • Organisms actively and passively move between streams and downstream waters, carrying with them nutrients, contaminants, pathogens, and other organisms (3.5, B.4.2.4, B.4.3.3). **B** • Organisms can enhance the supply of materials to downstream waters (3.5.1, 3.5.2). **B**
Sink Function
• Streams can divert surface flow from downstream waters via infiltration into underlying alluvium and evapotranspiration to the atmosphere (3.3.1, B.5.3, B.5.4.2, B.5.5.1). **P** • Streams can divert nitrate from downstream waters via denitrification (3.4.1, B.4.3.2.1). **C** • Streams can prevent sediment and associated contaminants from being transported to downstream waters through deposition on floodplains (3.3.2, 3.4.4, B.5.3). **C**
Refuge Function
• Streams can afford protection from temperature extremes, drying, predators, and competition with nonnative species for organisms that inhabit downstream waters (3.5, B.4.3.3). **B**
Transformation Function
• Streams can mediate the form and mobility of nutrients before they enter downstream waters via nutrient spiraling (3.4.1, B.4.3.2.1). **C** • Streams can mediate the form and mobility of organic matter before they enter downstream waters via carbon spiraling (3.4.2, B.4.3.2.2). **C** • Streams can mediate the form and mobility of contaminants before they enter downstream waters via hyporheic exchange or exposure to other physicochemical gradients that lead to biogeochemical transformations (3.4.4). **C** • Organisms can mediate the transformation of materials through their trophic and physical activities (3.4.1, 3.4.2, 3.5.1, 3.5.2, B.4.3.2.2). **B**
Lag Function
• Streams can delay water from arriving at downstream waters through local and network structures, thus reducing flood magnitudes, but increasing baseflows in downstream waters (3.3.1, 3.3.3, B.4.3.1.1, B.5.3, B.5.4.2). **P** • Streams can delay sediment from arriving at downstream waters through local and network structures (3.3.2, 3.3.3, 3.4.4, B.5.3). **P** • Streams can delay nutrients from arriving at downstream waters through local and network structures and biological uptake (3.4.1, B.4.2.4, B.4.3.2.1). **C** • Streams can delay organic matter from arriving at downstream waters through local and network structures and biological uptake (3.3.3, 3.4.2, B.4.3.2.2). **C** • Streams can delay contaminants from arriving at downstream waters through local and network structures and exchanges that enhance mineralization and precipitation or adsorption to sediment, or both (3.4.4). **C** • Organisms can delay nutrients, organic matter, and contaminants from arriving at downstream waters through consumption, assimilation, and bioconsolidation (3.4.1, 3.4.2, 3.5.1, 3.5.2, B.4.3.2.2). **B**

CHAPTER 4. WETLANDS: PHYSICAL, CHEMICAL, AND BIOLOGICAL CONNECTIONS TO RIVERS

4.1 Abstract

Wetlands are transitional ecosystems that occur between terrestrial and aquatic systems. They are inundated or saturated by water at a frequency and duration sufficient to support hydrophytic vegetation and development of hydric soils. The effects of wetlands on rivers and other downstream waters depend on functions within the wetlands and connectivity between wetlands and downstream waters. Riparian/floodplain wetlands can be hydrologically connected to streams and rivers through unidirectional flows (i.e., from wetlands to rivers and streams, but not vice versa) of surface water and ground water from upgradient areas (e.g., hillslopes and nearby uplands). In addition, riparian/floodplain wetlands have bidirectional connections to streams and rivers (i.e., from wetlands to streams and rivers and vice versa) through lateral movement of surface and ground water between the channel and riparian/floodplain areas. Connections between riparian/floodplain wetlands and streams or rivers occur over a gradient of connectivity, for example, they can be permanent, can occur frequently (e.g., if the wetland is located within the mean high-water mark), or can occur infrequently (e.g., if the wetland occurs near the edge of the floodplain; Sections 1.2.2 and 2.4.2). Even riparian/floodplain wetlands that rarely flood can have important, long-lasting effects on streams and rivers. Riparian/floodplain wetlands can reduce flood peaks by storing floodwaters, store large amounts of sediment and nutrients from upland areas, influence stream geomorphology by providing woody debris and sediment, and regulate stream temperature. Riparian/floodplain wetlands also are sources of food for stream and river invertebrates and serve as rearing habitat for fish.

Wetlands in non-floodplain landscape settings lack bidirectional hydrologic connections with channels (i.e., water flows from the wetland to the channel but not from the channel to the wetland). These settings, however, have the potential for unidirectional hydrologic flows from wetlands to the river

network through surface water or ground water. Non-floodplain wetlands can attenuate floods through depressional storage and can recharge ground water and thereby contribute to baseflow. These wetlands can affect nutrient delivery and improve water quality by functioning as sources (e.g., of dissolved organic carbon) and as sinks for nutrients (e.g., nitrogen), metals, and pesticides. Non-floodplain wetlands also can provide habitat or serve as sources of colonists for biological communities in downstream waters, through movement of amphibians, reptiles, birds, and mammals. The extent to which non-floodplain wetlands perform these functions depends on their hydrologic and biological connectivity with downstream waters. Non-floodplain wetlands also occur on a hydrologic gradient, from wetlands having permanent connections with perennial channels, to geographically isolated wetlands having ground-water or occasional surface-water connections, to highly isolated wetlands having minimal hydrologic connection to the river network (but which could include surface and subsurface connections to other wetlands; Section 4.4.2). Non-floodplain wetlands that are connected to the river network through a channel (i.e., wetlands that serve as stream origins) will have an effect on downstream waters, regardless of whether the outflow is permanent, intermittent, or ephemeral. For non-floodplain wetlands that do not connect to the river network through a stream channel (i.e., geographically isolated wetlands and wetlands that spill into losing streams that are completely disconnected from the river network), the type and degree of connectivity with downstream waters will vary with position in the watershed and over time.

This literature review is unable to provide evaluations of connectivity for specific groups or classes of wetlands (e.g., prairie potholes or vernal pools). Evaluations of individual wetlands or groups of wetlands, however, could be possible through case-by-case analysis. We can conclude the following:

1. A non-floodplain wetland having a surface-water outflow to a stream network (e.g., a wetland that serves as a stream origin) is connected to the stream network and has an influence on downstream waters.
2. Many non-floodplain wetlands interact with ground water, which can travel long distances and affect downstream waters.
3. Even when wetlands lack a hydrologic connection to other water bodies, they can influence downstream water through water and material storage and mitigation of peak flows (flood reduction and flood attenuation). Sink functions of non-floodplain wetlands will have effects on a downstream water when these wetlands are situated between the downstream water and known point or nonpoint sources of pollution, thereby intersecting the flowpath between pollutant source and downstream water. More generally, wetland sink functions are likely to be greatest when the wetland is located downgradient from pollutant sources and upgradient from a stream or river.
4. Within a watershed or wetland landscape setting, wetlands and open waters that are closer to rivers and streams will have a higher probability of being connected than more distant areas, assuming that conditions governing type and quantity of flows (e.g., slope, soil, and aquifer permeability) are similar.

5. Caution should be used in interpreting connectivity for wetlands that have been designated as "geographically isolated."

4.2 Introduction

This chapter provides detailed information, based on a review of the pertinent peer-reviewed literature, on how wetlands connect to and influence streams and rivers. In particular, we address two questions (Section 1.1): (1) What are the connections to and effects of riparian/floodplain wetlands and open waters (e.g., oxbow lakes) on downstream waters? (2) What are the connections to and effects of non-floodplain wetlands and open waters on downstream waters?

In Chapter 1, we provided the scientific context for concepts and gradients of connectivity in hydrology and ecology (Section 1.2). In Chapter 2, we provided definitions for wetlands, gave a rationale for distinguishing between wetlands in riparian/floodplain and non-floodplain settings, and discussed general hydrologic and biological mechanisms by which wetlands can connect to and affect streams and rivers. Given that streams and rivers are the endpoints of interest, we limit our discussion of riparian/floodplain wetlands to those occurring in riparian and floodplain settings. Below, we provide a detailed review of the contributions of riparian/floodplain wetlands (Section 4.3) and non-floodplain wetlands (Section 4.4) to rivers, followed by conclusions concerning these wetlands and their effects on rivers (Section 4.5). Examples of some of the functions discussed in these two sections are found in Table 4-1. In addition, four case studies on specific types of wetlands or lentic waters representing different landscape settings and geographic regions are in Appendix B: Carolina and Delmarva bays (Section B.1), oxbow lakes (Section B.2), prairie potholes (Section B.3), and vernal pools (Section B.6).

Much of the literature that we evaluate in this chapter does not specify the type or size of the stream or river (or other water body) to which the wetland(s) are connected or which they influence. If available, we note this information (e.g., whether riparian areas were located in floodplains or along portions of river networks without floodplains), but often we can discuss only generic connections to streams, rivers, or downstream waters. Given that rivers are connected to all upstream components of the river network, including streams (Chapter 2), and the functional relationships between streams and rivers (Chapter 3), however, we consider any evidence of connectivity with a stream (other than endorheic streams; Sections 3.2 and B.5.5.1) to be evidence of connectivity with the river and other downstream waters.

4.3 Riparian/Floodplain Wetlands

4.3.1 Introduction

This section focuses on the connections and influence of riparian/floodplain wetlands on downstream waters. As previously defined in Section 2.2.1, riparian/floodplain wetlands are locations within riparian areas and floodplains (Figures 1-1A, 2-2, and 2-3), respectively, that meet the Cowardin et al. (1979)

Table 4-1. Examples of mechanisms by which riparian/floodplain wetlands and wetlands in non-floodplain settings influence downstream waters, by functional type. See relevant section and appendix numbers in parentheses for more detail. Note that the distinction between types of functions is not always clear, for example, denitrification could be considered a sink or transformation function.
Source Function
• Riparian/floodplain wetlands and non-floodplain wetlands connected to the stream network by channelized flow—ranging from ephemeral to permanent—are sources of downstream water (4.3.2.1, 4.4.2.1, B.1.2.3, B.2.3.1, B.3.3.1, B.6.3.1). • Wetlands that serve as origins for streams (e.g., seeps) can be sources of ground-water discharge, contributing to stream baseflow (4.4.2.3). • Non-floodplain wetlands lacking a channel outlet can be sources of water via overland flow to the stream network if wetland storage capacity is exceeded (4.4.2.1, B.3.3.1, B.6.3.1.1). They can also provide water via subsurface drains (“tile drains”) or surface ditches (4.4.2.1, B.1.3.1, B.3.3.1). • Riparian/floodplain wetlands and non-floodplain wetlands can be sources of nutrients and sediments to downstream waters (4.3.2.2, 4.3.3, 4.4.3.1, B.1.3.2, B.3.3.2). • Riparian areas are a source of allochthonous inputs, the primary energy input into the food webs of small, forested streams (4.3.3.4). They also are sources of woody debris that can affect stream morphology and flow regime, and provide habitat for aquatic organisms (4.3.2.2). • Riparian areas and non-floodplain wetlands can be sources of dissolved organic matter that aquatic food webs use, with additional potential effects on pH and mercury concentrations of downstream waters (4.3.3.4, 4.3.3.6, 4.4.3.1). • Riparian/floodplain wetlands and non-floodplain wetlands can be sources of organisms, including plants, invertebrates, amphibians, reptiles, and fish, to downstream waters transported via passive or active dispersal (4.3.4, 4.4.4, B.2.3.3, B.3.3.3, B.6.3.2). • Riparian/floodplain wetlands can provide feeding habitat for riverine organisms, such as fish, during periods of overbank flow (4.3.4.2, B.2.3.3).
Sink Function
• Riparian/floodplain wetlands and non-floodplain wetlands can be sinks for water by intercepting overland or subsurface flow, if available water storage capacity of the wetlands is not exceeded, which can reduce or attenuate flow to downstream waters and flooding (4.3.2.1, 4.4.2.3, B.3.3.1). • Riparian areas and non-floodplain wetlands can be sinks for sediment and chemical contaminants, such as pesticides, metals, mercury, and excess nutrients carried by overland or subsurface flow, potentially reducing loading to downstream waters (4.3.2.2, 4.3.3, 4.4.3.2). • Riparian areas can be sinks for water, sediment, pesticides, and nutrients from overbank flow events, reducing or attenuating downstream peak flows and materials entrained in the water column (4.3.2.1, 4.3.2.2, 4.3.3, B.2.3.2). They can also be sinks for seeds and plant fragments deposited via overbank flow (4.3.4.1). • Riparian/floodplain wetlands and non-floodplain wetlands can be sinks for nitrogen by converting oxidized forms of nitrogen to molecular nitrogen through denitrification, which is then lost to the atmosphere (4.3.3.2, 4.4.3.2).
Refuge Function
• Riparian/floodplain wetlands and non-floodplain wetlands can provide refuge for fish, aquatic insects, or other lotic organisms from predators or other environmental stressors, facilitating individual or population survival (4.3.4, 4.4.4). • Riparian/floodplain wetlands and non-floodplain wetlands can provide refuge during certain life stages for lotic organisms. For example, they are breeding sites for frogs and other amphibians that reside in streams as adults (4.4.4, B.1.3.3, B.6.3.2; Table 4-2); non-floodplain wetlands are additionally nesting and nursery sites for American alligators that otherwise primarily reside in streams (4.4.4).

Table 4-1. Examples of mechanisms by which riparian/floodplain wetlands and wetlands in non-floodplain settings influence downstream waters, by functional type. See relevant section and appendix numbers in parentheses for greater detail. Note that the distinction between types of functions, is not always clear, for example, denitrification could be considered a sink or transformation function (continued).
Transformation Function
• Microbial communities in riparian/floodplain wetlands and non-floodplain wetlands can transform elemental mercury to methylmercury before it enters a stream. Methylmercury is a particularly toxic and mobile form that bioaccumulates in aquatic food webs (4.3.3.6, 4.4.3.1). • Riparian/floodplain wetlands and non-floodplain wetlands can transform nitrate to molecular nitrogen through denitrification (4.3.3.2, 4.4.3.2).
Lag Function
• Riparian/floodplain wetlands can temporarily store water following overbank flow, which then can move back to the stream over time as baseflow (4.3.2.1). • Non-floodplain wetlands can contribute to ground-water recharge under low water table conditions, which ultimately contributes to baseflow (4.4.2.3, B.3.3.1). • Non-floodplain wetlands can increase the time for stream discharge to rise and fall in response to a precipitation event due to wetland storage capacity (4.4.2.3).

definition of having wetland hydrology, hydrophytic vegetation, or hydric soils. The terms “riparian wetland” and “floodplain wetland” frequently describe the same geographic area. Because riparian areas and floodplains also contain upland areas, some riparian/floodplain wetlands are geographically isolated (i.e., completely surrounded by upland).

Although ample literature is available on riparian/floodplain wetlands—especially bottomland hardwood and swamp wetlands—most papers on riparian areas and floodplains do not specify whether the area is a wetland. This lack of specification occurs because riparian areas and floodplains also are studied by stream ecologists and hydrologists who might not focus on whether their study site meets the Cowardin et al. (1979) definition of a wetland. This situation creates a dilemma, because limiting our literature review to papers that explicitly describe the area as a wetland would exclude a major portion of this body of literature and greatly restrict our discussion of wetland science. Alternatively, if we include papers that do not explicitly classify the area as a wetland, we could mistakenly incorporate results that are relevant only to upland riparian areas. Our response to this dilemma was to survey the floodplain and riparian literature broadly and include any results and conclusions that we judged pertinent to riparian/floodplain wetlands. This judgment was based, in part, on: (1) the processes described in the integrated systems perspective on interactions of watersheds, streams, wetlands and downstream waters (Sections 2.2.2 and 2.2.3); (2) whether the information applies to all riparian areas, regardless of whether they are wetlands or uplands (e.g., all riparian areas are subject to periodic overbank flooding); and (3) an understanding of the specific processes. For example, riparian studies of denitrification are likely to be either in a wetland or applicable to riparian/floodplain wetlands, because the alternating oxidation/reduction conditions required for denitrification are present in wetlands. Therefore, in our assessment of evidence regarding the connectivity and effects of riparian areas and floodplains, we have concluded that the processes and functions discussed occur in water bodies within those areas.

As addressed in Chapter 2, much of the theory developed to explain how river systems function has focused on linkages between system components (Vannote et al., 1980; Newbold et al., 1982a; Newbold et al., 1982b; Junk et al., 1989; Ward, 1989; Power et al., 1995a; Power et al., 1995b; Huggenberger et al., 1998; Ward, 1998; Fausch et al., 2002; Ward et al., 2002b; Wiens, 2002; Benda et al., 2004; Thorp et al., 2006; Humphries et al., 2015). The integral connectivity between rivers and their floodplains and riparian areas is a central tenet of stream hydrology and ecology, as is the substantial influence that this bidirectional exchange has on the physical form, hydrology, chemistry, and biology of the river system (Junk et al., 1989; Abbott et al., 2000; Tockner et al., 2000; Woessner, 2000; Amoros and Bornette, 2002; Ward et al., 2002a; King et al., 2003; Naiman et al., 2005; Church, 2006; Kondolf et al., 2006; Poole et al., 2006; Poole, 2010; Tockner et al., 2010; Vidon et al., 2010; Helton et al., 2011; McLaughlin et al., 2011; Humphries et al., 2015). For example, the flood pulse concept, which Junk et al. (1989) first articulated and Tockner et al. (2000) extended, is a fundamental paradigm in river ecology, depicting the lateral expansion and contraction of the river in its floodplain and the resulting exchange of matter and organisms.

The influence of riparian/floodplain wetlands on downstream waters is especially notable because of the potential magnitude and spatial extent of their interactions with rivers and their locations within river networks. Although floodplains can form in modest size streams (Hughes and Lewin, 1982), they typically form in the lower portion of river networks (Montgomery, 1999; Church, 2002, 2006), where they can provide transient storage and subsequent release of river water and materials (Stanford and Ward, 1993; Squillace, 1996; Mertes, 1997; Winter et al., 1998; Tockner et al., 2000; Fernald et al., 2001; Amoros and Bornette, 2002; Malard et al., 2002; Claxton et al., 2003; Davis et al., 2011). Floodplain patterns and river channel complexity are determined by sediment supply and character, river valley slope, stream power, woody debris, and vegetation (Montgomery, 1999; Church, 2002; Coulthard, 2005; Church, 2006; Osterkamp and Hupp, 2010; Sear et al., 2010; Collins et al., 2012). Circumstances conducive to the formation of complex, rapidly changing channel forms (e.g., anastomosing, braided, meandering) and the deposition of coarse sediment create conditions optimal for river-floodplain interactions (Nanson and Croke, 1992; Mertes et al., 1995; Fernald et al., 2001; Fernald et al., 2006; Poole et al., 2006; Whited et al., 2007).

Wetlands that occur in floodplains are referred to as riverine wetlands within the hydrogeomorphic classification system (Smith et al., 1995). Although floodplain wetlands can occur as marshes (Villar et al., 2001; Lee et al., 2005) or scrub-shrub wetlands (Chipps et al., 2006), these areas are known for supporting forested wetlands. Mitsch and Gosselink (2007) classify floodplain forested wetlands as freshwater swamps—for example, cypress-tupelo swamps (*Taxodium distichum* and *Nyssa aquatica*, respectively) and white cedar swamps (*Chamaecyparis thyoides*)—if water is available throughout most of the growing season, or as riparian ecosystems if the floodplain receives seasonal pulses of flooding. Examples of the latter are bottomland hardwoods in the Southeast—for example, sycamore-sweetgum (*Platanus occidentalis* and *Liquidambar styraciflua*, respectively) and cypress-tupelo forests—or cottonwood-willow (*Populus* spp. and *Salix* spp., respectively) and alder (*Alnus* spp.) riparian communities in the Southwest (Mitsch and Gosselink, 2007).

This section provides further details on the connections between riparian/floodplain wetlands and streams and rivers, and the resulting effects. Below, we examine the physical (Section 4.3.2), chemical (Section 4.3.3), and biological (Section 4.3.4) effects of riparian/floodplain wetlands on rivers and other downstream waters.

4.3.2 The Physical Influence of Riparian Areas on Streams

4.3.2.1 Hydrology

Riparian areas within and outside of floodplains are an important part of the overall riverine landscape (Ward, 1998). Riparian areas are also connected to streams and rivers by a diverse set of hydrologic inputs and outputs (Figure 2-6A; Junk et al., 1989; Winter and Rosenberry, 1998; Benke et al., 2000; Tockner et al., 2000; Bunn et al., 2006). These inputs and outputs are described in Section 2.2 and have been reviewed by various authors (National Research Council, 2002; Naiman et al., 2005; Vidon et al., 2010).

Many studies document that riparian floodplains help attenuate flood pulses in streams and rivers by capturing water from overbank flow and by storing excess water from streams (Mertes et al., 1995; Poole et al., 2006; Rassam et al., 2006). Bullock and Acreman (2003) reviewed the wetland literature and reported that floodplain wetlands reduced or delayed floods in 23 of 28 studies. Walton et al. (1996) found that peak discharges between upstream and downstream water gages on the Cache River in Arkansas were reduced 10–20%, primarily due to floodplain water storage. Gamble et al. (2007) reported that 12 floodplain wetlands in Ohio stored an average of 3,654 m^3 ha^{-1} of water. The authors developed equations relating volume to area and depth for more than 650 regional wetlands and reported that these systems could store approximately 1–2% of the daily flow of larger streams and approximately 40% of the daily flow of small streams. As streamflow decreases after hydrologic events, the water temporarily stored in riparian/floodplain areas can flow back into the channel, supporting stream baseflow (Whiting and Pomeranets, 1997; Chen and Chen, 2003). Although not all riparian/floodplain wetlands store the same amount of water, nearly all of them have the potential to perform this function.

The potential for hydrologic connectivity between riparian/floodplain wetlands and rivers and streams is high during periods of overbank flow and during periods of lower streamflow. Hyporheic exchange occurs when water moves from river or stream channels into riparian or floodplain alluvial deposits and back to the channels, and it occurs during flooded and non-flooded conditions (Sjodin et al., 2001; Gooseff et al., 2008; Bencala, 2011) and on scales ranging from meters to kilometers (Stanford and Ward, 1988; Bencala, 1993, 2005). Complex floodplains typically are environments with high levels of hyporheic exchange (Woessner, 2000; Poole et al., 2006; Poole, 2010).

Vegetation in riparian/floodplain wetlands can influence hyporheic and river water through transpiration. Phreatophytes (plants that obtain their water from the saturated zone) can intercept ground-water and overland flow before it enters a stream and decrease streamflow by directly taking up stream water through their roots. For example, Meyboom (1964) studied two streams in the prairie region of the United States to understand the effect of floodplain vegetation on streamflow fluctuations. When the two streams decreased in flow, the floodplain vegetation accounted for 20% and 100% of this reduction (Meyboom, 1964).

4.3.2.2 Geomorphology (Sediment-vegetation Interactions)

A bidirectional relationship exists between fluvial geomorphology and riparian and floodplain vegetation (Corenblit et al., 2007). Distributions of vegetation communities often are shaped by river flow dynamics and associated erosional and deposition processes, but the communities also exert controls on geomorphic processes and riverine landforms.

Riparian/floodplain wetlands are key depositional environments for sediment that overland flow carries from erosion of nearby uplands (Boto and Patrick, 1979; Whigham et al., 1988). Riparian areas retain portions of this sediment before it enters the stream, especially if the overland flow enters the riparian area as sheetflow runoff rather than as channelized flow, due to the greater volume of water exposed to riparian-wetland soils and vegetation surfaces (Dabney et al., 1995; Meyer et al., 1995; Naiman and Decamps, 1997; National Research Council, 2002; Naiman et al., 2005). Riparian open waters (e.g., oxbow lakes; Section B.2) and wetlands are effective at retaining eroded clays, silts, and sands that otherwise would enter stream channels (Cooper et al., 1987; Heimann and Roell, 2000). Riparian areas were shown to remove 80–90% of sediments leaving agricultural fields in North Carolina (Cooper et al., 1987; Daniels and Gilliam, 1996; Naiman and Decamps, 1997). Grassy riparian areas alone can trap more than 50% of sediments from uplands when overland water flows are less than 5 cm deep (Dillaha et al., 1989; Magette et al., 1989; Naiman and Decamps, 1997). Thus, riparian areas can buffer stream channels against excessive sediment input.

Riparian areas and floodplains can be both sinks and sources for sediments in streams. When streams flood their banks, increased surface contact and friction decrease the flow velocity. The slower moving water has a diminished capacity for keeping material in the water column in suspension, which causes the sediments to deposit (Church, 2002, 2006). Heavy particles such as sand are the first to be removed, whereas finer, lighter particles such as clays and silts take longer to deposit. In southeastern Coastal Plain systems, sediment deposition rates from the stream to the floodplain are high because of frequent overbank flow and relatively high sediment loads of the rivers (Hupp, 2000).

Conversely, riparian areas and floodplains can also be a source of sediment to the stream, particularly through streambank erosion. Although streambank erosion is a natural process, it can be accelerated through vegetational changes because root tensile strength of riparian vegetation reinforces the soil (Naiman and Decamps, 1997; Burt et al., 2002). Streambanks that are devoid of vegetation are often highly susceptible to channel widening (Hupp et al., 1995; Naiman and Decamps, 1997). In a study of 748 bends in four southern British Columbia streams, for example, Beeson and Doyle (1995) reported that bank erosion was 30 times more prevalent on nonvegetated versus vegetated banks. In a comparison of row-crop agricultural, grazing, and forested riparian areas in central Iowa, the forested areas exhibited significantly reduced streambank erosion rates (Zaimes et al., 2004). Certain riparian wetland vegetation types, such as black willow (*Salix nigra*), maintain bank integrity and decrease erosion so well that they are used in river restoration and bank stabilization projects (Pezeshki et al., 2007).

Riparian vegetation also influences stream and river geomorphology through inputs of woody debris or logs, which in turn shape stream channels (Brummer et al., 2006; Sear et al., 2010; Collins et al., 2012). Woody debris can enter streams through tree mortality, bank undercutting, windthrow, wildfire, floods, landslides, and debris flows (Gurnell et al., 2002; Reeves et al., 2003). Gurnell et al. (2002) reported that the amount of woody debris deposited into streams can range from 12 to 40 t km^{-1} yr^{-1}, depending on the type of stream and nearby vegetation. As discussed in Section 3.3.3, woody debris can alter stream channels, trap sediments, and form new aquatic habitat (Anderson and Sedell, 1979; Harmon et al., 1986; Nakamura and Swanson, 1993; Abbe and Montgomery, 1996; Naiman and Decamps, 1997; Gurnell et al., 2002).

4.3.2.3 Temperature and Sunlight

Riparian areas can modify stream temperatures and the amount of light available for photosynthesis in stream and river environments through stream shading, particularly in forested settings (Barton et al., 1985; Gregory et al., 1991; Blann et al., 2002). Dense, overhanging vegetation greatly reduces the intensity of light, whereas open canopies allow light to penetrate (Gregory et al., 1991). This radiant energy, or lack thereof, strongly influences stream temperature (Barton et al., 1985; Gregory et al., 1991; Blann et al., 2002). The maximum temperature of a stream in Oregon, for example, was 7 °C higher in a reach where the riparian vegetation was removed compared to its temperature when it was forested. Fifteen years of regrowth in the harvested area was required for the stream temperature to return to preharvest levels (Johnson and Jones, 2000).

By affecting stream temperatures, shading by riparian vegetation can alter fish growth, activity, and mortality, while also influencing their prey species (Beschta et al., 1987). Higher temperatures, for example, can lead to greater stream invertebrate biomass (Beschta et al., 1987). The net temperature effect on fish growth, however, depends on the balance between food availability and higher metabolic rates (Beschta et al., 1987). Riparian vegetation enhancement can be used by managers to promote fish habitat for certain desired species. Blann et al. (2002) investigated the degree to which different types of riparian vegetation could increase shade, reduce stream temperatures, and promote habitat for brook trout (*Salvelinus fontinalis*) in Minnesota. The researchers concluded that both forested and herbaceous riparian vegetation shaded the stream and buffered stream temperature, and could aid in creating appropriate coldwater trout habitat (Blann et al., 2002).

Shading of the stream by riparian vegetation also directly influences the instream net primary productivity of aquatic plants and other photosynthetic organisms, such as algae, by altering light availability (Gregory et al., 1991). Net primary production is greatest in open reaches and is significantly less in reaches that are forested and shaded (Gregory et al., 1991). For example, Gregory et al. (1991) reported that net primary productivity in open streams in Oregon averaged 210 mg carbon (C) m^{-2} d^{-1}, whereas forested reaches of streams with deciduous vegetation averaged 58 mg C m^{-2} d^{-1}. Reduced net primary production leads to lower densities of herbivores in streams (Hawkins and Sedell, 1981; Gregory et al., 1991). Shading can limit stream productivity (Hill and Knight, 1988; Gregory et al., 1991), but it can also be beneficial by reducing excessive algal production in nutrient-enriched waters. Algae can lead to excessive biological oxygen demand and turbidity and can decrease water quality in downstream systems (Volkmar and Dahlgren, 2006).

In addition to shading by riparian vegetation, riparian areas and floodplains can influence stream and river water temperature through hyporheic exchange (Brosofske et al., 1997; Naiman and Decamps, 1997; Poole and Berman, 2001; Naiman et al., 2005). Hyporheic cooling of stream and river water during warm summer periods has been observed in a wide range of settings, including large gravel bed rivers in Oregon (Fernald et al., 2006; Burkholder et al., 2008; Seedang et al., 2008), an alpine stream in the mountains of Colorado (Constantz, 1998), a boreal river in Sweden (Nyberg et al., 2008), and small streams in Illinois (Peterson and Sickbert, 2006) and northern California (Loheide and Gorelick, 2006). Important to note, however, is that hyporheic exchange can warm streams (Valett et al., 1990). Arscott et al. (2001) found that hyporheic and other thermal regulating processes can lead to large thermal heterogeneity of water bodies associated with complex floodplains. Hester and Gooseff (2010) argue that, for streams impacted by human activities, restoration of hyporheic zones is essential for the recovery of stream functions and ecosystem services.

4.3.3 The Chemical-nutrient Influence of Riparian Areas on Streams

Riparian areas in and outside of floodplains are instrumental in controlling the biogeochemistry of riverine systems through (1) overbank flooding (flood pulse); (2) internal biogeochemical processes; and (3) hyporheic exchange (Junk et al., 1989; Thurman et al., 1991; Heiler et al., 1995; Tockner et al., 2000; Adair et al., 2004; Noe and Hupp, 2005; Valett et al., 2005; Noe and Hupp, 2007; Helton et al., 2011; Powers et al., 2012; Bennett et al., 2015). All three mechanisms help shape nitrogen, carbon, phosphorus, and pesticide cycling with the riverine environment.

Wetlands have been described as depositional areas in an eroding landscape (Brittain and Eikeland, 1988). Pollutants and materials relevant to discussions on water quality—such as nutrients, pesticides, and metals—enter wetlands (e.g., Tiner, 2003c; Comer et al., 2005) through flowpaths that include dry and wet (e.g., rain, snow) atmospheric deposition; point sources such as outfalls, pipes, and ditches; and nonpoint sources, such as runoff from agricultural and urban fields and lawns, drift spray, and diffuse near-surface water inputs (Nixon and Lee, 1986; Whigham and Jordan, 2003; Whitmire and Hamilton, 2008). For riparian/floodplain wetlands, transport from upstream reaches or through the hyporheic zone (Figure 2-6) is another important source of these substances. Such materials can then be sequestered via sorption (adsorption and absorption) or sedimentation processes, assimilated into the flora and fauna, transformed into other compounds, or lost to the atmosphere through transformational processes (Nixon and Lee, 1986; Johnston, 1991; Mitsch and Gosselink, 2007). These processes include conversion between particulate and dissolved forms of compounds via biologically mediated degradation (e.g., Bärlocher et al., 1978) and reduction-oxidation (redox) reactions (Nixon and Lee, 1986; Reddy and DeLaune, 2008). Redox reactions are essential to microbial respiration and are critical to both defining wetland systems and understanding transformational processes that microbes mediate (Boon, 2006; Reddy and DeLaune, 2008).

4.3.3.1 Hyporheic/Soil Processing of Nutrients

Riparian areas connect upland and aquatic environments through both surface and subsurface hydrologic flowpaths (Figure 2-6; Naiman et al., 2005). Riparian areas act as buffers that are among the most effective tools for mitigating nonpoint source pollution (Knight et al., 2010). These areas are uniquely situated in watersheds to receive and process waters that pass through the root zone before reaching streams (Gregory et al., 1991). These processes do not affect deep ground-water hydrologic flowpaths (Figure 2-5) that enter a river or stream below the active riparian root zone. The focus of this section, however, is on surface and shallow subsurface flows; we do not address deep ground-water flowpaths here.

Riparian areas can significantly influence nutrients and other exports from watersheds (Gregory et al., 1991) and can be considered areas of major nutrient transformation as subsurface waters move through them (Dahm et al., 1998). Riparian areas remove nutrients such as nitrogen and phosphorus from water as it flows from uplands to streams (Lowrance et al., 1997; Dosskey, 2001; Mayer et al., 2007). For instance, Johnston (1993) reported that a floodplain wetland retained, 15.2, 13.7, and 14.2% of the solids, total nitrogen, and total phosphorus fluxes, respectively, from the watershed. The degree to which a riparian area serves as either a source or a sink for nitrogen, phosphorus, organic matter, pesticides, and mercury is controlled largely by the substance's concentration in riparian soils (Gregory et al., 1991), soil redox conditions, and hydrology (Vidon et al., 2010). For example, riparian plant communities can release seasonal pulses of dissolved leachates derived from stream litter (Fisher and Likens, 1973). Riparian areas are therefore central to watershed water quality management (Burt, 1997; Lowrance et al., 1997).

4.3.3.2 Nitrogen

Riparian areas can remove dissolved nitrogen (N) in subsurface flowpaths that would otherwise flow into streams (Vidon et al., 2010). Removal occurs via plant uptake and microbial transformations (i.e., assimilative uptake, assimilatory nitrate reduction to ammonium, and dissimilatory nitrate reduction to ammonium or nitrogen gases such as dinitrogen, nitric oxide, and nitrous oxide via denitrification). One study demonstrated that intact riparian and hyporheic zones are critical in decreasing the amount of dissolved inorganic nitrogen that moves from headwaters to larger, downstream waters (Triska et al., 2007). Vidon et al. (2010) showed that riparian areas remove more than half the nitrogen from surface and shallow subsurface water transporting ammonium and nitrate through the rhizosphere (Vidon et al., 2010). Leaching from nitrogen-fixing plants (e.g., red alder, *Alnus rubra*) in riparian systems, however, also can be a major source of nitrogen to stream systems (Compton et al., 2003).

Denitrification potential in surface and shallow subsurface flows is not homogeneous across the riparian area, increasing markedly in the presence of organic carbon or anoxic conditions that create denitrification “hot spots” (McClain et al., 2003; Orr et al., 2014). Therefore, for riparian areas to appreciably increase nitrogen removal, flowpaths that convey nitrate-rich water into such denitrification “hot spots” must be present (Vidon et al., 2010).

The highest denitrification potentials occur in floodplain systems where high organic matter levels, denitrifying microbes, and saturated soil conditions are present (Vidon et al., 2010). Rates of denitrification are greater in riparian soils nearer to streams (Gregory et al., 1991). Johnston (1993) reported nitrate removal along a floodplain gradient of 6.6 g per 100-m distance from the stream. High soil moisture and deposited organic matter enhance microbial activity, thereby tending to increase denitrification (Reddy and DeLaune, 2008).

As subsurface flow passes through riparian areas, vegetative demand for dissolved nutrients also can reduce nutrient loads (Vidon et al., 2010). More than three-quarters of the dissolved nitrate (NO_3^-) transported from agricultural fields to a Maryland river (Vidon et al., 2010) was removed by riparian forests. Nitrogen was removed at a rate of 45 kg N ha^{-1} yr^{-1} as subsurface flow moved from agricultural fields through riparian zones to nearby streams (Peterjohn and Correll, 1984). In the coastal plains of Georgia, riparian forests retained more than 65% of the nitrogen and 30% of the phosphorus contributed from nearby agriculture (Vidon et al., 2010). In southern Pennsylvania, a forested riparian area had a subsurface nitrate budget with an average removal of 90 kg NO_3^- ha^{-1} yr^{-1}, which was 26% of the total nitrate input (Newbold et al., 2010).

4.3.3.3 Phosphorus

The movement and uptake of phosphorus in riparian areas are a function of phosphorus sources, hydrology, and biogeochemistry (Vidon et al., 2010), with interactions between ground water and surface waters driving the biogeochemical processes (Hoffmann et al., 2009). Phosphorus loss and retention in riparian areas are related to the flowpath of the water through the riparian area to the stream (e.g., overland flow of water from nearby agricultural fields, river-water inundation of floodplain riparian areas). Flowpath dictates the confluence and interaction of phosphorus with minerals that drive biogeochemical cycling of phosphorus in riparian areas (Hoffmann et al., 2009). The physical processes of sedimentation and plant uptake are active in these flowpaths and can account for particulate phosphorus retention rates as high as 128 kg P ha^{-1} yr^{-1} and 15 kg P ha^{-1} yr^{-1}, respectively (Hoffmann et al., 2009). Retention of dissolved phosphorus in riparian areas is more modest, with values less than 0.5 kg P ha^{-1} yr^{-1} often reported. Studies show, however, significantly higher numbers for the release of dissolved phosphorus: up to 8 kg P ha^{-1} yr^{-1} (Hoffmann et al., 2009).

Although riparian soils generally serve as sources of phosphorus when soils are anoxic or when mineral dissolution releases phosphorus (Baldwin and Mitchell, 2000; Chacon et al., 2008), riparian areas are phosphorus sinks in oxic soils (Carlyle and Hill, 2001). Portions of riparian areas where agricultural sediments are deposited are phosphorus sources to streams if the phosphorus is desorbed and leached but can be sinks by adsorbing dissolved phosphorus if sediment phosphorus concentrations are low

(Dillaha and Inamdar, 1997; Sharpley and Rekolainen, 1997). Riparian areas also serve as phosphorus sinks when upland surface runoff travels through the riparian area or when fine-grained sediment containing phosphorus is deposited overbank onto the riparian area (Dillaha and Inamdar, 1997). These sediments, however, can become sources of phosphorus if they are later saturated with water and iron and manganese are reductively dissolved during anoxic conditions, thus causing them to desorb phosphorus (Reddy and DeLaune, 2008).

4.3.3.4 Carbon and Allochthonous Inputs

Both production and consumption of organic and inorganic carbon occur in riparian areas. In areas with reducing conditions, microbes generally oxidize organic carbon and reduce available electron acceptors, releasing carbon dioxide gas and making the soils more alkaline (Vidon et al., 2010). This process can result in chemical gradients in which electron acceptor concentrations decrease and alkalinity increases along subsurface flowpaths (Burns, 1996; Cirmo et al., 2000; Bailey Boomer and Bedford, 2008). Riparian areas, especially those in low-lying flatlands, tend to have low subsurface flow velocities resulting in anoxic conditions, shallow water tables, and slow organic matter decomposition, as is often seen in riparian wetlands. This is why riparian areas are active areas for biogeochemical transformations (Vidon et al., 2010).

Allochthonous inputs from riparian areas to streams are critical to aquatic food webs, particularly in headwater catchments (reviewed in Tank et al., 2010). Allochthonous inputs are terrestrial organic materials that enter the stream through vegetation litter (i.e., woody debris, leaves, and partially decomposed plant parts), erosion, and hydrologic flows (Wetzel, 1992). In small forested watersheds, overhanging trees provide organic matter inputs, while simultaneously reducing photosynthesis by autotrophic organisms (Vannote et al., 1980). This dual effect makes allochthonous inputs the primary source of energy flow into the food webs of these streams. For example, in a New Hampshire stream the surrounding forest supplied more than 98% of the organic matter (Gregory et al., 1991). Organic matter inputs are important because they affect food availability to aquatic organisms by releasing organic carbon and nitrogen into streams (Wetzel and Manny, 1972; Mulholland and Hill, 1997). For example, in a small headwater stream near Louisville, KY, macroinvertebrate communities, which are critical food sources for fish (Wallace and Webster, 1996), relied almost exclusively on leaf inputs (Minshall, 1967). Excluding litter from the riparian area changed the food web structure of a North Carolina stream (Wallace et al., 1997) and decreased its dissolved organic carbon concentrations and loadings (Meyer et al., 1998). In addition to the impacts of total inputs, the composition and timing of allochthonous inputs, largely determined by riparian plant species composition, also can influence instream decomposition and aquatic invertebrates (Cummins et al., 1989; Swan and Palmer, 2006).

Downstream, much less of the stream is directly influenced by streamside vegetation, due to larger stream widths and consequently greater distances from the banks. This decreases the relative importance of allochthonous inputs while concomitantly increasing the importance of instream photosynthesis (Vannote et al., 1980). The macroinvertebrate community responds to this shift in input types. For example, macroinvertebrate shredders that use large inputs, such as leaves, become less prevalent as streams increase in size. Besides changing longitudinally with stream size, riparian allochthonous inputs also can vary seasonally, with a large pulse occurring in deciduous forests during autumn leaf fall.

4.3.3.5 Pesticides

The roots in riparian areas can be important in removing pesticides from shallow subsurface flow, because the labile organic matter and organic residues that accumulate near roots can increase microbial biomass and activity (Vidon et al., 2010). Pesticides and their metabolites can be mineralized and adsorbed where surface area contact is high and contact time with roots is sufficient (Krutz et al., 2006). A study of the pesticides alachlor and atrazine in a riparian area notes the importance of plant uptake in the fate of these pesticides, and suggests that vegetated buffer zones help protect water supplies (Paterson and Schnoor, 1992). Studies examining specific pesticides—for example, isoproturon (Benoit et al., 1999), metolachlor (Staddon et al., 2001), and atrazine (Mudd et al., 1995)—found that the presence of vegetation, associated root zones, and accumulated organic matter increased the removal of those pesticides (Vidon et al., 2010). Pesticide-degrading microbial populations increase after repeated chemical applications (Gonod et al., 2006), suggesting that riparian areas can become better at degrading pesticides that enter these zones (Vidon et al., 2010). In addition, microbial biomass has been shown to be positively correlated with the loss of the herbicides 2,4-D (2,4-dichlorophenoxyacetic acid) and dicamba, suggesting a relationship between the amount of microbial biomass in the soil and the capacity of an ecosystem to degrade pesticides (Voos and Groffman, 1996).

4.3.3.6 Mercury

Mercury enters the global atmosphere primarily through waste incineration and coal combustion. It can directly enter wetland systems or can be deposited on terrestrial areas and then transported into riparian areas and wetlands via rainfall and runoff (St. Louis et al., 1994). Riparian soils and wetlands are important both for mercury mobilization (Mierle and Ingram, 1991; Driscoll et al., 1995) and the production of methylmercury, a particularly toxic and mobile form of the element. Mercury methylation occurs in the presence of anoxic, saturated soils high in organic matter, mercury-methylating microbes, and mercury from either atmospheric deposition or soils (St. Louis et al., 1996). The redox conditions found in the presence of a fluctuating water table are thought to be a strong driver of mercury methylation (Heyes et al., 2000; Branfireun and Roulet, 2002; Branfireun, 2004). Export of mercury and methylmercury can expose organisms in downstream aquatic ecosystems to potential toxicity (Thurman, 1985; Driscoll et al., 1995). Mercury bioaccumulates in fish, and consumption of fish is the main human pathway for exposure to mercury (Rypel et al., 2008).

The source-sink dynamics of riparian areas with respect to mercury are complex. Because soils accumulate mercury, they buffer aquatic ecosystems against the full impact of this pollutant (Aastrup et al., 1991). Because some of this mercury and methylmercury moves from soils to surface waters, however, riparian areas might also be a source of the mercury that ends up in the aquatic food web.

4.3.4 Biological Connections Between Riparian Areas and Streams

The dynamic nature of river systems is most apparent in riparian areas and floodplains, where a shifting landscape mosaic supports diverse communities of aquatic, amphibious, and terrestrial plant and animal species adapted to periodic or episodic inundation of riparian areas and floodplains (Power et al., 1995a; Power et al., 1995b; Galat et al., 1998; Robinson et al., 2002; Toth and van der Valk, 2012; Rooney et al., 2013; Granado and Henry, 2014). In unregulated rivers, floodplain inundation greatly increases the area and diversity of aquatic habitats (Junk et al., 1989; Tockner et al., 2000; Brooks and Serfass, 2013). It also enables rapid cycling of nutrients imported from river channels (Section 4.3.3.2), resulting in high primary productivity of plants and algae (Junk et al., 1989; Tockner et al., 1999). The combination of diverse habitat types and abundant food resources makes floodplains important foraging, hunting, and breeding sites for fish (Copp, 1989; Bestgen et al., 2000; Schramm and Eggleton, 2006; Sullivan and Watzin, 2009; Alford and Walker, 2013; Magana, 2013), aquatic life stages of amphibians (Richardson et al., 2005), and aquatic invertebrates (Smock et al., 1992; Smock, 1994). Many of these organisms have growth stages or reproductive cycles timed to coincide with seasonal hydrologic connectivity between rivers and floodplains. Thus, lateral fluctuations in hydrologic connectivity can increase overall levels of species productivity and biodiversity in river systems (Junk et al., 1989) and can be integral to the viability of many riverine species (Bunn and Arthington, 2002). Here, we review examples of adaptation to and exploitation of riparian habitats by aquatic species of plants, fish, mammals, and invertebrates.

4.3.4.1 Vascular Plants and Phytoplankton

Channels and riparian/floodplain wetlands provide habitat for aquatic vegetation, emergent vegetation, and phytoplankton. When seeds, plant fragments, or whole organisms move back and forth between riparian/floodplain wetlands and the river network (via water, wind, or animal dispersal), these areas become biologically connected. Species can disperse via overbank flow between channels and riparian/floodplain wetlands (e.g., Schneider and Sharitz, 1988; Middleton, 2000; Nilsson et al., 2010). Seeds from vegetation within the channel or that have been mobilized from upstream riparian/floodplain wetlands can be deposited on bordering or downstream riparian areas and floodplains (Nilsson et al., 2010), much like sediment and in many cases with sediment (Gurnell, 2007; Gurnell et al., 2008). For example, in the southwestern United States, soil seed banks of wetland plants can be established or replenished in floodplains when those areas are connected to a stream channel by overbank flow (Boudell and Stromberg, 2008). In another example, 41% of plant species for which the seeds were deposited on riparian areas during winter flood flow in two United Kingdom rivers were wetland or aquatic plants (Gurnell et al., 2008). Overland flow or flooding also can dislodge viable plant fragments in riparian/floodplain wetlands, which then are transported down the river network. Fragments of seep monkeyflower (*Mimulus guttatus*) are easily dislodged by the relatively high flow velocities along the riparian-channel interface, and fragments can survive and reestablish downstream at rates exceeding 90% (Truscott et al., 2006).

Floodplains can function as sinks for seeds and plant fragments. For example, in a forested floodplain wetland in Illinois, many bald cypress (*Taxodium distichum*) seeds dispersed by the river network were deposited but did not germinate (Middleton, 2000). Alternatively, establishment and reproduction of refuge floodplain populations can become important wetland seed sources for the river network, especially if catastrophic flooding scours vegetation and seed banks that can exist on streambeds (Gurnell et al., 2008).

Hydrologic connectivity between channels and riparian/floodplain wetlands can significantly enhance riparian vegetation diversity (Jansson et al., 2005) and determine floodplain wetland community structure (Boschilia et al., 2008). For nonnative species, however, connectivity can facilitate invasion, resulting in changes in riparian vegetation community structure. In an intermittent stream in Illinois, tubers of the nonnative Chinese yam (*Dioscorea oppositifolia*) were dispersed via stormflow and overbank flow and became established along a narrow upstream riparian area and wider channel and floodplain more than 1 km downstream; the presence of the nonnative plant significantly reduced native plant cover (Thomas et al., 2006). Vegetation community composition, in turn, can affect the function of riparian areas as nutrient sources or sinks to the river network (Sections 4.3.3.2 and 4.3.3.3). Invasion by nonnative riparian plants also can result in altered stream invertebrate diversity, among other effects (Lecerf et al., 2007).

Seeds of aquatic and riparian plants also can be actively dispersed by animals that consume them. For example, seeds of the aquatic emergent bur-reed (*Sparganium emersum*) were ingested and viably excreted by common carp (*Cyprinus carpio*) (Pollux et al., 2007), which elsewhere have been observed using channel and floodplain wetland habitat (King et al., 2003). Riparian floodplain and wetland vegetation can also disperse and exchange seeds via terrestrial animal vectors and the wind. Animals that travel overland can also disperse ingested seeds or seeds adhering to fur, feathers, or limbs between riparian/floodplain wetlands and the river network (see Sections 4.3.4.2, 4.4.4, and B.3.3.3 for discussions of animal movement). Many macrophyte species have evolved for dispersal by wind, including some of the most invasive in North America, cattail and reed canary grass (Barrat-Segretain, 1996; Soons, 2006 and references therein). Given the proximity of riparian/floodplain wetlands and the river network itself, dispersal of pollen and seeds between these habitats could be quite frequent. For example, seeds of some 20 species found in floodplain wetlands in bald cypress swamps in Illinois were caught in aerial seed traps, and dispersal of three species averaged more than 100 seeds m^{-2} yr^{-1} (Middleton, 2000).

Phytoplankton also move via water between floodplain wetlands and the river network. A river with overbank flow can homogenize the phytoplankton communities in floodplain wetlands separated by more than 5 km (Angeler et al., 2010), and phytoplankton communities in river networks can be bolstered by high-productivity conditions in temporarily connected floodplain wetlands. For example, a portion of flow from California's Sacramento River is seasonally diverted from the main channel into the Yolo Bypass, a nearby 240 km^2 floodplain. From January to June 2003, 14 and 31% of total diatom and total green algae biomass, respectively, was produced in the floodplain (Lehman et al., 2008). This considerable contribution of carbon to the aquatic food web, which ultimately supports downstream fisheries, resulted from the high net primary productivity of the floodplain. This observation is particularly noteworthy because the median flow through the floodplain during the period of measurement (23 m s^{-1}) was just 3% of the median flow through the main channel. Considered collectively, these studies indicate riparian/floodplain wetlands can be both sources and sinks for phytoplankton and water-, animal-, and wind-dispersed vascular plants with respect to the river network.

4.3.4.2 Vertebrates

Animals, including many fish and mammals, move between riparian/floodplain wetlands and the river network. The evidence is strong and abundant that fish can move between the main river channel and riparian/floodplain wetlands when the channel and wetlands are hydrologically connected, even when, in some cases, the connection is seasonal or temporary. Such wetlands provide refuge, feeding, and rearing habitat for many fish species and augment recruitment to the river network (Boltz and Stauffer, 1989); examples include fish taxa in forested floodplain wetlands of the southeastern and southwestern United States and salmonids of the northwestern United States such as coho salmon (*Oncorhynchus kisutch*) and Chinook salmon (*Oncorhynchus tshawytscha*) (e.g., Wharton et al., 1982; Matheney and Rabeni, 1995; Pease et al., 2006; Henning et al., 2007; Jeffres et al., 2008). In one section of the mainstem Rio Grande in New Mexico, more than 90% of the larval and juvenile fish of six captured species were from riparian areas with zero water velocity (backwaters, former side channels, and isolated pools; Pease et al., 2006). Oxbow lakes are also important habitats for fish feeding and rearing. Based on a 5-year study of fish in oxbow lakes, Shoup and Wahl (2009) concluded that the entire floodplain should be considered a single functioning unit that supports the overall biological integrity of a river (Section B.2). The use of riparian/floodplain wetlands by fish depends on many factors intrinsic to the particular river system (e.g., periodicity and duration of floodplain inundation) and the characteristics of the resident or migratory fish community (King et al., 2003).

Fish also move between lacustrine wetlands (wetlands associated with lakes) and large lakes when hydrologic connections exist. Fish communities in the Great Lakes and their surrounding wetlands become more homogeneous when surface connections between the wetlands and lake are present. Fish use these wetlands for refuge from predators and as rearing habitat (Jude and Pappas, 1992). Miyazono et al. (2010), studying floodplain lakes in the Yazoo River Basin, found that conditions that included decreases in habitat connectivity, wetland buffers, and certain water quality parameters led to the increased dominance of environmentally tolerant fish in those lakes. Fish assemblages in riparian wetlands along the semiarid region of the Murray River, Australia showed a large decline in diversity when those wetlands were disconnected from the river through hydrologic modifications. This trend was reversed after a managed inundation treatment restored connections between the wetlands and the river (Vilizzi et al., 2013). River-dwelling mammals also move between rivers and riparian/floodplain wetlands, including river otters, which have been observed using wetlands extensively as latrines (Newman and Griffin, 1994). In addition, both river otters and beavers have a strong preference for riparian areas that are pond- and lake-dominated (Swimley et al., 1999). Thus, movement of animals, especially fish, connects riparian/floodplain wetlands to the river network and supplies streams and rivers with a source of biological materials.

In addition to acting as sources, sinks, and refuges for individual species of organisms, riparian/floodplain wetlands can improve the overall health of biological communities. For example, a positive relationship between wetland cover and an index of biological integrity for fish communities in rivers was observed in 23 sites in several small catchments of the River Raisin in Michigan (Roth et al., 1996).

Besides providing a form of biological connectivity that can link riparian/floodplain wetlands and downstream waters, vertebrates in riparian areas can affect stream characteristics and influence various forms of connectivity. Perhaps the most familiar example of this is the beaver (*Castor canadensis*). Although beaver damming would be expected to reduce hydrologic connectivity through impoundment, their influence can be more complex. For example, Westbrook et al. (2006) found that beaver dams in the Colorado River affected depth, extent, and duration of inundation resulting from a 10-year flood event. In addition, beaver dams attenuated declines in water tables during drier summer periods in 25% of their 58 ha study area. They concluded that the main hydrologic effects occurred downstream, however, rather than near the dam (Westbrook et al., 2006). The hydraulic head generated by the dam raised the water level above the banks, resulting in lateral and downstream spreading of flows during high- and low-flow periods; these effects extended over hundreds of meters. For example, mottled soils occurred throughout the study area, suggesting that the dams caused waterlogged soils for extended periods. Increased overbank flooding increases hydrologic connectivity between riparian areas and streams. In contrast, when no dams were present, flooding was limited to the area immediately near the stream channel. Beaver dams also can affect stream biogeochemistry. For example, beaver dams modify nutrient cycling and decomposition dynamics and can affect downstream transport of materials (Naiman et al., 1988; Naiman et al., 1994). For example, beaver-dam wetlands can serve as a source of methylmercury (Roy et al., 2009). Beaver dams also can affect fish species, such as coho salmon (Pollock et al., 2004).

Vertebrates also can indirectly affect hydrologic connectivity through cascading effects on riparian plant communities. Beschta and Ripple (2012) provide evidence from analyses at three western National Parks for a trophic cascade model where large predators can affect the morphology of river channels through intermediate effects on ungulate browsers and riparian plant community structure. For example, extirpation of wolves (*Canis lupus)* at Yellowstone National Park by the mid-1920s led to an increase in elk (*Cervus canadensis*) numbers. This increase caused suppression and mortality of riparian willow (*Salix* spp.) communities, ultimately resulting in changes to stream morphology such as bank erosion, decreased sinuosity, increased active channel width, and increased amount of unvegetated alluvium (Beschta and Ripple, 2012). Based on results from the three National Parks and other sites, Beschta and Ripple (2012) concluded that the removal of apex predators due to extirpation increased ungulate herbivory, which altered riparian plant communities, thereby increasing bank erosion that led to either widening of the active channel or channel incision. These channel alterations, in turn, reduced the frequency of overbank flows, which decreases hydrologic connectivity between the riparian area and downstream waters.

4.3.4.3 Invertebrates

Stream macroinvertebrates (e.g., insects, crayfish, mollusks) and microinvertebrates (e.g., cladocerans, copepods, rotifers, gastropods) colonize nutrient-rich riparian areas and floodplains in large numbers during seasonal or episodic immersion by rivers and streams (Junk et al., 1989; Ilg et al., 2008). Macroinvertebrates and microinvertebrates (also called zooplankton) are the intermediate link between primary producers (e.g., algae), detrital pools (e.g., leaf litter), and predators (e.g., fish, amphibians) in river food webs (Malmqvist, 2002; Woodward and Hildrew, 2002; Stead et al., 2005; Woodford and McIntosh, 2010). The distribution of invertebrate populations in dynamic river systems is governed by the location of resources required for different needs and life stages, and invertebrates actively dispersing to find and exploit resources wherever they become available (Malmqvist, 2002). As with vascular plants, hydrologic connectivity between channels and riparian/floodplain wetlands can significantly influence macroinvertebrate community structure in riparian areas (Paillex et al., 2009; Yetter, 2013). For example, the species diversity and abundance of macroinvertebrates in the wetlands of a river delta have been found to be positively correlated with a gradient of connectivity (Dou et al., 2015).

Invertebrates have evolved two basic strategies to exploit habitats near streams and rivers: (1) rapid colonization of flooded areas and short life cycles that complete before floodplains dry again, or (2) use of aquatic refuges or dormant life stages to persist in permanent waters, the hyporheic zone, or floodplain soils between inundations (Tronstad et al., 2007). To evaluate the relative importance of each strategy in the same river system, Jenkins and Boulton (2003) compared the abundance and species composition of microinvertebrates emerging from floodplain sediments to those transported by floodwater from instream habitats at reach and watershed scales. Initially, most colonizers of newly flooded riparian habitats came from distant upstream reaches of the river network, washed downstream by floodwaters. After a few days, however, species hatching from eggs diapausing in soils greatly increased the diversity and size of the river/floodplain community. This study illustrates two important points about biological connectivity of river/riparian habitats:

1. Stream invertebrate communities comprise species adapted to different stresses in their environment (in this case, resilient species adapted to high flows and resistant species adapted to desiccation).
2. Floods that periodically connect different parts of the river network generate potential for gene flow across time and space by mixing individuals from different locations (e.g., upstream/downstream, channel/floodplain) and different years (e.g., eggs that might have diapaused for tens or even hundreds of years).

The findings by Jenkins and Boulton (2003), that resting egg banks in riparian soils are important to the persistence of aquatic species and the composition of river communities, were validated in a separate study by Frisch and Threlkeld (2005), who compared flood-pulse colonization in a field study with laboratory hatching of copepod microcrustaceans from egg banks of inundated soils in Mississippi. The laboratory samples showed that, in the absence of hydrologic connections, egg banks were sufficient for persistence of copepod populations; the field samples showed that when hydrologic connections were present, water dispersal and hatching from dormant stages were both important colonization pathways for copepods. In a perched floodplain in Missouri, Fisher and Willis (2000) showed that flood-pulsed movement of water and organisms between river channels and floodplains was bidirectional. Adaptations by stream-dwelling invertebrates to variable moisture conditions, and rapid two-way dispersal to exploit temporary or seasonal hydrologic connections, are strong evidence of long-term biological connectivity between rivers and riparian areas.

Invertebrates that disperse by aerial means also take advantage of flooded riparian habitats. Tronstad et al. (2007) investigated aerial colonization of floodplains by insects during multiple flood pulses having different inundation periods in an unregulated river in Alabama's Coastal Plain. At least 41 genera in 21 families across 7 orders of flight-capable insects colonized floating trays placed in floodplain waters in June, August, November, and April. Insect densities varied across the period and reached a maximum in August of about 80,000 individuals m^{-2}, most of which were seeking mates or oviposition sites rather than foraging or hunting. High densities (21,291 individuals m^{-2}) of passively dispersing (e.g., via wind or animal vectors) microcrustaceans also were observed. Vanschoenwinkel et al. (2009) erected 9 windsocks (sampling devices for aerially dispersing organisms) near temporary rock pools for 1 month, during which 850 viable dormant eggs, larvae, and adults from 17 invertebrate taxa were collected. Results from these studies illustrate that aerial dispersal of multiple taxonomic orders and phyla is a significant source of stream invertebrate colonists in newly inundated floodplain habitats.

4.4 Non-floodplain Wetlands

4.4.1 Introduction

This section focuses on the connections and influence of non-floodplain wetlands (defined in Section 2.2.1) on downstream waters. Brinson (1993), in his hydrogeomorphic classification system, categorized wetlands according to four geomorphic settings. This system subsequently was expanded to the following seven classes by Smith et al. (1995): riverine, depressional, slope, mineral soil flats, organic soil flats, estuarine fringe, and lacustrine fringe. Non-floodplain wetlands consist of certain depressional, slope, and flats wetlands (although some of these wetlands can occur in riparian and floodplain wetland settings; Section 2.2.1). Depressional wetlands, as their name suggests, occur in topographic depressions and might or might not have a surface water inlet or outlet. Common types of depressional wetlands include kettles, potholes, vernal pools, playa lakes, and Carolina bays (Brinson, 1993). Slope wetlands (also known as seeps) are located in breaks of slopes and are sites of ground-water discharge (Hall et al., 2001a; O'Driscoll and DeWalle, 2010). Slope wetlands include fens, which typically are ground-water driven and have diffuse outputs (Brinson, 1993; Bedford and Godwin, 2003). Mineral soil flats commonly occur on interfluves, relic lake bottoms, or large floodplain terraces.

Precipitation dominates the water sources in mineral soil flats, with little ground-water input. Wet pine flatwoods and large playas are examples of this wetland type. Non-floodplain wetlands also include organic soil flats. These contain extensive peatlands, or peat bogs, where the accumulation of partially decayed organic matter dominates (Mitsch and Gosselink, 2007). Precipitation also generally dominates the water inputs to bogs, which can connect to downstream waters via a channel outlet or diffuse overland flow (Brinson, 1993). Bogs are generally more acidic than fens (Bedford and Godwin, 2003). Depressional, slope, or flats wetlands also can serve as stream origins (Figure 2-18A).

Below, we examine the physical (Section 4.4.2), water quality (Section 4.4.3), and biological (Section 4.4.4) effects of non-floodplain wetlands on rivers and other downstream waters. We then briefly consider the issue of geographic isolation in non-floodplain wetlands (Section 4.4.5).

4.4.2 The Physical Influence of Non-floodplain Wetlands on Streams

Section 2.4.1 provided a general description of how non-floodplain wetlands can connect to downstream waters via surface and ground-water flow (Figure 2-18). In this section, we provide further details on these connections and discuss how such connections affect streamflow.

4.4.2.1 Surface-water Connections

Non-floodplain wetlands can be connected by perennial surface flows to river networks. For example, seeps are likely to have perennial connections to streams that provide important sources of baseflow, particularly during summer (Morley et al., 2011). In a study in Maine, seeps were found to provide 40–80% of stream water during baseflow periods (Morley et al., 2011). In other cases, surface connections between non-floodplain wetlands and streams can be intermittent or ephemeral. Rains et al. (2008) and Rains et al. (2006) showed that California vernal pools, situated on both clay and hardpan soils, connected with streams through channels containing transient water flow (Section B.6). The series of vernal pools on the clay soils were filled with water for 200 days of the year, and water spilled from these wetlands through swales and channels for 60% of those days (Rains et al., 2008). McDonough et al. (2015) found that forested Delmarva bays had seasonally intermittent surface water connections to streams; these connections occurred during periods of low evapotranspiration and high water tables, that is, from mid-fall to late-spring. In contrast, surface-water connectivity of restored and prior converted (wetlands converted to agriculture before 1985) bays was ephemeral, that is, it occurred in response to rainfall. The cumulative duration of connections to perennial streams was greater and had fewer transitions between connected and disconnected states for forested bays than for restored and prior converted bays (McDonough et al., 2015). Drainage of wetlands via ditching also can produce surface water outflows from depressional wetlands directly to streams (Section 2.4.4); ditches, however, also can introduce nutrients and ions into downstream waters (Brunet and Westbrook, 2012).

Even non-floodplain wetlands that are considered to be geographically isolated (i.e., completely surrounded by uplands), can have surface-water outflows that connect them to other water bodies (Figure 2-18B). Tiner (2003b) identifies vernal pools as 1 of 10 types of geographically isolated wetlands. Yet, as just discussed, the studies by Rains et al. (2008) and Rains et al. (2006) indicate that vernal pools can be connected to stream networks by channels. As another example, a recent study of depressional wetlands in the Texas Gulf Coast area showed that, although classified as geographically isolated, these wetlands are actually connected to nearby waterways via intermittent streams (Wilcox et al., 2011). During a study period of almost 4 years, nearly 20% of the precipitation that fell on a wetland complex flowed as surface runoff through the stream to a nearby water body, the Armand Bayou (Wilcox et al., 2011). Non-floodplain wetlands also can have temporary hydrologic connections to each other. Such connections can occur through the expansion and contraction of surface water that occur between wet and dry periods (e.g., Figure 2 in Niemuth et al., 2010) and through fill and spill of surface waters. One consequence of fill-and-spill behavior is that the contributing area of such a wetland is dynamic and has a nonlinear relationship to potential storage area (Shaw et al., 2012; Shaw et al., 2013). In the intermontane West, evidence suggests that depressional wetlands can connect to one another via temporary overland or shallow ground-water flows (Cook and Hauer, 2007). In the prairie pothole region, temporary overland connectivity between potholes has been observed in wet years. In 1996, during heavy spring rains, an estimated 28% of the wetlands in the study area had surface-water connections to at least one other wetland (Leibowitz and Vining, 2003). Le and Kumar (2014) analyzed topographic depressions in five study areas across the United States and found that hydrologic connectivity—as determined by nearest neighbor distances—followed a universal power law distribution. One implication of this distribution is that, although most depressions are connected over short distances, a few are connected by long distances, which could cause rapid increases in hydrologic connectivity as the system wets up (Le and Kumar, 2014). However, the distribution can be altered through wetland drainage (Van Meter and Basu, In press). Although some of these studies focused on wetland-to-wetland connections, the findings illustrate (1) the potential for geographically isolated wetlands to exhibit temporary surface water connections with other water bodies, and (2) that interacting wetland complexes might best be understood as a functional unit (Section 4.4.5).

4.4.2.2 Ground-water Connections

In addition to surface-water connections, ground-water flow can connect non-floodplain wetlands with other water bodies, potentially over great distances (Figures 2-5 and 2-18C). Many studies have shown that non-floodplain wetlands can connect to ground water, either receiving ground-water discharge (flow of ground water to the wetland), contributing to ground-water recharge (flow of water from the wetland to the ground water), or both (e.g., Lide et al., 1995; Devito et al., 1996; Matheney and Gerla, 1996; Rosenberry and Winter, 1997; Pyzoha et al., 2008). For example, a 1989 study of four North Dakota prairie pothole wetlands by Arndt and Richardson (1989) clearly demonstrated ground-water connections as one wetland recharged ground water, one was a flow-through wetland, and one was a discharge system. Hunt et al. (2006) found that benthic invertebrate communities were correlated with amounts of ground-water discharge to stream-wetland complexes in northern Wisconsin. Using stable hydrogen and oxygen isotopes in water, Matheney and Gerla (1996) concluded that, although most of the water in a depressional prairie wetland came from precipitation, ground-water connections accounted for the high salinity of the wetland soil. The high salinity is indicative of net ground-water discharge to the wetland (Brinson, 1993). Min et al. (2010) reported that 38% of rainfall that entered four historically geographically isolated wetlands in Florida was recharged to ground water. A literature survey by Bullock and Acreman (2003) found 69 studies making reference to ground-water recharge from wetlands; of these, 32 studies observed ground-water recharge from a wetland, whereas 18 studies did not.

Ground-water flow-through wetlands are sites of both ground-water discharge and recharge, in essence a surface expression of the ground-water system (Richardson et al., 1992; Kehew et al., 1998; Ferone and Devito, 2004). In these wetlands, ground-water discharge generally flows into the wetland on one side or area, and flows back into the ground water on the other side or area of the wetland. This dynamic has been shown in many locations, including prairie potholes (Richardson et al., 1992), wetlands in glacially formed landscapes in southwest Michigan (Kehew et al., 1998), Alaskan ponds (Rains, 2011), Florida cypress dome systems (Sun et al., 1995), and small Wisconsin lakes (Born et al., 1979). The lakes and wetlands of the Nebraska Sand Hills are also predominantly flow-through and an expression of a large regional ground-water system (Winter, 1999). The flow-through wetland influences the chemistry of the transiting, shallow ground water. Kehew et al. (1998) found a wetland of this type diluted nitrogen concentrations in the ground water of an agricultural watershed.

Whether a wetland recharges ground water, is a site of ground-water discharge, or both, is determined by topography, geology, soil features, and seasonal position of the water table relative to the wetland. Shedlock et al. (1993), for example, concluded that ground water discharged into a bog along Lake Michigan through a breach in the sediments underlying the wetland. In dry periods when water tables are low, water tends to move from wetlands into the ground water, while in wetter periods with higher water tables, water can flow in the opposite direction from shallow ground water into the wetlands (Phillips and Shedlock, 1993; Pyzoha et al., 2008; McLaughlin et al., 2014). Lide et al. (1995) observed both ground-water flow into and from a Carolina bay wetland, with discharge to the wetland when the water table was high and recharge to the ground water when the water table was low. Sun et al. (1995) observed similar phenomena in a Florida cypress dome. This exchange and temporary storage of water represents a lag function that can make wetlands particularly important for ground-water recharge during dry periods. Rosenberry and Winter (1997) indicated that ground-water discharge to a wetland often alternates with flow from the wetland to ground water, and the direction of flow is controlled by the balance of recent precipitation with current evapotranspiration demands.

The magnitude and transit time of ground-water flow from a wetland to other surface waters depends on the intervening distance and the properties of the rock or unconsolidated sediments between the water bodies (i.e., the hydraulic conductivity of the material). In some carbonate or volcanic rocks, for example, ground water can flow relatively freely through large openings; while in unconsolidated material—such as gravel, sand, silt, or clay—the spaces between particles determine the time required for water to flow a given distance (Winter et al., 2003). In porous material, such as gravel, water can travel a distance of a kilometer in a few days; in fine-textured materials, such as silt or clay, hundreds to thousands of years might be required for a single parcel of water to travel the same distance (Winter and LaBaugh, 2003).

In agricultural regions, the transit time of subsurface flows can be decreased substantially by artificial subsurface drainage pipes, known as tile drains (Section 2.4.4; Schiller et al., 2012). Wetlands in these areas are sometimes fitted with inlets that connect directly to tile drains, quickly moving temporarily ponded water through the subsurface and to outlets that discharge directly to ditches or streams (Tomer et al., 2010).

In summary, non-floodplain wetlands can have a range of hydrologic connectivity with other waters (Figure 2-18). Non-floodplain wetlands can be connected by permanent, intermittent, or ephemeral surface flows through swales or channels, or be connected to other water bodies via shallow or deep ground-water flows. Conversely, a wetland can be isolated hydrologically if it lacks surface water and ground-water connections entirely and evapotranspiration is the dominant form of water loss. A wetland also can be hydrologically isolated from streams and rivers if it recharges a ground-water aquifer that does not feed surface waters. Wetlands that lack surface connectivity in a particular season or year can be connected, nevertheless, in wetter seasons or years. A wetland that serves as the origin of a stream will have a permanent or temporary surface water connection with a stream network through a stream channel, unless the wetland feeds an endorheic stream (Sections 3.2 and B.5.5.1).

4.4.2.3 Effects of Non-floodplain Wetlands on Streamflow

Non-floodplain wetlands can affect streamflow by altering baseflow or stormflow (Section 2.2.2; Figure 2-8) through several mechanisms, including surface storage and ground-water recharge. Depressional wetlands effectively store water because the aboveground portion of the wetland contains a largely empty volume for water storage, in contrast to belowground water storage where only part of the volume is available for water storage, for example, due to soil particles (i.e., the specific yield; Johnson, 1967; McLaughlin et al., 2014). Large-scale studies have shown that wetlands, by storing water, reduce peak streamflows, and thus, downstream flooding. Hubbard and Linder (1986), for example, calculated the water retention capacity of more than 200 closed depressional prairie potholes in northeastern South Dakota. They observed that a large amount of snowmelt and precipitation could be cumulatively held by many small wetlands, reducing the potential for flooding at downstream locations. Similarly, a USGS study in the prairie pothole region found that wetlands—including both depressional and nondepressional types—stored about 11−20% of the precipitation that fell in a given watershed, and that storage could be increased by wetland restoration (Gleason et al., 2007). Vining (2002) concluded that wetland storage in the Starkweather Coulee subbasin of North Dakota likely resulted in decreased streamflow. Rovansek et al. (1996) found snowmelt to be the most important source of water for wetlands and ponds in the Alaskan Arctic Coastal Plain, and that these wetlands and ponds functioned as surface storage, thereby removing water from the snowmelt floods. However, Ford and Bedford (1987) note that in permafrost-dominated areas of Alaska, wetland soils tend to be frozen during snowmelt events, resulting in a significant proportion of these floodwaters running directly to streams, thus rendering these wetlands unimportant in streamflow regulation. Likewise, Roulet and Woo (1986) found that wetlands in the Continuous Permafrost Region of Canada tended to be unimportant for either long-term water storage or streamflow regulation.

Regression equations developed to predict peak flows during flooding events generally use lake and wetland storage areas as variables. Using this approach for Wisconsin watersheds, Novitzki (1979) estimated that peak flood flows were only 20% as large in watersheds with 40% lake and wetland area relative to watersheds without lakes or wetlands. Johnston et al. (1990) found that small losses of wetlands in watersheds with <10% wetlands could have major effects on flood flow in basins around Minneapolis, Minnesota. Wang et al. (2010) modeled the influence of wetlands on hydrologic processes in Manitoba and Minnesota and found that the loss of 10-20% of the wetlands in the study basins would increase peak discharge by 40%. Similarly, Yang et al. (2010) calculated restoration of 600 ha of wetlands in a 25,139 ha watershed would decrease peak stream discharge by 23%. Peak streamflows were shown to be negatively correlated with lake and wetland storage in Minnesota (Jacques and Lorenz, 1988), although a later study found peak flows to be correlated with lake storage only and not wetland storage (Lorenz et al., 2010).

The ability of wetlands to reduce flooding via storage varies with topography, wetland type, antecedent moisture conditions, and available water storage capacity. Using stable hydrogen and oxygen isotopes of water, McEachern et al. (2006) found that snowmelt in boreal forests was discharged rapidly in a sloped watershed. In contrast, in a lowland watershed, much of the snowmelt was stored by wetlands, particularly by bogs with stream channel outlets. In northern Canada, stream runoff was positively correlated with slope and the presence of channel fens, but negatively correlated with lowland depressional bogs (Quinton et al., 2003). In a Light Detection and Ranging (LiDAR)-based assessment of depressional wetlands in Florida, Lane and D'Amico (2010) found an average potential wetland water storage capacity of 1,619 m^3 ha^{-1}, with values ranging from 1,283 m^3 ha^{-1} for palustrine scrub-shrub wetlands to 2,906 m^3 ha^{-1} for palustrine aquatic-bed wetlands. A literature review found that four out of four studies that examined surface water depressions having no direct connectivity to a river system concluded that those wetlands reduced or delayed flooding (Bullock and Acreman, 2003). Findings were more varied for slope wetlands with direct connectivity to a river: 26 of 62 studies found reduced flooding, while 27 of the 62 studies concluded that those wetlands increased flooding.

In addition to wetland type, antecedent moisture conditions and available storage capacity also influence wetland water retention. The wetlands noted above, that serve as stream origins, likely increased flood peaks under saturated conditions, with low additional wetland water storage capacity (due to spring rains or snowmelt, for example), and thus conveyed any additional precipitation rapidly downstream (Bullock and Acreman, 2003). Similarly, Branfireun and Roulet (1998) concluded that prior saturation of upland areas immediately surrounding a wetland produced increased stormflows. This might mean that wetlands have less attenuating effect on larger floods because floods commonly occur during saturated conditions.

Besides affecting peak flows and downstream flooding, non-floodplain wetlands can alter baseflow or stormflows during dry periods. Ground-water discharge wetlands that are connected to streams, such as fens or seeps, are important sources of baseflow (Morley et al., 2011). Moreover, wetlands can be focal points for ground-water recharge and thus might contribute to baseflow. Rains (2011), for example, found that perched and flow-through ponds in southwestern Alaska were sites of net ground-water recharge. Given the high prevalence of ponds on the landscape (Rains, 2011), these wetland types cumulatively could substantially affect stream baseflow via ground-water inputs.

Other wetlands, however, might actually reduce flows during dry periods. Bullock and Acreman (2003) concluded that this was the case in two-thirds of the studies they surveyed. Antecedent moisture conditions and available wetland storage could partially explain this finding, in combination with relatively high evaporation rates from wetland-dominated landscapes (Bullock and Acreman, 2003). One study cited in their review (Boelter and Verry, 1977) noted that two storms of nearly equal volume and intensity produced different runoff responses from the same peatland. One storm occurring in the spring at a time of already high water tables led to runoff. The other, in midsummer at a time of low water tables, increased the water depth in the peatland but did not exceed the wetland's water storage capacity, precluding runoff. This mechanism has been observed in simulations of prairie pothole hydrology, in which wetlands reduced streamflow until storage capacity was exceeded (Haan and Johnson, 1968). Thus, wetlands can function as a sink in dry periods if storage capacity is not exceeded and evaporation rates surpass ground-water recharge. Where storage capacity is exceeded during storm events in otherwise dry periods, watersheds containing extensive wetlands can require more time for water discharge to rise and fall in response to storm events (Lindsay et al., 2004). This finding suggests that watersheds with wetlands take longer to fill and exceed water-holding capacity than watersheds without wetlands and so, in this case, they provide a lag function by releasing water downstream more slowly.

Non-floodplain wetlands also can reduce the variability of baseflow through landscape hydrologic capacitance (McLaughlin et al., 2014). McLaughlin et al. (2014) simulated the effects of geographically isolated wetlands on the variation in baseflow and found that the magnitude of this effect increased with total wetland area. Holding area constant and increasing the number of wetlands (while decreasing their size) also increased this capacitance. The effect of these wetlands on baseflow was the result of differences in specific yield (the change in output or input depth from evaporation or rain per change in water level) between wetlands and uplands, which causes flow reversals between them (McLaughlin and Cohen, 2013; McLaughlin et al., 2014). Specifically, water flows from upland areas to wetlands (wetland discharge) during wet periods and from wetlands to uplands (wetland recharge) during dry periods, thereby buffering water tables and baseflow.

4.4.3 Effects of Non-floodplain Wetlands on Water Quality

Non-floodplain wetlands can affect water quality of rivers and other aquatic systems through processes that can be generalized as source and sink functions, often mediated by transformational processes (see Section 4.3.3 for details on specific mechanisms). In some cases, non-floodplain wetlands directly modify the water quality in downstream waters through their relative lack of surface water connections; this modification is accomplished by removal, sequestration, or transformation of pollutants such as nitrogen, phosphorus, and metals through processes described by Ewel and Odum (1984), Mitsch et al. (1995), Reddy and DeLaune (2008), and Kadlec and Wallace (2009), among others. Although non-floodplain wetlands can lack surface water connections to downstream waters, surface and near-surface hydrologic connections to downstream waters do occur in many non-floodplain systems (Section 4.4.2; Figure 2-18; Sun et al., 1995; Whigham and Jordan, 2003; Wilcox et al., 2011), providing pathways for materials transformed in non-floodplain wetlands (such as methylmercury or degraded organic matter) to reach and affect other aquatic systems.

Below we show that non-floodplain wetlands are areas where extensive microbially mediated processes occur that can affect downstream waters. In Section 4.4.3.1, we describe how non-floodplain wetlands are sources for dissolved organic matter and entrained elements like carbon, nitrogen, and phosphorus, which are important components of food webs in downstream waters. Dissolved organic matter is also shown to be important in regulating whole-lake acidity and buffering capacity. Mercury is another material affected by microbial processing in non-floodplain wetlands; mercury can be transported along with dissolved organic matter to downstream waters, where it can become incorporated into the food web with potentially deleterious effects. In Section 4.4.3.2, we discuss how non-floodplain wetlands serve as sinks by sequestering or transforming materials, thereby affecting the chemical, physical, or biological condition of downstream waters. Nitrogen, nitrate, ammonium, and phosphorus compounds are shown to be removed or assimilated—often at high rates—in non-floodplain wetlands. Pesticides, metals, and other potential pollutants also can be sequestered or assimilated in non-floodplain wetlands.

4.4.3.1 Non-floodplain Wetlands as Sources for Downstream Waters

Like all wetlands, non-floodplain wetlands contain diverse microbial populations that have adapted to hydrologic, physical, and chemical extremes (Reddy and DeLaune, 2008). Microbial populations abound in wetland systems; for example, Boon (1991) reported that Australian wetlands contained 100 times more microbes in the water column than nearby rivers, with up to 157×10^9 cells L^{-1}. Functions that occur in non-floodplain wetlands can affect streams, rivers, and lakes when compounds that are transformed in wetland environments move to downstream waters through overland flow or shallow ground water (Section 4.4.2; Winter et al., 2003). Two processes that occur in non-floodplain wetlands (and in riparian/floodplain wetlands) are useful to illustrate the influence of non-floodplain wetlands on downstream waters: the methylation and transport of the bioaccumulating pollutant mercury, and the breakdown and transport of organic compounds to receiving waters.

Freshwater wetlands/peatlands are areas of active methylmercury (MeHg) production (Grigal, 2002). Ullrich et al. (2001) noted that methylmercury production was linked to low pH, low salinity, and presence of decomposable organic matter in reducing environments. Sulfate-reducing bacteria are primarily responsible for biological mercury methylation and thrive in the reduced conditions at wetland aerobic/anaerobic boundaries (Benoit et al., 1999); the addition of sulfate (e.g., through atmospheric acid deposition) increases the formation of methylmercury in peatlands (Branfireun et al., 1999). Once formed through microbial (or other) processes, mercury and methylmercury export is controlled by the export of organic matter, such as dissolved organic compounds and humic and fulvic acids (Linqvist et al., 1991; Mierle and Ingram, 1991; Driscoll et al., 1995). Methylmercury can be translocated in watersheds having non-floodplain wetlands by entrainment with organic matter exports. It also can move through near-surface and surface flows from non-floodplain peatlands to downstream waters. For example, Branfireun et al. (1996) reported 58% of MeHg-laden peat porewater leaving a headwater catchment study area occurred during stormflow, 41% during baseflow, and 1% transported via ground water. St. Louis et al. (1994) found that boreal forest catchments in Minnesota with non-floodplain wetlands reduced total mercury concentrations, but had yields of methylmercury from wetlands that were 26−79 times higher than upland areas. This yielded 1.84−5.55 mg MeHg ha^{-1} yr^{-1} to streams in the Great Lakes basin, where mercury could be incorporated into lake-wide food webs. Hurley et al. (1995) contrasted MeHg yields from different land use groups in Wisconsin and found that wetland/forest sites were higher than agricultural/forested and agricultural-only sites. Similarly, Porvari and Verta (2003) found that bioaccumulating methylmercury export from non-floodplain peatlands to downstream waters ranged from 0.03 to 3.8 ng MeHg L^{-1}, and that catchments with greater wetland abundances had greater methylmercury export.

Export of dissolved organic matter can have negative effects on downstream waters because contaminants, such as methylmercury and other trace metals, can be adsorbed to it (Thurman, 1985; Driscoll et al., 1995). Dissolved organic matter, however, is also an important source of energy for downstream aquatic communities (Hobbie and Wetzel, 1992; Reddy and DeLaune, 2008). Wetlands are the principal source of dissolved organic compounds to downstream waters in forested ecosystems (Mulholland and Kuenzler, 1979; Urban et al., 1989; Eckhardt and Moore, 1990; Koprivnjak and Moore, 1992; Kortelainen, 1993; Clair et al., 1994; Hope et al., 1994; Dillon and Molot, 1997; Gergel et al., 1999). Over prolonged periods, reductions in dissolved organic carbon (DOC) export (e.g., through wetland conversion or degradation or alterations in hydrology) decrease the ability of downstream waters to support primary productivity, due to reduced export of entrained carbon, nitrogen, sulfur, and phosphorus (Hedin et al., 1995; Nuff and Asner, 2001). Changes in DOC export also affect the pH and buffering capacity of downstream aquatic systems (Eshelman and Hemond, 1985) and their exposure to damaging UV-B rays (Schindler and Curtis, 1997). Boreal forest basins composed of non-floodplain wetlands in central Ontario were found to export between 11.4 and 31.5 kg C ha^{-1} yr^{-1} to downstream waters (Creed et al., 2003). Furthermore, near-surface lateral transport of DOC explained 88% of the variation in basin DOC export to lake systems where it directly affected pH and buffering capacity. Other studies have similarly shown a relationship between the proportion of wetlands in a watershed and the average annual concentration of DOC in the receiving streams of that area, and other areas of the boreal forest/Precambrian Shield (Urban et al., 1989; Eckhardt and Moore, 1990; Koprivnjak and Moore, 1992; Detenbeck et al., 1993; Clair et al., 1994; Hope et al., 1994; Dillon and Molot, 1997; Johnston et al., 2008).

The export of dissolved organic compounds from non-floodplain wetlands also can affect the acidity of downstream waters. Gorham et al. (1986) addressed watershed factors associated with lake and forest acidification in Nova Scotia, Canada. In addition to atmospheric deposition of acid precipitates, they found that the ratio of non-floodplain muskeg peatlands to lakes was significantly correlated with lake acidification, as muskeg wetland-dominated watersheds exported high-molecular-weight organic acids via either overland or shallow ground-water flow. Further linking non-floodplain wetlands to lakes, Gorham et al. (1986) reported that even small amounts of humic DOC can greatly affect lake water pH; the pH of waters with a dissolved organic carbon value of 4.5 mg DOC L^{-1} (the log-normal mean) was

100 times more acidic than waters with a dissolved organic carbon of <1 mg DOC L^{-1} (the minimum concentration).

4.4.3.2 Non-floodplain Wetlands as Sinks and Transformers for Downstream Waters

The wetland literature is replete with examples of wetlands improving water quality through assimilation, transformation, or sequestration of nutrients and other pollutants (e.g., Ewel and Odum, 1984; Nixon and Lee, 1986; Johnston, 1991; Detenbeck et al., 1993; Mitsch and Gosselink, 2007; Reddy and DeLaune, 2008; Kadlec and Wallace, 2009). These functions act on the large pool of pollutants that are available through nonpoint sources. Non-floodplain wetland processes that affect pollutant attenuation include denitrification, ammonia volatilization, and microbial and plant biomass assimilation (Reddy and DeLaune, 2008). Other pollutants in wetland systems can be retained through sedimentation, sorption and precipitation reactions, biological uptake, and long-term storage in plant detritus (Reddy et al., 1999; Reddy and DeLaune, 2008).

Non-floodplain wetlands act as sinks and transformers for various pollutants. For example, high levels of human sewage were applied to a forested non-floodplain wetland site for 4.5 years (Ewel and Odum, 1984 and chapters therein). More than 95% of the phosphorus (P), nitrate, ammonium, and total nitrogen (N) were removed by the wetland during the study period (Dierberg and Brezonik, 1984), and 66−86% of the nitrate removed was attributed to the process of denitrification. In another example, phosphorus retention in non-floodplain marshes of the lower Lake Okeechobee basin ranged from 0.3 to 8.0 mg soluble reactive P m^{-2} d^{-1} (Dunne et al., 2006). This retention represents a sizeable amount of phosphorus removal, because only about 7% of the watershed comprised non-floodplain marsh. Similarly, wetlands in the Lake Okeechobee, Florida basin were found to have greater storage of total phosphorus than the uplands in which they were bedded, 236 kg ha^{-1} vs. 114 kg ha^{-1} (Cheesman et al., 2010). These findings were echoed by Dunne et al. (2007), who reported that more phosphorus was stored in wetland plant biomass and soil than in corresponding upland compartments, with wetland surface soils (0−10 cm) representing the largest phosphorus reservoir (>87%) and soil organic matter accounting for >69% of the soil total phosphorus variability. They further suggest that restoring 5−20% of the geographical isolated wetland area in priority basins draining to Lake Okeechobee, Florida, could increase phosphorus storage in geographical isolated wetlands by up to 13 kg P ha^{-1}, mostly through increased soil organic matter with its concomitant phosphorus in wetland soils (Dunne et al., 2007). Marton et al. (2014) found that mean phosphorus sorption was approximately two to three times greater in natural depressional wetlands than in restored wetlands and agricultural fields (297, 114, and 86 mg P kg $soil^{-1}$, respectively). Marton et al. (2014) also found that depressional wetlands sorbed twice as much phosphorus as riparian systems. Craft and Casey (2000) reported similar accretion rates in depression and floodplain wetlands of Georgia for sediment, organic carbon, and nitrogen, and significantly highly floodplain storage of phosphorus. Cohen et al. (2007) found that riparian wetlands had higher phosphorus-sorption capacities than non-riverine wetlands. Non-floodplain wetland flats studied in Maryland and Delaware had microbially mediated denitrification enzyme activity (an indicator of potential denitrification) rates of 0.06−0.76 mg N kg^{-1} d^{-1} (Jordan et al., 2007). Because flats comprise greater than 70% of the wetland area in the basin, this value indicates a significant denitrification capacity. Marton et al. (2014) found that depressional wetlands denitrified at twice the rate upland systems did, 12.3 ± 4.5 ng N g^{-1} hr^{-1} versus 5.3 ± 1.7 ng N g^{-1} hr^{-1}. Craft and Chiang (2002) determined that wetland soils stored a disproportionately large share of nitrogen, compared with upland soils, in spite of uniform soil organic matter across the landscape. A non-floodplain bog in Massachusetts was reported to sequester nearly 80% of the system's various nitrogen inputs, including precipitation that had a range of 1.2−1.9 mg N L^{-1} (Hemond, 1983). Prairie pothole wetlands in the upper Midwest removed >80% of the nitrate load via denitrification (Moraghan, 1993). A large non-floodplain prairie marsh removed 86% of nitrate, 78% of ammonium, and 20% of phosphate through assimilation and sedimentation, sorption, and other mechanisms (Davis et al., 1981). Geographically isolated, non-floodplain wetland systems in Michigan were found to remove nitrate-nitrogen (NO_3-N) and sulfate (SO_4^{2-}) at rates of 0.04−0.55 mg NO_3-N L^{-1} ha^{-1} and 0.06−0.30 mg SO_4^{2-} L^{-1} ha^{-1}. These rates are significant, considering that nitrate-nitrogen pollution of ground water in Michigan was reported to average 0.50 mg NO_3-N L^{-1} (Whitmire and Hamilton, 2008). Bhadha et al. (2011) found that infiltration to the ground accounted for 14% of phosphorus loss from two historically isolated wetlands in a Florida study area, suggesting that near-surface flow gradients are important to landscape-level phosphorus dynamics. Together, these studies indicate that sink removal of nutrients by non-floodplain wetlands is significant and geographically widespread.

Other pollutants and compounds can be mitigated by non-floodplain wetland sink and transformation processes. For example, microbial methanogenesis completely removed the pesticide atrazine from a mountainous bog in North Carolina (Kao et al., 2002). The environmental contaminants cobalt (Co) and nickel (Ni) can be phytoremediated by wetland plants common in forested non-floodplain wetlands of the Southeast; plant concentrations were found to range from 1 to 530 mg Co kg^{-1} and up to 250 mg Ni kg^{-1} (Brooks et al., 1977). A bog in Massachusetts that Hemond (1980) extensively studied acted as a sink and annually stored 54 mg magnesium m^{-2}, 36 mg potassium m^{-2}, and 46 mg lead m^{-2}; the bog also provided acid-rain buffering for downstream waters. Based on the literature, Boon (2006) concluded that wetland microbial communities can mediate processes that degrade diesel fuel and other hydrocarbons, pesticides, heavy metals and metalloids, and chlorinated solvents that can pollute ground water.

4.4.4 Biological Connections Between Non-floodplain Wetlands and Streams

Many of the same factors that affect movement of organisms between riparian/floodplain wetlands and the river network (Section 4.3.4) govern movement of organisms between non-floodplain wetlands and the river network. Non-floodplain wetlands, however, are generally farther from stream channels than riparian/floodplain wetlands, which reduces hydrologic connectivity. The distance, number, and variety of heterogeneous landscape patches (including barriers) over which organisms must disperse also can be greater. Organisms have evolved numerous complex dispersal strategies to overcome non-floodplain flows, reduced hydrologic connectivity, and increased geographic distance between habitats and spatially subdivided populations. Passive transport (e.g., wind dispersal, "hitchhiking" on other animals) and active movement (e.g., walking, crawling, flying) are common modes of dispersal that can establish connectivity in the absence of hydrologic flows. Such dispersal events are often sporadic and asymmetric in non-floodplain wetland landscapes, making them more difficult to observe than surface water flows. Their effects on community structure and diversity—including metapopulation effects of wetland-to-wetland connectivity—have been well documented (e.g., Wellborn et al., 1996; Snodgrass et al., 2000; Julian et al., 2013), especially for amphibians. Other effects, such as water quality and population or species persistence, are not well understood. Below we review the various dispersal mechanisms that operate in non-floodplain wetland landscapes.

Despite being sessile, plants have evolved many adaptations that facilitate dispersal. Considerable attention has been given to waterborne dispersal of aquatic and emergent macrophytes (Nilsson et al., 2010), which can play a role in non-floodplain wetlands that are periodically connected hydrologically to river networks. In addition, significant numbers of such plants can be dispersed as seeds or pollen by wind (Soons, 2006). Wind dispersal enables colonization of geographically isolated non-floodplain wetlands such as prairie potholes (Galatowitsch and van der Valk, 1996). Given that geographically isolated wetlands are surrounded by uplands, using wind as a vector carries the relatively high risk that propagules of obligate wetland plants will land in unsuitable habitat. Plants have developed colonization strategies to compensate for such risks. For example, Soons and Heil (2002) showed that producing large numbers of seeds increased colonization success of short- and long-distance dispersing grassland forbs; results from this and other studies are being applied to models of wetland dispersal and colonization (e.g., Soons, 2006). Viable seeds or vegetative plant parts also can travel great distances within the guts of or externally attached to migratory birds (Murkin and Caldwell, 2000; Amezaga et al., 2002; Figuerola and Green, 2002), which move between non-floodplain wetlands and river networks, depending on temporally dynamic habitat availability (Murkin and Caldwell, 2000; Haukos et al., 2006 and references therein).

Identifying specific source and recipient populations for any organism over these distances can be challenging, but especially for plants having passively mobile life stages that cannot be precisely tracked. Determining whether wetlands function as sources to or recipients of plant propagules from river networks is especially difficult. Genetic similarity between populations can provide general evidence of connectivity between non-floodplain wetlands and the river network. Sawgrass (*Cladium jamaicense*) populations in Everglades wetlands showed low population genetic divergence at distances greater than 100 km; wind pollination and water dispersal of propagules through flooding likely keeps channel and wetland populations genetically similar (Ivey and Richards, 2001). Another approach that can provide evidence for dispersal is community-level surveying, which takes into account local determinants of community composition and structure. Controlling for local conditions like rainfall and soil type, a study in Connecticut (Capers et al., 2010) found that bodies of water—from small isolated wetlands to large lakes—that were located closer together had more similar plant communities. This finding suggests biological connectivity between proximal lakes and wetlands.

Recent evidence suggests that invertebrate hitchhiking on birds and mammals is more common than previously thought (Figuerola and Green, 2002; Figuerola et al., 2005). Allen (2007) trapped zooplankton dispersing from a pond in Illinois and found that animals wider than 3 cm were the primary vector of reproductive adult zooplankton forms. These results suggest that animals moving among water bodies can be an important factor in structuring non-floodplain wetland invertebrate metapopulations. Frisch et al. (2007) found that diapausing invertebrate eggs that dispersed by hitchhiking on birds had higher incidences of hatching in January (59.4%) than in November (11.5%). These invertebrates included nematodes, zooplankton (i.e., rotifers, ostracods, copepods), and insects (i.e., crane flies, nonbiting midges, hemipterans). This study indicates that winter migrations of aquatic birds can be an important mechanism for spring colonization of habitats separated by hundreds or even thousands of kilometers. Studies have thus shown that migratory birds can passively connect viable plant matter, macroinvertebrates, and zooplankton from disparate habitats across the landscape, with likely—although unresolved—impacts on food web dynamics (Polis et al., 1997).

The scientific literature has many examples of migratory birds—especially migratory waterfowl, including cranes, geese, ducks, and shorebirds—actively moving between and using the different available resources of estuarine, riverine, and riparian systems and non-floodplain wetlands. For example, wood ducks (*Aix sponsa*) are found throughout freshwater deciduous forests of North America. Preferred breeding sites include river floodplains, remote ponds, and woodland pools that receive snowmelt and spring rain, the latter particularly indicative of non-floodplain wetland use (Haramis, 1990). Below we provide several examples of this type of biological connectivity that can connect non-floodplain wetlands to each other and to other aquatic systems.

Approximately 80% of the entire North American population of redhead ducks (*Aythya americana*) winters along coastal Texas and northern Mexico (Weller, 1964). Woodin (1994) identified more than 20,000 redheads using both estuarine systems and freshwater wetlands, reporting that the estuarine systems were exclusively used for feeding, while freshwater coastal pond wetlands were used almost exclusively for drinking water and courting (Mitchell et al., 1992). The coastal ponds redheads used were seasonal basins, which frequently dried completely (Ballard et al., 2010). Ballard et al. (2010) further noted that although the ponds were densely distributed in coastal Texas (up to 4.8 coastal basins per km^2), water availability varied year-to-year. As a result, during dry years redheads would use available coastal ponds up to 8.1 km from the estuarine forging areas, while in wetter years closer ponds would be used (likely to minimize energy expended through flying). Similarly, Adair et al. (1996) reported that lesser scaup (*Aythya affinis*) and redheads avoided salt stress and metabolically expensive osmoregulation through salt-gland excretory functions by feeding in estuaries; drinking, preening, and resting in coastal basins; and then returning to estuaries. Grey teals (*Anas gibberifrons gracilis*) in Australia that feed in saline areas similarly required freshwater to osmoregulate (Lavery, 1972). Mallard ducks (*Anas platyrhynchos*) transiting Iowa during spring migration used seasonally flooded farmed basins in agricultural fields (also known as sheetwater wetlands; LaGrange and Dinsmore, 1989) for feeding and roosted in more permanent emergent wetlands at night. In the study, these shallow sheetwater wetlands provided 19,530 mallard use-days during the daytime compared with 103 use-days for the emergent wetlands.

Nebraska's Rainwater Basin historically had more than 11,000 playas, shallow wind-formed wetland depressions, although human activities over the past 100 years have resulted in the loss of 90% of the number and approximately 88% of the area (Webb et al., 2010; Uden et al., 2014). Nevertheless, the remaining basins are critical to dependent migratory waterfowl, with 7–10 million waterfowl using the approximately 16,000 km^2 area, including “virtually all of the 600,000 midcontinental greater white-fronted geese (*Anser albifrons*), 500,000 Canada geese (*Branta Canadensis)*, 50% of midcontinent mallards (*Anas platyrhynchos*), and 30% of continental northern pintails (*Anas acuta*)” (Webb et al., 2010, p. 109), 38 shorebird species, and the endangered whooping crane (*Grus americana*). In a 3-year spring migration study of 36–40 playas, Webb et al. (2010) identified 72 migratory species and more than 1.6 million birds actively using these playa basins. The abundance of all wetland bird taxa was related to wetland area within 5–10 km of the study playas, although diving duck abundance (e.g., redhead, canvasback, lesser scaup) was specifically related to riparian area within 5 km, likely due to the presence of open water within these systems (Webb et al., 2010; see their Table 1 for a complete list of taxa found).

Many additional studies have identified Nebraska as an important staging and stopover area for numerous species, perhaps due to its location on the Central Flyway. For example, almost the entire population of midcontinent sandhill cranes (*Grus canadensis*) uses the Central Platte River Valley. Avian researchers reported that cranes roost along both the current and former Platte River channel (Krapu et al., 1984) and forage in grasslands on semipermanent (unconsolidated mud bottom) and temporary palustrine wetlands (Folk and Tacha, 1990) and on frequently inundated soils—especially those within 4.8 km of roost sites (Anteau et al., 2011). Pearse et al. (2010) noted that after feeding in cornfields, sandhill cranes roosted along the Central Platte River Valley in pastures with ponds. These pond systems are likely either playas, as noted above, or palustrine wetlands often surrounded by croplands (Austin and Richert, 2005). Austin and Richert (2005) further stated that the endangered whooping crane was noted as roosting, feeding, and resting in both riverine and palustrine wetlands of the Great Plains. Vrtiska and S.Sullivan (2009) found that lesser snow geese (*Chen caerulescens*) and Ross’s geese (*Chen rossii*), which numbered up to 7.3 million in 2001 during peak migration, used wetland habitats in both the Rainwater Basin and Central Platte River Valley, depending on the availability of suitable (e.g., inundated) habitat.

Blanchong et al. (2006) found that this concentrated use of the Rainwater Basin by migratory lesser snow geese resulted in greater contact between individuals, contributing to the spread of *Pastruella multocida*, the bacterium that causes avian cholera. The loss of wetlands within the basin has resulted in higher concentrations of migratory birds within the remaining wetlands, which has led to higher risks of outbreaks of infectious diseases (Blanchong et al., 2006).

The U.S. Fish and Wildlife Service’s Subcommittee on Rocky Mountain Greater Sandhill Cranes (SRMGSC, 2007) reviewed the literature on habitat use for the migratory population of Rocky Mountain sandhill cranes. This population, one of five in North America, migrates from wintering areas in Arizona, New Mexico, and central Mexico to breeding areas in Canada, Montana, Idaho, Wyoming, Utah, and Colorado. SRMGSC (2007) reported that this population of sandhill cranes overwintered in multiple riverine, riparian, and non-floodplain habitats, including playas in New Mexico and southeastern Arizona. Areas used in the breeding range include non-floodplain wetlands, such as northern boreal forest bogs, and other habitat types (e.g., large marsh complexes, smaller, scattered marshes, intermittent streams, beaver ponds, subirrigated wet meadows along riparian zones; SRMGSC, 2007).

Shorebirds also use multiple habitat types during their North American migration. Skagen and Knopf (1993) concluded that dispersion and opportunism, rather than concentration and predictability, characterize movements of shorebirds in the Great Plains. For example, Haig et al. (1998) noted that large population declines of the endangered migratory piping plover (*Charadrius melodus*) along the Missouri River were not actually declines, but a result of the birds moving to the Missouri Coteau (a 7.3 million ha region of the Upper Midwest and Canada replete with closed-basin prairie potholes; Phillips et al., 2005), due to increased flooding along the Missouri. Farmer and Parent (1997) monitored pectoral sandpipers (*Calidris melanotus*) migrating through non-floodplain sheetwater wetlands in Missouri and small depressional wetlands of the Rainwater Basin in Nebraska and found that habitat connectivity affected shorebird movements. Habitat patch density affected movements such that pectoral sandpipers often perceived groups of wetlands as functionally connected and actively exploited the best feeding habitat within that wetland complex. As the landscape became disconnected, however, the monitored species altered their movement behavior, minimizing energy expenditure (Farmer and Parent, 1997).

Other taxa have been reported as linking downstream systems and non-floodplain wetlands. Fish tend to disperse between non-floodplain wetlands and the river network during periodic surficial hydrologic connections or when humans create surface-water connections via ditching (Snodgrass et al., 1996; Langston and Kent, 1997; Zimmer et al., 2001; Baber et al., 2002; Hanson et al., 2005; Herwig et al., 2010). Mammals that can disperse overland can also contribute to connectivity. Although muskrat territories are usually restricted (Shanks and Arthur, 1952), dispersal between suitable river and non-floodplain wetland habitat over longer distances that is seasonal, climate-induced, and density-dependent has been observed (Serfass et al., 1999; Clark, 2000 and references therein). Spinola et al. (2008) tracked translocated river otters (*Lontra canadensis*) in New York and found that, after release, most otters inhabited a mosaic of isolated aquatic habitats distributed throughout the agriculture-dominated landscape. As noted above for waterfowl, mammals (including muskrats) also can act as transport vectors for hitchhiking organisms like algae (Roscher, 1967).

Numerous flight-capable insects, including mayflies, caddisflies, diving beetles, backswimmers, whirligig beetles, water striders, water boatmen, scavenger beetles, crane flies, and nonbiting midges, use both streams and non-floodplain wetlands (Williams, 1996). Aerial dispersal enables such insects to move outside the stream network to seek suitable habitat for overwintering, refuge from adverse conditions, hunting, foraging, or breeding (Williams, 1996; Bohonak and Jenkins, 2003).

Amphibians and reptiles also move between streams or rivers and non-floodplain wetlands to satisfy part of their life-history requirements (Table 4-2). For example, Subalusky et al. (2009a) and Subalusky et al. (2009b) reported movement of adult female alligators (*Alligator mississippiensis*) from creeks to shallow, seasonal limesink wetlands for nesting and use of the wetlands as nurseries for juveniles. Subadults then shift to habitats within the river network by moving overland to the creek (Subalusky et al., 2009a; Subalusky et al., 2009b). Lamoureux and Madison (1999) used radio tracking to follow movements of green frogs (*Rana clamitans*) for 9 months in New York. Green frogs, which breed in wetlands and then move into terrestrial habitats, are susceptible to freezing temperatures. In late autumn, the frogs moved from upland habitats near breeding ponds to rapidly flowing streams and seeps to overwinter. Boreal toads (*Bufo boreas boreas*) disperse long distances (>1 km) in streams through home ranges (Adams et al., 2005). Knutson et al. (1999) found that the strongest land-use predictor of anuran richness was urban land use. They speculated that, in addition to urban landscapes being detrimental to anuran habitat quality, their tendency to fragment (i.e., disconnect) anuran habitats is also a factor in the decline of these assemblages. In northwestern Ohio and southern Michigan wetland complexes, the abundance of northern watersnakes (*Nerodia sipedon sipedon*) was positively correlated with wetland size and wetland connectivity, defined by the authors as a wetland's distance to other wetlands (Attum et al., 2007). The American toad (*Anaxyrus* [=*Bufo*] *americanus*) and eastern newt (*Notophthalmus viridescens*) are widespread habitat generalists that move among streams and wetlands to take advantage of both habitats, feed on aquatic invertebrate prey, and avoid predators (Table 4-2; Babbitt et al., 2003; Green, 2005; Hunsinger and Lannoo, 2005; Petranka and Holbrook, 2006).

4.4.5 Geographic Isolation of Non-floodplain Wetlands

In defining non-floodplain wetlands (Section 2.2.1), we noted that this category could include wetlands that are geographically isolated and those that are not. Further, we noted (Section 2.4.1) that certain types of wetlands can be found with or without an outlet and can occur along a gradient of hydrologic connectivity. This gradient can include non-floodplain wetlands that have permanent hydrologic connections to the river network through perennial channels; wetlands that have losing streams that are completely disconnected from the river network as output channels; geographically isolated wetlands that have ground-water or occasional surface-water connections; and geographically isolated wetlands that have minimal hydrologic connection to the river network (but which could include surface and subsurface connections to other wetlands). The existence of this gradient (Section 1.2.2) can make determining the degree to which particular non-floodplain wetlands are connected to or isolated from downstream waters difficult.

A related issue is that spatial scale must be considered when determining geographic isolation. Tiner (2003c) provided examples of how a wetland that was not isolated at a local scale could be geographically isolated at a larger scale. Conversely, individual wetlands that are geographically isolated could be connected to downstream waters when considered as a complex (a group of interacting wetlands). This concept is demonstrated by Wilcox et al. (2011), who examined a depressional wetland complex on the Texas Coastal Plain. Although the wetlands are hydrologically connected to each other by shallow swales, they might be geographically isolated, because swales often are considered upland. In fact, Tiner (2003c) classifies these Coastal Plain wetlands as geographically isolated. At the scale of the wetland complex, however, the wetlands are connected to a nearby waterway via an intermittent stream. During an almost 4-year study, nearly 20% of the precipitation that fell on the wetland complex flowed as surface runoff through the channel to a nearby waterway, the Armand Bayou (Wilcox et al., 2011). Although these wetlands might be geographically isolated at the local scale, the wetland

Table 4-2. Partial list of amphibian and reptile species known to use both streams and non-floodplain wetlands or other lentic waters.

Common Name	Scientific Name	Habitat Use
Green frog	*Rana clamitans*	Breeds in wetlands and pools; overwinters in streams (Lamoureux and Madison, 1999)
Leopard frog	*Rana pipiens*	Breeds in wetlands and pools; overwinters in streams (Rorabaugh, 2005)
Bullfrog	*Rana catesbeiana*	Uses seasonal pools as complementary nonbreeding habitat (Gahl et al., 2009)
Columbia spotted frog	*Rana luteventris*	Breeds in streams and wetlands; overwinters in streams (Pilliod et al., 2002)
Southern leopard frog	*Rana sphenocephala*	Breeds in shallow pools and wetlands; adults inhabit many shallow freshwater habitats, including temporary pools, cypress ponds, ponds, lakes, ditches, streams, river edges, floodplain pools, and slightly brackish coastal wetlands (Butterfield, 2005)
Pacific chorus frog	*Pseudacris regilla*	Breeds in wetlands, ponds, temporary pools, streams, lakes, rivers, and other aquatic habitats (Rorabaugh and Lannoo, 2005)
American toad	*Anaxyrus* [=*Bufo*] *americanus*	Breeds in lakes, ponds, streams, ephemeral wetlands, prairie potholes, ditches, and floodplain pools (Green, 2005)
Fowler's toad	*Anaxyrus* [=*Bufo*] *fowleri*	Breeds in ponds, temporary pools, streams, ditches, lake shores, and shallows of rivers (Green, 2005)
Two-toed amphiuma	*Amphiuma means*	Adults inhabit a wide variety of aquatic environments, including ponds, lakes, ephemeral wetlands, wet prairies, streams, and ditches (Gibbons and Semlitsch, 1991; Johnson and Owen, 2005)
Greater siren	*Siren lacertina*	Breeds in shallow pools and streams, adults live in lakes, streams, ponds, and wetlands (Gibbons and Semlitsch, 1991; Hendricks, 2005)
Eastern newt	*Notophthalmus viridescens*	Breeds in permanent and semipermanent pools, ponds, wetlands, and low-flow areas of streams; adults live in pools, ponds, streams, and wetlands (Hunsinger and Lannoo, 2005; Timm et al., 2007)

Table 4-2. Partial list of amphibian and reptile species known to use both streams and non-floodplain wetlands or other lentic waters (continued).

Common Name	Scientific Name	Habitat Use
Yellow-bellied watersnake	*Nerodia erythrogaster flavigaster*	Hunts in temporary pools and wetlands (Roe et al., 2004; Mitchell et al., 2007)
Copper-bellied watersnake	*Nerodia erythrogaster neglecta*	Hunts in temporary pools and wetlands (Roe et al., 2004; Mitchell et al., 2007)
Spotted turtle	*Clemmys guttata*	Uses temporary wetlands for foraging, mating, basking, and aestivating (Joyal et al., 2001)
Blanding's turtle	*Emydoidea blandingii*	Uses temporary wetlands for foraging, mating, basking, and aestivating (Joyal et al., 2001)
Painted turtle	*Chrysemys picta*	Uses temporary wetlands for basking and foraging (Mitchell et al., 2007)
Snapping turtle	*Chelydra serpentina*	Uses temporary wetlands for basking and foraging (Mitchell et al., 2007)
American alligator	*Alligator mississippiensis*	Juveniles use seasonal wetlands as nurseries, subadults move back to river networks (Subalusky et al., 2009a; Subalusky et al., 2009b)

complex serves as the source of water for a headwater stream, and therefore, the complex is not geographically isolated at a larger scale.

Besides the spatial scale of the wetland unit, assessments of non-floodplain wetland to stream connectivity can be affected by the resolution and source of the spatial data that are used. For example, higher connectivity was found in the Tuckahoe Creek watershed in Maryland, when wetland connectivity was evaluated for streams determined from LiDAR compared to streams from both the High Resolution National Hydrography Dataset (NHD) and NHD Plus (Lang et al., 2012). Yang and Chu (2013) found that Digital Elevation Model (DEM) resolution also affected connectivity assessments, with finer DEMs having a higher number of connected areas and less total connected area than coarser DEMs.

Given this discussion, caution should be used in interpreting connectivity for wetlands that have been designated as "geographically isolated," because (1) the term can be broadly applied to a heterogeneous group of wetlands that can include wetlands that are not actually geographically isolated, (2) wetlands with permanent channels could be miscategorized as geographically isolated if the designation is based on maps or imagery with inadequate spatial resolution (e.g., Lang et al., 2012), obscured views, etc., and (3) wetland complexes could have connections to downstream waters through stream channels even if individual wetlands within the complex are geographically isolated. The term "geographically isolated" should be applied only to groups of wetlands if all those wetlands are, in fact, known to be geographically isolated. Further, even geographically isolated wetlands can be connected to other wetlands and downstream waters through ground-water connections, occasional spillage, or biological connections. Thus, the term "geographically isolated" should not be used to infer lack of hydrologic, chemical, or biological connectivity.

Finally, precisely this isolation is responsible for many of the functions that geographically isolated wetlands provide to downstream waters. In particular, many of the sink and lag functions of these wetlands result from their relative isolation from the river network. This relative isolation, combined with the wetlands' storage capacity, enables them to store water and reduce peak streamflows and downstream flooding (Novitzki, 1979; Hubbard and Linder, 1986; Vining, 2002; Bullock and Acreman, 2003; McEachern et al., 2006; Gleason et al., 2007). For example, depressional wetlands in Florida had an average potential wetland water storage capacity of 1,619 m^3 ha^{-1} (Lane and D'Amico, 2010). These same sink and lag functions will also act on any materials associated with stored water, such as sediments and pollutants. Increased isolation also can decrease the spread of pathogens (e.g., Hess, 1996) and invasive species (e.g., Bodamer and Bossenbroek, 2008) and increase the rate of local adaptation (e.g., Fraser et al., 2011).

4.5 Wetlands: Synthesis and Implications

4.5.1 Riparian/Floodplain Wetlands

Based on our review of the literature, riparian/floodplain wetlands are highly connected to streams and rivers through surface water, shallow ground water, and biological connectivity. The effects of wetlands on streams and rivers are a function of the magnitude of floodwaters, the geomorphic structure of the floodplain, and the proximity of the channel. Although a gradient occurs in the frequency of connectivity within the floodplain (Section 1.2.2), even riparian/floodplain wetlands that rarely flood can be important because of long-lasting effects on streams and rivers. In fact, most of the major changes in sediment load and river-channel structure—for example, movement of rivers through meander belts and creation of oxbow lakes—that are critical to maintaining the health of the river result from large floods that provide infrequent connections with more distant riparian/floodplain wetlands. Areas that surface water infrequently floods also can be connected to the river more regularly through ground water and the organisms. Key conclusions from our literature review on riparian/floodplain wetlands are summarized in Table 4-3.

4.5.2 Non-floodplain Wetlands

Non-floodplain wetlands consist of depressional, slope, and flats wetlands that lack surface water inlets. Non-floodplain wetlands can include regional wetland types such as prairie potholes, playa lakes, vernal pools, and Carolina bays. Hydrologic flows through these wetlands are predominantly unidirectional, in contrast to bidirectional flows that occur in riparian/floodplain wetlands.

The literature we examined on non-floodplain wetlands indicates that these systems have important hydrologic, water-quality, and habitat functions that affect downstream waters and rivers provided a connection exists between the wetland and downstream water (Table 4-4). The challenge is to identify which non-floodplain wetlands have such a connection. Addressing this issue is difficult, because most wetland studies do not investigate wetland effects on downstream waters or, if they do, they rarely address connectivity explicitly.

Based on what is known about how water flows across the landscape (Chapter 2), hydrologists and ecologists would generally agree that all non-floodplain wetlands are interconnected to some degree and are connected with stream networks, which is why the water-cycle environment is referred to as the hydrosphere. Hydrologists and ecologists also generally agree that some areas are more connected or have a greater influence than others. The purpose of this review is to determine, based on the peer-reviewed literature, the degree of connectivity and associated effects between different non-floodplain wetlands and downstream waters.

Non-floodplain wetlands occur along the gradient discussed in Chapter 1, and can be described in terms of the frequency, duration, magnitude, timing, and rate of change of water, material, and biotic fluxes to downstream waters. With respect to hydrologic connectivity, this gradient includes wetlands that have permanent hydrologic connections to the river network through perennial channels; wetlands that have

Table 4-3. Key conclusions on the effects of riparian/floodplain wetlands on rivers.
Physical Connectivity and Function
• Riparian areas are highly connected to streams, so much so that considering the riparian influence on streams is essential to understanding their structure and function. • Riparian connectivity ranges from longitudinal flow and exchange in mountainous headwater streams to increasing lateral flow and exchange in river valleys and coastal terrain. • Water storage by riparian areas, especially wetlands and lentic water bodies (such as oxbow lakes) that lack surface channel connections to stream networks, attenuate downstream flood pulses. • Heterogeneous riparian areas that include wetlands and open waters remove large amounts of sediment and nutrients from upland areas before they can enter the stream network. • Riparian areas influence stream geomorphology during periodic flooding by releasing stored sediments. • Forested riparian areas provide woody debris that helps shape stream morphology. • Riparian vegetation shades the stream and influences and regulates stream temperature and stream net primary productivity. • Ground water that flows through riparian areas and into the stream helps moderate stream temperatures.
Chemical Connectivity and Function
• Riparian areas, acting as buffers, are critical to protecting stream-water quality. • The structure of the riparian area (e.g., vegetation, wetlands, redox potential) influences its ability to increase water quality before it reaches the stream. • The near-stream portion of a riparian area is often more important in protecting stream-water quality than is the near-field (near uplands) portion. • Allochthonous inputs generally are most important to food webs in small headwater streams, especially in forested areas. As rivers become larger, primary production becomes increasingly important. • Some of the best-documented functions of oxbow lakes are as sinks for nutrients from upland runoff that might otherwise flow into rivers.
Biological Connectivity and Function
• Many types of organisms move between riparian/floodplain wetlands and the river network; those transported by water often move in response to flooding and those transported by other mechanisms (e.g., wind) move in response to seasonal cues or life-history stage requirements. • Riparian/floodplain wetlands and oxbow lakes can be sources or sinks of organisms; one of the most important source functions is to provide rearing habitat for fish. • Riparian/floodplain wetlands provide food sources for stream and river invertebrates. • Many riparian/floodplain wetlands and open waters (e.g., oxbow lakes) are used by fish and other organisms from the stream or river during flooding.

output channels but are isolated from the river network; geographically isolated wetlands (i.e., wetlands completely surrounded by uplands) that have local or regional ground-water or occasional surface-water connections; and geographically isolated wetlands that have minimal hydrologic connection to the river network (but which could include surface and subsurface connections to other wetlands).

Based on our literature review and basic hydrologic principles, we conclude that non-floodplain wetlands that are connected to the river network through surface water will have an influence on downstream waters, regardless of whether the outflow is permanent, intermittent, or ephemeral. Such non-floodplain wetlands include wetlands that are the origins of streams or are connected downstream to the river network through ditches. They also would include geographically isolated wetlands that are connected downstream to the river network through upland swales. Further, although the literature review did not address other non-floodplain water bodies to the same extent as wetlands, our overall conclusions also apply to these water bodies (e.g., ponds and lakes that lack surface water inlets) because the same principles govern hydrologic connectivity between these water bodies and downstream waters (Chapter 2).

Non-floodplain wetlands that do not connect to the river network through surface water include wetlands that spill into losing streams that are completely disconnected from the river network; that is, the wetland exports water through an output channel but the water is completely lost before it reaches the river network due to evapotranspiration or loss to ground water. Also included are geographically isolated wetlands that either do not spill, or spill into an upland swale that does not enter the river network. Although such wetlands lack surface-water connections to streams and rivers, they can be connected through local, intermediate, or regional ground-water flows or through biological movement. Connectivity between these wetlands and downstream waters will vary within a watershed as a function of local factors (e.g., position, topography, and soil characteristics; Sections 2.4.1 and 2.4.2), some of which are identified and discussed in this section. Connectivity also will vary over time, as the river network and water table expand and contract in response to local climate.

It is difficult to generalize about the specific downstream effects of non-floodplain wetlands that lack surface water connections to downstream waters. In Chapter 2 we note that the influence of wetlands and streams on downstream waters depends on two factors: (1) functions that affect material fluxes and (2) connectivity (or isolation) that allows (or prevents) transport of materials between the systems (Section 2.3). The literature we reviewed and summarized provides ample evidence that non-floodplain wetlands provide hydrological, chemical, and biological functions that affect material fluxes. Thus, these wetlands could affect downstream waters if they are connected to (or isolated from) the river network in such a way that it allows (or prevents) transport of materials to downstream waters. However, the more than 200 peer-reviewed references on non-floodplain wetlands we reviewed infrequently evaluated connections between non-floodplain wetlands and river networks and rarely examined the frequency, duration, magnitude, timing, and rate of change of these connections. Even if it is known from an article that the study site is located near a downstream water, connectivity cannot be established without specific information on frequency and magnitude of precipitation events, soil infiltration rate, wetland storage capacity, hydraulic gradients, etc.—information that is only rarely available in publications. Thus, the literature provided no evaluations of connectivity for specific groups or classes of wetlands (e.g., prairie potholes or vernal pools). This lack of information applies to groups of these wetlands within a particular watershed and to comparisons between different types of regional wetlands. For example, our review did not reveal whether connectivity between vernal pools and downstream waters is greater than connectivity between prairie potholes and downstream waters. We emphasize that this does not mean these wetlands do or do not have connectivity with downstream waters: It simply means the literature we reviewed does not enable us to distinguish connectivity of these wetland types from each other. Literature that was not included in our review, such as reports

Table 4-4. Key conclusions on the effects of non-floodplain wetlands on rivers.
Physical Connectivity and Function
• The connections of non-floodplain wetlands with downstream waters exist along a spectrum from isolated depressional wetlands, to those connected through ground water, to those connected via intermittent or permanent surface flows. • The degree to which outputs (or connections) are dominated by surface water vs. ground water is controlled in part by soil permeability: Permeable soils favor ground-water outputs, while impermeable soils result in surface water outputs. Other factors, such as topographic setting, also can play a role. • Ground-water recharge is common in non-floodplain wetlands and can be a particularly important source of water to aquifers during dry periods. • Ground-water networks extend from the local to the intermediate and regional scales, and provide a mechanism by which non-floodplain wetlands can influence other water bodies over various periods. • Even when non-floodplain wetlands lack a connection to other water bodies, they can influence downstream water through water storage and mitigation of peak flows (flood reduction and attenuation).
Chemical Connectivity and Function
• Insofar as they often act as buffers between sources of pollution and riparian areas, non-floodplain wetlands are a "first line of defense" in protecting streams from polluted waters. • Non-floodplain wetlands affect nutrient delivery and water quality. • Non-floodplain wetlands are a principal source for dissolved organic carbon (which supports primary productivity) to some downstream waters; the area of a basin with non-floodplain wetlands is directly correlated to the contribution of that basin to dissolved organic carbon in downstream waters. • Non-floodplain wetlands are sources of mercury: Microbial processes in non-floodplain wetlands methylate mercury, which can be translocated through near-surface and surface flows to downstream waters where it can bioaccumulate. • Non-floodplain wetlands are sinks for sediment, nutrients (including phosphorus, nitrate, and ammonium), metals (e.g., nickel and cobalt), and pesticides (e.g., atrazine). • Non-floodplain wetlands can remove, retain, or transform many of the nutrient inputs to which they are exposed.
Biological Connectivity and Function
• Natural periodic and permanent human-engineered surface-water connections can connect biological communities in non-floodplain wetlands and the river network; in addition, wind dispersal and overland movement connect these types of water bodies with frequency decreasing as a function of distance, landscape barriers, or both. • Migratory birds are vectors of plants and invertebrates between non-floodplain wetlands and the river network, although their influence has not been quantified fully. • Non-floodplain wetlands promote biological interactions that can be critical to the life-history requirements of some stream species. • Overland ("fill-and-spill") hydrologic connections can support biological connections. For example, stream fish found in wetlands that periodically dry down indicate presence of surface flows sufficient for colonization.

from local resource agencies, could allow the connectivity of these wetlands to be evaluated further, as could analysis of existing or new data or field evaluation.

Further complicating our evaluation is that some of the effects that wetlands have on downstream waters are due to their isolation, rather than their connectivity. Wetland functions that trap materials and prevent their export to downstream waters (e.g., sediment and entrained pollutant removal, water storage) result because of the wetland's ability to isolate material fluxes. As above, to establish that a wetland influences a downstream water through its isolation, it would have to be known that the wetland intercepted materials that would otherwise reach the downstream water, and this information is typically not provided in publications. The literature we reviewed does provide limited examples of the direct effects of such isolation on downstream waters for some specific wetlands, but not for classes of wetlands (e.g., vernal pools). However, the literature we reviewed allows us to conclude that sink functions of non-floodplain wetlands, which result in part from their relative isolation, will have effects on a downstream water when these wetlands are situated between the downstream water and known point or nonpoint sources of pollution, and thus intersect the flowpath between pollutant source and downstream water. For example, in cases where agricultural land use is a known contributor of sediment to downstream waters, the presence of depressional wetlands along the flowpath between the agricultural land and downstream water will result in reduced sediment loading to the downstream water. These effects would also be realized from sink functions that do not result from the wetland's isolation *per se*, but are emergent wetland properties (e.g., biogeochemical reactivity based on anoxic conditions). Using the same example, if the agricultural land use is a known contributor of nitrogen to downstream waters, depressional wetlands occurring along the flowpath will result in reduced nitrogen loading to the downstream water. In such settings, wetland loss or increased connectivity (e.g., due to ditching or tiling) is likely to reduce the effects of such functions on downstream waters (although functions that depend on connectivity could be increased).

To provide more specific evaluations of the connectivity of non-floodplain wetlands to downstream waters, studies are needed that: (1) further develop and validate methods for assessing wetland and watershed connectivity; (2) apply such methods to different classes of non-floodplain wetlands, especially those that lack channelized surface-water or regular shallow subsurface-water connections; (3) evaluate the frequency, duration, magnitude, timing, and rate of change of water, material, and biotic fluxes to downstream waters; and (4) consider aggregate functions and connectivity of wetland complexes (groups of closely located and interacting wetlands). Such studies are needed throughout the country to cover the breadth of wetlands in non-floodplain settings satisfactorily (e.g., across areas with different climate, geology, and terrain).

Despite these limitations, we can make some conclusions:

1. A non-floodplain wetland having a surface-water outflow to a stream network (e.g., a wetland that serves as a stream origin) is connected to the stream network and has an influence on downstream waters.
2. Many non-floodplain wetlands interact with ground water, which can travel long distances and affect downstream waters.
3. Even when wetlands lack a hydrologic connection to other water bodies, they can influence downstream water through water and material storage and mitigation of peak flows (flood reduction and flood attenuation). Sink functions of non-floodplain wetlands will have effects on a downstream water when these wetlands are situated between the downstream water and known point or nonpoint sources of pollution, thereby intersecting the flowpath between

pollutant source and downstream water. More generally, wetland sink functions are likely to be greatest when the wetland is located downgradient from pollutant sources and upgradient from a stream or river.

4. Non-floodplain wetlands provide unique and important habitats for many species, both common and rare. Some of these species require multiple types of waters to complete their full life cycles, including downstream waters. Abundant or highly mobile species play important roles in transferring energy and materials between non-floodplain wetlands and downstream waters.
5. Biological connections are likely to occur between most non-floodplain wetlands and downstream waters through either direct or stepping stone movement of amphibians, invertebrates, reptiles, mammals, and seeds of aquatic plants, including colonization by invasive species. Many species in those groups that use both stream and wetland habitats are capable of dispersal distances equal to or greater than distances between many wetlands and river networks. Migratory birds can be an important vector of long-distance dispersal of plants and invertebrates between non-floodplain wetlands and the river network, although their influence has not been quantified. Whether those connections are of sufficient magnitude to impact downstream waters will either require estimation of the magnitude of material fluxes or evidence that these movements of organisms are required for the survival and persistence of biota that contribute to the integrity of downstream waters.
6. Spatial proximity is one important determinant of the magnitude, frequency and duration of connections between wetlands and streams that will ultimately influence the fluxes of water, materials and biota between wetlands and downstream waters. However, proximity alone is not sufficient to determine connectivity, due to local variation in factors such as slope and permeability.
7. The cumulative influence of many individual wetlands within watersheds can strongly affect the spatial scale, magnitude, frequency, and duration of hydrologic, biological and chemical fluxes or transfers of water and materials to downstream waters. Because of their aggregated influence, any evaluation of changes to individual wetlands should be considered in the context of past and predicted changes (e.g., from climate change) to other wetlands within the same watershed
8. Caution should be used in interpreting connectivity for wetlands that have been designated as "geographically isolated" because
   a. the term can be applied broadly to a heterogeneous group of wetlands, which can include wetlands that are not actually geographically isolated (e.g., some vernal pools are not geographically isolated because they have output channels;
   b. wetlands with permanent channels could be miscategorized as geographically isolated if the designation is based on maps or imagery with inadequate spatial resolution, obscured views, etc.; and

c. wetland complexes could have connections to downstream waters through stream channels even if individual wetlands within the complex are geographically isolated.

Thus, the term "geographically isolated" should be applied only to groups of wetlands if all those wetlands are, in fact, known to be geographically isolated, something that we cannot determine based on this literature review. As previously noted, additional information that was not included in our literature review (e.g., reports from local resource agencies, analysis of existing or new data, field evaluations) could allow some wetlands that are truly geographically isolated to be distinguished from some of those that are not. Further, even geographically isolated wetlands can be connected to other wetlands and downstream waters through ground-water connections, occasional spillage, or biological connections. Thus, the term "geographically isolated" should not be used to infer lack of hydrologic, chemical, or biological connectivity. Key conclusions from our literature review on non-floodplain wetlands are summarized in Table 4-4.

CHAPTER 5. APPLICATIONS AND DISCUSSION: CONNECTIVITY CASE STUDIES

5.1 Introduction

Chapters 3 and 4 of this report review evidence from the literature for the physical, chemical, and biological connections of three broad categories of waters—streams, riparian/floodplain wetlands, and non-floodplain wetlands—to, and their resulting effects on, downstream waters. In addition to the three questions in Table 1-1, the EPA's Office of Water asked us to provide detailed information on six specific water body types: Carolina and Delmarva bays, oxbow lakes, prairie potholes, prairie streams, southwestern streams, and vernal pools (Appendix B).

In this chapter, we summarize the results of the six case studies, applying the concepts in Chapters 1 and 2 to the detailed evidence in Appendix B, for each habitat. The full body of evidence and supporting citations, which we omitted here to improve readability, are provided in Appendix B. We summarize evidence from the individual case studies in terms of (1) the descriptors of connectivity (i.e., the frequency, duration, magnitude, timing, rate of change of fluxes to and biological exchanges with downstream waters; Section 1.2.2); (2) the consequences of different systems and degrees of connectivity on downstream waters (Sections 1.2.3 and 2.3); (3) and the effects of typical human alterations (Sections 1.2.4 and 2.4.4). We then use the information from these case studies and from Chapters 3 and 4 to illustrate, hypothetically, where streams, riparian/floodplain wetlands, and non-floodplain wetlands are positioned along a connectivity gradient, highlighting the primary lines of evidence that support that positioning.

5.2 Carolina and Delmarva Bays

Carolina bays are elliptical, ponded, depressional wetlands that occur along the Atlantic Coastal Plain from northern Florida to New Jersey, although they are most abundant in North Carolina and South Carolina (Section B.1). Carolina bays that are geographically specific to the Delmarva Peninsula are often referred to as Delmarva bays. Carolina and Delmarva bays range in size from less than 1 ha to greater than 3,600 ha and are densely concentrated in many areas. In the 1950s, roughly 500,000 bays existed, although the number today is markedly less due to human modification of the landscape. Bays primarily gain water from direct precipitation on their surfaces (with some water deriving from inlet channels, surface runoff, shallow ground water, and natural springs) and lose water through evapotranspiration. As a result, these relatively permanent bays experience fluctuating water levels. Their extensive distribution and wet-dry cycles promote and support a diverse biota.

5.2.1 Connectivity and Consequences on Downstream Waters

Some Carolina and Delmarva bays connect to each other and some connect to downstream waters. Delmarva bays inundate seasonally and connect hydrologically to other bays and to stream networks via intermittent stream channels. Studies also document shallow ground-water connections, via both nearly continuous shallow ground-water recharge and periodic shallow ground-water discharge.

When they occur, hydrologic connections are likely to result in effects on downstream waters. Carolina and Delmarva bays can reduce the amount of nitrate transported between surface-water systems and ground water via denitrification, which is promoted by the periodicity of wetting and drying that occurs in bays, and dilution. Seasonal connections of Delmarva bays to stream networks export accumulated organic matter from wetlands into tributaries of Chesapeake Bay. Hydrologic connections also export methylmercury from these systems (see below).

Although the current published evidence for biological connections is limited and primarily indirect, the potential for movement of organisms between bays and other water bodies is high. These bays provide valuable habitat and food web support for numerous plant and animal species. Fish presence in bays known to dry out periodically indirectly demonstrates that these bays must be connected to other waters. Amphibians and reptiles use bays extensively for breeding and for rearing young. In bays that lack fish, the absence of predators allows abundant amphibian populations to thrive, particularly those with aquatic larval stages. These animals can then disperse many meters across the landscape and colonize downstream waters. Bays also foster abundant aquatic insects, and their emergence can have consequences for nearby waters. Many species documented in Carolina and Delmarva bays are known to live in pond, wetland, and stream environments. As a result, species emerging from bays can become important food sources for organisms in nearby streams after aerial or terrestrial dispersal. Cumulative emergence from thousands of small bays across the landscape could create a significant food source for downstream waters.

5.2.2 Effects of Human Alteration

Human alteration of Carolina and Delmarva bays has affected their physical, chemical, and biological connections to, and effects on, downstream waters. Agriculture, logging, and other human activities have altered the vast majority of Carolina and Delmarva bays, affecting the frequency, duration, magnitude, and timing of hydrologic connections between bays and other waters. Agricultural practices have greatly reduced the number of bays over the past several decades. Channelization and ditching of bays for agriculture is common. Draining bays for agricultural use disrupts or alters numerous wetland functions: sediment and chemical storage and transformation, biological habitat and sources, and organic matter export. Because the ditches commonly connect the surface water of bays that drain agricultural fields to stream networks that drain into downstream water bodies, they serve as conveyances for nutrients, sediment, and contaminants—thereby increasing physical, chemical, and biological connections between bays and the downstream systems. The consequences of this increased connectivity for downstream waters can be especially important in terms of nutrient and contaminant transport. In addition to runoff from farmed fields, periodic drying and flooding of shallow Carolina and Delmarva bays promote the bacteria-mediated methylation of mercury. Subsequent transport of bioavailable methylmercury through ditches can pose a contamination risk to fish and piscivorous birds inhabiting downstream water bodies.

5.3 Oxbow Lakes

Oxbow lakes are natural features of floodplains, originating from curves (meanders) in the river that become cut off from the active river channel (Section B.2). They are located in flat, unconstrained floodplains of river systems.

5.3.1 Connectivity and Consequences on Downstream Waters

The evidence for physical, chemical, and biological connectivity of oxbow lakes to downstream waters is considerable. Because of their location within river floodplains, many oxbows are connected seasonally or episodically to downstream waters during natural flood events via surface and shallow subsurface flows. The frequency, duration, magnitude, and timing of these hydrologic connections depend on river stage, lake geomorphology, and relative position along and distance from the river network. Despite this spatial and temporal variability, oxbow lakes collectively are likely to influence downstream waters.

The frequency, magnitude, and duration of physical connection between oxbow lakes and the river channel have important consequences on the river network. Physical surface connections facilitate biological and chemical exchange between oxbow lakes and rivers. Oxbow lakes function as sinks, because they intercept and store nutrients and other materials from upland runoff that otherwise would flow directly into the river network. In these cases, the lack of a permanent connection between an oxbow lake and a river helps to preserve the chemical integrity of the river network.

When oxbow lakes are connected, the biological material produced within them can subsidize riverine food webs by passive or active transport from the lake to downstream waters. Oxbow lakes are important areas of biological productivity on floodplains. Periodic surface-water connections between rivers and oxbow lakes facilitate the movement of fish, allowing riverine fish to exploit these productive floodplain water bodies before they move back to the river. In this way, connectivity between oxbow lakes and rivers supports the biological integrity of the river network.

5.3.2 Effects of Human Alteration

Human alterations of the natural flow regime in rivers can influence connectivity between oxbow lakes and the active river channel. In some cases, permanent channels are constructed between oxbows and the river channel and connectivity is increased; in other cases, such as the creation of dikes or levees, connectivity is reduced between oxbows and the altered area of the river network. Practices that alter the natural flow regime of the river (e.g., dams) or inhibit periodic flooding of oxbow lakes (e.g., levees) affect movement of water and sediment and the use of oxbow lakes by riverine fish. When cut off from periodic inundation by the river channel, water in oxbow lakes can evaporate. Over time, these lakes can dry up, be colonized by terrestrial vegetation, and eventually become dry land.

5.4 Prairie Potholes

The prairie pothole region, located in northern-central North America, is named for the abundant, glacially formed wetlands that occur throughout the region, typically as depressions lacking natural outlets (Section B.3). The prairie pothole region covers approximately 777,000 km^2, a vast area that varies in climate, terrain, geology, land use, and human alteration. These variations result in a gradient of connectivity to and effects on downstream waters across the potholes themselves. For instance, the three major physiographic areas within the prairie pothole region (Red River Valley, Drift Prairie, and Missouri Coteau) vary in precipitation, distribution, and density of potholes and streams connecting potholes to downstream waters. Potholes exhibit a wide range of hydrologic permanence, from holding permanent standing water to wetting only in years with high precipitation. Differences in the frequency, duration, and timing of pothole inundation across the region influence wetland function and the diversity and structure of their biological communities.

5.4.1 Connectivity and Consequences on Downstream Waters

Individual prairie potholes span the continuum of isolation from and connection to the river network and other water bodies. In addition to differences among individual potholes, interactions between regional factors (e.g., precipitation) and local factors (e.g., landscape relief) can result in spatial patterns of connectivity across the landscape (Sections 2.4.5 and B.3.2.1) that have consequences for the downstream connectivity and effects of prairie potholes. Considered collectively, unaltered prairie pothole systems have infrequent direct surface-water connections to downstream waters. Evidence of the consequences of these connections on downstream waters is variable. Some studies document measurable effects of water storage capacity of potholes on flood attenuation and maintenance of stream baseflow, whereas other studies show no effect of pothole water storage on streamflows. These differences in observed effects might be explained, in part, by the spatial variation observed within the prairie pothole region. Potholes can connect to downstream waters via ground-water flows when both are within a continuous zone of a shallow local aquifer. In areas with restricted surface-water and ground-water interactions, the magnitude of effects from such connections will be small.

The chemical connectivity of prairie potholes is largely mediated by their hydrologic connectivity. As depressions on the landscape, potholes tend to accumulate nutrients, sediment, and pesticides that can be chemically transformed and decrease potential effects on downstream waters (e.g., denitrification frequently occurs in saturated pothole sediments). Although chemical sink (storage) functions and periodic source functions of potholes have been documented in the literature, their overall influence on lakes and river networks has been difficult to quantify. This difficulty exists in part because altered and unaltered potholes co-occur in watersheds with different land use and management practices, and many different parts of this complex landscape can affect the integrity of downstream waters. Thus, prairie potholes can have substantial hydrologic and chemical consequences on downstream water levels and flows, but this type of connectivity and its downstream effects are difficult to predict, demonstrate, and quantify.

Although direct evidence is sparse, indirect evidence suggests that prairie potholes are highly biologically connected. Prairie pothole systems have biological connections to downstream waters via annual bird migrations—especially for migratory waterfowl such as cranes, geese, ducks, and shorebirds, which actively move between and use multiple aquatic habitats, including prairie pothole systems. For instance, the prairie pothole region has been identified as an area of global and regional importance for migratory birds, and at least 15 duck species use prairie pothole wetlands. Mammals and many species of amphibians also use potholes. Plants and invertebrates disperse to and from prairie potholes via "hitchhiking" on waterfowl. That potholes lack an endemic aquatic and semiaquatic flora and fauna indicates that communities in potholes are biologically well connected with other aquatic ecosystems, but evidence for effects of biological connections on downstream waters is limited.

5.4.2 Effects of Human Alteration

Human alterations of the landscape affect the connectivity of prairie potholes. Land use in an upland that drains to a wetland can alter the amount of runoff that wetland receives. Much of Upper Midwest cropland is artificially drained to increase agricultural productivity. Filling potholes and lowering the regional water table through agriculture tile drainage have increased the isolation of remaining potholes by decreasing the density of depressions containing water. In some areas, extensive surface draining and ditching has directly and dramatically increased connectivity between pothole basins and the river network. Ditches create surface-water outlets from potholes, connecting potholes to streams and rivers; drains and underground pipes fitted at the bottoms of potholes often discharge to open ditches or streams. This increased hydrologic and chemical connectivity decreases water retention time, thereby reducing storage and biogeochemical processing of nutrients, sediments, and pesticides. The cumulative influence of human alterations on connectivity between potholes and downstream waters has not been systematically studied or reported across the entire prairie pothole region.

5.5 Prairie Streams

Prairie streams drain temperate grasslands in the Great Plains physiographic region of the central United States and Canada (Section B.4). Eventually, these streams drain into the Mississippi River or flow directly into the Gulf of Mexico or the Hudson Bay. Climate in the Great Plains region ranges from semiarid to moist subhumid and intra- and interannual variation in precipitation and evapotranspiration is high. This variation is reflected in the hydrology of prairie streams, which include ephemeral, intermittent, and perennial streamflows. Row cropping and livestock agriculture are the dominant land uses in the region, resulting in the withdrawal of water from stream channels and regional aquifers and its storage in reservoirs to support agriculture.

5.5.1 Connectivity and Consequences on Downstream Waters

Prairie streams typically are connected to downstream waters. Like other types of streams, prairie streams present strong fluvial geomorphic evidence for connectivity to downstream waters, in that they have continuous channels (bed and banks) that make them physically contiguous with downstream waters. Prairie river networks are dendritic and generally have a high drainage density, so they are particularly efficient at transferring water and materials to downstream waters. Their pool-riffle morphology, high sinuosity, and seasonal drying, however, also enhance material storage and transformation. The timing of connections between prairie streams and downstream waters is seasonal and therefore relatively predictable. For example, high-magnitude floods tend to occur in late fall into later spring, although they also occur at other times during the year (Section B.4.2.1); this observation indicates that the magnitude of connections to downstream also varies seasonally.

The frequent and predictable connections between prairie streams and downstream waters have multiple physical, chemical, and biological consequences for downstream waters. Dissolved solids, sediment, and nutrients are exported from the prairie river network to downstream waters. Ultimately, the expansion of the hypoxic zone in the Gulf of Mexico is a downstream consequence of cumulative nutrient loading to the Mississippi River network. Relative to small streams and large rivers draining the moist eastern parts of the Mississippi River basin, small to midsized prairie streams deliver less than 25–50% of their nutrient load to the Gulf of Mexico. Nonetheless, given the large number and spatial extent of headwater prairie streams connected to the Mississippi River, their cumulative effect likely contributes substantially to downstream nutrient loading.

Organisms inhabiting prairie streams have adapted to their variable hydrologic regimes and harsh physicochemical conditions via evolutionary strategies that include rapid growth, high dispersal ability, resistant life stages, fractional reproduction, and life cycles timed to avoid predictably harsh periods. Alterations in the frequency, duration, magnitude, and timing of flows—and thus hydrologic connectivity—are associated with the extinction or extirpation of species in downstream systems. Moreover, many fish species (e.g., Arkansas River shiner, speckled chub, flathead chub) in prairie river networks require sufficient unfragmented (i.e., connected) channel length with adequate discharge to keep their nonadhesive, semibuoyant eggs in suspension for incubation and early development. When these conditions are not met, the biological integrity of downstream waters is impaired.

5.5.2 Effects of Human Alteration

Human alteration of prairie river networks has affected the physical, chemical, and biological connectivity to and their consequences for downstream waters. Impoundments and water removal, through both surface flow diversions and pumping of ground-water aquifers, are common in this region. These activities have reduced flood magnitude and variability, altered timing, and increased predictability of flows to downstream waters. As a result, physical, chemical, and biological connections to downstream waters have been altered. In addition to the altered land uses and application of nutrients and pesticides for agriculture, human alteration of the river network itself, through channelization, levee construction, desnagging, dredging, and ditching, has enhanced longitudinal connectivity while reducing lateral and vertical connectivity with the floodplain and hyporheic zone, respectively. Pumping from streams and ground water has caused historically perennial river segments to regularly dry during summer months. Changes to the prairie's grazing (from bison to cattle) and burning regimes increase nutrient and suspended sediment loading to downstream waters. Introduced species have extirpated endemic species and altered food web structure and processes in prairie streams, thereby affecting the biological integrity of downstream waters.

5.6 Southwestern Intermittent and Ephemeral Streams

Southwestern streams are predominantly ephemeral and intermittent (nonperennial) systems located in the southwestern United States (Section B.5). Based on the National Hydrography Dataset, 94%, 89%, 88%, and 79% of the streams in Arizona, Nevada, New Mexico, and Utah, respectively, are nonperennial. Most of these streams connect to downstream waters, although 66% and 20% of the drainage basins in Nevada and New Mexico, respectively, are closed and drain into playas (dry lakes). Southwestern streams generally are steep and can be divided into two main types: (1) mountainous streams that drain higher portions of basins and receive higher rates of precipitation, often as snow, compared to lower elevations; and (2) streams located in valley or plateau regions that generally flow in response to high-intensity thunderstorms. Headwater streams are common in both types of southwestern streams.

5.6.1 Connectivity and Consequences on Downstream Waters

Nonperennial southwestern streams, excluding those that drain into playas, are periodically connected to downstream waters by low-duration, high-magnitude flows. In contrast to streams in humid regions where discharge is typically supplemented by ground water as drainage area increases, many southwestern streams lose streamflow to channel transmission losses as runoff travels downstream (Figure B-10). Connection of runoff and associated materials in ephemeral and intermittent streams to downstream waters is therefore a function of distance, the relative magnitude of the runoff event, and transmission losses.

Spatial and temporal variation in frequency, duration, and timing of southwestern stream runoff is largely explained by elevation, climate, channel substrate, geology, and the presence of shallow ground water. In nonconstraining substrate, southwestern rivers are dendritic and their watersheds tend to have a high drainage density. When high flows are present, southwestern streams are efficient at transferring water, sediment, and nutrients to downstream reaches. Due to the episodic nature of flow in ephemeral and intermittent channels, sediment and organic matter can be deposited some distance downstream, and then moved farther downstream by subsequent precipitation events. Over time, sediment and organic matter continue to move downstream and affect downstream waters.

The southwestern streams case study (Section B.5) describes the substantial connection and important consequences of runoff, nutrients, and particulate matter originating from ephemeral tributaries on the integrity and sustainability of downstream perennial streams. Channel transmission losses can be an important source of ground-water recharge that sustains downstream perennial stream and riparian systems. For example, isotopic studies indicate that runoff from ephemeral tributaries like Walnut Gulch, Arizona supplies roughly half the San Pedro River's baseflow through shallow alluvial aquifer recharge.

5.6.2 Effects of Human Alteration

Human alterations to southwestern river networks affect the physical, chemical, and biological connectivity to downstream waters. Impoundments trap water, sediment, and particulate nutrients and result in downstream impacts on channel morphology and aquatic function. Diversion of water for consumptive uses can decrease downstream baseflows but typically does not affect the magnitude of peak flows. Excessive ground-water pumping can lower ground-water tables, thereby diminishing or eliminating baseflows. Urbanization increases runoff volume and flow velocity, resulting in more erosive energy that can cause bank erosion, streambed downcutting, and reduced infiltration to ground water.

5.7 Vernal Pools

Vernal pools are shallow, rain-fed, fishless pools situated on bedrock or low-permeability soils (Section B.6). Vernal pools inundate seasonally and lack continuous surface-water connections to downstream water bodies. Although they can occur in other parts of the United States, this case study focuses on pools in the western states and the glaciated areas of northeastern states. Western vernal pools typically occur in open grasslands; most northern vernal pools are detrital and are fully contained within forest ecosystems. When inundation occurs, vernal pools can fill and overflow through swales or intermittent streams, which connect them to downstream waters.

5.7.1 Connectivity and Consequences on Downstream Waters

Direct surface connection of vernal pools to downstream waters is infrequent. The duration and magnitude of such connections are highly variable and depend on the climate, terrain, and geology of the region and on the location of the vernal pool in the watershed. Vernal pools generally are clustered, forming wetland complexes. Pools located at the downgradient end of a complex can receive surface water through stepping-stone spillage in addition to precipitation, and generally are inundated longer than upper pools. Because they experience greater inundation and are likely to be located nearer to streams, these downgradient pools are also more likely to be directly connected to streams. Temporary storage of heavy rainfall and snowmelt in individually small vernal pool systems (pools plus soils) can attenuate flooding, provide a reservoir for nearby vegetation during the spring growth period, and increase nutrient availability.

The timing of seasonal inundation and lack of permanent surface connections make vernal pools important biological refuges, which has consequences on the biological health of downstream waters. Vernal pools are highly productive ecosystems that have evolved in a “balance between isolation and connectedness” (Zedler, 2003; page 597). Because they are connected to other aquatic habitats through dispersal, they provide rich reservoirs of genetic and species diversity. Food webs in vernal pools include highly fecund amphibians and insects that convert detrital organic matter into biomass, which is then exported to aquatic ecosystems in other parts of the watershed. Northern vernal pools can provide alternative breeding habitat, refuge from predators or environmental stressors, hunting or foraging habitat, or stepping-stone corridors for dispersal and migration.

5.7.2 Effects of Human Alteration

Vernal pools have been drained and converted to other land uses (e.g., agriculture, logging, urban development). These activities have increased fragmentation of habitats for amphibians, plants, and invertebrates, and had similar effects on the frequency, duration, magnitude, and timing of inundations, surface-water outflows, and shallow subsurface-water connections to downstream waters as those described in Section 5.2.1 (Carolina and Delmarva bays).

5.8 Synthesis

These case study summaries highlight the key connections between specific water body types and downstream waters. The case study evidence provides further support that the structure and function of downstream waters highly depend on constituent materials and organisms contributed by and transported through water bodies located throughout the watershed. In addition, the studies support that variation in the types and degrees of connectivity determines the range of downstream effects.

These case study summaries illustrate two key points. First, each type of water body addressed here demonstrates variability in connectivity to and effects on downstream waters. Oxbow lakes, for example, are more or less connected to the main river channel based largely on their relative position in the landscape: Systems close to the river channel are highly connected and those farther away are connected less often or the impact on the river takes longer to be realized. Evidence presented in the prairie pothole case study also demonstrates variation in connectivity patterns across the region and shows the consequences of this variability on downstream rivers and lakes. The prairie streams case study discusses functions and varying degrees of connectivity of streams and their cumulative effects on downstream waters.

Second, the effects of human alteration on the connectivity to and effects on downstream waters depend on the type of water body. Human alteration of different types of streams and wetlands can be complex, either increasing or decreasing connectivity and subsequent effects on downstream waters. For example, evidence shows that ditches in the prairie pothole region increase hydrologic connectivity, and connectivity of oxbow lakes near active river channels can be reduced if that portion of the river is leveed. Coupled human-natural systems are an area of active research and new information about the effects of human activities on connectivity and water integrity is emerging in the peer-reviewed literature.

Positioning the specific water body types in the case studies (Appendix B) along a gradient of connectivity and effect proved to be premature for several reasons. First, the amount of documented evidence (i.e., number of published studies) varied among the water body types. In some instances, a large body of evidence exists and in others, only a few studies exist, limiting sound comparisons. Second, variation in connectivity consistently was reported to be high within some water body types, creating substantial overlap in ranges of connectivity among those water body types. In addition to a need for more studies documenting connectivity in less studied regions, a more refined classification using the descriptors of connectivity described in Chapter 1 (or others) and their controls (e.g., climate, geology, and terrain) within wetland landscape settings are required.

Based on the evidence presented in Chapters 3 and 4, ordering the three broad categories of water bodies considered in this report—streams, floodplain wetlands, and non-floodplain wetlands—along a connectivity gradient (Figure 5-1) is possible. Of these three water body types, streams are, in general, more connected to and have better-documented effects on downstream waters than either wetland category. Floodplain wetlands, in turn, tend to be more connected to downstream waters, and have better-documented downstream effects, than non-floodplain wetlands. This ordering must be recognized as a broad generalization, and considerable overlap can occur among the types, given the spatial and temporal variability in connectivity documented in these habitats (Figure 5-1). Nevertheless, several key lines of evidence support this hypothesized ordering of water body types along the gradient.

1. Streams are connected to rivers by a continuous channel, which is a physical reflection of surface connectivity. Formation of a channel indicates that connectivity, in terms of its combined descriptors (frequency, duration, magnitude, timing) is sufficiently strong (or "effective") and outweighs terrestrialization processes (e.g., revegetation, wind-mediated processes, soil formation processes).
2. Within-channel flows are more efficient for moving water, sediment, pollutants, and other materials than overland flow; for some aquatic organisms, channels are the only possible transport routes. Channels are places where excess water and materials from the landscape are concentrated as they are transmitted downstream. Recurrent flow of sufficient magnitude over a given area of landscape selects routes with least resistance, which develop into branched

channel networks with a repeating, cumulative pattern of smaller channels that join at confluences to form larger channels.

3. The continuous channels connecting streams to rivers also represent areas of relatively high shallow subsurface connectivity (shallow ground-water recharge and upwelling). Channels are typically more permeable than surrounding soils, lack dense terrestrial vegetation (and thus have lower uptake and evapotranspiration loss), and are topographic low points closer to concentrated shallow ground water.

4. Floodplain wetlands and open waters are connected to rivers by historical and recurrent surface connectivity. Riparian/floodplain wetlands are maintained by the recurrent inundation and deposition of materials from streams and rivers during the peak and recession of flood flows.

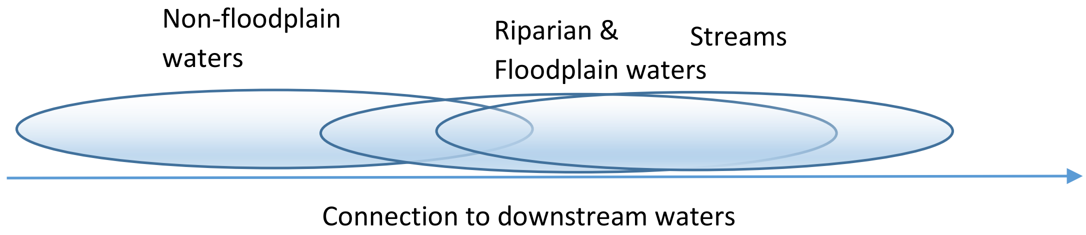
5. Riparian/floodplain wetlands and open waters are close to river networks and thus more likely to have strong connectivity with the downstream water than more distant wetlands, when all other conditions are similar.

6. Non-floodplain wetlands are positioned outside the floodplain, and so are not subject to direct flooding from the river or stream. Any hydrologic connections to the river system are therefore unidirectional (from wetland to downstream water and not vice-versa). They are also likely to be more distant from the network, increasing the flowpath lengths and travel time to the network.

7. Because of their large numbers, headwater streams and associated wetlands cumulatively represent a large portion of the landscape interface with a downstream water. These areas provide functions that enhance both exchanges with and buffering of the downstream water, making them critical to mediating the recognized relationship between the integrity of downstream waters and the land use and stressor loadings from the surrounding landscape.

8. Connectivity to downstream waters is reflected in the distribution of aquatic organisms and their dependence on particular aquatic habitats across different stages of their life cycles. For example, the recurrent presence of completely aquatic organisms (i.e., organisms that lack terrestrial life stages, overland dispersal, stages resistant to drying) in streams and wetlands that periodically dry provides indirect evidence for surface-water connections. Because many aquatic species can move and disperse overland, aquatic habitats can be highly connected biologically in the absence of hydrologic connectivity.

Figure 5-1. Relative positioning of streams, riparian and floodplain waters, and non-floodplain waters along a gradient of connectivity. Ellipses are used to illustrate the degree of expected overlap among water-body types based on the range of variation documented in the reviewed literature.



CHAPTER 6. CONCLUSIONS

This chapter presents the five major conclusions of this report, with a summary of key findings from the literature synthesized to develop these conclusions. It also discusses the relative abundance of literature on topics reviewed in this report. Finally, it briefly discusses emerging research that can close some current data gaps and help further clarify the role of connectivity in maintaining the integrity of downstream waters.

Citations have been omitted from the text of the conclusions and key findings to improve readability; please refer to individual chapters for supporting publications and additional information.

6.1 Major Conclusions and Key Findings

Based on our review and synthesis of the literature, we developed five major conclusions, which are presented in this section with a summary of key findings for each conclusion.

6.1.1 Conclusion 1: Streams

The scientific literature unequivocally demonstrates that streams, individually or cumulatively, exert a strong influence on the integrity of downstream waters. All tributary streams, including perennial, intermittent, and ephemeral streams, are physically, chemically, and biologically connected to downstream rivers via channels and associated alluvial deposits where water and other materials are concentrated, mixed, transformed, and transported. Streams are the dominant source of water in most rivers, and the majority of tributaries are perennial, intermittent, or ephemeral headwater streams. Headwater streams also convey water into local storage compartments such as ponds, shallow aquifers, or stream banks, and into regional and alluvial aquifers; these local storage compartments are important sources of water for maintaining baseflow in rivers. In addition to water, streams transport sediment, wood, organic matter, nutrients, chemical contaminants, and many of the organisms found in rivers. The literature provides robust evidence that streams are biologically connected to downstream waters by the dispersal and migration of aquatic and semiaquatic organisms, including fish, amphibians, plants, microorganisms, and invertebrates, that use both upstream and downstream habitats during one or more stages of their life cycles, or provide food resources to downstream communities. In addition to material transport and biological connectivity, ephemeral, intermittent, and perennial flows influence fundamental biogeochemical processes by connecting channels and shallow ground water with other landscape elements. Physical, chemical, and biological connections between streams and downstream waters interact via integrative processes such as nutrient spiraling, in which stream communities assimilate and chemically transform large quantities of nitrogen and other nutrients that otherwise would be transported directly downstream, increasing nutrient loads and associated impairments due to excess nutrients in downstream waters.

6.1.1.1 Conclusion 1, Key Findings

- Streams are hydrologically connected to downstream waters via channels that convey surface and subsurface water either year-round (i.e., perennial flow), weekly to seasonally (i.e., intermittent flow), or only in direct response to precipitation (i.e., ephemeral flow). Streams are the dominant source of water in most rivers, and the majority of tributaries are perennial, intermittent, or ephemeral headwater streams. For example, headwater streams, which are the smallest channels where streamflows begin, are the cumulative source of approximately 60% of the total mean annual flow to all northeastern U.S. streams and rivers.
- In addition to downstream transport, headwaters convey water into local storage compartments such as ponds, shallow aquifers, or stream banks, and into regional and alluvial aquifers. These local storage compartments are important sources of water for maintaining baseflow in rivers. Streamflow typically depends on the delayed (i.e., lagged) release of shallow ground water from local storage, especially during dry periods and in areas with shallow ground-water tables and pervious subsurfaces. For example, in the southwestern United States, short-term shallow ground-water storage in alluvial floodplain aquifers, with gradual release into stream channels, is a major source of annual flow in rivers.
- Infrequent, high-magnitude events are especially important for transmitting materials from headwater streams in most river networks. For example, headwater streams, including ephemeral and intermittent streams, shape river channels by accumulating and gradually or episodically releasing stored materials such as sediment and large woody debris. These materials help structure stream and river channels by slowing the flow of water through channels and providing substrate and habitat for aquatic organisms.
- There is strong evidence that headwater streams function as nitrogen sources (via export) and sinks (via uptake and transformation) for river networks. For example, one study estimated that rapid nutrient cycling in small streams with no agricultural or urban impacts removed 20−40% of the nitrogen that otherwise would be delivered to downstream waters. Nutrients are necessary to support aquatic life, but excess nutrients lead to eutrophication and hypoxia, in which over-enrichment causes dissolved oxygen concentrations to fall below the level necessary

to sustain most aquatic animal life in the stream and streambed. Thus, the influence of streams on nutrient loads can have significant repercussions for hypoxia in downstream waters.

- Headwaters provide habitat that is critical for completion of one or more life-cycle stages of many aquatic and semiaquatic species capable of moving throughout river networks. Evidence is strong that headwaters provide habitat for complex life-cycle completion; refuge from predators, competitors, parasites, or adverse physical conditions in rivers (e.g., temperature or flow extremes, low dissolved oxygen, high sediment); and reservoirs of genetic- and species-level diversity. Use of headwater streams as habitat is especially critical for the many species that migrate between small streams and marine environments during their life cycles (e.g., Pacific and Atlantic salmon, American eels, certain lamprey species). The presence of these species within river networks provides robust evidence of biological connections between headwaters and larger rivers; because these organisms also transport nutrients and other materials as they migrate, their presence also provides evidence of biologically mediated chemical connections. In prairie streams, many fishes swim upstream into tributaries to release eggs, which develop as they are transported downstream.
- Human alterations affect the frequency, duration, magnitude, timing, and rate of change of connections between headwater streams, including ephemeral and intermittent streams, and downstream waters. Human activities and built structures (e.g., channelization, dams, ground-water withdrawals) can either enhance or fragment longitudinal connections between headwater streams and downstream waters, while also constraining lateral and vertical exchanges and tightly controlling the temporal dimension of connectivity. In many cases, research on human alterations has enhanced our understanding of the headwater stream-downstream water connections and their consequences. Recognition of these connections and effects has encouraged the development of more sustainable practices and infrastructure to reestablish and manage connections, and ultimately to protect and restore the integrity of downstream waters.

6.1.2 Conclusion 2: Riparian/Floodplain Wetlands and Open Waters

The literature clearly shows that wetlands and open waters in riparian areas and floodplains are physically, chemically, and biologically integrated with rivers via functions that improve downstream water quality, including the temporary storage and deposition of channel-forming sediment and woody debris, temporary storage of local ground water that supports baseflow in rivers, and transformation and transport of stored organic matter. Riparian/floodplain wetlands and open waters improve water quality through the assimilation, transformation, or sequestration of pollutants, including excess nutrients and chemical contaminants such as pesticides and metals, that can degrade downstream water integrity. In addition to providing effective buffers to protect downstream waters from point source and nonpoint source pollution, these systems form integral components of river food webs, providing nursery habitat for breeding fish and amphibians, colonization opportunities for stream invertebrates, and maturation habitat for stream insects. Lateral expansion and contraction of the river in its floodplain result in an exchange of organic matter and organisms, including fish populations that are adapted to use floodplain habitats for feeding and spawning during high water, that are critical to river ecosystem function. Riparian/floodplain wetlands and open waters also affect the integrity of downstream waters by subsequently releasing (desynchronizing) floodwaters and retaining large volumes of stormwater, sediment, and contaminants in runoff that could otherwise negatively affect the condition or function of downstream waters.

6.1.2.1 Conclusion 2, Key Findings

- Riparian areas and floodplains connect upland and aquatic environments through both surface and subsurface hydrologic flowpaths. These areas are therefore uniquely situated in watersheds to receive and process waters that pass over densely vegetated areas and through subsurface zones before the waters reach streams and rivers. When pollutants reach a riparian or floodplain wetland, they can be sequestered in sediments, assimilated into wetland plants and animals, transformed into less harmful or mobile forms or compounds, or lost to the atmosphere. Wetland potential for biogeochemical transformations (e.g., denitrification) that can improve downstream water quality is influenced by local factors, including anoxic conditions and slow organic matter decomposition, shallow water tables, wetland plant communities, permeable soils, and complex topography.
- Riparian/floodplain wetlands can reduce flood peaks by storing and desynchronizing floodwaters. They can also maintain river baseflows by recharging alluvial aquifers. Many studies have documented the ability of riparian/floodplain wetlands to reduce flood pulses by storing excess water from streams and rivers. One review of wetland studies reported that riparian wetlands reduced or delayed floods in 23 of 28 studies. For example, peak discharges between upstream and downstream gaging stations on the Cache River in Arkansas were reduced 10−20% primarily due to floodplain water storage.
- Riparian areas and floodplains store large amounts of sediment and organic matter from upstream and from upland areas. For example, riparian areas have been shown to remove 80−90% of sediments leaving agricultural fields in North Carolina.
- Ecosystem function within a river system is driven in part by biological connectivity that links diverse biological communities with the river system. Movements of organisms that connect aquatic habitats and their populations, even across different watersheds, are important for the survival of individuals, populations, and species, and for the functioning of the river ecosystem. For example, lateral expansion and contraction of the river in its floodplain result in an exchange of matter and organisms, including fish populations that are adapted to use floodplain habitats for feeding and spawning during high water. Wetland and aquatic plants in floodplains can become important seed sources for the river network, especially if catastrophic flooding scours vegetation and seed banks in other parts of the channel. Many invertebrates exploit temporary hydrologic connections between rivers and floodplain wetland habitats, moving into these wetlands to feed, reproduce, or avoid harsh environmental conditions and then returning to the

river network. Amphibians and aquatic reptiles commonly use both streams and riparian/floodplain wetlands to hunt, forage, overwinter, rest, or hide from predators. Birds can spatially integrate the watershed landscape through biological connectivity.

6.1.3 Conclusion 3: Non-floodplain Wetlands and Open Waters

Wetlands and open waters in non-floodplain landscape settings (hereafter called "non-floodplain wetlands") provide numerous functions that benefit downstream water integrity. These functions include storage of floodwater; recharge of ground water that sustains river baseflow; retention and transformation of nutrients, metals, and pesticides; export of organisms or reproductive propagules to downstream waters; and habitats needed for stream species. This diverse group of wetlands (e.g., many prairie potholes, vernal pools, playa lakes) can be connected to downstream waters through surface-water, shallow subsurface-water, and ground-water flows and through biological and chemical connections.

In general, connectivity of non-floodplain wetlands occurs along a gradient (Conclusion 4), and can be described in terms of the frequency, duration, magnitude, timing, and rate of change of water, material, and biotic fluxes to downstream waters. These descriptors are influenced by climate, geology, and terrain, which interact with factors such as the magnitudes of the various functions within wetlands (e.g., amount of water storage or carbon export) and their proximity to downstream waters to determine where wetlands occur along the connectivity gradient. At one end of this gradient, the functions of non-floodplain wetlands clearly affect the condition of downstream waters if a visible (e.g., channelized) surface-water or a regular shallow subsurface-water connection to the river network is present. For non-floodplain wetlands lacking a channelized surface or regular shallow subsurface connection (i.e., those at intermediate points along the gradient of connectivity), generalizations about their specific effects on downstream waters from the available literature are difficult because information on both function and connectivity is needed. Although there is ample evidence that non-floodplain wetlands provide hydrologic, chemical, and biological functions that affect material fluxes, to date, few scientific studies explicitly addressing connections between non-floodplain wetlands and river networks have been published in the peer-reviewed literature. Even fewer publications specifically focus on the frequency, duration, magnitude, timing, or rate of change of these connections. In addition, although areas that are closer to rivers and streams have a higher probability of being connected than areas farther away when conditions governing the type and quantity of flows—including soil infiltration rate, wetland storage capacity, hydraulic gradient, etc.—are similar, information to determine if this similarity holds is generally not provided in the studies we reviewed. Thus, current science does not support evaluations of the degree of connectivity for specific groups or classes of wetlands (e.g., prairie potholes or vernal pools). Evaluations of individual wetlands or groups of wetlands, however, could be possible through case-by-case analysis.

Some effects of non-floodplain wetlands on downstream waters are due to their isolation, rather than their connectivity. Wetland sink functions that trap materials and prevent their export to downstream waters (e.g., sediment and entrained pollutant removal, water storage) result because of the wetland's ability to isolate material fluxes. To establish that such functions influence downstream waters, we also need to know that the wetland intercepts materials that otherwise would reach the downstream water. The literature we reviewed does provide limited examples of direct effects of wetland isolation on downstream waters, but not for classes of wetlands (e.g., vernal pools). Nevertheless, the literature we reviewed enables us to conclude that sink functions of non-floodplain wetlands, which result in part from their relative isolation, will affect a downstream water when these wetlands are situated between the downstream water and known point or nonpoint sources of pollution, and thus intersect flowpaths between the pollutant source and downstream waters.

6.1.3.1 Conclusion 3, Key Findings

- Water storage by wetlands well outside of riparian or floodplain areas can affect streamflow. Hydrologic models of prairie potholes in the Starkweather Coulee subbasin (North Dakota) that drains to Devils Lake indicate that increasing the volume of pothole storage across the subbasin by approximately 60% caused simulated total annual streamflow to decrease 50% during a series of dry years and 20% during wet years. Similar simulation studies of watersheds that feed the Red River of the North in North Dakota and Minnesota demonstrated qualitatively comparable results, suggesting that the ability of potholes to modulate streamflow could be widespread across eastern portions of the prairie pothole region. This work also indicates that reducing water storage capacity of wetlands by connecting formerly isolated potholes through ditching or drainage to the Devils Lake and Red River basins could increase stormflow and contribute to downstream flooding. In many agricultural areas already crisscrossed by extensive drainage systems, total streamflow and baseflow are increased by directly connecting potholes to stream networks. The impacts of changing streamflow are numerous, including altered flow regime, stream geomorphology, habitat, and ecology. The presence or absence of an effect of prairie pothole water storage on streamflow depends on many factors, including patterns of precipitation, topography, and degree of human alteration. For example, in parts of the prairie pothole region with low precipitation, low stream density, and little human alteration, hydrologic connectivity between prairie potholes and streams or rivers is likely to be low.
- Non-floodplain wetlands act as sinks and transformers for various pollutants, especially nutrients, which at excess levels can adversely impact human and ecosystem health and pose a serious pollution problem in the United States. In one study, sewage wastewaters were applied to forested wetlands in Florida for 4.5 years; more than 95% of the phosphorus, nitrate, ammonium, and total nitrogen were removed by the wetlands during the study period, and 66−86% of the nitrate removed was attributed to the process of denitrification. In another study, sizeable phosphorus retention (0.3 to 8.0 mg soluble reactive P m^{-2} d^{-1}) occurred in marshes that comprised only 7% of the lower Lake Okeechobee basin area in Florida. A non-floodplain bog in Massachusetts was reported to sequester nearly 80% of nitrogen inputs from various sources, including atmospheric deposition, and prairie pothole wetlands in the upper Midwest were found to remove >80% of the nitrate load via denitrification. A large prairie marsh was found to remove 86% of nitrate, 78% of ammonium, and 20% of phosphate through

assimilation and sedimentation, sorption, and other mechanisms. Together, these and other studies indicate that onsite nutrient removal by non-floodplain wetlands is substantial and geographically widespread. The effects of this removal on rivers are generally not reported in the literature.

- Non-floodplain wetlands provide unique and important habitats for many species, both common and rare. Some of these species require multiple types of waters to complete their full life cycles, including downstream waters. Abundant or highly mobile species play important roles in transferring energy and materials between non-floodplain wetlands and downstream waters.
- Biological connections are likely to occur between most non-floodplain wetlands and downstream waters through either direct or stepping stone movement of amphibians, invertebrates, reptiles, mammals, and seeds of aquatic plants, including colonization by invasive species. Many species in those groups that use both stream and wetland habitats are capable of dispersal distances equal to or greater than distances between many wetlands and river networks. Migratory birds can be an important vector of long-distance dispersal of plants and invertebrates between non-floodplain wetlands and the river network, although their influence has not been quantified. Whether those connections are of sufficient magnitude to impact downstream waters will either require estimation of the magnitude of material fluxes or evidence that these movements of organisms are required for the survival and persistence of biota that contribute to the integrity of downstream waters.
- Spatial proximity is one important determinant of the magnitude, frequency, and duration of connections between wetlands and streams that will ultimately influence the fluxes of water, materials, and biota between wetlands and downstream waters. However, proximity alone is not sufficient to determine connectivity, due to local variation in factors such as slope and permeability.
- The cumulative influence of many individual wetlands within watersheds can strongly affect the spatial scale, magnitude, frequency, and duration of hydrologic, biological, and chemical fluxes or transfers of water and materials to downstream waters. Because of their aggregated influence, any evaluation of changes to individual wetlands should be considered in the context of past and predicted changes (e.g., from climate change) to other wetlands within the same watershed.
- Non-floodplain wetlands can be hydrologically connected directly to river networks through natural or constructed channels, nonchannelized surface flows, or subsurface flows, the latter of which can travel long distances to affect downstream waters. A wetland surrounded by uplands is defined as "geographically isolated." Our review found that, in some cases, wetland types such as vernal pools and coastal depressional wetlands are collectively—and incorrectly—referred to as geographically isolated. Technically, the term "geographically isolated" should be applied only to the particular wetlands within a type or class that are completely surrounded by uplands. Furthermore, "geographic isolation" should not be confused with functional isolation, because

geographically isolated wetlands can still have hydrologic, chemical, and biological connections to downstream waters.

- Non-floodplain wetlands occur along a gradient of hydrologic connectivity-isolation with respect to river networks, lakes, or marine/estuarine water bodies. This gradient includes, for example, wetlands that serve as origins for stream channels that have permanent surface-water connections to the river network; wetlands with outlets to stream channels that discharge to deep ground-water aquifers; geographically isolated wetlands that have local ground-water or occasional surface-water connections to downstream waters; and geographically isolated wetlands that have minimal hydrologic connection to other water bodies (but which could include surface and subsurface connections to other wetlands). This gradient can exist among wetlands of the same type or in the same geographic region.
- Caution should be used in interpreting connectivity for wetlands that have been designated as "geographically isolated" because (1) the term can be applied broadly to a heterogeneous group of wetlands, which can include wetlands that are not actually geographically isolated; (2) wetlands with permanent channels could be miscategorized as geographically isolated if the designation is based on maps or imagery with inadequate spatial resolution, obscured views, etc.; and (3) wetland complexes could have connections to downstream waters through stream channels even if individual wetlands within the complex are geographically isolated. For example, a recent study examined hydrologic connectivity in a complex of wetlands on the Texas Coastal Plain. The wetlands in this complex have been considered to be a type of geographically isolated wetland. Collectively, however, they are connected both geographically and hydrologically to downstream waters in the area: During an almost 4-year study period, nearly 20% of the precipitation that fell on the wetland complex flowed out through an intermittent stream into downstream waters. Thus, wetland complexes could have connections to downstream waters through stream channels even when the individual wetland components are geographically isolated.

6.1.4 Conclusion 4: Degrees and Determinants of Connectivity

Watersheds are integrated at multiple spatial and temporal scales by flows of surface water and ground water, transport and transformation of physical and chemical materials, and movements of organisms. Although all parts of a watershed are connected to some degree—by the hydrologic cycle or dispersal of organisms, for example—the degree and downstream effects of those connections vary spatially and temporally, and are determined by characteristics of the physical, chemical, and biological environments and by human activities.

Stream and wetland connections have particularly important consequences for downstream water integrity. Most of the materials—broadly defined as any physical, chemical, or biological entity—in rivers, for example, originate from aquatic ecosystems located upstream or elsewhere in the watershed. Longitudinal flows through ephemeral, intermittent, and perennial stream channels are much more efficient for transport of water, materials, and organisms than diffuse overland flows, and areas that concentrate water provide mechanisms for the storage and transformation, as well as transport, of materials.

Connectivity of streams and wetlands to downstream waters occurs along a continuum that can be described in terms of the frequency, duration, magnitude, timing, and rate of change of water, material, and biotic fluxes to downstream waters. These terms, which we refer to collectively as connectivity descriptors, characterize the range over which streams and wetlands vary and shift along the connectivity gradient in response to changes in natural and anthropogenic factors and, when considered in a watershed context, can be used to predict probable effects of different degrees of connectivity over time. The evidence unequivocally demonstrates that the stream channels and riparian/floodplain wetlands or open waters that together form river networks are clearly connected to downstream waters in ways that profoundly influence downstream water integrity. The connectivity and effects of non-floodplain wetlands and open waters are more variable and thus more difficult to address solely from evidence available in peer-reviewed studies.

Variations in the degree of connectivity influence the range of functions provided by streams and wetlands, and are critical to the integrity and sustainability of downstream waters. Connections with low values of one or more descriptors (e.g., low-frequency, low-duration streamflows caused by flash floods) can have important downstream effects when considered in the context of other descriptors (e.g., large magnitude of water transfer). At the other end of the frequency range, high-frequency, low-magnitude vertical (surface-subsurface) and lateral flows contribute to aquatic biogeochemical processes, including nutrient and contaminant transformation and organic matter accumulation. The timing of an event can alter both connectivity and the magnitude of its downstream effect. For example, when soils become saturated by previous rainfall events, even low or moderate rainfall can cause streams or wetlands to overflow, transporting water and materials to downstream waters. Fish that use nonperennial or perennial headwater stream habitats to spawn or rear young, and invertebrates that move into seasonally inundated floodplain wetlands prior to emergence, have life cycles that are synchronized with the timing of flows, temperature thresholds, and food resource availability in those habitats.

6.1.4.1 Conclusion 4, Key Findings

- The surface-water and ground-water flowpaths (hereafter, hydrologic flowpaths), along which water and materials are transported and transformed, determine variations in the degree of physical and chemical connectivity. These flowpaths are controlled primarily by variations in climate, geology, and terrain within and among watersheds and over time. Climate, geology, and terrain are reflected locally in factors such as rainfall and snowfall intensity, soil infiltration rates, and the direction of ground-water flows. These local factors interact with the landscape positions of streams and wetlands relative to downstream waters, and with functions (such as the removal or transformation of pollutants) performed by those streams and wetlands to determine connectivity gradients.

- Gradients of biological connectivity (i.e., the active or passive movements of organisms through water or air and over land that connect populations) are determined primarily by species assemblages, and by features of the landscape (e.g., climate, geology, terrain) that facilitate or impede the movement of organisms. The temporal and spatial scales at which biological pathways connect aquatic habitats depend on characteristics of both the landscape and species, and overland transport or movement can occur across watershed boundaries. Dispersal is essential for population persistence, maintenance of genetic diversity, and evolution of aquatic species. Consequently, dispersal strategies reflect aquatic species' responses and adaptations to biotic and abiotic environments, including spatial and temporal variation in resource availability and quality. Species' traits and behaviors encompass species-environment relationships over time, and provide an ecological and evolutionary context for evaluating biological connectivity in a particular watershed or group of watersheds.
- Pathways for chemical transport and transformation largely follow hydrologic flowpaths, but sometimes follow biological pathways (e.g., nutrient transport from wetlands to coastal waters by migrating waterfowl, upstream transport of marine-derived nutrients by spawning of anadromous fish, uptake and removal of nutrients by emerging stream insects).
- Human activities alter naturally occurring gradients of physical, chemical, and biological connectivity by modifying the frequency, duration, magnitude, timing, and rate of change of fluxes, exchanges, and transformations. For example, connectivity can be reduced by dams, levees, culverts, water withdrawals, and habitat destruction, and can be increased by effluent discharges, channelization, drainage ditches and tiles, and impervious surfaces.

6.1.5 Conclusion 5: Cumulative Effects

The incremental effects of individual streams and wetlands are cumulative across entire watersheds and therefore must be evaluated in context with other streams and wetlands. Downstream waters are the time-integrated result of all waters contributing to them. For example, the amount of water or biomass contributed by a specific ephemeral stream in a given year might be small, but the aggregate contribution of that stream over multiple years, or by all ephemeral streams draining that watershed in a given year or over multiple years, can have substantial consequences on the integrity of the downstream waters. Similarly, the downstream effect of a single event, such as pollutant discharge into a single stream or wetland, might be negligible but the cumulative effect of multiple discharges could degrade the integrity of downstream waters.

In addition, when considering the effect of an individual stream or wetland, all contributions and functions of that stream or wetland should be evaluated cumulatively. For example, the same stream transports water, removes excess nutrients, mitigates flooding, and provides refuge for fish when conditions downstream are unfavorable; if any of these functions is ignored, the overall effect of that stream would be underestimated.

6.1.5.1 Conclusion 5, Key Findings

- Structurally and functionally, stream-channel networks and the watersheds they drain are fundamentally cumulative in how they are formed and maintained. Excess water from precipitation that is not evaporated, taken up by organisms, or stored in soils and geologic layers moves downgradient by gravity as overland flow or through channels carrying sediment, chemical constituents, and organisms. These channels concentrate surface-water flows and are more efficient than overland (i.e., diffuse) flows in transporting water and materials, and are reinforced over time by recurrent flows.
- Connectivity between streams and rivers provides opportunities for materials, including nutrients and chemical contaminants, to be transformed chemically as they are transported downstream. Although highly efficient at the transport of water and other physical materials, streams are dynamic ecosystems with permeable beds and banks that interact with other ecosystems above and below the surface. The exchange of materials between surface and subsurface areas involves a series of complex physical, chemical, and biological alterations that occur as materials move through different parts of the river system. The amount and quality of such materials that eventually reach a river are determined by the aggregate effect of these sequential alterations that begin at the source waters, which can be at some distance from the river. The opportunity for transformation of material (e.g., biological uptake, assimilation, or beneficial transformation) in intervening stream reaches increases with distance to the river. Nutrient spiraling, the process by which nutrients entering headwater streams are transformed by various aquatic organisms and chemical reactions as they are transported downstream, is one example of an instream alteration that exhibits significant beneficial effects on downstream waters. Nutrients (in their inorganic form) that enter a headwater stream (e.g., via overland flow) are first removed from the water column by streambed algal and microbial populations. Fish or insects feeding on algae and microbes take up some of those nutrients, which are subsequently released back into the stream via excretion and decomposition (i.e., in their organic form), and the cycle is repeated. In each phase of the cycling process—from dissolved inorganic nutrients in the water column, through microbial uptake, subsequent transformations through the food web, and back to dissolved nutrients in the water column—nutrients are subject to downstream transport. Stream and wetland capacities for nutrient cycling have important implications for the form and concentration of nutrients exported to downstream waters.
- Cumulative effects across a watershed must be considered when quantifying the frequency, duration, and magnitude of connectivity, to evaluate the downstream effects of streams and wetlands. For example, although the probability of a large-magnitude transfer of organisms from any given headwater stream in a given year might be low (i.e., a low-frequency connection when each stream is considered individually), headwater streams are the most abundant type of stream in most watersheds. Thus, the overall probability of a large-magnitude transfer of organisms is higher when considered for all headwater streams in a watershed—that is, a high-

frequency connection is present when headwaters are considered cumulatively at the watershed scale, compared with probabilities of transport for streams individually. Similarly, a single pollutant discharge might be negligible but the cumulative effect of multiple discharges could degrade the integrity of downstream waters. Riparian open waters (e.g., oxbow lakes), wetlands, and vegetated areas cumulatively can retain up to 90% of eroded clays, silts, and sands that otherwise would enter stream channels. The larger amounts of snowmelt and precipitation cumulatively held by many wetlands can reduce the potential for flooding at downstream locations. For example, wetlands in the prairie pothole region cumulatively stored about 11–20% of the precipitation in one watershed.

- The combination of diverse habitat types and abundant food resources cumulatively makes floodplains important foraging, hunting, and breeding sites for fish, aquatic life stages of amphibians, and aquatic invertebrates. The scale of these cumulative effects can be extensive; for example, coastal ibises travel up to 40 km to obtain food from freshwater floodplain wetlands for nesting chicks, which cannot tolerate salt levels in local food resources until they fledge.

6.2 Strength of Evidence for Conclusions and Data Gaps in the Available Literature

This report synthesizes a large body of scientific evidence to address the questions in Table 1-1 of this report. The major conclusions (Section 6.1) reflect the strength of evidence currently available in the peer-reviewed scientific literature for assessing the connectivity and downstream effects of water bodies identified in Table 1-1.

The conclusions of this report were corroborated by two independent peer reviews by scientists identified in the front matter of this report.

The term connectivity is defined in this report as the degree to which components of a watershed are joined and interact by transport mechanisms that function across multiple spatial and temporal scales (Sections 1.2.2 and 2.3.2.1). Our review found strong evidence supporting the central roles of the physical, chemical, and biological connectivity of streams, wetlands, and open waters—encompassing varying degrees of both connection and isolation—in maintaining the structure and function of downstream waters, including rivers, lakes, estuaries, and oceans. Our review also found strong evidence demonstrating the various mechanisms by which material and biological linkages from streams, wetlands, and open waters affect downstream waters, classified here into five functional categories (source, sink, refuge, lag, and transformation), modify the timing of transport and the quantity and quality of resources available to downstream ecosystems and communities. Thus, the currently available literature provided a large body of evidence for assessing the connections and functions by which streams and wetlands produce the range of observed effects on the integrity of downstream waters.

The body of literature on functions provided by streams and riparian/floodplain wetlands was abundant in all five categories (Table 6-1). The body of literature on functions of non-floodplain wetlands was abundant in two categories (sink and transformation) and moderate in the other three categories (source, refuge, and lag; Table 6-1). The evidence unequivocally demonstrates that the stream channels and wetlands or open waters that together form river networks are clearly connected to downstream waters in ways that profoundly influence downstream water integrity. The body of literature documenting connectivity and downstream effects was most abundant for perennial and intermittent streams, and for riparian/floodplain wetlands (Table 6-2). Although less abundant, the available evidence for connectivity and downstream effects of ephemeral streams was strong and compelling, particularly in context with the large body of evidence supporting the physical connectivity and cumulative effects of channelized flows that form and maintain stream networks.

As stated in Conclusion 3 (Section 6.1.3), the connectivity and effects of wetlands and open waters that are not structurally linked to other waters by stream channels and their lateral extensions into riparian areas and floodplains are more difficult to address solely from evidence available in peer-reviewed studies. One limitation was the relatively small number of published, peer-reviewed studies examining the relationships of non-floodplain wetlands to downstream waters (Table 6-2). The literature on non-floodplain wetlands that is available shows that these systems have important hydrologic, water-quality, and habitat functions that can affect downstream waters where connections to them exist; the literature also provides limited examples of direct effects of non-floodplain wetland isolation on downstream water integrity. Currently available peer-reviewed literature, however, does not identify which types of non-floodplain wetlands have or lack the types of connections needed to convey the effects on downstream waters of functions, materials, or biota provided by those wetlands. These limitations of the literature, considered in context with comments from the Science Advisory Board on an external review draft of this report (U.S. EPA, 2014), are reflected in the lower strength of evidence expressed in the conclusions (Section 6.1.3).

Additional information from other sources not included in this report (e.g., field assessments, analysis of existing or new data, reports from local resource agencies) could be used in case-by-case analysis of non-floodplain wetlands. Importantly, information from emerging research into the connectivity of non-floodplain wetlands, including studies of the types identified in Section 4.5.2 of this report, could close some of the current data gaps in the near future. Recent scientific advances in the fields of mapping (e.g., Heine et al., 2004; Tiner, 2011; Lang et al., 2012), assessment (e.g., McGlynn and McDonnell, 2003; Gergel, 2005; McGuire et al., 2005; Ver Hoef et al., 2006; Leibowitz et al., 2008; Moreno-Mateos et al., 2008; Lane and D'Amico, 2010; Ver Hoef and Peterson, 2010; Shook and Pomeroy, 2011; Powers et al., 2012; McDonough et al., 2015), modeling (e.g., Golden et al., 2013; McLaughlin et al., 2014), and landscape classification (e.g., Wigington et al., 2013) indicate that increasing availability of high-resolution data sets, promising new technologies for watershed-scale analyses, and methods for classifying landscape units by hydrologic behavior can facilitate and improve the accuracy of connectivity assessments. Emerging research that expands our ability to detect and monitor ecologically relevant connections at appropriate scales, metrics to accurately measure effects on downstream integrity, and management practices that apply what we already know about ecosystem function, will contribute to our ability to identify waters of national importance and maintain the long-term sustainability and resiliency of valued water resources.

Table 6-1. Relative abundance of literature by functional category. The table shows our confidence, which is based on the relative size of the body of literature documented in the report, in the evidence for source, sink, refuge, lag, and transformation functions of streams and wetlands and their associated effects on downstream waters. A small dot (•) indicates relatively lower confidence, a medium dot (●) indicates relatively intermediate confidence, and a large dot (⬤) indicates a relatively high level of confidence. The dot size does not necessarily correspond with the number of associated citations in this report because some citations are review articles or meta-analyses, which summarize information for many references. The dot size also does not correspond with the level of confidence in particular conclusions.

Type of water body	Function					Uncertainty discussion (Section)
	Source	Sink (Storage)	Refuge	Lag	Transformation	
Streams	Large dot	Large dot	Large dot	Large dot	Large dot	3.6
Riparian/floodplain wetlands	Large dot	Large dot	Large dot	Large dot	Large dot	4.5.1
Non-floodplain wetlands	Medium dot	Large dot	Medium dot	Medium dot	Large dot	4.5.2

Table 6-2. Relative abundance of literature by review topic area. The table shows the relative size of the body of literature documented in the report that addresses the physical, chemical, or biological connectivity to and effects on downstream waters. A small dot (•) indicates a relatively smaller body of literature, a medium dot (●) indicates a relatively intermediate body of literature, and a large dot (⬤) indicates a relatively large body of literature. The dot size does not necessarily correspond with the number of associated citations in this report because some citations are review articles or meta-analyses, which summarize information from many references. The dot size also does not correspond with level of confidence in particular conclusions.

Topic	Question		Biological		Chemical		Physical	
			Connection	Effect	Connection	Effect	Connection	Effect
Streams	What are the physical, chemical, and biological connections to and effects of ephemeral, intermittent, and perennial streams on downstream waters?	ephemeral	[medium dot]	[small dot]	[large dot]	[medium dot]	[large dot]	[medium dot]
		intermittent	[large dot]	[medium dot]	[large dot]	[medium dot]	[large dot]	[medium dot]
		perennial	[large dot]	[large dot]	[large dot]	[large dot]	[large dot]	[large dot]
Riparian/ Floodplain Wetlands	What are the physical, chemical, and biological connections to and effects of riparian or floodplain wetlands and open waters (e.g., riverine wetlands, oxbow lakes) on downstream waters?		[large dot]	[large dot]	[large dot]	[large dot]	[large dot]	[large dot]
Non-floodplain wetlands	What are the physical, chemical, and biological connections to and effects of wetlands and open waters in non-floodplain settings (e.g., most prairie potholes, vernal pools) on downstream waters?		[medium dot]	[small dot]	[medium dot]	[small dot]	[small dot]	[small dot]

CHAPTER 7. REFERENCES

Aastrup, M., J. Johnson, E. Bringmark, L. Bringmark, and A. Iverfeldt. 1991. Occurrence and transport of mercury within a small catchment area. Water, Air, and Soil Pollution **56**:155-167.

Abbe, T. E., and D. R. Montgomery. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers: Research & Management **12**:201-221.

Abbott, M. D., A. Lini, and P. R. Bierman. 2000. ^{18}O, D, and ^{3}H measurements constrain groundwater recharge patterns in an upland fractured bedrock aquifer, Vermont, USA. Journal of Hydrology **228**:101-112.

Abdelnour, A., R. B. McKane, M. Stieglitz, F. Pan, and Y. Cheng. 2013. Effects of harvest on carbon and nitrogen dynamics in a Pacific Northwest forest catchment. Water Resources Research **49**:1292-1313.

Acreman, M., and J. Holden. 2013. How wetlands affect floods. Wetlands **33**:773-786.

Acuña, V., I. Muñoz, A. Giorgi, M. Omella, F. Sabater, and S. Sabater. 2005. Drought and postdrought recovery cycles in an intermittent Mediterranean stream: Structural and functional aspects. Journal of the North American Benthological Society **24**:919-933.

Adair, E. C., D. Binkley, and D. C. Andersen. 2004. Patterns of nitrogen accumulation and cycling in riparian floodplain ecosystems along the Green and Yampa rivers. Oecologia **139**:108-116.

Adair, S. E., J. L. Moore, and W. H. Kiel. 1996. Wintering diving duck use of coastal ponds: An analysis of alternative hypotheses. The Journal of Wildlife Management **60**:83-93.

Adams, S. B., D. A. Schmetterling, and M. K. Young. 2005. Instream movements by boreal toads (*Bufo boreas boreas*). Herpetological Review **36**:27–33.

Ademollo, N., S. Capri, L. Patrolecco, A. Puddu, S. Polesello, M. Rusconi, S. Valsecchi, and J. Froebrich. 2011. Fate and monitoring of hazardous substances in temporary rivers. Trends in Analytical Chemistry **30**:1222-1232.

Ågren, A., I. Buffam, M. Jansson, and H. Laudon. 2007. Importance of seasonality and small streams for the landscape regulation of dissolved organic carbon export. Journal of Geophysical Research: Biogeosciences **112**:G03003.

Alexander, L. C., D. J. Hawthorne, M. A. Palmer, and W. O. Lamp. 2011. Loss of genetic diversity in the North American mayfly *Ephemerella invaria* associated with deforestation of headwater streams. Freshwater Biology **56**:1456-1467.

Alexander, R., J. Böhlke, E. Boyer, M. David, J. Harvey, P. Mulholland, S. Seitzinger, C. Tobias, C. Tonitto, and W. Wollheim. 2009. Dynamic modeling of nitrogen losses in river networks unravels the coupled effects of hydrological and biogeochemical processes. Biogeochemistry **93**:91-116.

Alexander, R. B., E. W. Boyer, R. A. Smith, G. E. Schwarz, and R. B. Moore. 2007. The role of headwater streams in downstream water quality. Journal of the American Water Resources Association **43**:41-59.

Alexander, R. B., R. A. Smith, and G. E. Schwarz. 2000. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. Nature **403**:758-761.

Alford, J. D., and M. R. Walker. 2013. Managing the flood pulse for optimal fisheries production in the Atchafalaya River basin, Louisiana (USA). River Research and Applications **29**:279-296.

Ali, G. A., and A. G. Roy. 2010. Shopping for hydrologically representative connectivity metrics in a humid temperate forested catchment. Water Resources Research **46**:W12544.

Allan, J. D. 1995. Stream ecology – Structure and function of running waters. Chapman & Hall, New York, NY.

Allen, M. R. 2007. Measuring and modeling dispersal of adult zooplankton. Oecologia **153**:135-143.

Amezaga, J. M., L. Santamaria, and A. J. Green. 2002. Biotic wetland connectivity—supporting a new approach for wetland policy. Acta Oecologica **23**:213-222.

Amoros, C., and G. Bornette. 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshwater Biology **47**:761-776.

Anderson, C. D., B. K. Epperson, M. J. Fortin, R. Holderegger, P. M. A. James, M. S. Rosenberg, K. T. Scribner, and S. Spear. 2010. Considering spatial and temporal scale in landscape-genetic studies of gene flow. Molecular Ecology **19**:3565-3575.

Anderson, N. H., and J. R. Sedell. 1979. Detritus processing by macroinvertebrates in stream ecosystems. Annual Review of Entomology **24**:351-377.

Angeler, D. G., M. Alvarez-Cobelas, C. Rojo, and S. Sanchez-Carrillo. 2010. Phytoplankton community similarity in a semiarid floodplain under contrasting hydrological connectivity regimes. Ecological Research **25**:513-520.

Anteau, M. J., M. H. Sherfy, and A. A. Bishop. 2011. Location and agricultural practices influence spring use of harvested cornfields by cranes and geese in Nebraska. The Journal of Wildlife Management **75**:1004-1011.

Arce, M. I., M. d. M. Sánchez-Montoya, M. R. Vidal-Abarca, M. L. Suárez, and R. Gómez. 2014. Implications of flow intermittency on sediment nitrogen availability and processing rates in a Mediterranean headwater stream. Aquatic Sciences **76**:173-186.

Armsworth, P. R., and J. E. Roughgarden. 2005. The impact of directed versus random movement on population dynamics and biodiversity patterns. The American Naturalist **165**:449-465.

Arndt, J. L., and J. L. Richardson. 1989. Geochemistry of hydric soil salinity in a recharge-throughflow-discharge prairie-pothole wetland system. Soil Science Society of America Journal **53**:848-855.

Arrigoni, A. S., G. C. Poole, L. A. K. Mertes, S. J. O'Daniel, W. W. Woessner, and S. A. Thomas. 2008. Buffered, lagged, or cooled? Disentangling hyporheic influences on temperature cycles in stream channels. Water Resources Research **44**:W09418.

Arscott, D. B., K. Tockner, and J. V. Ward. 2001. Thermal heterogeneity along a braided floodplain river (Tagliamento River, northeastern Italy). Canadian Journal of Fisheries and Aquatic Sciences **58**:2359-2373.

Ashworth, A. C. 1999. Climate change in North Dakota since the last glaciation—review of the paleontological record. Proceedings of the North Dakota Academy of Science **53**:171-176.

Atkinson, E. 1995. Methods for assessing sediment delivery in river systems. Hydrological Sciences Journal **40**:273-280.

Attum, O., Y. M. Lee, J. H. Roe, and B. A. Kingsbury. 2007. Upland–wetland linkages: Relationship of upland and wetland characteristics with watersnake abundance. Journal of Zoology **271**:134-139.

Augspurger, C., G. Gleixner, C. Kramer, and K. Kusel. 2008. Tracking carbon flow in a 2-week-old and 6-week-old stream biofilm food web. Limnology and Oceanography **53**:642-650.

Austin, J., and A. Richert. 2005. Patterns of habitat use by whooping cranes during migration: Summary from 1977-1999 site evaluation data. Proceedings North American Crane Workshop **9**:79-107.

Axtmann, E. V., and S. N. Luoma. 1991. Large-scale distribution of metal contamination in the fine-grained sediments of the Clark Fork River, Montana, USA. Applied Geochemistry **6**:75-88.

Babbitt, K. J., M. J. Baber, and T. L. Tarr. 2003. Patterns of larval amphibian distribution along a wetland hydroperiod gradient. Canadian Journal of Zoology **81**:1539-1552.

Babbitt, K. J., and G. W. Tanner. 2000. Use of temporary wetlands by anurans in a hydrologically modified landscape. Wetlands **20**:313–322.

Baber, M. J., D. L. Childers, K. J. Babbitt, and D. H. Anderson. 2002. Controls on fish distribution and abundance in temporary wetlands. Canadian Journal of Fisheries and Aquatic Sciences **59**:1441-1450.

Bailey Boomer, K. M., and B. L. Bedford. 2008. Influence of nested groundwater systems on reduction-oxidation and alkalinity gradients with implications for plant nutrient availability in four New York fens. Journal of Hydrology **351**:107-125.

Baillie, M., J. F. Hogan, B. Ekwurzel, A. K. Wahi, and C. J. Eastoe. 2007. Quantifying water sources to a semiarid riparian ecosystem, San Pedro River, Arizona. Journal of Geophysical Research: Biogeosciences **112**:G03S02.

Baldwin, D. S., and A. M. Mitchell. 2000. The effects of drying and re-flooding on the sediment and soil nutrient dynamics of lowland river-floodplain systems: A synthesis. Regulated Rivers: Research & Management **16**:457-467.

Ballard, B., J. Dale James, R. Bingham, M. Petrie, and B. Wilson. 2010. Coastal pond use by redheads wintering in the Laguna Madre, Texas. Wetlands **30**:669-674.

Banks, E. W., C. T. Simmons, A. J. Love, and P. Shand. 2011. Assessing spatial and temporal connectivity between surface water and groundwater in a regional catchment: Implications for regional scale water quantity and quality. Journal of Hydrology **404**:30-49.

Barling, R. D., I. D. Moore, and R. B. Grayson. 1994. A quasi-dynamic wetness index for characterizing the spatial distribution of zones of surface saturation and soil water content. Water Resources Research **30**:1029-1044.

Bärlocher, F., R. J. Mackay, and G. B. Wiggins. 1978. Detritus processing in a temporary vernal pool in southern Ontario. Archiv für Hydrobiologie **81**:269–295.

Baron, J. S., N. L. Poff, P. L. Angermeier, C. N. Dahm, P. H. Gleick, N. G. Hairston, R. B. Jackson, C. A. Johnston, B. D. Richter, and A. D. Steinman. 2002. Meeting ecological and societal needs for freshwater. Ecological Applications **12**:1247-1260.

Barrat-Segretain, M. H. 1996. Strategies of reproduction, dispersion, and competition in river plants: A review. Vegetatio **123**:13-37.

Barton, D. R., W. D. Taylor, and R. M. Biette. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. North American Fisheries Management **5**:364-378.

Battin, T. J., L. A. Kaplan, S. Findlay, C. S. Hopkinson, E. Marti, A. I. Packman, J. D. Newbold, and F. Sabater. 2009. Biophysical controls on organic carbon fluxes in fluvial networks. Nature Geoscience **1**:95-100.

Battin, T. J., and D. Sengschmitt. 1999. Linking sediment biofilms, hydrodynamics, and river bed clogging: Evidence from a large river. Microbial Ecology **37**:185-196.

Baxter, C. V., K. D. Fausch, M. Murakami, and P. L. Chapman. 2004. Fish invasion restructures stream and forest food webs by interrupting reciprocal prey subsidies. Ecology **85**:2656-2663.

Baxter, C. V., and F. R. Hauer. 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*). Canadian Journal of Fisheries and Aquatic Sciences **57**:1470-1481.

Bayless, M. A., M. G. McManus, and J. F. Fairchild. 2003. Geomorphic, water quality and fish community patterns associated with the distribution of *Notropis topeka* in a Central Missouri watershed. American Midland Naturalist **150**:58-72.

Bedford, B. L., and K. S. Godwin. 2003. Fens of the United States: Distribution, characteristics, and scientific connection versus legal isolation. Wetlands **23**:608-629.

Beeson, C. E., and P. F. Doyle. 1995. Comparison of bank erosion at vegetated and non-vegetated channel bends. Journal of the American Water Resources Association **31**:983-990.

Bencala, K. E. 1993. A perspective on stream-catchment connections. Journal of the North American Benthological Society **12**:44-47.

Bencala, K. E. 2005. Hyporheic exchange flows. Pages 1733-1740 *in* Encyclopedia of hydrological sciences. M. G. Anderson, editor. John Wiley and Son, Ltd., New York, NY.

Bencala, K. E. 2011. Stream-groundwater interactions. Pages 537-546 *in* Treatise on water science. P. Wilderer, editor. Academic Press, Oxford, UK.

Bencala, K. E., M. N. Gooseff, and B. A. Kimball. 2011. Rethinking hyporheic flow and transient storage to advance understanding of stream-catchment connections. Water Resources Research **47**:W00H03.

Benda, L. 2008. Confluence environments at the scale of river networks. Pages 271-300 *in* River confluences, tributaries and the fluvial network. S. P. Rice, A. G. Roy, and B. L. Rhoads, editors. John Wiley & Sons, Chichester, UK.

Benda, L., and T. Dunne. 1987. Sediment routing by debris flow. Pages 213-223 *in* Erosion and sedimentation in the Pacific Rim. IAHS Publication 165. R. L. Beschta, T. Blinn, G. E. Grant, F. J. Swanson, and G. G. Ice, editors. International Association for Hydrological Science, Wallingfor, UK.

Benda, L., M. A. Hassan, M. Church, and C. L. May. 2005. Geomorphology of steepland headwaters: The transition from hillslopes to channels. Journal of the American Water Resources Association **41**:835-851.

Benda, L., N. L. Poff, D. Miller, T. Dunne, G. Reeves, G. Pess, and M. Pollock. 2004. The network dynamics hypothesis: How channel networks structure riverine habitats. BioScience **54**:413-427.

Benda, L. E., and T. W. Cundy. 1990. Predicting deposition of debris flows in mountain channels. Canadian Geotechnical Journal **27**:409-417.

Benda, L. E., D. J. Miller, T. Dunne, G. H. Reeves, and J. K. Agee. 1998. Dynamic landscape systems. Pages 261-288 *in* River ecology and management: Lessons from the Pacific coastal ecoregion. R. J. Naiman and R. E. Bilby, editors. Springer-Verlag, New York, NY.

Benfield, E. F. 1997. Comparison of litterfall input to streams. Journal of the North American Benthological Society **16**:104-108.

Benke, A. C., I. Chaubey, G. M. Ward, and E. L. Dunn. 2000. Flood pulse dynamics of an unregulated river floodplain in the southeastern US coastal plain. Ecology **81**:2730-2741.

Bennett, M. G., K. A. Fritz, A. Hayden-Lesmeister, J. P. Kozak, and A. Nickolotsky. 2015. An estimate of basin-wide denitrification based on floodplain inundation in the Atchafalaya River basin, Louisiana. River Research and Applications: doi: 10.1002/rra.2854.

Benoit, P., E. Barriuso, P. Vidon, and B. Réal. 1999. Isoproturon sorption and degradation in a soil from grassed buffer strip. Journal of Environmental Quality **28**:121-129.

Benstead, J. P., and D. S. Leigh. 2012. An expanded role for river networks. Nature Geoscience **5**:678-679.

Bergsten, A., and A. Zetterberg. 2013. To model the landscape as a network: A practitioner's perspective. Landscape and Urban Planning **119**:35-43.

Bernhardt, E. S., R. O. Hall, and G. E. Likens. 2002. Whole-system estimates of nitrification and nitrate uptake in streams of the Hubbard Brook Experimental Forest. Ecosystems **5**:419-430.

Beschta, R. L., R. E. Bilby, G. W. Brown, L. B. Holtby, and T. D. Hofstra. 1987. Stream temperature and aquatic habitat: Fisheries and forestry interactions. Pages 191-232 *in* Streamside management: Forestry and fishery interactions. E. O. Salo and T. W. Cundy, editors. College of Forest Resources, University of Washington, Seattle, WA, USA.

Beschta, R. L., and W. J. Ripple. 2012. The role of large predators in maintaining riparian plant communities and river morphology. Geomorphology **157**:88-98.

Best, J. L. 1988. Sediment transport and bed morphology at river channel confluences. Sedimentology **35**:481-498.

Bestgen, A. C., I. Chaubey, G. M. Ward, and L. Dunn. 2000. Flood pulse dynamics of an unregulated river floodplain in the southeastern U.S. Coastal Plain. Ecology **81**:2730-2741.

Beven, K., and P. Germann. 1982. Macropores and water flow in soils. Water Resources Research **18**:1311-1325.

Beven, K. J., and M. J. Kirkby. 1979. A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin **24**:43-69.

Bhadha, J., J. Jawitz, and J.-H. Min. 2011. Phosphorus mass balance and internal load in an impacted subtropical isolated wetland. Water, Air, & Soil Pollution **218**:619-632.

Bigelow, P. E., L. E. Benda, D. J. Miller, and K. M. Burnett. 2007. On debris flows, river networks, and the spatial structure of channel morphology. Forest Science **53**:220-238.

Bilby, R. A., and G. E. Likens. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology **61**:1107-1113.

Bilby, R. A., and J. W. Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Transactions of the American Fisheries Society **118**:368-378.

Bilby, R. E., and P. A. Bisson. 1998. Function and distribution of large woody debris. Pages 324-346 *in* River ecology and management: Lessons from the Pacific coastal ecoregion. R. J. Naiman and R. E. Bilby, editors. Springer-Verlag, New York, NY.

Bischel, H. N., J. E. Lawrence, B. J. Halaburka, M. H. Plumlee, A. S. Bawazir, J. P. King, J. E. McCray, V. H. Resh, and R. G. Luthy. 2013. Renewing urban streams with recycled water for streamflow augmentation: Hydrologic, water quality, and ecosystem services management. Environmental Engineering Science **30**:455-479.

Blanchong, J. A., M. D. Samuel, and G. Mack. 2006. Multi-species patterns of avian cholera mortality in Nebraska's Rainwater Basin. Journal of Wildlife Diseases **42**:81-91.

Blann, K., J. F. Nerbonne, and B. Vondracek. 2002. Relationship of riparian buffer type to water temperature in the driftless area ecoregion of Minnesota. North American Journal of Fisheries Management **22**:441-451.

Blann, K. L., J. L. Anderson, G. R. Sands, and B. Vondracek. 2009. Effects of agricultural drainage on aquatic ecosystems: A review. Critical Reviews in Environmental Science and Technology **39**:909-1001.

Bodamer, B. L., and J. M. Bossenbroek. 2008. Wetlands as barriers: Effects of vegetated waterways on downstream dispersal of zebra mussels. Freshwater Biology **53**:2051-2060.

Boelter, D., and E. S. Verry. 1977. Peatland and water in the northern lake states. General Technical Report NC-31, U.S. Department of Agriculture, U.S. Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Bogan, M. T., and K. S. Boersma. 2012. Aerial dispersal of aquatic invertebrates along and away from arid-land streams. Freshwater Science **31**:1131-1144.

Bogan, M. T., and D. A. Lytle. 2007. Seasonal flow variation allows 'time-sharing' by disparate aquatic insect communities in montane desert streams. Freshwater Biology **52**:290-304.

Böhlke, J., R. Antweiler, J. Harvey, A. Laursen, L. Smith, R. Smith, and M. Voytek. 2009. Multi-scale measurements and modeling of denitrification in streams with varying flow and nitrate concentration in the upper Mississippi River basin, USA. Biogeochemistry **93**:117-141.

Bohonak, A. J., and D. G. Jenkins. 2003. Ecological and evolutionary significance of dispersal by freshwater invertebrates. Ecology Letters **6**:783-796.

Boltz, J. M., and R. R. J. Stauffer. 1989. Fish assemblages of Pennsylvania wetlands. Pages 158-170 *in* Wetland ecology and conservation: Emphasis in Pennsylvania. S. K. Majumdar, editor. The Pennslyvania Academy of Sciences, Lafayette College, Easton, PA.

Boon, P. I. 1991. Bacterial assemblages in rivers and billabongs of southeastern Australia. Microbial Ecology **22**:27-52.

Boon, P. I. 2006. Biogeochemistry and bacterial ecology of hydrologically dynamic wetlands. Pages 115-176 *in* Ecology of freshwater and estuarine wetlands. D. P. Batzer and R. R. Sharitz, editors. University of California Press, Berkeley, CA.

Booth, D. B. 1990. Stream-channel incision following drainage-basin urbanization. Journal of the American Water Resources Association **26**:407-417.

Booth, D. B., D. Hartley, and R. Jackson. 2002. Forest cover, impervious-surface area, and the mitigation of stormwater impacts. Journal of the American Water Resources Association **38**:835-845.

Bormann, F. H., and G. E. Likens. 1979. Catastrophic disturbance and the steady-state in northern hardwood forests. American Scientist **67**:660-669.

Born, S. M., S. A. Smith, and D. A. Stephenson. 1979. Hydrogeology of glacial-terrain lakes, with management and planning applications. Journal of Hydrology **43**:7-43.

Borselli, L., P. Cassi, and D. Torri. 2008. Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. CATENA **75**:268-277.

Boschilia, S. M., E. F. Oliveira, and S. M. Thomaz. 2008. Do aquatic macrophytes co-occur randomly? An analysis of null models in a tropical floodplain. Oecologia **156**:203-214.

Boss, S. M., and J. S. Richardson. 2002. Effects of food and cover on the growth, survival, and movement of cutthroat trout (*Oncorhynchus clarki*) in coastal streams. Canadian Journal of Fisheries and Aquatic Sciences **59**:1044-1053.

Boto, K. G., and W. H. Patrick. 1979. Role of wetlands in the removal of suspended sediments. Pages 479-489 *in* Wetland functions and values: The state of our understanding. Proceedings of National Symposium on Wetlands. P. E. Greeson, J. R. Clark, and J. E. Clark, editors. American Water Resources Association, Minneapolis, MN.

Boudell, J. A., and J. C. Stromberg. 2008. Flood pulsing and metacommunity dynamics in a desert riparian ecosystem. Journal of Vegetation Science **19**:373-380.

Boulton, A. 2000. The subsurface macrofauna. Pages 337-361 *in* Streams and Ground Waters. J. B. Jones and P. J. Mulholland, editors. Academic Press, San Diego, CA.

Boulton, A. J., S. Findlay, P. Marmonier, E. H. Stanley, and H. M. Valett. 1998. The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecology and Systematics **29**:59-81.

Bracken, L. J., and J. Croke. 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrological Processes **21**:1749-1763.

Bracken, L. J., J. Wainwright, G. A. Ali, D. Tetzlaff, M. W. Smith, S. M. Reaney, and A. G. Roy. 2013. Concepts of hydrological connectivity: Research approaches, pathways and future agendas. Earth-Science Reviews **119**:17-34.

Bradford, M. J., J. A. Grout, and S. Moodie. 2001. Ecology of juvenile Chinook salmon in a small non-natal stream of the Yukon River drainage and the role of ice conditions on their distribution and survival. Canadian Journal of Zoology **79**:2043-2054.

Brahana, J. V., and E. F. Hollyday. 1988. Dry stream reaches in carbonate terranes: Surface indicators of ground-water reservoirs. Water Resources Bulletin **24**:577-580.

Bramblett, R. G., M. D. Bryant, B. E. Wright, and R. G. White. 2002. Seasonal use of small tributary and main-stem habitats by juvenile steelhead, coho salmon, and Dolly Varden in a southeastern Alaska drainage basin. Transactions of the American Fisheries Society **131**:498-506.

Branfireun, B. 2004. Does microtopography influence subsurface pore-water chemistry? Implications for the study of methylmercury in peatlands. Wetlands **24**:207-211.

Branfireun, B., N. Roulet, C. Kelly, and J. Rudd. 1999. In situ sulphate stimulation of mercury methylation in a boreal peatland: Toward a link between acid rain and methylmercury contamination in remote environments. Global Biogeochemical Cycles **13**:743-750.

Branfireun, B. A., A. Heyes, and N. T. Roulet. 1996. The hydrology and methylmercury dynamics of a Precambrian shield headwater peatland. Water Resources Research **32**:1785-1794.

Branfireun, B. A., and N. T. Roulet. 1998. The baseflow and storm flow hydrology of a Precambrian shield headwater peatland. Hydrological Processes **12**:57-72.

Branfireun, B. A., and N. T. Roulet. 2002. The boreal catchment hydrological cascade: Controls on the fate and transport of methylmercury. Hydrology and Earth System Sciences **6**:785-794.

Brinson, M. M. 1993. A hydrogeomorphic classification for wetlands. Technical Report WRP-DE-4, U.S. Army Corps of Engineers, Waterways Experiment Station, Wetlands Research Program, Vicksburg, MS.

Brittain, J. E., and T. J. Eikeland. 1988. Invertebrate drift: A review. Hydrobiologia **166**:77-93.

Brooks, B. W., T. M. Riley, and R. D. Taylor. 2006. Water quality of effluent-dominated ecosystems: Ecotoxicological, hydrological, and management considerations. Hydrobiologia **556**:365-379.

Brooks, P. D., P. A. Haas, and A. K. Huth. 2007. Seasonal variability in the concentration and flux of organic matter and inorganic nitrogen in a semiarid catchment, San Pedro River, Arizona. Journal of Geophysical Research: Biogeosciences **112**:G03S04.

Brooks, P. D., and M. M. Lemon. 2007. Spatial variability in dissolved organic matter and inorganic nitrogen concentrations in a semiarid stream, San Pedro River, Arizona. Journal of Geophysical Research: Biogeosciences **112**:G03S05.

Brooks, R. J., P. J. Wigington, D. L. Phillips, R. Comeleo, and R. Coulombe. 2012. Willamette River basin surface water isoscape ($\delta^{18}O$ and $\delta^{2}H$): Temporal changes of source water within the river. Ecosphere **3**:39.

Brooks, R. P., and T. L. Serfass. 2013. Wetland-riparian wildlife of the Mid-Atlantic Region: An overview. Pages 259-268 *in* Mid-Atlantic freshwater wetlands: Advances in wetlands science, management, policy, and practice. R. P. Brooks and D. H. Wardrop, editors. Springer, New York, NY.

Brooks, R. R., J. A. McCleave, and E. K. Schofield. 1977. Cobalt and nickel uptake by the Nyssaceae. Taxon **26**:197-201.

Brooks, R. T., and E. A. Colburn. 2011. Extent and channel morphology of unmapped headwater stream segments of the Quabbin watershed, Massachusetts. Journal of the American Water Resources Association **47**:158-168.

Brosofske, K. D., J. Q. Chen, R. J. Naiman, and J. F. Franklin. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. Ecological Applications **7**:1188-1200.

Brown, J. H., and A. Kodric-Brown. 1977. Turnover rates in insular biogeography: Effect of immigration on extinction. Ecology **58**:445-449.

Brown, T. G., and G. F. Hartman. 1988. Contribution of seasonally flooded lands and minor tributaries to the production of coho salmon in Carnation Creek, British Columbia. Transactions of the American Fisheries Society **117**:546-551.

Brummer, C. J., T. B. Abbe, J. R. Sampson, and D. R. Montgomery. 2006. Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA. Geomorphology **80**:295-309.

Brunet, N. N., and C. J. Westbrook. 2012. Wetland drainage in the Canadian prairies: Nutrient, salt and bacteria characteristics. Agriculture, Ecosystems & Environment **146**:1-12.

Brunke, M., and T. O. M. Gonser. 1997. The ecological significance of exchange processes between rivers and groundwater. Freshwater Biology **37**:1-33.

Buffington, J. M., and D. Tonina. 2009. Hyporheic exchange in mountain rivers II: Effects of channel morphology on mechanics, scales, and rates of exchange. Geography Compass **3**:1038-1062.

Bukaveckas, P. A. 2009. Rivers. Pages 721-732 *in* Encyclopedia of inland waters. G. E. Likens, editor. Elsevier, Oxford, UK.

Bull, W. B. 1991. Geomorphic responses to climate change. Oxford University Press, New York, NY.

Bull, W. B., and K. M. Scott. 1974. Impact of mining gravel from urban stream beds in the southwestern United States. Geology **2**:171-174.

Bullock, A., and M. Acreman. 2003. The role of wetlands in the hydrological cycle. Hydrology and Earth System Sciences **7**:358-389.

Bunn, S. E., and A. H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management **30**:492-507.

Bunn, S. E., M. C. Thoms, S. K. Hamilton, and S. J. Capon. 2006. Flow variability in dryland rivers: Boom, bust and the bits in between. River Research and Applications **22**:179-186.

Burchsted, D., M. Daniels, R. Thorson, and J. Vokoun. 2010. The river discontinuum: Applying beaver modifications to baseline conditions for restoration of forested headwaters. BioScience **60**:908-922.

Burkart, M. R., W. W. Simpkins, P. J. Squillace, and M. Helmke. 1999. Tributary stream infiltration as a source of herbicides in an alluvial aquifer. Journal of Environmental Quality **28**:69-74.

Burkholder, B. K., G. E. Grant, R. Haggerty, T. Khangaonkar, and P. J. Wampler. 2008. Influence of hyporheic flow and geomorphology on temperature of a large, gravel-bed river, Clackamas River, Oregon, USA. Hydrological Processes **22**:941-953.

Burns, D. A. 1996. The effects of liming an Adirondack lake watershed on downstream water chemistry. Biogeochemistry **32**:339-362.

Burt, T. P. 1997. The hydrological role of buffer zones within the drainage basin system. Pages 21-32 *in* Buffer zones: Their processes and potential in water protection. Proceedings of the International Conference on Buffer Zones, September 1996. N. E. Haycock, T. P. Burt, K. W. T. Goulding, and G. Pinay, editors. Quest Environmental, Hertfordshire, UK.

Burt, T. P., G. Pinay, F. E. Matheson, N. E. Haycock, A. Butturini, J.-C. Clement, S. Danielescu, D. J. Dowrick, M. M. Hefting, A. Hillbricht-Ilkowska, and V. Maitre. 2002. Water table fluctuations in the riparian zone: Comparative results from a pan-European experiment. Journal of Hydrology **265**:129-148.

Butterfield, B. P. 2005. *Rana sphenocephala*, Southern leopard frog. Pages 586-587 *in* Amphibian declines: The conservation status of United States species. M. Lannoo, editor. University of California Press, Berkeley, CA.

Buttle, J. 2006. Mapping first-order controls on streamflow from drainage basins: The T3 template. Hydrological Processes **20**:3415-3422.

Cairns, M. A., J. L. Ebersole, J. P. Baker, and P. J. Wigington. 2005. Influence of summer stream temperatures on black spot infestation of juvenile coho salmon in the Oregon Coast Range. Transactions of the American Fisheries Society **134**:1471-1479.

Caissie, D. 2006. The thermal regime of rivers: A review. Freshwater Biology **51**:1389-1406.

Calabrese, J. M., and W. F. Fagan. 2004. A comparison-shopper's guide to connectivity metrics. Frontiers in Ecology and the Environment **2**:529-536.

Callahan, M. K., M. C. Rains, J. C. Bellino, C. M. Walker, S. J. Baird, D. F. Whigham, and R. S. King. 2015. Controls on temperature in salmonid-bearing headwater streams in two common hydrogeologic settings, Kenai Peninsula, Alaska. Journal of the American Water Resources Association: doi: 10.1111/jawr.12235.

Cantone, J., and A. Schmidt. 2011. Dispersion mechanisms and the effect of parameter uncertainty on hydrologic response in urban catchments. Water Resources Research **47**:W05503.

Capers, R. S., R. Selsky, and G. J. Bugbee. 2010. The relative importance of local conditions and regional processes in structuring aquatic plant communities. Freshwater Biology **55**:952-966.

Carey, R., and K. Migliaccio. 2009. Contribution of wastewater treatment plant effluents to nutrient dynamics in aquatic systems: A review. Environmental Management **44**:205-217.

Carlyle, G. C., and A. R. Hill. 2001. Groundwater phosphate dynamics in a river riparian zone: Effects of hydrologic flowpaths, lithology, and redox chemistry. Journal of Hydrology **247**:151-168.

Caruso, B. S., and J. Haynes. 2011. Biophysical-regulatory classification and profiling of streams across management units and ecoregions. Journal of the American Water Resources Association **47**:386-407.

Castro, N. M., and G. M. Hornberger. 1991. Surface-surface water interactions in an alluviated mountain stream channel. Water Resources Research **27**:1613-1621.

Cayan, D. R., and D. H. Peterson. 1989. The influence of North Pacific atmospheric circulation on streamflow in the West. Geophysical Monographs **55**:375-397.

Chacon, N., N. Dezzeo, M. Rangel, and S. Flores. 2008. Seasonal changes in soil phosphorus dynamics and root mass along a flooded tropical forest gradient in the lower Orinoco River, Venezuela. Biogeochemistry **87**:157-168.

Chahinian, N., C. Bancon-Montigny, A. Caro, P. Got, J. L. Perrin, D. Rosain, C. Rodier, B. Picot, and M. G. Tournoud. 2012. The role of river sediments in contamination storage downstream of a waste water treatment plant in low flow conditions: Organotins, faecal indicator bacteria and nutrients. Estuarine, Coastal and Shelf Science **114**:70-81.

Chapra, S. C. 1996. Surface water quality modeling. McGraw-Hill, New York, NY.

Chaput-Bardy, A., C. Fleurant, C. Lemaire, and J. Secondi. 2009. Modelling the effect of in-stream and overland dispersal on gene flow in river networks. Ecological Modelling **220**:3589-3598.

Chartin, C., O. Evrard, Y. Onda, J. Patin, I. Lefèvre, C. Ottlé, S. Ayrault, H. Lepage, and P. Bonté. 2013. Tracking the early dispersion of contaminated sediment along rivers draining the Fukushima radioactive pollution plume. Anthropocene **1**:23-34.

Chase, E., J. Hunting, C. Staley, and V. J. Harwood. 2012. Microbial source tracking to identify human and ruminant sources of faecal pollution in an ephemeral Florida river. Journal of Applied Microbiology **113**:1396-1406.

Cheesman, A. W., E. J. Dunne, B. L. Turner, and K. R. Reddy. 2010. Soil phosphorus forms in hydrologically isolated wetlands and surrounding pasture uplands. Journal of Environmental Quality **39**:1517-1525.

Chen, X., and X. Chen. 2003. Stream water infiltration, bank storage, and storage zone changes due to stream-stage fluctuations. Journal of Hydrology **280**:246-264.

Cheng, J. D. 1988. Subsurface stormflows in the highly permeable forested watersheds of southwestern British Columbia. Journal of Contaminant Hydrology **3**:171-191.

Chick, J. H., R. J. Cosgriff, and L. S. Gittinger. 2003. Fish as potential dispersal agents for floodplain plants: First evidence in North America. Canadian Journal of Fisheries and Aquatic Sciences **60**:1437-1439.

Chin, A., and K. J. Gregory. 2001. Urbanization and adjustment of ephemeral stream channels. Annals of the Association of American Geographers **91**:595-608.

Chipps, S. R., D. E. Hubbard, K. B. Werline, N. J. Haugerud, K. A. Powell, J. Thompson, and T. Johnson. 2006. Association between wetland disturbance and biological attributes in floodplain wetlands. Wetlands **26**:297-508.

Church, M. 2002. Geomorphic thresholds in riverine landscapes. Freshwater Biology **47**:541-557.

Church, M. 2006. Bed material transport and the morphology of alluvial river channels. Annual Review of Earth and Planetary Sciences **34**:325-354.

Cirmo, C. P., C. T. Driscoll, and K. Bowes. 2000. Chemical fluxes from sediments in two Adirondack wetlands: Effects of an acid-neutralization experiment. Soil Science Society of America Journal **64**:790-799.

Clair, T. A., T. L. Pollock, and J. M. Ehrman. 1994. Exports of carbon and nitrogen from river basins in Canada's Atlantic Provinces. Global Biogeochemical Cycles **8**:441-450.

Clark, W. R. 2000. Ecology of muskrats in prairie wetlands. Pages 287-313 *in* Prairie wetland ecology: The contribution of the marsh ecology research program. H. R. Murkin, A. G. van der Valk, and W. R. Clark, editors. Iowa State University Press, Ames, IA.

Claxton, A. J., P. D. Bates, and H. L. Cloke. 2003. Mixing of hillslope, river, and alluvial ground waters in lowland floodplains. Ground Water **41**:926-936.

Clobert, J., J.-F. Le Galliard, J. Cote, S. Meylan, and M. Massot. 2009. Informed dispersal, heterogeneity in animal dispersal syndromes and the dynamics of spatially structured populations. Ecology Letters **12**:197-209.

Coes, A. L., and D. R. Pool. 2005. Ephemeral-stream channel and basin-floor infiltration and recharge in the Sierra Vista subwatershed of the Upper San Pedro Basin, southeastern Arizona. USGS Open-File Report 2005–1023, U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Cohen, M., J. Paris, and M. Clark. 2007. P-sorption capacity estimation in southeastern USA wetland soils using visible/near infrared (VNIR) reflectance spectroscopy. Wetlands **27**:1098-1111.

Collen, P., and R. J. Gibson. 2001. The general ecology of beavers (*Castor* spp.), as related to their influence on stream ecosystems and riparian habitats, and the subsequent effects on fish – a review. Reviews in Fish Biology and Fisheries **10**:439-461.

Collier, M., R. J. Webb, and J. C. Schmidt. 1996. Dams and rivers: A primer on the downstream effects of dams. USGS Circular 1126, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Collins, B. D., D. R. Montgomery, K. L. Fetherston, and T. B. Abbe. 2012. The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperature forested alluvial valleys in the North Pacific coastal ecoregion. Geomorphology **139-140**:460-470.

Colvin, M. E., and C. M. Moffitt. 2009. Evaluation of irrigation canal networks to assess stream connectivity in a watershed. River Research and Applications **25**:486-496.

Colvin, R., G. R. Giannico, J. Li, K. L. Boyer, and W. J. Gerth. 2009. Fish use of intermittent watercourses draining agricultural lands in the Upper Willamette River Valley, Oregon. Transactions of the American Fisheries Society **138**:1302-1313.

Comer, P., K. Goodin, A. Tomaino, G. Hammerson, G. Kittel, S. Menard, C. Nordman, M. Pyne, M. Reid, L. Sneddon, and K. Snow. 2005. Biodiversity values of geographically isolated wetlands in the United States. NatureServe, Arlington, VA.

Compton, J. E., M. R. Church, S. T. Larned, and W. E. Hogsett. 2003. Nitrogen export from forested watersheds in the Oregon Coast Range: The role of N_2-fixing red alder. Ecosystems **6**:773-785.

Constantz, J. 1998. Interaction between stream temperature, streamflow, and groundwater exchanges in alpine streams. Water Resources Research **34**:1609-1615.

Constantz, J., A. E. Stewart, R. Niswonger, and L. Sarma. 2002. Analysis of temperature profiles for investigating stream losses beneath ephemeral channels. Water Resources Research **38**:1316.

Cook, B. J., and F. R. Hauer. 2007. Effects of hydrologic connectivity on water chemistry, soils, and vegetation structure and function in an intermontane depressional wetland landscape. Wetlands **27**:719-738.

Cook, N., F. J. Rahel, and W. A. Hubert. 2010. Persistence of Colorado River cutthroat trout populations in isolated headwater streams of Wyoming. Transactions of the American Fisheries Society **139**:1500-1510.

Cooper, A., J. W. Gilliam, R. B. Daniels, and W. P. Robarge. 1987. Riparian areas as filters for agricultural sediment. Soil Science Society of America Journal **51**:416-420.

Copp, G. H. 1989. The habitat diversity and fish reproductive function of floodplain ecosystems. Environmental Biology of Fishes **26**:1-27.

Corenblit, D., E. Tabacchi, J. Steiger, and A. M. Gurnell. 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. Earth-Science Reviews **84**:56-86.

Corti, R., and T. Datry. 2012. Invertebrates and sestonic matter in an advancing wetted front travelling down a dry river bed (Albarine, France). Freshwater Science **31**:1187-1201.

Corti, R., T. Datry, L. Drummond, and S. T. Larned. 2011. Natural variation in immersion and emersion affects breakdown and invertebrate colonization of leaf litter in a temporary river. Aquatic Sciences **73**:537-550.

Costelloe, J. F., A. Shields, R. B. Grayson, and T. A. McMahon. 2007. Determining loss characteristics of arid zone river waterbodies. River Research and Applications **23**:715-731.

Cote, D., D. Kehler, C. Bourne, and Y. Wiersma. 2009. A new measure of longitudinal connectivity for stream networks. Landscape Ecology **24**:101-113.

Coulthard, T. J. 2005. Effects of vegetation on braided stream pattern and dynamics. Water Resources Research **41**:W04003.

Coutant, C. C. 1999. Perspectives on temperature in the Pacific Northwest's fresh waters. ORNL/TM-1999/44, Oak Ridge National Laboratory Environmental Sciences Division Publication 4849, Springfield, VA.

Covich, A. P., M. A. Palmer, and T. A. Crowl. 1999. The role of benthic invertebrate species in freshwater ecosystems: Zoobenthic species influence energy flows and nutrient cycling. BioScience **49**:119-127.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Office of Biological Services, Washington, DC.

Craft, C., and W. Casey. 2000. Sediment and nutrient accumulation in floodplain and depressional freshwater wetlands of Georgia, USA. Wetlands **20**:323-332.

Craft, C. B., and C. Chiang. 2002. Forms and amounts of soil nitrogen and phosphorus across a longleaf pine–depressional wetland landscape. Soil Science Society of America Journal **66**:1713-1721.

Creed, I. F., and F. D. Beall. 2009. Distributed topographic indicators for predicting nitrogen export from headwater catchments. Water Resources Research **45**:W10407.

Creed, I. F., S. E. Sanford, F. D. Beall, L. A. Molot, and P. J. Dillon. 2003. Cryptic wetlands: Integrating hidden wetlands in regression models of the export of dissolved organic carbon from forested landscapes. Hydrological Processes **17**:3629-3648.

Cristea, N. C., and S. J. Burges. 2009. Use of thermal infrared imagery to complement monitoring and modeling of spatial stream temperatures. Journal of Hydrologic Engineering **14**:1080-1090.

Cross, F. B., and R. E. Moss. 1987. Historic changes in fish communities and aquatic habitats in plains streams of Kansas. Pages 155-165 *in* Community and evolutionary ecology of North American stream fishes. W. J. Matthews and D. C. Heins, editors. University of Oklahoma Press, Norman, OK.

Cuffney, T. F., J. B. Wallace, and G. J. Luthgart. 1990. Experimental evidence quantifying the role of benthic invertebrates in organic matter dynamics of headwater streams. Freshwater Biology **23**:281-299.

Cummins, K. W., C. E. Cushing, and G. W. Minshall. 2006. Introduction: An overview of stream ecosystems. Pages 1-8 *in* River and stream ecosystems of the world. C. E. Cushing, K. W. Cummins, and G. W. Minshall, editors. University of California Press, Berkley, CA.

Cummins, K. W., and M. J. Klug. 1979. Feeding ecology of stream invertebrates. Annual Review of Ecology and Systematics **10**:147-172.

Cummins, K. W., R. C. Petersen, F. O. Howard, J. C. Wuycheck, and V. I. Holt. 1973. Utilization of leaf litter by stream detritivores. Ecology **54**:336-345.

Cummins, K. W., G. L. Spengler, G. M. Ward, R. M. Speaker, R. W. Ovink, D. C. Mahan, and R. L. Mattingly. 1980. Processing of confined and naturally entrained leaf litter in a woodland stream ecosystem. Limnology and Oceanography **25**:952-957.

Cummins, K. W., M. A. Wilzbach, D. M. Gates, J. B. Perry, and W. B. Taliferro. 1989. Shredders and riparian vegetation - Leaf litter that falls into streams influences communities of stream invertebrates. BioScience **39**:24-30.

Curriero, F. C., J. A. Patz, J. B. Rose, and S. Lele. 2001. The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. American Journal of Public Health **91**:1194-1199.

Curry, R. A., C. Brady, D. L. G. Noakes, and R. G. Danzmann. 1997. Use of small streams by young brook trout spawned in a lake. Transactions of the American Fisheries Society **126**:77-83.

Dabney, S. M., L. D. Meyer, W. C. Harmon, C. V. Alonso, and G. R. Foster. 1995. Depositional patterns of sediment trapped by grass hedges. Transactions of the American Society of Agricultural Engineers **38**:1719-1729.

Dahl, T. E. 1990. Wetlands Losses in the United States 1780's to 1980's. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Washington, DC.

Dahm, C. N., N. B. Grimm, P. Marmonier, H. M. Valett, and P. Vervier. 1998. Nutrient dynamics at the interface between surface waters and groundwaters. Freshwater Biology **40**:427-451.

Daniels, R. B., and J. G. Gilliam. 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Science Society of America Journal **60**:246-251.

Danks, H. V. 2007. How aquatic insects live in cold climates. Canadian Entomologist **139**:443-471.

Darracq, A., and G. Destouni. 2005. In-stream nitrogen attenuation: Model-aggregation effects and implications for coastal nitrogen impacts. Environmental Science & Technology **39**:3716-3722.

Darracq, A., and G. Destouni. 2007. Physical versus biogeochemical interpretations of nitrogen and phosphorus attenuation in streams and its dependence on stream characteristics. Global Biogeochemical Cycles **21**:GB3003.

David, A., C. Bancon-Montigny, C. Salles, C. Rodier, and M.-G. Tournoud. 2012. Contamination of riverbed sediments by hazardous substances in the Mediterranean context: Influence of hydrological conditions. Journal of Hydrology **468–469**:76-84.

Davis, C. B., J. L. Baker, A. G. van der Valk, and C. E. Beer. 1981. Prairie pothole marshes as traps for nitrogen and phosphorus in agricultural runoff. Pages 153-163 *in* Selected proceedings of the Midwest conference on wetland values and management, June 17-19, 1981, St. Paul, MN. B. Richardson, editor. The Freshwater Society, St. Paul, MN.

Davis, J. H., S. M. Griffith, and P. J. Wigington. 2011. Surface and ground water nitrogen dynamics in a well-drained riparian forest within a poorly-drained agricultural landscape. Journal of Environmental Quality **40**:505-516.

Day, D. G. 1978. Drainage density changes during rainfall. Earth Surface Processes and Landforms **3**:319-326.

de Vries, J. J. 1995. Seasonal expansion and contraction of stream networks in shallow groundwater systems. Journal of Hydrology **170**:15-26.

Deiner, K., J. C. Garza, R. Coey, and D. J. Girman. 2007. Population structure and genetic diversity of trout (*Oncorhynchus mykiss*) above and below natural and man-made barriers in the Russian River, California. Conservation Genetics **8**:437-454.

Demars, B. O. L., J. Russell Manson, J. S. Ólafsson, G. M. Gíslason, R. Gudmundsdóttir, G. U. Y. Woodward, J. Reiss, D. E. Pichler, J. J. Rasmussen, and N. Friberg. 2011. Temperature and the metabolic balance of streams. Freshwater Biology **56**:1106-1121.

Detenbeck, N. E., C. A. Johnston, and G. J. Niemi. 1993. Wetland effects on lake water quality in the Minneapolis/St. Paul metropolitan area. Landscape Ecology **8**:39-61.

Devito, K., I. Creed, T. Gan, C. Mendoza, R. Petrone, U. Silins, and B. Smerdon. 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plain: Is topography the last thing to consider? Hydrological Processes **19**:1705-1714.

Devito, K. J., A. R. Hill, and N. Roulet. 1996. Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield. Journal of Hydrology **181**:127-147.

Dias, M. S., T. Oberdorff, B. Hugueny, F. Leprieur, C. Jézéquel, J.-F. Cornu, S. Brosse, G. Grenouillet, and P. A. Tedesco. 2014. Global imprint of historical connectivity on freshwater fish biodiversity. Ecology Letters **17**:1130-1140.

Dickinson, J. E., J. R. Kennedy, D. R. Pool, J. T. Cordova, J. T. Parker, J. P. Macy, and B. Thomas. 2010. Hydrogeologic framework of the middle San Pedro watershed, southeastern Arizona. USGS Scientific Investigations Report 2010-5126, prepared in cooperation with the Arizona Department of Water Resources, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Dierberg, F. E., and P. L. Brezonik. 1984. Nitrogen and phosphorus mass balances in a cypress dome receiving wastewater. Pages 112-118 *in* Cypress swamps. K. C. Ewel and H. T. Odum, editors. University Press of Florida, Gainesville, FL.

Dieter, D., D. von Schiller, E. M. García-Roger, M. M. Sánchez-Montoya, R. Gómez, J. Mora-Gómez, F. Sangiorgio, J. Gelbrecht, and K. Tockner. 2011. Preconditioning effects of intermittent stream flow on leaf litter decomposition. Aquatic Sciences **73**:599-609.

Dietrich, W. E., and T. Dunne. 1993. The channel head. Pages 175-219 *in* Channel network hydrology. K. Beven and M. J. Kirby, editors. John Wiley & Sons, New York, NY.

Dillaha, T. A., and S. P. Inamdar. 1997. Buffer zones as sediment traps or sources. Pages 33-42 *in* Buffer zones: Their processes and potential in water protection. Proceedings of the International Conference on Buffer Zones, September 1996. N. E. Haycock, T. P. Burt, K. W. T. Goulding, and G. Pinay, editors. Quest Environmental, Hertfordshire, UK.

Dillaha, T. A., R. B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Transactions of the American Society of Agricultural Engineers **32**:513-519.

Dillon, P. J., and L. A. Molot. 1997. Effects of landscape form on export of dissolved organic carbon, iron, and phosphorus from forested stream catchments. Water Resources Research **33**:2591-2600.

Dosskey, M. G. 2001. Toward quantifying water pollution abatement in response to installing buffers on crop land. Environmental Management **28**:577-598.

Dou, P., B. Cui, T. Xie, D. Dong, and B. Gu. 2015. Macrobenthos diversity response to hydrological connectivity gradient. Wetlands: doi: 10.1007/s13157-13014-10580-13158.

Doyle, M. W., E. H. Stanley, and J. M. Harbor. 2003. Hydrogeomorphic controls on phosphorus retention in streams. Water Resources Research **39**:1147.

Driscoll, C. T., V. Blette, C. Yan, C. L. Schofield, R. Munson, and J. Holsapple. 1995. The role of dissolved organic carbon in the chemistry and bioavailability of mercury in remote Adirondack lakes. Water Air and Soil Pollution **80**:499-508.

Dugdale, S. J., N. E. Bergeron, and A. St-Hilaire. 2013. Temporal variability of thermal refuges and water temperature patterns in an Atlantic salmon river. Remote Sensing of Environment **136**:358-373.

Duncan, S. H., R. E. Bilby, J. W. Ward, and J. T. Heffner. 1987. Transport of road-surface sediment through ephemeral stream channel. Water Resources Bulletin **23**:113-119.

Dunkerley, D. L. 1992. Channel geometry, bed material, and inferred flow conditions in ephemeral stream systems, Barrier Range, western N.S.W. Australia. Hydrological Processes **6**:417-433.

Dunne, E. J., K. R. Reddy, and M. K. Clark. 2006. Phosphorus release and retention by soils of natural isolated wetlands. International Journal of Environment and Pollution **28**:496-516.

Dunne, E. J., J. Smith, D. B. Perkins, M. W. Clark, J. W. Jawitz, and K. R. Reddy. 2007. Phosphorus storages in historically isolated wetland ecosystems and surrounding pasture uplands. Ecological Engineering **31**:16-28.

Dunne, T., and R. D. Black. 1970. Partial area contributions to storm runoff in a small New England watershed. Water Resources Research **6**:1296-1311.

Dunne, T., and L. B. Leopold. 1978. Water in environmental planning. W.H. Freeman and Co., San Francisco, CA.

Eaton, L. S., B. A. Morgan, R. C. Kochel, and A. D. Howard. 2003. Role of debris flows in long-term landscape denudation in the central Appalachians of Virginia. Geology **31**:339-342.

Eberle, L. C., and J. A. Stanford. 2010. Importance and seasonal availability of terrestrial invertebrates as prey for juvenile salmonids in floodplain spring brooks of the Kol River (Kamchatka, Russian Federation). River Research and Applications **26**:682-694.

Ebersole, J. L., M. E. Colvin, P. J. Wigington, S. G. Leibowitz, J. P. Baker, M. R. Church, J. E. Compton, B. A. Miller, M. A. Cairns, B. P. Hansen, and H. R. LaVigne. 2009. Modeling stream network-scale variation in coho salmon overwinter survival and smolt size. Transactions of the American Fisheries Society **138**:564-580.

Ebersole, J. L., W. J. Liss, and C. A. Frissell. 2003. Cold water patches in warm streams: Physicochemical characteristics and the influence of shading. Journal of the American Water Resources Association **39**:355-368.

Ebersole, J. L., P. J. Wigington, J. P. Baker, M. A. Cairns, M. R. Church, B. P. Hansen, B. A. Miller, H. R. LaVigne, B. W. Compton, and S. G. Leibowitz. 2006. Juvenile coho salmon growth and survival across stream network seasonal habitats. Transactions of the American Fisheries Society. Transactions of the American Fisheries Society **135**:1681-1697.

Ebersole, J. L., P. J. Wigington, S. G. Leibowitz, R. L. Comeleo, and J. V. Sickle. 2015. Predicting the occurrence of cold-water patches at intermittent and ephemeral tributary confluences with warm rivers. Freshwater Science: doi:10.1086/678127.

Eckhardt, B. W., and T. R. Moore. 1990. Controls on dissolved organic carbon concentrations in streams of southern Quebec. Canadian Journal of Fisheries and Aquatic Sciences **47**:1537-1544.

Edwards, E. D., and A. D. Huryn. 1995. Annual contribution of terrestrial invertebrates to a New Zealand trout stream. New Zealand Journal of Marine and Freshwater Research **29**:467-477.

Elliott, J. M. 1971. Distances travelled by drifting invertebrates in a Lake District stream. Oecologia **6**:350-379.

Elliott, J. M. 2003. A comparative study of the dispersal of 10 species of stream invertebrates. Freshwater Biology **48**:1652-1668.

Elmore, A. J., and S. S. Kaushal. 2008. Disappearing headwaters: Patterns of stream burial due to urbanization. Frontiers in Ecology and the Environment **6**:308-312.

Elwood, J. W., J. D. Newbold, R. V. O'Neill, and W. Van Winkle. 1983. Resource spiralling: An operational paradigm for analyzing lotic ecosystems. Pages 3-23 *in* Dynamics of lotic ecosystems. T. D. Fontaine and S. M. Bartell, editors. Ann Arbor Science Publishers, Ann Arbor, MI.

Ensign, S. H., and M. W. Doyle. 2006. Nutrient spiraling in streams and river networks. Journal of Geophysical Research: Biogeosciences **111**:G04009.

Epperson, B. K., B. H. McRae, K. Scribner, S. A. Cushman, M. S. Rosenberg, M. J. Fortin, P. M. A. James, M. Murphy, S. Manel, P. Legendre, and M. R. T. Dale. 2010. Utility of computer simulations in landscape genetics. Molecular Ecology **19**:3549-3564.

Erman, D. C., and V. M. Hawthorne. 1976. The quantitative importance of an intermittent stream in the spawning of rainbow trout. Transactions of the American Fisheries Society **105**:675-681.

Eros, T., J. Olden, R. Schick, D. Schmera, and M.-J. Fortin. 2012. Characterizing connectivity relationships in freshwaters using patch-based graphs. Landscape Ecology **27**:303-317.

Eshelman, K. N., and H. F. Hemond. 1985. The role of organic acids in the acid-base status of surface waters at Bickford Watershed, Massachusetts. Water Resources Research **21**:1503-1510.

Euliss, N. H., J. W. Labaugh, L. H. Fredrickson, D. M. Mushet, M. R. K. Laubhan, G. A. Swanson, T. C. Winter, D. O. Rosenberry, and R. D. Nelson. 2004. The wetland continuum: A conceptual framework for interpreting biological studies. Wetlands **24**:448-458.

Ewel, K. C., and H. T. Odum. 1984. Cypress swamps. University Presses of Florida, Gainesville, FL.

Fagan, W. F. 2002. Connectivity, fragmentation, and extinction risk in dendritic metapopulations. Ecology **83**:3243-3249.

Falke, J. A., K. R. Bestgen, and K. D. Fausch. 2010. Streamflow reductions and habitat drying affect growth, survival, and recruitment of brassy minnow across a Great Plains landscape. Transactions of the American Fisheries Society **139**:1566-1583.

Falke, J. A., and K. B. Gido. 2006. Effects of reservoir connectivity on stream fish assemblages in the Great Plains. Canadian Journal of Fisheries and Aquatic Sciences **63**:480-493.

Farmer, A. H., and A. H. Parent. 1997. Effects of the landscape on shorebird movements at spring migration stopovers. The Condor **99**:698-707.

Farrar, D., L. C. Alexander, L. L. Yuan, and J. Gerritsen. 2014. Regional observational studies: Addressing confounding. Pages 187-202 *in* Ecological causal assessment. S. B. Norton, S. M. Cormier, and G. W. Suter, editors. CRC Press, London, UK.

Fausch, K. D., and K. R. Bestgen. 1997. Ecology of fishes indigenous to the central and southwestern Great Plains. Pages 131-166 *in* Ecology and conservation of Great Plains vertebrates. F. L. Knopf and F. B. Samson, editors. Springer-Verlag, New York, NY.

Fausch, K. D., B. E. Rieman, J. B. Dunham, M. K. Young, and D. P. Peterson. 2009. Invasion versus isolation: Trade-offs in managing native salmonids with barriers to upstream movement. Conservation Biology **23**:859-870.

Fausch, K. D., C. E. Torgersen, C. V. Baxter, and H. W. Li. 2002. Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. BioScience **52**:483-498.

Fekete, B. M., C. J. Vörösmarty, and W. Grabs. 2002. High-resolution fields of global runoff combining observed river discharge and simulated water balances. Global Biogeochemical Cycles **16**:15-11-15-10.

Fellman, J. B., K. C. Petrone, and P. F. Grierson. 2013. Leaf litter age, chemical quality, and photodegradation control the fate of leachate dissolved organic matter in a dryland river. Journal of Arid Environments **89**:30-37.

Feminella, J. W. 1996. Comparison of benthic macroinvertebrate assemblages in small streams along a gradient of flow permanence. Journal of the North American Benthological Society **15**:651-669.

Feminella, J. W., and C. P. Hawkins. 1995. Interactions between stream herbivores and periphyton: A quantitative analysis of past experiments. Journal of the North American Benthological Society **14**:465-509.

Fer, T., and Z. Hroudova. 2008. Detecting dispersal of *Nuphar lutea* in river corridors using microsatellite markers. Freshwater Biology **53**:1409-1422.

Ferguson, C., A. M. d. R. Husman, N. Altavilla, D. Deere, and N. Ashbolt. 2003. Fate and transport of surface water pathogens in watersheds. Critical Reviews in Environmental Science and Technology **33**:299-361.

Ferguson, R., and T. Hoey. 2008. Effects of tributaries on main-channel geomorphology. Pages 183-208 *in* River confluences, tributaries and the fluvial network. S. P. Rice, A. G. Roy, and B. L. Rhoads, editors. John Wiley & Sons, Chichester, UK.

Ferguson, R. I., J. R. Cudden, T. Hoey, and S. P. Rice. 2006. River system discontinuities due to lateral inputs: Generic styles and controls. Earth Surface Processes and Landforms **31**:1149-1166.

Fernald, A. F., D. Landers, and P. J. Wigington. 2006. Water quality changes along hyporheic flow paths between a large gravel bar river and off-channel alcoves in Oregon, USA. . River Research and Applications **22**:1111-1114.

Fernald, A. F., P. J. Wigington, and D. Landers. 2001. Transient storage and hyporheic flow along the Willamette River, Oregon: Field measurements and model estimates. Water Resources Research **37**:1681-1694.

Ferone, J. M., and K. J. Devito. 2004. Shallow groundwater-surface water interactions in pond-peatland complexes along a Boreal Plains topographic gradient. Journal of Hydrology **292**:75-95.

Figuerola, J., and A. J. Green. 2002. Dispersal of aquatic organisms by waterbirds: A review of past research and priorities for future studies. Freshwater Biology **47**:483-494.

Figuerola, J., A. J. Green, and T. C. Michot. 2005. Invertebrate eggs can fly: Evidence of waterfowl-mediated gene flow in aquatic invertebrates. The American Naturalist **165**:274-280.

Finkelstein, P. L., and L. E. Truppi. 1991. Spatial distribution of precipitation seasonality in the United States. Journal of Climate **4**:373-385.

Fisher, S. G., L. J. Gray, N. B. Grimm, and D. E. Busch. 1982. Temporal succession in a desert stream ecosystem following flash flooding. Ecological Monographs **52**:93-110.

Fisher, S. G., and G. E. Likens. 1973. Energy flow in Bear Brook, New Hampshire: An integrative approach to stream ecosystem metabolism. Ecological Monographs **43**:421-439.

Fisher, S. G., J. Welter, J. Schade, and J. Henry. 2001. Landscape challenges to ecosystem thinking: Creative flood and drought in the American Southwest. Scientia Marina **65 (Supplement 2)**:181-192.

Fisher, S. J., and D. W. Willis. 2000. Seasonal dynamics of aquatic fauna and habitat parameters in a perched upper Missouri River wetland. Wetlands **20**:470-478.

Fleming, S. W., P. H. Whitfield, R. D. Moore, and E. J. Quilty. 2007. Regime-dependent streamflow sensitivities to Pacific climate modes cross the Georgia-Puget transboundary ecoregion. Hydrological Processes **21**:3264-3287.

Florsheim, J. L., J. F. Mount, and L. T. Rutten. 2001. Effect of baselevel change on floodplain and fan sediment storage and ephemeral tributary channel morphology, Navarro River, California. Earth Surface Processes and Landforms **26**:219-232.

Folk, M. J., and T. C. Tacha. 1990. Sandhill crane roost site characteristics in the North Platte River valley. The Journal of Wildlife Management **54**:480-486.

Ford, J., and B. L. Bedford. 1987. The hydrology of Alaskan wetlands, USA: A review. Arctic and Alpine Research **19**:209-229.

Franklin, S., J. Kupfer, S. R. Pezeshki, R. Gentry, and R. D. Smith. 2009. Complex effects of channelization and levee construction on western Tennessee floodplain forest function. Wetlands **29**:451-464.

Fraser, D. F., J. F. Gilliam, and T. Yiphoi. 1995. Predation as an agent of population fragmentation in a tropical watershed. Ecology **76**:1461-1472.

Fraser, D. J., L. K. Weir, L. Bernatchez, M. M. Hansen, and E. B. Taylor. 2011. Extent and scale of local adaptation in salmonid fishes: Review and meta-analysis. Heredity **106**:404-420.

Freeman, M. C., C. M. Pringle, and C. R. Jackson. 2007. Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. Journal of the American Water Resources Association **43**:5-14.

Freeze, A. R., and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Englewood Cliffs, NJ.

Freeze, R. A. 1971. Three-dimensional, transient, saturated-unsaturated flow in a groundwater basin. Water Resources Research **7**:347-366.

Frisch, D., A. J. Green, and J. Figuerola. 2007. High dispersal capacity of a broad spectrum of aquatic invertebrates via waterbirds. Aquatic Sciences **69**:568-574.

Frisch, D., and S. T. Threlkeld. 2005. Flood-mediated dispersal versus hatching: Early recolonisation strategies of copepods in floodplain ponds. Freshwater Biology **50**:323-330.

Frissell, C. A., W. J. Liss, C. E. Warren, and M. D. Hurley. 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. Environmental Management **10**:199-214.

Fritz, K. M., and W. K. Dodds. 2002. Macroinvertebrate assemblage structure across a tallgrass prairie stream landscape. Archiv für Hydrobiologie **154**:79-102.

Fritz, K. M., and W. K. Dodds. 2004. Resistance and resilience of macroinvertebrate assemblages to drying and flood in a tallgrass prairie stream system. Hydrobiologia **527**:99-112.

Fritz, K. M., J. W. Feminella, C. Colson, B. G. Lockaby, R. Governo, and R. B. Rummer. 2006a. Biomass and decay rates of roots and detritus in sediments of intermittent coastal plain streams. Hydrobiologia **556**:265-277.

Fritz, K. M., J. M. Glime, J. Hribljan, and J. L. Greenwood. 2009. Can bryophytes be used to characterize hydrologic permanence in forested headwater streams? Ecological Indicators **9**:681-692.

Fritz, K. M., B. R. Johnson, and D. M. Walters. 2006b. Field operations manual for assessing the hydrologic permanence and ecological condition of headwater streams. EPA/600/R-06/126, U.S. Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory, Washington, DC.

Fritz, K. M., B. R. Johnson, and D. M. Walters. 2008. Physical indicators of hydrologic permanence in forested headwater streams. Journal of the North American Benthological Society **27**:690-704.

Fronhofer, E. A., A. Kubisch, F. M. Hilker, T. Hovestadt, and H. J. Poethke. 2012. Why are metapopulations so rare? Ecology **93**:1967-1978.

Fuller, C. C., and J. W. Harvey. 2000. Reactive uptake of trace metals in the hyporheic zone of a mining-contaminated stream, Pinal Creek, Arizona. Environmental Science & Technology **34**:1150-1155.

Fullerton, A. H., K. M. Burnett, E. A. Steel, R. L. Flitcroft, G. R. Pess, B. E. Feist, C. E. Torgersen, D. J. Miller, and B. L. Sanderson. 2010. Hydrological connectivity for riverine fish: Measurement challenges and research opportunities. Freshwater Biology **55**:2215-2237.

Gahl, M. K., A. J. K. Calhoun, and R. Graves. 2009. Facultative use of seasonal pools by American bullfrogs (*Rana catesbeiana*). Wetlands **29**:697-703.

Galat, D. L., L. H. Fredrickson, D. D. Humburg, K. J. Bataille, J. R. Bodie, J. Dohrenwend, G. T. Gelwicks, J. E. Havel, D. L. Helmers, J. B. Hooker, J. R. Jones, M. F. Knowlton, J. Kubisiak, J. Mazourek, A. C. McColpin, R. B. Renken, and R. D. Semlitsch. 1998. Flooding to restore connectivity of regulated, large-river wetlands. BioScience **48**:721-733.

Galatowitsch, S. M., and A. G. van der Valk. 1996. The vegetation of restored and natural prairie wetlands. Ecological Applications **6**:102-112.

Galloway, M. E., and B. A. Branfireun. 2004. Hydrological and biogeochemical controls on mercury fate and transport in a southern Ontario forested wetland. The Science of Total Environment **325**:239-254.

Galpern, P., M. Manseau, and A. Fall. 2011. Patch-based graphs of landscape connectivity: A guide to construction, analysis and application for conservation. Biological Conservation **144**:44-55.

Galster, J. C. 2007. Natural and anthropogenic influences on the scaling of discharge with drainage area for multiple watersheds. Geosphere **3**:260-271.

Galster, J. C. 2009. Testing the linear relationship between peak annual river discharge and drainage area using long-term USGS river gauging records. Pages 159-171 *in* Management and restoration of fluvial systems with broad historical changes and human impacts. L. A. James, S. L. Rathburn, and G. R. Whittecar, editors. Geological Society of America, Boulder, CO.

Galster, J. C., F. J. Pazzaglia, B. R. Hargreaves, D. P. Morris, S. C. Peters, and R. N. Weisman. 2006. Effects of urbanization on watershed hydrology: The scaling of discharge with drainage area. Geology **34**:713-716.

Gamble, D. E., J. Grody, J. J. Mack, and M. Micacchion. 2007. An ecological and functional assessment of urban wetlands in central Ohio. Columbus, Ohio. Ohio EPA Technical Report WET/ 2007-3B, Ohio Environmental Protection Agency, Wetland Ecology Group, Division of Surface Water, Columbus, OH.

Ganio, L. M., C. E. Torgersen, and R. E. Gresswell. 2005. A geostatistical approach for describing spatial pattern in stream networks. Frontiers in Ecology and the Environment **3**:138-144.

Gannett, M. W., J. K. E. Lite, D. S. Morgan, and C. A. Collins. 2001. Ground-water hydrology of the Upper Deschutes Basin, Oregon. USGS Water-Resources Investigations Report 00-4162, U.S. Department of the Interior, U.S. Geological Survey, Portland, OR.

Gardner, B., and P. J. Sullivan. 2004. Spatial and temporal stream temperature prediction: Modeling nonstationary temporal covariance structures. Water Resources Research **40**:1-9.

Gardner, K. K., and B. L. McGlynn. 2009. Seasonality in spatial variability and influence of land use/land cover and watershed characteristics on stream water nitrate concentrations in a developing watershed in the Rocky Mountain West. Water Resources Research **45**:W08411.

Gasith, A., and V. H. Resh. 1999. Streams in Mediterranean climate regions: Abiotic influences and biotic responses to predictable seasonal events. Annual Review of Ecology and Systematics **30**:51-81.

Gehrke, G. E., J. D. Blum, and M. Marvin-DiPasquale. 2011. Sources of mercury to San Francisco Bay surface sediment as revealed by mercury stable isotopes. Geochimica et Cosmochimica Acta **75**:691-705.

Gergel, S. E. 2005. Spatial and non-spatial factors: When do they affect landscape indicators of watershed loading? Landscape Ecology **20**:177-189.

Gergel, S. E., M. G. Turner, and T. K. Kratz. 1999. Dissolved organic carbon as an indicator of the scale of watershed influence on lakes and rivers. Ecological Applications **9**:1377-1390.

Germanoski, D., and D. F. Ritter. 1988. Tributary response to local base level lowering below a dam. Regulated Rivers: Research & Management **2**:11-24.

Gibbons, J. W. 2003. Terrestrial habitat: A vital component for herpetofauna of isolated wetlands. Wetlands **23**:630-635.

Gibbons, J. W., and R. D. Semlitsch. 1991. Guide to amphibians and reptiles of the Savannah River Site. University of Georgia Press, Athens, GA.

Gibbons, J. W., C. T. Winne, D. E. Scott, J. D. Willson, X. Glaudas, K. M. Andrews, B. D. Todd, L. A. Fedewa, L. Wilkinson, R. N. Tsaliagos, S. J. Harper, J. L. Greene, T. D. Tuberville, B. S. Metts, M. E. Dorcast, J. P. Nestor, C. A. Young, T. Akre, R. N. Reed, K. A. Buhlmann, J. Norman, D. A. Croshaw, C. Hagen, and B. B. Rothermel. 2006. Remarkable amphibian biomass and abundance in an isolated wetland: Implications for wetland conservation. Conservation Biology **20**:1457-1465.

Gilvear, D., and R. Bryant. 2003. Analysis of aerial photography and other remotely sensed data. Pages 135-170 *in* Tools in fluvial geomorphology. G. M. Kondolf and H. Piegay, editors. John Wiley & Sons, Chichester, UK.

Gleason, R. A., B. A. Tangen, M. K. Laubhan, K. E. Kermes, and N. H. Euliss. 2007. Estimating water storage capacity of existing and potentially restorable wetland depressions in a subbasin of the Red River of the North. USGS Open-File Report 2007-1159, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Gleeson, T., L. Marklund, L. Smith, and A. H. Manning. 2011. Classifying the water table at regional to continental scales. Geophysical Research Letters **38**:L05401.

Golden, H. E., and C. D. Knightes. 2011. Simulated watershed mercury and nitrate flux responses to multiple land cover conversion scenarios. Environmental Toxicology and Chemistry **30**:773-786.

Golden, H. E., C. D. Knightes, P. A. Conrads, T. D. Feaster, G. M. Davis, S. T. Benedict, and P. M. Bradley. 2013. Climate change and watershed mercury export: A multiple projection and model analysis. Environmental Toxicology and Chemistry **32**:2165-2174.

Golden, H. E., C. R. Lane, D. M. Amatya, K. W. Bandilla, H. Raanan Kiperwas, C. D. Knightes, and H. Ssegane. 2014. Hydrologic connectivity between geographically isolated wetlands and surface water systems: A review of select modeling methods. Environmental Modelling & Software **53**:190-206.

Gomez-Uchida, D., T. W. Knight, and D. E. Ruzzante. 2009. Interaction of landscape and life history attributes on genetic diversity, neutral divergence and gene flow in a pristine community of salmonids. Molecular Ecology **18**:4854-4869.

Gomi, T., and R. C. Sidle. 2003. Bed load transport in managed steep-gradient headwater streams of southeastern Alaska. Water Resources Research **39**:1336.

Gomi, T., R. C. Sidle, and J. S. Richardson. 2002. Understanding processes and downstream linkages of headwater systems. BioScience **52**:905-916.

Gonod, L. V., J. Chadoeuf, and C. Chenu. 2006. Spatial distribution of microbial 2,4-dichlorophenoxy acetic acid mineralization from field to microhabitat scales. Soil Science Society of America Journal **70**:64-70.

Gooderham, J. P. R., L. A. Barmuta, and P. E. Davis. 2007. Upstream heterogeneous zones: Small stream systems structured by a lack of competence? Journal of the North American Benthological Society **26**:365-374.

Goodrich, D. C., L. J. Lane, R. M. Shillito, S. N. Miller, K. H. Syed, and D. A. Woolhiser. 1997. Linearity of basin response as a function of scale in a semiarid watershed. Water Resources Research **33**:2951-2965.

Goodrich, D. C., D. G. Williams, C. L. Unkrich, J. F. Hogan, R. L. Scott, K. R. Hultine, D. R. Pool, A. L. Coes, and S. Miller. 2004. Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River basin, Arizona. Pages 77-99 *in* Recharge and vadose zone processes: Alluvial basins of the southwestern United States. F. M. Phillips, J. F. Hogan, and B. Scanlon, editors. American Geophysical Union, Washington, DC.

Gooseff, M. N., K. E. Bencala, and S. M. Wondzell. 2008. Solute transport along stream and river networks. Pages 395-417 *in* River confluences, tributaries, and the fluvial network. S. P. Rice, A. G. Roy, and B. L. Rhoads, editors. John Wiley & Sons, Chichester, UK.

Gorham, E., J. K. Underwood, F. B. Martin, and J. G. Ogden. 1986. Natural and anthropogenic causes of lake acidification. Nature **324**:451-453.

Gorman, O. T. 1986. Assemblage organization of stream fishes: The effect of rivers on adventitious streams. The American Naturalist **128**:611-616.

Graf, W. L. 1994. Plutonium and the Rio Grande: Environmental change and contamination in the nuclear age. Oxford University Press, New York, NY.

Graf, W. L., S. L. Clark, M. T. Kammerer, T. Lehman, K. Randall, and R. Schroeder. 1991. Geomorphology of heavy metals in the sediments of Queen Creek, Arizona, USA. CATENA **18**:567-582.

Granado, D. C., and R. Henry. 2014. Phytoplankton community response to hydrologic variations in oxbow lakes with different levels of connection to a tropical river. Hydrobiologia **721**:223-238.

Grant, E. H. C., W. H. Lowe, and W. F. Fagan. 2007. Living in the branches: Population dynamics and ecological processes in dendritic networks. Ecology Letters **10**:165-175.

Grant, E. H. C., J. D. Nichols, W. H. Lowe, and W. F. Fagan. 2010. Use of multiple dispersal pathways facilitates amphibian persistence in stream networks. Proceedings of the National Academy of Sciences of the United States of America **107**:6936-6940.

Gray, L. J. 1993. Response of insectivorous birds to emerging aquatic insects in riparian habitats of a tallgrass prairie stream. American Midland Naturalist **129**:288-300.

Greathouse, E. A., C. M. Pringle, W. H. McDowell, and J. G. Holmquist. 2006. Indirect upstream effects of dams: Consequences of migratory consumer extirpation in Puerto Rico. Ecological Applications **16**:339-352.

Green, A. J., and J. Figuerola. 2005. Recent advances in the study of long-distance dispersal of aquatic invertebrates via birds. Diversity and Distributions **11**:149-156.

Green, D. M. 2005. *Bufo americanus*, American toad. Pages 692-704 *in* Amphibian declines: The conservation status of United States species. M. Lannoo, editor. University of California Press, Berkeley, CA.

Gregory, K. J. 1976. Drainage networks and climate. Pages 289-315 *in* Geomorphology and climate. E. Derbyshire, editor. John Wiley & Sons, London, UK.

Gregory, K. J. 2006. The human role in changing river channels. Geomorphology **79**:172-191.

Gregory, K. J., and D. E. Walling. 1968. The variation of drainage density within a catchment. Bulletin of the International Association of Scientific Hydrology **13**:61-68.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummings. 1991. An ecosystem perspective of riparian zones: Focus on links between land and water. BioScience **41**:540-551.

Grenouillet, G., D. Pont, and C. Herisse. 2004. Within-basin fish assemblage structure: The relative influence of habitat versus stream spatial position on local species richness. Canadian Journal of Fisheries and Aquatic Sciences **61**:93-102.

Grigal, D. F. 2002. Inputs and outputs of mercury from terrestrial watersheds: A review. Environmental Reviews **10**:1-39.

Grimshaw, D. L., and J. Lewin. 1980. Source identification for suspended sediments. Journal of Hydrology **47**:151-162.

Gupta, V. K., E. Waymire, and C. T. Wang. 1980. A representation of an instantaneous unit hydrograph from geomorphology. Water Resources Research **16**:855-862.

Gurnell, A., K. Thompson, J. Goodson, and H. Moggridge. 2008. Propagule deposition along river margins: Linking hydrology and ecology. Journal of Ecology **96**:553-565.

Gurnell, A. M. 2003. Wood storage and mobility. Pages 75-91 *in* Ecology and management of wood in world rivers. S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. American Fisheries Society Symposium 37, Bethesda, MD.

Gurnell, A. M. 2007. Analogies between mineral sediment and vegetative particle dynamics in fluvial systems. Geomorphology **89**:9-22.

Gurnell, A. M., K. J. Gregory, and G. E. Petts. 1995. The role of coarse woody debris in forest aquatic habitats: Implications for management. Aquatic Conservation: Marine and Freshwater Ecosystems **5**:143-166.

Gurnell, A. M., H. Piegay, F. J. Swanson, and S. V. Gregory. 2002. Large wood and fluvial processes. Freshwater Biology **47**:601-619.

Guy, T. J., R. E. Gresswell, and M. A. Banks. 2008. Landscape-scale evaluation of genetic structure among barrier-isolated populations of coastal cutthroat trout, *Oncorhynchus clarkii clarkii*. Canadian Journal of Fisheries and Aquatic Sciences **65**:1749-1762.

Haag, K. H., and W. R. Pfeiffer. 2012. Flooded area and plant zonation in isolated wetlands in well fields in the Northern Tampa Bay Region, Florida, following reductions in groundwater-withdrawal rates. USGS Scientific Investigations Report 2012–5039. U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Haan, C. T., and H. P. Johnson. 1968. Hydraulic model of runoff from depressional areas. Part I: General considerations. Transactions of the American Society of Agricultural Engineers **11**:364–367.

Haig, S. M., D. W. Mehlman, and L. W. Oring. 1998. Avian movements and wetland connectivity in landscape conservation. Conservation Biology **12**:749-758.

Haitjema, H. M., and S. Mitchell-Bruker. 2005. Are water tables a subdued replica of the topography? Ground Water **43**:781–786.

Hall, B. R., D. J. Raynal, and D. J. Leopold. 2001a. Environmental influences on plant species composition in ground-water seeps in the Catskill Mountains of New York. Wetlands **21**:125-134.

Hall, C. J., A. Jordaan, and M. G. Frisk. 2011. The historic influence of dams on diadromous fish habitat with a focus on river herring and hydrologic longitudinal connectivity. Landscape Ecology **26**:95-107.

Hall, R. O., M. A. Baker, C. D. Arp, and B. J. Koch. 2009. Hydrologic control of nitrogen removal, storage, and export in a mountain stream. Limnology and Oceanography **54**:2128-2142.

Hall, R. O., G. E. Likens, and H. M. Malcom. 2001b. Trophic basis of invertebrate production in 2 streams at the Hubbard Brook Experimental Forest. Journal of the North American Benthological Society **20**:432-447.

Hall, R. O., and J. L. Meyer. 1998. The trophic significance of bacteria in a detritus-based stream food web. Ecology **79**:1995-2012.

Hall, R. O., J. B. Wallace, and S. L. Eggert. 2000. Organic matter flow in stream food webs with reduced detrital resource base. Ecology **81**:3445-3463.

Hamilton, S. K., S. E. Bunn, M. C. Thoms, and J. C. Marshall. 2005. Persistence of aquatic refugia between flow pulses in a dryland river system (Cooper Creek, Australia). Limnology and Oceanography **50**:743-754.

Hammersmark, C. T., M. C. Rains, and J. F. Mount. 2008. Quantifying the hydrological effects of stream restoration in a montane meadow environment. River Research and Applications **24**:735–753.

Hanfling, B., and D. Weetman. 2006. Concordant genetic estimators of migration reveal anthropogenically enhanced source-sink population structure in the river sculpin, *Cottus gobio*. Genetics **173**:1487-1501.

Hansen, W. F. 2001. Identifying stream types and management implications. Forest Ecology and Management **143**:39-46.

Hanski, I. 1999. Metapopulation ecology. Oxford University Press, Oxford, UK.

Hanson, M. A., K. D. Zimmer, M. G. Butler, B. A. Tangen, B. R. Herwig, and N. H. Euliss. 2005. Biotic interactions as determinants of ecosystem structure in prairie wetlands: An example using fish. Wetlands **25**:764-775.

Haramis, G. M. 1990. Breeding ecology of the wood duck: A review. Pages 45-60 *in* Proceedings of the 1988 North American Wood Duck Symposium. L. H. Fredrickson, G. V. Burger, S. P. Havera, D.A. Graber, R.E. Kirby, and T.S. Taylor, editor., St. Louis, MO.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, and K. W. Cummins. 1986. Ecology of coarse woody debris in temperature ecosystems. Advances in Ecological Research **15**:133-302.

Harrington, G. A., P. G. Cook, and A. L. Herczeg. 2002. Spatial and temporal variability of ground water recharge in central Australia: A tracer approach. Ground Water **40**:518-528.

Harvey, B. C., R. J. Nakamoto, and J. L. White. 2006. Reduced streamflow lowers dry-season growth of rainbow trout in a small stream. Transactions of the American Fisheries Society **135**:998-1005.

Harvey, J. W., J. D. Drummond, R. L. Martin, L. E. McPhillips, A. I. Packman, D. J. Jerolmack, S. H. Stonedahl, A. F. Aubeneau, A. H. Sawyer, L. G. Larsen, and C. R. Tobias. 2012. Hydrogeomorphology of the hyporheic zone: Stream solute and fine particle interactions with a dynamic streambed. Journal of Geophysical Research: Biogeosciences **117**:G00N11.

Harvey, J. W., and C. C. Fuller. 1998. Effect of enhanced manganese oxidation in the hyporheic zone on basin-scale geochemical mass balance. Water Resources Research **34**:623-636.

Hassan, M. A. 1990. Observations of desert flood bores. Earth Surface Processes and Landforms **15**:481-485.

Hassan, M. A., A. S. Gottesfeld, D. R. Montgomery, J. F. Tunnicliffe, G. K. C. Clarke, G. Wynn, H. Jones-Cox, R. Poirier, E. MacIsaac, H. Herunter, and S. J. Macdonald. 2008. Salmon-driven bed load transport and bed morphology in mountain streams. Geophysical Research Letters **35**:L04405.

Hastings, A., and S. Harrison. 1994. Metapopulation dynamics and genetics. Annual Review of Ecology and Systematics **25**:167-188.

Haukos, D. A., M. R. Miller, D. L. Orthmeyer, J. Y. Takekawa, J. P. Fleskes, M. L. Casazza, W. M. Perry, and J. A. Moon. 2006. Spring migration of northern pintails from Texas and New Mexico, USA. Waterbirds **29**:127-136.

Hawkins, C. P., and J. R. Sedell. 1981. Longitudinal and seasonal-changes in functional-organization of macroinvertebrate communities in four Oregon streams. Ecology **62**:387-397.

Hecnar, S. J., and R. T. McLoskey. 1996. Regional dynamics and the status of amphibians. Ecology **77**:2091-2097.

Hedin, L. O., J. J. Armesto, and A. H. Johnson. 1995. Patterns of nutrient loss from unpolluted old-growth temperate forests: Evaluation of biogeochemical theory. Ecology **76**:493-509.

Heiler, G., T. Hein, F. Schiemer, and G. Bornette. 1995. Hydrological connectivity and flood pulses as the central aspects of a river-floodplain system. Regulated Rivers Research and Management **11**:351-361.

Heimann, D. C., and M. J. Roell. 2000. Sediment loads and accumulation in a small riparian wetland system in northern Missouri. Wetlands **20**:219-231.

Heine, R. A., C. L. Lant, and R. R. Sengupta. 2004. Development and comparison of approaches for automated mapping of stream channel networks. Annals of the Association of American Geographers **94**:477-490.

Helfield, J. M., and R. J. Naiman. 2006. Keystone interactions: Salmon and bear in riparian forests of Alaska. Ecosystems **9**:167-180.

Helton, A. M., G. C. Poole, J. L. Meyer, W. M. Wollheim, B. J. Peterson, P. J. Mulholland, E. S. Bernhardt, J. A. Stanford, C. Arango, L. R. Ashkenas, L. W. Cooper, W. K. Dodds, S. V. Gregory, R. O. Hall, S. K. Hamilton, S. L. Johnson, W. H. McDowell, J. D. Potter, J. L. Tank, S. M. Thomas, H. M. Valett, J. R. Webster, and L. Zeglin. 2011. Thinking outside the channel: Modeling nitrogen cycling in networked river ecosystems. Frontiers in Ecology and the Environment **9**:229-238.

Hemond, H. F. 1980. Biogeochemistry of Thoreau's Bog, Concord, Massachusetts. Ecological Monographs **50**:507-526.

Hemond, H. F. 1983. The nitrogen budget of Thoreau's Bog. Ecology **64**:99-109.

Hendricks, R. 2005. *Siren lacertina* Linnaeus, 1766, Greater Siren. Pages 912-914 *in* Amphibian declines: The conservation status of United States species. M. Lannoo, editor. University of California Press, Berkeley, CA.

Henning, J. A., R. E. Gresswell, and I. A. Fleming. 2007. Use of seasonal freshwater wetlands by fishes in a temperate river floodplain. Journal of Fish Biology **71**:476-492.

Hermoso, V., M. J. Kennard, and S. Linke. 2012. Integrating multidirectional connectivity requirements in systematic conservation planning for freshwater systems. Diversity and Distributions **18**:448-458.

Hershey, A. E., J. Pastor, B. J. Peterson, and G. W. Kling. 1993. Stable isotopes resolve the drift paradox for baetis mayflies in an arctic river. Ecology **74**:2315-2325.

Herwig, B. R., K. D. Zimmer, M. A. Hanson, M. L. Konsti, J. A. Younk, R. W. Wright, S. R. Vaughn, and M. D. Haustein. 2010. Factors influencing fish distributions in shallow lakes in prairie and prairie-parkland regions of Minnesota, USA. Wetlands **30**:609-619.

Hess, G. R. 1996. Linking extinction to connectivity and habitat destruction in metapopulation models. The American Naturalist **148**:226-236.

Hester, E. T., and M. W. Doyle. 2008. In-stream geomorphic structures as drivers of hyporheic exchange. Water Resources Research **44**:W03417.

Hester, E. T., M. W. Doyle, and G. C. Poole. 2009. The influence of in-stream structures on summer water temperatures via induced hyporheic exchange. Limnology and Oceanography **54**:355.

Hester, E. T., and M. N. Gooseff. 2010. Moving beyond the banks: Hyporheic restoration is foundation to restoring ecological services and functions of streams. Environmental Science & Technology **44**:1521-1525.

Hewlett, J. D. 1982. Principles of forest hydrology. University of Georgia Press, Athens, GA.

Hewlett, J. D., G. B. Cunningham, and C. A. Troendle. 1977. Predicting stormflow and peakflow from small basin in humid areas by the R-index method. Water Resources Bulletin **13**:231-253.

Hewlett, J. D., and A. R. Hibbert. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. Pages 275-290 *in* International symposium on forest hydrology. W. S. Sopper and H. W. Hull, editors. Pergamon Press, New York, NY.

Heyes, A., T. R. Moore, J. W. M. Rudd, and J. J. Dugoua. 2000. Methyl mercury in pristine and impounded boreal peatlands, Experimental Lakes Area, Ontario, Canada. Canadian Journal of Fisheries and Aquatic Sciences **57**:2211-2222.

Hill, A. R., C. F. Labadia, and K. Sanmugadas. 1998. Hyporheic zone hydrology and nitrogen dynamics in relation to the streambed topography of a N-rich stream. Biogeochemistry **42**:285-310.

Hill, A. R., and D. J. Lymburner. 1998. Hyporheic zone chemistry and stream-subsurface exchange in two groundwater-fed streams. Canadian Journal of Fisheries and Aquatic Sciences **55**:495-506.

Hill, W. R., and A. W. Knight. 1988. Nutrient and light limitations of algae in two northern California streams. Journal of Phycology **24**:125-132.

Hitt, N. P., and P. L. Angermeier. 2008. Evidence for fish dispersal from spatial analysis of stream network topology. Journal of the North American Benthological Society **27**:304-320.

Hitt, N. P., C. A. Frissell, C. C. Muhlfeld, and F. W. Allendorf. 2003. Spread of hybridization between native westslope cutthroat trout, *Oncorhynchus clarki lewisi*, and nonnative rainbow trout, *Oncorhynchus mykiss*. Canadian Journal of Fisheries and Aquatic Sciences **60**:1440-1451.

Hladyz, S., S. C. Watkins, K. L. Whitworth, and D. S. Baldwin. 2011. Flows and hypoxic blackwater events in managed ephemeral river channels. Journal of Hydrology **401**:117-125.

Hobbie, J. E., and R. G. Wetzel. 1992. Microbial control of dissolved organic carbon in lakes: Research for the future. Hydrobiologia **229**:169-180.

Hoffmann, C. C., C. Kjaergaard, J. Uusi-Kämppä, H. C. Hansen, and B. Kronvang. 2009. Phosphorus retention in riparian buffers: Review of their efficiency. Journal of Environmental Quality **38**:1942-1955.

Holloway, J. M., R. A. Dahlgren, B. Hansen, and W. H. Casey. 1998. Contribution of bedrock nitrogen to high nitrate concentrations in stream water. Nature **395**:785-788.

Holmstrup, M., A.-M. Bindesbøl, G. J. Oostingh, A. Duschl, V. Scheil, H.-R. Köhler, S. Loureiro, A. M. V. M. Soares, A. L. G. Ferreira, C. Kienle, A. Gerhardt, R. Laskowski, P. E. Kramarz, M. Bayley, C. Svendsen, and D. J. Spurgeon. 2010. Interactions between effects of environmental chemicals and natural stressors: A review. Science of The Total Environment **408**:3746-3762.

Hooke, J. 2003. Coarse sediment connectivity in river channel systems: A conceptual framework and methodology. Geomorphology **56**:79-94.

Hope, D., M. F. Billet, and M. S. Cresser. 1994. A review of the export of carbon in river water: Fluxes and processes. Environmental Pollution **84**:301-324.

Hornberger, G. M., J. P. Raffensperger, and P. L. Wilberg. 1998. Elements of physical hydrology. Johns Hopkins University Press, Baltimore, MD.

Hornberger, M. I., S. N. Luoma, M. L. Johnson, and M. Holyoak. 2009. Influence of remediation in a mine-impacted river: Metal trends over large spatial and temporal scales. Ecological Applications **19**:1522-1535.

Horton, R. E. 1945. Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. Bulletin of the Geological Society of America **56**:275-370.

Horwitz, R. J. 1978. Temporal variability patterns and the distributional patterns of stream fishes. Ecological Monographs **48**:307-321.

Howarth, R. W., J. R. Fruci, and D. Sherman. 1991. Inputs of sediment and carbon to an estuarine ecosystem: Influence of land use. Ecological Applications **1**:27-39.

Huang, C., Y. Peng, M. Lang, I.-Y. Yeo, and G. McCarty. 2014. Wetland inundation mapping and change monitoring using Landsat and airborne LiDAR data. Remote Sensing of Environment **141**:231-242.

Hubbard, D. E., and R. L. Linder. 1986. Spring runoff retention in prairie pothole wetlands. Journal of Soil and Water Conservation **41**:122-125.

Hudy, M., J. A. Coombs, K. H. Nislow, and B. H. Letcher. 2010. Dispersal and within-stream spatial population structure of brook trout revealed by pedigree reconstruction analysis. Transactions of the American Fisheries Society **139**:1276-1287.

Huggenberger, P., E. Hoehn, R. Beschta, and W. Woessner. 1998. Abiotic aspects of channels and floodplains in riparian ecology. Freshwater Biology **40**:407-425.

Hughes, D. A., and J. Lewin. 1982. A small-scale flood plain. Sedimentology **29**:891-895.

Hughes, D. A., and K. Sami. 1992. Transmission losses to alluvium and associated moisture dynamics in a semiarid ephemeral channel system in southern Africa. Hydrological Processes **6**:45-53.

Hughes, J. M., D. J. Schmidt, and D. S. Finn. 2009. Genes in streams: Using DNA to understand the movement of freshwater fauna and their riverine habitat. BioScience **59**:573-583.

Humphries, P., H. Keckeis, and B. Finlayson. 2015. The river wave concept: Integrating river ecosystem models. BioScience: doi: 10.1093/biosci/biu1130.

Humphries, S., and G. D. Ruxton. 2002. Is there really a drift paradox? Journal of Animal Ecology **71**:151-154.

Hunsinger, T. W., and M. J. Lannoo. 2005. *Notophthalmus viridescens*, eastern newt. Pages 912-914 *in* Amphibian declines: The conservation status of United States species. M. Lannoo, editor. University of California Press, Berkeley, CA.

Hunt, R. J., M. Strand, and J. F. Walker. 2006. Measuring groundwater-surface water interaction and its effect on wetland stream benthic productivity, Trout Lake watershed, northern Wisconsin, USA. Journal of Hydrology **320**:370-384.

Hunter, M. A., T. Quinn, and M. P. Hayes. 2005. Low flow spatial characteristics in forested headwater channels of southwest Washington. Journal of the American Water Resources Association **41**:503-516.

Hupp, C. R. 2000. Hydrology, geomorphology and vegetation of Coastal Plain rivers in the south-eastern USA. Hydrological Processes **14**:2991-3010.

Hupp, C. R., and W. R. Osterkamp. 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology **14**:277-295.

Hupp, C. R., W. R. Osterkamp, and A. D. Howard. 1995. Biogeomorphology, terrestrial and freshwater systems. Elsevier Science, Amsterdam, The Netherlands.

Hupp, C. R., A. R. Pierce, and G. B. Noe. 2009. Floodplain geomorphic processes and environmental impacts of human alteration along Coastal Plain rivers, USA. Wetlands **29**:413-429.

Hurley, J. P., J. M. Benoit, C. L. Babiarz, M. M. Shafer, A. W. Andren, J. R. Sullivan, R. Hammond, and D. A. Webb. 1995. Influences of watershed characteristics on mercury levels in Wisconsin rivers. Environmental Science & Technology **29**:1867-1875.

Huryn, A. D., and K. E. Gibbs. 1999. Riparian sedge meadows in Maine. A macroinvertebrate community structured by river-floodplain interaction. Pages 363-382 *in* Invertebrates in freshwater wetlands of North America: Ecology and management. D. P. Batzer, R. B. Rader, and S. A. Wissinger, editors. John Wiley & Sons, New York, NY.

Huryn, A. D., K. A. Slavik, R. L. Lowe, S. M. Parker, D. S. Anderson, and B. J. Peterson. 2005. Landscape heterogeneity and the biodiversity of arctic stream communities: A habitat template analysis. Canadian Journal of Fisheries and Aquatic Sciences **62**:1905-1919.

Ijjasz-Vasquez, E. J., R. L. Bras, and I. Rodriguez-Iturbe. 1993. Hack's relation and optimal channel networks: The elongation of river basins as a consequence of energy minimization. Geophysical Research Letters **20**:1583-1586.

Ilg, C., F. Dziock, F. Foeckler, K. Follner, M. Gerisch, J. Glaeser, A. Rink, A. Schanowski, M. Scholz, O. Deichner, and K. Henle. 2008. Long-term reactions of plants and macroinvertebrates to extreme floods in floodplain grasslands. Ecology **89**:2392-2398.

Ivey, C. T., and J. H. Richards. 2001. Genetic diversity of everglades sawgrass, *Cladium jamaicense* (Cyperaceae). International Journal of Plant Sciences **162**:817-825.

Izbicki, J. A. 2007. Physical and temporal isolation of mountain headwater streams in the western Mojave Desert, southern California. Journal of the American Water Resources Association **43**:26-40.

Jackson, C. R., and C. M. Pringle. 2010. Ecological benefits of reduced hydrologic connectivity in intensively developed landscapes. BioScience **60**:37-46.

Jacobson, L. M., M. B. David, and L. E. Drinkwater. 2011. A spatial analysis of phosphorus in the Mississippi river basin. Journal of Environmental Quality **40**:931-941.

Jacques, J., and D. L. Lorenz. 1988. Techniques for estimating the magnitude and frequency of floods of ungauged streams in Minnesota. USGS Water-Resources Investigations Report 84-4170, U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

James, A. L., and N. T. Roulet. 2007. Investigating hydrologic connectivity and its association with threshold change in runoff response in a temperate forested watershed. Hydrological Processes **21**:3391-3408.

James, E. R., M. Manga, T. P. Rose, and G. B. Hudson. 2000. The use of temperature and the isotopes of O, H, C, and noble gases to determine the pattern and spatial extent of groundwater flow. Journal of Hydrology **237**:100-112.

Jansson, R., U. Zinko, D. M. Merritt, and C. Nilsson. 2005. Hydrochory increases riparian plant species richness: A comparison between a free-flowing and a regulated river. Journal of Ecology **93**:1094-1103.

Jeffres, C. A., J. J. Opperman, and P. B. Moyle. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environmental Biology of Fishes **83**:449-458.

Jencso, K. G., and B. L. McGlynn. 2011. Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. Water Resources Research **47**:W11527.

Jencso, K. G., B. L. McGlynn, M. N. Gooseff, S. M. Wondzell, K. E. Bencala, and L. A. Marshall. 2009. Hydrologic connectivity between landscapes and streams: Transferring reach- and plot-scale understanding to the catchment scale. Water Resources Research **45**:W04428.

Jenkins, K. M., and A. J. Boulton. 2003. Connectivity in a dryland river: Short-term aquatic microinvertebrate recruitment following floodplain inundation. Ecology **84**:2708-2723.

Johnson, A. I. 1967. Specific yield— Compilation of specific yields for various materials. USGS Water-Supply Paper 1662-D, U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Johnson, B. R., A. Haas, and K. M. Fritz. 2010. Use of spatially explicit physicochemical data to measure downstream impacts of headwater stream disturbance. Water Resources Research **46**:W09526.

Johnson, L. B., G. E. Host, J. H. Olker, and C. Richards. 2006. Landscape- and reach-scale predictors of large wood abundance in low-gradient streams. Pages 151-173 *in* Landscape influences on stream habitats and biological assemblages. R. M. Hughes, L. Wang, and P. W. Seelbach, editors. American Fisheries Society Symposium 48, Bethesda, MD.

Johnson, P. T. J., J. D. Olden, and M. J. Vander Zanden. 2008. Dam invaders: Impoundments facilitate biological invasions into freshwaters. Frontiers in Ecology and the Environment **6**:357-363.

Johnson, S. A., and R. B. Owen. 2005. *Amphiuma means* Garden, 1821, Two-toed amphiuma. Pages 642-646 *in* Amphibian declines: The conservation status of United States species. M. Lannoo, editor. University of California Press, Berkeley, CA.

Johnson, S. L., and J. A. Jones. 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Canadian Journal of Fisheries and Aquatic Sciences **57**:30-39.

Johnston, C., N. Detenbeck, and G. Niemi. 1990. The cumulative effect of wetlands on stream water quality and quantity. A landscape approach. Biogeochemistry **10**:105-141.

Johnston, C. A. 1991. Sediment and nutrient retention by freshwater wetlands: Effects on surface water quality. Critical Reviews in Environmental Control **21**:491-565.

Johnston, C. A. 1993. Material fluxes across wetland ecotones in Northern landscapes. Ecological Applications **3**:424-440.

Johnston, C. A., and R. J. Naiman. 1990a. Aquatic patch creation in relation to beaver population trends. Ecology **71**:1617-1621.

Johnston, C. A., and R. J. Naiman. 1990b. The use of a geographic information system to analyze long-term landscape alteration by beaver. Landscape Ecology **4**:5-19.

Johnston, C. A., B. A. Shmagin, P. C. Frost, C. Cherrier, J. H. Larson, G. A. Lamberti, and S. D. Bridgham. 2008. Wetland types and wetland maps differ in ability to predict dissolved organic carbon concentrations in streams. Sci Total Environ **404**:326-334.

Jones, J. B., and P. J. Mulholland. 2000. Streams and ground waters. Academic Press, San Diego, CA.

Jordan, T. E., M. P. Andrews, R. P. Szuch, D. F. Whigham, D. E. Weller, and A. D. Jacobs. 2007. Comparing functional assessments of wetlands to measurements of soil characteristics and nitrogen processing. Wetlands **27**:479-497.

Joyal, L. A., M. McCollough, and M. L. Hunter. 2001. Landscape ecology approaches to wetland species conservation: A case study of two turtle species in southern Maine. Conservation Biology **15**:1755-1762.

Jude, D. J., and J. Pappas. 1992. Fish utilization of Great Lakes coastal wetlands. Journal of Great Lakes Research **18**:651-672.

Julian, J. T., G. Rocco, M. M. Turner, and R. P. Brooks. 2013. Assessing wetland-riparian amphibian and reptile communities of the Mid-Atlantic Region. Pages 313-337 *in* Mid-Atlantic freshwater wetlands: Advances in wetlands science, management, policy, and practice. R. P. Brooks and D. H. Wardrop, editors. Springer, New York, NY.

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Pages 110-127 *in* Proceedings of the international large river symposium, Canadian Special Publication of Fisheries and Aquatic Sciences 106. D. P. Dodge, editor., Ottawa, Canada.

Kadlec, R. H., and S. D. Wallace. 2009. Treatment wetlands. 2nd edition. CRC Press, Boca Raton, FL.

Kanno, Y., B. H. Letcher, J. A. Coombs, K. H. Nislow, and A. R. Whiteley. 2014. Linking movement and reproductive history of brook trout to assess habitat connectivity in a heterogeneous stream network. Freshwater Biology **59**:142-154.

Kao, C. M., W. J. Y., K. F. Chen, H. Y. Lee, and M. J. Wu. 2002. Non-point source pesticide removal by a mountainous wetland. Water Science and Technology **46**:199-206.

Kaplan, L. A., and T. L. Bott. 1982. Diel fluctuations of DOC generated by algae in a piedmont stream. Limnology and Oceanography **27**:1091-1100.

Kaplan, L. A., T. N. Wiegner, J. D. Newbold, P. H. Ostrom, and H. Gandhi. 2008. Untangling the complex issue of dissolved organic carbon uptake: A stable isotope approach. Freshwater Biology **53**:855-864.

Karr, J. R., L. A. Toth, and D. R. Dudley. 1985. Fish communities of Midwestern rivers: A history of degradation. BioScience **35**:90-95.

Karwan, D. L., and J. E. Saiers. 2012. Hyporheic exchange and streambed filtration of suspended particles. Water Resources Research **48**:W01519.

Katano, I., J. N. Negishi, T. Minagawa, H. Doi, Y. Kawaguchi, and Y. Kayaba. 2009. Longitudinal macroinvertebrate organization over contrasting discontinuities: Effects of a dam and a tributary. Journal of the North American Benthological Society **28**:331-351.

Kaushal, S., and K. Belt. 2012. The urban watershed continuum: Evolving spatial and temporal dimensions. Urban Ecosystems **15**:409-435.

Kaushik, N. K., and H. B. N. Hynes. 1971. The fate of dead leaves that fall into streams. Archiv für Hydrobiologie **68**:465-515.

Kawaguchi, Y., and S. Nakano. 2001. Contribution of terrestrial invertebrates to the annual resource budget for salmonids in forest and grassland reaches of a headwater stream. Freshwater Biology **46**:303-316.

Kehew, A. E., R. N. Passero, R. V. Krishnamurthy, C. K. Lovett, M. A. Betts, and B. A. Dayharsh. 1998. Hydrogeochemical interaction between a wetland and an unconfined glacial drift aquifer, southwestern Michigan. Ground Water **36**:849-856.

Keitt, T., D. L. Urban, and B. T. Milne. 1997. Detecting critical scales in fragmented landscapes. Ecology and Society **1**:4.

Keller, E. A., A. MacDonald, and T. Tally. 1981. Streams in the coastal redwood environment: The role of large organic debris. Pages 161-176 *in* Proceedings of a symposium on watershed rehabilitation in Redwood National Park and other Pacific coastal areas; 1981 August 25-28 in Arcata, CA. R. N. Coats, editor. Center for Natural Resources Studies of JMI, Inc., Sacramento, CA.

Keller, E. A., and F. J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes and Landforms **4**:361-380.

Kiffney, P. M., C. M. Greene, J. E. Hall, and J. R. Davis. 2006. Tributary streams create spatial discontinuities in habitat, biological productivity, and diversity in mainstem rivers. Canadian Journal of Fisheries and Aquatic Sciences **63**:2518-2530.

Kiffney, P. M., J. S. Richardson, and M. C. Feller. 2000. Fluvial and epilithic organic matter dynamics in headwater streams of southwestern British Columbia, Canada. Archiv für Hydrobiologie **149**:109-129.

Kimball, B. A., E. Callender, and E. V. Axtmann. 1995. Effects of colloids on metal transport in a river receiving acid mine drainage, Upper Arkansas River, Colorado, USA. Applied Geochemistry **10**:285-306.

King, A. J., P. Humphries, and P. S. Lake. 2003. Fish recruitment on floodplains: The roles of patterns of flooding and life history characteristics. Canadian Journal of Fisheries and Aquatic Sciences **60**:773-786.

Kish, G. R., C. E. Stringer, M. T. Stewart, M. C. Rains, and A. E. Torres. 2010. A geochemical mass-balance method for base-flow separation, upper Hillsborough River watershed, west-central Florida, 2003-2005 and 2009. USGS Scientific Investigations Report 2010–5092, U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Knight, K. W., R. C. Schultz, C. M. Mabry, and T. M. Isenhart. 2010. Ability of remnant riparian forests, with and without grass filters, to buffer concentrated surface runoff. Journal of the American Water Resources Association **46**:311-322.

Knightes, C. D., E. M. Sunderland, M. Craig Barber, J. M. Johnston, and R. B. Ambrose. 2009. Application of ecosystem-scale fate and bioaccumulation models to predict fish mercury response times to changes in atmospheric deposition. Environmental Toxicology and Chemistry **28**:881-893.

Knighton, A. D. 1980. Longitudinal changes in size and sorting of stream-bed material in four English rivers. Geological Society of America Bulletin **91**:55-62.

Knighton, A. D. 1998. Fluvial forms and processes: A new perspective. Hodder Arnold, London, UK.

Knispel, S., and E. Castella. 2003. Disruption of a longitudinal pattern in environmental factors and benthic fauna by a glacial tributary. Freshwater Biology **48**:604-618.

Knudby, C., and J. Carrera. 2005. On the relationship between indicators of geostatistical, flow and transport connectivity. Advances in Water Resources **28**:405-421.

Knutson, M. G., J. R. Sauer, D. A. Olsen, M. J. Mossman, L. M. Hemesath, and M. J. Lannoo. 1999. Effects of landscape composition and wetland fragmentation on frog and toad abundance and species richness in Iowa and Wisconsin, U.S.A. Conservation Biology **13**:1437-1446.

Kondolf, G. M. 1997. Hungry water: Effects of dams and gravel mining on river channels. Environmental Management **21**:533-551.

Kondolf, G. M., A. J. Boulton, S. O. O'Daniel, G. C. Poole, F. J. Rahel, E. H. Stanley, E. Wohl, A. Bang, J. Carlston, C. Cristoni, H. Huber, S. Koljonen, P. Louhi, and K. Nakamura. 2006. Process-based ecological river restoration: Visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. Ecology and Society **11**:5.

Koprivnjak, J.-F., and T. R. Moore. 1992. Sources, sinks, and fluxes of dissolved organic carbon in subarctic fen catchments. Arctic and Alpine Research **24**:204-210.

Kortelainen, P. 1993. Content of total organic carbon in Finnish lakes and its relationship to catchment characteristics. Canadian Journal of Fisheries and Aquatic Sciences **50**:1477-1483.

Krapu, G. L., D. E. Facey, E. K. Fritzell, and D. H. Johnson. 1984. Habitat use by migrant Sandhill cranes in Nebraska. The Journal of Wildlife Management **48**:407-417.

Krümmel, E., R. Macdonald, L. Kimpe, I. Gregory-Eaves, M. Demers, J. Smol, B. Finney, and J. Blais. 2003. Aquatic ecology: Delivery of pollutants by spawning salmon. Nature **425**:255-256.

Krutz, L. J., T. J. Gentry, S. A. Senseman, I. L. Pepper, and D. P. Tierney. 2006. Mineralization of atrazine, metolachlor and their respective metabolites in vegetated filter strips and cultivated soil. Pest Management Science **62**:505-514.

Labbe, T. R., and K. D. Fausch. 2000. Dynamics of intermittent stream habitat regulate persistence of a threatened fish at multiple scales. Ecological Applications **10**:1774-1791.

LaGrange, T. G., and J. J. Dinsmore. 1989. Habitat use by mallards during spring migration through central Iowa. Journal of Wildlife Management **53**:1076-1081.

Lake, P. S. 2000. Disturbance, patchiness, and diversity in streams. Journal of the North American Benthological Society **19**:573-592.

Lamberti, G. A., and V. H. Resh. 1987. Seasonal patterns of suspended bacteria and algae in 2 northern California streams. Archiv für Hydrobiologie **110**:45-57.

Lamoureux, V. S., and D. M. Madison. 1999. Overwintering habitats of radio-implanted green frogs, *Rana clamitans*. Journal of Herpetology **33**:430-435.

Lampkin, A. J., and M. R. Sommerfeld. 1986. Impact of acid mine-drainage from abandoned spoils on the chemistry of an intermittent-stream in the arid southwest. Hydrobiologia **139**:135-142.

Lancaster, S. T., S. K. Hayes, and G. E. Grant. 2003. Effects of wood on debris flow runout in small mountain watersheds. Water Resources Research **39**:1168.

Lande, R., and S. Shannon. 1996. The role of genetic variation in adaptation and population persistence in a changing environment. Evolution **50**:434-437.

Lane, C. R., and E. D'Amico. 2010. Calculating the ecosystem service of water storage in isolated wetlands using LiDAR in north central Florida, USA. Wetlands **30**:967-977.

Lane, E. W. 1955. The importance of fluvial morphology in hydraulic engineering. Journal of the Hydraulics Division American Society of Civil Engineers **81**:1-17.

Lane, S. N., S. M. Reaney, and A. L. Heathwaite. 2009. Representation of landscape hydrological connectivity using a topographically driven surface flow index. Water Resources Research **45**:W08423.

Lang, M., O. McDonough, G. McCarty, R. Oesterling, and B. Wilen. 2012. Enhanced detection of wetland-stream connectivity using LiDAR. Wetlands **32**:461-473.

Lange, J. 2005. Dynamics of transmission losses in a large arid stream channel. Journal of Hydrology **306**:112-126.

Langston, M. A., and D. M. Kent. 1997. Fish recruitment to a constructed wetland. Journal of Freshwater Ecology **12**:123-129.

Larned, S. T., D. B. Arscott, J. Schmidt, and J. C. Diettrich. 2010. A framework of analyzing longitudinal and temporal variation in river flow and developing flow-ecology relationships. Journal of the American Water Resources Association **46**:541-553.

Larned, S. T., D. M. Hicks, J. Schmidt, A. J. H. Davey, K. Dey, M. Scarsbrook, D. B. Arscott, and R. A. Woods. 2008. The Selwyn River of New Zealand: A benchmark system for alluvial plain rivers. River Research and Applications **24**:1-21.

Laronne, J. B., and I. Reid. 1993. Very high rates of bedload sediment transport by ephemeral desert rivers. Nature **366**:148-150.

Larsen, L. G., J. Choi, M. K. Nungesser, and J. W. Harvey. 2012. Directional connectivity in hydrology and ecology. Ecological Applications **22**:2204-2220.

Lautz, L. K., and R. M. Fanelli. 2008. Seasonal biogeochemical hotspots in the streambed around restoration structures. Biogeochemistry **91**:85-104.

Lavery, H. J. 1972. The grey teal at saline drought-refuges in north Queensland. Wildfowl **23**:56-63.

Lawrence, J. E., M. E. Skold, F. A. Hussain, D. R. Silverman, V. H. Resh, D. L. Sedlak, R. G. Luthy, and J. E. McCray. 2013. Hyporheic zone in urban streams: A review and opportunities for enhancing water quality and improving aquatic habitat by active management. Environmental Engineering Science **30**:480-501.

Le, P. V. V., and P. Kumar. 2014. Power law scaling of topographic depressions and their hydrologic connectivity. Geophysical Research Letters **41**:1553-1559.

LeBlanc, R. T., R. D. Brown, and J. E. FitzGibbon. 1997. Modeling the Effects of Land Use Change on the Water Temperature in Unregulated Urban Streams. Journal of Environmental Management **49**:445-469.

Lecerf, A., D. Patfield, A. Boiche, M. P. Riipinen, E. Chauvet, and M. Dobson. 2007. Stream ecosystems respond to riparian invasion by Japanese knotweed (*Fallopia japonica*). Canadian Journal of Fisheries and Aquatic Sciences **64**:1273-1283.

Lee, M. A. B., K. L. Snyder, P. Valentine-Darby, S. J. Miller, and K. J. Ponzio. 2005. Dormant season prescribed fire as a management tool for the control of *Salix caroliniana* Michx. in a floodplain marsh. Wetlands Ecology and Management **13**:479-487.

Lehman, P. W., T. Sommer, and L. Rivard. 2008. The influence of floodplain habitat on the quantity and quality of riverine phytoplankton carbon produced during the flood season in San Francisco Estuary. Aquatic Ecology **42**:363-378.

Leibowitz, S. G. 2003. Isolated wetlands and their functions: An ecological perspective. Wetlands **23**:517-531.

Leibowitz, S. G., and K. C. Vining. 2003. Temporal connectivity in a prairie pothole complex. Wetlands **23**:13-25.

Leibowitz, S. G., P. J. Wigington, M. C. Rains, and D. M. Downing. 2008. Non-navigable streams and adjacent wetlands: Addressing science needs following the Supreme Court's Rapanos decision. Frontiers in Ecology and the Environment **6**:364-371.

Leigh, C., F. Sheldon, R. T. Kingsford, and A. H. Arthington. 2010. Sequential floods drive 'booms' and wetland persistence in dryland rivers: A synthesis. Marine and Freshwater Research **61**:896-908.

Leopold, L. B. 1968. Hydrology for urban planning. A guidebook on the hydrologic effects of urban land use. USGS Circular 554, U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Leopold, L. B. 1994. A view of the river. Harvard University Press, Cambridge, MA.

Leopold, L. B., and T. Maddock. 1953. The hydraulic geometry of stream channels and some physiographic implications. USGS Professional Paper 252, U.S. Department of the Interior, U.S. Geological Service, Washington, DC.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman and Co., San Francisco, CA.

Lerner, D. N. 1986. Leaking pipes recharge ground water. Ground Water **24**:654-662.

Letcher, B. H., K. H. Nislow, J. A. Coombs, M. J. O'Donnell, and T. L. Dubreuil. 2007. Population response to habitat fragmentation in a stream-dwelling brook trout population. PLOS ONE **2**:e1139.

Levick, L., J. Fonseca, D. Goodrich, M. Hernandez, D. Semmens, R. Leidy, M. Scianni, P. Guertin, M. Tluczek, and W. Kepner. 2008. The ecological and hydrological significance of ephemeral and intermittent streams in the arid and semi-arid American Southwest. EPA/600/R-08/134 and ARS/233046, U.S. Environmental Protection Agency, Office of Research and Development and U.S. Department of Agriculture/Agricultural Research Service. Southwest Watershed Research Center, Washington, DC.

Lewis, M. A. 1977. Aquatic inhabitants of a mine waste stream in Arizona. Research Note RM-349, U.S. Department of Agriculture, U.S. Forest Service, Fort Collins, CO.

Lewis, M. A., and R. Burraychak. 1979. Impact of copper mining on a desert intermittent stream. Journal of Arizona-Nevada Academy of Science **14**:22-29.

Lexartza-Artza, I., and J. Wainwright. 2009. Hydrological connectivity: Linking concepts with practical implications. CATENA **79**:146-152.

Lide, R. F., V. G. Meentemeyer, J. E. Pinder, and L. M. Beatty. 1995. Hydrology of a Carolina bay located on the upper Coastal Plain of western South Carolina. Wetlands **15**:47-57.

Ligon, F. K., W. E. Dietrich, and W. J. Trush. 1995. Downstream ecological effects of dams. BioScience **45**:183-192.

Limm, M. P., and M. P. Marchetti. 2009. Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) growth in off-channel and main-channel habitats on the Sacramento River, CA using otolith increment widths. Environmental Biology of Fishes **85**:141-151.

Lindsay, J. B., I. F. Creed, and F. D. Beall. 2004. Drainage basin morphometrics for depressional landscapes. Water Resources Research **4**:W09307.

Linqvist, O., K. Johansson, M. Aastrup, A. Andersson, L. Bringmark, G. Hovsenius, L. Hakanson, A. Iverfeldt, M. Meili, and B. Timm. 1991. Mercury in the Swedish environment— recent research on causes, consequences, and remedial measures. Water Air and Soil Pollution **55**:xi-xiii.

Lloyd, O. B., and W. L. Lyke. 1995. Ground water atlas of the United States, segment 10. USGS Hydrologic Investigations Atlas 730-K, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Loheide, S. P., and S. M. Gorelick. 2006. Quantifying stream-aquifer interactions through the analysis of remotely sensed thermographic profiles and in situ temperature histories. Environmental Science & Technology **40**:3336-3341.

Lorenz, D. L., C. A. Sanocki, and M. J. Kocian. 2010. Techniques for estimating the magnitude and frequency of peak flows on small streams in Minnesota based on through water year 2005. USGS Scientific Investigations Report 2009-5250, U.S. Department of the Interior, U.S. Geological Survey, in cooperation with the Minnesota Department of Transportation and the Minnesota Pollution Control Agency, Reston, VA.

Lowrance, R., L. S. Altier, J. D. Newbold, R. R. Schnabel, P. M. Groffman, J. M. Denver, D. L. Correll, J. W. Gilliam, J. L. Robinson, R. B. Brinsfield, K. W. Staver, W. Lucas, and A. H. Todd. 1997. Water quality functions of riparian forest buffers in Chesapeake Bay watersheds. Environmental Management **21**:687-712.

Luttrell, G. R., A. A. Echelle, W. L. Fisher, and D. J. Eisenhour. 1999. Declining status of two species of the *Macrhybopsis aestivalis* complex (Teleostei: Cyprinidae) in the Arkansas River basin and related effects of reservoirs as barriers to dispersal. Copeia **1999**:981-989.

Lytle, D. A., and N. L. Poff. 2004. Adaptation to natural flow regimes. Trends in Ecology and Evolution **19**:94-100

MacDonald, L. H., and D. Coe. 2007. Influence of headwater streams on downstream reaches in forested areas. Forest Science **53**:148-168.

Magana, H. A. 2013. Flood pulse trophic dynamics of larval fishes in a restored arid-land, river floodplain, middle Rio Grande, Los Lunas, New Mexico. Reviews in Fish Biology and Fisheries **23**:507-521.

Magette, W. L., R. B. Brinsfield, R. E. Palmer, and J. D. Wood. 1989. Nutrient and sediment removal by vegetated filter strips. Transactions of the American Society of Agricultural Engineers **32**:663-667.

Malard, F., K. Tockner, M. Dole-Olivier, and J. V. Ward. 2002. A landscape perspective on surface-subsurface hydrological exchanges in river corridors. Freshwater Biology **47**:621-640.

Malard, F., K. Tockner, and J. V. Ward. 1999. Shifting dominance of subcatchment water sources and flow paths in a glacial floodplain, Val Roseg, Switzerland. Arctic, Antarctic, and Alpine Research **31**:135-150.

Malard, F., U. Uehlinger, R. Zah, and K. Tockner. 2006. Flood-pulse and riverscape dynamics in a braided glacier river. Ecology **87**:704-716.

Malmqvist, B. 2002. Aquatic invertebrates in riverine landscapes. Freshwater Biology **47**:679-694.

Malvadkar, U., F. Scatena, and M. Leon. 2015. A comparison of connectivity metrics on watersheds and implications for water management. River Research and Applications: doi: 10.1002/rra.2730.

Marcus, W. A. 1987. Copper dispersion in ephemeral stream sediments. Earth Surface Processes and Landforms **12**:217-228.

Marker, A. F. H., and R. J. M. Gunn. 1977. Benthic algae of some streams in southern England. III. Seasonal variations in chlorophyll *a* in the seston. Journal of Ecology **65**:223-234.

Martin, S. L., and P. A. Soranno. 2006. Lake landscape position: Relationships to hydrologic connectivity and landscape features. Limnology and Oceanography **51**:801-814.

Marton, J. M., M. S. Fennessy, and C. B. Craft. 2014. USDA conservation practices increase carbon storage and water quality improvement functions: An example from Ohio. Restoration Ecology **22**:117-124.

Matheney, M. P., and C. F. Rabeni. 1995. Patterns of movement and habitat use by northern hogsuckers in an Ozark stream. Transactions of the American Fisheries Society **124**:886-897.

Matheney, R. K., and P. J. Gerla. 1996. Environmental isotopic evidence for the origins of ground and surface water in a prairie discharge wetland. Wetlands **16**:109-120.

Matthews, W. J., and E. Marsh-Matthews. 2007. Extirpation of red shiner in direct tributaries of Lake Texoma (Oklahoma-Texas): A cautionary case history from a fragmented river-reservoir system. Transactions of the American Fisheries Society **136**:1041-1062.

Matthews, W. J., and H. W. Robinson. 1998. Influence of drainage connectivity, drainage area and regional species richness on fishes of the interior highlands in Arkansas. American Midland Naturalist **139**:1-19.

May, C. L., and R. E. Gresswell. 2003. Processes and rates of sediment and wood accumulation in headwater streams of the Oregon Coast Range, USA. Earth Surface Processes and Landforms **28**:409-424.

May, C. L., and D. C. Lee. 2004. The relationship among in-channel sediment storage, pool depth, and summer survival of juvenile salmonids in Oregon Coast Range streams. North American Journal of Fisheries Management **24**:761-774.

Mayer, P. M., S. K. Reynolds, M. D. McCutchen, and T. J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. Journal of Environmental Quality **36**:1172-1180.

Mayer, T. D., and S. W. Naman. 2011. Streamflow response to climate as influenced by geology and elevation. Journal of the American Water Resources Association **47**:724-738.

McCauley, L. A., and M. J. Anteau. 2014. Generating nested wetland catchments with readily-available digital elevation data may improve evaluations of land-use change on wetlands. Wetlands **34**:1123-1132.

McClain, M. E., E. W. Boyer, C. L. Dent, S. E. Gergel, N. B. Grimm, P. M. Groffman, S. C. Hart, J. W. Harvey, C. A. Johnston, E. Mayorga, W. H. McDowell, and G. Pinay. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems **6**:301-312.

McDonough, O. T., M. W. Lang, J. D. Hosen, and M. A. Palmer. 2015. Surface hydrologic connectivity between Delmarva bay wetlands and nearby streams along a gradient of agricultural alteration. Wetlands: doi 10.1007/s13157-13014-10591-13155.

McEachern, P., E. E. Prepas, and D. S. Chanasyk. 2006. Landscape control of water chemistry in northern boreal streams of Alberta. Journal of Hydrology **323**:303-324.

McGlynn, B. L., and J. J. McDonnell. 2003. Quantifying the relative contributions of riparian and hillslope zones to catchment runoff. Water Resources Research **39**:1310.

McGlynn, B. L., J. J. McDonnell, J. Seibert, and C. Kendall. 2004. Scale effects on headwater catchment runoff timing, flow sources, and groundwater-streamflow relations. Water Resources Research **40**:W07504.

McGuire, K. J., J. J. McDonnell, M. Weiler, C. Kendall, B. L. McGlynn, J. M. Welker, and J. Seibert. 2005. The role of topography on catchment-scale water residence time. Water Resources Research **41**:W05002.

McLaughlin, D. L., and M. J. Cohen. 2013. Realizing ecosystem services: Wetland hydrologic function along a gradient of ecosystem condition. Ecological Applications **23**:1619-1631.

McLaughlin, D. L., D. A. Kaplan, and M. J. Cohen. 2014. A significant nexus: Geographically isolated wetlands influence landscape hydrology. Water Resources Research **50**:7153-7166.

McLaughlin, J. W., E. B. W. Calhoon, M. R. Gale, M. F. Jurgensen, and C. C. Trettin. 2011. Biogeochemical cycling and chemical fluxes in a managed northern forested wetland, Michigan, USA. Forest Ecology and Management **261**:649-661.

Meador, M. R. 1996. Water transfer projects and the role of fisheries biologists. Fisheries **21**:18-23.

Meixner, T. A., A. K. Huth, P. D. Brooks, M. H. Conklin, N. B. Grimm, R. C. Bales, P. A. Haas, and J. R. Petti. 2007. Influence of shifting flow paths on nitrogen concentrations during monsoon floods, San Pedro River, Arizona. Journal of Geophysical Research: Biogeosciences **112**:G03S03.

Merriam, J. L., W. H. McDowell, J. L. Tank, W. M. Wollheim, C. L. Crenshaw, and S. L. Johnson. 2002. Characterizing nitrogen dynamics, retention and transport in a tropical rainforest stream using an *in situ* 15N addition. Freshwater Biology **47**:143-160.

Mertes, L. A. K. 1997. Documentation and significance of the perirheic zone. Water Resources Research **33**:1749-1762.

Mertes, L. A. K., D. L. Daniel, J. M. Melack, B. Nelson, A. Martinelli, and B. R. Forsberg. 1995. Spatial patterns of hydrology, geomorphology, and vegetation on the floodplain of the Amazon River in Brazil from a remote sensing perspective. Geomorphology **13**:215-232.

Meyboom, P. 1964. Three observations on streamflow depletion by phreatophytes. Journal of Hydrology **2**:248-261.

Meyer, A., N. Kaschek, and E. I. Meyer. 2004. The effect of low flow and stream drying on the distribution and relative abundance of the alien amphipod, *Echinogammarus berilloni* (Catta, 1878) in a karstic stream system (Westphalia, Germany). Crustaceana **77**:909-922.

Meyer, J. L. 1994. The microbial loop in flowing waters. Microbial Ecology **28**:195-199.

Meyer, J. L., and G. E. Likens. 1979. Transport and transformation of phosphorus in a forest stream ecosystem. Ecology **60**:1255-1269.

Meyer, J. L., D. L. Strayer, J. B. Wallace, S. L. Eggert, G. S. Helfman, and N. E. Leonard. 2007. The contribution of headwater streams to biodiversity in river networks. Journal of the American Water Resources Association **43**:86-103.

Meyer, J. L., and J. B. Wallace. 2001. Lost linkages and lotic ecology: Rediscovering small streams. Pages 295-317 *in* Ecology: Achievement and challenge. M. C. Press, N. J. Huntly, and S. Levin, editors. Blackwell Science, Oxford, UK.

Meyer, J. L., J. B. Wallace, and S. L. Eggert. 1998. Leaf litter as a source of dissolved organic carbon in streams. Ecosystems **1**:240-249.

Meyer, L. D., S. M. Dabney, and W. C. Harmon. 1995. Sediment-trapping effectiveness of stiff-grass hedges. Transactions of the American Society of Agricultural Engineers **38**:809-815.

Michalzik, B., K. Kalbitz, J. H. Park, S. Solinger, and E. Matzner. 2001. Fluxes and concentrations of dissolved organic carbon and nitrogen – a synthesis for temperate forests. Biogeochemistry **52**:173-205.

Middleton, B. 2000. Hydrochory, seed banks, and regeneration dynamics along the landscape boundaries of a forested wetland. Plant Ecology **146**:169-184.

Middleton, S., and D. Liittschwager. 1994. Witness: Endangered species of North America. Chronicle Books, San Francisco, CA.

Mierle, G., and R. Ingram. 1991. The role of humic substances in the mobilization of mercury from watersheds. Water Air and Soil Pollution **56**:349-357.

Miller, E. L., R. S. Beasley, and E. R. Lawson. 1988. Forest harvest and site preparation effects on stormflow and peakflow of ephemeral streams in the Ouachita Mountains. Journal of Environmental Quality **17**:212-218.

Min, J.-H., D. Perkins, and J. Jawitz. 2010. Wetland-groundwater interactions in subtropical depressional wetlands. Wetlands **30**:997-1006.

Minshall, G. W. 1967. Role of allochthonous detritus in the tropic structure of a woodland springbrook community. Ecology **48**:139-149.

Minshall, G. W., R. C. Petersen, T. L. Bott, C. E. Cushing, K. W. Cummins, R. L. Vannote, and J. R. Sedell. 1992. Stream ecosystem dynamics of the Salmon River, Idaho: An 8th-order system. Journal of the North American Benthological Society **11**:111-137.

Minshall, G. W., R. C. Petersen, K. W. Cummins, T. L. Bott, J. R. Sedell, C. E. Cushing, and R. L. Vannote. 1983. Interbiome comparison of stream ecosystem dynamics. Ecological Monographs **53**:1-25.

Mitchell, C. A., T. W. Custer, and P. J. Zwank. 1992. Redhead duck behavior on lower Laguna Madre and adjacent ponds of southern Texas. The Southwestern Naturalist **37**:65-72.

Mitchell, C. P. J., P. W. C. Paton, and C. J. Raithel. 2007. The importance of vernal pools to reptiles, birds and mammals. Pages 169-192 *in* Science and conservation of vernal pools in northeastern North America. A. J. K. Calhoun and P. G. deMaynadier, editors. CRC Press, Boca Raton, FL.

Mitsch, W. J., J. K. Cronk, X. Wu, R. W. Nairn, and D. L. Hey. 1995. Phosphorus retention in constructed freshwater riparian marshes. Ecological Applications **5**:830-845.

Mitsch, W. J., and J. G. Gosselink. 2007. Wetlands. 4th edition. John Wiley & Sons Inc., Hoboken, NJ.

Mitsch, W. J., J. G. Gosselink, C. Anderson, J., and L. Zhang. 2009. Wetland ecosystems. 1st edition. John Wiley & Sons, Hoboken, NJ.

Miyazono, S., J. N. Aycock, L. E. Miranda, and T. E. Tietjen. 2010. Assemblage patterns of fish functional groups relative to habitat connectivity and conditions in floodplain lakes. Ecology of Freshwater Fish **19**:578-585.

Mock, S. J. 1971. A classification channel links in stream networks. Water Resources Research **7**:1558-1566.

Moilanen, A., and I. Hanski. 1998. Metapopulation dynamics: Effects of habitat quality and landscape structure. Ecology **79**:2503-2515.

Moilanen, A., and M. Nieminen. 2002. Simple connectivity measures in spatial ecology. Ecology **83**:1131-1145.

Moll, D. 1990. Population sizes and foraging ecology in a tropical freshwater stream turtle community. Journal of Herpetology **24**:48-53.

Montgomery, D. R. 1994. Road surface drainage, channel initiation, and slope instability. Water Resources Research **30**:1925-1932.

Montgomery, D. R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association **35**:397-410.

Montgomery, D. R., B. D. Collins, J. M. Buffington, and T. B. Abbe. 2003. Geomorphic effects of wood in rivers. Pages 21-47 *in* Ecology and management of wood in world rivers. S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. American Fisheries Society Symposium 37, Bethesda, MD.

Moore, R. D., D. L. Spittlehouse, and A. Story. 2005. Riparian microclimate and stream temperature response to forest harvesting: A review. Journal of the American Water Resources Association **41**:813-834.

Moraghan, J. T. 1993. Loss and assimilation of 15N-nitrate added to a North Dakota cattail marsh. Aquatic Botany **46**:225-234.

Moreno-Mateos, D., U. Mander, F. A. Comin, C. Pedrocchi, and E. Uuemaa. 2008. Relationships between landscape pattern, wetland characteristics, and water quality in agricultural catchments. Journal of Environmental Quality **37**:2170-2180.

Morisawa, M. 1957. Accuracy of determination of stream lengths from topographic maps. Transactions of the American Geophysical Union **38**:86-88.

Morita, K., and S. Yamamoto. 2002. Effects of habitat fragmentation by damming on the persistence of stream-dwelling charr populations. Conservation Biology **16**:1318-1323.

Morley, T. R., A. S. Reeve, and A. J. K. Calhoun. 2011. The role of headwater wetlands in altering streamflow and chemistry in a Maine, USA catchment. Journal of the American Water Resources Association **47**:337-349.

Morrissey, C. A., I. L. Pollet, S. J. Ormerod, and J. E. Elliott. 2011. American dippers indicate contaminant biotransport by Pacific salmon. Environmental Science & Technology **46**:1153-1162.

Morrissey, M. B., and D. T. de Kerckhove. 2009. The maintenance of genetic variation due to asymmetric gene flow in dendritic metapopulations. The American Naturalist **174**:875-889.

Mudd, E., J. Entry, R. Lowrance, and H. Walker. 1995. The influence of management of riparian areas on movement of C-14 labelled atrazine through undisturbed soil cores. Pages 201-210 *in* Versatility of wetlands in the agricultural landscape. K. L. Campbell, editor. American Society of Agricultural Engineers, St. Joseph, MI.

Mulholland, P. J., A. M. Helton, G. C. Poole, R. O. Hall, S. K. Hamilton, B. J. Peterson, J. L. Tank, L. R. Ashkenas, L. W. Cooper, C. N. Dahm, W. K. Dodds, S. E. G. Findlay, S. V. Gregory, N. B. Grimm, S. L. Johnson, W. H. McDowell, J. L. Meyer, H. M. Valett, J. R. Webster, C. P. Arango, J. J. Beaulieu, M. J. Bernot, A. J. Burgin, C. L. Crenshaw, L. T. Johnson, B. R. Niederlehner, J. M. O'Brien, J. D. Potter, R. W. Sheibley, D. J. Sobota, and S. M. Thomas. 2008. Stream denitrification across biomes and its response to anthropogenic nitrate loading. Nature **452**:202-205.

Mulholland, P. J., and W. R. Hill. 1997. Seasonal patterns in streamwater nutrient and dissolved organic carbon concentrations: Separating catchment flow path and in-stream effects. Water Resources Research **33**:1297-1306.

Mulholland, P. J., and E. J. Kuenzler. 1979. Organic carbon export from upland and forested wetland watersheds. Limnology and Oceanography **24**:960-966.

Mulholland, P. J., E. R. Marzolf, S. P. Hendricks, R. V. Wilkerson, and A. K. Baybayan. 1995. Longitudinal patterns of nutrient cycling and periphyton characteristics in streams: A test of upstream-downstream linkage. Journal of the North American Benthological Society **14**:357-370.

Mulholland, P. J., R. A. Minear, and J. W. Elwood. 1988. Production of soluble, high molecular weight phosphorus and its subsequent uptake by stream detritus. Verhandlungen der Internationale Vereinigung für Theoretische und Angewandte Limnologie **23**:1190-1197.

Mulholland, P. J., H. M. Valett, J. R. Webster, S. A. Thomas, L. W. Cooper, S. K. Hamilton, and B. J. Peterson. 2004. Stream denitrification and total nitrate uptake rates measured using a field ^{15}N tracer addition approach. Limnology and Oceanography **49**:809-820.

Mulhouse, J. M., and S. M. Galatowitsch. 2003. Revegetation of prairie pothole wetlands in the mid-continental US: Twelve years post-reflooding. Plant Ecology **169**:143-159.

Mullen, L. B., H. Arthur Woods, M. K. Schwartz, A. J. Sepulveda, and W. H. Lowe. 2010. Scale-dependent genetic structure of the Idaho giant salamander (*Dicamptodon aterrimus*) in stream networks. Molecular Ecology **19**:898-909.

Müller, K. 1982. The colonization cycle of insects. Oecologia **53**:202-207.

Murkin, H. R., and P. J. Caldwell. 2000. Avian use of prairie wetlands. Pages 249-286 *in* Prairie wetland ecology: The contribution of the marsh ecology research program. H. R. Murkin, A. G. van der Valk, and W. R. Clark, editors. Iowa State University Press, Ames, IA.

Nadeau, T. L., and M. C. Rains. 2007. Hydrological connectivity between headwater streams and downstream waters: How science can inform policy. Journal of the American Water Resources Association **43**:118-133.

Naiman, R. J. 1982. Characteristics of sediment and organic carbon export from pristine boreal forest watersheds. Canadian Journal of Fisheries and Aquatic Sciences **39**:1699-1718.

Naiman, R. J., and R. E. Bilby. 1998. River ecology and management: Lessons from the Pacific coastal ecoregion Springer-Verlag, New York, NY.

Naiman, R. J., and H. Decamps. 1997. The ecology of interfaces: Riparian zones. Annual Review of Ecology and Systematics **28**:621-658.

Naiman, R. J., H. Decamps, and M. E. McClain. 2005. Riparia: Ecology, conservation, and management of streamside communities. Elsevier Academic Press, Burlington, MA.

Naiman, R. J., C. A. Johnston, and J. C. Kelley. 1988. Alteration of North-American streams by beaver. BioScience **38**:753-762.

Naiman, R. J., G. Pinay, C. A. Johnston, and J. Pastor. 1994. Beaver influences on the long-term biogeochemical characteristics of boreal forest drainage networks. Ecology **75**:905-921.

Naiman, R. J., and J. R. Sedell. 1979. Characterization of particulate organic matter transported by some Cascade Mountain streams. Journal of the Fisheries Research Board of Canada **36**:17-31.

Nakamura, F., and F. J. Swanson. 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. Earth Surface Processes and Landforms **18**:43-61.

Nakano, S., H. Miyasaka, and N. Kuhara. 1999. Terrestrial-aquatic linkages: Riparian arthropod inputs alter trophic cascades in a stream food web. Ecology **80**:2435-2441.

Nakano, S., and M. Murakami. 2001. Reciprocal subsidies: Dynamic interdependence between terrestrial and aquatic food webs. Proceedings of the National Academy of Sciences **98**:166-170.

Nanson, G. C., and J. C. Croke. 1992. A genetic classification of floodplains. Geomorphology **4**:459-486.

National Research Council. 2002. Riparian areas: Functions and strategies for management. The National Academies Press, Washington, DC.

Nedeau, E. J., R. W. Merritt, and M. G. Kaufman. 2003. The effect of an industrial effluent on an urban stream benthic community: Water quality vs. habitat quality. Environmental Pollution **123**:1-13.

Neubauer, E., S. J. Köhler, F. von der Kammer, H. Laudon, and T. Hofmann. 2013. Effect of pH and stream order on iron and arsenic speciation in boreal catchments. Environmental Science & Technology **47**:7120-7128.

Newbold, J. D. 1992. Cycles and spirals of nutrients. Pages 379-408 *in* The rivers handbook. Volume 1. Hydrological and ecological principles. P. Calow and G. E. Petts, editors. Blackwell Scientific, Oxford, UK.

Newbold, J. D., J. W. Elwood, R. V. Oneill, and A. L. Sheldon. 1983a. Phosphorus dynamics in a woodland stream ecosystem: A study of nutrient spiralling. Ecology **64**:1249-1265.

Newbold, J. D., J. W. Elwood, R. V. Oneill, and W. Vanwinkle. 1981. Measuring nutrient spiralling in streams. Canadian Journal of Fisheries and Aquatic Sciences **38**:860-863.

Newbold, J. D., J. W. Elwood, M. S. Schulze, R. W. Stark, and J. C. Barmeier. 1983b. Continuous ammonium enrichment of a woodland stream: Uptake kinetics, leaf decomposition, and nitrification. Freshwater Biology **13**:193-204.

Newbold, J. D., S. Herbert, B. W. Sweeney, P. Kiry, and S. J. Alberts. 2010. Water quality functions of a 15-year-old riparian forest buffer system. Journal of the American Water Resources Association **46**:299-310.

Newbold, J. D., P. J. Mulholland, J. W. Elwood, and R. V. Oneill. 1982a. Organic carbon spiralling in stream ecosystems. Oikos **38**:266-272.

Newbold, J. D., R. V. O'Neill, J. W. Elwood, and W. Van Winkle. 1982b. Nutrient spiraling in streams: Implications for nutrient limitation and invertebrate activity. The American Naturalist **120**:628-665.

Newbold, J. D., S. A. Thomas, G. W. Minshall, C. E. Cushing, and T. Georgian. 2005. Deposition, benthic residence, and resuspension of fine organic particles in a mountain stream. Limnology and Oceanography **50**:1571-1580.

Newman, D. G., and C. R. Griffin. 1994. Wetland use by river otters in Massachusetts. Journal of Wildlife Management **58**:18-23.

NHD. 2008. National Hydrography Dataset. U.S. Geological Survey.

Nielsen, J. L. 1992. Microhabitat-specific foraging behavior, diet, and growth of juvenile coho salmon. Transactions of the American Fisheries Society **121**:617-634.

Niemuth, N. D., B. Wangler, and R. E. Reynolds. 2010. Spatial and temporal variation in wet area of wetlands in the Prairie Pothole Region of North Dakota and South Dakota. Wetlands **30**:1053-1064.

Nilsson, C., R. L. Brown, R. Jansson, and D. M. Merritt. 2010. The role of hydrochory in structuring riparian and wetland vegetation. Biological Reviews **85**:837-858.

Nixon, S. W., and V. J. Lee. 1986. Wetlands and water quality: A regional review of recent research in the United States on the role of freshwater and saltwater wetlands as sources, sinks, and transformers of nitrogen, phosphorus, and various heavy metals. Technical Report Y-86-2, U.S. Army Corp of Engineers, Waterways Experiment Station, Vicksburg, MS.

Noe, G. B., and C. R. Hupp. 2005. Carbon, nitrogen, and phosphorus accumulation in floodplains of Atlantic Coastal Plain rivers, USA. Ecological Applications **15**:1178-1190.

Noe, G. B., and C. R. Hupp. 2007. Seasonal variation in nutrient retention during inundation of a short-hydroperid floodplain. River Research and Applications **23**:1088-1101.

Norton, J. B., J. A. Sandor, C. S. White, and V. Laahty. 2007. Organic matter transformations through arroyos and alluvial fan soils within a Native American agroecosystem. Soil Science Society of America Journal **71**:829-835.

Novitzki, R. P. 1979. Hydrologic characteristics of Wisconsin's wetlands and their influence on floods. Pages 377-388 *in* Wetland functions and values: The status of our understanding. Proceedings of the national symposium on wetlands. P. Greeson, J. Clark, and J. E. Clark, editors. American Water Resources Association, Minneapolis MN.

Nuff, J. C., and G. P. Asner. 2001. Dissolved organic carbon in terrestrial ecosystems: Synthesis and a model. Ecosystems **4**:29-48.

Nyberg, L., O. Calles, and L. Greenberg. 2008. Impact of short-term regulation on hyporheic water quality in a boreal river. River Research and Applications **24**:407-419.

O'Brien, J. M., S. K. Hamilton, L. E. Kinsman-Costello, J. T. Lennon, and N. E. Ostrom. 2012. Nitrogen transformations in a through-flow wetland revealed using whole-ecosystem pulsed ^{15}N additions. Limnology and Oceanography **57**:221-234.

O'Driscoll, M. A., and D. R. DeWalle. 2010. Seeps regulate stream nitrate concentration in a forested Appalachian catchment. Journal of Environmental Quality **39**:420-431.

Obermann, M., K.-H. Rosenwinkel, and M.-G. Tournoud. 2009. Investigation of first flushes in a medium-sized Mediterranean catchment. Journal of Hydrology **373**:405-415.

OMB. 2004. Final information quality bulletin for peer review. (Memorandum M-05-03), Office of Management and Budget, Washington, DC.

Orr, C. H., K. I. Predick, E. H. Stanley, and K. L. Rogers. 2014. Spatial autocorrelation of denitrification in a restored and a natural floodplain. Wetlands **34**:89-100.

Osborne, L. L., and M. Wiley. 1992. Influence of tributary position on the structure of warmwater fish communities. Canadian Journal of Fisheries and Aquatic Sciences **49**:671-681.

Osterkamp, W., L. Lane, and C. Savard. 1994. Recharge estimates using a geomorphic/distributed-parameter simulation approach, Amargosa River Basin. Journal of the American Water Resources Association **30**:493-507.

Osterkamp, W. R. 2008. Annotated definitions of selected geomorphic terms and related terms of hydrology, sedimentology, soil science and ecology USGS Open File Report 2008-1217, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Osterkamp, W. R., and C. R. Hupp. 2010. Fluvial processes and vegetation— glimpses of the past, the present, and perhaps the future. Geomorphology **116**:274-285.

Paik, K., and P. Kumar. 2004. Hydraulic geometry and the nonlinearity of the network instantaneous response. Water Resources Research **40**:W03602.

Paillex, A., S. Doledec, E. Castella, and S. Merigoux. 2009. Large river floodplain restoration: Predicting species richness and trait responses to the restoration of hydrological connectivity. Journal of Applied Ecology **46**:250-258.

Paller, M. H. 1994. Relationships between fish assemblage structure and stream order in South-Carolina coastal-plain streams. Transactions of the American Fisheries Society **123**:150-161.

Palmer, M. A., and C. M. Febria. 2012. The heartbeat of ecosystems. Science **336**:1393-1394.

Pannell, J. R., and B. Charlesworth. 2000. Effects of metapopulation processes on measures of genetic diversity. Philosophical Transactions of the Royal Society of London B-Biological Sciences **355**:1851-1864.

Park, D., M. Sullivan, E. Bayne, and G. Scrimgeour. 2008. Landscape-level stream fragmentation caused by hanging culverts along roads in Alberta's boreal forest. Canadian Journal of Forest Research **38**:566-575.

Parker, J. K., D. McIntyre, and R. T. Noble. 2010. Characterizing fecal contamination in stormwater runoff in coastal North Carolina, USA. Water Research **44**:4186-4194.

Pascual-Hortal, L., and S. Saura. 2006. Comparison and development of new graph-based landscape connectivity indices: towards the priorization of habitat patches and corridors for conservation. Landscape Ecology **21**:959-967.

Paterson, K. G., and J. L. Schnoor. 1992. Fate of alachlor and atrazine in a riparian zone field site. Water Environment Research **64**:274-283.

Patten, D. T., L. Rouse, and J. C. Stromberg. 2008. Isolated spring wetlands in the Great Basin and Mojave Deserts, USA: Potential response of vegetation to groundwater withdrawal. Environmental Management **41**:398-413.

Patz, M. J., K. J. Reddy, and Q. D. Skinner. 2006. Trace elements in coalbed methane produced water interacting with semi-arid ephemeral stream channels. Water Air and Soil Pollution **170**:55-67.

Paul, M. J., and J. L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics **32**:333-365.

Paul, M. J., J. L. Meyer, and C. A. Couch. 2006. Leaf breakdown in streams differing in catchment land use. Freshwater Biology **51**:1684-1695.

Payne, S. M., and W. W. Woessner. 2010. An aquifer classification system and Geographical Information System-based analysis tool for watershed managers in the western U.S. Journal of the American Water Resources Association **46**:1003-1023.

Pearse, A. T., G. L. Krapu, D. A. Brandt, and P. J. Kinzel. 2010. Changes in agriculture and abundance of snow geese affect carrying capacity of Sandhill cranes in Nebraska. Journal of Wildlife Management **74**:479-488.

Pease, A. A., J. J. Davis, M. S. Edwards, and T. F. Turner. 2006. Habitat and resource use by larval and juvenile fishes in an arid-land river (Rio Grande, New Mexico). Freshwater Biology **51**:475-486.

Perkin, J. S., and K. B. Gido. 2012. Fragmentation alters stream fish community structure in dendritic ecological networks. Ecol Appl **22**:2176-2187.

Person, H. S., E. J. Coil, and R. T. Beall. 1936. Little waters. A study of headwater streams and other little waters, their use and relations to the land. The Upstream Engineering Conference, The 75th Congress, 2nd Session, Senate Document No. 198, U.S. Government Printing Office, Washington, DC.

Peterjohn, W. T., and D. L. Correll. 1984. Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest. Ecology **65**:1466-1475.

Petersen, R. C., and K. W. Cummins. 1974. Leaf processing in a woodland stream. Freshwater Biology **4**:343-368.

Peterson, B. J., W. M. Wollheim, P. J. Mulholland, J. R. Webster, J. L. Meyer, J. L. Tank, E. Martí, W. B. Bowden, H. M. Valett, A. E. Hershey, W. H. McDowell, W. K. Dodds, S. K. Hamilton, S. Gregory, and D. D. Morrall. 2001. Control of nitrogen export from watersheds by headwater streams. Science **292**:86-90.

Peterson, E. E., D. M. Theobald, and J. M. Ver Hoef. 2007. Geostatistical modelling on stream networks: Developing valid covariance matrices based on hydrologic distance and stream flow. Freshwater Biology **52**:267-279.

Peterson, E. W., and T. B. Sickbert. 2006. Stream water bypass through meander neck, laterally extending the hyporheic zone. Hydrogeology Journal **14**:1443-1451.

Petranka, J. W., and C. T. Holbrook. 2006. Wetland restoration for amphibians: Should local sites be designed to support metapopulations or patchy populations? Restoration Ecology **14**:404-411.

Pezeshki, S. R., S. W. Li, F. D. Shields, and L. T. Martin. 2007. Factors governing survival of black willow (*Salix nigra*) cuttings in a streambank restoration project. Ecological Engineering **29**:56-65.

Phillips, P. J., and R. J. Shedlock. 1993. Hydrology and chemistry of groundwater and seasonal ponds in the Atlantic coastal-plain in Delaware, USA. Journal of Hydrology **141**:157-178.

Phillips, R., O. Beeri, and E. DeKeyser. 2005. Remote wetland assessment for Missouri Coteau prairie glacial basins. Wetlands **25**:335-349.

Phillips, R. W., C. Spence, and J. W. Pomeroy. 2011. Connectivity and runoff dynamics in heterogeneous basins. Hydrological Processes **25**:3061-3075.

Pilliod, D. S., C. R. Peterson, and P. I. Ritson. 2002. Seasonal migration of Columbia spotted frogs (*Rana luteiventris*) among complementary resources in a high mountain basin. Canadian Journal of Zoology **80**:1849-1862.

Pires, A. M., I. G. Cowx, and M. M. Coelho. 1999. Seasonal changes in fish community structure of intermittent streams in the middle reaches of the Guadiana basin, Portugal. Journal of Fish Biology **54**:235-249.

Platania, S. P., and C. S. Altenbach. 1998. Reproductive strategies and egg types of seven Rio Grande basin cyprinids. Copeia **1998**:559-569.

Poff, N. L. 1992. Why disturbances can be predictable: A perspective on the definition of disturbance in streams. Journal of the North American Benthological Society **11**:86-92.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime: A paradigm for river conservation and restoration. BioScience **47**:769-784.

Poff, N. L., J. D. Olden, D. M. Merritt, and D. M. Pepin. 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. Proceedings of the National Academy of Sciences of the United States of America **104**:5732-5737.

Polis, G. A., W. B. Anderson, and R. D. Holt. 1997. Toward an integration of landscape and food web ecology: The dynamics of spatially subsidized food webs. Annual Review of Ecology and Systematics **28**:289-316.

Pollock, M. M., G. R. Pess, T. J. Beechie, and D. R. Montgomery. 2004. The importance of beaver ponds to coho salmon production in the Stillaguamish River Basin, Washington, USA. North American Journal of Fisheries Management **24**:749-760.

Pollux, B. J. A., N. J. Ouborg, J. M. Van Groenendael, and M. Klaassen. 2007. Consequences of intraspecific seed-size variation in *Sparganium emersum* for dispersal by fish. Functional Ecology **21**:1084-1091.

Poole, G. C. 2010. Stream hydrogeomorphology as a physical science basis for advances in stream ecology. Journal of the North American Benthological Society **29**:12-25.

Poole, G. C., and C. H. Berman. 2001. An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. Environmental Management **27**:787-802.

Poole, G. C., J. A. Stanford, S. W. Running, and C. A. Frissell. 2006. Multiscale geomorphic drivers of groundwater flow paths: Subsurface hydrologic dynamics and hyporheic diversity. Journal of the North American Benthological Society **25**:288-303.

Porvari, P., and M. Verta. 2003. Total and methyl mercury concentrations and fluxes from small boreal forest catchments in Finland. Environmental Pollution **123**:181-191.

Powell, D. M., R. Brazier, A. Parsons, J. Wainwright, and M. Nichols. 2007. Sediment transfer and storage in dryland headwater streams. Geomorphology **88**:152-166.

Power, G., R. S. Brown, and J. G. Imhof. 1999. Groundwater and fish: Insights from northern North America. Hydrological Processes **13**:401-422.

Power, M. E., and W. E. Dietrich. 2002. Food webs in river networks. Ecological Research **17**:451-471.

Power, M. E., G. Parker, W. E. Dietrich, and A. Sun. 1995a. How does floodplain width affect floodplain river ecology? A preliminary exploration using simulations. Geomorphology **13**:301-317.

Power, M. E., A. Sun, G. Parker, W. E. Dietrich, and J. T. Wootton. 1995b. Hydraulic food-chain models. BioScience **45**:159-167.

Powers, S. M., R. A. Johnson, and E. H. Stanley. 2012. Nutrient retention and the problem of hydrologic disconnection in streams and wetlands. Ecosystems **15**:435-449.

Pringle, C., G. Blake, A. Covich, K. Buzby, and A. Finley. 1993. Effects of omnivorous shrimp in a montane tropical stream: Sediment removal, disturbance of sessile invertebrates and enhancement of understory algal biomass. Oecologia **93**:1-11.

Pringle, C. M. 2001. Hydrologic connectivity and the management of biological reserves: A global perspective. Ecological Applications **11**:981-998.

Progar, D. J., and A. R. Moldenke. 2002. Insect production from temporary and perennially flowing headwater streams in western Oregon. Journal of Freshwater Ecology **17**:391-407.

Pyzoha, J. E., T. J. Callahan, G. Sun, C. C. Trettin, and M. Miwa. 2008. A conceptual hydrologic model for a forested Carolina bay depressional wetland on the Coastal Plain of South Carolina, USA. Hydrological Processes **22**:2689-2698.

Quinn, P. F., K. J. Beven, and R. Lamb. 1995. The in(a/tan/β) index: How to calculate it and how to use it within the topmodel framework. Hydrological Processes **9**:161-182.

Quinton, W. L., M. Hayashi, and A. Pietroniro. 2003. Connectivity and storage functions of channel fens and flat bogs in northern basins. Hydrological Processes **17**:3665-3684.

Rabalais, N. N., R. E. Turner, and W. J. Wiseman. 2002. Gulf of Mexico hypoxia, a.k.a. "the dead zone". Annual Review of Ecology and Systematics **33**:235-263.

Rader, R. B. 1997. A functional classification of the drift: Traits that influence invertebrate availability to salmonids. Canadian Journal of Fisheries and Aquatic Sciences **54**:1211-1234.

Rae, C., K. Rothley, and S. Dragicevic. 2007. Implications of error and uncertainty for an environmental planning scenario: A sensitivity analysis of GIS-based variables in a reserve design exercise. Landscape and Urban Planning **79**:210-217.

Rains, M. C. 2011. Water sources and hydrodynamics of closed-basin depressions, Cook Inlet region, Alaska. Wetlands **31**:377-387.

Rains, M. C., R. A. Dahlgren, G. E. Fogg, T. Harter, and R. J. Williamson. 2008. Geological control of physical and chemical hydrology in California vernal pools. Wetlands **28**:347-362.

Rains, M. C., G. E. Fogg, T. Harter, R. A. Dahlgren, and R. J. Williamson. 2006. The role of perched aquifers in hydrological connectivity and biogeochemical processes in vernal pool landscapes, Central Valley, California. Hydrological Processes **20**:1157-1175.

Randall, G. W., D. R. Huggins, M. P. Russelle, D. J. Fuchs, W. W. Nelson, and J. L. Anderson. 1997. Nitrate losses through subsurface tile drainage in conservation reserve program, alfalfa, and row crop systems. Journal of Environmental Quality **26**:1240-1247.

Rassam, D. W., C. S. Fellows, R. De Hayr, H. Hunter, and P. Bloesch. 2006. The hydrology of riparian buffer zones; two case studies in an ephemeral and a perennial stream. Journal of Hydrology **325**:308-324.

Rayfield, B., M.-J. Fortin, and A. Fall. 2010. Connectivity for conservation: A framework to classify network measures. Ecology **92**:847-858.

Reaney, S. M. 2008. The use of agent based modelling techniques in hydrology: Determining the spatial and temporal origin of channel flow in semi-arid catchments. Earth Surface Processes and Landforms **33**:317-327.

Reddy, K. R., and R. D. DeLaune. 2008. Biogeochemistry of wetlands: Science and applications. CRC Press, Boca Raton, FL.

Reddy, K. R., R. H. Kadlec, E. Flaig, and P. M. Gale. 1999. Phosphorus retention in streams and wetlands: A review. Critical Reviews in Environmental Science and Technology **29**:83-146.

Reeves, G. H., K. M. Burnett, and E. V. McGarry. 2003. Sources of large wood in the main stem of a fourth-order watershed in coastal Oregon. Canadian Journal of Forest Research **33**:1363-1370.

Rehg, K. J., A. I. Packman, and J. Ren. 2005. Effects of suspended sediment characteristics and bed sediment transport on streambed clogging. Hydrological Processes **19**:413-427.

Renard, K. G., and R. V. Keppel. 1966. Hydrographs of ephemeral streams in the southwest. Journal of the Hydraulics Division Proceedings of the American Society of Civil Engineers **92(HY2)**:33-52.

Reneau, S. L., P. G. Drakos, D. Katzman, D. V. Malmon, E. V. McDonald, and R. T. Ryti. 2004. Geomorphic controls on contaminant distribution along an ephemeral stream. Earth Surface Processes and Landforms **29**:1209-1223.

Renwick, W., S. Smith, J. Bartley, and R. Buddemeier. 2005. The role of impoundments in the sediment budget of the conterminous United States. Geomorphology **71**:99-111.

Resh, V. H., A. V. Brown, A. P. Covich, M. E. Gurtz, H. W. Li, G. W. Minshall, S. R. Reice, A. L. Sheldon, J. B. Wallace, and R. C. Wissmar. 1988. The role of disturbance in stream ecology. Journal of the North American Benthological Society **7**:433-455.

Rhoads, B. L. 1987. Changes in stream channel characteristics at tributary junctions. Physical Geography **8**:346-367.

Ribeiro, M. L., K. Blanckaert, A. G. Roy, and A. J. Schleiss. 2012. Flow and sediment dynamics in channel confluences. Journal of Geophysical Research: Earth Surface **117**:F01035.

Rice, S., and M. Church. 1998. Grain size along two gravel-bed rivers: Statistical variation, spatial pattern and sedimentary links. Earth Surface Processes and Landforms **23**:345-363.

Rice, S. P., M. T. Greenwood, and C. B. Joyce. 2001. Tributaries, sediment sources, and the longitudinal organization of macroinvertebrate fauna along river systems. Canadian Journal of Fisheries and Aquatic Sciences **58**:824-840.

Rice, S. P., P. M. Kiffney, C. M. Greene, and G. R. Press. 2008. The ecological importance of tributaries and confluences. Pages 209-242 *in* River Confluences, Tributaries and the Fluvial Network. S. P. Rice, A. G. Roy, and B. L. Rhoads, editors. John Wiley & Sons, Chichester, UK.

Richardson, D. C., L. A. Kaplan, J. D. Newbold, and A. K. Aufdenkampe. 2009. Temporal dynamics of seston: A recurring nighttime peak and seasonal shifts in composition in a stream ecosystem. Limnology and Oceanography **54**:344-354.

Richardson, J. L., L. P. Wilding, and R. B. Daniels. 1992. Recharge and discharge of groundwater in aquic conditions illustrated with flownet analysis. Geoderma **53**:65-78.

Richardson, J. S., R. J. Naiman, F. J. Swanson, and D. E. Hibbs. 2005. Riparian communities associated with Pacific Northwest headwater streams: Assemblages, processes, and uniqueness. Journal of the American Water Resources Association **41**:935-947.

Rieke-Zapp, D. H., and M. H. Nichols. 2011. Headcut retreat in a semiarid watershed in the southwestern United States since 1935. CATENA **87**:1-10.

Rinaldi, M., B. Wyzga, and N. Surian. 2005. Sediment mining in alluvial channels: Physical effects and management perspectives. River Research and Applications **21**:805-828.

Rinaldo, A., A. Marani, and R. Rigon. 1991. Geomorphological dispersion. Water Resources Research **27**:513-525.

Roach, W. J., J. B. Heffernan, N. B. Grimm, J. R. Arrowsmith, C. Eisinger, and T. Rychener. 2008. Unintended consequences of urbanization for aquatic ecosystems: A case study from the Arizona desert. BioScience **58**:715-727.

Robinson, C. T., K. Tockner, and J. V. Ward. 2002. The fauna of dynamic riverine landscapes. Freshwater Biology **47**:661-677.

Rodriguez-Iturbe, I., R. Muneepeerakul, E. Bertuzzo, S. A. Levin, and A. Rinaldo. 2009. River networks as ecological corridors: A complex systems perspective for integrating hydrologic, geomorphologic, and ecologic dynamics. Water Resources Research **45**:W01413.

Rodríguez-Iturbe, I., and J. B. Valdes. 1979. The geomorphologic structure of hydrologic response. Water Resources Research **15**:1409-1420.

Roe, J. H., B. A. Kingsbury, and N. R. Herbert. 2004. Comparative water snake ecology: Conservation of mobile animals that use temporally dynamic resources. Biological Conservation **118**:79-89.

Rooney, R. C., C. Carli, and S. Bayley. 2013. River connectivity affects submerged and floating aquatic vegetation in floodplain wetlands. Wetlands **33**:1165-1177.

Rorabaugh, J. C. 2005. *Rana pipiens*, northern leopard frog. Pages 570-577 *in* Amphibian declines: The conservation status of United States species. M. Lannoo, editor. University of California Press, Berkeley, CA.

Rorabaugh, J. C., and M. J. Lannoo. 2005. *Pseudacris regilla* Baird and Girard, 1852(b), Pacific treefrog. Pages 478-484 *in* Amphibian declines: The conservation status of United States species. M. Lannoo, editor. University of California Press, Berkeley, CA.

Rosado, J., M. Morais, and K. Tockner. 2015. Mass dispersal of terrestrial organisms during first flush events in a temporary stream. River Research and Applications: doi: 10.1002/rra.2791.

Roscher, J. P. 1967. Alga dispersal by muskrat intestinal contents. Transactions of the American Microscopical Society **86**:497-498.

Rose, S. 2007. The effects of urbanization on the hydrochemistry of base flow within the Chattahoochee River Basin (Georgia, USA). Journal of Hydrology **341**:42-54.

Rosenberry, D. O., and T. C. Winter. 1997. Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlands in North Dakota. Journal of Hydrology **191**:266-289.

Rosenfeld, J. S., and E. Raeburn. 2009. Effects of habitat and internal prey subsidies on juvenile coho salmon growth: Implications for stream productive capacity. Ecology of Freshwater Fish **18**:572-584.

Roth, N. E., J. D. Allan, and D. L. Erickson. 1996. Landscape influences on stream biotic integrity assessed at multiple spatial scales. Landscape Ecology **11**:141-156.

Roulet, N. T., and M.-K. Woo. 1986. Hydrology of a wetland in the continuous permafrost region. Journal of Hydrology **89**:73-91.

Rovansek, R. J., L. D. Hinzman, and D. L. Kane. 1996. Hydrology of a tundra wetland complex on the Alaskan arctic coastal plain, USA. Arctic and Alpine Research **28**:311-317.

Rowan, J. S., S. J. A. Barnes, S. L. Hetherington, B. Lambers, and F. Parsons. 1995. Geomorphology and pollution: The environmental impacts of lead mining, Leadhills, Scotland. Journal of Geochemical Exploration **52**:57-65.

Roy, A. G., and M. J. Woldenberg. 1986. A model for changes in channel form at a river confluence. Journal of Geology **94**:402-411.

Roy, A. H., A. L. Dybas, K. M. Fritz, and H. R. Lubbers. 2009. Urbanization affects the extent and hydrologic permanence of headwater streams in a midwestern US metropolitan area. Journal of the North American Benthological Society **28**:911-928.

Royer, T. V., M. B. David, and L. E. Gentry. 2006. Timing of riverine export of nitrate and phosphorus from agricultural watersheds in Illinois: Implications for reducing nutrient loading to the Mississippi River. Environmental Science & Technology **40**:4126-4131.

Royer, T. V., J. L. Tank, and M. B. David. 2004. Transport and fate of nitrate in headwater agricultural streams in Illinois. Journal of Environmental Quality **33**:1296-1304.

Rutherford, J. C., N. A. Marsh, P. M. Davies, and S. E. Bunn. 2004. Effects of patchy shade on stream water temperature: How quickly do small streams heat and cool? Marine and Freshwater Research **55**:737-748.

Rypel, A. L., D. A. Arrington, and R. H. Findlay. 2008. Mercury in southeastern US riverine fish populations linked to water body type. Environmental Science & Technology **42**:5118-5124.

Saco, P. M., and P. Kumar. 2002. Kinematic dispersion in stream networks 1. Coupling hydraulics and network geometry. Water Resources Research **38**:1244.

Saco, P. M., and P. Kumar. 2008. Hydrologic dispersion in fluvial networks. Pages 307-335 *in* River confluences, tributaries and the fluvial network. S. P. Rice, A. G. Roy, and B. L. Rhoads, editors. John Wiley & Sons, Chichester, UK.

Sandor, J. A., J. B. Norton, J. A. Homburg, D. A. Muenchrath, C. S. White, S. E. Williams, C. I. Havener, and P. D. Stahl. 2007. Biogeochemical studies of a Native American runoff agroecosystem. Geoarchaeology **22**:359-386.

Sass, G. Z., and I. F. Creed. 2008. Characterizing hydrodynamics on boreal landscapes using archived synthetic aperture radar imagery. Hydrological Processes **22**:1687-1699.

Saura, S., and L. Pascual-Hortal. 2007. A new habitat availability index to integrate connectivity in landscape conservation planning: Comparison with existing indices and application to a case study. Landscape and Urban Planning **83**:91-103.

Sawyer, A. H., M. Bayani Cardenas, and J. Buttles. 2011. Hyporheic exchange due to channel-spanning logs. Water Resources Research **47**:W08502.

Sawyer, A. H., M. Bayani Cardenas, and J. Buttles. 2012. Hyporheic temperature dynamics and heat exchange near channel-spanning logs. Water Resources Research **48**:W01529.

Scanlon, B. R., C. C. Faunt, L. Longuevergne, R. C. Reedy, W. M. Alley, V. L. McGuire, and P. B. McMahon. 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. Proceedings of the National Academy of Sciences **109**:9320-9325.

Scanlon, B. R., R. S. Goldsmith, and J. G. Paine. 1997. Analysis of focused unsaturated flow beneath fissures in the Chihuahuan Desert, Texas, USA. Journal of Hydrology **203**:58-78.

Scanlon, B. R., K. E. Keese, A. L. Flint, L. E. Flint, C. B. Gaye, W. M. Edmunds, and I. Simmers. 2006. Global synthesis of groundwater recharge in semiarid and arid regions. Hydrological Processes **20**:3335-3370.

Schalk, C. M., and T. M. Luhring. 2010. Vagility of aquatic salamanders: Implications for wetland connectivity. Journal of Herpetology **44**:104-109.

Scheidegger, A. E. 1965. The algebra of stream-order numbers. USGS Professional Paper 525-B, U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Schelker, J., K. Öhman, S. Löfgren, and H. Laudon. 2014. Scaling of increased dissolved organic carbon inputs by forest clear-cutting – What arrives downstream? Journal of Hydrology **508**:299-306.

Schemel, L. E., T. R. Sommer, A. B. Muller-Solger, and W. C. Harrell. 2004. Hydrologic variability, water chemistry, and phytoplankton biomass in a large floodplain of the Sacramento River, CA, USA. Hydrobiologia **513**:129-139.

Schiller, K. E., P. Jindal, N. B. Basu, and M. J. Helmers. 2012. Impact of artificial subsurface drainage on groundwater travel times and baseflow discharge in an agricultural watershed, Iowa (USA). Hydrological Processes **26**:3092-3100.

Schindler, D. E., P. R. Leavitt, C. S. Brock, S. P. Johnson, and P. D. Quay. 2005. Marine-derived nutrients, commercial fisheries, and production of salmon and lake algae in Alaska. Ecology **86**:3225-3231.

Schindler, D. W., and P. J. Curtis. 1997. The role of DOC in protecting freshwaters subjected to climate warming and acidification from UV exposure. Biogeochemistry **36**:1-8.

Schlesinger, W. H., and C. S. Jones. 1984. The comparative importance of overland runoff and mean annual rainfall to shrub communities of the Mojave Desert. Botanical Gazette **145**:116-124.

Schlosser, I. J. 1987. A conceptual framework for fish communities in small warmwater streams. Pages 17-24 *in* Community and evolutionary ecology of North American stream fishes. W. J. Matthews and D. C. Heins, editors. University of Oklahoma Press, Norman, OK.

Schlosser, I. J. 1991. Stream fish ecology: A landscape perspective. BioScience:704-712.

Schmidt, J. C., and P. R. Wilcock. 2008. Metrics for assessing the downstream effects of dams. Water Resources Research **44**:W04404.

Schneider, R. L., and R. R. Sharitz. 1988. Hydrochory and regeneration in a bald cypress water tupelo swamp forest. Ecology **69**:1055-1063.

Schramm, H. L., and M. A. Eggleton. 2006. Applicability of the flood-pulse concept in a temporal floodplain river ecosystem: Thermal and temporal components. River Research and Applications **22**:543-553.

Schrank, A. J., and F. J. Rahel. 2004. Movement patterns in inland cutthroat trout (*Oncorhynchus clarki utah*): Management and conservation implications. Canadian Journal of Fisheries and Aquatic Sciences **61**:1528-1537.

Schrank, S. J., C. S. Guy, M. R. Whiles, and B. L. Brock. 2001. Influence of instream and landscape-level factors on the distribution of Topeka shiners *Notropis topeka* in Kansas streams. Copeia **2001**:413-421.

Schroder, B. 2006. Pattern, process, and function in landscape ecology and catchment hydrology— how can quantitative landscape ecology support predictions in ungauged basins? Hydrology and Earth System Sciences **10**:967-979.

Schumm, S. A. 1956. The evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Bulletin of the Geological Society of America **67**:597-646.

Schwalb, A. N., M. Garvie, and J. D. Ackerman. 2010. Dispersion of freshwater mussel larvae in a lowland river. Limnology and Oceanography **55**:628-638.

Schwalb, A. N., T. J. Morris, N. E. Mandrak, and K. Cottenie. 2013. Distribution of unionid freshwater mussels depends on the distribution of host fishes on a regional scale. Diversity and Distributions **19**:446-454.

Scott, R. L., W. J. Shuttleworth, T. O. Keefer, and A. W. Warrick. 2000. Modeling multiyear observations of soil moisture recharge in the semiarid American Southwest. Water Resources Research **36**:2233-2247.

Scrivener, J. C., T. G. Brown, and B. C. Andersen. 1994. Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) utilization of Hawks Creek, a small and nonnatal tributary of the Upper Fraser River. Canadian Journal of Fisheries and Aquatic Sciences **51**:1139-1146.

Sear, D. A., C. E. Millington, D. R. Kitts, and R. Jeffries. 2010. Log jam controls on channel: Floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns. Geomorphology **116**:305-319.

Sedell, J. R., G. H. Reeves, F. R. Hauer, J. A. Stanford, and C. P. Hawkins. 1990. Role of refugia in recovery from disturbances: Modern fragmented and disconnected river systems. Environmental Management **14**:711-724.

Seedang, S., A. G. Fernald, R. M. Adams, and D. H. Landers. 2008. Economic analysis of water temperature reduction practices in a large river floodplain: An exploratory study of the Willamette River, Oregon. River Research and Applications **24**:941-959.

Seitzinger, S. P., R. W. Sanders, and R. Styles. 2002. Bioavailability of DON from natural and anthropogenic sources to estuarine plankton. Limnology and Oceanography **47**:353-366.

Selvendiran, P., C. T. Driscoll, J. T. Bushey, and M. R. Montesdeoca. 2008. Wetland influence on mercury fate and transport in a temperate forested watershed. Environmental Pollution **154**:46-55.

Semlitsch, R. D. 2008. Differentiating migration and dispersal processes for pond-breeding amphibians. The Journal of Wildlife Management **72**:260-267.

Semlitsch, R. D., and J. R. Bodie. 2003. Biological criteria for buffer zones around wetlands and riparian habitats for amphibians and reptiles. Conservation Biology **17**:1219-1228.

Senderovich, Y., I. Izhaki, and M. Halpern. 2010. Fish as reservoirs and vectors of *Vibrio cholerae*. PLOS ONE **5**:e8607.

Seo, J. I., F. Nakamura, D. Nakano, H. Ichiyanagi, and K. W. Chun. 2008. Factors controlling the fluvial export of large woody debris, and its contribution to organic carbon budgets at watershed scales. Water Resources Research **44**:W04428.

Serfass, T. L., M. J. Lovallo, R. P. Brooks, A. H. Hayden, and D. H. Mitcheltree. 1999. Status and distribution of river otters in Pennsylvania following a reintroduction project. Journal of the Pennsylvania Academy of Science **73**:10-14.

Shaman, J., M. Stieglitz, and D. Burns. 2004. Are big basins just the sum of small catchments? Hydrological Processes **18**:3195-3206.

Shanks, C. E., and G. C. Arthur. 1952. Muskrat movements and population dynamics in Missouri farm ponds and streams. Journal of Wildlife Management **16**:138-148.

Sharitz, R. R. 2003. Carolina bay wetlands: Unique habitats of the southeastern United States. Wetlands **23**:550-562.

Sharma, K. D., and J. S. R. Murthy. 1995. Hydrologic routing of flow in arid ephemeral channels. Journal of Hydraulic Engineering **121**:466-471.

Sharpley, A. N., and S. Rekolainen. 1997. Phosphorus in agriculture and its environmental implications. Pages 1-54 *in* Phosphorus losses from soil to water. H. Tunney, O. T. Carton, P. C. Brookes, and A. E. Johnston, editors. CAB International, Cambridge, UK.

Shaw, D. A., A. Pietroniro, and L. W. Martz. 2013. Topographic analysis for the prairie pothole region of western Canada. Hydrological Processes **27**:3105-3114.

Shaw, D. A., G. Vanderkamp, F. M. Conly, A. Pietroniro, and L. Martz. 2012. The fill-spill hydrology of prairie wetland complexes during drought and deluge. Hydrological Processes **26**:3147-3156.

Shaw, P. A., and R. G. Bryant. 2011. Pans, playas and salt lakes. Pages 373-401 *in* Arid zone geomorphology: Process, form and change in drylands. D. S. G. Thomas, editor. John Wiley & Sons, New York, NY.

Sheaves, M. 2009. Consequences of ecological connectivity: the coastal ecosystem mosaic. Marine Ecology Progress Series **391**:107-115.

Shedlock, R. J., D. A. Wilcox, T. A. Thompson, and D. A. Cohen. 1993. Interactions between ground-water and wetlands, southern shore of Lake-Michigan, USA. Journal of Hydrology **141**:127-155.

Sheldon, A. L. 1988. Conservation of stream fishes: Patterns of diversity, rarity, and risk. Conservation Biology **2**:149-156.

Shentsis, I., and E. Rosenthal. 2003. Recharge of aquifers by flood events in an arid region. Hydrological Processes **17**:695-712.

Shih, J. S., R. B. Alexander, R. A. Smith, E. W. Boyer, G. E. Schwarz, and S. Chung. 2010. An initial SPARROW model of land use and in-stream controls on total organic carbon in streams of the conterminous United States. USGS Open File Report 2010-1276, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Shook, K. R., and J. W. Pomeroy. 2011. Memory effects of depressional storage in northern prairie hydrology. Hydrological Processes **25**:3890-3898.

Shoup, D. E., and D. H. Wahl. 2009. Fish diversity and abundance in relation to interannual and lake-specific variation in abiotic characteristics of floodplain lakes of the lower Kaskaskia River, Illinois. Transactions of the American Fisheries Society **138**:1076-1092.

Shreve, R. L. 1967. Infinite topologically random channel networks. Journal of Geology **75**:178-186.

Simmons, J. A. 2010. Phosphorus removal by sediment in streams contaminated with acid mine drainage. Water Air and Soil Pollution **209**:123-132.

Sjodin, A., W. M. Lewis, and J. F. Saunders. 2001. Analysis of groundwater exchange for a large plains river in Colorado (USA). Hydrological Processes **15**:609-620.

Skagen, S. K., and F. L. Knopf. 1993. Toward conservation of midcontinental shorebird migrations. Conservation Biology **7**:533-541.

Smith, M. W., L. J. Bracken, and N. J. Cox. 2010. Toward a dynamic representation of hydrological connectivity at the hillslope scale in semiarid areas. Water Resources Research **46**:W12540.

Smith, R. D., A. Ammann, C. Bartoldus, and M. M. Brinson. 1995. An approach for assessing wetland functions using hydrogeomorphic classification, reference wetlands, and functional indices. Wetlands Research Program Technical Report WRP-DE-9, U.S. Army Corps of Engineers, Waterways Experiment Station, Wetlands Research Program, Vicksburg, MS.

Smith, T. A., and C. E. Kraft. 2005. Stream fish assemblages in relation to landscape position and local habitat variables. Transactions of the American Fisheries Society **134**:430-440.

Smock, L. A. 1994. Movements of invertebrates between stream channels and forested floodplains. Journal of the North American Benthological Society **13**:524-531.

Smock, L. A., J. E. Gladden, J. L. Riekenberg, L. C. Smith, and C. R. Black. 1992. Lotic macroinvertebrate production in three dimensions: Channel surface, hyporheic, and floodplain environments. Ecology **73**:876-886.

Snell, J. D., and M. Sivapalan. 1994. On geomorphological dispersion in natural catchments and the geomorphological unit hydrograph. Water Resources Research **30**:2311-2323.

Snodgrass, J. W., A. L. Bryan, R. F. Lide, and G. M. Smith. 1996. Factors affecting the occurrence and structure of fish assemblages in isolated wetlands of the upper Coastal Plain, USA. Canadian Journal of Fisheries and Aquatic Sciences **53**:443-454.

Snodgrass, J. W., M. J. Komoroski, A. L. Bryan, and J. Burger. 2000. Relationships among isolated wetland size, hydroperiod, and amphibian species richness: Implications for wetland regulations. Conservation Biology **14**:414-419.

Sobota, D. J., S. V. Gregory, and J. Van Sickle. 2006. Riparian tree fall directionality and modeling large wood recruitment to streams. Canadian Journal of Forest Research **36**:1243-1254.

Soons, M. B. 2006. Wind dispersal in freshwater wetlands: Knowledge for conservation and restoration. Applied Vegetation Science **9**:271-278.

Soons, M. B., and G. W. Heil. 2002. Reduced colonization capacity in fragmented populations of wind-dispersed grassland forbs. Journal of Ecology **90**:1033-1043.

Spence, C., and R. W. Phillips. 2015. Refining understanding of hydrological connectivity in a boreal catchment. Hydrological Processes: doi: 10.1002/hyp.10270.

Spinola, R. M., T. L. Serfass, and R. P. Brooks. 2008. Survival and post-release movements of river otters translocated to western New York. Northeastern Naturalist **15**:13-24.

Squillace, P. J. 1996. Observed and simulated movement of bank-storage water. Ground Water **34**:121-134.

SRMGSC. 2007. Management plan of the Pacific and Central Flyways for the Rocky Mountain population of greater sandhill cranes. [Joint] Subcommittees, Rocky Mountain Population Greater Sandhill Cranes, Pacific Flyway Study Committee, Central Flyway Webless Migratory Game Bird Tech. Committee [c/o USFWS, MBMO], Portland, OR.

St. Louis, V. L., J. W. M. Rudd, C. A. Kelly, K. G. Beaty, N. S. Bloom, and R. J. Flett. 1994. Importance of wetlands as sources of methyl mercury to boreal forest ecosystems. Canadian Journal of Fisheries and Aquatic Sciences **51**:1065-1076.

St. Louis, V. L., J. W. M. Rudd, C. A. Kelly, K. G. Beaty, R. J. Flett, and N. Roulet. 1996. Production and loss of methylmercury and loss of total mercury from boreal forest catchments containing different types of wetlands. Environmental Science & Technology **30**:2719-2729.

Staddon, W. J., R. M. Zablotowicz, and M. A. Locke. 2001. Microbiological characteristics of a vegetative buffer strip soil and degradation and sorption of metolachlor. Soil Science Society of America Journal **65**:1136-1142.

Stanford, J. A., and J. V. Ward. 1984. The effects of regulation on the limnology of the Gunnison River: A North American case history. Pages 467-480 *in* Regulated rivers. Proceedings of the second international symposium on regulated streams, Oslo, August 1982. A. Lillehammer and S. J. Salveit, editors. Universitetsforlaget AS, Oslo, Norway.

Stanford, J. A., and J. V. Ward. 1988. The hyporheic habitat of river ecosystems. Nature **335**:64-66.

Stanford, J. A., and J. V. Ward. 1993. An ecosystem perspective of alluvial rivers: Connectivity and the hyporheic corridor. Journal of the North American Benthological Society **12**:48-60.

Stanley, E. H., S. G. Fisher, and N. B. Grimm. 1997. Ecosystem expansion and contraction in streams. BioScience **47**:427-435.

Statzner, B. 2012. Geomorphological implications of engineering bed sediments by lotic animals. Geomorphology **157–158**:49-65.

Stead, T. K., J. M. Schmid-Araya, and A. G. Hildrew. 2005. Secondary production of a stream metazoan community: Does the meiofauna make a difference? Limnology and Oceanography **50**:398-403.

Steward, A. L., D. von Schiller, K. Tockner, J. C. Marshall, and S. E. Bunn. 2012. When the river runs dry: Human and ecological values of dry riverbeds. Frontiers in Ecology and the Environment **10**:202-209.

Stoddard, J. L., D. V. Peck, A. R. Olsen, D. P. Larsen, J. Van Sickle, C. P. Hawkins, R. M. Hughes, T. R. Whittier, G. Lomnicky, A. T. Herlihy, P. R. Kaufmann, S. A. Peterson, P. L. Ringold, S. G. Paulsen, and R. Blair. 2005. Environmental Monitoring and Assessment Program (EMAP) western streams and rivers statistical summary. EPA 620/R-05/006, U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

Stonedahl, S. H., J. W. Harvey, A. Wörman, M. Salehin, and A. I. Packman. 2010. A multiscale model for integrating hyporheic exchange from ripples to meanders. Water Resources Research **46**:W12539.

Strahler, A. N. 1957. Quantitative analysis of watershed geomorphology. American Geophysical Union Transactions **38**:913-920.

Subalusky, A. L., L. A. Fitzgerald, and L. L. Smith. 2009a. Ontogenetic niche shifts in the American alligator establish functional connectivity between aquatic systems. Biological Conservation **142**:1507-1514.

Subalusky, A. L., L. l. Smith, and L. A. Fitzgerald. 2009b. Detection of American alligators in isolated, seasonal wetlands. Applied Herpetology **6**:199-210.

Sullivan, S. M. P., and M. C. Watzin. 2009. Stream-floodplain connectivity and fish assemblage diversity in the Champlain Valley, Vermont, U.S.A. Journal of Fish Biology **74**:1394-1418.

Sun, G. W., H. Riekerk, and L. V. Korhnak. 1995. Shallow groundwater table dynamics of cypress wetland pine upland systems in Florida flatwoods. Soil and Crop Science Society of Florida Proceedings **54**:66-71.

Suter, G. W., and S. M. Cormier. 2011. Why and how to combine evidence in environmental assessments: Weighing evidence and building cases. Science of The Total Environment **409**:1406-1417.

Suter, G. W., S. B. Norton, and S. M. Cormier. 2002. A methodology for inferring the causes of observed impairments in aquatic ecosystems. Environmental Toxicology and Chemistry **21**:1101-1111.

Swan, C. M., and M. A. Palmer. 2006. Composition of speciose leaf litter alters stream detritivore growth, feeding activity and leaf breakdown. Oecologia **147**:469-478.

Swanson, C. D., and R. W. Bachmann. 1976. Model of algal exports in some Iowa streams. Ecology **57**:1076-1080.

Swanson, F. J., S. L. Johnson, S. V. Gregory, and S. A. Acker. 1998. Flood disturbance in a forested mountain landscape - Interactions of land use and floods. BioScience **48**:681-689.

Swimley, T. J., R. P. Brooks, and T. L. Serfass. 1999. Otter and beaver interactions in the Delaware Water Gap National Recreation Area. Journal of the Pennsylvania Academy of Science **72**:97-101.

Tang, C., I. Machida, S. Shindo, A. Kondoh, and Y. Sakura. 2001. Chemical and isotopic methods for confirming the roles of wadis in regional groundwater recharge in a regional arid environment: A case study in Al Ain, UAE. Hydrological Processes **15**:2195-2202.

Tank, J. L., E. J. Rosi-Marshall, N. A. Griffiths, S. A. Entrekin, and M. L. Stephen. 2010. A review of allochthonous organic matter dynamics and metabolism in streams. Journal of the North American Benthological Society **29**:118-146.

Tarboton, D. G. 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resources Research **33**:309-319.

Taylor, B. W., A. S. Flecker, and R. O. Hall. 2006. Loss of a harvested fish species disrupts carbon flow in a diverse tropical river. Science **313**:833-836.

Taylor, M. P., and J. A. Little. 2013. Environmental impact of a major copper mine spill on a river and floodplain system. Anthropocene **3**:36-50.

Temnerud, J., J. Fölster, I. Buffam, H. Laudon, M. Erlandsson, and K. Bishop. 2010. Can the distribution of headwater stream chemistry be predicted from downstream observations? Hydrological Processes **24**:2269-2276.

Temnerud, J., J. Siebert, M. Jansson, and K. Bishop. 2007. Spatial variation in discharge and concentrations of organic carbon in a catchment network of boreal streams in northern Sweden. Journal of Hydrology **342**:72-87.

Tetzlaff, D., and C. Soulsby. 2008. Sources of baseflow in larger catchments– using tracers to develop a holistic understanding of runoff generation. Journal of Hydrology **359**:287-302.

Thomas, J. R., B. Middleton, and D. J. Gibson. 2006. A landscape perspective of the stream corridor invasion and habitat characteristics of an exotic (*Dioscorea oppositifolia*) in a pristine watershed in Illinois. Biological Invasions **8**:1103-1113.

Thorp, J. H., M. C. Thoms, and M. D. Delong. 2006. The riverine ecosystem synthesis: Biocomplexity in river networks across space and time. River Research and Applications **22**:123-147.

Thurman, E. M. 1985. Organic geochemistry of natural waters. Martinus Nijhoff/Dr. W. Junk Publishers, Boston, MA.

Thurman, E. M., D. A. Goolsby, M. T. Meyer, and D. W. Kolpin. 1991. Herbicides in surface waters of the midwestern United States: The effect of spring flush. Environmental Science & Technology **25**:1794-1796.

Tihansky, A. B. 1999. Sinkholes, west-central Florida. Pages 121-140 *in* Land subsidence in the United States. USGS Circular 1182. D. Galloway, D. R. Jones, and S. E. Ingebritsen, editors. U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Timm, B. C., K. McGarigal, and B. W. Compton. 2007. Timing of large movement events of pond-breeding amphibians in western Massachusetts, USA. Biological Conservation **136**:442-454.

Tiner, R. W. 2003a. Dichotomous keys and mapping codes for wetland landscape position, landform, water flow path, and waterbody type descriptors. U.S Fish and Wildlife Service, National Wetlands Inventory Program, Northeast Region, Hadley, MA.

Tiner, R. W. 2003b. Estimated extent of geographically isolated wetlands in selected areas of the United States. Wetlands **23**:636-652.

Tiner, R. W. 2003c. Geographically isolated wetlands of the United States. Wetlands **23**:494-516.

Tiner, R. W. 2011. Dichotomous keys and mapping codes for wetland landscape position, landform, water flow path, and waterbody type descriptors: Version 2.0. U.S. Fish and Wildlife Service, National Wetlands Inventory Program, Northeast Region, Hadley, MA.

Tischendorf, L., and L. Fahrig. 2000. On the usage and measurement of landscape connectivity. Oikos **90**:7-19.

Tockner, K., F. Malard, and J. V. Ward. 2000. An extension of the flood pulse concept. Hydrological Processes **14**:2861-2883.

Tockner, K., M. Pusch, D. Borchardt, and M. S. Lorang. 2010. Multiple stressors in coupled river-floodplain ecosystems. Freshwater Biology **55 (Suppl. 1)**:135-151.

Tockner, K., F. Schiemer, C. Baumgartner, G. Kum, E. Weigand, I. Zweimüller, and J. V. Ward. 1999. The Danube restoration project: Species diversity patterns across connectivity gradients in the floodplain system. Regulated Rivers: Research & Management **15**:245-258.

Tomer, M. D., C. G. Wilson, T. B. Moorman, K. J. Cole, D. Heer, and T. M. Isenhart. 2010. Source-pathway separation of multiple contaminants during a rainfall-runoff event in an artificially drained agricultural watershed. Journal of Environmental Quality **39**:882-895.

Torgersen, C. E., R. N. Faux, B. A. McIntosh, N. J. Poage, and D. J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. Remote Sensing of Environment **76**:386-398.

Torgersen, C. E., R. E. Gresswell, D. S. Bateman, and K. M. Burnett. 2008. Spatial identification of tributary impacts in river networks. Pages 159-181 *in* River confluences, tributaries and the fluvial network. S. P. Rice, A. G. Roy, and B. L. Rhoads, editors. John Wiley & Sons, Chichester, UK.

Tóth, J. 1963. A theoretical analysis of groundwater flow in small drainage basins. Journal of Geophysical Research **68**:4795-4812.

Toth, L. A., and A. van der Valk. 2012. Predictability of flood pulse driven assembly rules for restoration of a floodplain plan community. Wetlands Ecology and Management **20**:59-75.

Townsend-Small, A., D. E. Pataki, H. Liu, Z. Li, Q. Wu, and B. Thomas. 2013. Increasing summer river discharge in southern California, USA, linked to urbanization. Geophysical Research Letters **40**:4643-4647.

Townsend, C. R. 1989. The patch dynamics concept of stream community ecology. Journal of the North American Benthological Society **8**:36-50.

Trimble, S. W. 1997. Stream channel erosion and change resulting from riparian forests. Geology **25**:467-469.

Trimble, S. W. 1999. Decreased rates of alluvial sediment storage in the Coon Creek basin, Wisconsin, 1975-93. Science **285**:1244-1246.

Trimble, S. W. 2010. Streams, valleys and floodplains in the sediment cascade. Pages 307-343 *in* Sediment cascades: An integrated approach. T. Burt and R. Allison, editors. John Wiley & Sons, West Sussex, UK.

Triska, F. J., J. H. Duff, R. W. Sheibley, A. P. Jackman, and R. J. Avanzino. 2007. DIN retention-transport through four hydrologically connected zones in a headwater catchment of the Upper Mississippi River. Journal of the American Water Resources Association **43**:60-71.

Tromp-van Meerveld, H. J., and J. J. McDonnell. 2006. Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. Water Resources Research **42**:W02411.

Tronstad, L. M., B. P. Tronstad, and A. C. Benke. 2007. Aerial colonization and growth: Rapid invertebrate responses to temporary aquatic habitats in a river floodplain. Journal of the North American Benthological Society **26**:460-471.

Truscott, A. M., C. Soulsby, S. C. F. Palmer, L. Newell, and P. E. Hulme. 2006. The dispersal characteristics of the invasive plant *Mimulus guttatus* and the ecological significance of increased occurrence of high-flow events. Journal of Ecology **94**:1080-1091.

Turton, D. J., C. T. Haan, and E. L. Miller. 1992. Subsurface flow responses of a small forested catchment in the Ouachita Mountains. Hydrological Processes **6**:111-125.

U.S. EPA. 2010. Causal Analysis/Diagnosis Decision Information System (CADDIS). U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

U.S. EPA. 2014. SAB review of the draft EPA report Connectivity of Streams and Wetlands to Downstream Waters: A Review and Synthesis of the Scientific Evidence. EPA-SAB-15-001, U.S. Environmental Protection Agency, Washington, DC.

Uden, D. R., M. L. Hellman, D. G. Angeler, and C. R. Allen. 2014. The role of reserves and anthropogenic habitats for functional connectivity and resilience of ephemeral wetlands. Ecological Applications **24**:1569-1582.

Ullrich, S. M., T. W. Tanton, and S. A. Abdrashitova. 2001. Mercury in the aquatic environment: A review of factors affecting methylation. Critical Reviews in Environmental Science and Technology **31**:241-293.

Urban, D., and T. Keitt. 2001. Landscape connectivity: A graph-theoretic perspective. Ecology **82**:1205-1218.

Urban, N. R., S. E. Bayley, and S. J. Eisenreich. 1989. Export of dissolved organic carbon and acidity from peatlands. Water Resources Research **25**:1619-1628.

USACE. 1987. Wetlands delineation manual. Technical Report Y-87-1, U.S. Army Corps of Engineers, Waterways Experiment Station, Wetlands Research Program, Vicksburg, MS.

USACE. 2009. National Inventory of Dams. U.S. Army Corps of Engineers.

Valett, H. M., M. A. Baker, J. A. Morrice, C. S. Crawford, M. C. Molles, C. N. Dahm, D. L. Moyer, J. R. Thibault, and L. M. Ellis. 2005. Biogeochemical and metabolic responses to the flood pulse in a semiarid floodplain. Ecology **86**:220-234.

Valett, H. M., S. G. Fisher, and E. H. Stanley. 1990. Physical and chemical characteristics of the hyporheic zone of a Sonoran Desert stream. Journal of the North American Benthological Society **9**:201-215.

Van Looy, K., C. Cavillon, T. Tormos, J. Piffady, P. Landry, and Y. Souchon. 2013. A scale-sensitive connectivity analysis to identify ecological networks and conservation value in river networks. Landscape Ecology **28**:1239-1249.

Van Meter, K. J., and N. B. Basu. In press. Signatures of human impact: Size distributions and spatial organization of wetlands in the Prairie Pothole landscape. Ecological Applications: doi.org/10.1890/1814-0662.1891.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences **37**:130-137.

Vanschoenwinkel, B., S. Gielen, M. Seaman, and L. Brendonck. 2009. Wind mediated dispersal of freshwater invertebrates in a rock pool metacommunity: Differences in dispersal capacities and modes. Hydrobiologia **635**:363-372.

Ver Hoef, J. M., E. Peterson, and D. Theobald. 2006. Spatial statistical models that use flow and stream distance. Environmental and Ecological Statistics **13**:449-464.

Ver Hoef, J. M., and E. E. Peterson. 2010. A moving average approach for spatial statistical models of stream networks. Journal of the American Statistical Association **105**:6-18.

Vidon, P., C. Allan, D. Burns, T. P. Duval, N. Gurwick, S. Inamdar, R. Lowrance, J. Okay, D. Scott, and S. Sebestyen. 2010. Hot spots and hot moments in riparian zones: Potential for improved water quality management. Journal of the American Water Resources Association **46**:278-298.

Vilizzi, L., B. J. McCarthy, O. Scholz, C. P. Sharpe, and D. B. Wood. 2013. Managed and natural inundation: Benefits for conservation of native fish in a semi-arid wetland system. Aquatic Conservation: Marine and Freshwater Ecosystems **23**:37-50.

Villar, C. A., L. de Cabo, P. Vaithiyanathan, and C. Bonetto. 2001. Litter decomposition of emergent macrophytes in a floodplain marsh of the Lower Parana River. Aquatic Botany **70**:105-116.

Vining, K. C. 2002. Simulation of streamflow and wetland storage, Starkweather Coulee subbasin, North Dakota. Water years 1981-98. U.S.G.S. Water-Resources Investigations Report 02-4113, U.S. Department of the Interior, U.S. Geological Survey in cooperation with the North Dakota State Water Commission, Bismarck, ND.

Vivoni, E., R. S. Bowman, R. L. Wyckoff, R. T. Jakubowski, and K. E. Richards. 2006. Analysis of a monsoon flood event in an ephemeral tributary and its downstream hydrologic effects. Water Resources Research **42**:W03404.

Volkmar, E. C., and R. A. Dahlgren. 2006. Biological oxygen demand dynamics in the lower San Joaquin River, California. Environmental Science & Technology **40**:5653-5660.

Voos, G., and P. M. Groffman. 1996. Relationships between microbial biomass and dissipation of 2,4-D and dicamba in soil. Biology and Fertility of Soils **24**:106-110.

Vörösmarty, C. J., B. M. Fekete, M. Meybeck, and R. B. Lammers. 2000. Global system of rivers: Its role in organizing continental land mass and defining land-to-ocean linkages. Global Biogeochemical Cycles **14**:599-621.

Vrtiska, M. P., and S.Sullivan. 2009. Abundance and distribution of lesser snow and Ross's geese in the rainwater basin and Central Platte River Valley of Nebraska. Great Plains Research **19**:147-155.

Wagener, T., M. Sivapalan, P. Troch, and R. Woods. 2007. Catchment classification and hydrologic similarity. Geography Compass **1**:901-931.

Wainwright, J., L. Turnbull, T. G. Ibrahim, I. Lexartza-Artza, S. F. Thornton, and R. E. Brazier. 2011. Linking environmental régimes, space and time: Interpretations of structural and functional connectivity. Geomorphology **126**:387-404.

Waits, E. R., M. J. Bagley, M. J. Blum, F. H. McCormick, and J. M. Lazorchak. 2008. Source-sink dynamics sustain central stonerollers (*Campostoma anomalum*) in a heavily urbanized catchment. Freshwater Biology **53**:2061-2075.

Wallace, J. B., T. F. Cuffney, J. R. Webster, G. J. Lugthart, K. Chung, and B. S. Goldowitz. 1991. Export of fine organic particles from headwater streams: Effects of season, extreme discharges, and invertebrate manipulation. Limnology and Oceanography **36**:670-682.

Wallace, J. B., S. L. Eggert, J. L. Meyer, and J. R. Webster. 1997. Multiple trophic levels of a forest stream linked to terrestrial litter inputs. Science **277**:102-104.

Wallace, J. B., D. H. Ross, and J. L. Meyer. 1982. Seston and dissolved organic carbon dynamics in a southern Appalachian stream. Ecology **63**:824-838.

Wallace, J. B., and J. R. Webster. 1996. The role of macroinvertebrates in stream ecosystem function. Annual Review of Entomology **41**:115-139.

Wallace, J. B., J. R. Webster, S. L. Eggert, J. L. Meyer, and E. R. Siler. 2001. Large woody debris in a headwater stream: Long-term legacies of forest disturbance. International Review of Hydrobiology **86**:501-513.

Wallace, J. B., M. R. Whiles, S. Eggert, T. F. Cuffney, G. H. Lugthart, and K. Chung. 1995. Long-term dynamics of coarse particulate organic matter in three Appalachian Mountain streams. Journal of the North American Benthological Society **14**:217-232.

Walling, D. E. 1983. The sediment delivery problem. Journal of Hydrology **65**:209-237.

Wallis, E., R. Mac Nally, and P. S. Lake. 2008. A Bayesian analysis of physical habitat changes at tributary confluences in cobble-bed upland streams of the Acheron River basin, Australia. Water Resources Research **44**:W11421.

Wallis, E., R. Mac Nally, and S. Lake. 2009. Do tributaries affect loads and fluxes of particulate organic matter, inorganic sediment and wood? Patterns in an upland river basin in south-eastern Australia. Hydrobiologia **636**:307-317.

Walsh, C. J., T. D. Fletcher, and M. J. Burns. 2012. Urban stormwater runoff: A new class of environmental flow problem. PLOS ONE **7**:e45814.

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Morgan. 2005. The urban stream syndrome: Current knowledge and the search for a cure. Journal of the North American Benthological Society **24**:706-723.

Walters, D. M., K. M. Fritz, and R. R. Otter. 2008. The dark side of subsidies: Adult stream insects export organic contaminants to riparian predators. Ecological Applications **18**:1835-1841.

Walton, R., J. E. Davis, T. H. Martin, and R. S. Chapman. 1996. Hydrology of the black swamp wetlands on the Cache River, Arkansas. Wetlands **16**:279-287.

Wang, X., A. M. Melesse, M. E. McClain, and W. Yang. 2007. Water quality changes as a result of coalbed methane development in a rocky mountain watershed. Journal of the American Water Resources Association **43**:1383-1399.

Wang, X., S. Shang, Z. Qu, T. Liu, A. M. Melesse, and W. Yang. 2010. Simulated wetland conservation-restoration effects on water quantity and quality at watershed scale. Journal of Environmental Management **91**:1511-1525.

Waples, R. S. 2010. Spatial-temporal stratifications in natural populations and how they affect understanding and estimation of effective population size. Molecular Ecology Resources **10**:785-796.

Ward, J. V. 1989. The four-dimensional nature of lotic ecosystems. Journal of the North American Benthological Society **8**:2-8.

Ward, J. V. 1998. Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. Biological Conservation **83**:269-278.

Ward, J. V., C. T. Robinson, and K. Tockner. 2002a. Applicability of ecological theory to riverine ecosystems. Verhandlungen der Internationale Vereinigung für Theoretische und Angewandte Limnologie **28**:443-450.

Ward, J. V., and J. A. Stanford. 1983. The serial discontinuity concept of lotic ecosystems. Pages 29-42 *in* Dynamics of lotic ecosystems. T. D. Fontaine and S. M. Bartell, editors. Ann Arbor Science, Ann Arbor, MI.

Ward, J. V., K. Tockner, D. B. Arscott, and C. Claret. 2002b. Riverine landscape diversity. Freshwater Biology **47**:517-539.

Webb, B. W. 1996. Trends in stream and river temperature. Hydrological Processes **10**:205-226.

Webb, E. B., L. M. Smith, M. P. Vrtiska, and T. G. Lagrange. 2010. Effects of local and landscape variables on wetland bird habitat use during migration through the Rainwater Basin. Journal of Wildlife Management **74**:109-119.

Webster, J. R. 1983. The role of benthic macroinvertebrates in detritus dynamics of streams: A computer simulation. Ecological Monographs **53**:383-404.

Webster, J. R. 2007. Spiraling down the river continuum: Stream ecology and the U-shaped curve. Journal of the North American Benthological Society **26**:375-389.

Webster, J. R., E. F. Benfield, T. P. Ehrman, M. A. Schaeffer, J. L. Tank, J. J. Hutchens, and D. J. D'Angelo. 1999. What happens to allochthonous material that falls into streams? A synthesis of new and published information from Coweeta. Freshwater Biology **41**:687-705.

Webster, J. R., and J. L. Meyer. 1997. Stream organic matter budgets. Journal of the North American Benthological Society **16**:3-161.

Webster, J. R., and B. C. Patten. 1979. Effects of watershed perturbation on stream potassium and calcium dynamics. Ecological Monographs **49**:51-72.

Wellborn, G. A., D. K. Skelly, and E. E. Werner. 1996. Mechanisms creating community structure across a freshwater habitat gradient. Annual Review of Ecology and Systematics **27**:337-363.

Weller, M. W. 1964. Distribution and migration of the redhead. The Journal of Wildlife Management:64-103.

Wemple, B. C., J. A. Jones, and G. E. Grant. 1996. Channel network extension by logging roads in two basins, Western Cascades, Oregon. Journal of the American Water Resources Association **32**:1195-1207.

Wemple, B. C., F. J. Swanson, and J. A. Jones. 2001. Forest roads and geomorphic process interactions, Cascade Range, Oregon. Earth Surface Processes and Landforms **26**:191-204.

Westbrook, C. J., D. J. Cooper, and B. W. Baker. 2006. Beaver dams and overbank floods influence groundwater-surface water interactions of a Rocky Mountain riparian area. Water Resources Research **42**:W06404.

Western, A. W., G. Blöschl, and R. B. Grayson. 2001. Toward capturing hydrologically significant connectivity in spatial patterns. Water Resources Research **37**:83-97.

Wetzel, R. G. 1992. Gradient-dominated ecosystems: Sources and regulatory functions of dissolved organic matter in freshwater ecosystems. Hydrobiologia **229**:181-198.

Wetzel, R. G., and B. A. Manny. 1972. Decomposition of dissolved organic carbon and nitrogen compounds from leaves in an experimental hard-water stream. Limnology and Oceanography **17**:927-931.

Wharton, C. H., W. M. Kitchens, E. C. Pendleton, and T. W. Sipe. 1982. The ecology of bottomland hardwood swamps of the Southeast: A community profile. FWS/OBS-81/37, U.S. Department of the Interior, U.S. Fish and Wildlife Service, Biological Services Program, Washington, DC.

Whigham, D. F., C. Chitterling, and B. Palmer. 1988. Impacts of fresh-water wetlands on water-quality: A landscape perspective. Environmental Management **12**:663-671.

Whigham, D. F., and T. E. Jordan. 2003. Isolated wetlands and water quality. Wetlands **23**:541-549.

Whiles, M. R., and W. K. Dodds. 2002. Relationships between stream size, suspended particles, and filter-feeding macroinvertebrates in a Great Plains drainage network. Journal of Environmental Quality **31**:1589-1600.

Whited, D. C., M. S. Lorang, M. J. Harner, R. Hauer, J. S. Kimball, and J. A. Stanford. 2007. Climate, hydrologic disturbance, and succession: Drivers of floodplain pattern. Ecology **88**:940-953.

Whiteley, A. R., K. Hastings, J. K. Wenburg, C. A. Frissell, J. C. Martin, and F. W. Allendorf. 2010. Genetic variation and effective population size in isolated populations of coastal cutthroat trout. Conservation Genetics **11**:1929-1943.

Whiting, P. J., and M. Pomeranets. 1997. A numerical study of bank storage and its contribution to streamflow. Journal of Hydrology **202**:121-136.

Whitmire, S. L., and S. K. Hamilton. 2008. Rates of anaerobic microbial metabolism in wetlands of divergent hydrology on a glacial landscape. Wetlands **28**:703-714.

Wiens, J. A. 2002. Riverine landscapes: Taking landscape ecology into the water. Freshwater Biology **47**:501-515.

Wigington, P. J., J. L. Ebersole, M. E. Colvin, S. G. Leibowitz, B. Miller, B. Hansen, H. R. LaVigne, D. White, J. P. Baker, M. R. Church, J. R. Brooks, M. A. Cairns, and J. E. Compton. 2006. Coho salmon dependence on intermittent streams. Frontiers in Ecology and the Environment **4**:513-518.

Wigington, P. J., S. M. Griffith, J. A. Field, J. E. Baham, W. R. Horwath, J. Owen, J. H. Davis, S. C. Rain, and J. J. Steiner. 2003. Nitrate removal effectiveness of a riparian buffer along a small agricultural stream in western Oregon. Journal of Environmental Quality **32**:162-170.

Wigington, P. J., S. G. Leibowitz, R. L. Comeleo, and J. L. Ebersole. 2013. Oregon hydrologic landscapes: A classification framework. Journal of the American Water Resources Association **49**:163-182.

Wigington, P. J., T. J. T.J. Moser, and D. R. Lindeman. 2005. Stream network expansion: A riparian water quality factor. Hydrological Processes **19**:1715-1721.

Wigmosta, M. S., and W. A. Perkins. 2001. Simulating the effects of forest roads on watershed hydrology. Pages 127-143 *in* Land use and watersheds: Human influence on hydrology and geomorphology in urban and forest areas. M. S. Wigmosta and S. J. Burges, editors. American Geophysical Union, Washington, DC.

Wilcock, P., J. Pitlick, and Y. Cui. 2009. Sediment transport primer estimating bed-material transport in gravel-bed rivers. General Technical Report RMRS-GTR-226, U.S. Department of Agriculture, U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Wilcox, B. P., D. D. Dean, J. S. Jacob, and A. Sipocz. 2011. Evidence of surface connectivity for Texas Gulf Coast depressional wetlands. Wetlands **31**:451-458.

Wilkes, G., J. Brassard, T. A. Edge, V. Gannon, C. C. Jokinen, T. H. Jones, N. Neumann, K. D. M. Pintar, N. Ruecker, P. J. Schmidt, M. Sunohara, E. Topp, and D. R. Lapen. 2013. Bacteria, viruses, and parasites in an intermittent stream protected from and exposed to pasturing cattle: Prevalence, densities, and quantitative microbial risk assessment. Water Research **47**:6244-6257.

Williams, D. D. 1996. Environmental constraints in temporary fresh waters and their consequences for the insect fauna. Journal of the North American Benthological Society **15**:634-650.

Williams, G. P., and M. G. Wolman. 1984. Downstream effects of dams on alluvial rivers. USGS Professional Paper 1286, U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Wilson, C. O., and Q. Weng. 2011. Simulating the impacts of future land use and climate changes on surface water quality in the Des Plaines River watershed, Chicago Metropolitan Statistical Area, Illinois. Science of The Total Environment **409**:4387-4405.

Wilson, J. L., and H. Guan. 2004. Mountain-block hydrology and mountain-front recharge. Pages 113-137 *in* Groundwater recharge in a desert environment: The southwestern United States. F. M. Phillips, J. Hogan, and B. R. Scanlon, editors. American Geophysical Union, Washington, DC.

Wilzbach, M. A., and K. W. Cummins. 1989. An assessment of short-term depletion of stream macroinvertebrate benthos by drift. Hydrobiologia **185**:29-39.

Wilzbach, M. A., K. W. Cummins, and J. D. Hall. 1986. Influence of habitat manipulations on interactions between cutthroat trout and invertebrate drift. Ecology **67**:898-911.

Winston, M. R., C. M. Taylor, and J. Pigg. 1991. Upstream extirpation of four minnow species due to damming of a prairie stream. Transactions of the American Fisheries Society **120**:98-105.

Winter, T. C. 1999. Relation of streams, lakes, and wetlands to groundwater flow systems. Hydrogeology Journal **7**:28-45.

Winter, T. C. 2001. The concept of hydrologic landscapes. Journal of the American Water Resources Association **37**:335-349.

Winter, T. C. 2007. The role of groundwater in generating streamflow in headwater areas and in maintaining base flow. Journal of the American Water Resources Association **43**:15-25.

Winter, T. C., J. W. Harvey, O. L. Franke, and W. M. Alley. 1998. Ground water and surface water: A single resource. USGS Circular 1139, U.S. Department of the Interior, U.S. Geological Survey, Denver, CO.

Winter, T. C., and J. W. LaBaugh. 2003. Hydrologic considerations in defining isolated wetlands. Wetlands **23**:532-540.

Winter, T. C., and D. O. Rosenberry. 1998. Hydrology of prairie pothole wetlands during drought and deluge: A 17-year study of the cottonwood lake wetland complex in North Dakota in the perspective of longer term measured and proxy hydrological records. Climatic Change **40**:189-209.

Winter, T. C., D. O. Rosenberry, and J. W. LaBaugh. 2003. Where does the ground water in small watersheds come from? Ground Water **41**:989-1000.

Wipfli, M. S., and D. P. Gregovich. 2002. Export of invertebrates and detritus from fishless headwater streams in southeastern Alaska: Implications for downstream salmonid production. Freshwater Biology **47**:957-969.

Wipfli, M. S., and J. Musslewhite. 2004. Density of red alder (*Alnus rubra*) in headwaters influences invertebrate and detritus subsidies to downstream fish habitats in Alaska. Hydrobiologia **520**:153-163.

Wipfli, M. S., J. S. Richardson, and R. J. Naiman. 2007. Ecological linkages between headwaters and downstream ecosystems: Transport of organic matter, invertebrates, and wood down headwater channels. Journal of the American Water Resources Association **43**:72-85.

Wiskow, E., and R. R. van der Ploeg. 2003. Calculation of drain spacings for optimal rainstorm flood control. Journal of Hydrology **272**:163-174.

With, K. A., R. H. Gardner, and M. G. Turner. 1997. Landscape connectivity and population distributions in heterogeneous environments. Oikos **78**:151-169.

Withers, P. J. A., and H. P. Jarvie. 2008. Delivery and cycling of phosphorus in rivers: A review. Science of The Total Environment **400**:379-395.

Woessner, W. W. 2000. Stream and fluvial plain ground water interactions: Rescaling hydrogeologic thought. Ground Water **38**:423-429.

Wofford, J. E. B., R. E. Gresswell, and M. A. Banks. 2005. Influence of barriers to movement on within-watershed genetic variation of coastal cutthroat trout. Ecological Applications **15**:628-637.

Wohl, E. 2005. Disconnected rivers: Human impacts to rivers in the United States. Reviews in Engineering Geology **16**:19-34.

Wohl, E., and N. D. Beckman. 2014. Leaky rivers: Implications of the loss of longitudinal fluvial disconnectivity in headwater streams. Geomorphology **205**:27-35.

Wollheim, W. M., B. J. Peterson, S. M. Thomas, C. H. Hopkinson, and C. J. Vorosmarty. 2008. Dynamics of N removal over annual time periods in a suburban river network. Journal of Geophysical Research: Biogeosciences **113**:G03038.

Wolman, M. G., and J. P. Miller. 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology **68**:54-74.

Wolock, D. M., T. C. Winter, and G. McMahon. 2004. Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analysis. Environmental Management **34**:S71-S88.

Wood, P. J., and P. D. Armitage. 1997. Biological effects of fine sediment in the lotic environment. Environmental Management **21**:203-217.

Woodford, D. J., and A. R. McIntosh. 2010. Evidence of source-sink metapopulations in a vulnerable native galaxiid fish driven by introduced trout. Ecological Applications **20**:967-977.

Woodin, M. 1994. Use of saltwater and freshwater habitats by wintering redheads in southern Texas. Pages 279-287 *in* Aquatic birds in the trophic web of lakes. J. Kerekes, editor. Springer Netherlands.

Woodward, G. U. Y., and A. G. Hildrew. 2002. Food web structure in riverine landscapes. Freshwater Biology **47**:777-798.

Wright, S. 1943. Isolation by distance. Genetics **28**:114-138.

Yamamoto, S., K. Morita, I. Koizumi, and K. Maekawa. 2004. Genetic differentiation of white-spotted charr (*Salvelinus leucomaenis*) populations after habitat fragmentation: Spatial-temporal changes in gene frequencies. Conservation Genetics **5**:529-538.

Yang, J., and X. Chu. 2013. Effects of DEM resolution on surface depression properties and hydrologic connectivity. Journal of Hydrologic Engineering **18**:1157-1169.

Yang, W., X. Wang, Y. Liu, S. Gabor, L. Boychuk, and P. Badiou. 2010. Simulated environmental effects of wetland restoration scenarios in a typical Canadian prairie watershed. Wetlands Ecology and Management **18**:269-279.

Yetter, S. E. 2013. Freshwater macroinvertebrates of the Mid-Atlantic Region. Pages 339-379 *in* Mid-Atlantic freshwater wetlands: Advances in wetlands science, management, policy, and practice. R. P. Brooks and D. H. Wardrop, editors. Springer, New York.

Zaimes, G. N., R. C. Schultz, and T. M. Isenhart. 2004. Stream bank erosion adjacent to riparian forest buffers, row-crop fields, and continuously-grazed pastures along Bear Creek in central Iowa. Journal of Soil and Water Conservation **59**:19-27.

Zedler, P. H. 2003. Vernal pools and the concept of "isolated wetlands". Wetlands **23**:597-607.

Zimmer, K. D., M. A. Hanson, and M. G. Butler. 2001. Effects of fathead minnow colonization and removal on a prairie wetland ecosystem. Ecosystems **4**:346-357.

Zwieniecki, M. A., and M. Newton. 1999. Influence of streamside cover and stream features on temperature trends in forested streams of western Oregon. Western Journal of Applied Forestry **14**:106-113.

APPENDIX A. GLOSSARY

Absorption—A reversible process that occurs when molecules in one state or phase penetrate those of another phase.

Adsorption—Adhesion of molecules to a surface, either physically or chemically. Physical adsorption occurs when the surface tension of a solid causes molecules to be held at its surface; this process can be reversible, depending on environmental conditions. Chemical adsorption occurs when chemicals bond at the surface of a solid, and is not readily reversible.

Allochthonous—Describing organic material that originates from outside of streams, rivers, wetlands, or lakes (e.g., terrestrial plant litter, soil).

Alluvial Aquifer—An aquifer with geologic materials deposited by a stream or river (alluvium) that retains a hydraulic connection with the depositing stream.

Alluvial Deposits—*See* Alluvium.

Alluvial Ground Water—Ground water occurring in an alluvial aquifer.

Alluvium—Deposits of clay, silt, sand, gravel, or other particulate materials that have been deposited by a stream or other body of running water in a streambed, on a flood plain, on a delta, or at the base of a mountain. *See* Colluvium.

Anastomosing Channel—A multithreaded stream or river channel in which the channels (distributaries) branch and rejoin farther downstream; distributary channels are separated by stable islands (usually vegetated) that are large relative to the size of the channels.

Anoxic Conditions—Without detectable dissolved oxygen; anaerobic. *See* Hypoxia.

Aquatic Ecosystem—Any aquatic environment, including all of the environment's living and nonliving constituents and the interactions among them.

Aquifer—A geologic formation (e.g., soil, rock, alluvium) with permeable materials partially or fully saturated with ground water that yields ground water to a well, spring, or stream.

Artificial Drainage—Use of constructed channels or subsurface structures to drain an area by increasing the rate of flow of water from the area.

Assimilatory Processes—The incorporation or transformation of simple compounds into more complex compounds.

Autochthonous—Describing organic matter that originates from production within streams, rivers, wetlands, or lakes (e.g., periphyton, macrophytes, phytoplankton).

Bank Storage—Storage of water that flows from a stream to an alluvial aquifer during a flood or period of high streamflow. The volume of water is stored and released after the high-water event over days to months. The volume of water stored and the timing of release depends on the hydraulic properties of the alluvial aquifer.

Baseflow—Sustained flow of a stream (or river) in the absence of stormflow (direct runoff). Natural baseflow is sustained by ground-water discharge in the stream network. Baseflow also can be sustained by human sources (e.g., irrigation recharges to ground water).

Basin—*See* Drainage Basin*.*

Bedrock—Solid rock underlying loose deposits such as soil or alluvium.

Bog—A peat-accumulating wetland that is generally nutrient poor.

Braided Channel—A multithreaded channel in which the channels (distributaries) branch and rejoin farther downstream and the channels are separated by mobile, transient bars (poorly vegetated) that are small relative to the size of the channels.

Carolina Bays—Elliptical, ponded, depressional wetlands that range along the Atlantic Coastal Plain from northern Florida to New Jersey. *See* Delmarva Bays.

Catchment—The area drained by a stream, river, or other water body; typically defined by the topographic divides between one water body and another. *Synonymous with* Watershed *and* Drainage Basin*.*

Channel—A natural or constructed passageway or depression of perceptible linear extent that conveys water and associated material downgradient.

Channelization—A type of artificial drainage in which complex channels are straightened to increase the rate of water flow from an area.

Channelized Flow—Flow that occurs in a natural or artificial channel.

Colluvium—A layer of unconsolidated soils, sediment and rock fragments deposited by surface runoff and gravitational processes; colluvium generally occurs as a blanket of poorly sorted sediment and rock fragments on the lower parts of hillslopes underlain by bedrock. *See* Alluvium.

Condition—General health or quality of an ecosystem, typically assessed using one or more indicators.

Confined Aquifer—An aquifer bounded above and below by confining units of distinctly lower permeability than that of the aquifer itself.

Confluence—The point at which two stream channels intersect to form a single channel.

Connectivity—The degree to which components of a river system are joined, or connected, by various transport mechanisms; connectivity is determined by the characteristics of both the physical landscape and the biota of the specific system.

Connectivity Descriptors (for streams and wetlands)—The frequency, duration, magnitude, timing, and rate of change of fluxes to and biological exchanges with downstream waters.

Contributing Area—Location within a watershed/river network that serves as a source of stream flow or material flux.

Contaminants—Any material that might be harmful to humans or other organisms when released to the environment.

Deep Ground Water—Ground-water flow systems having the deepest and longest flowpaths; also referred to as regional ground-water flow systems, they can occur beneath local and intermediate ground-water flow systems. *See* Local Ground Water, Regional Ground Water.

Delmarva Bays—Carolina bays that are geographically specific to the Delmarva Peninsula. These wetlands frequently have the same elliptical shape and orientation as Carolina bays. *See* Carolina Bays.

Dendritic Stream Network—A stream network pattern of branching tributaries (see Figure 2-19B).

Depressional Wetland—A wetland occupying a topographic low point that allows the accumulation of surface water. Depressional wetlands can have any combination of inlets and outlets or lack them completely. Examples include kettles, prairie potholes, and Carolina bays. This category also includes slope wetlands (wetlands associated with surface discharge of ground water or saturated overflow with no channel formation).

Diadromous—Migratory between fresh and salt waters.

Direct Runoff—Runoff that occurs in direct response to precipitation. *See* Stormflow.

Discharge—The volume of water (surface water or ground water) that passes a given location over a given period of time; the rate of runoff. Often expressed as $ft^3\ s^{-1}$ or $m^3\ s^{-1}$.

Discontinuous Flow—Refers to stream and river reaches that have flow in one part of the reach but not another part of the reach. *See* Reach.

Dispersal—Movement from natal breeding sites to new breeding sites.

Drainage Area—The spatial extent of a drainage basin. Typically expressed in mi^2 or km^2.

Drainage Basin—The area drained by a stream, river, or other water body; typically defined by the topographic divides between one water body and another. *Synonymous with* Catchment *and* Watershed.

Drainage Density—The total length of stream channels per unit drainage area (e.g., per mi^2 or km^2).

Drainage Network—*See* River Network.

Egg Bank—Viable dormant eggs that accumulate in soil or in sediments under water. *See* Seed bank.

Endorheic Basins—A closed drainage basin with no outflows to other water bodies.

Endorheic Stream—A stream or river reach that experiences a net loss of water to a ground-water system. *See* Losing Stream or Wetland.

Ephemeral Stream—A stream or river that flows briefly in direct response to precipitation; these channels are always above the water table.

Eutrophication—Natural or artificial enrichment of a water body by nutrients, typically phosphates and nitrates. If enrichment leads to impairment (e.g., toxic algal blooms), eutrophication is a form of pollution.

Evapotranspiration—The combined loss of water to the atmosphere due to evaporation and transpiration losses. Transpiration is the loss of water vapor to air by plants.

Fen—A peat-accumulating wetland characterized by mineral-rich water inputs.

Flood—The occurrence of stream or river flow of such magnitude that it overtops the natural or artificial banks in a reach of the stream or river; where a floodplain exists, a flood is any flow that spreads over or inundates the floodplain. Floods also can result from rising stages in lakes and other water bodies.

Flood (100-year)—Flood level (stage or discharge) with a 1% probability of being equaled or exceeded in a given year.

Flood Flows—Discharge or flow of sufficient (or greater) magnitude to cause a flood.

Flood Stage—The stage at which streams or rivers overtop their natural or artificial banks.

Floodwater—Water associated with a flood event.

Floodplain—A level area bordering a stream or river channel that was built by sediment deposition from the stream or river under present climatic conditions and is inundated during moderate to high flow events. Floodplains formed under historic or prehistoric climatic conditions can be abandoned by rivers and form terraces.

Floodplain Wetland—Portions of floodplains that meet the Cowardin et al. (1979) three-attribute definition of a wetland (i.e., having wetland hydrology, hydrophytic vegetation, or hydric soils). *See* Wetland.

Flow—Water movement above ground or below ground.

Flow Duration Class—A classification that assigns streamflow duration to ephemeral, intermittent, or perennial classes.

Flow Regime—Descriptor of flow types in a temporal or magnitude sense (i.e., slow-flow regime, low-flow regime)

Flowpath—*See* Hydrologic Flowpath*.*

Fluvial—Refers to or pertains to streams; e.g., stream processes (fluvial processes), fluvial landforms, such as fluvial islands and bars, and biota living in and near stream channels.

Flux—Flow of materials between system components per unit time.

Gaining Stream or Wetland—A wetland or a stream or river reach that experiences a net gain of water from ground water (see Figure 2-5). In this situation, the water table elevation near the stream or wetland is higher than the stream or wetland water surface. Conditions conducive to losing or gaining streams and wetlands can change over short distances within river networks and river basins. *See* Losing Stream or Wetland.

Geographically Isolated Wetland—A wetland that is completely surrounded by uplands; for example, hydrophytic plant communities surrounded by terrestrial plant communities or undrained hydric soils surrounded by nonhydric soils. This term often is mistakenly understood to mean hydrologically isolated. Geographically isolated wetlands vary in their degree of hydrologic and biotic connectivity.

Ground Water—Any water that occurs and flows in the saturated zone. *See* Saturated Zone.

Ground-water Discharge —The flow of ground water to surface waters; discharge areas occur where the water tables intersect land surfaces. *See* Seep*,* Spring*.*

Ground-water Discharge Wetland—A wetland that receives ground-water discharge.

Ground-water Flow—Flow of water in the subsurface saturated zone.

Ground-water Flow-through Wetland—A wetland that has both ground-water inputs and outputs. Ground water enters the wetland through the upgradient direction and exits the wetland downgradient.

Ground-water Recharge—The process by which ground water is replenished; a recharge area occurs where precipitation or surface water infiltrates and is transmitted downward to the saturated zone (aquifer). *See* Infiltration, Percolation, Transmission.

Ground-water Recharge Wetland—A wetland that recharges ground water.

Ground-water Reservoir—A saturated body of ground water having loosely definable spatial limits.

Ground-water System—Reference to the ground water and geologic materials comprising the saturated zone; the ground-water system, as a whole, is a three-dimensional flow field.

Ground water–Surface water Interactions—Movement of water between surface-water bodies and ground-water systems. Flows can occur in either direction.

Ground-water Withdrawal—Pumping of water from aquifers for human uses.

Habitat—Environment (place and conditions) in which organisms reside.

Headwater—Areas from which water originates within a river or stream network. This term typically refers to stream channels but can also describe wetlands or open waters, such as ponds.

Headwater Stream—Headwater streams are first- to third-order streams. Headwater streams can be ephemeral, intermittent, or perennial. *See* Stream Order, Flow Duration Class*.*

Hillslope—A sloping segment of land surface.

Hydraulic Conductivity—A measure of the permeability of a porous medium. For a given hydraulic gradient, water moves more rapidly through media with high hydraulic conductivity than low hydraulic conductivity.

Hydraulic Gradient—Slope of the water table. *See* Water Table.

Hydraulic Head—The height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point; for a well, the hydraulic head is the height of the water level in the well compared to a datum elevation.

Hydraulics—The physics of water in its liquid state.

Hydric—An area, environment, or habitat that is generally very wet with plenty of moisture. *See* Mesic, Xeric.

Hydrograph—A graph of stream or river discharge over time. Stage or water table elevation also can be plotted.

Hydrologic Event—An increase in streamflow resulting from precipitation or snowmelt.

Hydrologic Flowpath—The pathway that water follows as it moves over the watershed surface or through the subsurface environment.

Hydrology—The study of the properties, distribution, and effects of water as a liquid, solid, and gas on Earth's surface, in the soils and underlying rocks, and in the atmosphere.

Hydrologic Landscape—A landscape with a combination of geology, soils, topography, and climate that has characteristic influences on surface water and ground water.

Hydrologic Permanence—The frequency and duration of streamflow in channels or the frequency and duration of standing water in wetlands.

Hyporheic Flow—Water from a stream or river channel that enters subsurface materials of the streambed and bank and then returns to the stream or river.

Hyporheic Exchange—Water and solutes exchanged between a surface channel and the shallow subsurface. *See* Hyporheic Flow*.*

Hyporheic Zone—The area adjacent to and beneath a stream or river in which hyporheic flow occurs. The dimensions of the hyporheic zone are controlled by the distribution and characteristics of alluvium and hydraulic gradients between streams and local ground water.

Hypoxia—The condition in which dissolved oxygen is below the level necessary to sustain most animal life. *See* Anoxic Conditions.

Infiltration—The downward entry of water from the land surface into the subsurface.

Infiltration Capacity—The maximum rate at which infiltration can occur at a given location.

Interfluve—The area of higher terrain between adjacent stream valleys.

Intermediate Ground Water—Ground-water flow systems representative of the wide range of flowpath lengths and depths that occur between local and regional ground-water systems.

Intermittent—This term also can be applied to other surface-water bodies and ground-water flow or level*. See* Intermittent Stream.

Intermittent Stream—A stream or portion of a stream that flows continuously only at certain times of year; for example, when it receives water from a spring, ground-water source, or a surface source such as melting snow. At low flow, dry segments alternating with flowing segments can be present.

Inundation—To cover dry land with floodwaters.

Isolation—Condition defined by reduced or nonexistent transport mechanisms between system components.

Isotopic Tracer—*See* Stable Isotope Tracer.

Lag Function—Any function within a stream or wetland that provides temporary storage and subsequent release of materials without affecting cumulative flux (exports = imports); delivery is delayed and can be prolonged.

Lateral Source Stream—A first-order stream that flows into a higher order stream.

Lentic—Of, relating to, or living in still water. *See* Lotic.

Levee (Artificial)—An engineered structure built next to a stream or river from various materials to prevent flooding of surrounding areas. The levee raises the elevation of the channel height to convey greater discharge of water without flooding.

Levee (Natural)—A broad, low ridge or embankment of coarse silt and sand that is deposited by a stream on its floodplain and along either bank of its channel. Natural levees are formed by reduced velocity of flood flows as they spill onto floodplain surfaces and can no longer transport the coarse fraction of the suspended sediment load.

Local Ground Water—Ground water with a local flow system. Water that recharges at a high point in the water table that discharges to a nearby lowland. Local ground-water flow is the most dynamic and shallowest of ground-water flow systems. Therefore, it has the greatest interchange with surface water. Local flow systems can be underlain by intermediate and regional flow systems. Water in these deeper flow systems have longer flowpaths and longer contact time with subsurface materials. Deeper flow systems also eventually discharge to surface waters and influence their condition.

Losing Stream or Wetland—A stream, wetland, or river reach that experiences a net loss of water to a ground-water system (see Figure 2-5). In this situation, the water table elevation near the stream or wetland is lower than the stream or wetland water surface. Conditions conducive to losing or gaining streams and wetlands can change over short distances within river networks and river basins. *See* Gaining Stream or Wetland.

Lotic—Of, relating to, or living in moving water. *See* Lentic.

Mainstem—Term used to distinguish the larger (in terms of discharge) of two intersecting channels in a river network.

Materials—Any physical, chemical, or biological entity, including but not limited to water, heat energy, sediment, wood, organic matter, nutrients, chemical contaminants, and organisms.

Meltwater—Liquid water that results from the melting of snow, snowpacks, ice, or glaciers.

Mesic—An area, environment, or habitat with a moderate amount of moisture. *See* Hydric, Xeric.

Migration—Long-distance movements undertaken by organisms on a seasonal basis.

Non-floodplain Wetland—An area outside of the floodplain that meets the Cowardin et al. (1979) three-attribute definition of a wetland (i.e., having wetland hydrology, hydrophytic vegetation, or hydric soils). For the purposes of this report, riparian wetlands that occur outside of the floodplain are not included as non-floodplain wetlands, since these wetlands are subject to bidirectional, lateral hydrologic flows. *See* Floodplain, Wetland*.*

Nutrients (In Aquatic Systems)—Elemental forms of nitrogen, phosphorus, and trace elements, including sulfur, potassium, calcium, and magnesium, that are essential for the growth of organisms but can be contaminants when present in high concentrations.

Nutrient Spiraling—Longitudinal cycles ("spirals") of nutrient uptake and release along the stream or river continuum. The spirals are created as aquatic organisms consume, transform, and regenerate nutrients, altering the rates of nutrient transport to downstream waters.

Open-channel Flow—Water flowing within natural or artificial channels.

Open Waters—Nontidal lentic water bodies such as lakes and oxbow lakes that are frequently small or shallow.

Overbank Flow—Streamflow that overtops a stream or river channel.

Overland Flow—The portion of streamflow derived from net precipitation that fails to infiltrate the land surface at any point and runs over the surface to the nearest stream channel.

Oxbow Lakes—Water bodies that originate from the cutoff meanders of rivers; such lakes are common in floodplains of large rivers.

Peatland—A wetland that accumulates partially decayed organic matter. Fens and bogs are common examples.

Perched Ground Water—Unconfined ground water separated from an underlying body of ground water by an unsaturated zone; perched ground water is supported by a perching layer (bed) for which the permeability is so low that water percolating downward to the underlying unsaturated zone is restricted.

Perching Water Tables—*See* Perched Ground Water.

Percolation—The downward movement of water through soil or rock formations.

Perennial— *See* Perennial Stream. This term can be applied to other surface-water bodies and to ground-water flow or level.

Perennial Stream—A stream or portion of a stream that flows year-round and is maintained by local, intermediate, or regional ground-water discharge or flow from higher in the river network.

Permanent Waters—Water bodies that contain water year-round; perennial waters.

Permeability—Property of a porous medium that enables it to transmit fluids under a hydraulic gradient. For a given hydraulic gradient, water will move more rapidly through high permeability materials than low permeability materials.

Phreatophyte—Plants that use water from the saturated zone.

Potential Evapotranspiration—The amount of water that would be lost to the atmosphere over a given area through evaporation and transpiration, assuming no limits on the water supply. *See* Evapotranspiration.

Potentiometric Surface—The surface representing the level to which ground water will rise in a well penetrating a confined aquifer.

Prairie Potholes—Complex of glacially formed wetlands, usually lacking natural outlets, found in the central United States and Canada.

Precipitation—Water that condenses in the atmosphere and falls to a land surface. Common types include rain, snow, hail, and sleet.

Precipitation Intensity—The rate at which precipitation occurs; generally refers to rainfall intensity.

Primary Production—The fixation of inorganic carbon into organic carbon (e.g., plant and algae biomass) through the process of photosynthesis. Primary production is the first level of the food web, and provides most of the autochthonous carbon produced in ecosystems. The rate of fixation is referred to as gross primary productivity (GPP) or net primary productivity (NPP), where NPP is equal to GPP minus respiration. *See* Respiration, Secondary Production.

Propagule—Any part of an organism that can give rise to a new individual organism. Seeds, eggs, and spores are propagules.

Reach—A length of stream channel with relatively uniform discharge, depth, area, and slope.

Recession [of Flow)—Decrease in flow following a hydrologic event.

Recharge Area—An area in which water infiltrates the surface and reaches the zone of saturation.

Refuge Function—The protective function of a stream or wetland that allows an organism (or material) to avoid mortality (or loss) in a nearby sink area, thereby preventing the net decrease in material flux that otherwise would have occurred (exports = imports). This term typically refers to organisms but can be used for nonliving materials. *See* Sink Function.

Regional Ground Water—Ground water with a deep, regional-scale flow system; also referred to as deep ground water. These flow systems can occur beneath local and intermediate ground-water flow systems. *See* Local Ground Water, Deep Ground Water.

Respiration—The chemical process by which organisms break down organic matter and produce energy for growth, movement, and other biological processes. Aerobic respiration uses oxygen and produces carbon dioxide.

Return Flow—Water that infiltrates into a land surface and moves to the saturated zone and then returns to the land surface (or displaces water that returns to the soil surface).

Riparian Areas—Transition areas or zones between terrestrial and aquatic ecosystems that are distinguished by gradients in biophysical conditions, ecological processes, and organisms. They are areas through which surface hydrology and subsurface hydrology connect water bodies with their uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems. Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes, and estuarine-marine shorelines. *See* Upland.

Riparian Wetland—Portions of riparian areas that meet the Cowardin et al. (1979) three-attribute definition of a wetland (i.e., having wetland hydrology, hydrophytic vegetation, hydric soils). *See* Wetland.

River—A relatively large volume of flowing water within a visible channel, including subsurface water moving in the same direction as the surface water, and lateral flows exchanged with associated floodplain and riparian areas. *See* Stream.

River Network—A hierarchical, interconnected population of channels or swales that drain water to a river. Flow through these channels can be perennial, intermittent, or ephemeral.

River Network Expansion/Contraction—The extent of flowing water in a river network increases during wet seasons and large precipitation events and decreases during dry periods. *See* Variable Source Area.

River System—A river and its entire drainage basin, including its river network, associated riparian areas, floodplains, alluvial aquifers, regional aquifers, connected water bodies, geographically isolated water, and terrestrial ecosystems.

Runoff—The part of precipitation, snowmelt, or other flow contributions (e.g., irrigation water) that appears in surface streams at the outlet of a drainage basin; it can originate from both above land surface (e.g., overland flow) and below land surface sources (e.g., ground water). Units of runoff are depth of water (similar to precipitation units, e.g., mm). This measurement is the depth of water if it were spread across the entire drainage basin. Can also be expressed as a volume of water (i.e., m^3, $feet^3$, acre-ft).

Saturated Zone—The zone below the land surface where the voids in soil and geologic material are completely filled with water. Water in the saturated zone is referred to as ground water. The upper surface of the saturated zone is referred to as the water table. *See* Ground Water, Unsaturated Zone, Water Table.

Saturation Overland Flow—Water that falls onto a saturated land surface and moves overland to the nearest stream or river.

Seasonality—Refers to the seasonal distribution of water surplus of a river system. *See* Water Surplus.

Secondary Production—The generation of biomass of consumer organisms that feed on organic material from primary producers (algae, microbes, aquatic and terrestrial plants), and biomass of predators that feed on consumer organisms. *See* Primary Production.

Seed Bank—Viable dormant seeds that accumulate in soil or in sediments under water. *See* Egg bank.

Seep—A small area where water slowly flows from the subsurface to the surface. A seep can also refer to a wetland formed by a seep; such a wetland is referred to as a ground-water slope wetland.

Seepage—Water that flows from a seep.

Shallow Ground Water—Ground water with shallow hydrologic flowpaths. *See* Local Ground Water.

Sink Function—Any function within a stream or wetland that causes a net decrease in material flux (imports exceed exports).

Snowpack—Accumulation of snow during the winter season; an important source of water for streams and rivers in the western United States.

Snowmelt—The complete or partial melting and release of liquid water from seasonal snowpacks.

Solute—A substance that is dissolved in water.

Source Area—The originating location of water or other materials that move through a river system.

Source Function—Any function within a stream or wetland that causes a net increase in material flux (exports exceed imports).

Spillage—Overflow of water from a depressional wetland to a swale or channel.

Spring—A surface-water body formed when the side of a hill, a valley bottom, or other excavation intersects a flowing body of ground water at or below the local water table.

Stable Isotope Tracer—Certain elements such as oxygen, hydrogen, carbon, and nitrogen have multiple isotopes that occur in nature that do not undergo radioactive decay. These isotopes can be used to track the source and movement of water and other substances.

Stage—The elevation of the top of a water surface.

Stream—A relatively small volume of flowing water within a visible channel, including subsurface water moving in the same direction as the surface water, and lateral flows exchanged with associated floodplain and riparian areas. *See* River.

Stream Burial—The process of incorporating streams—particularly headwaters—into storm sewer systems, usually by routing through underground pipes.

Stream Power—A measure of the erosive capacity of flowing water in stream channels or the rate of energy dissipation against the stream bed or banks per unit of channel length that has the mathematical form: $\omega_a = \rho gQS$ where ω_a is the stream power, ρ is the density of water (1000 kg/m^3), g is acceleration due to gravity (9.8 m/s^2), Q is discharge (m^3/s), and S is the channel slope.

Stream Network—*See* River Network. A stream network is the same as river network, but typically refers to a smaller spatial scale.

Stream Reach—*See* Reach.

Storm—A precipitation event that produces an increase in streamflow.

Stormflow—The part of flow through a channel that occurs in direct response to precipitation; it includes surface and subsurface sources of flow. *See* Direct Runoff.

Stream Order (Strahler)—A method for stream classification based on relative position within a river network, when streams lacking upstream tributaries (i.e., headwater streams) are first-order streams and the junction of two streams of the same order results in an increase in stream order (i.e., two first-order streams join to form a second-order stream, two second-order streams join to form a third-order stream, and so on). When streams of different order join, the order of the larger stream is retained. Stream-order classifications can differ, depending on the map scale used to determine order.

Streamflow—Flow of water through a stream or river channel. *See* Discharge.

Subsurface Water—All water that occurs below the land surface.

Surface Runoff—*See* Overland Flow.

Surface Water—Water that occurs on Earth's surface (e.g., springs, streams, rivers, lakes, wetlands, estuaries, oceans).

Surface-water Bodies—Types of water bodies that comprise surface water. *See* Surface Water.

Swale—A nonchannelized, shallow trough-like depression that carries water mainly during rainstorms or snowmelt. A swale might or might not be considered a wetland depending on whether it meets the Cowardin et al. (1979) three-attribute wetland criteria. *See* Wetland.

Symmetry Ratio—The size ratio of a minor tributary ($T2$) to a major tributary ($T1$) at a confluence. Discharge ($Q2/Q1$), drainage area ($A2/A1$), or channel width ($W2/W1$) can be used to characterize the ratio of tributary size.

Terminal Source Stream—A first-order stream that intersects another first-order stream.

Terrace—An historic or prehistoric floodplain that has been abandoned by its river and is not currently in the active floodplain. *See* Floodplain.

Terrene Wetlands—"Wetlands surrounded or nearly so by uplands and lacking a channelized outlet stream; a stream may enter or exit this type of wetland but it does not flow through it as a channel; includes a variety of wetlands and natural and human-made ponds" (Tiner, 2011).

Tracer—A substance that can be used to track the source and movement of water and other substances.

Transformation Function—Any function within a stream or wetland that converts a material into a different form; the amount of the base material is unchanged (base exports equal base imports), but the mass of the different forms can vary.

Transmission Loss—The loss of runoff water by infiltration into stream and river channel beds as water moves downstream; this process is common in arid and semiarid environments.

Transport Mechanism—Any physical mechanism, such as moving water, wind, or movement of organisms, which can transport materials or energy. As used in this report, the term specifically refers to physical mechanisms that move material or energy between streams or wetlands and downstream waters.

Tributary—A stream or river that flows into a higher order stream or river.

Turnover Length—The ratio of the downstream flux of organic carbon to ecosystem respiration per length of stream. It approximates the average distance that organic carbon is expected to travel before it is consumed and mineralized by aquatic organisms.

Unconfined Aquifer—An aquifer that has a water table; the aquifer is not bounded by lower permeability layers. *See* Confined Aquifer.

Unsaturated Zone— Also referred to as the vadose zone. The zone between land surface and the water table within which the moisture content is less than saturation and pressure is less than atmospheric. Soil pore spaces also typically contain air or other gases. *See* Saturated Zone.

Uplands—(1) Higher elevation lands surrounding streams and their floodplains. (2) Within the wetland literature, specifically refers to any area that is not a water body and does not meet the Cowardin et al. (1979)-attribute wetland definition. *See* Wetland.

Uptake Length (for dissolved nitrogen in streams)—The distance traveled in the water column before algal and microbial assimilation occurs.

Valley—A depression of the earth's surface that drains water between two upland areas.

Variable Source Area—Neither stormflow nor baseflow is uniformly produced from the entire surface or subsurface area of a basin. Instead, the flow of water in a stream at any given moment is influenced by dynamic, expanding or shrinking source areas, normally representing only a few percent of the total basin areas. The source area is highly variable during stormflow. During large rainfall or snowmelt events, the flowing portions of the river network, and associated source areas, expand. As the event ends, the network and source areas contract.

Vernal Pool—Shallow seasonal wetlands that generally accumulate water during colder, wetter months and gradually dry down during warmer, dryer months.

Water Balance—The accounting of the volume of water that enters, leaves, and is stored in a hydrologic unit, area, or arbitrarily defined control volume, typically a drainage basin or aquifer, during a specified period of time.

Water Body—Any sizable accumulation of water on the land surface, including streams, rivers, lakes, and wetlands.

Water Surplus—Water that is available for streamflow or recharge of ground water; precipitation minus evapotranspiration.

Water Table—The top of the zone of saturation of an unconfined aquifer.

Watershed—The area drained by a stream, river, or other water body; typically defined by the topographic divides between one water body and another. *Synonymous with* Catchment *and* Drainage Basin*.*

Wet Channel—Channel with flowing or standing water.

Wetland—An area that generally exhibits at least one of the following three attributes (Cowardin et al., 1979): (1) is inundated or saturated at a frequency sufficient to support, at least periodically, plants adapted to a wet environment; (2) contains undrained hydric soil; or (3) contains nonsoil saturated by shallow water for part of the growing season.

Wetland Storage—The capacity of a wetland to detain or retain water from various sources.

Xeric—An area, environment, or habitat that is generally dry with very little moisture. *See* Hydric, Mesic.

References

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Office of Biological Services, Washington, DC.

Tiner, R. W. 2011. Dichotomous keys and mapping codes for wetland landscape position, landform, water flow path, and waterbody type descriptors: Version 2.0. U.S. Fish and Wildlife Service, National Wetlands Inventory Program, Northeast Region, Hadley, MA.

APPENDIX B. CASE STUDIES

B.1 Case Study: Carolina and Delmarva Bays

B.1.1 Abstract

Carolina and Delmarva bays are ponded depressional wetlands that occur along the Atlantic Coastal Plain from northern Florida to New Jersey. Most bays receive water through precipitation, lose water through evapotranspiration, and lack natural surface outlets. Both mineral-based and peat-based bays have shown connections to shallow ground water. Bays typically are near each other or near permanent waters, providing the potential for surface-water connections in large rain events via overland flow. Fish are reported in bays that are known to dry out, indirectly demonstrating surficial connections. Amphibians and reptiles use bays extensively for breeding and for rearing young. These animals can disperse many meters on the landscape and can colonize, or serve as a food source to, downstream waters. Similarly, bays foster abundant insects that can become part of the downstream food web. Humans have ditched and channelized a high percentage of bays, creating new surface connections to other waters and allowing transfer of nutrients, sediment, and methylmercury.

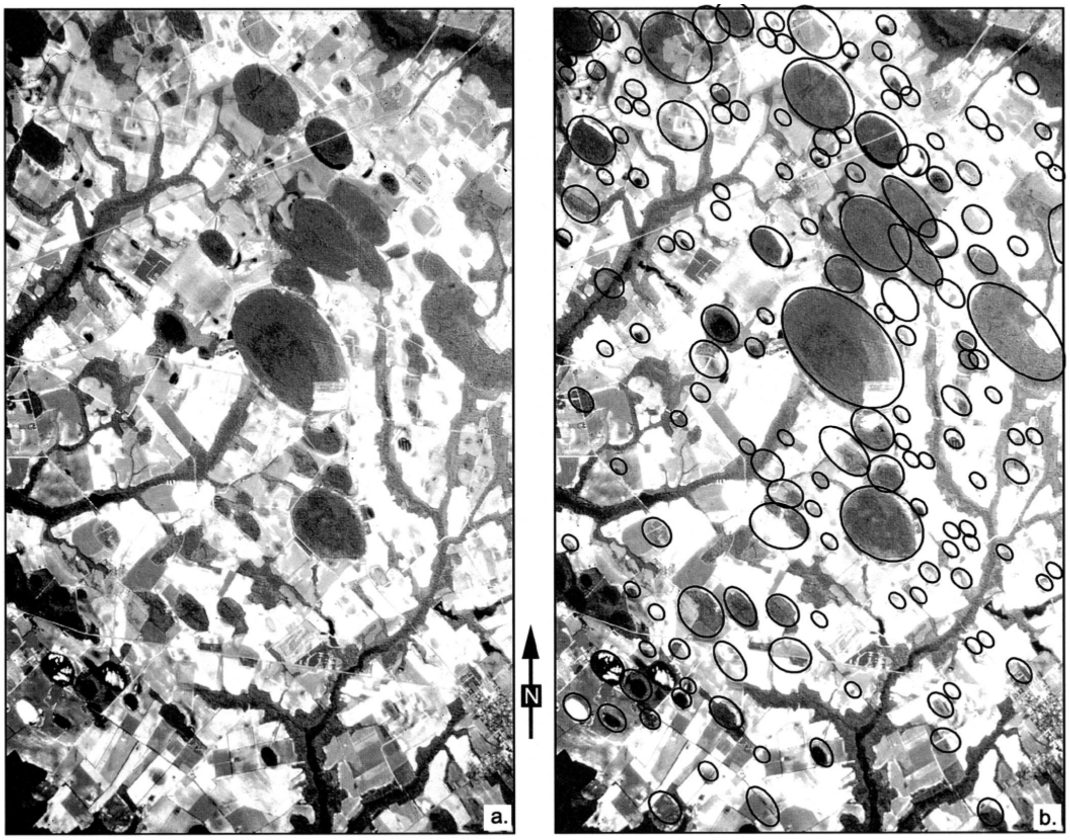
B.1.2 Introduction

B.1.2.1 Definition and Geographic Extent

Carolina bays are elliptical, ponded, depressional wetlands that occur along the Atlantic Coastal Plain from northern Florida to New Jersey (Prouty, 1952; Williams, 1996; Hunsinger and Lannoo, 2005). They have been called "geographically isolated" wetlands (i.e., wetlands surrounded by uplands; Tiner, 2003), and range from permanently inundated to frequently dry (Sharitz, 2003). Carolina bays range in size from greater than 3,600 ha to less than 1 ha and are most abundant in North Carolina and South Carolina (Sharitz and Gibbons, 1982; Sharitz, 2003). Carolina bays that are geographically specific to the Delmarva Peninsula are often referred to as Delmarva bays. Delmarva bays frequently have the same elliptical shape and orientation as other Carolina bays (Stolt and Rabenhorst, 1987a), yet some lack the shape or rim (Sharitz, 2003).

The number of Carolina bays was estimated at 500,000 in the 1950s (Prouty, 1952), but only 10,000–20,000 remained by the early 1990s (Richardson and Gibbons, 1993). Carolina and Delmarva bays have been ditched and drained for agricultural purposes (Figure B-1; Sharitz, 2003). A study of 2,651 Carolina bays in South Carolina found that 97% of bays larger than 0.8 ha had been disturbed by agriculture or logging (Bennett and Nelson, 1991). The northern Delmarva Peninsula has an estimated 1,500–2,500 Delmarva bays remaining (Stolt and Rabenhorst, 1987a). The number of Carolina and Delmarva bays is likely an underestimation, because many are too small to be readily mapped. The National Wetlands Inventory maps have mapping units of 0.4–1.2 ha, but the Department of Energy's

Figure B-1. Aerial photograph of Carolina bays within a region of the upper Coastal Plain of South Carolina. (A) Infrared image showing the pattern of intact and disturbed Carolina bays within a region of the upper Coastal Plain of South Carolina (scale: 1 cm = 1.5 km), and (B) the same image with bays (or former bays that have been disturbed by agriculture) outlined. Reprinted with permission from Sharitz (2003).



Savannah River Site on the upper Coastal Plain of South Carolina has 371 known Carolina bays with 46% having an area of 1.2 ha or less (Sharitz, 2003).

B.1.2.2 Geology

The origin of Carolina and Delmarva bays is unknown, but has been attributed to meteorite impacts, substrate dissolution, and historic modification of shallow ponds through the action of waves generated by winds (Johnson, 1942; Savage, 1982; Ross, 1987; Stolt and Rabenhorst, 1987a; Grant et al., 1998). The soils of Carolina and Delmarva bays range from mineral to organic depending on the position in the landscape, hydrologic conditions, vegetation, and disturbance (Stolt and Rabenhorst, 1987b; Sharitz, 2003). Most bays have alternating layers of sand or silt with impervious clay (Bliley and Pettry, 1979). The organic horizons in bays can range from 1 to 200 cm, with bays near the coast more likely to have the thicker peat deposits (Newman and Schalles, 1990). Despite variation in soil content, water often quickly infiltrates these soils before reaching an impervious clay layer (Sharitz, 2003).

B.1.2.3 Hydrology

Carolina and Delmarva bays gain water primarily from precipitation and lose water by evapotranspiration (Sharitz, 2003). Thus, these systems respond to seasonal rainfall, snowmelt, and temperature. The water levels of Carolina and Delmarva bays therefore fluctuate. The water level in a bay can change from 1−2 m above the soil surface to more than 1 m below the surface (Knight et al., 1989; Schalles and Shure, 1989; Lide et al., 1995; Sharitz, 2003). Bays often are wetter in winter and early spring, when evapotranspiration rates are low, and tend to dry down in summer when evapotranspiration rates are high. Recent work by Lang et al. (2012) using highly accurate LiDAR-derived stream maps has shown that the proportion of wetlands intersected by stream channels (and thus not geographically isolated) is higher than previously thought.

In an analysis of the Tuckahoe Creek watershed in the Delmarva Peninsula, the High Resolution NHD and NHD Plus were found to underestimate the number of wetlands intersected by natural stream channels by 13% and 27%, respectively (Lang et al., 2012). Other hydrologic inputs to bays include artesian wells (Wells and Boyce, 1953), shallow ground water (Phillips and Shedlock, 1993; Lide et al., 1995; Caldwell et al., 2007b), inlet channels (Sharitz, 2003), and some surface runoff during periods of high rainfall. Some bays, particularly those along the coast, can be flooded by high tides and thus are connected to coastal waters (Bliley and Pettry, 1979; Sharitz, 2003).

Despite the prevalence of clay substrates below many of these bays, some studies have found that bays exchange shallow ground water with the surroundings (Phillips et al., 1993; Lide et al., 1995; Sun et al., 2006; Caldwell et al., 2007a; Pyzoha et al., 2008). Some Carolina bays have natural outlet channels (Sharitz, 2003), and many have human-created outlet channels (i.e., ditches) typically resulting in connections to other bays or small streams (Sharitz, 2003).

B.1.2.4 Water Chemistry

Water chemistry of Carolina and Delmarva bays is affected by their position on the landscape, weathering of underlying mineral substrate, accrual and decomposition of organic matter, and the degree to which surface runoff, precipitation, and ground water influence their hydrology (Sharitz, 2003). In general, precipitation-fed wetlands are typically acidic and low in nutrients (Whigham and Jordan, 2003).

Newman and Schalles (1990) reported variable water chemistry in a study of 49 Carolina bays in North Carolina and South Carolina that spanned two transects from inland to the coast. All 49 bays were acidic (median pH = 4.6) and were classified as soft waters (median calcium = 1.69 mg Ca^{2+} L^{-1}). DOC represented 38% of the water anions (median DOC = 17.2 mg L^{-1}). Bays with thick peat layers tended to be low in nutrients, whereas bays with thin peat layers had water quality characteristics similar to local ground water (Newman and Schalles, 1990). Phillips and Shedlock (1993) also associated bay water chemistry with shallow ground water; their study found similarities in water chemistry between upland ground water and the margins of three Delmarva bays. The few studies of nutrient cycling within bays indicate some have the proper wetting and drying cycles to promote denitrification.

Several studies have shown that Carolina bays have the proper hydrology, organic matter content, and pH for the methylation of mercury (Snodgrass et al., 2000b; Brant et al., 2002). Mercury pollution enters water bodies from atmospheric deposition, typically in the ionic form of Hg^{2+}. Bacteria can convert Hg^{2+} to methylmercury, the bioavailable form of mercury that can accumulate in fish, birds, and other organisms. Periodic drying and flooding of Carolina bays, especially shallow ones, promotes mercury methylation and release (Snodgrass et al., 2000b). Mercury levels did not reach acute doses but posed a chronic risk to fish (Snodgrass et al., 2000b) and birds that feed on these fish (Brant et al., 2002).

B.1.2.5 Biological Communities

The wetting and drying cycles of Carolina and Delmarva bays promote a diverse biota, including the presence of numerous rare and endemic species (Sutter and Kral, 1994; Edwards and Weakley, 2001; Sharitz, 2003). Eleven types of vegetation communities have been described in regional surveys of Carolina bays, including species-rich herbaceous communities and cypress ponds (Bennett and Nelson, 1991; Weakley and Schafale, 1991). A seed bank study at the Savannah River Site in South Carolina reported higher diversity than any other reported freshwater wetland habitat (Kirkman and Sharitz, 1994). Researchers estimate that more than one-third of rare plant species in the Southeast occur in nonalluvial wetlands, including Carolina bays (Sutter and Kral, 1994; Sharitz, 2003).

Carolina and Delmarva bays are highly valuable for providing habitat and food web support for invertebrates and vertebrates (Sharitz, 2003). For example, a Savannah River Site study of zooplankton found 44 species of cladocerans and 7 species of copepods (Mahoney et al., 1990). Another invertebrate study showed that a 1.5-ha Carolina bay contained 115 taxa of aquatic and semiaquatic insects from 29 families and 7 orders; more than 11,600 and 8,400 insects emerged from the bay in 1992 and 1993, respectively (Leeper and Taylor, 1998).

Approximately 10−21% of sampled Carolina and Delmarva bays had fish populations (Gibbons and Semlitsch, 1991; Snodgrass et al., 2000a; Sharitz, 2003). The absence of predatory fish in many bays enables abundant amphibian populations to thrive, especially those that have aquatic larval stages (Sharitz and Gibbons, 1982; Sharitz, 2003). For example, one study sampled two 1-ha bays over the course of a year and captured more than 72,000 amphibians, including 9 salamander and 16 frog species (Sharitz and Gibbons, 1982). The Savannah River Site supports 34 species of amphibians, 16 of which depend entirely on seasonal wetlands for breeding (Gibbons and Semlitsch, 1991). Several of these amphibians are endangered or threatened, including the flatwoods salamander (*Ambystoma cingulatum*) and the gopher frog (*Rana capito*) (Sharitz, 2003).

Sharitz and Gibbons (1982) reported 6 turtle species, 9 lizard species, 19 snake species, and 13 small mammal species in bays. American alligators (*Alligator mississippiensis*) are indigenous to southern Carolina bays (Sharitz and Gibbons, 1982). Endangered wood storks (*Mycteria americana*) nest in Carolina bays, and birds such as egrets, coots, wood ducks, and other migratory waterfowl also use Carolina and Delmarva bays (Sharitz and Gibbons, 1982).

B.1.3 Evidence of Connectivity

B.1.3.1 Physical Connections

Research is ongoing on the hydrologic connectivity of Carolina and Delmarva bays to surrounding areas via ground-water flows and intermittent surface flows. A few studies have found ground-water connections or indirect evidence of surface-water connections.

A study by Lide et al. (1995) found a ground-water connection to a Carolina bay. The study examined a 7-ha Carolina bay on the Savannah River Site typical of other bays in western South Carolina with loamy-sand substrate and an underlying clay layer (Lide et al., 1995). The 2-year study examined data from 38 piezometers, borehole logs, pond-stage records, and weather data. They concluded that the Carolina bay was not a perched wetland, but a surface expression of the water table. Although fluctuation of pond stage was largely controlled by precipitation and evapotranspiration, nearly continuous shallow ground-water recharge was present and shallow ground-water discharge occurred periodically.

Phillips and Shedlock (1993) studied three Delmarva bays and also concluded that the bays were connected to local ground water. They studied water table levels and chemistry in transects that ran from uplands through the Delmarva bays. Local ground water strongly influenced the height of the water table in the Delmarva bays. The ground water also was attributed to maintaining a low pH, contributing dissolved aluminum and lowering bicarbonate in the Delmarva bay (Phillips et al., 1993).

Another Carolina bay study in western South Carolina also found evidence for ground-water connectivity (Pyzoha et al., 2008). The more than 13-year study examined piezometer and bay water levels monthly in an 8-ha bay with sandy-loam substrate and an underlying clay layer. Researchers concluded that surface-water and ground-water connections were important to bay hydrology and the bay was not an isolated system. Sun et al. (2006) incorporated climate, vegetation, and soil information to model the hydrology of this bay, which confirmed that the bay was receiving ground-water discharge and recharging ground water to lower topographic areas.

Caldwell et al. (2007b) also used a model to understand the hydrology of three Carolina bays in North Carolina and inferred ground-water connections. All three bays were larger than 100 ha, and their hydrology had not been altered by artificial drainage. Soil types were mineral on the perimeter to mostly organic in the center. The team modeled bay hydrology using climate, vegetation, soils, and hydrology data. They estimated that 10% of water inputs to the bays were surface runoff. Ground-water inflow was the source of 3−26% of water volume into the perimeter of the bays, and ground-water outflow volume (2−21%) was frequent in the center of the bays (Caldwell et al., 2007b).

In addition to ground water, several studies infer Carolina and Delmarva bays are connected to other water bodies through surface-water connections. For example, a study of Carolina bays in Virginia revealed that several of the largest bays were at sea level and bordered the Chesapeake Bay (Bliley and Pettry, 1979). Tidal marshes have encroached and entered these Carolina bays, reflecting a direct link between the Carolina bays and the estuarine environment.

Researchers have used geographic information system methods to determine the nearest river or tributary to Carolina bays (Sharitz, 2003). A geographic information system analysis at the Savannah River Site of 371 Carolina bays showed that 8% were within 50 m of a stream or tributary and 12% were within 100 m (mapping units with a minimum resolution of 0.22 ha; Sharitz, 2003). The same methods showed that 12% of the 2,170 Delmarva bays in Maryland were within 50 m and 19% were within 100 m of streams (mapping units with a minimum resolution of 0.40 ha; Sharitz, 2003). During large storms, the bays located closest to the river network can exhibit hydrologic connections via overland flow or shallow ground-water flow.

Perhaps the strongest evidence that Carolina bays are connected hydrologically to streams or estuaries is that many of these bays are ditched, creating a conveyance for surface water. These ditches commonly connect the surface water of bays to other bays that are lower on the landscape, and ultimately, to streams (Sharitz, 2003).

B.1.3.2 Chemical Connections

Few peer-reviewed papers examine chemical connections between Carolina and Delmarva bays and other waters. One, by Phillips et al. (1993), examined ground water in the Delmarva Peninsula and found that the amount of nitrate in ground water decreased with the presence of forested depressional bays. The authors speculated that the nitrate reduction was due to denitrification in the wetlands. These systems do have the appropriate wetting and drying hydrology to promote denitrification, which could reduce the amount of nitrate in both ground water and surface waters (Groffman et al., 1992).

Carolina and Delmarva bays are frequently connected chemically to downstream waters through ditches. If the bays are sediment and nutrient sinks due to their surficial isolation, ditch connections would make them sources for these materials. For example, Bennett and Nelson (1991) reported that 71% of 2,600 bays were disturbed by agriculture. Whereas the bays might have been a nutrient sink for excess fertilizer that was in surface runoff, these nutrients now could pass through the bays and into the ditches, reaching downstream locations. Additionally, the conditions in Carolina bays have been shown to promote mercury methylation (Snodgrass et al., 2000b). If these bays connect to downstream waters via ditches, some bioavailable mercury would be expected to move to other waters.

B.1.3.3 Biological Connections

Carolina and Delmarva bays are "hotspots" for regional biological diversity and animal use (Sharitz, 2003), which indicates a high potential for movement between bays and other water bodies. The current published evidence for biological connections between bays and other waters is, however, limited or indirect.

The presence of fish in Carolina and Delmarva bays indirectly demonstrates that these bays are connected to other waters. For example, fish were found in 21% of 63 Carolina bays on the Savannah River Site, many of which dry out during parts of the year; fish likely colonized these bays through intermittent or permanent surface hydrologic connections (Snodgrass et al., 1996). One Carolina bay in

North Carolina, Mattamuskeet Bay, has been colonized by both freshwater and estuarine fishes through four canals connecting the bay to Pamlico Sound (Rulifson and Wall, 2006).

Insect emergence from bays can affect nearby waters. Leeper and Taylor (1998) studied insects in a 1.5-ha Carolina bay and recorded 115 taxa representing 29 families. Of the 39 genera of the family Chironomidae represented, 16 are known to live in both pond and stream environments (Hudson et al., 1990; Leeper and Taylor, 1998). Although Leeper and Taylor (1998) did not directly document movement, these species can hatch in Carolina bays and then become important food sources for fish in nearby streams after adult emergence and aerial dispersal. The total number of chironomids emerging from the aforementioned Carolina bay was moderate compared to other wetlands, but cumulative emergence from thousands of bays across the landscape would create a significant food source for organisms, including fishes, in other nearby waters.

Carolina and Delmarva bays are immensely productive amphibian breeding habitats, and are critical for persistence of pond-breeding amphibian populations that can move to other water bodies (Sharitz and Gibbons, 1982). Gibbons et al. (2006) documented more than 360,000 juvenile amphibians from 24 species, emigrating from one Carolina bay during a single breeding season. More than 95% of the biomass (about 1,330 kg) came from juveniles of the southern leopard frog (*Rana sphenocephala*), which is known to use both stream and wetland habitats (Table 4-2). Given the finding that 12−19% of Carolina and Delmarva bays were within 100 m of a tributary (Sharitz, 2003), amphibians emigrating from these bays could transfer extremely high levels of energy and organic matter into rivers and streams. About 90% of Carolina bays located in the Savannah River Site have a tributary or river within 1,600 m (Sharitz, 2003).

B.1.4 Carolina and Delmarva Bays: Synthesis and Implications

The key findings of this case study are as follows:

- Both peat-based and mineral-based bays have been shown to have shallow ground-water inputs and outputs.
- Some Delmarva bays have surface-water connections to the Chesapeake Bay, and the many bays near each other and near permanent waters can be connected during high-precipitation events.
- Human channeling and ditching of the bays are widespread and create surface connections to other waters.
- Fish are found in bays that periodically dry out, indirectly showing that a hydrologic connection occurred at some time.
- Dispersive amphibians and reptiles use bays for breeding or rearing young.
- The abundant insects in bays could become part of the food web for downstream fish.

Although generally supporting the existence of or potential for connectivity between Carolina and Delmarva bays and regional rivers or estuaries, the preponderance of evidence found in the literature we reviewed for this case study is indirect. Furthermore, evidence from this literature review that these connections influence the physical, chemical, and biological conditions and functions of rivers or estuaries is circumstantial. Therefore, the literature that we reviewed does not provide sufficient information to evaluate fully the influence of Carolina and Delmarva bays on rivers and estuaries at this time.

B.2 Case Study: Oxbow Lakes

B.2.1 Abstract

Oxbow lakes are water bodies that originate from the meanders of rivers that become cut off. They are common in the floodplains of large rivers around the world. In the following case study, we provide evidence from the peer-reviewed literature to support two conclusions: (1) oxbow lakes periodically connect to the active river channel, and (2) the connection between oxbow lakes and the active river channel provides for several ecological effects on the river ecosystem.

B.2.2 Introduction

B.2.2.1 Origin and Description

Oxbow lakes and ponds (hereafter referred to as oxbow lakes) originate from river meanders that are cut off from the active river channel. In floodplain rivers, natural erosion of the outer banks of curves in the active river channel leads to increased meandering over time. As these meanders grow, the active channel can come into contact with itself and cut off the curved segment of the river; this cutoff channel becomes an oxbow lake within the floodplain.

Oxbow lakes are dynamic ecosystems. Young oxbow lakes are located near the active river channel and tend to have steep banks. As oxbow lakes are subjected to flooding over time and begin to fill with sediment, they can become shallower and eventually develop terrestrial characteristics. Continued movement and meandering of unconstrained, shallow river channels can leave some oxbow lakes at considerable distances from the active river channel (Winemiller et al., 2000). Owing to the dynamic physical processes that create and promote succession in oxbow lakes, among-lake variation in the character and connectivity of individual oxbow lakes within a floodplain often is large.

Oxbow lakes are an integral element in alluvial floodplain valleys of meandering rivers around the world (Winemiller et al., 2000; Glinska-Lewczuk, 2009). Studies of these ecosystems have been conducted in river floodplains in Australia (Crook and Gillanders, 2006), Europe (Hein et al., 2003), North America (Winemiller et al., 2000; Zeug et al., 2005), and South America (da Silva et al., 2010). Due to the common origin, characteristics of, and interactions between oxbow lakes and rivers, evidence from around the world is presented here.

B.2.3 Evidence

Oxbow lakes commonly connect with the active river channel. The most evident connections are direct physical linkages, in which water movement between the active river channel and oxbow lakes is traceable. Although these physical connections are intrinsically important, they also facilitate the movement and exchange of chemical and biological material between the river and lake ecosystems.

B.2.3.1 Physical Connections

Physical connections between the active river channel and oxbow lakes can be through water movement as overland surface flow, subsurface flow from river infiltration, and subsurface flow from hillslope aquifers (Amoros and Bornette, 2002). In some cases, natural or constructed stream channels are present between the river and the oxbow lake. For the purpose of this report, oxbow lakes with this type of permanent physical connection are a priori considered an integrated part of the river network. Evidence presented here is largely for oxbow lakes that lack permanent physical connections to the river network; therefore, we focus on overland flow events (i.e., temporary connections occurring during high river stages and floods) and shallow ground-water flow as the dominant surface connections between ecosystems.

Regional- and local-scale climate and hydrogeologic patterns are important for understanding the dynamics of physical connectivity between oxbow lakes and active river channels. Regional differences influence the predictability of hydrologic connectivity between rivers and oxbow lakes. In temperate rivers (e.g., Brazos River, TX), surface flow connections between the river channel and oxbow lakes are likely to occur at irregular intervals, in response to flow magnitude and lake geomorphology (Humphries et al., 1999; Zeug and Winemiller, 2008). Tropical rivers, in contrast, are likely to have more regular inundation patterns associated with seasonal flooding (Junk et al., 1989; da Silva et al., 2010). The predictability of subsurface connections also can vary regionally. An isotope tracer analysis of lakes in the Old Crow Flats, Yukon Territory, Canada, indicated that oxbow lakes receive much of their water input from shallow ground-water flow during the relatively short thaw season (Turner et al., 2010). The regularity of connectivity has important implications for the exchange of chemical and biological material between oxbow lakes and the river (Junk et al., 1989; Humphries et al., 1999).

Local landscape characteristics and position of water bodies in the floodplain influence the relative contribution of surface-water and subsurface-water movement between individual lakes and the active river channel, as a study of oxbow lakes on the Loire and Allier Rivers, France, demonstrates. Water in two oxbow lakes had different geochemical signatures, suggesting a difference between when river water was introduced to the lakes (Negrel et al., 2003). The younger oxbow lake was more connected to the surface network due to its closer proximity to the river channel and a small stream connection, while an older oxbow lake, which was more distant from the river channel, was more dependent on subsurface flow (Negrel et al., 2003).

In addition to these spatial differences, temporal differences can occur in the short-term dynamics of hydrologic connectivity. Amoros and Bornette (2002) describe a system of pulsing connectivity, where the direction of water exchange between floodplain water bodies, including oxbow lakes, and a river is related to river stage. At low water stage, floodplain water bodies might receive water from a hillslope aquifer, and water from the oxbow lake likely drains through the alluvium toward the river. In contrast, when a river has a high water stage, water is more likely to seep through the alluvium from the river to the oxbow lake. Finally, inundation would result in surface-water connectivity, where river water moves overland to the oxbow lake. This pattern of pulsing connectivity is influenced by the local topography and the characteristics of the floodplain alluvium (Amoros and Bornette, 2002) and is an illustration of the expansion and contraction concepts described in the framework (Section 2.2.3; Figure 1-2).

Physical connectivity between oxbow lakes and the river network has direct consequences on the hydrologic dynamics of that river network. Oxbow lakes provide flood protection. Like other floodplain water bodies, they retain water. This retention lowers water velocity and can reduce the height of floodwater over nearby terrestrial landscapes (Winemiller et al., 2000). In addition to storing floodwaters, oxbows trap sediment as the velocity of floodwaters declines during the process of retention, allowing sediment to settle out of suspension.

Human alterations of natural flow patterns in rivers can influence connectivity between oxbow lakes and the active river channel. On one hand, connectivity can be enhanced. Channels between oxbow lakes and the river channel often are constructed for their benefits to biological productivity (Glinska-Lewczuk, 2009). On the other hand, isolation might be enhanced. An analysis of sediment cores in two small oxbow lakes in the Vistula River valley, Poland, showed changes in sedimentation rate and grain size following flood dike construction along the river (Galbarczyk-Gasiorowska et al., 2009). These changes in sedimentation can alter the balance of subsurface connections. The absence of channel migration since the 1980s has restricted flooding to areas close to the main channel of the Ebro River, Spain. The effects of this diminished river-floodplain interaction (e.g., erosive floods) left two of three oxbow lakes examined relatively isolated from the river channel, with a thick layer of fine sediment and thus little connection to subsurface flows (Cabezas et al., 2009).

B.2.3.2 Chemical Connections

The dynamics of hydrologic connectivity are important for understanding the chemical character of oxbow lakes. Flooding of the river facilitates exchange of chemicals between the river water and the water in oxbow lakes. In some cases, these surface-water exchanges reset the chemical environment in oxbow lakes (e.g., periodic floods introducing well-aerated water to oxbow lakes in Poland; Obolewski et al., 2009). The chemical effects of flooding are not limited to changes in the water column. For example, the isolation of oxbow lakes from the active river channel corresponded with changes in sediment chemistry, and ultimately, an acceleration of eutrophication (Galbarczyk-Gasiorowska et al., 2009).

Subsurface connections also influence oxbow lake chemistry in important ways. For example, an assessment of oxbow lakes on the River Lyna, Poland indicated that nutrient concentrations in oxbow lakes likely were influenced by a combination of river water from surface connections, ground-water seepage from the alluvial aquifer, infiltration from hillslope runoff, and inlake nutrient processing (Glinska-Lewczuk, 2009). In some cases, these other connection types can play a more important role in oxbow lake chemistry than periodic surface connections created during flood events. An examination of sediment chemistry in floodplain water bodies on the River Havel, Germany showed little effect of flooding on sediment chemistry (particulate organic matter, carbon, nitrogen, phosphorus, and iron) in oxbow lakes (Knosche, 2006). As is the case with physical connectivity, the relative importance of surface and subsurface connectivity depends on local characteristics of the floodplain ecosystem.

Alterations of natural flood dynamics affect the exchange of chemical materials between the river and oxbow lakes. Total organic carbon accretion and total nitrogen accretion in river floodplains are important ecosystem functions of floodplain water bodies, like oxbow lakes, that might improve water quality in rivers (Mitsch, 1992). An analysis of sediment, carbon, and nitrogen accretion in oxbow lakes on the River Ebro, Spain showed lower recent accumulation (1963−2007) compared to the past (1927−1963; Cabezas et al., 2009). In this example, the reduced accumulation of carbon and nitrogen concentrations in oxbow lake sediment was related to reduced size and frequency of flood events in this floodplain ecosystem (Cabezas et al., 2009).

Importantly, oxbow lakes reduce pollution loading to the river network. Oxbow lakes can intercept nutrients from upland runoff, leaving them in the oxbow lake rather than in the river (Glinska-Lewczuk, 2009). A similar process of physical interception is observed in riparian wetlands, where wetland ecosystems have been considered habitats that might control nonpoint-source pollution of nutrients (Mitsch, 1992), sediment (Brix, 1994), or pesticides (Gregoire et al., 2009) to rivers. In addition to being areas of deposition, high mineralization rates in oxbow lakes suggest that these lakes can process and remove some nutrients in terrestrial runoff before the runoff reaches the river channel (Winemiller et al., 2000).

B.2.3.3 Biological Connections

Hydrologic connectivity influences the biological character of oxbow lakes and facilitates exchange of biological material between oxbow lakes and the active river channel. Evidence also suggests a temporally dynamic relationship between biological assemblages of river and oxbow lake ecosystems.

Oxbow lakes represent important areas of relatively high biological productivity in the floodplain landscape. Oxbow lakes can be a source of plankton to the active river channel (Hein et al., 2003). In contrast to terrestrial sources of carbon that often dominate the water column of rivers, plankton is more labile and easier to assimilate into aquatic food webs (Thorp and Delong, 2002; Bunn et al., 2003).

The connectivity relationship has added complexity for plankton, because oxbow lakes need to be periodically isolated from the river to establish populations of these organisms. Intermediate residence times (i.e., the amount of time a water molecule spends in a lake) of between 10 and 27 days in oxbow lakes along the River Danube resulted in the highest carbon flow between phytoplankton and zooplankton (Keckeis et al., 2003). Likewise, the time since inundation is an important factor influencing the composition of zooplankton communities. Recently inundated floodplain water bodies are dominated by rapid-colonizing rotifers, and then become dominated by cladocerans as the time since inundation increases (Baranyi et al., 2002). In this study, total zooplankton biomass, crustacean biomass, and the number of crustacean species were positively related to time since inundation. These results indicate a relationship between the time since inundation and plankton assemblages, and suggest that this relationship exists because colonization and reproduction within an oxbow lake requires time without disturbance.

Although short periods of isolation are necessary for the development of within-oxbow productivity, periodic connections are important for plankton exchange between oxbow lakes and the active river channel. Exchange can occur from the river to the oxbow lake (e.g., juvenile riverine fish might feed in floodplain water bodies; Baranyi et al., 2002) or from the oxbow lake to the river (e.g., phytoplankton; Hein et al., 2003). These periodic connections between floodplain water bodies and the corresponding export of labile phytoplankton from floodplain water bodies to rivers contribute to the food sources of biological assemblages in nearby rivers (Thorp and Delong, 2002; Bunn et al., 2003; Keckeis et al., 2003).

Connectivity between oxbow lakes in the floodplain and the active river channel is important for maintaining mollusk populations in oxbow lakes. A comparison of three oxbow lakes with different levels of connectivity (lotic, semilotic, and isolated) showed the highest level of mollusk diversity in the semilotic lake (eight vs. four taxa in each of the other lakes) on the Lyna River, Poland (Obolewski et al., 2009). In this example, the occurrence of taxa was associated with physiochemical characteristics (oxygen, temperature, and phosphorus) of oxbow lakes. These findings support the idea that the degree of oxbow lake-river connectivity influences the abundance and composition of mollusk communities in floodplain water bodies, and these communities support the diversity of mollusk taxa throughout the river system (Reckendorfer et al., 2006).

Physical connectivity between oxbow lakes and the active river channel influences the composition of benthic macroinvertebrate communities in oxbow lakes. For example, hydrologic connection explained 28% of the variability in benthic invertebrate communities among sites in the active river channel, constructed oxbow lakes, and natural oxbow lakes of the Middle Ebro River, Spain (Gallardo et al., 2008). Macroinvertebrate richness and abundance increased with hydrologic connectivity (i.e., floods and flow pulses) between oxbow lakes and the river channel, and a diversity metric (Shannon index) peaked at intermediate levels of connectivity (Gallardo et al., 2008).

Oxbow lakes have food resources and habitat that often support abundant fish populations (Winemiller et al., 2000; Zeug et al., 2005; Zeug and Winemiller, 2008; Zeug et al., 2009). A comparison of fish biomass in oxbow lakes and a river channel showed that fish biomass in oxbow lakes was three times the biomass caught in rivers. Average catch per unit effort in oxbow lakes was 364.3 g per 10-m seine haul and 5,318 g m^{-1} ha^{-1} of gillnet sampling, versus 138.1 g per 10-m seine haul and 495 g m^{-1} ha^{-1} of gillnet sampling in the river (Winemiller et al., 2000). Additional studies by this research group have found similar patterns for juvenile fish (Zeug and Winemiller, 2008).

Periodic surface-water connections between the river and oxbow lakes facilitate the movement of fish from the river to oxbow lakes, where riverine fish can exploit these relatively productive floodplain water bodies before moving back to the river. Dietary data provide evidence that oxbow lakes are important spawning and nursery habitats for gizzard shad in the Brazos River, TX (Zeug et al., 2009).

Isotope analysis showed that gizzard shad in oxbow lakes had different isotopic signatures based on habitat type: oxbow, river, and an oxbow-river mix (Zeug et al., 2009). Although oxbow lakes clearly provided habitat for both juvenile and adult shad, the authors did not observe oxbow-specific isotopic signatures in shad in the river channel (Zeug et al., 2009). In addition, an analysis of otolith chemical signatures by Crook and Gillanders (2006) indicates that floodplain lakes were an important source of carp recruitment to the Murray-Darling River, where floodplain lakes were estimated to be the source of 98% of the young-of-year carp for areas 140 km downstream of the floodplain lakes. In a third example, floodplain water bodies, with their diverse and productive habitats, were considered nurseries for drifting larvae of migratory fish (Meschiatti et al., 2000). Half the migratory fish species from the Mogi-Guaçu River, Brazil also were observed as juveniles in oxbow lakes along the river (24 of the 46 migratory riverine species were observed in 2 oxbow lakes), and most of the migratory fish observed in oxbow lakes were juveniles, rather than larvae or reproductively mature age classes (Meschiatti et al., 2000). This age structure suggests that the oxbow lakes were not the site of reproduction, but were important habitats for juvenile fish.

Individual fish species have specific habitat and reproductive requirements and use floodplain habitats in different ways, giving the dynamic hydrologic connectivity of oxbow lakes and the river network added significance. For example, owing to variable flow in the Rio Grande, NM, recruitment success varies between years of high (Junk et al., 1989) and low flow (Humphries et al., 1999), which contributes to overall fish diversity in the Rio Grande (Pease et al., 2006). Likewise, in a 5-year study of fish in floodplain lakes, Shoup and Wahl (2009) discuss how individual oxbow lakes had different conditions and thus varied in suitability for different fish species. In their study, interannual variability was present in oxbow lake hydrology (lake-river connectivity ranged from 0 to more than 21 weeks per year) and water chemistry, and in associated differences in fish assemblages (Shoup and Wahl, 2009). Because of the complex relationships observed in their study, Shoup and Wahl (2009) concluded that the entire floodplain should be considered a single functioning unit that supports the overall biological integrity of a river.

B.2.4 Oxbow Lakes: Synthesis and Implications

The key findings of this case study are as follows:

- Evidence indicates the presence of physical, chemical, and biological connections between oxbow lakes and the river channel. The specific local and regional characteristics of both the oxbow lakes and the river influence these connections.
- Some of the best-documented observed functions of oxbow lakes are as sources or sinks for water, sinks for nutrients from upland runoff that might otherwise flow into rivers, and sources of food and refuges for riverine organisms.
- Human alteration of these connections can be detrimental to the dynamics that balance connectivity and exchange between oxbow lakes and the active river channel. Practices that alter the natural flow regime of the river (e.g., river regulation) or inhibit periodic flooding of

oxbow lakes (e.g., levees) affect movement of water and sediment, the use of oxbow lakes by riverine fish, and the regional biological diversity of floodplain water bodies.

- Interannual variability in oxbow lake hydrology, water chemistry, and fish assemblages demonstrate complex relationships between rivers and floodplain open waters and river systems, in which the water bodies in floodplains function as single unit supporting the overall biological integrity of the river.

Although the incidence of observed connectivity between oxbow lakes and river networks varies according to spatial, temporal, physical, and biological factors, most of the evidence examined indicates that oxbow lakes are important determinants of the physical, chemical, and biological condition and function of rivers.

B.3 Case Study: Prairie Potholes

B.3.1 Abstract

Prairie potholes are a complex of glacially formed wetlands, usually occurring in depressions that lack permanent natural outlets, that are found in the central United States and Canada. The vast area they occupy is variable in many aspects, including climatically, topographically, geologically, and in terms of land use and alteration, which imparts variation on the potholes themselves. Potholes demonstrate a wide range of hydrologic permanence, from holding permanent standing water to wetting only in years with high precipitation, which in turn influences the diversity and structure of their biological communities. Owing in large part to their spatial and temporal variability, individual prairie potholes span the entire continuum of connectivity to and isolation from the river network and other bodies of water. Potholes generally accumulate and retain water effectively due to the low permeability of their underlying soil, which can modulate flow characteristics of nearby streams and rivers. Potholes also can accumulate chemicals in overland flow, thereby reducing chemical loading to other bodies of water. When potholes are artificially connected to streams and lakes through drainage, isolation is eliminated and they become sources of water and chemicals. Potholes also support a community of highly mobile organisms, from plants to invertebrates to birds, that travel among potholes and that can biologically connect the entire complex to the river network.

B.3.2 Introduction

Prairie potholes are a complex of wetlands and water bodies that cover more than 700,000 km^2 of the north-central United States and southern Canada, in an area referred to as the prairie pothole region (PPR; Kantrud et al., 1989). Formed by the retreat of Pleistocene glaciers, potholes are shallow depressions underlain by low-permeability, clay-rich glacial tills that allow for the collection and temporary retention of water. Prairie potholes range widely from more than 200 ha to less than 0.5 ha in surface area with an average of 1 ha or less (Cowardin et al., 1981; Kahara et al., 2009). Their density across the landscape varies from region to region, from roughly 5 potholes km^{-2} in the eastern part of the region to up to 90 km^{-2} in the western part as a result of several factors, including patterns of glacial movement, topography, and climate (van der Valk and Pederson, 2003; Kahara et al., 2009).

By the 1980s, more than 50% of potholes in the region were filled, drained, or ditched, with much higher percentages lost in agriculturally intensive regions like Iowa (Figure 2-21; Dahl, 1990). Conservation of remaining potholes and restoration of others have been prompted by various means, including the "Swampbuster" provision of the 1985 Food Security Act and the Wetland Reserve Program (administered by the U.S. Department of Agriculture National Resource Conservation Service since 1990).

B.3.2.1 Hydrologic Dynamics

Prairie potholes are hydrologically dynamic and heterogeneous, varying both spatially and temporally (Euliss et al., 2004). Water inflows consist largely of precipitation in the form of spring snowmelt runoff or summer rain falling directly into the depressions (Carroll et al., 2005). Some potholes also receive ground-water discharge (Winter and Rosenberry, 1998). Evapotranspiration accounts for most of the water outflow in most potholes (Carroll et al., 2005; van der Kamp and Hayashi, 2009). In some situations, water can leave the basin as overland flow (known as "fill-and-spill") and shallow or regional ground-water recharge. Potholes with ground-water flow-through or with directional reversal of ground-water flow (discharge under some conditions and recharge under others) also have been identified (Rosenberry and Winter, 1997).

Prairie potholes experience seasonal cycles in water level. Potholes fill in the spring, typically reaching maximum water volume as melting snow, unable to infiltrate frozen upland soils, runs overland into topographically low places on the landscape. Water levels decline through the summer, although they can be maintained or increase due to summer rains (Winter and Rosenberry, 1995). Hydrologic permanence of these systems varies among prairie potholes in response to precipitation, pothole depth, underlying soil permeability, and position in relation to the water table. Temporary potholes have intermittent standing water only in periods of high precipitation. Seasonal potholes collect water in spring, but typically dry by mid-summer each year. Semipermanent potholes usually maintain standing water throughout the year and occasionally dry in years with low precipitation. Permanent potholes have standing water year-round and maintain standing water from year to year. Importantly, loss of temporary and seasonal potholes has occurred at higher rates than loss of permanent pothole wetlands, because shallower, less permanent basins are easier to drain (Miller et al., 2009).

Spatial variation in precipitation affects interannual variation in water level and hydrologic permanence. The east-west gradient across much of the PPR delivers more than 800 mm of average precipitation to northwestern Iowa each year and less than 500 mm of average precipitation to most of North Dakota. These dynamics also depend on 20- to 200-year, large-scale climate cycles, including periodic flood and drought conditions (Ashworth, 1999; Leibowitz and Vining, 2003). Annual average climate and longer climate cycles profoundly affect individual pothole dynamics and the interactions both among potholes and between potholes and broader landscape features (Winter and Rosenberry, 1998; Johnson et al., 2004). Hydrologic dynamics can have major effects on the diversity and abundance of organisms (Euliss and Mushet, 2004).

In addition, topography at multiple scales, soil characteristics, and underlying geology influence pothole dynamics and interactions. Three major physiographic regions comprise the PPR from east to west: the Red River Valley, Drift Prairie, and Missouri Coteau. The Red River Valley was formerly a vast lake filled with glacial melt, and today consists of the relatively topographically flat, clay-rich till surrounding the Red River of the North. The Drift Prairie is higher in elevation than the Red River Valley, and consists of rolling, hummocky terrain formed by glacial deposits. The Missouri Coteau has the highest elevation of the region and relatively steep relief due to thick glacial debris deposits (Kantrud et al., 1989). More restricted local landform zones, various till plains in the Des Moines Lobe in Iowa and the Prairie Coteau in eastern South Dakota for example, also influence hydrologic characteristics of potholes (Miller et al., 2009).

B.3.2.2 Chemical Functions

The chemical composition of prairie potholes is determined largely by the degree of connectivity with ground water and the position of the wetland with respect to local and regional ground-water systems. Seasonal wetlands located high in the landscape tend to be less saline than the wetlands situated low in the landscape. This simplistic view is made more complex, however, by watershed characteristics, concentration of solutes by evapotranspiration, variability in ground-water and surface-water residence times, changing wetland volumes, and climatic variability. For example, LaBaugh et al. (1996) documented substantial interannual changes in dominant ionic species in response to climatic variability. These changes persisted beyond the climatic inputs, indicating that antecedent moisture conditions also influence wetland response to a changing climate.

Nutrient (including carbon, nitrogen, and phosphorus) cycling in prairie potholes likely depends on fluctuating water levels, wet-dry cycles, and resulting effects of vegetation cycling. Potholes tend to be nitrogen-limited environments, with the notable exception of potholes located on agricultural land that tend to receive runoff high in nitrate (Crumpton and Goldsborough, 1998). Denitrification that takes place in the anaerobic zone of these and other wetlands can make them effective nitrogen sinks (van der Valk, 2006).

B.3.2.3 Ecological Characteristics

The high spatial and temporal abiotic heterogeneity, both within an individual pothole and between potholes across the region, creates a variety of ecological niches and contributes to high biodiversity in these habitats. In response to hydrologic cycles, a semipermanent pothole can have up to four distinct, concentric zones of vegetation, ranging from floating aquatic plants to upland plants. Depending on the timing within annual or between interannual wet-dry cycles, a given pothole can have all zones or just one zone. A pothole also could be in the process of developing zones (regenerative phase) or losing zones (degenerative phase). Invasive species like reed canarygrass (*Phalaris arundinacea*) and cattail

(*Typha angustifolia* and *T. x glauca*) have established in streams and wetlands across the region, disrupting natural pothole vegetation communities.

Perhaps the best-known and most well-studied attribute of prairie potholes is their role as productive feeding and nesting habitat for waterfowl. Of the 34 species of duck that breed in North America, 12 are common in the region, which contributes up to 80% of the continent's waterfowl game (Batt et al., 1989). In addition, a diverse assemblage of microorganisms, invertebrates, amphibians, reptiles, and sometimes fish, obligately or facultatively use potholes to feed or reproduce. For example, 44 different invertebrate taxa, including nematodes, mollusks, and arthropods, were collected in Iowa potholes (Hentges and Stewart, 2010).

B.3.3 Evidence

B.3.3.1 Physical Connections

Because prairie potholes are small wetlands that form in depressions often lacking permanent outlets, they have been described as hydrologically isolated from each other and from other waters. In some instances, this generalization has proved true but in others, it is false.

One of the most noted hydrologic functions of potholes is water storage. Because most of the water outflow in potholes is via evapotranspiration, potholes can become water sinks, preventing flow to other waters in their river or terminal lake basins. Several studies have quantified the large water storage capacity of prairie pothole complexes. A conservative estimate puts the amount of precipitation that can be retained in prairie potholes on land enrolled in the federal Conservation Reserve Program and Wetland Reserve Program at more than 555 million m^3 (Gleason et al., 2008). In various subbasins across the PPR, including those that feed Devils Lake and the Red River of the North, both of which have a long history of flooding, potholes have consistently been estimated to hold tens of millions of cubic meters of water (Hubbard and Linder, 1986; Vining, 2002; Gleason et al., 2007).

Water storage by prairie potholes can affect streamflow. Simulations of the Starkweather Coulee subbasin that drains to Devils Lake indicate that streamflow declines substantially with increased wetland storage capacity. Increasing the volume of pothole storage across the subbasin by approximately 60% caused simulated total annual streamflow to decrease by 50% during a series of dry years and by 20% during wet years. The weaker effect of potholes on streamflow during wet years is likely due to high soil moisture conditions and maintenance of high water levels within potholes across years, which causes a greater proportion of runoff to reach streams relative to dry years (Vining, 2002). Similar simulation studies of watersheds in the Red River basin (one in North Dakota and one in Minnesota) produced qualitatively comparable results, suggesting that the ability of potholes to modulate streamflow can be widespread across the PPR (Vining, 2004). This work also indicates that reducing water storage capacity of wetlands by connecting formerly isolated potholes through ditching or drainage to the Devils Lake and Red River basins could increase stormflow and contribute to downstream flooding. In many agricultural areas already crisscrossed by extensive surface and subsurface drainage systems (Figure 2-21), total streamflow and baseflow are increased by directly connecting potholes to stream networks (Blann et al., 2009). The ensuing impacts of changing streamflow are numerous, including effects on stream geomorphology, habitat alteration, and ecological effects (reviewed in Blann et al., 2009).

Studies in some regions show a lack of association between pothole water storage and aspects of streamflow. For instance, modeling of an Iowa watershed indicated that total pothole outflow and total maximum pothole volume do not affect streamflow characteristics (Du et al., 2005). At the Minnesota watershed within the Red River basin discussed previously, simulated annual and daily streamflow decreased with increased pothole water storage capacity but peak streamflow was not reduced during a simulated flooding event, possibly due to an overwhelmed capacity of wetlands and upland soils to retain additional water (Vining, 2004). In yet another Minnesota watershed, wetland water storage provided no explanatory power in estimating peak streamflows for small streams (Lorenz et al., 2010).

The presence or absence of an effect of pothole water storage on streamflow depends on many factors, including patterns of precipitation, topography, and degree of human alteration. For instance, in parts of the PPR with low precipitation, low stream density, and little human alteration, the extreme hydrologic isolation of potholes likely results in few effects on larger waters. Neither a comprehensive examination of the downstream effects nor a systematic characterization of potholes for the factors that determine those effects has been conducted.

Surface-water isolation is common for many prairie potholes under average precipitation conditions, but intense precipitation events or high cumulative precipitation over one or more seasons can result in temporary hydrologic connectivity via overland flow. These "fill-and-spill" events between potholes have been witnessed and measured in the Missouri Coteau and in the Drift Prairie zones of the PPR in North Dakota (Winter and Rosenberry, 1998; Leibowitz and Vining, 2003), and inferred using digital aerial photography (Kahara et al., 2009). All else being equal, a wetter climate such as that experienced in the southeastern part of the PPR should promote hydrologic connectivity (Johnson et al., 2005). Local topography can enhance or diminish the likelihood and frequency of temporary surface-water connections. Authors have reasoned that the relatively wet and topographically low Red River Valley zone of the PPR should display greater surface-water connectivity of potholes than either the Drift Prairie or Missouri Coteau zones. Furthermore, they suggest that stream density will influence the chance that pothole spillage connects to the larger river network. Thus, potholes in the Missouri Coteau, with its limited network of streams, should be more hydrologically isolated than potholes in the Red River Valley or Drift Prairie (Leibowitz and Vining, 2003).

Individual potholes range from isolated to highly connected to other potholes via shallow local and deeper regional ground-water flows. A high water table and soil pocketed with root pores or fractures from wet-dry cycles promote water movement between wetlands via shallow ground-water aquifers. In these cases, water moves most often from topographically high, recharge wetlands to low, discharge wetlands (van der Kamp and Hayashi, 2009), although a single wetland can shift from recharge to discharge in years where the water table is high (Carroll et al., 2005). Other wetlands shift multiple times from recharge to discharge conditions during a single year, which can either facilitate or prevent ground-water connections to nearby wetlands (Rosenberry and Winter, 1997). Potholes can connect to the river network via ground water if both are located within the zone of shallow local aquifer flows. One study in North Dakota described prairie wetlands and lakes as water sources to the topographically low James River via shallow ground-water flow (Swanson et al., 1988). Broader, regional movement of ground water is restricted by very low permeability clay-rich tills that can keep deep ground-water recharge to only millimeters per year on average over a drainage basin (van der Kamp and Hayashi, 1998).

Human alterations of the landscape have had an impact on the connectivity of prairie potholes. Presence or absence of a crop on the upland near a wetland can alter the degree to which the wetland receives overland flow from the upland and the removal of water via transpiration that otherwise would recharge ground water (Hayashi et al., 1998). Up to 30% of cropland in the Upper Midwest is artificially drained to increase agricultural productivity (Pavelis, 1987). Filling potholes and lowering the water table through use of field tiling for agriculture has likely increased isolation of remaining potholes by decreasing the density of depressions containing water. Extensive surface draining and ditching, however, have directly and dramatically increased connectivity between pothole basins and surface waters of the river network, converting these systems from precipitation sinks to water sources (Blann et al., 2009). Ditches create new surface-water outlets from potholes, allowing collected water to flow into streams and rivers; drains fitted at the bottom of potholes connected to shallow subsurface pipes often discharge to open ditches or streams (Ginting et al., 2000).

B.3.3.2 Chemical Connections

The chemical connectivity of prairie potholes is largely mediated by their hydrologic connectivity. Hydrologically isolated potholes tend also to be isolated chemically. Unaltered potholes with no outlet can accumulate nutrients, sediment, and other chemical compounds as they collect runoff (Crumpton and Goldsborough, 1998; Donald et al., 1999). Such accumulations have measurable effects on the water quality of potholes and the resident organisms (Gleason et al., 2003). Presence of these materials in potholes is influenced by inflow, itself a function of precipitation and surrounding land use. Potholes surrounded by tilled fields with higher precipitation, for example, tend to accumulate nutrients, sediment, and pesticides (Gleason et al., 2008). Additionally, potholes within agricultural areas that have not been drained or ditched are hypothesized to be nitrogen sinks, transforming nitrate in the agricultural runoff they receive to nitrous oxide or nitrogen gas. Denitrification can transform up to 80% of nitrate that runs off into potholes (Crumpton and Goldsborough, 1998 and references therein).

On the other hand, potholes that periodically are connected hydrologically to other bodies of water via overland flow can transfer chemicals, such as dissolved ions (Leibowitz and Vining, 2003). Potholes modified by ditching or drainage also have increased hydrologic connectivity and, therefore, chemical connectivity to other water bodies (Whigham and Jordan, 2003). Wetlands drained for agriculture can contribute nitrogen, phosphorus, sediment, pesticides, and herbicides to the waters into which they drain (reviewed in Blann et al., 2009). For example, two wetlands in southwestern Minnesota fitted with surface drains that connected to subsurface tiles emptying into the Watonwan River (a tributary of the

Minnesota River) were found to be sources of total solids and total phosphorus to the river during periods of high runoff (Ginting et al., 2000).

Although the chemical sink and periodic chemical source functions of potholes have been documented in the literature, the overall influence of these functions on larger waters and river networks have been difficult to quantify. This inability is partly because altered and unaltered potholes are embedded in a matrix of land use and land management types, and many different parts of this complex landscape affect downstream water quality and ecological communities (Blann et al., 2009). The most fruitful future approach might be to model drainage basin sediment, nutrient, and pesticide transport under various climatic conditions, using pothole characteristics and functions as independent, explanatory variables (Gleason et al., 2008).

B.3.3.3 Biological Connections

Dispersal capabilities of organisms residing in potholes and features of the landscapes they must traverse help determine the strength of biological connectivity. Although some research has focused on internal seed and egg bank dynamics (van der Valk and Davis, 1978; Gleason et al., 2004), increasing evidence suggests that potholes are not biologically isolated. In fact, the observation that potholes lack an endemic aquatic and semiaquatic flora or fauna suggests that, at least over evolutionary time, potholes have been well connected biologically to communities in other ecosystems (van der Valk and Pederson, 2003).

Organisms can move into and out of potholes via wind, water, or land, by either self-propelling or hitchhiking on other mobile organisms. Many species of wetland plants and insects are dispersed on the wind (Keiper et al., 2002; Soons, 2006), including cattail (*Typha* spp.) seeds, which can disperse over huge areas (more than 80 ha; van Digglen, 2006) and have been found to colonize, quickly and passively, previously drained, restored potholes (Galatowitsch and van der Valk, 1996). Plants and invertebrates also can travel by becoming attached to or consumed and excreted by waterfowl (Amezaga et al., 2002). Seeds of up to half a dozen common pothole plants can be consumed and excreted by ducks in a viable state; because migrating waterfowl fly such long distances, the maximum dispersal distance of these hitchhiking plants is estimated to be 1,400 km (Mueller and van der Valk, 2002). Additionally, fast and efficient recolonization of species in restored potholes, including floating aquatics and emergent perennials, is likely facilitated by waterfowl movement (Aronson and Galatowitsch, 2008). Waterfowl often move between wetlands during the breeding season in search of food and cover, and some species also use habitats within the river network as wetlands dry or freeze (Pattenden and Boag, 1989; Murkin and Caldwell, 2000). Water also can provide a means for biologically connecting potholes. Fish and other organisms or parts of organisms that can be suspended in water (e.g., floating insect larvae or seeds) have been hypothesized to move between potholes during spillage events (Zimmer et al., 2001; van der Valk and Pederson, 2003; Herwig et al., 2010). Dispersal of waterborne organisms also can occur through manmade waterways (i.e., ditches) that connect potholes to stream networks (Hanson et al., 2005; Hentges and Stewart, 2010; Herwig et al., 2010). Most of these studies cite only anecdotal evidence for dispersal through ditches. Populations of aquatic plants in agricultural ditches in Europe, however, are genetically highly structured along these man-made waterways, suggesting that these watercourses determine dispersal pathways (Gornall et al., 1998).

Finally, overland dispersal of amphibians and mammals can connect potholes. Eight of twelve amphibian species were able to quickly recolonize restored potholes near source populations (Lehtinen and Galatowitsch, 2001). Although muskrat territories in the PPR are usually restricted (less than 100 m from the home stream or wetland), they can disperse longer distances to feed and breed in prairie wetland habitat under certain conditions (Clark, 2000 and references therein). In North Dakota, muskrats have been observed taking up residence in potholes for a series of years, provided suitable water levels and vegetation existed, and then emigrating, presumably to more permanent and larger lakes and streams (Winter and LaBaugh, 2003). Not all wetland animals disperse widely, however. Populations of the pothole-dwelling salamander *Ambystoma tigrinum* (studied in small, non-pothole wetlands, in this case) can be genetically differentiated from each other down to 1.5 km, indicating low dispersal (Routman, 1993).

Landscape features, including distance, relief, and human alterations, can promote or restrict biological connections between wetlands and larger bodies of water. Spatial distance is one important factor to consider. For a given species, wetlands located closer together will exchange more organisms than wetlands that are farther apart. Therefore, landscapes in which potholes are located in relative proximity to each other and to the river network are likely to be connected more frequently and by more species. For example, restored potholes in pothole-dense areas tend to be recolonized by plants more efficiently (Mulhouse and Galatowitsch, 2003), and high pothole density promotes greater movement of waterfowl (Krapu et al., 1997). Unfortunately, quantification of biological effects of potholes on larger waters is severely limited. In most cases, studies involving biological isolation or connectivity in the PPR have focused on the potholes themselves as sources and recipients of organisms.

B.3.4 Prairie Potholes: Synthesis and Implications

The key findings for this case study are as follows:

- The degree to which prairie potholes are connected or could connect to river networks depends on many factors. These factors include distance to rivers or streams, topography, precipitation, climate cycles (seasonal and on longer time scales), biotic community composition, and artificial drainage. Within the PPR, distance to rivers and streams is strongly influenced by the three major physiographic regions (Red River Valley, Drift Prairie, and Missouri Coteau), which vary in the number of potholes and stream density (e.g., Figures 2-20A and 2-20B).
- On a watershed scale, unaltered potholes often function as hydrologic sinks, sequestering water and reducing annual streamflow, but can become sources as they spill overland under high precipitation or low relief, or both. When artificially drained or ditched, potholes can become sources of water, nutrients, sediment, and pesticides. Their roles as sinks and sources affect river geomorphology and biological communities.

- Potholes also might have direct biological effects on river networks via connectivity of resident populations, although these effects are less well known and studied.

Because of wide variation in the conditions that determine the incidence or magnitude of connections between prairie potholes and river networks, pothole complexes in some watersheds are more likely to have important effects on associated rivers and lakes than others are. Given evidence in the current literature, however, when proper climatic or topographic conditions occur, or biotic communities are present that promote potential or observed connections, measurable influence on the physical, chemical, and biological condition and function of downstream waters is highly likely.

B.4 Case Study: Prairie Streams

B.4.1 Abstract

Prairie streams drain temperate grasslands in the central United States. Periods of flooding and drying characterize their hydrology, with spring-fed, perennial pools and reaches embedded within more intermittently flowing reaches; thus, water flow along prairie stream networks exhibits high temporal and spatial variability. Existing evidence indicates that small prairie streams are connected to downstream reaches, most notably via flood propagation and the extensive transport and movement of fish species throughout these networks. Nutrient retention in small prairie streams also significantly influences nutrient loading in downstream rivers.

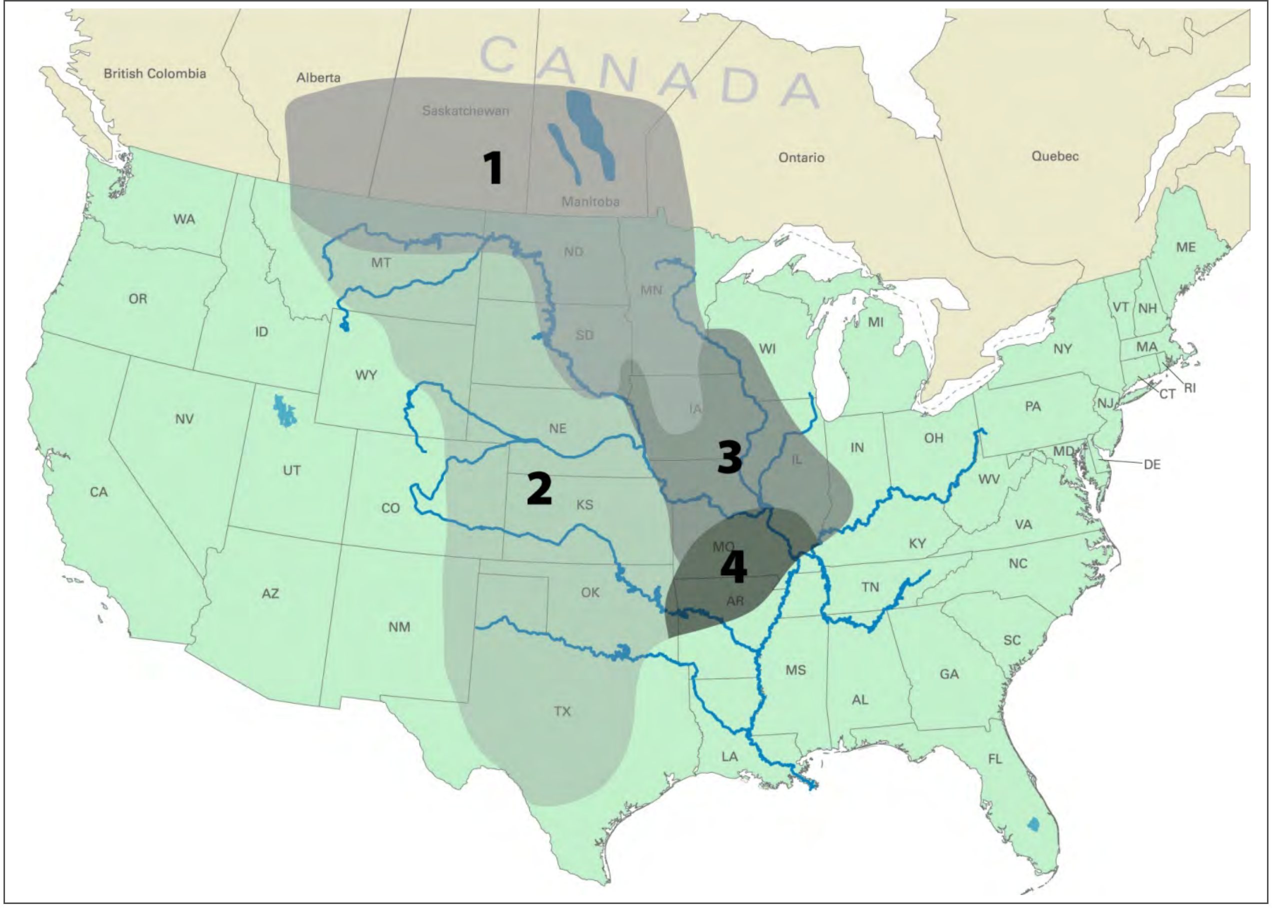
B.4.2 Introduction

B.4.2.1 Geography and Climate

Prairies are temperate grasslands located in the Great Plains physiographic region of the central United States and Canada (Figure B-2). Grasses and forbs (broad-leaf plants other than grasses) dominate the region, particularly in upland areas. Shrubs and trees can be found in lowlands, and are commonly called gallery forests. Native prairie ecosystems once covered approximately 1.62 million km^2 in North America but have been lost almost completely since European settlement, mainly replaced by row-crop agriculture (Samson and Knopf, 1994). Because of drastic alterations to much of the historical eastern plains (Iowa, Illinois, Missouri, Indiana, Minnesota), our discussion centers principally on river networks in the high plains subregion of the Great Plains (Subregion 2 in Figure B-2), where drier climate and thin, rocky soil have limited row-crop agriculture.

Prairies generally can be characterized by their relatively low topographic relief, although areas such as the Flint Hills in eastern Kansas, the Arikaree Breaks in northwestern Kansas, and the Arbuckle Mountains in south-central Oklahoma have relatively steep terrain compared to that of western Kansas or the Oklahoma panhandle (Osterkamp and Costa, 1987; Matthews, 1988). The underlying geology consists of extensive limestone deposits, but sandstone and shale deposits or unconsolidated sands, silts, and clays characterize other areas (Brown and Matthews, 1995). Soils in the Great Plains are predominantly loess, but some areas such as Nebraska's Sand Hills have high percentages of sand (Wolock et al., 2004). Although prairie soils tend to be less permeable than more humic forest soils,

Figure B-2. Map of the United States showing physiographic subregions and major rivers of the Great Plains: (1) glaciated prairie; (2) high plains; (3) eastern plains; and (4) Ozark Plateau. Modified from Covich et al. (1997).



fractures and macropores of the limestone geology in some prairie areas, such as the Flint Hills, allow for relatively rapid percolation and recharge of local ground water (Macpherson and Sophocleous, 2004).

Most of the large rivers draining the high plains subregion (e.g., the Missouri, Yellowstone, Milk, Cheyenne, White, Niobrara, Platte, Kansas-Republican, Arkansas, Cimarron, Canadian, Red, and Washita Rivers) are major tributaries to the Mississippi River. The southern portions of the subregion contain the headwaters of the Rio Grande River (Pecos River) or rivers that flow directly into the Gulf of Mexico (the Guadalupe, San Antonio, Colorado of Texas, Brazos, and Nueces Rivers). Some rivers in the northern portions of the glaciated prairie flow north, eventually into the Hudson Bay (notably the Red River of the North).

The climate in this region ranges from semiarid in the western portions to moist subhumid in the eastern portions. Mean annual precipitation ranges from 200 to 1,000 mm y^{-1} from west to east across the Great Plains (Lauenroth et al., 1999). Potential evaporation typically exceeds precipitation (Transeau, 1905, 1935). Mean annual temperatures increase from north (4–8 °C) to south (16–20 °C;

Lauenroth et al., 1999). Winters tend to be dry, with less than 20% of the annual precipitation (Borchert, 1950; Lauenroth et al., 1999; Boughton et al., 2010). Most precipitation falls in late spring and early summer (Borchert, 1950; Lauenroth et al., 1999), and much of the summer precipitation results from localized convective thunderstorms. Because of the region's geographic location relative to the Gulf of Mexico and the Rocky Mountains, however, substantial interannual variation exists, particularly in terms of summer rainfall deficit (Borchert, 1950).

B.4.2.2 Hydrology and Geomorphology

The hydrology of most prairie river networks is highly variable (Matthews, 1988; Brown and Matthews, 1995; Dodds et al., 2004). These systems are frequently subjected to the extremes of drying and flooding, and intermittent or flashy hydrology is prevalent in river networks throughout most of the Great Plains (Matthews, 1988; Zale et al., 1989; Poff, 1996; Dodds et al., 2004). The topology of most prairie river networks is dendritic due to the relatively flat landscape and uniform geology (Brown and Matthews, 1995). Prairie river networks tend to have high drainage density (Section 2.4.2), and are therefore efficient at transferring rainfall from uplands to downstream reaches (Gregory, 1976; Osterkamp and Friedman, 2000). Flood magnitudes tend to be higher in the semiarid Great Plains than in other regions, despite comparable rainfall intensities, due to low infiltration and vegetation interception (Osterkamp and Friedman, 2000). Although floods tend to occur in late fall through late spring, they can occur any time during the year (Brown and Matthews, 1995; Poff, 1996). Like most river networks, those draining prairie landscapes often contain ephemeral, intermittent, and perennial streams. Although many headwater prairie streams are ephemeral or intermittent (Matthews, 1988; Brown and Matthews, 1995; Dodds et al., 2004), some have perennial spring-fed reaches located at the network origins or distributed between intermittent reaches along headwater streams (Matthews et al., 1985; Sawin et al., 1999; Dodds et al., 2004; Bergey et al., 2008).

The flow regimes of streams draining the Rocky Mountains, Black Hills, and northern prairies are largely tied to snowmelt. Most systems originating in the mountains quickly transition in flow and morphology as they cross the Great Plains, becoming intermittent and then slowly gaining flow from large streams before joining the Mississippi River (Brown and Matthews, 1995). Some areas, however, have stable streamflow with few intermittent streams because flow is derived from large, permeable ground-water sources (e.g., Sand Hills in Nebraska; Winter, 2007).

The High Plains (Ogallala) aquifer system and other aquifers (e.g., Edwards-Trinity) are important hydrologic features interconnected with Great Plains river networks. The High Plains aquifer system is the largest (450,658 km^2) and most intensively pumped U.S. aquifer, underlying much of the Great Plains from southern South Dakota and southeastern Wyoming to central Texas (Sophocleous, 2005; Ashworth, 2006; Sophocleous, 2010). The High Plains aquifer is composed of blanket sand and gravel derived mainly from alluvial deposits and ancient marine sands. It is unconfined regionally, but locally can be confined where beds of silt, clay, or marl are present. Regional movement of water through the aquifer is from west to east, but locally the water moves toward major tributaries. Northern areas of the Great Plain are underlain by glacial deposit aquifers that can be a mixture of till (unsorted material ranging from clay to boulders) and outwash (stratified sand and gravel) that was deposited by glacial meltwater.

Most headwater streams originating in the prairie have riffle-pool morphology with alluvial gravel; only headwater streams originating in the western mountains have high gradient, cobble-boulder channels (Brown and Matthews, 1995). Southern prairie headwater streams tend to have finer substrate than those in the northern and central Great Plains (Brown and Matthews, 1995). Larger streams tend to have broad sand beds that are frequently braided (Section B.4.2.5). In contrast to headwater streams in forested regions, the riparian areas of prairie headwater streams typically lack overhanging trees. Grasses and shrubs are the dominant riparian vegetation, so channels lack woody debris and generally receive direct sunlight. Because of intense flooding, prairie streams tend to form wide, deep channels relative to their drainage areas, regardless of flow permanence (Hedman and Osterkamp, 1982; Brown and Matthews, 1995). Because of similarity in topography, climate, geology, and soils, stream geomorphology across the Great Plains is largely comparable (Miller and Onesti, 1988). High plains channels, however, tend to be slightly steeper in gradient and more sinuous than wider and deeper channels of the eastern plains (Miller and Onesti, 1988). During floods, the relatively incised channels and lack of woody debris in prairie headwater streams make them less retentive of organic matter and other materials than those of high-gradient forested channels; their pool-riffle morphology, high sinuosity, and seasonal drying, however, can enhance retention (Brown and Matthews, 1995).

B.4.2.3 Physicochemistry

The factors discussed above are strong drivers of prairie stream physicochemistry (Matthews, 1988; Brown and Matthews, 1995). Hot summers and cold winters in this region cause substantial direct and indirect changes in water temperature, dissolved oxygen, and nutrient concentrations. Isolation of surface water into pools during summer drying exacerbates these changes (Zale et al., 1989; Ostrand and Marks, 2000; Ostrand and Wilde, 2004). For example, water surfaces can be covered with ice in winter, whereas summer water temperatures can reach 35−40 °C with 9−10 °C diel (i.e., daily) fluctuations (Matthews, 1988; Matthews and Zimmerman, 1990). Concomitant fluctuations in dissolved oxygen occur, which when combined with stream respiration, contribute to dissolved oxygen values approaching anoxic conditions.

Prairie rivers and streams naturally have higher concentrations of dissolved solids (e.g., calcium, carbonate, bicarbonate, sodium, chloride, magnesium, sulfate) due to dissolution of the underlying geologic layers (Huntzinger, 1995). Associated with these high levels of dissolved ions are elevated alkalinity and pH. Mean total dissolved solids concentrations for many Great Plains rivers are among the highest in the United States, exceeding 500 mg L^{-1}; many Great Plains rivers, however, also receive anthropogenic total dissolved solid inputs from wastewater treatment effluents, agricultural runoff, irrigation contributions to baseflow, and disposal of produced water associated with fossil fuel production (Mathis and Dorris, 1968; Huntzinger, 1995; Farag et al., 2010). Some river networks, such as the headwaters of the Red River in Texas and Oklahoma, are saline because they derive from brine springs (Taylor et al., 1993).

Streams and rivers of the central United States are often cited as having elevated nutrient (i.e., nitrogen and phosphorus) loads. These loads are primarily attributable to nonpoint source runoff from fertilizer application and livestock waste, especially during higher flows in winter and spring (Huntzinger, 1995; Royer et al., 2006; Alexander et al., 2008). Data from streams draining native prairie indicate that nitrogen and phosphorus concentrations and fluxes are lower or comparable to other intact ecosystems (McArthur et al., 1985a; Dodds et al., 1996a; Kemp and Dodds, 2001).

B.4.2.4 Ecology

The low diversity of aquatic flora and fauna of prairie river networks, especially compared to assemblages in the eastern and southeastern United States (Jewell, 1927; Fausch and Bestgen, 1997), is likely due to the environmental instability of these river networks, their evolutionary history, and the magnitude and extent of human alterations. Most organisms have adapted to erratic hydrologic regimes and harsh physiochemical conditions in prairie streams by having rapid growth, high dispersal ability, resistant life stages, fractional or extended reproduction (i.e., spawn multiple times during a reproductive season), broad physiological tolerances, and life cycles timed to avoid predictably harsh periods (Matthews, 1988; Dodds et al., 1996b; Fausch and Bestgen, 1997).

Algae are foundational components of prairie streams, acting to retain nutrients and provide an important energy source to consumers (Gelwick and Matthews, 1997; Dodds et al., 2000; Evans-White et al., 2001; Evans-White et al., 2003). Flooding and drying in prairie streams reset algal assemblages, spur successional sequences, and maintain high levels of primary production (Power and Stewart, 1987; Dodds et al., 1996b; Murdock et al., 2010). Algal assemblages are composed primarily of diatoms (e.g., *Cymbella*, *Cocconeis*, *Pinnularia*, *Achnanthes*, *Navicula*, and *Gomphonema*), filamentous green algae (e.g., *Cladophora*, *Spirogyra*, *Rhizoclonium*, *Stigeoclonium*, *Zygnema*, and *Oedogonium*), and cyanobacteria (e.g., *Oscillatoria*, *Nostoc*).

Because of high light availability, algal primary production in prairie streams occasionally can be substantially higher than in forested headwaters (Hill and Gardner, 1987a; Dodds et al., 1996b; Mulholland et al., 2001; Bernot et al., 2010). Gallery forests farther downstream provide shade and contribute organic matter. Shade from the gallery forests lowers light transmission to algae, resulting in lower algal primary production in these reaches than in unshaded prairie headwater reaches. Thus, in contrast to conventional longitudinal paradigms like the River Continuum Concept, the organic matter driving prairie headwater streams derives mainly from within the channel (autochthonous production), whereas leaf litter and other detritus from nearby gallery forests (allochthonous production) dominate in intermediate-sized streams (Gurtz et al., 1982; Gurtz et al., 1988; Wiley et al., 1990). Despite having greater primary production than forested headwaters, prairie streams—like forested ones—tend to be net heterotrophic systems (Mulholland et al., 2001), but those that agricultural activities (e.g., elevated nutrients, channelization) influence can at times be net autotrophic (Prophet and Ransom, 1974; Gelroth and Marzolf, 1978; Wiley et al., 1990).

Invertebrates in prairie streams are represented by various aquatic insect groups (e.g., Diptera, Coleoptera, Plecoptera, Ephemeroptera, Trichoptera), crustaceans (crayfish, isopods, amphipods), mollusks, and oligochaetes. Consumers of fine benthic organic matter, epilithic algae, and other invertebrates tend to dominate invertebrate communities (Gray and Johnson, 1988; Harris et al., 1999; Stagliano and Whiles, 2002). Diversity and abundance of invertebrates tend to increase with flow permanence, but species composition generally highly overlaps, with intermittent stream assemblages representing a nested subset of those from perennial streams (McCoy and Hales, 1974; Miller and Golladay, 1996; Fritz and Dodds, 2002).

As with algae, flooding and drying are important drivers of invertebrate assemblages in prairie streams. Distinct successional transitions are apparent following these disturbances (Chou et al., 1999; Fritz and Dodds, 2002), and recovery to predisturbance levels can be rapid (Miller and Golladay, 1996; Miller and Nudds, 1996; Fritz and Dodds, 2004). Woody debris is often rare in prairie streams, but where it is present, invertebrates tend to be more abundant and more resistant to flooding, relative to those associated with less stable sand and gravel substrates (Golladay and Hax, 1995; Hax and Golladay, 1998; Johnson and Kennedy, 2003).

Fish are a well-studied component of river networks in the Great Plains, and are among the most threatened (Rabeni, 1996; Fausch and Bestgen, 1997; Hubert and Gordon, 2007; Hoagstrom et al., 2010). Approximately 200 fish species are found across prairie river networks, about 50 of which are endemic to these streams. The most common taxa are minnows (Cyprinidae), suckers (Catastomidae), darters (Percidae), sunfishes (Centrarchidae), and catfishes (Ictaluridae).

Longitudinal organization of fish assemblages has been recognized widely in Great Plains river networks (Harrell et al., 1967; Smith and Powell, 1971; Schlosser, 1987), and like macroinvertebrates these assemblages often are nested such that intermittent headwater communities are subsets of those in downstream perennial segments. Unlike algae and macroinvertebrates, fish inhabiting intermittent headwater streams have no terrestrial or drying-resistant life stages. Fish, however, are highly mobile and avoid desiccation by moving into downstream perennial reaches or perennial spring-fed pools in upstream segments (Deacon, 1961; Fausch and Bramblett, 1991). Periodic floods are important for creating perennial refuges and providing connectivity between habitats for the dispersal of fish and their eggs in prairie stream networks (Section B.4.3.3; Labbe and Fausch, 2000; Franssen et al., 2006).

B.4.2.5 Human Alterations

Human alterations to prairie river networks have affected physical, chemical, and biological connectivity in these systems both directly and indirectly. Crop and livestock agriculture are predominant land uses in the Great Plains (Galat et al., 2005; Matthews et al., 2005) and represent major nonpoint sources of nutrients, sediment, and pesticides (Battaglin et al., 2003; U.S. EPA, 2006; Alexander et al., 2008). Livestock concentrate in and near streams for shade, food, and water, leading to bank erosion, increased soil bulk density, sedimentation, and elevated fecal bacteria concentrations (Armour et al., 1991; Strand and Merritt, 1999).

To support these agricultural enterprises, water has been diverted from channels, withdrawn from regional aquifers, and stored in reservoirs. Ground-water withdrawals in the Great Plains are the highest in the United States (Sophocleous, 2010), causing many once perennial river segments to regularly dry up completely during summer months, particularly in the drier western portions of the Great Plains (Cross and Moss, 1987; Ferrington, 1993; Falke et al., 2011). Nearly all river networks in prairie regions have been altered by impoundments for irrigation storage and flood control, from small farm ponds in headwaters to large reservoirs on river mainstems (Smith et al., 2002; Galat et al., 2005; Matthews et al., 2005). Decline in flood magnitude, altered flow timing, and reduced flow variability and turbidity are evident in many prairie rivers compared to historically documented conditions (Cross and Moss, 1987; Hadley et al., 1987; Galat and Lipkin, 2000). Reductions in peak discharge derived from prairie streams have contributed to the narrowing of the region's once broad and shallow river channels (Friedman et al., 1998; Wohl et al., 2009). Dynamic mosaics of sand bars common in most prairie rivers have become stabilized and coalesced islands. The establishment of trees along prairie river riparian zones was limited by floods prior to settlement, but now dense zones of native and invasive trees and shrubs further reduce flows through high evapotranspiration (Johnson, 1994; Dahm et al., 2002).

B.4.3 Evidence

B.4.3.1 Physical Connections

B.4.3.1.1 Water

As in other river systems, water is the primary medium by which materials are transported from streams to rivers in prairie networks. Floods are common in Great Plains streams (Fausch and Bramblett, 1991; Hill et al., 1992; Fritz and Dodds, 2005), and propagation of these floods from streams to downstream rivers demonstrates hydrologic connectivity. Fritz and Dodds (2004, 2005) characterized the hydrology of intermittent streams draining native tallgrass prairie in a study that coincided with the highest flow on record (on May 13, 1995, with a return interval of at least 50 years). Kings Creek and one of its headwater streams (N01B) are both headwater streams draining into the Kansas River, downstream of the USGS gaging station at Fort Riley and upstream from the confluence of the Big Blue and Kansas Rivers and the USGS gaging station at Wamego (Figure B-3). The peak-flow rising and descending limbs were very rapid at Kings Creek and N01B compared to those recorded for the Kansas River at Wamego, where the peak arrived approximately 12 hours later (Figure B-4). Hydrographs for the upstream Fort Riley gage on the Kansas River and the Big Blue River indicate that the May 13, 1995 peak at the downstream Wamego gage was associated with floods propagating from Kings Creek and other small streams (Figure B-4). The subsequent peak at the Wamego gage that occurred 5 days later was associated with a storm mainly affecting portions of the Kansas River basin upstream of the Fort Riley gage, which elicited only a slight increase in discharge at Kings Creek and N01B (Figure B-4).

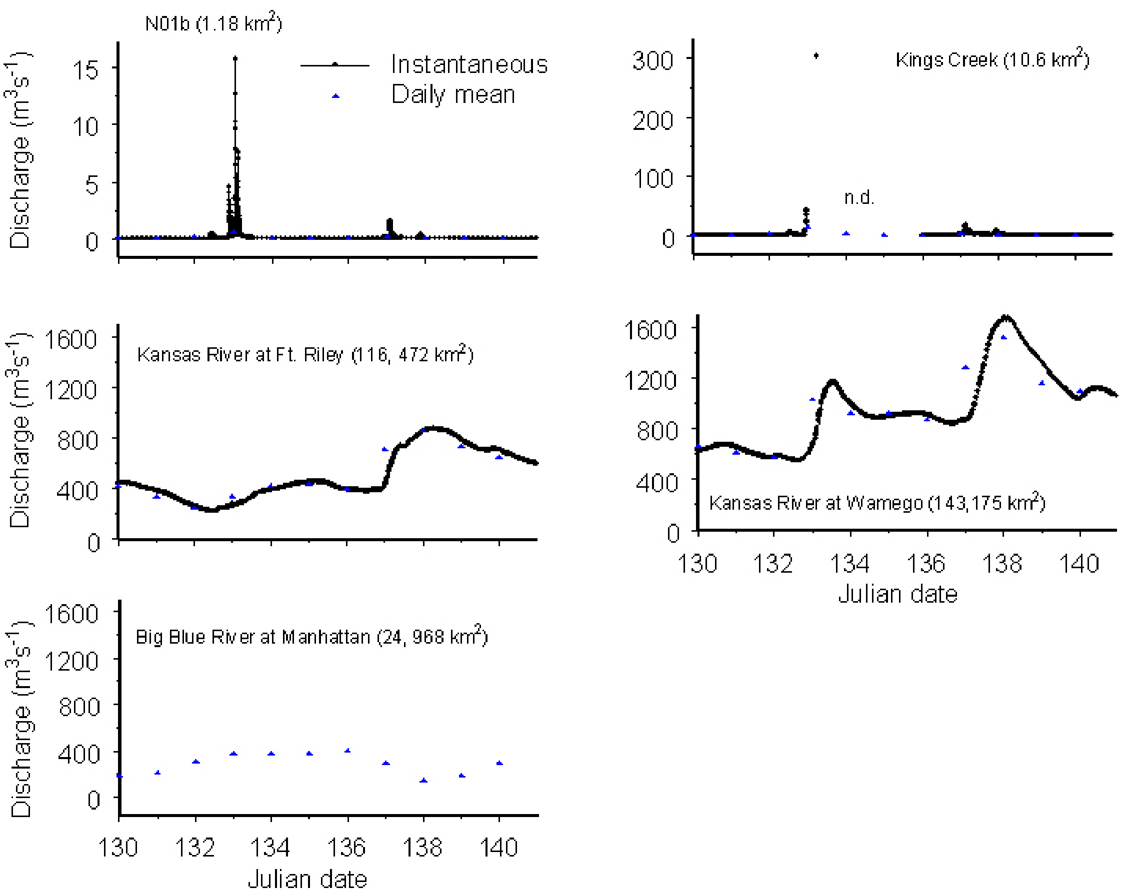
A flood occurring June 14–20, 1965 on the Platte River (Colorado and Nebraska) is among the largest U.S. floods in recorded history, with a recurrence interval of 900 to 1,600 years (Matthai, 1969). This flood originated from runoff of intense rainfall (360 mm in 4 hours) over headwater portions of the drainage south of Denver, CO. Normal annual precipitation for this area is approximately 400 mm. Flows in Plum Creek, one of the intermittent headwater streams to the Platte River that received the heaviest

Figure B-3. Map showing the location of Kings Creek and N01B, intermittent tributaries to the Kansas River.

rains, rose from <5 $m^3 s^{-1}$ to 4,360 $m^3 s^{-1}$ in only 40 minutes. Under the Federal Flood Control Act of 1944, detention impoundments were extensively constructed on headwater streams in the Great Plains to retard flooding in downstream rivers (Schoof et al., 1978; Van Haveren, 1986). Headwater impoundments reduced runoff to the Washita River in Oklahoma by 36%, but channel dredging of streams offset these reductions by increasing flow from ground water and reducing transmission loss (Schoof et al., 1978).

Machavaram et al. (2006) examined hydrologic connectivity between intermittent prairie streams, a headwater pond, and a perennial stream reach approximately 10 km downstream using chemical and isotopic tracers in a southeastern Kansas system. They found that, following precipitation, 20% of downstream water originated from the upstream pond, fed by ephemeral and intermittent streams; elevated oxygen stable isotope tracer associated with the pond water took 26–31 hours to reach the downstream site (Machavaram et al., 2006). Streams connected to lakes and wetlands contributed proportionally more flow to a southeastern Minnesota river in summer, when other water sources were minimal, than in spring (Lenhart et al., 2010). Flow from these streams has a delayed or lagged release because of storage in lakes and wetlands, and stream flow backed up because of high mainstem flows (Lenhart et al., 2010).

Figure B-4. Hydrographs (instantaneous and daily mean) showing propagation of the 13 May 1995 (Julian date 133) flood downstream from headwater sites (N01B and Kings Creek) to the Kansas River at Wamego. Also shown are hydrographs from upstream gages on the Kansas River at Fort Riley and the Big Blue River (see Figure B-3 for all site locations). Instantaneous data were not available at Kings Creek immediately following the flood because of damage to the USGS gage and were not available from Big Blue River. The peak instantaneous discharge for Kings Creek was estimated by USGS.



B.4.3.1.2 Temperature (heat energy)

Water temperatures represent a substantial stress to biotic communities in Great Plains rivers (Section B.4.3.3). Rivers to the north experience cold winters, and those to the south and west experience hot summers. Streams, particularly those strongly connected to more stable ground water, can provide thermal refuges for avoiding temporary hypothermic and hyperthermic stress (Section B.4.3.3.2). Wide, shallow channels with little overhead canopy can result in high water temperatures under summer low flows. Over a 1-km reach of the South Canadian River in Oklahoma, summer (August 18–19, 1976) maximum mainstem water temperatures were 36–37 °C, with cooler water (32–35 °C) in backwater pools and a tributary stream (Matthews and Zimmerman, 1990). Mean water temperatures of seven streams immediately upstream from confluences with the Missouri River (at the Kansas-Missouri border) did not differ from water temperatures in the mainstem river, 200–300 m downstream of the confluences, except during March when streams were warmer than the river (Braaten and Guy, 1999). Mean water temperature was determined to be homogeneous with no relationship between drainage area and water temperature across two agriculturally dominated drainages in Illinois, where most flow was derived from surface and shallow subsurface runoff (agricultural tiles) rather than deeper ground water (Wiley et al., 1990).

B.4.3.1.3 Sediment

Great Plains rivers are naturally turbid (Jewell, 1927; Cross and Moss, 1987; Huntzinger, 1995), with suspended sediment derived from the fine soils through which these river networks flow. Turbidity and suspended sediment concentration increase in prairie networks with increasing discharge and drainage area (Hill and Gardner, 1987b; Wiley et al., 1990; Lenhart et al., 2010), and can vary seasonally (Lenhart et al., 2010). Seasonal turbidity levels at tributary outlets and nearby mainstem reaches, however, were not related across seven Missouri River confluences in Kansas and Missouri (Braaten and Guy, 1999), suggesting that these streams did not influence river turbidity at baseflow conditions. In contrast to other studies in the prairie region, no relationship was found between suspended particle concentration and stream size among 22 sites ranging in land use and network position (second- to eighth-order) in the Kansas River basin (Whiles and Dodds, 2002). A significant positive relationship did exist when the authors excluded suburban sites and sites influenced by impoundments. Concentrations of suspended fine inorganic and organic matter were highest in the smallest stream draining suburban land use, whereas a comparably small stream draining native tallgrass prairie had among the lowest concentrations (Whiles and Dodds, 2002).

The downstream transport of metal-contaminated sediment was documented from mine tailings near a South Dakota headwater stream down through the river network to a reservoir approximately 200 km downstream, at the confluence of the Cheyenne and Missouri Rivers (Horowitz et al., 1988; Marron, 1989). The total amount of mine tailings transported from the headwater stream to downstream waters and floodplains over a 100-year span was estimated to be approximately 100 million metric tons (Marron, 1989). Contributions from streams to large rivers can therefore depend on the quantities available for transport from headwater streams from surrounding land uses.

B.4.3.2 Chemical Connections

B.4.3.2.1 Nutrients and other chemicals

Studies show that chemical constituents are exported from small prairie streams (Dodds et al., 1996a) and these chemical connections, or the downstream, flow-associated transport of nutrients, ions, dissolved and particulate organic matter, and other substances along prairie stream drainage networks, can significantly influence downstream water quality (Kemp and Dodds, 2002; Dodds et al., 2004; Dodds and Oakes, 2006).

Small prairie streams also can be important in preventing downstream nutrient transport. Studies conducted in Kings Creek, a stream draining a 1,060-ha tallgrass prairie catchment in Kansas, indicate that small prairie streams are highly nitrogen retentive (Tate, 1990; Dodds et al., 1996a; Dodds et al., 2000). For example, Dodds et al. (1996a) found that nitrogen transport through four second- and third-order streams in the Kings Creek watershed ranged from 0.01 to 6.0% of the total nitrogen supplied by precipitation, the balance being retained by the stream system. Similar patterns of nutrient retention have been demonstrated at larger spatial scales, as well. Alexander et al. (2000; 2008) modeled the contribution of different-sized streams and rivers (including prairie streams) to nutrient loading in the Gulf of Mexico. They found that large rivers deliver more of their nitrogen and phosphorus loads to the Gulf of Mexico than small streams, largely due to increased instream nutrient uptake and removal by small streams (Alexander et al., 2000). Despite their relative retentiveness, however, small streams do make substantial contributions to downstream nutrient loading due to their large numbers, with small to mid-sized streams in the western regions of the Mississippi River basin (which includes the Great Plains) delivering approximately 25−50% of their nitrogen loads to the Gulf (Alexander et al., 2008).

Correlations between water quality and upstream land use also indicate that prairie stream headwaters affect downstream reaches. Dodds and Oakes (2006, 2008) examined relationships between water quality and watershed land use at different spatial scales, along one fifth-order prairie stream network (Dodds and Oakes, 2006) and across 68 small prairie streams (Dodds and Oakes, 2008) in eastern Kansas. In the single drainage study, they found that concentrations of total nitrogen and nitrate were significantly related to riparian cover in the 2 km upstream of sampling sites, even when controlled for catchment land cover at each site (Dodds and Oakes, 2006). In the cross-drainage study, riparian cover along first-order streams was more closely correlated with total nitrogen, nitrate, ammonium, total phosphorus, atrazine, dissolved oxygen, and fecal coliform concentrations than riparian cover 2 or 4 km immediately upstream of sites across the 68 drainages (Dodds and Oakes, 2008). Nutrients are elevated in most prairie streams and rivers and nutrient concentrations in these systems are related to nonpoint land uses (Dodds and Oakes, 2004). These, along with widespread nature of headwater streams in river networks, are highly indicative that streams have strong chemical connection, functioning as important links between the surrounding lands to downstream waters.

Because prairie streams frequently experience intermittent flow, their influence on downstream waters is often discharge-dependent and temporally variable. For example, nitrate concentrations tend to be higher in intermittent prairie streams immediately after flows resume, versus when flow recedes (Tate, 1990). In addition, nitrogen uptake lengths (Dodds et al., 2000) and total phosphorus loads (Banner et al., 2009) increase with discharge. The effect of precipitation-driven flows on downstream water quality can depend on the relative contributions of surface water delivered from upstream channels and ground water. Prairie streams typically are tied closely to ground-water sources (Section B.4.2.2), so the influence of headwaters can be especially pronounced during periods of high precipitation. Kemp and Dodds (2001) found that nitrate concentrations in fourth- and fifth-order lowland prairie reaches were lowest during periods of high precipitation, when more low-nitrate water was delivered downstream from second- and third-order reaches and high-nitrate ground-water influences were minimized.

B.4.3.2.2 Dissolved and particulate organic matter

Differences in DOC inputs along the prairie stream longitudinal gradient provide further indirect evidence of chemical connections between prairie stream headwaters and downstream reaches. McArthur et al. (1985b) isolated bacteria from stream sediments of grassland reaches and gallery forest reaches of a prairie stream and exposed them to leachates derived from grasses and bur oak (a common gallery forest species). Grassland bacteria only grew when provided with grass leachates as a carbon source, whereas gallery forest bacteria grew when provided with either grass or bur oak leachates. This finding suggests that either (1) grass-derived DOC-consuming bacteria are transported downstream and then coexist with bacteria consuming forest-derived DOC, or (2) grass-derived DOC is transported downstream, and local bacterial communities have adapted to use more refractory DOC exported from upstream reaches (McArthur et al., 1985b).

Studies measuring POM exported from low-order prairie stream reaches show significant temporal and spatial variability. For example, Golladay (1997) documented little POM export from a third-order prairie stream in Kansas, whereas two prairie streams in Texas had much higher rates of POM transport (Hill and Gardner, 1987b). In part, these differences might reflect variability between stormflow and baseflow sampling, as organic matter concentrations can be positively correlated with stream discharge (Hill and Gardner, 1987b; Golladay, 1997). Whiles and Dodds (2002) examined seston (suspended fine particles) dynamics along the Kansas River drainage network (second- to eighth-order), and found that seston concentrations showed a significant positive relationship with stream size, increasing approximately 17-fold along the longitudinal gradient. This increase in seston was correlated with an increase in the taxa richness of filter-feeding invertebrates (Whiles and Dodds, 2002), illustrating that detrital transport along the stream gradient can influence invertebrate assemblages, which is a basic tenet of the River Continuum Concept (Vannote et al., 1980).

Stagliano and Whiles (2002) found that the standing stock of fine particulate organic matter FPOM in a perennial reach of a tallgrass prairie stream was insufficient to support the annual secondary production (i.e., the rate of heterotrophic biomass formation) of collector-gatherers (Cummins and Klug, 1979), the dominant group of macroinvertebrates feeding on deposited FPOM. The replenishment of FPOM standing stocks, at least in part from upstream sources via algal senescence, the transport and settlement of suspended POM, and the breakdown and transport of coarse POM, likely accounted for this apparent imbalance: Turnover of FPOM standing stocks was estimated to occur every 20 days (Stagliano and Whiles, 2002). Whiting et al. (2011) examined organic matter dynamics and trophic structure along a tallgrass prairie stream network (first- to fifth-order). They found that collector-filterers (macroinvertebrates that feed on suspended POM; Cummins and Klug, 1979) in upstream reaches consumed <1% of suspended POM flux; gatherers that feed on fine and very fine POM dominated secondary production in downstream reaches; and predators in downstream forested reaches consumed 107% of locally derived macroinvertebrate production. Predators in the upstream and middle reaches consumed 65% and 74% of available macroinvertebrate production, respectively. These findings support the idea that downstream secondary production depends in part on the export of energy sources (i.e., POM and invertebrates) from upstream reaches (in order for downstream predators to consume >100% of locally derived macroinvertebrate production).

As discussed earlier (Section B.4.2.4), prairie stream headwaters typically are open-canopied systems that receive little organic matter from terrestrial inputs, relative to forested headwaters (Jewell, 1927). Given the importance of autochthonous production in these systems, that algal-based contributions to prairie stream seston can be significant (Swanson and Bachmann, 1976; Hill and Gardner, 1987b; Lenhart et al., 2010) is not surprising. In four Iowa streams, export of chlorophyll *a* (a measure of algal biomass) was positively correlated with upstream channel bottom area, suggesting that downstream suspended algae originated as benthic algae in upstream portions of the network (Swanson and Bachmann, 1976). This downstream transport of algae also can provide colonists for downstream reaches after flooding or drying of stream channels. For example, Dodds et al. (1996b) examined the recovery of periphyton biomass upon channel rewetting in an intermittent prairie stream. Within 2 weeks, chlorophyll had returned to maximum levels on rocks placed in the stream, even when the rocks had been treated and scrubbed to remove desiccation-resistant propagules; this finding suggests that algal colonists in this stream were transported downstream from permanent upstream pools (Dodds et al., 1996b).

Coarse POM can connect prairie stream headwaters to downstream reaches. Johnson and Covich (1997) examined detrital inputs along a second- to fifth-order prairie stream network in Oklahoma. They found that leaves in the stream originated from farther upstream than expected, with the percentage of whole leaves at a site best explained by riparian forest cover in reaches 500 and 1,000 m upstream. The percentage of leaf fragments >1 mm was best explained by downstream distance along the stream network (Johnson and Covich, 1997), suggesting increased processing and fragmentation of leaves as they move down the longitudinal gradient.

B.4.3.3 Biological Connections

B.4.3.3.1 Invertebrates

Existing evidence for invertebrate-mediated biological connectivity along prairie stream networks mainly comes from studies of invertebrate assemblage recovery following flooding and drying in small prairie streams. Recovery from these disturbances tends to be relatively rapid, with substantial gains in invertebrate taxa richness and density observed within days to weeks (Miller and Golladay, 1996; Hax and Golladay, 1998; Fritz and Dodds, 2004), suggesting that these reaches are quickly repopulated by invertebrate drift from upstream sources, aerially dispersing adults, or disturbance-resistant survivors.

Fritz and Dodds (2002, 2004, 2005) examined postflooding and postdrying recovery of invertebrates in small intermittent and perennial prairie streams along an approximately 5-km stretch of Kings Creek in Kansas. They found that initial recovery of invertebrate taxa richness in intermittent reaches, and taxa richness of invertebrate drift and aerially colonizing insects, were negatively related to distance from upstream perennial water (Fritz and Dodds, 2002, 2004). Distance from upstream refuges, however, was not a significant predictor of invertebrate diversity measures across annual time scales (Fritz and

Dodds, 2005); they speculated that movement of water along the entire stream network (i.e., maintenance of hydrologic connectivity) makes proximity to colonists less important over longer time scales. These findings suggest that recovery from disturbance in these systems depends on biological connectivity via both downstream drift of colonizers and downstream (and potentially upstream) movement of aerially dispersing, egg-depositing adults (Miller and Golladay, 1996; Dodds et al., 2004).

B.4.3.3.2 Fishes

Research on fish assemblages in prairie streams provides perhaps the strongest and most well-studied evidence of biological connections throughout these networks. Much of this evidence focuses on two related aspects of the ecology of prairie stream fish: the dispersal and recruitment of pelagic-spawning prairie stream fish and the recovery of fish assemblages after disturbance, especially flooding and drying.

Many prairie stream fish broadcast spawn nonadhesive, semibuoyant eggs, which develop (typically hatching within 1 to 2 days) as they are transported downstream with water flow (Cross and Moss, 1987; Fausch and Bestgen, 1997; Platania and Altenbach, 1998; Durham and Wilde, 2006). The distance these eggs travel downstream depends on discharge and several other factors (e.g., development time); Platania and Altenbach (1998) estimated, however, that unimpeded eggs could travel as far as 144 km before hatching, and another 216 km as developing protolarvae (i.e., the swim-up stage), illustrating that downstream transport of these drifting organisms can be extensive. Without adequate water flow along sufficient lengths of the stream network, eggs can drop out of suspension before hatching (Platania and Altenbach, 1998; Durham and Wilde, 2006). Based on historical and contemporary fish surveys, eight species of pelagic-spawning cyprinids require a minimum length of greater than approximately 100 km (ranging from 103 to 297 km, depending on the species) of undisrupted stream channel (e.g., channels with no impoundments and no drying associated with human withdrawal) to support persistent populations (Perkin and Gido, 2011).

This pelagic-spawning reproductive strategy also necessitates upstream movement by adult fish, if populations are to be maintained in small prairie streams (Fausch and Bestgen, 1997; Durham and Wilde, 2008). Prairie stream fishes generally are highly vagile, with adults capable of long-distance migrations. For example, individuals of one species of prairie fish (*Hybognathus placitus*) in the South Canadian River, NM were observed to move approximately 250 m upstream over a 15-minute period, illustrating that prairie fishes can move substantial distances over relatively short periods (Fausch and Bestgen, 1997).

The effect that impoundment of prairie streams and rivers has had on the region's native fish assemblages highlights the importance of hydrologic connectivity in these systems. Many studies have documented statistically significant associations between impoundment of prairie streams and loss of native fishes (Winston et al., 1991; Luttrell et al., 1999; Schrank et al., 2001; Falke and Gido, 2006; Matthews and Marsh-Matthews, 2007). For example, Schrank et al. (2001) found that, across 26 streams in the Flint Hills region of Kansas, sites from which Topeka shiners (*Notropis topeka*) had been extirpated had significantly more small impoundments on them and higher largemouth bass

(*Micropterus salmoides*) catch-per-unit-effort than sites at which the shiners were extant. Fewer studies have specifically examined the mechanisms by which impoundments affect these changes, although impoundments likely disrupt both the downstream transport of developing eggs and larvae (Platania and Altenbach, 1998) and the upstream and downstream movement of adult fish.

Because many small prairie streams have intermittent flow, maintenance of fish populations often depends on dispersal out of intermittent reaches before drying occurs and recolonization of these habitats once water flow resumes—both of which require hydrologic connectivity along the stream network. Many fishes also require different habitats during different life stages, further necessitating hydrologic connectivity across these areas (Labbe and Fausch, 2000; Falke et al., 2010).

For dispersal and recolonization to occur, fishes must be able to access refuge habitats under adverse conditions, and then expand into newly habitable areas once adverse conditions abate. Small, spring-fed prairie streams serve as key refuges for endemic prairie fishes (Hoagstrom et al., 2010), because they are ground water fed and maintain permanent pools that can provide habitat during periods of channel drying (Wohl et al., 2009). This ground-water influence also allows these spring-fed streams to provide refuge from adverse temperatures. For example, a spring-fed stream in Missouri had more stable temperatures than the mainstem river, with cooler summer and warmer winter temperatures; in winter, fish from the mainstem river moved into this habitat, where their food availability, growth, and average egg size were greater than those of fish that stayed in the mainstem (Peterson and Rabeni, 1996).

During and after floods, juvenile and adult fishes can move upstream or downstream (or get displaced downstream) into newly available habitat (Fritz et al., 2002; Franssen et al., 2006). Once channels are rewetted, prairie stream fishes can move quickly into these previously unoccupied habitats (Harrell et al., 1967; Fritz et al., 2002; Franssen et al., 2006). For example, Harrell et al. (1967) examined fish response to channel drying in third- to sixth-order reaches of Otter Creek, an intermittent prairie stream in north-central Oklahoma, and found that most fish species collected after 8 months of flow prior to channel drying were already present 3 days after channel rewetting (Harrell et al., 1967). After a flood in an intermittent prairie stream in Kansas, fish dispersed into the headwaters from a perennial reach approximately 5 km downstream (Franssen et al., 2006).

B.4.4 Prairie Streams: Synthesis and Implications

Prairie streams typically represent a collection of spring-fed, perennial pools and reaches, embedded within larger, intermittently flowing segments (Labbe and Fausch, 2000). Due to the region's geographic location, substantial interannual variation in rainfall exists. Expansion (flooding) and contraction (drying) of these systems, particularly in terms of summer rainfall deficit (Borchert, 1950), determine the timing of hydrologic connectivity at any given time. Because of this temporal variability, connectivity in prairie river networks must be considered over relatively long time scales (multiple years).

- Studies have demonstrated significant physical, chemical, and biological connections from prairie headwater streams to larger rivers, despite extensive alteration of historical prairie regions by agriculture, water impoundment, water withdrawals, and other human activities

(Matthews and Robinson, 1998; Dodds et al., 2004), and the challenges these alterations create for assessing connectivity.

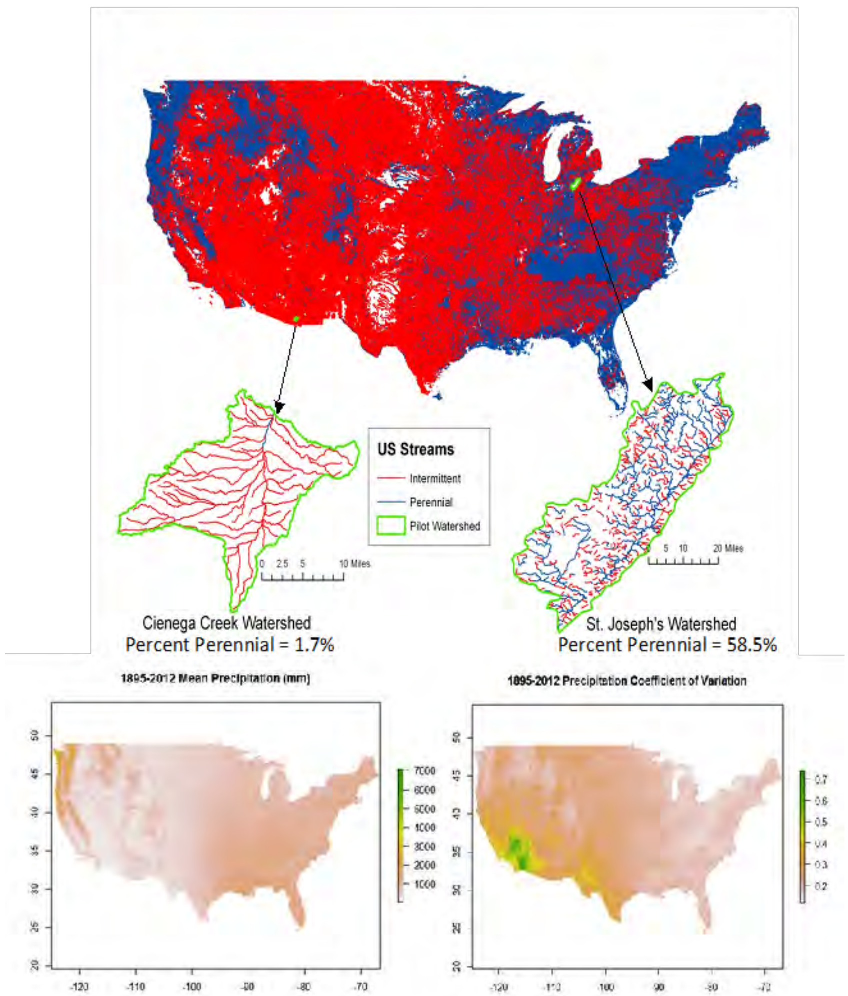
- The most compelling evidence for connectivity along prairie river networks comes from examples of streams as sources of water via flood propagation (Matthai, 1969; Fritz and Dodds, 2004, 2005), sources of contaminated sediment transport (Horowitz et al., 1988; Marron, 1989), sites of nutrient lags and transformation (Dodds et al., 1996a; Alexander et al., 2008), the downstream transport of prairie fish eggs and larvae (Platania and Altenbach, 1998; Perkin and Gido, 2011), and refuges for prairie fishes (Fausch and Bestgen, 1997; Franssen et al., 2006).
- Impoundments for irrigation storage and flood control have altered flood magnitude, altered flow timing, and reduced flow variability and turbidity across the prairie regions (Cross and Moss, 1987; Hadley et al., 1987; Galat and Lipkin, 2000). The effect that impoundment of prairie streams and rivers has had on the regions' native fish assemblages highlights the importance of hydrologic connectivity in these systems. Maintenance of fish populations often depends on dispersal out of intermittent reaches before drying occurs and recolonization of these habitats once water flow resumes—both of which require hydrologic connectivity along the stream network—and many fishes also require different habitats during different life stages (Labbe and Fausch, 2000; Falke et al., 2010).

B.5 Case Study: Southwestern Intermittent and Ephemeral Streams

B.5.1 Abstract

Ephemeral and intermittent streams are abundant in the arid and semiarid landscapes of the West and particularly the Southwest (Figure B-5.). These areas are characterized by low and highly variable precipitation where potential evapotranspiration exceeds precipitation. Based on the National Hydrography Dataset; 94%, 89%, 88%, and 79% of the streams in Arizona, Nevada, New Mexico, and Utah are intermittent or ephemeral (NHD, 2008). The heavily studied Upper San Pedro Basin in southeastern Arizona is discussed in detail because it is a well-understood example of the hydrologic behavior and connectivity of rivers common to the southwestern United States where ephemeral and intermittent tributaries comprise the majority of the basin's stream reaches. Flows and floods from ephemeral and intermittent streams are also major drivers of the dynamic hydrology of the relatively few perennial reaches in the Southwest. These streams also supply water to mainstem alluvial aquifers and regional ground-water aquifers. Both alluvial and regional aquifers, in turn, supply baseflow to perennial mainstem stream reaches over extended periods (sometimes months) when little or no precipitation occurs. It is this baseflow and shallow ground water that supports the limited naturally occurring, vibrant riparian communities in the region. In addition, ephemeral streams export sediment, which contributes to shaping the fluvial geomorphology and alluvial aquifers of streams in the regions (Shaw and Cooper, 2008), and nutrients, which contribute to river productivity. Several studies found

Figure B-5. Upper: Geographic distribution of intermittent and ephemeral (red) and perennial (blue) streams in the Continental United States and two example watersheds in Arizona and Michigan/Ohio/Indiana from the National Hydrography Dataset (NHD) stream map (http://nhd.usgs.gov/). Lower: maps of mean precipitation and the precipitation coefficient of variation (equal to the standard deviation divided by the mean) of annual precipitation from 1895 to 2012. Note that the NHD might not accurately reflect the total extent of ephemeral or intermittent streams, as it does not include stream segments less than 1.6 km (1 mile) long, combines intermittent and ephemeral streams, and is based on 1:100,000-scale topographic maps.



that native fishes and invertebrates are well adapted to the variable flow regimes common in rivers of the Southwest and are heavily influenced by ephemeral tributary streams (Turner and List, 2007).

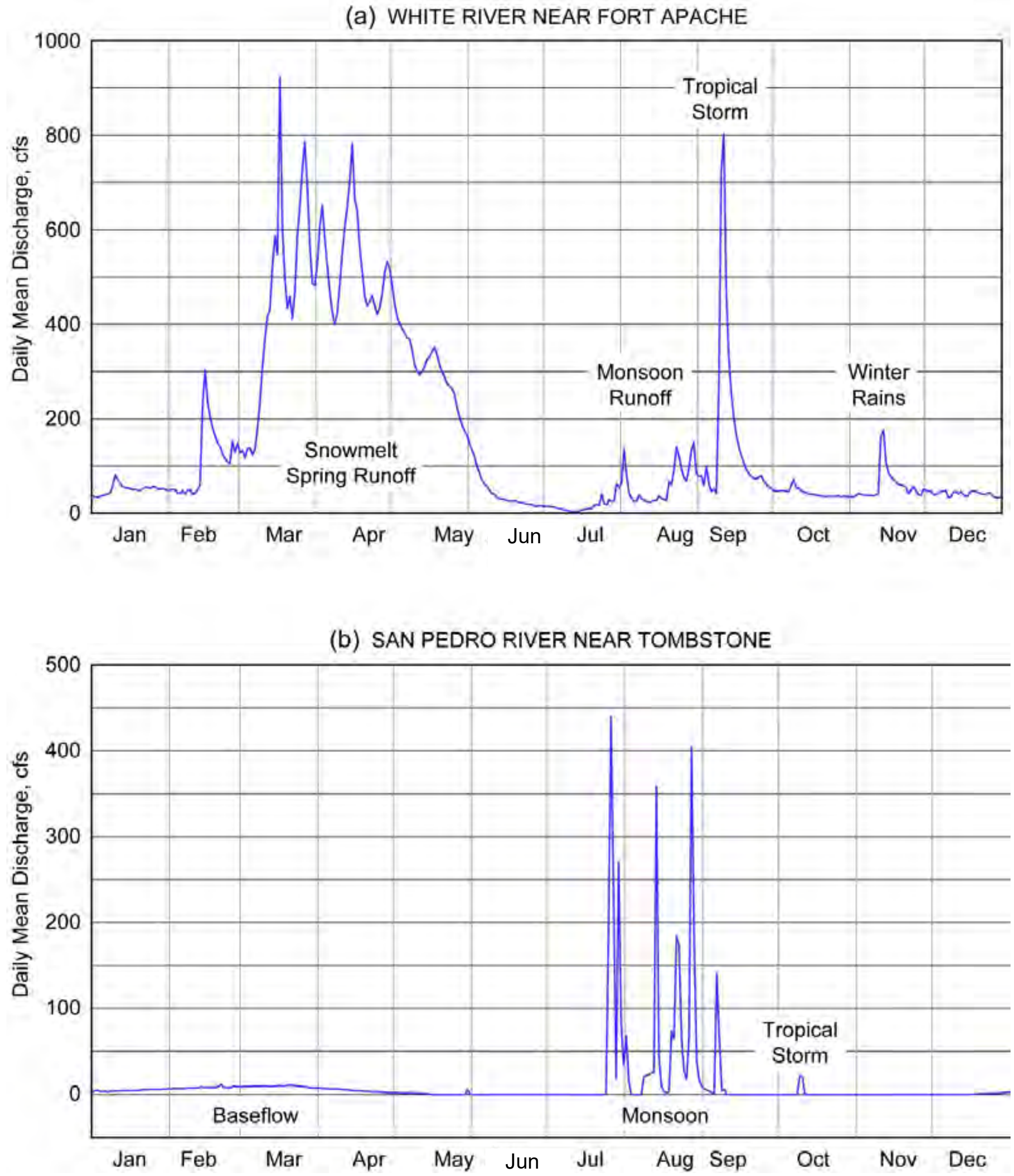
B.5.2 Introduction

This case study addresses the hydrologic and ecological influence of ephemeral and intermittent streams on perennial or intermittent rivers in the arid and semiarid southwestern United States with particular emphasis on Arizona and New Mexico. The structure of this case study differs slightly from the other case studies because of the uniquely thorough understanding of one particular southwestern river system, the San Pedro River, which has been the subject of a long-term research program (Goodrich et al., 2000; Stromberg and Tellman, 2009). Hence, evidence for the function and connectivity of ephemeral and intermittent tributaries to the San Pedro River is described in detail, and its application to other river systems in the Southwest is subsequently explored.

B.5.3 Southwestern Rivers

Understanding the unique characteristics of southwestern American rivers is necessary to evaluate the connectivity and influence of ephemeral and intermittent streams on these rivers (Levick et al., 2008). Southwestern rivers differ in many ways from rivers in the humid eastern United States or in the Midwest and West. Southwestern rivers typically can be divided into two main types, particularly in the Basin and Range geologic province. The first type comprises rivers in the mountainous upper basins that receive more precipitation, often as snow, and the second type comprises those rivers located in the arid or semiarid plateau regions and valley plains dominated by ephemeral streams (Blinn and Poff, 2005). For example, more than 80% of the Gila River corridor in New Mexico and Arizona meanders through desert scrublands. Precipitation is seasonal. In summer, precipitation is strongly influenced by atmospheric moisture flowing from the Gulf of Mexico and the Gulf of California (Mexican monsoon), where local heating triggers high-intensity air-mass thunderstorms. In fall, tropical depressions, often remnants of hurricanes, can bring infrequent but long-duration rainfall events; such storms are responsible for many of the larger floods in the region (Webb and Betancourt, 1992). Cyclonic storms from the Pacific Ocean, resulting in large frontal systems, dominate winter precipitation in the form of snow in higher elevations and typically as low-intensity rainfall in lower elevations (Blinn and Poff, 2005). Figure B-6 illustrates the 2003 calendar year hydrograph from the White River near the Fort Apache USGS gaging station (upper) in east-central Arizona, and the San Pedro River near Tombstone, in southeastern Arizona (lower). Although the two gaging stations differ in elevation by less than 200 m, the watershed contributing to the White River is substantially larger and is higher in elevation than the San Pedro watershed, resulting in long-duration spring runoff from snowmelt. Monsoon-generated, short-duration runoff dominates the San Pedro watershed but monsoonal influence also is apparent in the White River hydrograph. Runoff generated from late monsoon precipitation in September caused a major increase in discharge in the White River and a minor increase in the San Pedro. Most perennial and intermittent rivers in the Southwest are ground water dependent, flowing primarily in a baseflow regime and supported by discharge from a connected regional or alluvial aquifer or both. As discussed in more detail below, part of the baseflow is often sustained or augmented by slow drainage of a shallow alluvial aquifer from past flooding. In arid and semiarid regions, the riparian areas that perennial and intermittent streams support occupy a small percentage of the overall landscape but they host a disproportionately greater percentage of the biodiversity than the areas surrounding them (Goodrich et al., 2000; Stromberg et al., 2005). Reservoir construction, irrigation withdrawals, and the cumulative impacts of ground-water pumping have converted many historical, perennially flowing reaches into intermittently flowing reaches (Blinn and Poff, 2005).

Figure B-6. 2003 calendar year hydrographs from (a) the White River near Fort Apache, AZ and (b) the San Pedro River near Tombstone, AZ.



Abrupt changes in streamflow regimes (i.e., a change from perennial to intermittent or ephemeral and back again) can also result from underlying geology. Streams with abrupt changes are often referred to as interrupted streams (Meinzer, 1923; Hall and Steidl, 2007). A constriction and rise in bedrock geology can force regional ground water to the surface resulting in perennial flow while streamflow encountering highly fractured bedrock or a highly porous karst system can virtually disappear over very short distances. Another relatively abrupt transition in arid and semiarid stream hydrology and morphology occurs where steep mountain slopes transition into lower valley slopes. At this transition, watersheds with high sediment transport out of the mountainous portion often form alluvial fans. The stream channel system above the transition is typically dendritic and below the transition, the channel system often becomes a diffusive set of shallow braided channels. Runoff over alluvial fans typically becomes less concentrated or confined to a single large channel but more diffuse and shallower turning into broad sections of sheet flow (Parker et al., 1998). The diffuse runoff is more likely to infiltrate into the alluvial fan. Very large flows may be required for runoff to cross the alluvial fan and connect to downstream waters.

Dominant hydrologic flowpaths vary with location within southwestern river basins. After climate and weather, recharge and infiltration mechanisms are the next most important factors determining the occurrence of ephemeral, intermittent, and perennial streams. Recharge over longer time scales (months to centuries) is essential to replenishing regional ground water and near-stream alluvial aquifers, which in turn are essential to maintaining baseflow in perennial streams. Primary recharge mechanisms include mountain block recharge, mountain front recharge, diffuse hillslope or interchannel recharge, and ephemeral channel recharge. Key advances brought forth in a recent synthesis of research on ground-water recharge in the southwestern and western United States include (1) desert vegetation effectively eliminates diffuse recharge in most areas of the basin floor; (2) ephemeral channel recharge can be very important in wet years and greatly dominates recharge in basin-floor environments; and (3) environmental tracers are now available to "fingerprint the sources and amounts of ground-water recharge at the basin scale" (Phillips et al., 2004).

Mountains with deeper soils or those consisting of fractured rock will have higher infiltration capacities, less frequent occurrences of overland flow, and serve as recharge areas for regional ground water (Wilson and Guan, 2004; Blasch and Bryson, 2007; Wahi et al., 2008). Mountains with shallow soils and more consolidated rock will shed stormflow and shallow ground water off the mountain block onto the valley, which often consists of deep alluvium, particularly in the basin and range geologic province. This area is where mountain-front recharge occurs. High-elevation perennial streams often become intermittent or ephemeral at this transition, with their downstream disappearance of surface flow dependent on the flow rates coming off the mountain block and the permeability of the valley alluvium into which they enter. During periods of high flow, they can reconnect with other perennial stream reaches maintained by ground-water flow (Blinn and Poff, 2005; Blasch and Bryson, 2007; Yuan and Miyamoto, 2008).

Runoff generation in arid and semiarid valley floors and lowlands where basin alluvium is relatively porous and deep is dominated by the infiltration-excess mechanism in which precipitation rates exceed infiltration rates. In the arid and semiarid Southwest, high-intensity convective thunderstorms typically trigger this situation. Generally, such storms are relatively short in duration, resulting in ephemeral flows with short runoff duration (Goodrich et al., 1997). As water flows down dry ephemeral channels, it infiltrates the channel bottom and sides (i.e., channel transmission losses occur) where channel substrate is porous. If restricting soil or geologic layers underlying the channel do not substantially inhibit downward motion, channel transmission losses will recharge either the regional or alluvial ground water (Tang et al., 2001; Constantz et al., 2002; Harrington et al., 2002; Goodrich et al., 2004; Coes and Pool, 2005; Vivoni et al., 2006; Blasch and Bryson, 2007). In this influent stream environment typical of many southwestern streams, the volume of transmission water losses in ephemeral channels increases as watershed size increases, resulting in a losing stream environment as opposed to a gaining stream environment encountered in wetter hydroclimatic regimes (Goodrich et al., 1997). As noted above and discussed in Phillips et al. (2004), these ephemeral tributary channels are the dominant source of recharge in valley floors, and at the basin scale they can provide substantial recharge during wet years. Typically, as stream drainage area increases, the alluviums under and next to streams begin to serve as important shallow aquifers that receive and store streamflow infiltration during hydrologic events and sustain baseflow and riparian communities between storms (Stromberg et al., 2005; Baillie et al., 2007; Dickinson et al., 2010).

The magnitude of aquifer recharge is highly temporally variable in the Southwest. Winter precipitation, which has a predominant effect on mountain-block and mountain-front recharge in the Arizona-New Mexico portion of the Southwest, is correlated with the El Niño/Southern Oscillation (Woolhiser et al., 1993) at interannual time scales. Over decadal climate cycles, winter precipitation also is related to the Pacific Decadal Oscillation (Pool, 2005). The magnitude of ephemeral channel recharge varies widely from year to year, depending on the strength of the monsoon season (Goodrich et al., 2004) and the occurrence of relatively infrequent and prolonged precipitation events resulting from tropical depressions. Floods and large runoff events caused by any of these mechanisms can have a long-lasting influence (6 to 10 months) on baseflow of southwestern rivers by recharging near-stream alluvial aquifers and thereby sustaining streamflow as they drain (Brooks and Lemon, 2007).

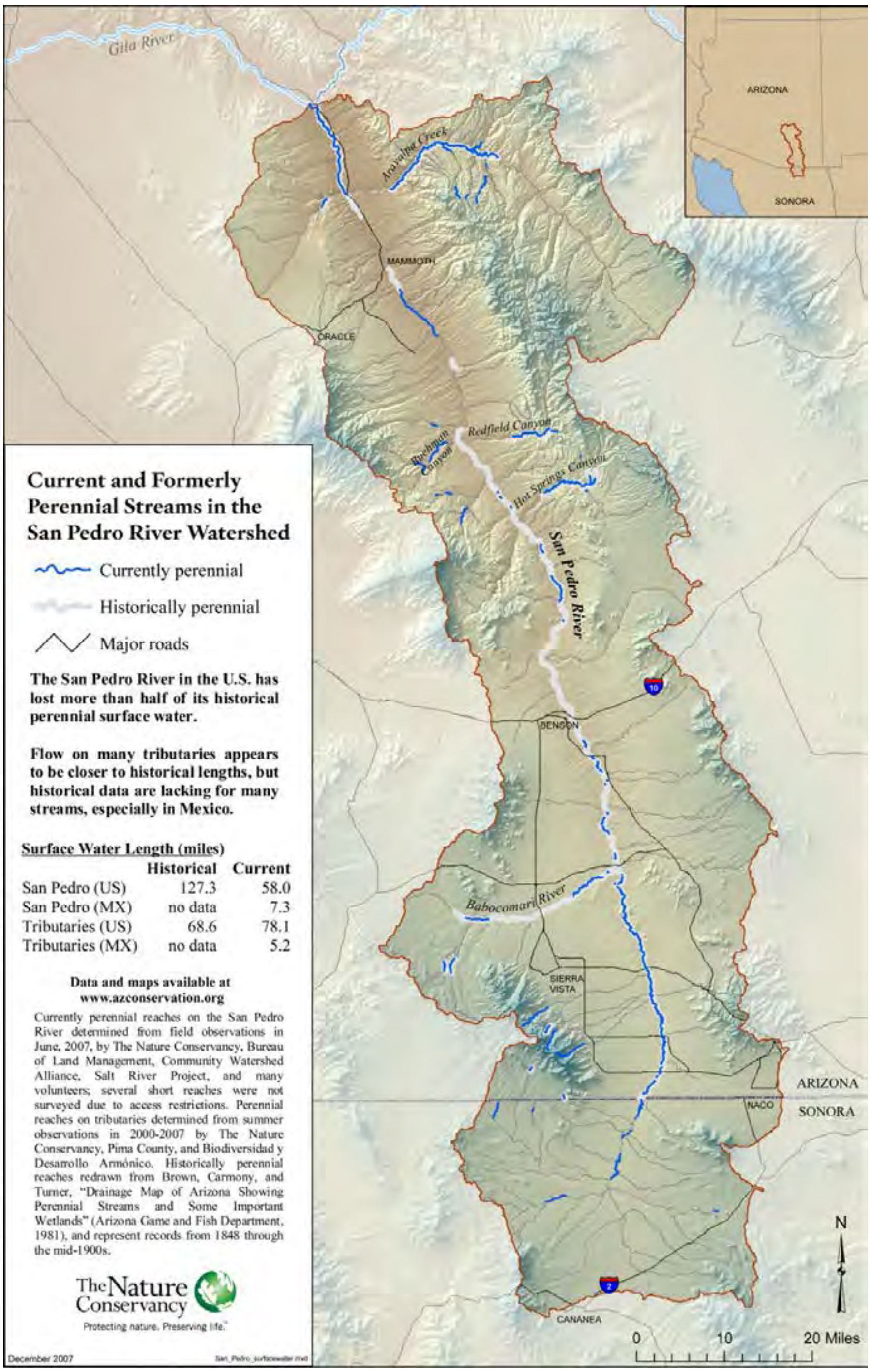
B.5.4 San Pedro River

B.5.4.1 Basin Characteristics

Because of a rich research and long-term monitoring history, the San Pedro Basin and River in southeastern Arizona represents an excellent case study of the hydrologic behavior and connectivity of southwestern rivers (Goodrich et al., 2000; Stromberg and Tellman, 2009; Brookshire et al., 2010). The San Pedro River originates in Mexico, flowing undammed north to its confluence with the Gila River. The San Pedro is the only significant un-impounded river in Arizona and the last remaining stream in southern Arizona with long perennial reaches (Figure B-7; Kennedy and Gungle, 2010). Most tributaries to the river are ephemeral at their confluence with the mainstem. The river basin, located in the Basin and Range Province, has a valley that is generally 30−50 km wide, comprising sedimentary fill deposits, and slopes upward from the river to mountains with elevation ranging from 2,000 to 2,900 m. The San Pedro Basin consists of 93% nonperennial reaches (including ephemeral and intermittent), 6.3% artificial path (canals, diversions, pipeline, connectors), and 0.7% perennial reaches in the U.S. portion of the basin as derived from the USGS NHD[1] (Figure B-8). The percentage of streams types is not static but varies from year-to-year. The Nature Conservancy and its partners annually map the wet and dry reaches along the San Pedro mainstem and several large tributary streams since 2007

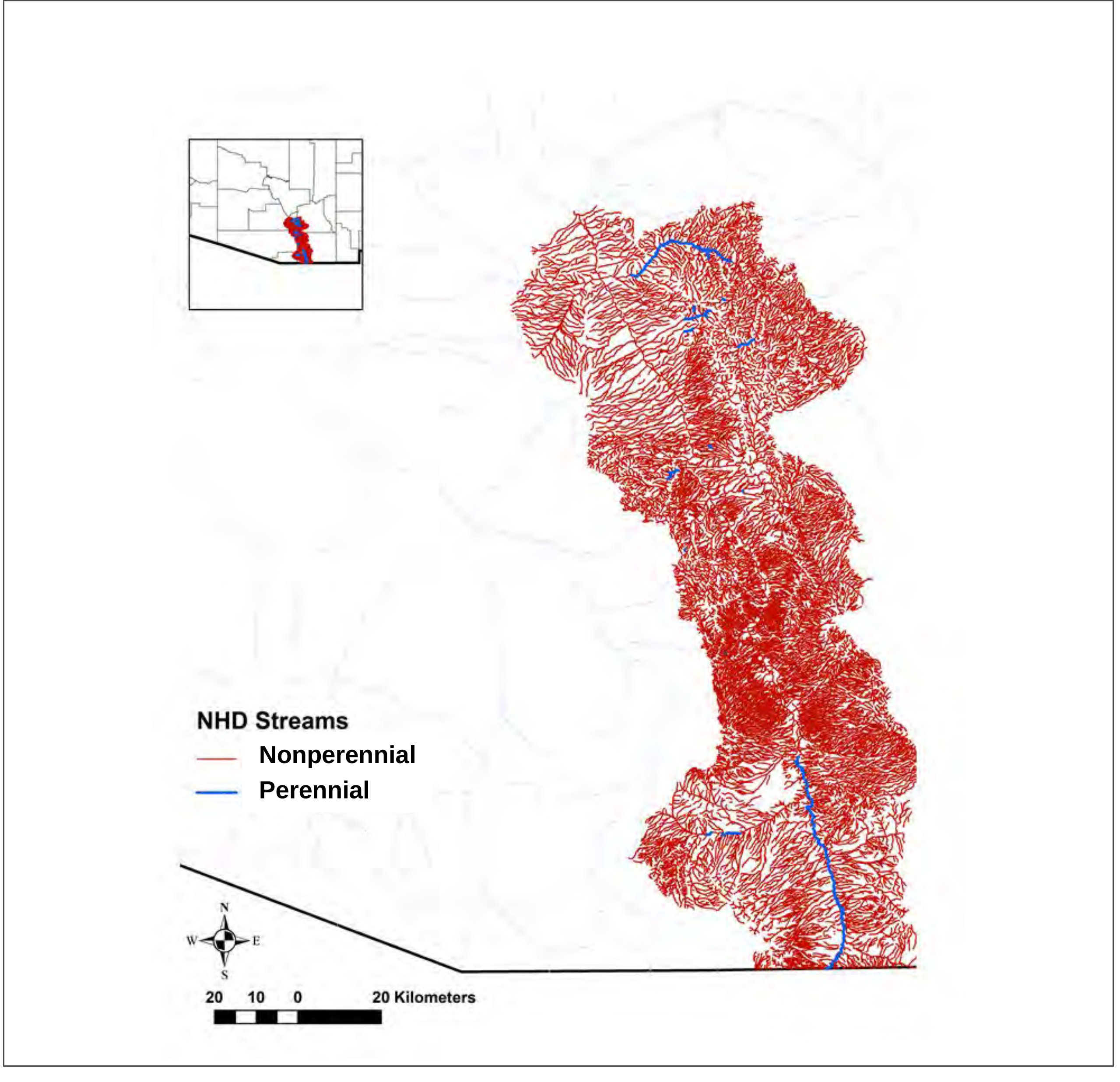
[1]Based on USGS National Hydrography Dataset (NHD) stream map (http://nhd.usgs.gov/). Note that the NHD might not reflect the total extent of ephemeral or intermittent streams accurately, as it does not include stream segments less than 1.6 km (1 mile) long, combines intermittent and ephemeral streams, and is based on 1:100,000-scale topographic maps.

Figure B-7. San Pedro River basin map showing major physiographic features and current and historical perennial reaches. From Levick et al. (2008), courtesy of The Nature Conservancy, Arizona. Available online at http://azconservation.org/map_gallery/current_and_formerly_perennial_san_pedro_river_surface_water.



(Turner and Richter, 2011). The wet-dry mapping is conducted roughly in the middle June, historically the time of lowest streamflow, prior to the onset of the monsoon. For 2014, about 25% (54.1 km) of the 214 km surveyed were found to be wet (214 km is ~1.1% of the stream length plotted in Figure B-8).

Figure B-8. Perennial (blue) and nonperennial (red) streams in the San Pedro Basin from the U.S.-Mexico border to its confluence with the Gila River based on USGS National Hydrography Dataset (NHD) stream map (http://nhd.usgs.gov/).



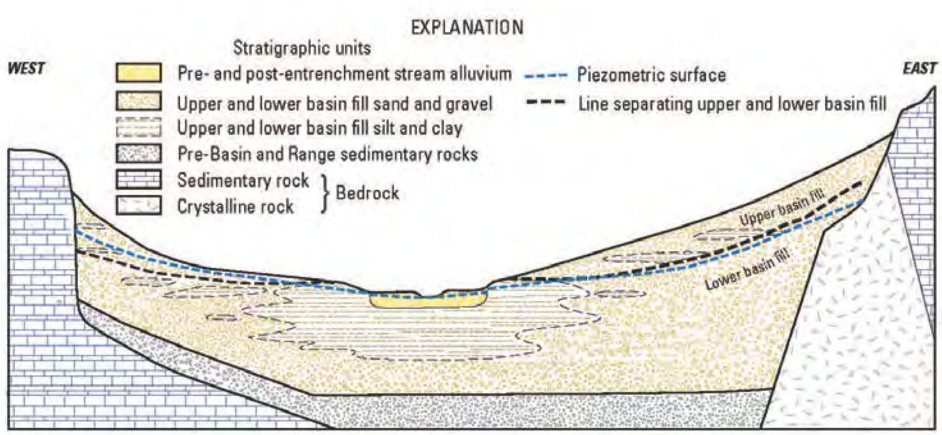
The wet-dry survey data is accessible at:
(http://azconservation.org/downloads/category/san_pedro_river).

Annual precipitation within the basin ranges from 300 to 750 mm with highest amounts occurring in the mountains. Vegetation includes desert scrub, grasslands, oak woodland savannah, mesquite woodland, riparian forest, coniferous forest, and agriculture (Kepner et al., 2000; Kepner et al., 2004). Brush and grasses typical of southwestern semiarid landscapes (Goodrich et al., 1997) dominate the valley floor vegetation.

At the Walnut Gulch Experimental Watershed (WGEW—a subwatershed of the San Pedro watershed near Tombstone, Arizona), operated by U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS), approximately two-thirds of the annual precipitation on the watershed occurs as high-intensity, convective thunderstorms of limited aerial extent (Goodrich et al., 1997). Winter rains (and occasional snows) are generally low-intensity events associated with slow-moving cold fronts and are typically of greater aerial extent than summer rains. Runoff on the lower elevations of the WGEW is generated almost exclusively from convective storms during the summer monsoon season via infiltration excess that produces overland flow. The hydrogeology of the San Pedro River basin is typical of many alluvial basins in the Southwest (Dickinson et al., 2010). Ground water flows through the basin-fill aquifer (regional aquifer) from recharge areas near the mountains and beneath ephemeral tributaries to perennial reaches of the San Pedro River (Wahi et al., 2008; Dickinson et al., 2010). A narrow band of highly permeable stream alluvium is incised into the basin-fill along the major stream channels (Figure B-9). The stream and floodplain alluvium is an important alluvial aquifer that receives discharge from the basin-fill aquifer and streamflow via streambank infiltration occurring during high stream stages.

This bank and alluvial aquifer storage supports riparian vegetation during periods lacking runoff (Dickinson et al., 2010). The San Pedro River network with associated shallow alluvial aquifers (mainstem and portions of some tributaries) supports extensive riparian vegetation communities (Stromberg et al., 2005) that provide habitat for more than 350 species of birds, 80 species of mammals, and 40 species of reptiles and amphibians (Kennedy and Gungle, 2010). Alluvial aquifers also are zones of extensive hyporheic exchange (Stanford and Ward, 1988; Fernald et al., 2001).

Figure B-9. Generalized east-west section and stratigraphic units in the middle San Pedro watershed. From Dickinson et al. (2010).



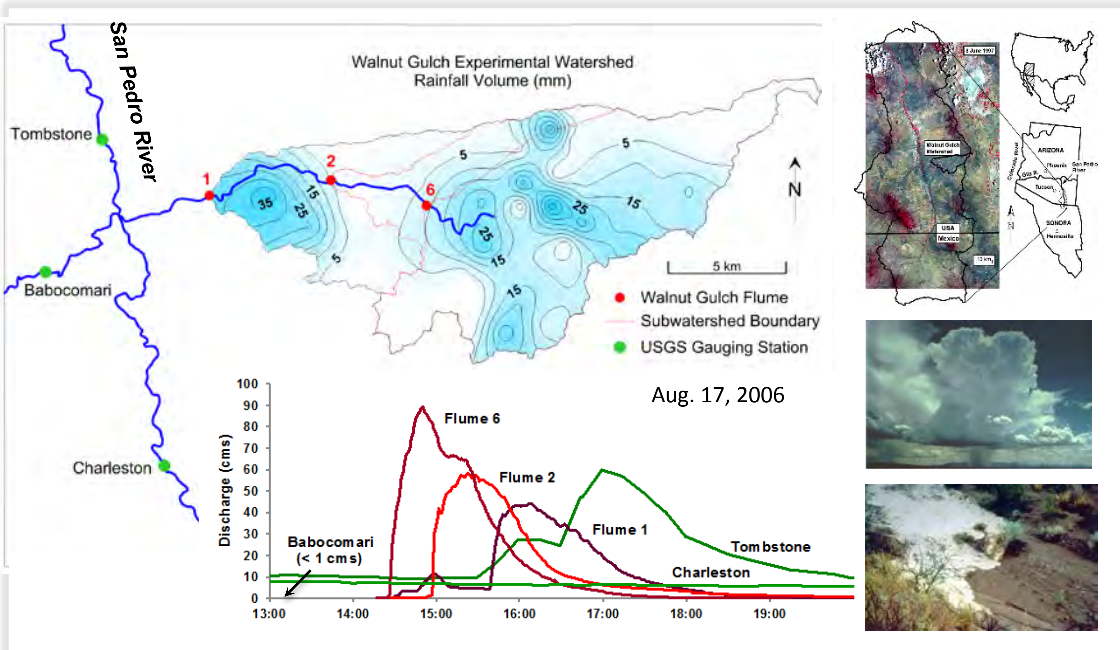
B.5.4.2 Ephemeral Stream Connections and Their Influence on the San Pedro River

Overland runoff generation and associated ephemeral streamflow is common in San Pedro tributary streams. Goodrich et al. (1997) examined hundreds of hydrologic events in different-sized catchments at the USDA-ARS WGEW and found that the relationship between watershed area and runoff volume was increasingly nonlinear as drainage area increased. The authors found a critical threshold watershed area of approximately 36−60 ha, at which runoff responses became much less linear and channel transmission losses increased more rapidly with increasing watershed area. This relationship is very different from commonly observed relationships in humid streams of the East, where runoff generally is proportional to watershed area (Section 3.3.1). Two reasons for this variability in runoff produced per unit watershed area are: (1) the spatial variability and limited spatial extent of runoff producing precipitation, and (2) the loss of runoff by infiltration into the bed of ephemeral channels (transmission losses). Figure B-10 illustrates this process. During a major rainstorm on 17 August 2006, most of the precipitation from multiple air-mass thunderstorm cells occurred over relatively localized areas in the upper and lower portions of the USDA WGEW. As overland flow occurred and became concentrated in the ephemeral tributary network, streamflow dramatically diminished as the runoff hydrograph traveled downstream through the channel network. However, a substantial amount of runoff from this storm traversed the ephemeral Walnut Gulch tributary and reached the mainstem of the San Pedro River, augmenting the flow as measured at the USGS Tombstone stream gage. Runoff in Walnut Gulch (149 km^2 drainage area) and many arid and semiarid streams is characterized by short duration, highly episodic flows. The longitudinal extent of the effects of these flows on downstream waters is a function of the flow magnitude, its duration, the depth, conductivity and antecedent moisture conditions of the ephemeral channel substrate that the runoff flows across, and the depth to ground water. For example, in 2006 there were 23 runoff flows measured at Walnut Gulch flume 1 (the outlet of the WGEW). The average volume, peak runoff rate, and duration of these runoff events was 31,460 m^3, 7.23 m^3/s, and 239 minutes, respectively. Four (4) of the 23 runoff events recorded at Flume 1 were estimated to have measureable impacts on flows measured at the downstream USGS Tombstone stream gage (4510 km^2) on the San Pedro River (including the event shown in Figure B-10).

Evidence is strong that transmission losses in ephemeral tributary streams recharge alluvial and regional aquifers (Goodrich et al., 1997; Callegary et al., 2007). Using three fundamental approaches to estimate ephemeral channel recharge (1—closing the water balance for the channel reach, 2—measuring changes in ground-water volume directly [well levels] or indirectly [microgravity], and 3—using geochemical tracers), Goodrich et al. (2004) estimated that during the relatively wet 1999 and 2000 monsoon seasons, regional aquifer ground-water recharge from ephemeral streams ranged from approximately 15 to 40% of total average annual recharge as estimated from a calibrated regional ground-water model (Pool and Dickinson, 2007). During the dry monsoon seasons of 2001 and 2002, limited ephemeral runoff and stream channel infiltration occurred, but no discernible deep aquifer recharge was detected.

The influence of stormflows from ephemeral tributary streams extends to the San Pedro River mainstem. As stormflow is exported from the tributaries to the mainstem and water moves downstream, transmission losses and bank recharge occur within the mainstem river itself and supply water to the alluvial aquifer of the mainstem (Kennedy and Gungle, 2010). Using geochemical tracers (chloride, sulfate, and stable isotopes of hydrogen and oxygen in water), Baillie et al. (2007) found two main sources of water in the alluvial aquifer for the upper San Pedro River: (1) regional ground water

Figure B-10. Storm rainfall and downstream hydrographs with decreasing runoff volume and peak rate due to channel transmission losses as measured by in the USDA-ARS Walnut Gulch Experimental Watershed (WGEW) and the impact of this storm runoff on the San Pedro River in SE Arizona. Inset photos show a typical air-mass thunderstorm and the front of surface flow progressing down an ephemeral channel. Photo of ephemeral stream from Levick et al. (2008).



recharged along the Huachuca Mountains (mountain block, mountain front) to the west, and (2) local recharge from monsoon floodwaters. Alluvial ground-water composition varied between gaining and losing reaches. Locally recharged floodwater comprised 60 to 85% of the alluvial ground water in losing reaches but only 10 to 40% in gaining reaches. Baseflow also contained a significant component of monsoon floodwater throughout the year, from 80% in upstream reaches to 55% after passing through several gaining reaches.

Ephemeral tributary stormflows are also sources of sediment and alluvium for the main San Pedro River. Only the largest, less frequent events can flush sediment completely through ephemeral tributaries (Lane et al., 1997). For example, a reach-scale study in the WGEW estimated sand transport distances of only 401 and 734 m in nine floods over two consecutive years (Powell et al., 2007). In another study, Lekach et al. (1992) found that more than 90% of the bedload yield originated from the mid-watershed channels during larger runoff events from an arid watershed in Israel. Ephemeral tributary stormflows and their associated sediment loads influence the character of river floodplains and alluvial aquifers (Nanson and Croke, 1992; Shaw and Cooper, 2008).

Extensive riparian plant communities along the mainstem San Pedro River depend on the availability of water in the alluvial aquifer along the river, including water derived from ephemeral stream stormflows (Stromberg et al., 2005; Baillie et al., 2007). These riparian areas, in turn, strongly influence river attributes through stream shading, channel stabilization, nutrient cycling, inputs of invertebrates and other organisms, and inputs of detritus, wood, and other materials (Gregory et al., 1991; National Research Council, 2002; Naiman et al., 2005).

Ephemeral tributary stormflow inputs heavily influence the nutrient and biogeochemical status of the San Pedro River. Brooks and Lemon (2007) performed synoptic sampling on a 95-km reach of the San Pedro River to identify the effects of regional hydrology and land use on dissolved carbon and nitrogen concentrations. They found that, during the summer monsoon season, baseflow increased 5- to 10-fold, and dissolved organic matter and inorganic nitrogen increased 2- to 10-fold. The fluorescence index of water samples indicated a large input of terrestrial solutes with the onset of monsoon runoff inflows, and values of both chloride and oxygen isotope tracers indicated that stream water and alluvial ground water were well mixed along the entire 95-km reach. Meixner et al. (2007) used chloride tracer samples and mixing analyses to examine sources of San Pedro River water during six summer floods in 2001 (wet year) and 2002 (dry year). Results of mixing models indicated that both a ground water-soil water end-member and a precipitation end-member (indicative of overland flow) contributed to the floods. The highest percentage of ground water-soil water in the flood flow (46%) occurred during an early 2001 flood and the lowest during large monsoonal floods of 2002. They noted that ground water probably made lower contributions than soil water to streamflow, because high river stage during flood events created hydraulic gradients from the river to alluvial ground water in the riparian area (water moved from the river to alluvial ground water via bank storage, Figure 2-13B). During the first floods of each year, nitrate and dissolved organic carbon increased dramatically in the river, whereas dissolved organic nitrogen did not exhibit increases in 2001 but did in 2002. During floods, nitrate-nitrogen (NO_3-N) concentrations in river water were 0.2–0.5 mg NO_3-N L^{-1} higher in 2002 than during 2001. This result was consistent with higher observed nitrate-nitrogen concentrations in soil water of the riparian zone (alluvial aquifer) in 2002 than in 2001.

In summary, ephemeral tributary streams have strong physical and chemical connections to the San Pedro River. The river ecosystem, including its abiotic and biotic components, depends on the influences exerted by the ephemeral tributary streams on the river environment.

B.5.5 Other Southwestern Rivers

B.5.5.1 Physical Connections

Hydrologic behavior and river-system connectivity similar to the San Pedro River have been observed in other southwestern rivers, increasing confidence that the observations made within the San Pedro are applicable to other southwestern river systems.

Plummer et al. (2004) found that the Rio Grande in New Mexico has two primary sources of regional ground water: (1) recharge from mountains and (2) seepage from the Rio Grande and Rio Puerco, and from Abo and Tijera Arroyos (arroyos are ephemeral streams). Vivoni et al. (2006) observed ground-water recharge processes in the Rio Puerco, a tributary river to the Rio Grande, and in the Rio Grande itself. They note that a summer monsoonal rainstorm produced a flood event on the Rio Puerco that, in turn, generated a pulse of floodwaters along a losing reach of the Rio Grande (Figure 3-2). Forty-nine percent (49%) of flood volume was lost to the shallow alluvial aquifer of the Rio Grande. Loss of river water to the alluvial aquifer was observed to decrease with distance down the river reach.

Another important drainage basin type in the western and southwestern United States is endorheic or closed drainage basins draining to lakes and playas having no outlet to the ocean. The largest of these western basins is the Great Basin, which is approximately 490,000 km^2 (~5% of the area of the United States) and covers most of Nevada and parts of Oregon, Utah, and California (Atwood, 1994). Closed basins can contain ephemeral, intermittent, and perennial stream reaches. Although endorheic streams do not drain into oceans, many support downstream waters and habitat and numerous large perennial lakes such as Lake Tahoe in California and Nevada and the Great Salt Lake in Utah.

The Pecos River basin in eastern New Mexico and western Texas comprises part of southern Rocky Mountains in the north and grasslands, irrigated farmlands, deserts, and deep canyons in the southern lower reaches of the river (Yuan and Miyamoto, 2008). Precipitation occurs as snow in the mountains and summer monsoonal rainfall in the lower river valley. Based on hydrogen and oxygen isotope composition of river water, Yuan and Miyamoto (2008) separated the river basin into three subbasins: (1) the upper basin, (2) the middle basin, and (3) the lower basin. Snowmelt dominates the mountainous upper basin. The river in the topographically gentle middle basin had mixed sources of water. Thirty-three percent (33%) of river water was lost through evaporation occurring in the streams channels and irrigated fields of the middle basin. Similar to the San Pedro River, up to 85% of streamflow in the lower basin was estimated to derive from local freshwater sources, mainly monsoonal rainfall. This finding is consistent with significant contributions of flow from ephemeral tributary streams.

Shaw and Cooper (2008) studied the 14 ephemeral stream reaches in the Little Colorado River Basin in northeastern Arizona. As derived from the USGS National Hydrography Dataset, this basin contains a lower percentage of ephemeral and intermittent stream reaches (70%) as compared to the ~93% of such reaches in the Upper San Pedro. Shaw and Cooper (2008) related watershed characteristics of the Little Colorado to downstream reaches and the riparian plant communities of those reaches. They found that, as the watershed area draining to the studied reaches increased, the overall basin channel slope deceased, which resulted in less erosive capacity due to channel transmission losses and a decrease in the variability of alluvial ground water in these channels. This resulted in "decreased disturbance potential and increased moisture availability in the downstream direction," and these reaches had a greater abundance of obligate riparian vegetation. Shaw and Cooper (2008) went on to develop a stream classification system that related the functional linkages between contributing upstream watersheds, stream reaches, and riparian plant ecology. Type I stream reaches have relatively small drainage areas (less than 10 km^2), which have the greatest disturbance potential with in-channel and near-channel plants resembling those of surrounding upland species. Between 10 and 100 km^2, Type II streams exhibit "more moderate shear stresses and more persistent alluvial groundwater" with riparian vegetation that is a mixture of upland and riparian species. Having larger areas (greater than 100 km^2), Type III reaches are "controlled mainly by upstream hydro-climatic conditions" with wetland tree and shrub communities. Shaw and Cooper (2008) concluded that the connection of streamflow and ground-water regimes to riparian vegetation in the larger Type III watersheds, draining greater than 100 km^2, to upstream reaches far removed from larger regional floodplain rivers "… were driven by climatic patterns from distant portions of the upper watershed and were relatively insensitive to local rainfall." This finding reinforces the fact that stream-reach characteristics are influenced and connected, often episodically, to distant portions of the contributing watershed.

B.5.5.2 Human Alterations

Anthropogenic uses and activities on arid and semiarid landscapes can have significant effects—both good and bad—on downstream waters and overall health of watersheds. Human alteration to arid and semiarid watersheds occurs in many forms and includes livestock grazing, land clearing, mining, timber harvesting, ground-water withdrawal, streamflow diversion for water supply and irrigation, channelization, urbanization, agriculture, roads and road construction, off-road vehicle use, camping, hiking, and vegetation conversion (Levick et al., 2008). Climate change likely will have increasing influence on streams and their connectivity in the Southwest. Most climate models predict important changes for the southwestern United States, including increased warming and drying, intensification of droughts, and increased variability of precipitation (Seager et al., 2007). These changes will result in less runoff, reduced snowpack, and changes in streamflow patterns. Reduced snowpack will result in shorter periods of longitudinal stream connectivity in intermittent streams, as snowmelt will occur more rapidly in a warmer climate.

Streamflow augmentation can occur in human-dominated watersheds in the form of treated municipal and industrial wastewater effluent discharges. Streams that would dry without these discharges are effluent-dependent streams, whereas those that receive most, but not all, of their flow from effluent are effluent-dominated streams (Brooks et al., 2006). Streams draining human-dominated areas also can acquire baseflow from ground water recharged by over-irrigation and leaky infrastructure (Lerner, 1986; Roach et al., 2008; Townsend-Small et al., 2013).

Riparian areas near mainly perennial streams, but also in many cases intermittent streams, historically have been attractive for human development, leading to their alteration on a scale similar to that of wetlands degradation nationally (National Research Council, 2002). This situation is especially true in arid and semiarid regions because riparian areas typically are indicative of water availability either as surface water or as shallow ground water. Riparian areas in arid and semiarid regions are also greener and cooler than most upland areas. Riparian areas are more sensitive to development impacts than wetter areas, however, because of their limited geographical extent, drier hydrologic characteristics, and fragile nature (e.g., erodible soils). Historically, riparian habitats represented about 1% of the landscape in the West, and within the past 100 years, an estimated 95% of this habitat has been lost due to a wide variety of land-use practices such as river channelization, unmanaged livestock grazing, agricultural clearing, water impoundments, and urbanization. The following subsections present some of the types of human-caused impacts on ephemeral and intermittent streams and their associated riparian areas.

B.5.5.2.1 Land development

Land development includes urban, suburban, and exurban development but is referred to here collectively as urban development. Before the 2008 recession, the Southwest was one of the fastest growing regions of the United States, having an increase in population of approximately 1,500% over the previous 90 years. In contrast, the population of the country as a whole grew by just 225% over that time. Arizona and Nevada have grown the most, with population increases of 2,880% and 2,840%, respectively. Typical urban development significantly changes the hydrologic characteristics of a watershed by covering uplands with impervious surfaces, and removal, channelization, or armoring of headwater streams (Box 3-1; Kennedy et al., 2013). Alteration of the natural stream network disrupts natural flow patterns and sediment transport and storage, resulting in downstream flooding and changes to the clarity and quality of the downstream flows and receiving waters. These effects can damage downstream water supplies and habitat. The aerial photograph presented in Figure B-11 shows a network of ephemeral streams that flows through a small community southeast of Tucson, AZ, to Cienega Creek, a protected perennial stream.

Figure B-11. Aerial photograph showing ephemeral tributaries to Cienega Creek, a perennial stream, flowing through the small community of Vail, southeast of Tucson, AZ. Photograph: Lainie Levick/Aerial flight courtesy of Lighthawk, www.lighthawk.org.

The impact of urbanization increases as the percentage of impermeable surface increases. Various studies have shown that semiarid stream systems become irreparably impaired once the impervious surfaces within the watershed exceed about 10% and experience dramatic morphological changes once those surfaces exceed about 20% (Schueler, 1994; Miltner et al., 2004).

As the amount of impervious surface increases, runoff increases and infiltration decreases (Kennedy et al., 2013), starting a chain of events that includes flooding, erosion, stream-channel alteration, increases in human-caused pollutants, and ecological damage. Floods become more severe and more frequent, and peak flows and runoff volumes will be many times greater than in natural basins. The greater volume and intensity of flooding causes increased erosion and sediment transport downstream. To accommodate the increased flow and sediment load, streams in urbanized areas tend to become deeper and straighter over time. The resulting bank erosion can destroy established streamside habitat and tree cover, leading to higher temperatures, sedimentation, and disruption of wildlife corridors.

Storm sewers and lined drainages increase the rate of water delivery to the downstream channel network. Erosion and sedimentation increases during construction and road building for new urban areas. Improperly constructed and maintained roads, especially unpaved roads, can alter hillslope drainage, and change baseflow and precipitation-runoff relationships, causing erosion and sedimentation in streams (USDA, 2002). The primary geomorphic consequence of these hydrologic changes is the erosional entrenchment of nearby channels and associated transportation of the excavated sediment downstream, causing a significant increase in sediment load. Sediment is of particular concern in arid and semiarid regions because many other pollutants tend to adhere to eroded soil particles. Additional pollutants from urban runoff can include pathogens, nutrients, toxic contaminants, sediment, and debris. Consequently, urban areas require stormwater management plans both during and after construction to control runoff and offsite pollution.

Streams are channelized in urbanizing areas to protect private property and control streambank erosion. Channelization typically straightens and steepens the stream, however, resulting in increased flow velocity and sediment movement. These changes transfer flooding and bank erosion downstream of the protected area. In the channelized reaches, the greatly reduced out-of-bank flow disrupts water, sediment, organic matter, and nutrient enrichment of the flood plain (National Research Council, 2002). In addition, removal of vegetation as part of the channelization process degrades wildlife habitat.

Habitat fragmentation is a common consequence of urbanization (Hilty et al., 2006). New developments can alter large areas of land, removing natural drainage systems and wildlife habitat, and replacing them with houses and roads. Altering, bisecting, or channelizing streams effectively can eliminate the main biological functions of the stream channel by disrupting vegetation communities and hydrologic function. Habitat fragmentation reduces wildlife diversity and abundance and might cause sensitive species to disappear (England and Laudenslayer, 1995).

B.5.5.2.2 Land use

In addition to urbanization, agriculture (livestock and crops) and mining, including sand and gravel operations, are major land uses in the desert Southwest. Livestock grazing is one of the more common uses of rural land in the Southwest. Late 1800s estimates of cattle numbers in Arizona and New Mexico exceeded 1.5 million and 2 million, respectively. During this period, the region experienced both significant droughts and floods. During drought, the resulting desiccation of the uplands drove cattle to the riparian areas, which were heavily damaged as a result. When the rains returned to the denuded landscape, erosive processes were greatly enhanced. The overgrazing that occurred during this time is one of the factors attributed to a relatively widespread period of channel downcutting, forming deep arroyos and lowering ground-water levels (Schumm and Hadley, 1957; Hastings, 1959; Graf, 1988).

In modern grazing-land management, livestock are provided with watering sources away from streams when possible, but frequently they must depend on the streams for water. Livestock management efforts attempt to avoid overuse of an area, but because water is scarce in arid environments, cattle and wildlife tend to linger near water sources. Where not properly managed, cattle can remain too long in a riparian area and trample streambanks, eat the riparian vegetation to the ground, contaminate the water with wastes, and compact the soil (Levick et al., 2008). Several literature sources have stressed that the cumulative impacts of unmanaged livestock in southwestern riparian ecosystems for the past several hundred years probably have been the single most important factor in riparian ecosystem degradation (Wagner, 1978; Ohmart, 1995).

Mining is another activity that historically has played a large role in the economy and land use in the Southwest. Some of the largest copper and gold mines in the world are found in this region, and some cover many thousands of hectares. Mining can cause major impacts on riparian areas along tributaries and downstream waters by altering the local hydrology. Mining not only dewaters the area, it removes vegetation and soil and changes the topography, severely affecting the watershed. Instream and floodplain gravel mining can alter channel dimensions, increase sediment yield, and increase fine sediment loading and deposition that can reduce infiltration into ephemeral channels (Bull and Scott, 1974).

Cultivated agriculture has had a long history in the southwestern deserts, and areas such as the Central Valley in California provide much of the country's food supply. Most crops, however, must be irrigated due to the low annual rainfall. Impacts to local hydrology from agricultural activities include (Levick et al., 2008):

- Increased salinity caused by clearing of native vegetation that raises the ground-water reservoir;
- Reduced flows from ground-water pumping or stream diversions for irrigation;
- Increased nutrients and turbidity from the use of fertilizers that run off into the streams across the land surface or through the soil, causing excessive algal growth; and
- Fish, aquatic invertebrate, and bird kills from pesticides that run off into the streams or leach into the ground water.

Due to the abundant solar resources in the arid and semiarid Southwest, numerous, large-scale solar energy projects are envisioned or already under development. O'Connor et al. (2014) note that development of solar energy zones will significantly affect ephemeral channel systems; the authors have developed a scoring system to conduct ephemeral stream assessments using publicly available geospatial data and high-resolution aerial imagery.

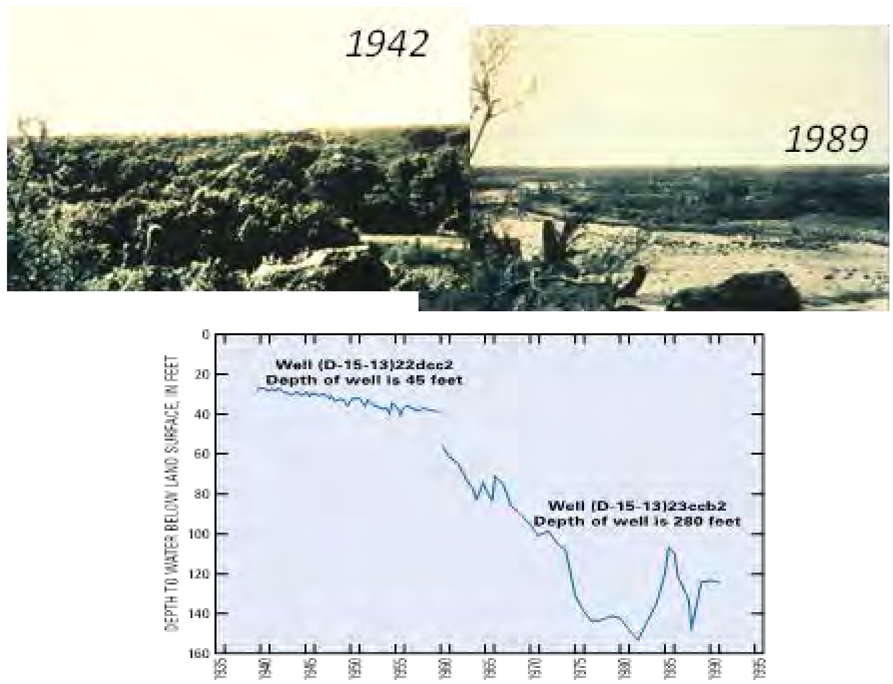
B.5.5.2.3 Water resources impacts

The Southwest has experienced rapid growth over the past several decades. This growth can be sustained only with reliable water supplies. Lack of surface-water flows has placed increased reliance on ground water for human and agricultural uses. The percentage of population dependent on ground water for domestic water needs in New Mexico, Arizona, and California is 90%, 60%, and 45% respectively (Anderson and Woosley, 2005). When ground-water pumping is sufficiently large or prolonged, it can result in lower water-table levels in regional and alluvial aquifers. If these aquifers are a primary source of water for sustaining surface-water flow in perennial or intermittent streams and if the drop in aquifer water levels is large enough, the pumping can effectively dewater these stream reaches, severing longitudinal and vertical connectivity (Winter et al., 1998; Scanlon et al., 2012). The perennial and intermittent streams effectively become ephemeral streams, and the habitat supported by reliable surface flow or shallow ground water is lost (Stromberg et al., 1996).

The impact of aquifer water-level declines is illustrated in Figure B-12 with repeat photography of the Santa Cruz River south of Tucson from 1942 and 1989 showing changes in riparian vegetation. Tucson's population in 1940 was roughly 36,000 and increased to approximately 405,000 by 1990. Until the Central Arizona Project brought Colorado River water to Tucson in the early 1990s, Tucson's domestic water supply was solely provided by ground water. As ground-water pumping increased to supply the growing population, the aquifer water level dropped by more than 25 meters and the riparian habitat was completely altered, as all phreatophytic vegetation died out. The growing population of Tucson also resulted in proportional increases in discharge of treated effluent. Portions of the Santa Cruz River downstream of the reach photographed in Figure B-12 near treatment plant outfalls are now effluent-dependent perennial stream reaches. Depending on the level of treatment, effluent can have various effects on the stream ecosystem (Brooks et al., 2006). Without careful water management and reuse (Bischel et al., 2013), the benefits of baseflow augmentation can be overshadowed by potential risks, such as increased contaminant and pathogen exposures (Jackson and Pringle, 2010).

Dams and retention or detention basins frequently are used to store water or as flood-control devices in the Southwest. They disrupt natural surface flow and sediment transport, interfere with natural geomorphic processes, alter water temperatures, and fragment the natural stream systems both upstream and downstream of the structure (Williams and Wolman, 1984). Upstream locations can experience flooding, whereas downstream locations can be dewatered and become starved of sediment (Sections 2.4.4 and 3.3.2).

Figure B-12. Change in riparian vegetation along the Santa Cruz River, Tucson, AZ, as the result of water-level declines in the regional aquifer. Photographs of the Santa Cruz River looking south from Tucson, AZ, provided by Robert H. Webb, U.S. Geological Survey Anderson and Woosley (2005).



B.5.5.3 Biological Connections

Much of the material in this section, as in Section B.5.5.2, is derived from the material presented in Levick et al. (2008). As noted in Chapter 3, ephemeral and intermittent streams perform many of the same functions in a watershed as perennial streams. In particular, in arid and semiarid regions, riparian areas, including those near ephemeral and intermittent streams, support the vast majority of wildlife species, are the predominant sites of woody vegetation including trees, and surround what are often the only available surface-water sources, even if they are available only for limited periods. Desert washes are easily recognizable by their dense corridors of vegetation that strongly contrast with the more sparsely vegetated uplands (Figure B-13). In contrast to the nearby uplands, these stream corridors and their associated vegetation communities provide structural elements of food, cover, nesting, and breeding habitat, and movement/migration corridors for organisms. These corridor vegetation communities moderate soil and air temperatures, stabilize channel banks, provide seed banking and trap silt and fine sediment that favor the establishment of diverse floral and faunal species, and dissipate stream energy (Levick et al., 2008). The resulting microclimates in and around ephemeral and intermittent stream vegetation corridors are used extensively by fauna. In arid climates, such conditions often benefit less mobile species that cannot avoid the harsh desert environment by moving to microclimates that are more favorable. These stream corridors provide primary habitat, predator protection, breeding and nesting sites, shade, travel corridors, migration stopover sites, and food sources.

Figure B-13. Aerial photograph showing dense corridor of vegetation lining ephemeral washes in southeastern Arizona. Image accessed from Google Earth from May 2005 imagery date.

Both passive and active biological connections exist in the intermittent and ephemeral streams network. Passive connections involve the transport of organisms and organic matter driven by water flow; these connections thus depend on hydrologic connectivity. Active connections do not depend on flowing water; instead, dispersal of organisms and organic matter occurs throughout the stream network through walking, flying, or hitchhiking on mobile organisms. All these organism-mediated connections form the basis of biological connectivity between headwater streams and downstream waters. Movement can be both longitudinal along the stream network and lateral, and can occur over the life cycles of numerous organisms (Schlosser, 1991; Fausch et al., 2002).

Meyer et al. (2007) noted the importance of headwater streams, including ephemeral and intermittent streams, as vital parts of the biological integrity of U.S. waterways. Ephemeral and intermittent stream channels are bordered by a zone of continuous or near-continuous vegetation, and thus they provide important wildlife movement corridors as they afford both cover and food. Summer monsoons in the Southwest coincide with periods when herptofauna such as snakes and amphibians are most active; the episodic flows provide a generally continuous aquatic corridor for their dispersal. The translocation and dispersal of species enables genetic interchange between subpopulations that are often isolated for most of the year. In addition, recolonization of sites can occur when subpopulations are lost due to drought or disturbance. Degradation of these habitats and loss of their connections to larger streams can have negative consequences for the diversity of downstream and riparian ecosystems and for the biological integrity of the entire river network. Nearly 81% of all streams are ephemeral or intermittent in the six Southwestern states (USGS, 2006). From a strictly numerical viewpoint, therefore, degradation of these ephemeral streams diminishes ecosystem functions in most southwestern watersheds.

B.5.5.3.1 Physical features important to biological connectivity and integrity

Ephemeral and intermittent riverbanks in the arid Southwest provide shelter for numerous species of wildlife, including reptiles, amphibians, birds, mammals, and invertebrates. These shelters typically are independent of whether the streams contain water year-round. Shelters are created through the action of water, wind, and gravity. Ephemeral dry-wash embankments notoriously are full of small caves and crevices critical in the life of desert animals such as the desert tortoise (*Gopherus agassizii*) (Van Devender, 2002). The alluvium in ephemeral and intermittent streams is often looser than the soils or colluvium of surrounding uplands. These conditions provide enhanced habitat by specialized sand-burrowing species of wildlife. High-value shelters also are created when woody debris is swept in from the watershed and collects in the floodplain and stream channel. In cases of deep ephemeral stream incision, cooler canyon-type environments might be created in which moisture loss is retarded.

B.5.5.3.2 Vegetation habitat features important to biological connectivity and integrity

Large ephemeral washes with shallow ground-water zones often are colonized with a variety of phreatophytic trees, such as Fremont cottonwood (*Populus fremontii*), Arizona sycamore (*Platanus wrightii*), and Arizona ash (*Fraxinus velutina*). These washes also include distinctive shrubs, such as willow (*Salix* spp.), seepwillow (*Baccharis* spp.), burrobrush (*Ambrosia monogyra*), and saltcedar (*Tamarix ramosissima*), and dense grass stands of sacaton (*Sporobolus* spp.). Those washes that lack a shallow ground-water system or water augmentation by effluent discharge nonetheless give rise to a distinctive vegetative habitat from the surrounding uplands. These environments often are referred to as xeroriparian habitat.

The floral species in these habitats is moderated by the frequency and magnitude of runoff events. Common tree species in xeroriparian habitat include subtropical legumes such as mesquite (*Prosopis* spp.), catclaw acacia (*Acacia greggii*), ironwood (*Olneya tesota*), and blue palo verde (*Cercidium floridum*). Mesquite has been identified as the key provider of food for numerous migrating birds (Van Riper and Cole, 2004). Netleaf hackberry (*Celtis reticulatata*) and Arizona sycamore (*Platanus wrightii*) have been identified as providing exceptional cover for nesting birds on intermittent streams (Powell and Steidl, 2002).

B.5.5.3.3 Hydrologic habitat features important to biological connectivity and integrity

Stanley et al. (1997) provide an excellent overview of the expansion and contraction of flowing waters within southwestern streams in response to variable precipitation events. This phenomenon commonly results in reaches of streams or rivers that have flow or residual pools with water surrounded by reaches without water. This phenomenon is common in dryland rivers across the globe (Arthington et al., 2005; Bunn et al., 2006). The isolated pools often serve as refuges for fish to survive in intermittent streams during dry periods (Labbe and Fausch, 2000).

Episodic stream flow might be the most visually prominent hydrologic aspect of a stream but is seldom the only hydrologic habitat feature of biological significance. An arid stream wash with a shallow ground-water system also might have moist banks fed by capillary flow that provide sites for turtle or insect reproduction. Distinct invertebrate fauna can inhabit the hyporheic (subsurface) zone of flow beneath a dry streambed. Episodic flooding, human excavations, and channel scour can produce in-channel or off-channel pools where amphibians breed. Within-channel or floodplain springs can provide distinct chemical compositions or thermal refuges from the main ephemeral or intermittent stream.

The natural episodic and intermittent flow regime in the arid Southwest is a competitive factor of native species over exotics adapted to lake and pond conditions (Minckley and Meffre, 1987; Poff et al., 1997). Louw and Seely (1982) and Williams (2005) concluded most desert species have developed adaptations to the water-limited conditions of these regions that enable them to survive under harsh environmental conditions. Fauna using ephemeral or intermittent waters include fish, mammals, amphibians, reptiles, birds, and invertebrates. The variability of climate and flow regime, which influences species abundance and diversity, however, makes evaluation difficult unless surveys are conducted over years in different community types (Boulton and Lake, 1992).

B.5.5.3.4 Fish and aquatic insects

As discussed in the previous section, the interplay between stormflow from ephemeral tributary streams, water from alluvial aquifers, and water from regional ground water control the distribution and timing of flowing water in southwestern rivers. Native fish species of southwestern streams and rivers are adapted to these dynamic environments (John, 1964; Meffe, 1984). Rinne and Miller (2006) compared fish assemblage data in river networks for two southwestern rivers, the Gila River (New Mexico and Arizona) and the Verde River (Arizona) over 7 to 12 years. They included river hydrology and geomorphology data in their analysis and found that variable streamflows and higher flow volumes favor native fish species over nonnatives. They also noted that the presence of unconstrained alluvial valley river reaches with shallow pools favored native fish. Furthermore, when humans alter the hydrologic dynamics of ephemeral and intermittent tributaries such that flows connecting them to the river network are more frequent or more consistent, nonnative fish can invade (Turner and List, 2007). Recent nonnative invasion and a corresponding decline in native fish species diversity were observed in the lower reaches of Aravaipa Creek, a tributary of the San Pedro River, which historically was only rarely connected to the mainstem (Eby et al., 2003).

Lytle et al. (2008) found a similar adaptation strategy in populations of an aquatic insect (*Abedus herberti*) occupying sites along a natural gradient of disturbance predictability. In their study, predictability was defined as the ability of a signal or cue (rainfall) to cause a disturbance. In this case, the disturbance was a flash flood. Using signal detection theory, they found that for 13 of 15 insect populations, the observed insect response times "were an optimal compromise between the competing risks of abandoning versus remaining in the stream, mediated by the rainfall-flood correlation of the local environment." They concluded that these aquatic insect populations could evolve in their responses to changes in the flow disturbance regime, providing evidence that these aquatic populations can adapt to "among-stream differences in flow regime."

B.5.6 Southwestern Intermittent and Ephemeral Streams: Synthesis and Implications

Rivers of the arid and semiarid Southwest are products of a highly variable and dynamic environment. Ephemeral and intermittent streams and their tributaries in the American Southwest provide a wide range of functions that are critical to the health and stability of arid and semiarid watersheds and ecosystems. Most importantly, they provide hydrologic connectivity within a basin, linking ephemeral, intermittent, and perennial stream segments. This linkage and the corridor of connectivity facilitates the movement of water, sediment, nutrients, debris, fish, wildlife, and plant propagules throughout the watershed. The relatively more vegetated streams corridors connected to downstream perennial reaches provide wildlife habitat and more humid environment than do the surrounding uplands. During ephemeral and intermittent streamflow, energy dissipates as part of natural fluvial adjustment, and sediment, organic matter, and debris are transported. The variability of the hydrologic regime in these streams is the key determinant of spatial and temporal distribution of plant community structure and the types of plants and wildlife present. Some of the major ways in which ephemeral streams are connected with and influence rivers are as follows:

- Flows from ephemeral streams are a major driver of the dynamic hydrology of southwestern rivers. Ephemeral tributary streamflows are especially important drivers of downstream floods during monsoon seasons.
- Fishes and invertebrates native to mainstem rivers are adapted to the variable flow regimes that ephemeral tributary streams strongly influence. Ephemeral flows prevent or mitigate invasion by introduced species.
- Ephemeral tributary streams supply water to mainstem river alluvial aquifers; these alluvial aquifers help sustain river baseflows.
- Ephemeral streams export sediment to rivers during major hydrologic events; the sediment contributes to materials that comprise alluvial aquifers and shape the fluvial geomorphology of rivers.
- Ephemeral tributaries export nutrients to mainstream rivers during hydrologic flow events; nutrients occur in many forms and contribute to river productivity.
- Ephemeral and intermittent streams and their associated vegetation communities provide structural elements of food, cover, nesting and breeding habitat, and movement/migration corridors for organisms.
- Water, sediment, and nutrients exported to the river from ephemeral tributaries support riparian communities of mainstem rivers; the riparian communities profoundly influence river attributes through shading and allochthonous inputs of organic matter, detritus, wood, and invertebrates to the river.

- Regional ground-water aquifers are in part recharged through infiltration of water to the streambed of ephemeral stream channels during wet years; the regional aquifer supplies a varying but critical portion of baseflow for perennial river reaches.

B.6 Case Study: Vernal Pools

B.6.1 Abstract

Vernal pools are shallow, seasonal wetlands that accumulate water during colder, wetter months and gradually dry down during warmer, dryer months. Despite differences in geology, climate, and biological communities, some common findings about the hydrologic connectivity of vernal pools in different regions include evidence for temporary or permanent outlets, frequent filling and spilling of higher pools into lower elevation swales and stream channels, and conditions supporting subsurface flows through pools without perched aquifers to nearby streams. Insects and amphibians that can live in streams or permanent pools opportunistically use glaciated vernal pools as alternative breeding habitat, refuge from predators or environmental stressors, hunting or foraging habitat, or stepping-stone corridors for dispersal and migration. Nonglaciated vernal pools in western states are reservoirs of biodiversity and can be connected genetically to other locations and aquatic habitats through wind- and animal-mediated dispersal.

B.6.2 Introduction

The term “vernal pool” is broadly used to describe shallow, fishless pools situated on bedrock or low-permeability soils that lack continuous surface-water connection to permanent water bodies but have a seasonal period of inundation on which aquatic species depend for completion of their life cycles (Zedler, 2003). This case study reviews evidence for physical and biological relationships between vernal pools and downstream waters in the western United States (western vernal pools) and glaciated areas of northeastern and midwestern states (northern vernal pools), where vernal pools are particularly abundant (Zedler, 2003).

B.6.2.1 Geography and Geology

B.6.2.1.1 Western vernal pools

Zedler (1987) used the term vernal pool to describe basin/swale systems in California’s Mediterranean climate that flood in winter, host diverse communities of aquatic plants and animals in early spring, transition to terrestrial ecosystems in late spring, and desiccate during hot, dry summer months. Western vernal pools are seasonal wetlands associated with topographic depressions; soils with poor drainage; mild, wet winters; and hot, dry summers in western North America from southeastern Oregon to northern Baja California, Mexico (Bauder and McMillan, 1998). Locally, wetlands that fit this definition might be known by other names, such as the upland playas in Oregon (Clausnitzer and Huddleston, 2002).

Historically, vernal pools covered 518 km^2, or 5−6% of the total land surface in southern California and northern Baja, but losses in that area have been substantial (Bauder and McMillan, 1998). Pools occur on impermeable or slowly permeable soils or bedrock (Smith and Verrill, 1998) that limit percolation and thus produce surficial aquifers that perch above regional ground-water aquifers. Pool-forming soil layers in this region include clay-rich soils, silica-cemented hardpans (duripans), volcanic mudflows, or bedrock (Weitkamp et al., 1996; Hobson and Dahlgren, 1998; Smith and Verrill, 1998; Rains et al., 2006). Because their hydrology and ecology are so tightly coupled with the local and regional geologic processes that formed them, western vernal pools typically occur within "vernal pool landscapes" (Smith and Verrill, 1998), or complexes of pools in which swales connect pools to each other and to seasonal streams (Weitkamp et al., 1996; Rains et al., 2008).

B.6.2.1.2 Northern vernal pools

The geologic formations underlying northern vernal pool landscapes were formed by the movement of glaciers across the northeastern and north-central states approximately 12,000 years ago. Retreating glaciers scoured basins in rock ledges and mountaintops, or left behind large pieces of ice that later collapsed to form topographic depressions containing deposits of gravel, sand, or mud (Colburn, 2004). Although not all vernal pools in these areas were formed by glaciers, the soils, geology, and evolutionary history of plants and animals in northern vernal pools have been profoundly affected by glacial events. Like western vernal pools, northern vernal pools are significantly grouped or clustered (Brooks, 2005). Grant (2005) found that pools in Massachusetts are more likely to occur in more porous substrates (alluvial, fine grained, or sand/gravel soils) than glacial till or impermeable bedrock, increasing their hydrologic connection to shallow ground water.

Unlike western vernal pools, which typically occur in open grasslands, most northern vernal pools are detrital wetlands fully contained within forest ecosystems that depend on the pulse of organic matter from leaf fall that coincides with initial filling of temporary pools in these regions.

B.6.2.2 Temporal Dynamics

Zedler (1987) identified four distinct ecosystem phases in the annual hydrologic cycle of western vernal pools, which we have generalized here (with additional citations) to describe the temporal dynamics of northern vernal pools as well:

- Wetting or newly flooded phase: Rainwater, snow, runoff, or snowmelt infiltrate upper layers of permeable soil and, when topsoils are saturated, collect in pool basins formed by impervious rock, clay, or till layers (aquitards or aquicludes; Rains et al., 2008). In early spring, perennial plants sprout and stored seeds germinate in wet soils. Aquatic invertebrate communities develop from resting eggs and seed banks (Colburn, 2004).
- Aquatic phase: Soils are saturated and pools hold standing water, in many locations filled to capacity. In some western vernal pools, surface and subsurface flows from upland pools through swales feed downgradient pools, connecting pools at a site and extending the aquatic phase of

the pool complex (Weitkamp et al., 1996; Hanes and Stromberg, 1998). Pools are colonized by dispersing insects and breeding amphibians.

- Terrestrial phase: Evapotranspiration rates increase and pool water recedes, although soils remain saturated. In western pools, aquatic plants flower and seed. Aquatic animals disperse or become dormant. Terrestrial plant communities persist.
- Dry phase: Pools and soils dry to moisture levels similar to uplands, and many plants senesce or die. Summer rains produce no new ponding or plant growth.

In the western United States, vernal complexes saturate and begin to pool during winter rains, reach maximum depth by early spring, and lose all standing water by late spring (Zedler, 1987). The timing of filling and drying of northern vernal pools varies, depending on pool type. Colburn (2004) proposed five hydrologic classes for northern vernal pools, based on time of filling and average duration of flooding: (1) short-cycle, spring-filling pools that stay wet for 3–4 months; (2) long-cycle, spring-filling pools that stay wet for 5–8 months; (3) short-cycle, fall-filling pools that stay wet for 7–9 months; (4) long-cycle, fall-filling pools that stay wet for 9–11 months; and (5) semipermanent pools that stay wet for 36–120 months. Many northern vernal pools do not dry down completely, but retain areas of saturated sediment or standing water in part of the basin. Such pools are considered "incompletely dry," to differentiate them from pools that are "continuously flooded" or "dry."

B.6.2.3 Ecology

Vernal pool ecosystems support large breeding populations of amphibians, aquatic invertebrates, and aquatic or semiaquatic plants, including many rare or endemic taxa (King et al., 1996; Zedler, 2003; Colburn, 2004; Calhoun and DeMaynadier, 2007). The annual cycle of basin flooding and drying plays an important role in structuring biological communities in vernal pools. The wet phase prevents establishment of upland plant species in pool basins, while the dry phase limits colonization by aquatic and semiaquatic plant and animal species that occur in permanent wetlands, ponds, or streams (Keeley and Zedler, 1998; Bauder, 2000). Despite their cyclical nature, vernal pool habitats are species rich and highly productive, in part because they provide relatively predator-free breeding habitat for invertebrates and amphibians (Keeley and Zedler, 1998; Calhoun et al., 2003). Many resident species are locally adapted to the timing and duration of inundation, soil properties, and spatial distribution of vernal pools in a specific geographic subregion. Other species that are widespread across regions and aquatic habitat types (including streams or lakes) use inundated pools periodically for refuge, reproduction, or feeding (King et al., 1996; Williams, 1996; Colburn, 2004).

B.6.3 Evidence

B.6.3.1 Physical Connections

Vernal pools are primarily precipitation fed and typically lack permanent inflows from or outflows to streams or other water bodies. They can be connected temporarily, however, to permanent waters by surface or shallow subsurface flow (flow through) or ground-water exchange (recharge; Weitkamp et al., 1996; Brooks, 2005; Rains et al., 2008). Hydrologic connectivity is typically limited to flow through in vernal pools formed by perching layers; ground-water exchange can occur in vernal pool systems without perching layers (Brooks, 2005).

B.6.3.1.1 Western vernal pools

Rains et al. (2006; 2008) examined the hydrology and biogeochemistry of two vernal pool complexes in the northern end of California's Central Valley (Smith and Verrill, 1998). The 2006 study evaluates water balance and the relative importance of direct precipitation, evaporation, surface flow, and shallow subsurface flow in a hardpan vernal pool complex (Rains et al., 2006). The 2008 study contrasts the role of geology and soil type—specifically, clay-rich versus hardpan soils—in controlling vernal pool hydroperiod, hydrodynamics, and water chemistry (Rains et al., 2008). Clay-rich and hardpan complexes are common vernal pool types in California's Central Valley (Smith and Verrill, 1998). In both studies, study sites were pool complexes located in the upper portion of the watersheds. Within each complex, upland (feeder) pools were connected to lower (collector) pools by ephemeral swales, and the lowest pool was connected by swale to a seasonal stream.

Results showed that high and low pools were connected via surface flows 10−60% of the time; surface water flowed through swales connecting low-elevation pools to streams during 60% of the inundation period (Table B-1). Underlying geology and soil type influenced ponding rates and inundation periods: In water year 2003, pools in clay-rich soils accumulated water at the onset of rainfall and held water longer than pools in hardpan soils, which have higher soil infiltration rates (Table B-1; Rains et al., 2008). Horizontal subsurface flows reduced the number and volume of higher elevation surface flows into hardpan pools, relative to the clay-rich pools. Most water discharging from the swale to the seasonal stream at the hardpan site was perched ground water that had flowed around, rather than through, the pool basins. In both soil types, however, vernal pool basins, swales, and seasonal streams were shown to be part of a single surface-water and shallow ground-water system connected to the river network when precipitation exceeds storage capacity of the system (Rains et al., 2006; Rains et al., 2008). Pyke (2004) reported that a complex of 38 vernal pools north of Sacramento was filled to capacity in 10 of 11 years from November 1999 to June 2001. A direct precipitation-evaporation model for another hardpan complex near this Sacramento site showed that direct precipitation could fill pools beyond capacity in most years (Hanes and Stromberg, 1998). Pools located at the lower end of a complex (and thus more likely to be directly connected to streams) can receive surface water through stepping-stone spillage in addition to direct input from precipitation; thus, they can remain wetted longer than upper pools. For example, Bauder (2005) found that "collector" pools with no outlet held water longer than headwater pools with no inlet. Collectively, these findings suggest that filling and overflow of vernal pools are not rare phenomena. Filling and spilling also can occur in other vernal pool types because all vernal pools are underlain by aquitards (Rains et al., 2008).

B.6.3.1.2 Northern vernal pools

Northern vernal pools include both perched and ground water-connected aquifers (Brooks, 2004; Boone et al., 2006). As in western vernal pools, rainfall or snowmelt in excess of pool capacity is lost to surface

Table B-1. California vernal pool inundation and hydrologic connectivity. Summarized from Rains et al. (2008)				
Soil; hydrology	Inundation period (days/water year[a])	Flow-through paths (pool-pool and pool-stream)	Surface flows between high- and low-elevation pools[b]	Surface flows between lowest elevation pool and stream network[b]
Fine-grained, clay-rich soils; perched surface water	200−205	surface only	120 (60%)	120−123 (60%)
Coarse-grained, hardpan soils; perched surface water and ground water	150−154	surface and horizontal subsurface	15 (10%)	90−92 (60%)

[a]October 1 2002−September 30, 2003.
[b] Units = days/water year[a], % of inundation period.

runoff or subsurface flows into shallow, nearby ground water (Brooks, 2005). Studies of surface and subsurface inflows and outflows were not found in the literature. Brooks (2004) reports that precipitation and potential evapotranspiration alone could not account for large observed water losses in four vernal pools he studied for 10 years. These losses could have been due to inaccurate estimates of precipitation or evapotranspiration (both of which were significantly related to water depth) or to surface overflow and soil infiltration, which were not measured. In a separate study, Boone et al. (2006) used a classic water-budget model to predict vernal pool hydroperiods in Minnesota and found that, although precipitation and evapotranspiration were good predictors of pool inundation in most cases, errors in model estimates for a few pools suggested that surface outflows or infiltration might have been occurring at some sites.

Individually small, temporary storage of heavy rainfall and snowmelt in vernal pool systems (pools plus soils) can attenuate flooding, provide a reservoir for nearby vegetation during the spring growth period, and increase nutrient availability (Hobson and Dahlgren, 1998).

B.6.3.2 Biological Connections

Dispersal of vernal pool organisms can be active or passive and occurs at multiple scales: local scale (among nearby pools), neighborhood scale (among pools in a geographic cluster or complex), or regional (outside of the complex, to other ecosystem types; Compton et al., 2007). Examples of active regional dispersal include insect flight or juvenile dispersal by amphibians. Passive transport is of particular interest for regional-scale dispersal, as it enables plants and low-vagility animals such as microcrustaceans to move long distances. Examples of passive transport to and from unidirectional wetlands and pools include water-mediated dispersal of larvae (Hulsmans et al., 2007); transport of diapausing (dormant) eggs by waterbirds (Figuerola et al., 2005; Frisch et al., 2007) or flying insects (Van De Meutter et al., 2007); and wind-mediated dispersal of dormant eggs, larvae, and adult zooplankton from dry rock pools (Vanschoenwinkel et al., 2009).

Western vernal pools are highly productive ecosystems that have evolved in what Zedler (2003) describes as a "balance between isolation and connectedness." Pacific vernal pool landscapes are tightly coupled with variable climate, soils, and geologic formations in the western United States, producing diverse habitats for organisms with different life-history strategies (Bauder and McMillan, 1998). Seasonal wetlands in this region might have served as evolutionary refuges since Mesozoic times (King et al., 1996). As a result, present-day vernal pool communities have a large proportion of passively dispersing, endemic (i.e., restricted to small geographic area) species in genera that are widely distributed across continents and aquatic systems (King et al., 1996; Keeley and Zedler, 1998; Zedler, 2003). This apparent paradox is explained by the fact that individuals transported passively over long distances have colonized, and through time have become locally adapted to, different vernal pool landscapes, creating new endemic species from the rootstock of ancient lineages. As a result, Pacific vernal pools are now rich reservoirs of genetic and species diversity connected to other locations and aquatic habitats through continuing dispersal. The existence and connectivity of such reserves are especially important at a time when changing climatic conditions are likely to increase intermittency of stream flows and decrease duration of wetland inundations in other areas.

Western vernal pools also support generalist invertebrate communities, including crustaceans and insects that are widely distributed in permanent wetlands, ponds, lakes, and streams (Zedler, 1987; 2003). Invertebrates and zooplankton can be flushed from vernal pools into streams or other water bodies during periods of overflow, carried by animal vectors (including humans), or dispersed by wind. Wind-mediated dispersal can be of particular importance in seasonal wetlands: during the dry phase, dry soils containing large numbers of transportable seeds, resting eggs, cysts, diapausing larvae, and adults are picked up and blown away (Vanschoenwinkel et al., 2009). The maximum distance such propagules can travel is not known, but, from currently available literature, pool-pool or pool-stream transport is clearly possible, and the potential for long-distance transport also exists.

Food webs in northern vernal pools include highly fecund amphibians and insects that convert detrital organic matter inputs into biomass that subsidizes terrestrial and aquatic ecosystems in other parts of the watershed (Semlitsch and Bodie, 1998; Brooks, 2000; Gibbons et al., 2006). Northern vernal pools can provide alternative breeding habitat, refuge from predators or environmental stressors, hunting or foraging habitat, or stepping-stone corridors for dispersal and migration. For example, Gahl et al. (2009) reports that bullfrog (*Rana catesbeiana*) densities per unit wetland perimeter were greater in two small seasonal pools than in a larger, permanent breeding wetland. Regular use of seasonal pools by bullfrogs throughout this study offers compelling evidence for the role of seasonal pools as a component of their nonbreeding habitat. Spotted turtles (*Clemmys guttata*) used seasonal pools for foraging, basking, and mating at two sites in Massachusetts (Milam and Melvin, 2001). Many insects and amphibians found in streams, lakes, or riparian/floodplain wetlands are facultative users of vernal pool habitats (Table 4-2).

B.6.4 Vernal Pools: Synthesis and Implications

The key findings from this case study are as follows:

- In the aquatic phase, some western vernal pools are filled to capacity in most years, creating conditions under which water flows from pools into swales and stream channels.
- Documented evidence of surface flows connecting western vernal pool complexes to the river network via swales and seasonal streams is available in the literature.
- Indirect evidence indicates that surface and subsurface flows connect northern pools without perched aquifers to shallow ground water and thus to nearby streams.
- Many insects and amphibians that can live in streams or pools that are more permanent opportunistically use northern vernal pools as alternative breeding habitat, refuge from predators or environmental stressors, hunting or foraging habitat, or stepping-stone corridors for dispersal and migration.
- Nonglaciated vernal pools in western states have achieved a long-term "balance between isolation and connectedness" and have functioned as refuges for plant and animal diversity since the Mesozoic era. They are current reservoirs of biodiversity connected genetically to other locations and aquatic habitats through continuing dispersal.

Direct evidence supports the existence of seasonal hydrologic connections and indirect evidence supports the movement of organisms between western vernal pool complexes and streams. Indirect evidence supports the existence of hydrologic and biological connections between northern vernal pools and river networks, with potential for storing water during the wet season, and providing alternative breeding habitat or food resources for stream organisms.

References

Alexander, R. B., R. A. Smith, and G. E. Schwarz. 2000. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. Nature **403**:758-761.

Alexander, R. B., R. A. Smith, G. E. Schwarz, E. W. Boyer, J. V. Nolan, and J. W. Brakebill. 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River basin. Environmental Science & Technology **42**:822-830.

Amezaga, J. M., L. Santamaria, and A. J. Green. 2002. Biotic wetland connectivity—supporting a new approach for wetland policy. Acta Oecologica **23**:213-222.

Amoros, C., and G. Bornette. 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshwater Biology **47**:761-776.

Anderson, M. T., and L. H. Woosley, Jr. 2005. Water availability for the Western United States—key scientific challenges. U.S. Geological Survey Circular 1261, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Armour, C. L., D. A. Duff, and W. Elmore. 1991. The effects of livestock grazing on riparian and stream ecosystems. Fisheries **16**:7-11.

Aronson, M. F. J., and S. Galatowitsch. 2008. Long-term vegetation development of restored prairie pothole wetlands. Wetlands **28**:883-895.

Arthington, A. H., S. R. Balcombe, G. A. Wilson, M. C. Thoms, and J. Marshall. 2005. Spatial and temporal variation in fish-assemblage structure in isolated waterholes during the 2001 dry season of an arid-zone floodplain river, Cooper Creek, Australia. Marine and Freshwater Research **56**:25-35.

Ashworth, A. C. 1999. Climate change in North Dakota since the last glaciation—review of the paleontological record. Proceedings of the North Dakota Academy of Science **53**:171-176.

Ashworth, W. 2006. Ogallala blue: Water and life on the High Plains. The Countryman Press, Woodstock, VT.

Atwood, G. 1994. Geomorphology applied to flooding problems of closed-basin lakes... specifically Great Salt Lake, Utah. Geomorphology **10**:197-219.

Baillie, M., J. F. Hogan, B. Ekwurzel, A. K. Wahi, and C. J. Eastoe. 2007. Quantifying water sources to a semiarid riparian ecosystem, San Pedro River, Arizona. Journal of Geophysical Research: Biogeosciences **112**:G03S02.

Banner, B. K., A. J. Stahl, and W. K. Dodds. 2009. Stream discharge and riparian land use influence in-stream concentrations and loads of phosphorus from Central Plains watersheds. Environmental Management **44**:552-565.

Baranyi, C., T. Hein, C. Holarek, S. Keckeis, and F. Schiemer. 2002. Zooplankton biomass and community structure in a Danube River floodplain system: Effects of hydrology. Freshwater Biology **47**:473-482.

Batt, B. D. J., M. G. Anderson, C. D. Anderson, and F. D. Caswell. 1989. The use of prairie potholes by North American ducks. Pages 204-227 *in* Northern prairie wetlands. A. G. van der Valk, editor. Iowa State University Press, Ames, IA.

Battaglin, W. S., E. M. Thurman, S. J. Kalkhoff, and S. D. Porter. 2003. Herbicides and transformation products in surface waters of the midwestern United States. Journal of the American Water Resources Association **39**:743-756.

Bauder, E. T. 2000. Inundation effects on small-scale plant distributions in San Diego, California vernal pools. Aquatic Ecology **34**:43-61.

Bauder, E. T. 2005. The effects of an unpredictable precipitation regime on vernal pool hydrology. Freshwater Biology **50**:2129-2135.

Bauder, E. T., and S. McMillan. 1998. Current distribution and historical extent of vernal pools in Southern California and Northern Baja California, Mexico. Pages 56-70 *in* Ecology, conservation, and management of vernal pool ecosystems—proceedings from a 1996 conference. C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren, Jr., and R. Ornduff, editors. California Native Plant Society, Sacramento, CA.

Bennett, S. H., and J. B. Nelson. 1991. Distribution and status of Carolina bays in South Carolina. Nongame and Heritage Trust Publication No. 1, South Carolina Wildlife and Marine Resources Department, Columbia, SC.

Bergey, E. A., W. J. Matthews, and J. E. Fry. 2008. Springs in time: Fish fauna and habitat changes in springs over a 20-year interval. Aquatic Conservation: Marine and Freshwater Ecosystems **18**:829-838.

Bernot, M. J., D. J. Sobota, R. O. Hall, P. J. Mulholland, W. K. Dodds, J. R. Webster, J. L. Tank, L. R. Ashkenas, L. W. Cooper, C. N. Dahm, S. V. Gregory, N. B. Grimm, S. K. Hamilton, S. L. Johnson, W. H. McDowell, J. L. Meyer, B. Peterson, G. C. Poole, H. M. Valett, C. Arango, J. J. Beaulieu, A. J. Burgin, C. Crenshaw, A. M. Helton, L. Johnson, J. Merriam, B. R. Niederlehner, J. M. O'Brien, J. D. Potter, R. W. Sheibley, S. M. Thomas, and K. Wilson. 2010. Inter-regional comparison of land-use effects on stream metabolism. Freshwater Biology **55**:1874-1890.

Bischel, H. N., J. E. Lawrence, B. J. Halaburka, M. H. Plumlee, A. S. Bawazir, J. P. King, J. E. McCray, V. H. Resh, and R. G. Luthy. 2013. Renewing urban streams with recycled water for streamflow augmentation: Hydrologic, water quality, and ecosystem services management. Environmental Engineering Science **30**:455-479.

Blann, K. L., J. L. Anderson, G. R. Sands, and B. Vondracek. 2009. Effects of agricultural drainage on aquatic ecosystems: A review. Critical Reviews in Environmental Science and Technology **39**:909-1001.

Blasch, K. W., and J. R. Bryson. 2007. Distinguishing sources of ground water recharge by using δ^2H and δ^{18}O. Ground Water **45**:294-308.

Bliley, D. J., and D. E. Pettry. 1979. Carolina bays on the Eastern Shore of Virginia. Soil Science Society of America Journal **43**:558-564.

Blinn, D. W., and N. L. Poff. 2005. Colorado River Basin. Pages 483-526 *in* Rivers of North America. A. C. Benke and C. E. Cushing, editors. Elseviar Academic Press, Amsterdam, The Netherlands.

Boone, R. B., C. M. Johnson, and L. B. Johnson. 2006. Simulating vernal pool hydrology in central Minnesota, USA. Wetlands **26**:581-592.

Borchert, J. R. 1950. The climate of the central North American grassland. Annals of the Association of American Geographers **40**:1-39.

Boughton, E. H., P. F. Quintana-Ascencio, P. J. Bohlen, D. G. Jenkins, and R. Pickert. 2010. Land-use and isolation interact to affect wetland plant assemblages. Ecography **33**:461-470.

Boulton, A. J., and P. S. Lake. 1992. The ecology of two intermittent streams in Victoria, Australia. Freshwater Biology **27**:99-121.

Braaten, P. J., and C. S. Guy. 1999. Relations between physicochemical factors and abundance of fishes in tributary confluences of the lower channelized Missouri River. Transactions of the American Fisheries Society **128**:1213-1221.

Brant, H. A., C. H. Jagoe, J. W. Snodgrass, A. L. Bryan, and J. C. Gariboldi. 2002. Potential risk to wood storks (*Mycteria americana*) from mercury in Carolina bay fish. Environmental Pollution **120**:405-413.

Brix, H. 1994. Use of constructed wetlands in water pollution control: Historical development, present status, and future perspectives. Water Science and Technology **30**:209-223.

Brooks, B. W., T. M. Riley, and R. D. Taylor. 2006. Water quality of effluent-dominated ecosystems: Ecotoxicological, hydrological, and management considerations. Hydrobiologia **556**:365-379.

Brooks, P. D., and M. M. Lemon. 2007. Spatial variability in dissolved organic matter and inorganic nitrogen concentrations in a semiarid stream, San Pedro River, Arizona. Journal of Geophysical Research: Biogeosciences **112**:G03S05.

Brooks, R. T. 2000. Annual and seasonal variation and the effects of hydroperiod on benthic macroinvertebrates of seasonal forest ("vernal") ponds in central Massachusetts, USA. Wetlands **20**:707-715.

Brooks, R. T. 2004. Weather-related effects on woodland vernal pool hydrology and hydroperiod. Wetlands **24**:104-114.

Brooks, R. T. 2005. A review of basin morphology and pool hydrology of isolated ponded wetlands: Implications for seasonal forest pools of the northeastern United States. Wetlands Ecology and Management **13**:335-348.

Brookshire, D. S., D. C. Goodrich, M. D. Dixon, A. Brand, K. Benedict, K. Lansey, J. Thacher, C. Broadbent, S. Stewart, M. McIntosh, and K. Doosun. 2010. Ecosystem services and reallocation choices: A framework for preserving semi-arid regions in the southwest. Journal of Contemporary Water Research and Education **144**:60-74.

Brown, A. V., and W. J. Matthews. 1995. Stream ecosystems of the central United States. Pages 89-116 *in* River and stream ecosystems. C. E. Cushing, K. W. Cummings, and G. W. Minshall, editors. Elsevier Science, Amsterdam, The Netherlands.

Bull, W. B., and K. M. Scott. 1974. Impact of mining gravel from urban stream beds in the southwestern United States. Geology **2**:171-174.

Bunn, S. E., P. M. Davies, and M. Winning. 2003. Sources of organic carbon supporting the food web of an arid zone floodplain river. Freshwater Biology **48**:619-635.

Bunn, S. E., M. C. Thoms, S. K. Hamilton, and S. J. Capon. 2006. Flow variability in dryland rivers: Boom, bust and the bits in between. River Research and Applications **22**:179-186.

Cabezas, A., F. A. Comin, and D. E. Walling. 2009. Changing patterns of organic carbon and nitrogen accretion on the Middle Ebro floodplain (NE Spain). Ecological Engineering **35**:1547-1558.

Caldwell, P. V., M. J. Vepraskas, and J. D. Gregory. 2007a. Physical properties of natural organic soils in Carolina bays of the southeastern United States. Soil Science Society of America Journal **71**:1051-1057.

Caldwell, P. V., M. J. Vepraskas, R. W. Skaggs, and J. D. Gregory. 2007b. Simulating the water budgets of natural Carolina bay wetlands. Wetlands **27**:1112-1123.

Calhoun, A. J. K., and P. G. DeMaynadier, editors. 2007. Science and conservation of vernal pools in northeastern North America: Ecology and conservation of seasonal wetlands in northeastern North America. CRC Press, New York, NY, USA.

Calhoun, A. J. K., T. E. Walls, S. S. Stockwell, and M. McCollough. 2003. Evaluating vernal pools as a basis for conservation strategies: A Maine case study. Wetlands **23**:70-81.

Callegary, J. B., J. M. Leenhouts, N. V. Paretti, and C. A. Jones. 2007. Rapid estimation of recharge potential in ephemeral-stream channels using electromagnetic methods, and measurements of cahnnel and vegetation characteristics. Journal of Hydrology **344**:17-31.

Carroll, R., G. Pohll, J. Tracy, T. Winter, and R. Smith. 2005. Simulation of a semipermanent wetland basin in the Cottonwood Lake area, east-central North Dakota. Journal of Hydrologic Engineering **10**:70-84.

Chou, R. Y. M., L. C. Ferrington, Jr., B. L. Hayford, and H. M. Smith. 1999. Composition and phenology of Chironomidae (Diptera) from an intermittent stream in Kansas. Archiv für Hydrobiologie **147**:35-64.

Clark, W. R. 2000. Ecology of muskrats in prairie wetlands. Pages 287-313 *in* Prairie wetland ecology: The contribution of the marsh ecology research program. H. R. Murkin, A. G. van der Valk, and W. R. Clark, editors. Iowa State University Press, Ames, IA.

Clausnitzer, D., and J. H. Huddleston. 2002. Wetland determination of a southeast Oregon vernal pool and management implications. Wetlands **22**:677-685.

Coes, A. L., and D. R. Pool. 2005. Ephemeral-stream channel and basin-floor infiltration and recharge in the Sierra Vista subwatershed of the Upper San Pedro Basin, southeastern Arizona. USGS Open-File Report 2005–1023, U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Colburn, E. A. 2004. Vernal pools: Natural history and conservation. McDonald and Woodward Publishing Company, Blacksburg, VA.

Compton, B. W., K. McGarigal, S. A. Cushman, and L. R. Gamble. 2007. A resistant-kernel model of connectivity for amphibians that breed in vernal pools. Conservation Biology **21**:788-799.

Constantz, J., A. E. Stewart, R. Niswonger, and L. Sarma. 2002. Analysis of temperature profiles for investigating stream losses beneath ephemeral channels. Water Resources Research **38**:1316.

Covich, A. P., S. C. Fritz, P. J. Lamb, R. D. Marzolf, W. J. Matthews, K. A. Poiani, E. E. Prepas, M. D. Richman, and T. C. Winter. 1997. Potential effects of climate change on aquatic ecosystems of the Great Plains of North America. Hydrological Processes **11**:993-1021.

Cowardin, L. M., D. S. Gilmer, and L. M. Mechlin. 1981. Characteristics of central North Dakota wetlands determined from sample aerial photographs and ground study. Wildlife Society Bulletin **9**:280-288.

Crook, D. A., and B. M. Gillanders. 2006. Use of otolith chemical signatures to estimate carp recruitment sources in the mid-Murray River, Australia. River Research and Applications **22**:871-879.

Cross, F. B., and R. E. Moss. 1987. Historic changes in fish communities and aquatic habitats in plains streams of Kansas. Pages 155-165 *in* Community and evolutionary ecology of North American stream fishes. W. J. Matthews and D. C. Heins, editors. University of Oklahoma Press, Norman, OK.

Crumpton, W. G., and L. G. Goldsborough. 1998. Nitrogen transformation and fate in prairie wetlands. Great Plains Science **8**:57-72.

Cummins, K. W., and M. J. Klug. 1979. Feeding ecology of stream invertebrates. Annual Review of Ecology and Systematics **10**:147-172.

da Silva, H. P., A. C. Petry, and C. J. da Silva. 2010. Fish communities of the Pantanal wetland in Brazil: Evaluating the effects of the upper Paraguay river flood pulse on *baia* Caiçara fish fauna. Aquatic Ecology **44**:275-288.

Dahl, T. E. 1990. Wetlands Losses in the United States 1780's to 1980's. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Washington, DC.

Dahm, C. N., J. R. Cleverly, J. E. Allred Coonrod, J. R. Thibault, D. E. McDonnell, and D. J. Gilroy. 2002. Evapotranspiration at the land/water interface in a semi-arid drainage basin. Freshwater Biology **47**:831-843.

Deacon, J. E. 1961. Fish populations, following a drought, in the Neosho and Marais de Cygnes Rivers of Kansas. Museum of Natural History **13**:359-427.

Dickinson, J. E., J. R. Kennedy, D. R. Pool, J. T. Cordova, J. T. Parker, J. P. Macy, and B. Thomas. 2010. Hydrogeologic framework of the middle San Pedro watershed, southeastern Arizona. USGS Scientific Investigations Report 2010-5126, prepared in cooperation with the Arizona Department of Water Resources, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Dodds, W. K., J. M. Blair, G. M. Henerbry, J. K. Koelliker, R. Ramundo, and C. M. Tate. 1996a. Nitrogen transport from tallgrass prairie watersheds. Journal of Environmental Quality **25**:973-981.

Dodds, W. K., M. A. Evans-White, N. M. Gerlanc, L. Gray, D. A. Gudder, M. J. Kemp, A. L. Lopez, D. Stagliano, E. A. Strauss, J. L. Tank, M. R. Whiles, and W. M. Wollheim. 2000. Quantification of the nitrogen cycle in a prairie stream. Ecosystems **3**:574-589.

Dodds, W. K., K. Gido, M. R. Whiles, K. M. Fritz, and W. J. Matthews. 2004. Life on the edge: The ecology of Great Plains prairie streams. BioScience **54**:205-216.

Dodds, W. K., R. E. Hutson, A. C. Eichem, M. A. Evans, D. A. Gudder, K. M. Fritz, and L. Gray. 1996b. The relationship of floods, drying, flow and light to primary production and producer biomass in a prairie stream. Hydrobiologia **333**:151-159.

Dodds, W. K., and R. M. Oakes. 2004. A technique for establishing reference nutrient concentrations across watersheds affected by humans. Limnology and Oceanography-Methods **2**:333-341.

Dodds, W. K., and R. M. Oakes. 2006. Controls on nutrients across a prairie stream watershed: Land use and riparian cover effects. Environmental Management **37**:634-646.

Dodds, W. K., and R. M. Oakes. 2008. Headwater influences on downstream water quality. Environmental Management **41**:367-377.

Donald, D. B., J. Syrgiannis, F. Hunter, and G. Weiss. 1999. Agricultural pesticides threaten the ecological integrity of northern prairie wetlands. The Science of the Total Environment **231**:173-181.

Du, B., J. G. Arnold, A. Saleh, and D. B. Jaynes. 2005. Development and application of SWAT to landscapes with tiles and potholes. Transactions of the American Society of Agricultural Engineers **48**:1121-1133.

Durham, B. W., and G. R. Wilde. 2006. Influence of stream discharge on reproductive success of a prairie stream fish assemblage. Transactions of the American Fisheries Society **135**:1644-1653.

Durham, B. W., and G. R. Wilde. 2008. Composition and abundance of drifting fish larvae in the Canadian River, Texas. Journal of Freshwater Ecology **23**:273-280.

Eby, L. A., W. F. Fagan, and W. L. Minckley. 2003. Variability and dynamics of a desert stream community. Ecological Applications **13**:1566-1579.

Edwards, A. L., and A. S. Weakley. 2001. Population biology and management of rare plants in depression wetlands of the southeastern coastal plain, USA. Natural Areas Journal **21**:12-35.

England, A. S., and W. F. Laudenslayer. 1995. Birds of the California Desert. Pages 337-372 *in* The California desert: An introduction to natural resources and man's impact, Volume 2. J. Latting and P. G. Rowlands, editors. June Latting Books, Riverside, CA.

Euliss, N. H., Jr., and D. M. Mushet. 2004. Impacts of water development on aquatic macroinvertebrates, amphibians, and plants in wetlands of a semi-arid landscape. Aquatic Ecosystem Health & Management **7**:73-84.

Euliss, N. H., J. W. Labaugh, L. H. Fredrickson, D. M. Mushet, M. R. K. Laubhan, G. A. Swanson, T. C. Winter, D. O. Rosenberry, and R. D. Nelson. 2004. The wetland continuum: A conceptual framework for interpreting biological studies. Wetlands **24**:448-458.

Evans-White, M. A., W. K. Dodds, L. J. Gray, and K. M. Fritz. 2001. A comparison of the trophic ecology of the crayfishes (*Orconectes nais* (Faxon) and *Orconectes neglectus* (Faxon)) and the central stoneroller minnow (*Campostoma anomalum* (Rafinesque)): Omnivory in a tallgrass prairie stream. Hydrobiologia **462**:131-144.

Evans-White, M. A., W. K. Dodds, and M. R. Whiles. 2003. Ecosystem significance of crayfishes and stonerollers in a prairie stream: Functional differences between co-occurring omnivores. Journal of the North American Benthological Society **22**:423-441.

Falke, J. A., K. R. Bestgen, and K. D. Fausch. 2010. Streamflow reductions and habitat drying affect growth, survival, and recruitment of brassy minnow across a Great Plains landscape. Transactions of the American Fisheries Society **139**:1566-1583.

Falke, J. A., K. D. Fausch, R. Magelky, A. Aldred, D. S. Durnford, L. K. Riley, and R. Oad. 2011. The role of groundwater pumping and drought in shaping ecological futures for stream fishes in a dryland river basin of the western Great Plains, USA. Ecohydrology **4**:682-697.

Falke, J. A., and K. B. Gido. 2006. Effects of reservoir connectivity on stream fish assemblages in the Great Plains. Canadian Journal of Fisheries and Aquatic Sciences **63**:480-493.

Farag, A. M., D. D. Harper, A. Senecal, and W. A. Hubert. 2010. Potential effects of coalbed natural gas development on fish and aquatic resources. Pages 227-242 *in* Coalbed natural gas: Energy and environment. K. R. Reddy, editor. Nova Science Publishers, New York, NY.

Fausch, K. D., and K. R. Bestgen. 1997. Ecology of fishes indigenous to the central and southwestern Great Plains. Pages 131-166 *in* Ecology and conservation of Great Plains vertebrates. F. L. Knopf and F. B. Samson, editors. Springer-Verlag, New York, NY.

Fausch, K. D., and R. G. Bramblett. 1991. Disturbance and fish communities in intermittent tributaries of a western Great Plains river. Copeia **1991**:659-674.

Fausch, K. D., C. E. Torgersen, C. V. Baxter, and H. W. Li. 2002. Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. BioScience **52**:483-498.

Fernald, A. F., P. J. Wigington, and D. Landers. 2001. Transient storage and hyporheic flow along the Willamette River, Oregon: Field measurements and model estimates. Water Resources Research **37**:1681-1694.

Ferrington, L. C. 1993. Endangered rivers: A case history of the Arkansas River in the Central Plains. Aquatic Conservation: Marine and Freshwater Ecosystems **3**:305-316.

Figuerola, J., A. J. Green, and T. C. Michot. 2005. Invertebrate eggs can fly: Evidence of waterfowl-mediated gene flow in aquatic invertebrates. The American Naturalist **165**:274-280.

Franssen, N. R., K. B. Gido, C. S. Guy, J. A. Tripe, S. J. Shrank, T. R. Strakosh, K. N. Bertrand, C. M. Franssen, K. L. Pitts, and C. P. Paukert. 2006. Effects of floods on fish assemblages in an intermittent prairie stream. Freshwater Biology **51**:2072-2086.

Friedman, J. M., W. R. Osterkamp, M. L. Scott, and G. T. Auble. 1998. Downstream effects of dams on channel geometry and bottomland vegetation: Regional patterns in the Great Plains. Wetlands **18**:619-633.

Frisch, D., A. J. Green, and J. Figuerola. 2007. High dispersal capacity of a broad spectrum of aquatic invertebrates via waterbirds. Aquatic Sciences **69**:568-574.

Fritz, K. M., and W. K. Dodds. 2002. Macroinvertebrate assemblage structure across a tallgrass prairie stream landscape. Archiv für Hydrobiologie **154**:79-102.

Fritz, K. M., and W. K. Dodds. 2004. Resistance and resilience of macroinvertebrate assemblages to drying and flood in a tallgrass prairie stream system. Hydrobiologia **527**:99-112.

Fritz, K. M., and W. K. Dodds. 2005. Harshness: Characterization of intermittent stream habitat over space and time. Marine and Freshwater Research **56**:13-23.

Fritz, K. M., J. A. Tripe, and C. S. Guy. 2002. Recovery of three fish species to flood and seasonal drying in a tallgrass prairie stream. Transactions of the Kansas Academy of Science **105**:209-219.

Gahl, M. K., A. J. K. Calhoun, and R. Graves. 2009. Facultative use of seasonal pools by American bullfrogs (*Rana catesbeiana*). Wetlands **29**:697-703.

Galat, D. L., C. R. Berry, Jr., E. J. Peters, and R. G. White. 2005. Missouri River basin. Pages 427-480 *in* Rivers of North America. A. C. Benke and C. E. Cushing, editors. Elsevier Academic Press, Burlington, MA.

Galat, D. L., and R. Lipkin. 2000. Restoring ecological integrity of great rivers: Historical hydrographs aid in defining reference conditions for the Missouri River. Hydrobiologia **422/423**:29-48.

Galatowitsch, S. M., and A. G. van der Valk. 1996. The vegetation of restored and natural prairie wetlands. Ecological Applications **6**:102-112.

Galbarczyk-Gasiorowska, L., M. Gasiorowski, and K. Szeroczynska. 2009. Reconstruction of human influence during the last two centuries on two small oxbow lakes near Warsaw (Poland). Hydrobiologia **631**:173-183.

Gallardo, B., M. Garcia, A. Cabezas, E. Gonzalez, M. Gonzalez, C. Ciancarelli, and F. A. Comin. 2008. Macroinvertebrate patterns along environmental gradients and hydrological connectivity within a regulated river-floodplain. Aquatic Sciences **70**:248-258.

Gelroth, J. V., and G. R. Marzolf. 1978. Primary production and leaf-litter decomposition in natural and channelized portions of a Kansas stream. American Midland Naturalist **99**:238-243.

Gelwick, F. P., and W. J. Matthews. 1997. Effects of algivorous minnows (*Campostoma*) on spatial and temporal heterogeneity of stream periphyton. Oecologia **112**:386-392.

Gibbons, J. W., and R. D. Semlitsch. 1991. Guide to amphibians and reptiles of the Savannah River Site. University of Georgia Press, Athens, GA.

Gibbons, J. W., C. T. Winne, D. E. Scott, J. D. Willson, X. Glaudas, K. M. Andrews, B. D. Todd, L. A. Fedewa, L. Wilkinson, R. N. Tsaliagos, S. J. Harper, J. L. Greene, T. D. Tuberville, B. S. Metts, M. E. Dorcast, J. P. Nestor, C. A. Young, T. Akre, R. N. Reed, K. A. Buhlmann, J. Norman, D. A. Croshaw, C. Hagen, and B. B. Rothermel. 2006. Remarkable amphibian biomass and abundance in an isolated wetland: Implications for wetland conservation. Conservation Biology **20**:1457-1465.

Ginting, D., J. F. Moncrief, and S. C. Gupta. 2000. Runoff, solids, and contaminant losses into surface tile inlets draining lacustrine depressions. Journal of Environmental Quality **29**:551-560.

Gleason, R. A., N. H. Euliss, D. Hubbard, and W. Duffy. 2003. Effects of sediment load on emergence of aquatic invertebrates and plants from wetland soil egg and seed banks. Wetlands **23**:26-34.

Gleason, R. A., N. H. Euliss, D. E. Hubbard, and W. G. Duffy. 2004. Invertebrate egg banks of restored, natural, and drained wetlands in the prairie pothole region of the United States. Wetlands **24**:562-572.

Gleason, R. A., M. K. Laubhan, and N. H. Euliss, Jr. 2008. Ecosystem services derived from wetland conservation practices in the United States prairie pothole region with an emphasis on the U.S. Department of Agriculture Conservation Reserve and Wetlands Reserve Programs. USGS Professional Paper 1745, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Gleason, R. A., B. A. Tangen, M. K. Laubhan, K. E. Kermes, and N. H. Euliss. 2007. Estimating water storage capacity of existing and potentially restorable wetland depressions in a subbasin of the Red River of the North. USGS Open-File Report 2007-1159, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Glinska-Lewczuk, K. 2009. Water quality dynamics of oxbow lakes in young glacial landscape of NE Poland in relation to their hydrological connectivity. Ecological Engineering **35**:25-37.

Golladay, S. W. 1997. Suspended particulate organic matter concentration and export in streams. Journal of the North American Benthological Society **16**:122-131.

Golladay, S. W., and C. L. Hax. 1995. Effects of an engineered flow disturbance on meiofauna in a north Texas prairie stream. Journal of the North American Benthological Society **14**:404-413.

Goodrich, D. C., A. Chehbouni, B. Goff, R. Mac Nish, T. Maddock, M. S. Moran, J. Shuttleworth, D. G. Williams, C. Watts, L. H. Hipps, D. I. Cooper, J. Schieldge, Y. H. Kerr, H. Arias, M. Kirkland, R. Carlos, P. Cayrol, W. Kepner, B. Jones, R. Avissar, A. Begue, J.-M. Bonnefond, G. Boulet, B. Branan, J. P. Brunel, L. C. Chen, T. Clarke, M. R. Davis, H. DeBruin, G. Dedieu, E. Elguero, W. E. Eichinger, J. Everitt, J. Garatuza-Payan, V. L. Gempko, H. Gupta, C. Harlow, O. Hartogensis, M. Helfert, C. Holifield, D. Hymer, A. Kahle, T. Keefer, S. Krishnamoorthy, J.-P. Lhomme, J.-P. Lagouarde, D. Lo Seen, D. Luquet, R. Marsett, B. Monteny, W. Ni, Y. Nouvellon, R. Pinker, C. Peters, D. Pool, J. Qi, S. Rambal, J. Rodriguez, F. Santiago, E. Sano, S. M. Schaeffer, M. Schulte, R. Scott, X. Shao, K. A. Snyder, S. Sorooshian, C. L. Unkrich, M. Whitaker, and I. Yucel. 2000. Preface paper to the Semi-Arid Land-Surface-Atmosphere (SALSA) program special issue. Agricultural and Forest Meteorology **105**:3-20.

Goodrich, D. C., L. J. Lane, R. M. Shillito, S. N. Miller, K. H. Syed, and D. A. Woolhiser. 1997. Linearity of basin response as a function of scale in a semiarid watershed. Water Resources Research **33**:2951-2965.

Goodrich, D. C., D. G. Williams, C. L. Unkrich, J. F. Hogan, R. L. Scott, K. R. Hultine, D. R. Pool, A. L. Coes, and S. Miller. 2004. Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River basin, Arizona. Pages 77-99 *in* Recharge and vadose zone processes: Alluvial basins of the southwestern United States. F. M. Phillips, J. F. Hogan, and B. Scanlon, editors. American Geophysical Union, Washington, DC.

Gornall, R. J., P. M. Hollingsworth, and C. D. Preston. 1998. Evidence for spatial structure and directional gene flow in a population of an aquatic plant, *Potamogeton coloratus*. Heredity **80**:414-421.

Graf, W. L. 1988. Fluvial processes in dryland rivers. Springer New York.

Grant, E. H. C. 2005. Correlates of vernal pool occurrence in the Massachusetts, USA landscape. Wetlands **25**:480-487.

Grant, J. A., M. J. Brooks, and B. E. Taylor. 1998. New constraints on the evolution of Carolina bays from ground-penetrating radar. Geomorphology **22**:325-345.

Gray, L. J., and K. W. Johnson. 1988. Trophic structure of benthic macroinvertebrates in Kings Creek. Transactions of the Kansas Academy of Science **91**:178-184.

Gregoire, C., D. Elsaesser, D. Huguenot, J. Lange, T. Lebeau, A. Merli, R. Mose, E. Passeport, S. Payraudeau, T. Schutz, R. Schulz, G. Tapia-Padilla, J. Tournebize, M. Trevisan, and A. Wanko. 2009. Mitigation of agricultural nonpoint-source pesticide pollution in artificial wetland ecosystems. Environmental Chemistry Letters **7**:205-231.

Gregory, K. J. 1976. Drainage networks and climate. Pages 289-315 *in* Geomorphology and climate. E. Derbyshire, editor. John Wiley & Sons, London, UK.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummings. 1991. An ecosystem perspective of riparian zones: Focus on links between land and water. BioScience **41**:540-551.

Groffman, P. M., A. J. Gold, and R. C. Simmons. 1992. Nitrate dynamics in riparian forests: Microbial studies. Journal of Environmental Quality **21**:666-671.

Gurtz, M. E., G. R. Marzolf, D. L. Killingbeck, D. L. Smith, and J. V. McArthur. 1988. Hydrologic and riparian influences on the import and storage of coarse particulate organic matter in a prairie stream. Canadian Journal of Fisheries and Aquatic Sciences **45**:655-665.

Gurtz, M. E., G. R. Marzolf, K. T. Killingbeck, D. L. Smith, and J. V. McArthur. 1982. Organic matter loading and processing in a pristine stream draining a tallgrass prairie/riparian forest watershed. Kansas Water Resources Research Institute Contribution 230, Manhattan, KS.

Hadley, R. F., M. R. Karlinger, A. W. Burns, and T. R. Eschner. 1987. Water development and associated hydrologic changes in the Platte River, Nebraska, U.S.A. Regulated Rivers: Research & Mangement **1**:331-341.

Hall, D. H., and R. J. Steidl. 2007. Movements, activity, and spacing of Sonoran mud turtles (*Kinosternon sonoriense*) in interrupted mountain streams. Copeia **2007**:403-412.

Hanes, T., and L. Stromberg. 1998. Hydrology of vernal pools on non-volcanic soils in the Sacramento Valley. Pages 38-49 *in* Ecology, conservation, and management of vernal pool ecosystems—proceedings from a 1996 Conference. C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren, Jr., and R. Ornduff, editors. California Native Plant Society, Sacramento, CA.

Hanson, M. A., K. D. Zimmer, M. G. Butler, B. A. Tangen, B. R. Herwig, and N. H. Euliss. 2005. Biotic interactions as determinants of ecosystem structure in prairie wetlands: An example using fish. Wetlands **25**:764-775.

Harrell, R. C., B. J. Davis, and T. C. Dorris. 1967. Stream order and species diversity of fishes in an intermittent Oklahoma stream. American Midland Naturalist **78**:428-436.

Harrington, G. A., P. G. Cook, and A. L. Herczeg. 2002. Spatial and temporal variability of ground water recharge in central Australia: A tracer approach. Ground Water **40**:518-528.

Harris, M. A., B. C. Kondratieff, and T. P. Boyle. 1999. Macroinvertebrate community structure of three prairie streams. Journal of the Kansas Entomological Society **72**:402-425.

Hastings, J. R. 1959. Vegetation change and arroyo cutting in southeastern Arizona. Journal of the Arizona Academy of Science:60-67.

Hax, C. L., and S. W. Golladay. 1998. Flow disturbance of macroinvertebrates inhabiting sediments and woody debris in a prairie stream. American Midland Naturalist **139**:210-223.

Hayashi, M., G. van der Kamp, and D. L. Rudolph. 1998. Water and solute transfer between a prairie wetland and adjacent uplands, 1. Water balance. Journal of Hydrology **207**:42-55.

Hedman, E. R., and W. R. Osterkamp. 1982. Streamflow characteristics related to channel geometry of streams in western United States. USGS Water Supply Paper 2193, U.S. Department of the Interior, U.S. Geological Survey, Alexandria, VA.

Hein, T., C. Baranyi, G. J. Herndl, W. Wanek, and F. Schiemer. 2003. Allochthonous and autochthonous particulate organic matter in floodplains of the River Danube: The importance of hydrological connectivity. Freshwater Biology **48**:220-232.

Hentges, V. A., and T. W. Stewart. 2010. Macroinvertebrate assemblages in Iowa prairie pothole wetlands and relation to environmental features. Wetlands **30**:501-511.

Herwig, B. R., K. D. Zimmer, M. A. Hanson, M. L. Konsti, J. A. Younk, R. W. Wright, S. R. Vaughn, and M. D. Haustein. 2010. Factors influencing fish distributions in shallow lakes in prairie and prairie-parkland regions of Minnesota, USA. Wetlands **30**:609-619.

Hill, B. H., and T. J. Gardner. 1987a. Benthic metabolism in a perennial and an intermittent Texas prairie stream. Southwestern Naturalist **32**:305-311.

Hill, B. H., and T. J. Gardner. 1987b. Seston dynamics in two Texas prairie streams. American Midland Naturalist **118**:85-93.

Hill, B. H., T. J. Gardner, and O. F. Ekisola. 1992. Predicatability of streamflow and particulate organic matter concentration as indicators of stability in prairie streams. Hydrobiologia **242**:7-18.

Hilty, J. A., W. Z. Lidicker Jr, and A. Merenlender. 2006. Corridor ecology: The science and practice of linking landscapes for biodiversity conservation. Island Press, Washington, DC.

Hoagstrom, C. W., J. E. Brooks, and S. R. Davenport. 2010. A large-scale conservation perspective considering endemic fishes of the North American plains. Biological Conservation **144**:21-34.

Hobson, W. A., and R. A. Dahlgren. 1998. Soil forming processes in vernal pools of Northern California, Chico area. Pages 24-37 *in* Ecology, conservation, and management of vernal pool ecosystems—proceedings from a 1996 conference. C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren, Jr., and R. Ornduff, editors. California Native Plant Society, Sacramento, CA.

Horowitz, A. J., K. A. Elrick, and E. Callender. 1988. The effect of mining on the sediment-trace element geochemistry of cores from the Cheyenne River Arm of Lake Oahe, South Dakota, USA. Chemical Geology **67**:17-33.

Hubbard, D. E., and R. L. Linder. 1986. Spring runoff retention in prairie pothole wetlands. Journal of Soil and Water Conservation **41**:122-125.

Hubert, W. A., and K. M. Gordon. 2007. Great Plains fishes declining or threatened with extirpation in Montana, Wyoming, or Colorado. Pages 3-13 *in* Status, distribution, and conservation of native freshwater fishes of western North America. M. J. Brouder and J. A. Scheurer, editors. American Fisheries Society Symposium 53, Bethesda, MD.

Hudson, P. L., D. R. Lenat, B. A. Caldwell, and D. Smith. 1990. Chironomidae of the southeastern United States: A checklist of species and notes on biology, distribution, and habitat. Fish and Wildlife Research 7, U.S. Department of the Interior, U.S. Fish and Wildlife Service, Washington, DC.

Hulsmans, A., K. Moreau, L. De Meester, B. J. Riddoch, and L. Brendonck. 2007. Direct and indirect measures of dispersal in the fairy shrimp *Branchipodopsis wolfi* indicate a small-scale isolation-by-distance pattern. Limnology and Oceanography **52**:676-684.

Humphries, P., A. J. King, and J. D. Koehn. 1999. Fish, flows and flood plains: Links between freshwater fishes and their environment in the Murray-Darling River system, Australia. Environmental Biology of Fishes **56**:129-151.

Hunsinger, T. W., and M. J. Lannoo. 2005. *Notophthalmus viridescens*, eastern newt. Pages 912-914 *in* Amphibian declines: The conservation status of United States species. M. Lannoo, editor. University of California Press, Berkeley, CA.

Huntzinger, T. L. 1995. Surface water: A critical resource of the Great Plains. Pages 253-273 *in* Conservation of Great Plains ecosystems: Current science, future options. S. R. Johnson and A. Bouzaher, editors. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Jackson, C. R., and C. M. Pringle. 2010. Ecological benefits of reduced hydrologic connectivity in intensively developed landscapes. BioScience **60**:37-46.

Jewell, M. E. 1927. Aquatic biology of the prairie. Ecology **8**:289-298.

John, K. R. 1964. Survival of fish in intermittent streams of the Chirichua Mountains, Arizona. Ecology **45**:112-119.

Johnson, D. W. 1942. The Origin of Carolina Bays. Columbia Univeristy Press, New York, NY.

Johnson, S. L., and A. P. Covich. 1997. Scales of observation of riparian forests and distributions of suspended detritus in a prairie river. Freshwater Biology **37**:163-175.

Johnson, W. C. 1994. Woodland expansion in the Platte River, Nebraska: Patterns and causes. Ecological Monographs **64**:45-84.

Johnson, W. C., S. E. Boettcher, K. A. Poiani, and G. Guntenspergen. 2004. Influence of weather extremes on the water levels of glaciated prairie wetlands. Wetlands **24**:385-398.

Johnson, W. C., B. V. Millett, T. Gilmanov, R. A. Voldseth, G. R. Guntenspergen, and D. E. Naugle. 2005. Vulnerability of northern prairie wetlands to climate change. BioScience **55**:863-872.

Johnson, Z. B., and J. H. Kennedy. 2003. Macroinvertebrate assemblages of submerged woody debris in the Elm Fork of the Trinity River, Texas. Journal of Freshwater Ecology **18**:187-197.

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Pages 110-127 *in* Proceedings of the international large river symposium, Canadian Special Publication of Fisheries and Aquatic Sciences 106. D. P. Dodge, editor., Ottawa, Canada.

Kahara, S. N., R. M. Mockler, K. F. Higgins, S. R. Chipps, and R. R. Johnson. 2009. Spatiotemporal patterns of wetland occurrence in the prairie pothole region of eastern South Dakota. Wetlands **29**:678-689.

Kantrud, H. A., G. L. Krapu, and G. A. Swanson. 1989. Prairie basin wetlands of the Dakotas: A community profile. Biological Report 85(7.28), U.S. Department of the Interior, U.S. Fish and Wildlife Service and U.S. Environmental Protection Agency, Washington, DC.

Keckeis, S., C. Baranyi, T. Hein, C. Holarek, P. Riedler, and F. Schiemer. 2003. The significance of zooplankton grazing in a floodplain system of the River Danube. Journal of Plankton Research **25**:243-253.

Keeley, J. E., and P. H. Zedler. 1998. Characterization and global distribution of vernal pools. Pages 1-14 *in* Ecology, conservation, and management of vernal pool ecosystems—proceedings from a 1996 conference. C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren, Jr., and R. Ornduff, editors. California Native Plant Society, Sacramento, CA.

Keiper, J. B., W. E. Walton, and B. A. Foote. 2002. Biology and ecology of higher diptera from freshwater wetlands. Annual Review of Entomology **47**:207-232.

Kemp, M. J., and W. K. Dodds. 2001. Spatial and temporal patterns of nitrogen concentrations in pristine and agriculturally-influenced prairie streams. Biogeochemistry **53**:125-141.

Kemp, M. J., and W. K. Dodds. 2002. Comparisons of nitrification and denitrification in prairie and agriculturally influenced streams. Ecological Applications **12**:998-1009.

Kennedy, J., D. Goodrich, and C. Unkrich. 2013. Using the KINEROS2 modeling framework to evaluate the increase in storm runoff from residential development in a semiarid environment. Journal of Hydrologic Engineering **18**:698-706.

Kennedy, J. R., and B. Gungle. 2010. Quantity and sources of base flow in the San Pedro River near Tombstone, Arizona. USGS Scientific Investigations Report 2010-5200, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Kepner, W. G., D. J. Semmens, S. D. Bassett, D. A. Mouat, and D. C. Goodrich. 2004. Scenario analysis for the San Pedro River, analyzing hydrological consequences of a future environment. Environmental Monitoring and Assessment **94**:115-127.

Kepner, W. G., C. J. Watts, C. M. Edmonds, J. K. Maingi, S. E. Marsh, and G. Luna. 2000. A landscape approach for detecting and evaluating change in a semi-arid environment. Environmental Monitoring and Assessment **64**:179-195.

King, J. L., M. A. Simovich, and R. C. Brusca. 1996. Species richness, endemism and ecology of crustacean assemblages in northern California vernal pools. Hydrobiologia **328**:85-116.

Kirkman, L. K., and R. R. Sharitz. 1994. Vegetation disturbance and maintenance of diversity in intermittently flooded Carolina bays in South Carolina. Ecological Applications **4**:177-188.

Knight, R. L., J. S. Bays, and F. R. Richardson. 1989. Floral composition, soil relations and hydrology of a Carolina bay in South Carolina. Pages 219-234 *in* Freshwater wetlands and wildlife. R. R. Sharitz and J. W. Gibbons, editors. U.S. Department of Energy, Office of Scientific and Technical Information, Oak Ridge, TN.

Knosche, R. 2006. Organic sediment nutrient concentrations and their relationship with the hydrological connectivity of floodplain waters (River Havel, NE Germany). Hydrobiologia **560**:63-76.

Krapu, G. L., J. G. Raymond, C. P. Dwyer, K. M. Kraft, and L. M. Cowardin. 1997. Wetland use, settling patterns, and recruitment in mallards. Journal of Wildlife Management **61**:736-746.

LaBaugh, J. W., T. C. Winter, G. A. Swanson, D. O. Rosenberry, R. D. Nelson, and N. H. Euliss. 1996. Changes in atmospheric circulation patterns affect midcontinent wetlands sensitive to climate. Limnology and Oceanography **41**:864-870.

Labbe, T. R., and K. D. Fausch. 2000. Dynamics of intermittent stream habitat regulate persistence of a threatened fish at multiple scales. Ecological Applications **10**:1774-1791.

Lane, L. J., M. Hernandez, and M. H. Nichols. 1997. Processes controlling sediment yield from watersheds as functions of spatial scale. Environmental Modelling and Software **12**:355-369.

Lang, M., O. McDonough, G. McCarty, R. Oesterling, and B. Wilen. 2012. Enhanced detection of wetland-stream connectivity using LiDAR. Wetlands **32**:461-473.

Lauenroth, W. K., I. C. Burke, and M. P. Gutmann. 1999. The structure and function of ecosystems in the central North American grassland region. Great Plains Research **9**:223-259.

Leeper, D. A., and B. E. Taylor. 1998. Insect emergence from a South Carolina (USA) temporary wetland pond, with emphasis on the Chironomidae (Diptera). Journal of the North American Benthological Society **17**:54-72.

Lehtinen, R. M., and S. M. Galatowitsch. 2001. Colonization of restored wetlands by amphibians in Minnesota. American Midland Naturalist **145**:388-396.

Leibowitz, S. G., and K. C. Vining. 2003. Temporal connectivity in a prairie pothole complex. Wetlands **23**:13-25.

Lekach, J., A. P. Shick, and A. Schlesinger. 1992. Bedload yield and in-channel provenance in a flash-flood fluvial system. Pages 537-554 *in* Dynamics of gravel-bed rivers. P. Billi, R. D. Hey, C. R. Thorne, and P. Tacconi, editors. John Wiley & Sons, New York, NY.

Lenhart, C. F., K. N. Brooks, D. Heneley, and J. A. Magner. 2010. Spatial and temporal variation in suspended sediment, organic matter, and turbidity in a Minnesota prairie river: Implications for TMDLs. Environmental Monitoring and Assessment **165**:435-447.

Lerner, D. N. 1986. Leaking pipes recharge ground water. Ground Water **24**:654-662.

Levick, L., J. Fonseca, D. Goodrich, M. Hernandez, D. Semmens, R. Leidy, M. Scianni, P. Guertin, M. Tluczek, and W. Kepner. 2008. The ecological and hydrological significance of ephemeral and intermittent streams in the arid and semi-arid American Southwest. EPA/600/R-08/134 and ARS/233046, U.S. Environmental Protection Agency, Office of Research and Development and U.S. Department of Agriculture/Agricultural Research Service. Southwest Watershed Research Center, Washington, DC.

Lide, R. F., V. G. Meentemeyer, J. E. Pinder, and L. M. Beatty. 1995. Hydrology of a Carolina bay located on the upper Coastal Plain of western South Carolina. Wetlands **15**:47-57.

Lorenz, D. L., C. A. Sanocki, and M. J. Kocian. 2010. Techniques for estimating the magnitude and frequency of peak flows on small streams in Minnesota based on through water year 2005. USGS Scientific Investigations Report 2009-5250, U.S. Department of the Interior, U.S. Geological Survey, in cooperation with the Minnesota Department of Transportation and the Minnesota Pollution Control Agency, Reston, VA.

Louw, G., and M. Seely. 1982. Ecology of desert organisms.

Luttrell, G. R., A. A. Echelle, W. L. Fisher, and D. J. Eisenhour. 1999. Declining status of two species of the *Macrhybopsis aestivalis* complex (Teleostei: Cyprinidae) in the Arkansas River basin and related effects of reservoirs as barriers to dispersal. Copeia **1999**:981-989.

Lytle, D. A., M. T. Bogan, and D. S. Finn. 2008. Evolution of aquatic insect behaviors across a gradient of disturbance predictability. Proceedings of the Royal Society - Series B **275**:453-462.

Machavaram, M. V., D. O. Whittemore, M. E. Conrad, and N. L. Miller. 2006. Precipitation induced stream flow: An event based chemical and isotopic study of a small stream in the Great Plains region of the USA. Journal of Hydrology **330**:470-480.

Macpherson, G. L., and M. Sophocleous. 2004. Fast ground-water mixing and basal recharge in an unconfined alluvial aquifer, Konza LTER site, northeastern Kansas. Journal of Hydrology **286**:271-299.

Mahoney, D. L., M. A. Mort, and B. E. Taylor. 1990. Species richness of calanoid copepods, cladocerans and other branchiopods in Carolina bay temporary ponds. American Midland Naturalist **123**:244-258.

Marron, D. C. 1989. The transport of mine tailings as suspended sediment in the Belle Fourche River, west-central South Dakota, USA. International Association of Hydrologic Sciences **184**:19-26.

Mathis, B. J., and T. C. Dorris. 1968. Community structure of benthic macroinvertebrates in an intermittent stream receiving oil field brines. American Midland Naturalist **80**:428-439.

Matthai, H. F. 1969. Floods of June 1965 in South Platte River basin, Colorado. USGS Water Supply Paper 1850-B., U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Matthews, W. J. 1988. North American prairie streams as systems for ecological study. Journal of the North American Benthological Society **7**:387-409.

Matthews, W. J., J. F. Hoover, and W. B. Milstead. 1985. Fishes of Oklahoma springs. Southwestern Naturalist **30**:23-32.

Matthews, W. J., and E. Marsh-Matthews. 2007. Extirpation of red shiner in direct tributaries of Lake Texoma (Oklahoma-Texas): A cautionary case history from a fragmented river-reservoir system. Transactions of the American Fisheries Society **136**:1041-1062.

Matthews, W. J., and H. W. Robinson. 1998. Influence of drainage connectivity, drainage area and regional species richness on fishes of the interior highlands in Arkansas. American Midland Naturalist **139**:1-19.

Matthews, W. J., C. C. Vaughn, K. B. Gido, and E. Marsh-Matthews. 2005. Southern Plains rivers. Pages 283-325 *in* Rivers of North America. A. C. Benke and C. E. Cushing, editors. Elsevier Academic Press, Burlington, MA.

Matthews, W. J., and E. G. Zimmerman. 1990. Potential effects of global warming on native fishes of the southern Great Plains and the Southwest. Fisheries **15**:26-32.

McArthur, J. V., M. E. Gurtz, C. M. Tate, and F. S. Gilliam. 1985a. The interaction of biological and hydrological phenomena that mediate the qualities of water draining native tallgrass prairie on the Konza Prairie Research Natural Area. Pages 478-482 *in* Perspectives on nonpoint source pollution, proceedings of 1985 national conference. U.S. Environmental Protection Agency, Office of Water Regulations and Standards, Washington, DC.

McArthur, J. V., G. R. Marzolf, and J. E. Urban. 1985b. Response of bacteria isolated from a pristine prairie stream to concentration and source of soluble organic carbon. Applied and Environmental Microbiology **49**:238-241.

McCoy, R. W., and D. C. Hales. 1974. A survey of eight streams in eastern South Dakota: Physical and chemical characteristics, vascular plants, insects and fishes. Proceedings of the South Dakota Academy of Sciences **53**:202-219.

Meffe, G. K. 1984. Effects of abiotic disturbance on coexistence of predator-prey fish species. Ecology **65**:1525–1534.

Meinzer, O. E. 1923. Outline of ground-water hydrology. US Geology Survey Water Supply Paper 494, U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Meixner, T. A., A. K. Huth, P. D. Brooks, M. H. Conklin, N. B. Grimm, R. C. Bales, P. A. Haas, and J. R. Petti. 2007. Influence of shifting flow paths on nitrogen concentrations during monsoon floods, San Pedro River, Arizona. Journal of Geophysical Research: Biogeosciences **112**:G03S03.

Meschiatti, A. J., M. S. Arcifa, and N. Fenerich-Verani. 2000. Fish communities associated with macrophytes in Brazilian floodplain lakes. Environmental Biology of Fishes **58**:133-143.

Meyer, J. L., D. L. Strayer, J. B. Wallace, S. L. Eggert, G. S. Helfman, and N. E. Leonard. 2007. The contribution of headwater streams to biodiversity in river networks. Journal of the American Water Resources Association **43**:86-103.

Milam, J. C., and S. M. Melvin. 2001. Density, habitat use, movements, and conservation of spotted turtles (*Clemmys guttuta*) in Massachusetts. Journal of Herpetology **35**:418-427.

Miller, A. M., and S. W. Golladay. 1996. Effects of spates and drying on macroinvertebrate assemblages of an intermittent and perennial prairie stream. Journal of the North American Benthological Society **15**:670-689.

Miller, B. A., W. G. Crumpton, and A. G. van der Valk. 2009. Spatial distribution of historical wetland classes on the Des Moines Lobe, Iowa. Wetlands **29**:1146-1152.

Miller, M. W., and T. D. Nudds. 1996. Prairie landscape change and flooding in the Mississippi River Valley. Conservation Biology **10**:847-853.

Miller, T. K., and L. J. Onesti. 1988. Interregional comparison of alluvial stream channel morphology: Great Plains versus Central Lowlands. Water Resources Bulletin **24**:1207-1217.

Miltner, R. J., D. White, and C. Yoder. 2004. The biotic integrity of streams in urban and suburbanizing landscapes. Landscape and Urban Planning **69**:87-100.

Minckley, W., and G. K. Meffre. 1987. Differential selection by flooding in stream-fish communities of the arid American Southwest. Pages 93-104 *in* Community and evolutionary ecology of North American stream fishes. W. J. Matthews and D. C. Heins, editors. University of Oklahoma Press, Norman, OK.

Mitsch, W. J. 1992. Landscape design and the role of created, restored, and natural riparian wetlands in controlling nonpoint source pollution. Ecological Engineering **1**:27-47.

Mueller, M. H., and A. G. van der Valk. 2002. The potential role of ducks in wetland seed dispersal. Wetlands **22**:170-178.

Mulholland, P. J., C. S. Fellows, J. L. Tank, N. B. Grimm, J. R. Webster, S. K. Hamilton, E. Marti, L. Ashkenas, W. B. Bowden, W. K. Dodds, W. H. McDowell, M. J. Paul, and B. J. Peterson. 2001. Inter-biome comparison of factors controlling stream metabolism. Freshwater Biology **46**:1503-1517.

Mulhouse, J. M., and S. M. Galatowitsch. 2003. Revegetation of prairie pothole wetlands in the mid-continental US: Twelve years post-reflooding. Plant Ecology **169**:143-159.

Murdock, J. N., K. B. Gido, W. K. Dodds, K. N. Bertrand, and M. R. Whiles. 2010. Consumer return chronology alters recovery trajectory of stream ecosystem structure and function following drought. Ecology **91**:1048-1062.

Murkin, H. R., and P. J. Caldwell. 2000. Avian use of prairie wetlands. Pages 249-286 *in* Prairie wetland ecology: The contribution of the marsh ecology research program. H. R. Murkin, A. G. van der Valk, and W. R. Clark, editors. Iowa State University Press, Ames, IA.

Naiman, R. J., H. Decamps, and M. E. McClain. 2005. Riparia: Ecology, conservation, and management of streamside communities. Elsevier Academic Press, Burlington, MA.

Nanson, G. C., and J. C. Croke. 1992. A genetic classification of floodplains. Geomorphology **4**:459-486.

National Research Council. 2002. Riparian areas: Functions and strategies for management. The National Academies Press, Washington, DC.

Negrel, P., E. Petelet-Giraud, J. Barbier, and E. Gautier. 2003. Surface water-groundwater interactions in an alluvial plain: Chemical and isotopic systematics. Journal of Hydrology **277**:248-267.

Newman, M. C., and J. F. Schalles. 1990. The water chemistry of Carolina bays: A regional survey. Archiv für Hydrobiologie **118**:147-168.

NHD. 2008. National Hydrography Dataset. U.S. Geological Survey.

O'Connor, B. L., Y. Hamada, E. E. Bowen, M. A. Grippo, H. M. Hartmann, T. L. Patton, R. A. Van Lonkhuyzen, and A. E. Carr. 2014. Quantifying the sensitivity of ephemeral streams to land disturbance activities in arid ecosystems at the watershed scale. Environmental Monitoring and Assessment **186**:7075-7095.

Obolewski, K., K. Glinska-Lewczuk, and S. Kobus. 2009. Effect of hydrological connectivity on the molluscan community structure in oxbow lakes of the Lyna River. Oceanological and Hydrobiological Studies **38**:75-88.

Ohmart, R. D. 1995. Historical and present impacts of livestock grazing on fish and wildlife resources in western riparian habitats. Pages 245-279 *in* Rangeland wildlife. P. R. Krausman, editor. The Society for Range Management, Denver, CO.

Osterkamp, W. R., and J. E. Costa. 1987. Changes accompanying an extraordinary flood on a sand-bed stream. Pages 201-224 *in* Catastrophic flooding. L. Mayer and D. Nash, editors. Allen & Unwin, Boston, MA.

Osterkamp, W. R., and J. M. Friedman. 2000. The disparity between extreme rainfall events and rare floods—with emphasis on the semi-arid American west. Hydrological Processes **14**:2817-2829.

Ostrand, K. G., and D. E. Marks. 2000. Mortality of prairie stream fishes confined in an isolated pool. Texas Journal of Science **52**:255-258.

Ostrand, K. G., and G. R. Wilde. 2004. Changes in prairie stream fish assemblages restricted to isolated streambed pools. Transactions of the American Fisheries Society **133**:1329-1338.

Parker, G., C. Paola, K. X. Whipple, and D. Mohrig. 1998. Alluvial fans formed by channelized fluvial and sheet flow. I: Theory. Journal of Hydraulic Engineering **124**:985-995.

Pattenden, R. K., and D. A. Boag. 1989. Skewed sex ratio in a northern wintering population of Mallards. Canadian Journal of Zoology **67**:1084-1087.

Pavelis, G. A. 1987. Farm drainage in the United States: History, status, and prospects. USDA Miscellaneous Publication 1455, U.S. Department of Agriculture, Economic Research Service, Washington, DC.

Pease, A. A., J. J. Davis, M. S. Edwards, and T. F. Turner. 2006. Habitat and resource use by larval and juvenile fishes in an arid-land river (Rio Grande, New Mexico). Freshwater Biology **51**:475-486.

Perkin, J. S., and K. B. Gido. 2011. Stream fragmentation thresholds for a reproductive guild of Great Plains fishes. Fisheries **36**:371-383.

Peterson, J. T., and C. F. Rabeni. 1996. Natural thermal refugia for temperate warmwater stream fishes. North American Journal of Fisheries Management **16**:738-746.

Phillips, F. M., J. F. Hogan, and B. R. Scanlon. 2004. Introduction and overview, in groundwater recharge in a desert environment: The southwestern United States. Pages 1-14 *in* Water science and applications series. J. F. Hogan, F. M. Phillips, and B. R. Scanlon, editors. American Geophysical Union., Washington, DC.

Phillips, P. J., J. M. Denver, R. J. Shedlock, and P. A. Hamilton. 1993. Effect of forested wetlands on nitrate concentrations in ground water and surface water on the Delmarva peninsula. Wetlands **13**:75-83.

Phillips, P. J., and R. J. Shedlock. 1993. Hydrology and chemistry of groundwater and seasonal ponds in the Atlantic coastal-plain in Delaware, USA. Journal of Hydrology **141**:157-178.

Platania, S. P., and C. S. Altenbach. 1998. Reproductive strategies and egg types of seven Rio Grande basin cyprinids. Copeia **1998**:559-569.

Plummer, L. N., S. K. Anderholm, W. E. Sanford, and E. Busenberg. 2004. Hydrochemical tracers in the middle Rio Grande basin, USA: 1. Conceptualization of groundwater flow. Hydrogeology Journal **12**:359-388.

Poff, N. L. 1996. A hydrogeography of unregulated streams in the United States and an examination of scale dependence in some hydrological descriptors. Freshwater Biology **36**:71-91.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime: A paradigm for river conservation and restoration. BioScience **47**:769-784.

Pool, D. R. 2005. Variations in climate and ephemeral channel recharge in southeastern Arizona, United States. Water Resources Research **41**:1-24.

Pool, D. R., and J. E. Dickinson. 2007. Ground-water flow model of the Sierra Vista subwatershed and Sonoran portions of the Upper San Pedro basin, southeastern Arizona, United States, and Northern Sonora, Mexico. USGS Scientific Investigations Report 2006-5228, U.S. Department of the Interior, U.S. Geological Survey prepared in cooperation with the Upper San Pedro Partnership and Bureau of Land Management, Reston, VA.

Powell, B. F., and R. J. Steidl. 2002. Habitat selection by riparian songbirds breeding in southern Arizona. The Journal of Wildlife Management:1096-1103.

Powell, D. M., R. Brazier, A. Parsons, J. Wainwright, and M. Nichols. 2007. Sediment transfer and storage in dryland headwater streams. Geomorphology **88**:152-166.

Power, M. E., and A. J. Stewart. 1987. Disturbance and recovery of an algal assemblage following flooding in an Oklahoma stream. American Midland Naturalist **117**:333-345.

Prophet, C. W., and J. D. Ransom. 1974. Summer stream metabolism values for Cedar Creek, Kansas. Southwestern Naturalist **19**:305-308.

Prouty, W. F. 1952. Carolina bays and their origin. Bulletin of the Geological Society of America **63**:167-224.

Pyke, C. R. 2004. Simulating vernal pool hydrologic regimes for two locations in California, USA. Ecological Modelling **173**:109-127.

Pyzoha, J. E., T. J. Callahan, G. Sun, C. C. Trettin, and M. Miwa. 2008. A conceptual hydrologic model for a forested Carolina bay depressional wetland on the Coastal Plain of South Carolina, USA. Hydrological Processes **22**:2689-2698.

Rabeni, C. F. 1996. Prairie legacies – fish and aquatic resources. Pages 111-124 *in* Prairie conservation: Preserving North America's most endangered ecosystem. F. B. Samson and F. L. Knopf, editors. Island Press, Washington, DC.

Rains, M. C., R. A. Dahlgren, G. E. Fogg, T. Harter, and R. J. Williamson. 2008. Geological control of physical and chemical hydrology in California vernal pools. Wetlands **28**:347-362.

Rains, M. C., G. E. Fogg, T. Harter, R. A. Dahlgren, and R. J. Williamson. 2006. The role of perched aquifers in hydrological connectivity and biogeochemical processes in vernal pool landscapes, Central Valley, California. Hydrological Processes **20**:1157-1175.

Reckendorfer, W., C. Baranyi, A. Funk, and F. Schiemer. 2006. Floodplain restoration by reinforcing hydrological connectivity: Expected effects on aquatic mollusc communities. Journal of Applied Ecology **43**:474-484.

Richardson, C. J., and J. W. Gibbons. 1993. Pocosins, Carolina bays, and mountain bogs. Pages 257-310 *in* Biodiversity of the southeastern United States. W. H. Martin, S. G. Boyce, and A. C. Echternacht, editors. John Wiley & Sons, New York, NY.

Rinne, J. N., and D. Miller. 2006. Hydrology, geomorphology and management: Implications for sustainability of native southwestern fishes. Reviews in Fisheries Science **14**:91-110.

Roach, W. J., J. B. Heffernan, N. B. Grimm, J. R. Arrowsmith, C. Eisinger, and T. Rychener. 2008. Unintended consequences of urbanization for aquatic ecosystems: A case study from the Arizona desert. BioScience **58**:715-727.

Rosenberry, D. O., and T. C. Winter. 1997. Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlands in North Dakota. Journal of Hydrology **191**:266-289.

Ross, T. E. 1987. A comprehensive bibleography of the Carolina bays literature. Journal of Elisha Mitchell Scientific Society **103**:28-42.

Routman, E. 1993. Population structure and genetic diversity of metamorphic and paedomorphic populations of the tiger salamander, *Ambystoma tigrinum*. Journal of Evolutionary Biology **6**:329-357.

Royer, T. V., M. B. David, and L. E. Gentry. 2006. Timing of riverine export of nitrate and phosphorus from agricultural watersheds in Illinois: Implications for reducing nutrient loading to the Mississippi River. Environmental Science & Technology **40**:4126-4131.

Rulifson, R. A., and B. L. Wall. 2006. Fish and blue crab passage through water control structures of a coastal bay lake. North American Journal of Fisheries Management **26**:317-326.

Samson, F., and F. Knopf. 1994. Prairie conservation in North America. BioScience **44**:418-421.

Savage, H., Jr. 1982. The mysterious Carolina bays. University of South Carolina Press, Columbia, SC.

Sawin, R. S., R. C. Buchanan, and W. Lebsack. 1999. Flint Hills springs. Transactions of the Kansas Academy of Science **102**:1-31.

Scanlon, B. R., C. C. Faunt, L. Longuevergne, R. C. Reedy, W. M. Alley, V. L. McGuire, and P. B. McMahon. 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. Proceedings of the National Academy of Sciences **109**:9320-9325.

Schalles, J. F., and D. J. Shure. 1989. Hydrology, community structure, and productivity patterns of a dystrophic Carolina bay wetland. Ecological Monographs **59**:365-385.

Schlosser, I. J. 1987. A conceptual framework for fish communities in small warmwater streams. Pages 17-24 *in* Community and evolutionary ecology of North American stream fishes. W. J. Matthews and D. C. Heins, editors. University of Oklahoma Press, Norman, OK.

Schlosser, I. J. 1991. Stream fish ecology: A landscape perspective. BioScience:704-712.

Schoof, R. R., J. W. Naney, and W. M. Boxley. 1978. Hydrologic effects of the Tonkawa Creek flood abatement program. Water Resources Bulletin **14**:629-639.

Schrank, S. J., C. S. Guy, M. R. Whiles, and B. L. Brock. 2001. Influence of instream and landscape-level factors on the distribution of Topeka shiners *Notropis topeka* in Kansas streams. Copeia **2001**:413-421.

Schueler, T. R. 1994. The importance of imperviousness. Watershed protection techniques **1**:100-111.

Schumm, S. A., and R. F. Hadley. 1957. Arroyos and the semiarid cycle of erosion [Wyoming and New Mexico]. American Journal of Science **255**:161-174.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, and N.-C. Lau. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. Science **316**:1181-1184.

Semlitsch, R. D., and J. R. Bodie. 1998. Are small, isolated wetlands expendable? Conservation Biology **12**:1129-1133.

Sharitz, R. R. 2003. Carolina bay wetlands: Unique habitats of the southeastern United States. Wetlands **23**:550-562.

Sharitz, R. R., and J. W. Gibbons. 1982. The ecology of southeastern shrub bogs (pocosins) and Carolina bays: A community profile. FWS/OBS-82/04, U.S. Department of the Interior, U.S. Fish and Wildlife Services Program, Washington, DC.

Shaw, J. R., and D. J. Cooper. 2008. Linkages among watersheds, stream reaches, and riparian vegetation in dryland ephemeral stream networks. Journal of Hydrology **350**:68-82.

Shoup, D. E., and D. H. Wahl. 2009. Fish diversity and abundance in relation to interannual and lake-specific variation in abiotic characteristics of floodplain lakes of the lower Kaskaskia River, Illinois. Transactions of the American Fisheries Society **138**:1076-1092.

Smith, C. L., and C. R. Powell. 1971. The summer fish communities of Brier Creek, Marshall County, Oklahoma. American Museum Novitates **2458**:1-30.

Smith, D. W., and W. L. Verrill. 1998. Vernal pool-soil-landform relationships in the Central Valley, California. Pages 15-23 *in* Ecology, conservation, and management of vernal pool ecosystems—proceedings from a 1996 conference. C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren, Jr., and R. Ornduff, editors. California Native Plant Society, Sacramento, CA.

Smith, S. V., W. H. Renwick, J. D. Bartley, and R. W. Buddemeier. 2002. Distribution and significance of small, artificial water bodies across the United States landscape. The Science of the Total Environment **299**:21-36.

Snodgrass, J. W., A. L. Bryan, and J. Burger. 2000a. Development of expectations of larval amphibian assemblage structure in southeastern depression wetlands. Ecological Applications **10**:1219-1229.

Snodgrass, J. W., A. L. Bryan, R. F. Lide, and G. M. Smith. 1996. Factors affecting the occurrence and structure of fish assemblages in isolated wetlands of the upper Coastal Plain, USA. Canadian Journal of Fisheries and Aquatic Sciences **53**:443-454.

Snodgrass, J. W., C. H. Jagoe, A. L. Bryan, H. A. Brant, and J. Burger. 2000b. Effects of trophic status and wetland morphology, hydroperiod, and water chemistry on mercury concentrations in fish. Canadian Journal of Fisheries and Aquatic Sciences **57**:171-180.

Soons, M. B. 2006. Wind dispersal in freshwater wetlands: Knowledge for conservation and restoration. Applied Vegetation Science **9**:271-278.

Sophocleous, M. 2005. Groundwater recharge and sustainability in the High Plains aquifer in Kansas, USA. Hydrogeology Journal **13**:351-365.

Sophocleous, M. 2010. Review: Groundwater management practices, challenges, and innovations in the High Plains aquifer, USA—lessons and recommended actions. Hydrogeology Journal **18**:559-575.

Stagliano, D. M., and M. R. Whiles. 2002. Macroinvertebrate production and trophic structure in a tallgrass prairie headwater stream. Journal of the North American Benthological Society **21**:97-113.

Stanford, J. A., and J. V. Ward. 1988. The hyporheic habitat of river ecosystems. Nature **335**:64-66.

Stanley, E. H., S. G. Fisher, and N. B. Grimm. 1997. Ecosystem expansion and contraction in streams. BioScience **47**:427-435.

Stolt, M. H., and M. C. Rabenhorst. 1987a. Carolina bays on the eastern shore of Maryland: 1. Soil characterization and classification. Soil Science Society of America Journal **51**:394-398.

Stolt, M. H., and M. C. Rabenhorst. 1987b. Carolina bays on the eastern shore of Maryland: 2. Distribution and origin. Soil Science Society of America Journal **51**:399-405.

Strand, M., and R. W. Merritt. 1999. Impacts of livestock grazing activities on stream insect communities and the riverine environment. American Entomologist **45**:13-29.

Stromberg, J., R. Tiller, and B. Richter. 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro, Arizona. Ecological Applications:113-131.

Stromberg, J. C., K. J. Bagstad, J. M. Leenhouts, S. J. Lite, and E. Makings. 2005. Effects of stream flow intermittency on riparian vegetation of a semiarid region river (San Pedro River, Arizona). River Research and Applications **21**:925-938.

Stromberg, J. C., and B. J. Tellman. 2009. Ecology and conservation of the San Pedro River. University of Arizona Press, Tucson, AZ.

Sun, G., T. J. Callahan, J. E. Pyzoha, and C. C. Trettin. 2006. Modeling the climatic and subsurface stratigraphy controls on the hydrology of a Carolina bay wetland in South Carolina, USA. Wetlands **26**:567-580.

Sutter, R. D., and R. Kral. 1994. The ecology, status, and conservation of two non-alluvial wetland communities in the south Atlantic and eastern Gulf Coastal Plain, USA. Biological Conservation **68**:235-243.

Swanson, C. D., and R. W. Bachmann. 1976. Model of algal exports in some Iowa streams. Ecology **57**:1076-1080.

Swanson, G. A., T. C. Winter, V. A. Adomaitis, and J. W. LaBaugh. 1988. Chemical characteristics of prairie lakes in south-central North Dakota—their potential for impacting fish and wildlife. U.S. Fish and Wildlife Technical Report 18, U.S. Department of the Interior, U.S. Fish and Wildlife Service, Washington, DC.

Tang, C., I. Machida, S. Shindo, A. Kondoh, and Y. Sakura. 2001. Chemical and isotopic methods for confirming the roles of wadis in regional groundwater recharge in a regional arid environment: A case study in Al Ain, UAE. Hydrological Processes **15**:2195-2202.

Tate, C. M. 1990. Patterns and controls of nitrogen in tallgrass prairie streams. Ecology **71**:2007-2018.

Taylor, C. M., M. R. Winston, and W. J. Matthews. 1993. Fish species-environment and abundance relationships in a Great Plains river system. Ecography **16**:16-23.

Thorp, J. H., and A. D. Delong. 2002. Dominance of autochthonous autotrophic carbon in food webs of heterotrophic rivers. Oikos **96**:543-550.

Tiner, R. W. 2003. Geographically isolated wetlands of the United States. Wetlands **23**:494-516.

Townsend-Small, A., D. E. Pataki, H. Liu, Z. Li, Q. Wu, and B. Thomas. 2013. Increasing summer river discharge in southern California, USA, linked to urbanization. Geophysical Research Letters **40**:4643-4647.

Transeau, E. N. 1905. Forest centers of eastern America. American Naturalist **39**:875-889.

Transeau, E. N. 1935. The prairie peninsula. Ecology **16**:423-437.

Turner, D. S., and M. D. List. 2007. Habitat mapping and conservation analysis to identify critical streams for Arizona's native fish. Aquatic Conservation: Marine and Freshwater Ecosystems **17**:737-748.

Turner, D. S., and H. E. Richter. 2011. Wet/dry mapping: Using citizen scientists to monitor the extent of perennial surface flow in dryland regions. Environmental Management **47**:497-505.

Turner, K. W., B. B. Wolfe, and T. W. D. Edwards. 2010. Characterizing the role of hydrological processes on lake water balances in the Old Crow Flats, Yukon Territory, Canada, using water isotope tracers. Journal of Hydrology **386**:103-117.

U.S. EPA. 2006. Wadeable streams assessment: A collaborative survey of the nation's streams. EPA 841-B-06-002, U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USDA. 2002. Management and techniques for riparian restoration, roads field guide, Volume 1. General Technical Report RMRS-GTR-1-2, U.S. Department of Agriculture, U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

USGS. 2006. National Hydrography Dataset.

Van De Meutter, F., L. De Meester, and R. Stoks. 2007. Metacommunity structure of pond macroinvertebrates: Effects of dispersal mode and generation time. Ecology **88**:1687-1695.

van der Kamp, G., and M. Hayashi. 1998. The groundwater recharge function of small wetlands in the semi-arid northern prairies. Great Plains Research **8**:39-56.

van der Kamp, G., and M. Hayashi. 2009. Groundwater-wetland ecosystem interaction in the semiarid glaciated plains of North America. Hydrogeology Journal **17**:203-214.

van der Valk, A. G. 2006. The biology of freshwater wetlands. Oxford University Press, New York, NY.

van der Valk, A. G., and C. B. Davis. 1978. The role of seed banks in the vegetation dynamics of prairie glacial marshes. Ecology **59**:322-335.

van der Valk, A. G., and R. L. Pederson. 2003. The SWANCC decision and its implications for prairie potholes. Wetlands **23**:590-596.

Van Devender, T. R. 2002. The Sonoran desert tortoise: Natural history, biology, and conservation. University of Arizona Press, Tucson, AZ.

van Digglen, R. 2006. Landscape: Spatial interactions. Pages 31-44 *in* Restoration Ecology. J. Andel and J. Aronson, editors. Blackwell, Oxford, UK.

Van Haveren, B. P. 1986. Management of instream flows through runoff detention and retention. Water Resources Bulletin **22**:399-404.

Van Riper, C., and K. L. Cole. 2004. The Colorado Plateau: Cultural, biological, and physical research. University of Arizona Press.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences **37**:130-137.

Vanschoenwinkel, B., S. Gielen, M. Seaman, and L. Brendonck. 2009. Wind mediated dispersal of freshwater invertebrates in a rock pool metacommunity: Differences in dispersal capacities and modes. Hydrobiologia **635**:363-372.

Vining, K. C. 2002. Simulation of streamflow and wetland storage, Starkweather Coulee subbasin, North Dakota. Water years 1981-98. U.S.G.S. Water-Resources Investigations Report 02-4113, U.S. Department of the Interior, U.S. Geological Survey in cooperation with the North Dakota State Water Commission, Bismarck, ND.

Vining, K. C. 2004. Simulation of runoff and wetland storage in the Hamden and Lonetree watershed sites within the Red River of the North basin, North Dakota and Minnesota. USGS Scientific Investigations Report 2004-5168, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Vivoni, E., R. S. Bowman, R. L. Wyckoff, R. T. Jakubowski, and K. E. Richards. 2006. Analysis of a monsoon flood event in an ephemeral tributary and its downstream hydrologic effects. Water Resources Research **42**:W03404.

Wagner, F. H. 1978. Livestock grazing and the livestock industry. Pages 121-145 *in* Wildlife and America. H. P. Brokaw, editor. Council on Environmental Quality, U.S. Government Printing Office, Washington, DC.

Wahi, A. K., J. F. Hogan, B. Ekwurzel, M. N. Baillie, and C. J. Eastoe. 2008. Geochemical quantification of semiarid mountain recharge. Ground Water **46**:414-425.

Weakley, A. S., and M. P. Schafale. 1991. Classification of pocosins of the Carolina Coastal Plain. Wetlands **11**:355-375.

Webb, R. H., and J. L. Betancourt. 1992. Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona. USGS Water-Supply Paper 2379, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Weitkamp, W. A., R. C. Graham, M. A. Anderson, and C. Amrhein. 1996. Pedogenesis of a vernal pool entisol-alfisol-vertisol catena in southern California. Soil Science Society of America Journal **60**:316-323.

Wells, B. W., and S. G. Boyce. 1953. Carolina bays: Additional data on their origin, age and history. Journal of Elisha Mitchell Scientific Society **69**:119-141.

Whigham, D. F., and T. E. Jordan. 2003. Isolated wetlands and water quality. Wetlands **23**:541-549.

Whiles, M. R., and W. K. Dodds. 2002. Relationships between stream size, suspended particles, and filter-feeding macroinvertebrates in a Great Plains drainage network. Journal of Environmental Quality **31**:1589-1600.

Whiting, D. P., M. R. Whiles, and M. L. Stone. 2011. Patterns of macroinvertebrate production, trophic structure, and energy flow along a tallgrass prairie stream continuum. Limnology and Oceanography **56**:887-898.

Wiley, M. J., L. L. Osborne, and R. W. Larimore. 1990. Longitudinal structure of an agricultural prairie river system and its relationship to current stream ecosystem theory. Canadian Journal of Fisheries and Aquatic Sciences **47**:373-384.

Williams, D. D. 1996. Environmental constraints in temporary fresh waters and their consequences for the insect fauna. Journal of the North American Benthological Society **15**:634-650.

Williams, D. D. 2005. The biology of temporary waters. Oxford University Press, Oxford, UK.

Williams, G. P., and M. G. Wolman. 1984. Downstream effects of dams on alluvial rivers. USGS Professional Paper 1286, U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Wilson, J. L., and H. Guan. 2004. Mountain-block hydrology and mountain-front recharge. Pages 113-137 *in* Groundwater recharge in a desert environment: The southwestern United States. F. M. Phillips, J. Hogan, and B. R. Scanlon, editors. American Geophysical Union, Washington, DC.

Winemiller, K. O., S. Tarim, D. Shormann, and J. B. Cotner. 2000. Fish assemblage structure in relation to environmental variation among Brazos River oxbow lakes. Transactions of the American Fisheries Society **129**:451-468.

Winston, M. R., C. M. Taylor, and J. Pigg. 1991. Upstream extirpation of four minnow species due to damming of a prairie stream. Transactions of the American Fisheries Society **120**:98-105.

Winter, T. C. 2007. The role of groundwater in generating streamflow in headwater areas and in maintaining base flow. Journal of the American Water Resources Association **43**:15-25.

Winter, T. C., J. W. Harvey, O. L. Franke, and W. M. Alley. 1998. Ground water and surface water: A single resource. USGS Circular 1139, U.S. Department of the Interior, U.S. Geological Survey, Denver, CO.

Winter, T. C., and J. W. LaBaugh. 2003. Hydrologic considerations in defining isolated wetlands. Wetlands **23**:532-540.

Winter, T. C., and D. O. Rosenberry. 1995. The interaction of groundwater with prairie pothole wetlands in the Cottonwood Lake area, east-central North Dakota, 1979-1990. Wetlands **15**:193-211.

Winter, T. C., and D. O. Rosenberry. 1998. Hydrology of prairie pothole wetlands during drought and deluge: A 17-year study of the cottonwood lake wetland complex in North Dakota in the perspective of longer term measured and proxy hydrological records. Climatic Change **40**:189-209.

Wohl, E., D. Egenhoff, and K. Larkin. 2009. Vanishing riverscapes: A review of historical channel change on the western Great Plains. Pages 131-142 *in* Management and restoration of fluvial systems with broad historical changes and human impacts. Geological Society of America Special Paper 451. L. A. James, S. L. Rathburn, and G. R. Whittecar, editors. Geological Society of America, Boulder, CO.

Wolock, D. M., T. C. Winter, and G. McMahon. 2004. Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analysis. Environmental Management **34**:S71-S88.

Woolhiser, D. A., T. O. Keefer, and K. T. Redmond. 1993. Southern Oscillation effects on daily precipitation in the southwestern United-States. Water Resources Research **29**:1287-1295.

Yuan, F., and S. Miyamoto. 2008. Characteristics of oxygen-18 and deuterium composition in waters from the Pecos River in American Southwest. Chemical Geology **255**:220-230.

Zale, A. V., D. M. Leslie Jr., W. L. Fisher, and S. G. Merrifield. 1989. The physicochemistry, flora, and fauna of intermittent prairie streams: A review of the literature. U.S. Fish and Wildlife Service Biological Report 89(5), U.S. Department of the Interior, U.S. Fish and Wildlife Service, Washington, DC.

Zedler, P. H. 1987. The ecology of southern California vernal pools: A community profile. U.S. Fish and Wildlife Service Biological Report 85(7.11), U.S. Department of the Interior, U.S. Fish and Wildlife Service, Washington, DC.

Zedler, P. H. 2003. Vernal pools and the concept of "isolated wetlands". Wetlands **23**:597-607.

Zeug, S. C., D. Peretti, and K. O. Winemiller. 2009. Movement into floodplain habitats by gizzard shad (*Dorosoma cepedianum*) revealed by dietary and stable isotope analyses. Environmental Biology of Fishes **84**:307-314.

Zeug, S. C., and K. O. Winemiller. 2008. Relationships between hydrology, spatial heterogeneity, and fish recruitment dynamics in a temperate floodplain river. River Research and Applications **24**:90-102.

Zeug, S. C., K. O. Winemiller, and S. Tarim. 2005. Response of Brazos River oxbow fish assemblages to patterns of hydrologic connectivity and environmental variability. Transactions of the American Fisheries Society **134**:1389-1399.

Zimmer, K. D., M. A. Hanson, and M. G. Butler. 2001. Effects of fathead minnow colonization and removal on a prairie wetland ecosystem. Ecosystems **4**:346-357.

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A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

Prepared by Pamela C. Dodds, Ph.D., Licensed Professional Geologist
Prepared for The Wilderness Society - January 24, 2023

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Functional Assessment Approach for High Gradient Streams

West Virginia
June, 2007

INTRODUCTION

This document describes the components and application of a method for assessing the condition of headwater streams and riparian areas in the mountains of West Virginia. It is specifically designed to address the typical impacts and likely mitigation proposals considered in the context of processing Clean Water Act Section 404 permit applications. The focus of this assessment method is on high gradient, headwater streams in West Virginia. These streams can be characterized as first and second order ephemeral and intermittent stream with a channel slope that ranges from 4 percent to greater than 10 percent. The stream channel sinuosity is low, but has common to many step pools and would classify as A, Aa, or Aa+ (Rosgen 1998) with a gravel, cobble or bolder controlled channel within a Type I valley. Flow rates in these streams are typically less than 7 cubic feet per second (cfs). The surrounding watershed contributing to the channel is forested with hardwood trees and woody shrubs, on moderately steep to very steep slopes (USDA 2004).

This approach, like various similar assessment tools developed for other regions and ecosystems, is based on the proposition that the condition of aquatic and wetland systems depends on a suite of physical and biological processes. These processes generally reflect the position of the system in the landscape, which controls how it interacts with geology, hydrology, and soils. These in turn influence vegetation, which further interacts with physical processes such as sediment movement, provides many elements of on-site animal habitat, and contributes nutrients and organic materials to the aquatic system on-site and downstream. Therefore, rapid assessment systems such as this one are designed to evaluate the extent to which key processes are operating or have been disrupted.

The approach involves visual evaluation of the physical and biological structure of the assessment site, or rating of the site as to the extent that it is functionally compromised by various stressors. These evaluations or ratings are formulated as simple equations, or models, where the condition assessments of a set of indicators are combined into an overall index of functionality for each of four functional categories: hydrology, biogeochemistry, plant communities, and wildlife habitat.

A set of eleven indicators are used in the models, where they are variously combined to reflect key elements of the functional category being assessed. The indicators are scaled from zero to 1.0, where 1.0 represents the fully functional (or reference), condition. The specific reason for using each indicator and the structure of the rating scale are explained further in the following sections of this document. Generally, however, the indicators (also called variables) are scaled based on a combination of field observations within a range of sites in the region, professional judgment, published literature, and rating scales developed for the same types of indicators in other regions and ecosystems. No field studies have been conducted in the region specifically to calibrate the indicators used here, therefore all scaling is approximate.

The method presented here is intended to be applied to potential or actual impact and mitigation sites by one experienced person in half a day or less. It is designed to produce consistent results across the range of headwater stream conditions typically encountered in the region.

PROCEDURE

1. Identify the Assessment Site on a topographic map. The Assessment Site includes the affected stream reach, and the watershed that drains to that reach.

2. Assemble any required materials and information, such as a camera, slope measuring device, a distance measuring tape, a ruler, and similar equipment. Review the data forms in the context of the size and accessibility of the Assessment Area to determine if you will require aerial photos and a soil survey. Bring any pertinent descriptions and maps of proposed impacts or mitigation plans. Make sufficient copies of data sheets from this document.

3. At each assessment area, assign a site identifier, take photos and keep notes concerning the orientation and principal subject of each photo (e.g., "channel looking downstream from midpoint of impact reach"). Complete the data sheets, consulting the individual variable descriptions for specific directions regarding the assignment of scores. Note that each indicator is scored using a weighted approach, where the percent of the assessment area in each score range is estimated and recorded.

4. If the average percent cover of either trees or shrubs is more than 10 percent the cover of herbaceous vegetation does not need to be determined.

5. Copy the basic spreadsheet and name the copy with the same site identifier recorded on the datasheets. Transfer values from data sheets to the spreadsheet and calculate Function Scores. Save and label all digital photos. Save the spreadsheet and all digital photos in a folder labeled with the same site identifier as used on the datasheets. Print hard copies of the spreadsheet, photos, and photo descriptions, and any other pertinent materials, and attach original data sheets.

6. Summarize the assessment. Depending on the scenario being investigated, the calculated index scores can be used in various ways. Typically, they should be converted to Functional Units by multiplying the index for each function by the stream length. Decisions about how to use the numbers are a matter of policy, and are not specified here. Normally, subsequent analyses are done without combining the four functions (i.e., the total habitat functional units lost to an impact are compared to the total habitat functional units gained by a mitigation action). However, some users of assessment systems find it convenient and more understandable to add all functional units together, or to average them, despite the obvious logic problems with this approach. Others base decisions on the "most impacted function." Similarly, impacts and mitigation credits can be calculated based on some target year (i.e., 5 years after impact) or on a projected average condition over the life of the project, or on some other criterion.

Variables

Stream channel alterations (*CHANNELALT*). This variable reflects alterations to the natural hydrology of the stream due to activities within the channel itself. Both natural and man-induced alterations can affect the hydrology of high gradient, ephemeral and intermittent streams. Examples in West Virginia include ditches, dams, culverted and unculverted road crossings, and downcutting or entrenchment of the channel. The intent of this variable is to capture those impacts that alter the hydrograph of the headwater stream system. This variable differs from *SLOPE* and *LANDUSE* in that the impacts occur within the stream channel and not in the surrounding landscape.

CHANNELALT is used in calculating the hydrology, biogeochemical, plant community, and habitat functional indices.

This variable is quantified by the type of structure or alteration to the stream channel. Measure *CHANNELALT* using the following procedure:

1) If stream is unaltered or no obstructions to natural water flow, and there is no excessive ponding within the channel, the score for this variable is 1.0.

2) If hydrology has been altered, identify the percentage of the stream affected by any permanent obstructions to channel flow such as dams, roads or fill, or by any deepening or straightening intended to speed flows, or any deepening or sedimentation that apparently resulted from land uses in the watershed, such as timber harvests. Do not include such changes if they appear to be the result of natural phenomena, such as increased incision following a forest fire or ponding by beaver.

3) Use Table 1 to determine the variable score for each of the alterations identified to the natural hydrology. Determine the weighted average for the entire stream reach impacted.

Table 1
Stream channel alterations (*CHANNELALT*)

Type of alteration	Score
unaltered	1.0
restored	0.75
incised, or excess sediment in channel	0.5
dammed	0.1
channelized/straightened	0.1
channel >50% filled	0.0

Average percent slope of the watershed (*SLOPE*). This variable reflects anthropogenic alterations to the natural slope of the headwater watershed. Under natural conditions in West Virginia, headwater stream systems form within moderately steep to extremely steep mountain coves, where average slope exceeds 45 percent. Steep slopes facilitate movement of water downslope to the stream channel, and removal of detrital material downstream to perennial streams. The intent of this variable is to capture changes to the watershed slope that can alter the movement of water and nutrients downstream at a reduced rate. This variable differs from *CHANNELALT* in that the impacts occur within the surrounding watershed and not directly in the stream channel.

SLOPE is used in calculating the hydrology and biogeochemical functional indices.

This variable is quantified by measuring alterations to slopes draining to the stream reach being assessed. Measure *SLOPE* using the following procedure:

1) If the watershed slope is unaltered, regardless of slope, then the score for this variable is 1.0.

2) Using topographic maps, soil survey maps, digital elevation maps, clinometers, Abney hand level, or other appropriate tools for measuring slope, determine the average percent slope of the watershed surrounding the stream reach being assessed. If the watershed slope is extremely variable (contains 3 or more categories identified in Table 2) determine a weighted average using the percent of the watershed for each category.

3) Use Table 2 to determine the variable score for the watershed slope.

Table 2
Average percent slope of the watershed (*SLOPE*)

Percent slope	Score
30 to 45 or unaltered	1.0
(20 to 29) or (45 to 65)	0.75
10 to 19	0.5
(5 to 9) or (66 to 90)	0.25
less than 5	0.1

Stream Sediment Size (*SED*). Stream sediment size is the predominant particle size of materials comprising the surface of the streambed. Sediment size is based on USDA texture classes for coarse and fine soil particles (USDA 1993). The composition of the streambed has a direct impact on the dissipation of water energy in the stream channel and influences habitat for vertebrates and invertebrates.

SED is used in calculating habitat functional indices.

Using the following procedure, determine the score for *SED*:

(1) During field reconnaissance, visually estimate the size of the predominant bed material in the stream channel.

(2) Use Table 3 to determine the variable score for Stream Sediment Size.

(3) If Stream Sediment Size is extremely variable in the watershed being assessed, determine a weighted average for this variable.

In West Virginia minimally altered headwater stream systems stream sediment is dominated by cobbles, stones, and boulders.

Table 3
Stream Sediment Size (*SED*)

USDA Soil Texture	Score
boulders, stones, cobbles (>3 in.)	1.0
Gravel (3/4 to 3 in.)	0.75
sand	0.5
silt	0.1
clay/pavement/bedrock	0.1

Land Cover within the Watershed (*COVER*). This variable is defined as the surface water runoff potential from the watershed into the stream. With increased disturbance and increased impervious surface surrounding the stream, more surface water enters the channel and it enters more quickly than under undisturbed conditions.

For headwater stream assessments in West Virginia, this variable is scored based on land cover that can be observed on aerial photographs and verified during field reconnaissance. Under undisturbed conditions, the watershed surrounding headwater slope streams is dominated by hardwood forest. Aerial photographs depicting land cover are available from a number of internet sources including TerraServer (http://terraserver.homeadvisor.msn.com/), Google Maps (http://maps.google.com/), and Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/). The score for *COVER* is based on the weighted average of scores for types of land cover identified in the upland and riparian areas within the catchment of the headwater stream being assessed. Areas affected by natural fire should be scored the same as undisturbed forest. Mined areas that have been reclaimed according to regulatory standards are considered to be highly, though not entirely, functional with respect to this variable.

COVER is used in calculating the hydrology, biogeochemistry, and habitat functional indices.

Using the following procedure, determine the score for *COVER*:

(1) Visually estimate the percent of the watershed and riparian zone covered by the cover types identified in Table 4.

(2) Calculate the weighted average for the watershed to determine the score for *COVER*.

Table 4
Land Cover Within the Watershed (*COVER*)

Land cover	Score
forest	1.0
shrub	0.75
orchards	0.5
pasture or hay	0.25
urban, roads	0.0

Average Percent Cover of Trees (*TREE*). This variable is defined as the average percent cover of trees in the watershed surrounding the headwater stream. Trees are defined as woody plants greater than or equal to 3 inches ($\geq$8 cm.) dbh. Percent cover of trees is only measured if percent tree cover is 10 percent or greater. Tree cover is a measure of the dominance and biomass of trees in a forest stand. Trees capture water in the canopy and reduce rainfall impact to the soil which reduces soil erosion and slows water runoff from the watershed to the stream. Trees are also the primary source for large woody debris and detritus in undisturbed high gradient, headwater riverine systems in West Virginia.

TREE is used in the assessment of all functions when tree or shrub cover is greater than 10 percent.

This variable is quantified by the average percent cover of trees. Measure *TREE* using the following procedure:

1) During a field reconnaissance of the watershed and riparian area, or using aerial photographs or other remote sensing data and verified during a field reconnaissance visually estimate the percent cover of trees. If the site is unaltered and the percent cover of trees is 90 percent or more the score for *TREE* would be 1.0.

2) If the site had been disturbed and percent cover of trees in some areas is less than 90 percent, estimate the percent cover of trees for each area.

3) Use Table 5 to determine the variable score for each area of the watershed or riparian area that differs in percent cover of trees. Determine the weighted average for *TREE*.

In reference standard sites, average percent cover of trees in the watershed and adjacent riparian area was greater than 90 percent.

Table 5
Average Percent Cover of Trees (*TREE*)

Percent	Score
greater than 90	1.0
70 to 90	0.75
50 to 69	0.5
20 to 49	0.25
10 to 19	0.1
less than 10	0.0

A score of 0.0 is assigned to severely altered sites that average less than 10 percent cover of trees.

Shrub cover (*SHRUB*). This variable is defined as the average percent cover of woody vegetation greater than 39 inches (>1 m) in height and less than 3 inches (8 cm) dbh (e.g., shrubs and small trees). Shrubs reduce erosion, slow runoff, take up nutrients, produce biomass, and provide cover and breeding sites for wildlife. Shrubs may dominate the community in headwater areas during early to mid-successional stages. In this context, *SHRUB* reflects the amount of woody vegetation in the understory and woody regeneration on the site that influences runoff directly to the headwater stream, affects nutrient cycling, and will eventually be the source of a mature forest canopy. Therefore, higher values of sapling/shrub cover are assumed to contribute more to these functions.

SHRUB is used in calculating the hydrology, biogeochemical, and plant community functional indices when tree or shrub cover is greater than 10 percent.

Use the following procedure to measure *SHRUB:*

1. During a field reconnaissance visually estimate the percent cover of shrubs within the watershed. If percent cover is extremely variable, develop a weighted average across the site.

2. Report the average shrub cover as a percent.

3. Use Table 6 to determine the variable score for *SHRUB*.

Table 6
Average Percent Cover of Shrubs (*SHRUB*)

Percent	Score
Greater than 50	1.0
20 to 50	0.5
10 to 19	0.25
Less than 10	0.0

A score of 0.0 is assigned to severely altered sites that average less than 10 percent cover of shrubs.

Average Percent Cover of Herbaceous Vegetation (*HERB*). This variable is defined as the average percent cover of ground vegetation. Ground vegetation is defined as all herbaceous vegetation, regardless of height, and woody vegetation less than 39 inches (1 m) in height. Ground vegetation cover is an index to the biomass of low vegetation in headwater areas, which affects the productivity and structure of these habitats.

HERB applies to the hydrology, biogeochemical, plant community, and habitat functions and only when canopy tree cover and shrub cover are each less than 10 percent.

If tree and shrub cover are each less than 10 percent, estimate average percent cover of herbaceous vegetation as follows:

1. During field reconnaissance visually estimate the percent cover of herbaceous vegetation in the watershed. If percent cover is extremely variable determine the weighted average of herbaceous vegetation by estimating the percentage of the Assessment Area in each cover class.

2. Use Table 7 to determine the score for *HERB*.

Table 7
Average Percent Cover of Herbaceous Vegetation (*HERB*)

Percent	Score
70 to 100	0.1
less than 70	0.0

Average percent cover of herbaceous vegetation is not used to evaluate headwater riverine systems in West Virginia that have a well-developed tree or shrub canopy. Instead, *HERB* is measured only in areas where tree and shrub cover are both less than 10 percent due to severe natural or anthropogenic disturbance. Even under these conditions, ground-layer vegetation contributes some reduction in erosion, organic material to the wetland's carbon cycle, provides some benefits for wildlife, and helps produce conditions favorable to the regeneration of a woody midstory and canopy. Because fully functional headwater areas typically are dominated by woody vegetation, even with 100 percent cover of herbaceous vegetation the maximum score that can be achieved is 0.1.

Vegetation composition and diversity (*COMP*). This variable reflects the "floristic quality" of the woody plant community based on concepts in Andreas and Lichvar (1995) and Smith and Klimas (2002). In undisturbed high gradient, headwater riverine systems in West Virginia, the tallest vegetation stratum is composed of native trees of a variety of species. In headwater riverine systems that have undergone recent and severe natural or anthropogenic disturbance, the tallest stratum may be dominated by shrubs or herbaceous species. Implicit in this approach is the assumption that the diversity of the tallest layer is a good indicator of overall community composition and successional patterns (i.e., appropriate shrub composition indicates appropriate future canopy composition). Note that the tree stratum includes all trees greater than 3 inches (8 cm) dbh, and the shrub layer includes all woody species at least 39 inches (1 m) tall but less than 3 inches (8 cm) dbh. There must be at least 10 percent tree cover to consider the tree stratum to be present and the focus of this evaluation. If tree cover is less than 10 percent, assess the composition of the sapling layer instead.

COMP applies to the plant community function and only when canopy tree or shrub cover is greater than 10 percent.

1. If tree cover is greater than 10 percent count the number of different species on the site being assessed during field reconnaissance.

2. If tree cover is less than 10 percent and shrub cover is greater than 10 percent, count the number of different woody species in the shrub stratum.

3. If both tree and shrub cover are each less than 10 percent then *COMP* would receive a score of zero.

4. Use Table 8 to determine the score for *COMP*.

In fully functional headwater areas in West Virginia, the number of native woody species present in the tallest stratum typically is 5 or more.

Table 8
Number of Native Species (*COMP*)

Number	Score
5 or more species	1.0
4 species	0.75
3 species	0.5
2 species	0.25
1 species	0.1
0 species	0.0

Soil Detritus (*DETRITUS*). The soil detrital layer is defined as the soil layer dominated by partially decomposed, but still recognizable organic material such as leaves, sticks (less than 3 inches in diameter), needles, flowers, fruits, dead moss, or detached lichens on the surface of the ground. Detritus is a direct indication of short term (one or two years) accumulation of organic matter primarily from vegetation within the watershed and the potential source for organic export to downstream systems.

DETRITUS is used in calculating the biogeochemical and habitat functional indices when tree or shrub cover is greater than 10 percent.

Using the following procedure to determine the score for *DETRITUS*:

(1) Visually estimate the percent of the ground surface covered by leaves, sticks (less than 3 inches in diameter or other organic material within the watershed.

(2) Use Table 9 to determine the subindex score for Soil Detritus

In West Virginia, minimally altered watersheds of headwater stream systems were observed to have soil detritus cover of greater than 75 percent.

Table 9
Soil Detritus (*DETRITUS*)

Percent cover	Score
greater than 75	1.0
50 to 75	0.75
25 to 49	0.5
10 to 24	0.25
less than 10	0.1

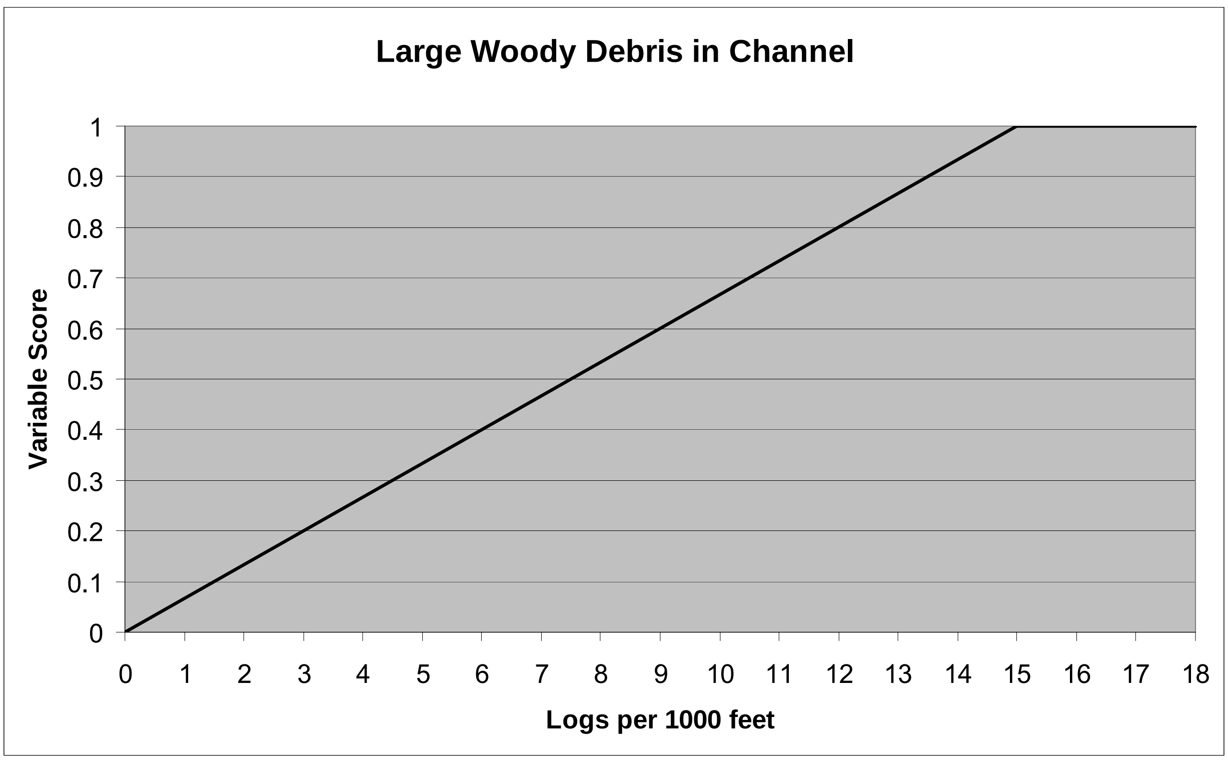
Large woody debris in channel (*LWDEBRIS*). This variable is defined as the number of down logs in the headwater stream channel per 1000 feet. Logs are defined as whole or partial dead tree stems. The portion of the log that is within the channel must be at least 39 inches (1 m) long, or if the channel is narrower than 39 inches (1 m), it must span the channel completely. The portion of the log that is within the channel must have a diameter greater than or equal to 3 inches (8 cm) at the widest point. Large woody debris is a measure of the dead biomass of trees within the high gradient, headwater stream ecosystem. Decomposing wood in the channel reduces channel erosion by dissipating stream energy, provides habitat for vertebrates and invertebrates, and contributes nutrients and organic matter to the downstream ecosystem.

LWDEBRIS is used in calculating the hydrology, biogeochemical, and habitat functional indices.

This variable is quantified by the number of logs in the stream channel per 1000 feet of channel length. Measure *LWDEBRIS* using the following procedure:

1) Measure the length of the stream channel being assessed and count the number of logs that are completely or partially lying in the channel.

2) Use Figure 1 to determine the variable score for the headwater stream. If the channel length is less than or greater than 1000 feet the number of logs needed to receive a variable score of 1.0 is proportional to the length.



In fully functional headwater stream systems in West Virginia the number of logs in the stream channel is 15 or more per 1000 feet of stream channel.

Stream channel geomorphology (*CHANNGEO*). This variable reflects direct alterations to the natural geomorphology of the stream channel. Examples in West Virginia include straightening, removal of the natural step-pool geomorphology, and reducing or increasing the slope or steepness of the stream channel. The intent of this variable is to capture those impacts that alter the slope and shape of natural headwater stream systems. This variable differs from *CHANNELALT* in that the impacts occur within the stream channel without affecting the amount of water in the channel, but do affect the energy of flows and how nutrients are retained within the headwater stream system.

This variable is quantified by the average channel slope and the frequency of step-pools within the stream channel. Measure *CHANNGEO* using the following procedure:

1) If stream is unaltered or the channel slope is greater than 4 percent and has many step-pools, then the subindex score for this variable is 1.0 and the following steps may be skipped.

2) If the channel has been altered or restored, use Table 10 to determine the variable score for stream channel geomorphology. Determine the weighted average for the entire stream reach impacted.

In reference standard sites, there were no alterations to the natural geomorphology of headwater stream channels.

Table 10
Stream channel geomorphology (*CHANNGEO*)

Slope and pools	Score
Greater than 4% slope with many step pools	1.0
2 to 4% slope with common step pools	0.5
1 to 1.9% slope with few step pools	0.1
Less than 1% slope with no step pools	0.0

Functions

Function 1: Hydrology

Definition

The Hydrology function is defined as the capacity of the high gradient, headwater riverine ecosystem to store water within the soil for a few days to several weeks and slowly release this water to streams down slope as well as to transport nutrients and organic matter through surface runoff. A potential independent, quantitative measure for validating the functional index is a direct measurement of the amount of surface water that runsoff as well as the water that is dynamically stored within the soil over a portion of the year.

Rationale for selecting the function

The annual water budget of high gradient headwater riverine streams in West Virginia is controlled mainly by precipitation and upland runoff and secondarily by interception of groundwater. Performance of the Hydrology function causes the ecosystem to retain water inputs for a sufficient period of time to develop other wetland characteristics (e.g., hydric soils, hydrophytic vegetation). Water storage also moderates the pulse of runoff that occurs following a storm event and prolongs the period of discharge into streams maintaining baseflow.

In addition to direct effects of water storage on the stream hydrograph, this function plays a role in all other wetland functions associated with headwater stream systems. Water storage has a significant effect on biogeochemical cycling in the stream. Prolonged saturation leads to anaerobic soil conditions and initiates chemical reactions that are highly dependent upon the redox capacity of the soil (Mausbach and Richardson 1994). The oxygen concentration in wetland soils greatly affects the redox potential and the chemical cycling properties of elements and compounds, particularly nutrients. This function also has important impacts on invertebrate and vertebrate populations. For example, some invertebrates, such as midges, have very short life cycles and are highly adapted to ephemeral systems.

Characteristics and processes that influence the function

The characteristics and processes that influence the capacity of a headwater ecosystem to store water have both natural and anthropogenic origins. Climate and landscape-scale geomorphic characteristics within and around the headwater system are factors largely established by natural processes. Anthropogenic alterations to these ecosystems (e.g., filling, logging) also influence the way the stream system stores and ultimately transports water. Such effects may occur due to changes in the dominant land cover in and near the watershed and stream and whether the stream channel has been hydrologically modified through filling or damming.

In West Virginia, rain is fairly evenly distributed throughout the year. Summer thunderstorms are common and tropical storms and hurricanes occasionally affect the area. Surface soil saturation and runoff can occur during any month and, in some sites, is evident all year. In others, saturation to the surface in the riparian zone is most evident in late winter and early spring before trees have completely leafed out.

In addition to geomorphic and climatic processes, human activities may also have a profound effect on the storage of water within a high gradient, headwater riverine ecosystem. Modifications to the uplands surrounding the stream or directly to the stream itself may affect the receipt and retention of water. Land-use changes, such as filling, soil compaction, road construction, urban development, and changes in evapotranspiration that result from logging are modifications that directly affect this function.

Filling for the purpose of mine spoil disposal and damming to provide stormwater retention have modified many headwater streams, converting them to depressions, lakes, or even uplands. Such modifications so significantly affect the natural short-term water storage of the headwater stream that they lose their natural characteristics and hydrologic functions.

Functional Capacity Index

The following variables are used in the assessment model for the Hydrology function:

- Channel Alterations (*CHANNELALT*)
- Channel Geomorphology (*CHANNELGEO*)
- Large Woody Debris (*LWDEBRIS*)
- Land Cover (*COVER*)
- Watershed Slope (*SLOPE*)
- Tree Cover (*TREE*)
- Shrub Cover (*SHRUB*)
- Herbaceous Cover (*HERB*)

The basic assessment model for calculating the functional capacity index (FCI) for the Hydrology function in forested or shrub-dominated headwater stream systems is as presented in equation 1, below. Equation 2 presents a modified version for application in systems dominated by herbaceous vegetation:

$$\left[\left(CHANNELALT \times \left\{\frac{CHANNELGEO + LWDEBRIS}{2}\right\}\right)^{1/2} \times \left(\frac{COVER + SLOPE + \left\{\frac{TREE + SHRUB}{2}\right\}}{3}\right)\right]^{1/2} \quad (1)$$

$$\left[\left(CHANNELALT \times \left\{\frac{CHANNELGEO + LWDEBRIS}{2}\right\}\right)^{1/2} \times \left(\frac{COVER + SLOPE + HERB}{3}\right)\right]^{1/2} \quad (2)$$

In this model (equation 1), the Hydrology function of high gradient, headwater streams depends on inputs of water from surface runoff from the surrounding upland. Water is removed from the system in surface outflow and evapotranspiration. The model assumes that, if natural hydrologic inputs from runoff from the surrounding uplands are unaltered, outflow is not reduced by filling or increased by downcutting or blocked by anthropogenic obstructions such as dams, and a mature forest is present to disperse runoff at characteristic rates, then the stream is functioning at reference standard condition.

This model addresses three main factors that influence water storage. The first part of the equation reflects natural or anthropogenic alterations to the stream channel (*CHANNELALT*) that affect its capacity move water to other channels downstream. However, storage of atypically large amounts of surface water due to damming the stream results in a decrease in function. The second part is a combination of physical features that slow water flow in the stream channel and relate to the stability of the channel (*CHANNELGEO* and *LWDEBRIS*). The third part of the equation is a combination of factors affecting the supply of water from the surrounding uplands (*COVER* and *SLOPE*) through runoff, and the effect of a mature forest (*TREE* and *SHRUB*) on surface water runoff and erosion of excessive fine sediment into the stream. The first two parts are combined using a geometric mean, the result being that if *CHANNELALT* equals zero the functional capacity index will equal zero for the hydrologic function. Variables in the third part of the equation are averaged using an arithmetic mean.

The three parts of the equation are combined using a geometric mean based on the assumption that *CHANNELALT* is as important as the combination of the other variables in relation to water storage. In other words, if the stream system is drained to the point that it no longer has riverine hydrology and has been changed from a headwater stream to a depressional, upland, or lacustrine system, then the subindex score for *CHANNELALT* would be 0.0 and the functional capacity for water storage would be zero as well. For herbaceous dominated ecosystems (equation 2), the maximum FCI is 0.67.

Function 2: Biogeochemical cycling

Definition

The biogeochemical function is defined as the ability of the high gradient, headwater ecosystem to retain and transform inorganic materials needed for biological processes into organic forms and to oxidize those organic molecules back into elemental forms through decomposition. Thus, biogeochemical cycling includes the biogeochemical processes of producers, consumers, and decomposers. Potential independent, quantitative measures that may be used in validating the functional index include direct measurements of net annual productivity (gm/m^2), annual accumulation of organic matter (gm/m^2), and annual decomposition of organic matter (gm/m^2).

Rationale for selecting the function

Biogeochemical cycling is a fundamental function performed by all ecosystems, but tends to be accomplished at particularly high rates in many wetland systems (Mitsch and Gosselink 2000). A sustained supply of organic carbon in the soil provides for maintenance of the characteristic plant community including annual primary productivity, composition, and diversity (Bormann and Likens 1970, Whittaker 1975, Perry 1994). The plant community (producers) provides the food and habitat structure (energy and materials) needed to maintain the characteristic animal community (consumers) (Crow and MacDonald 1978, Fredrickson 1978, Wharton et al. 1982). In time, the plant and animal communities serve as a source of detritus that is the source of energy and materials needed to maintain the characteristic community of decomposers. The decomposers break down these organic materials into simpler elements and compounds that can reenter the nutrient cycle (Reiners 1972, Dickinson and Pugh 1974, Pugh and Dickinson 1974, Schlesinger 1977, Singh and Gupta 1977, Hayes 1979, Harmon et al. 1986, Vogt et al. 1986).

Characteristics and processes that influence the function

Biogeochemical cycling is a function of biotic and abiotic processes that result from conditions within and around the headwater stream. In high gradient, headwater ecosystems carbon is stored within, and cycled among, four major compartments: (a) the soil, (b) primary producers such as vascular and nonvascular plants, (c) consumers such as animals, fungi, and bacteria, and (d) dead organic matter, such as leaf litter or woody debris, referred to as detritus. It is the maintenance of the characteristic primary productivity of the plant community that sets the stage for all subsequent transformations of energy and materials at each trophic level within the ecosystem. It follows that alterations to hydrologic inputs, outputs, or storage and/or changes to the characteristic plant community will directly affect the way in which the ecosystem can perform this function.

Abiotic processes affecting retention and cycling of carbon are dependent primarily on the adsorption of materials to soil particles, the amount of water that passes through the wetland carrying dissolved carbon, the hydroperiod or retention time of water, and the importation of materials from surrounding areas (Grubb and Ryder 1972, Federico 1977, Beaulac and Reckhow 1982, Ostry 1982, Shahan 1982, Strecker et al. 1992, Zarbock et al. 1994). Natural soils, hydrology, and vegetation are important factors in maintaining these characteristic processes.

The ability of a high gradient, headwater ecosystem to perform this function depends upon the transfer of carbon between trophic levels within the ecosystem, the rate of decomposition, and the flux of materials in and out of the wetland. A change in the ability of one trophic level to process carbon will result in changes in the processing of carbon in other trophic levels (Carpenter 1988).

The ideal approach for assessing biogeochemical cycling in a headwater riverine ecosystem would be to measure the rate at which carbon is transferred and transformed between and within trophic levels over several years. However, the time and effort required to make these measurements are well beyond a rapid assessment procedure, and instead we use plant community structure and detrital loading as indirect indicators. Reference data from other ecosystems suggest that land-use practices and forest management have great effect on plant community structure (species composition and coverage), diversity, and primary productivity. Changes in the vegetative cover directly affect the amount of organic carbon present in the ecosystem. Canopy removal in particular directly affects the amount and type of detritus present in the headwater stream system. Changes in hydrology or vegetation, deposition of fill material, excavation, or recent fire can alter the amount of soil detritus. Changes to the hydrology of headwater ecosystems through drainage, increased surface water flow, or ponding has a tremendous effect on biogeochemical cycling. Increased surface water flow can sweep nearly all detrital matter from the ecosystem and disrupt the biogeochemical cycle. Drainage, over time, changes the vegetative composition and, therefore, the type and amount of detrital matter. Ponding reduces the rate of decomposition and increases the accumulation of organic carbon, as well as changing the vegetative community. It is assumed that measurements of these characteristics reflect the level of biogeochemical cycling taking place within an ecosystem.

Functional capacity index

The following variables are used in the assessment model for the Biogeochemical function:

- Channel Alterations (*CHANNELALT*)
- Channel Geomorphology (*CHANNELGEO*)
- Soil Detritus (*DETRITUS*)
- Large Woody Debris (*LWDEBRIS*)
- Land Cover (*COVER*)
- Watershed Slope (*SLOPE*)
- Tree Cover (*TREE*)
- Shrub Cover (*SHRUB*)
- Herbaceous Cover (*HERB*)

The assessment models for calculating the FCI for the biogeochemical functions in high gradient, headwater riverine systems are given below. The models depend, in part, on the characteristics of the tree and shrub stratum of vegetation within the watershed, including the riparian area. If the site supports a tree or shrub layer ($\geq$10% total cover), then equation 3 is used. If the site is unvegetated or dominated by herbaceous vegetation (<10% canopy cover of trees or shrubs), then equation 4 is used.

$$\left[\left(CHANNELALT \times CHANNELGEO\right)^{1/2} \times \frac{\left(\frac{COVER + SLOPE}{2}\right) + \left(\frac{TREE + SHRUB}{2}\right) + \left(\frac{DETRITUS + LWDEBRIS}{2}\right)}{3}\right]^{1/2} \quad (3)$$

$$\left[\left(CHANNELALT \times CHANNELGEO\right)^{1/2} \times \left\{\frac{HERB + LWDEBRIS + \left(\frac{COVER + SLOPE}{2}\right)}{3}\right\}\right]^{1/2} \quad (4)$$

In these models, changes in the biogeochemical cycling capacity of high gradient, headwater riverine ecosystems relative to reference standard conditions depend on increased outflow of water, or on reductions in water inflows, organic matter, or quantity of vegetation. The models are based on the assumption that if organic matter and vegetation are in place, and anthropogenic hydrologic disturbance is not present in the stream channel or the surrounding watershed, then carbon cycling will occur at an appropriate rate. In the first part of each equation, removal or retention of surface water is represented by *CHANNELALT* and *CHANNGEO*. In the second part, *COVER* and *SLOPE* are averaged and represent inputs related to water quality and time that water and particulates are delivered to the stream system. *DETRITUS* is used as an indicator of recent organic input and accumulation. If vegetation has been removed from the watershed, including the riparian area during the previous year or two, then the amount of detritus will likely be reduced or absent. Also, if the hydrology of the wetland or adjacent watershed has been altered to the point that detritus is being flushed from the headwater ecosystem, then this alteration should be reflected in the amount of detrital cover. Large Woody Debris (*LWDEBRIS*) loading within the channel is an indicator of long-term organic matter accumulation within the watershed as a whole. If hydrology or vegetation has been altered for more than a few years, then the amount of Large Woody Debris should be reduced, reflecting a decrease in organic matter content in the stream system. Also, if fill material has been placed in the stream or adjacent watershed or soil excavation has taken place; the organic matter in the previous condition will have been buried by the fill or removed in excavation. These two variables, *DETRITUS* and *LWDEBRIS* are combined using an arithmetic mean. This is based on the assumption that detritus and large woody debris are of equal importance in biogeochemical cycling. Headwater riverine ecosystem vegetation is represented by the combination of *TREE* and *SHRUB*, or herbaceous vegetative cover (*HERB*). If the amount of vegetation, represented by percent cover, is reduced, then it is assumed that carbon cycling will be reduced.

In equation 3, the variables that directly relate to the channel and variables related to inputs to the stream are combined using a geometric mean. The implications are that if all of the variables in any part of the model equal zero, then the function would receive an FCI of zero. For watersheds where both tree and shrub strata have less than 10 percent cover the maximum FCI is 0.76 (equation 4).

Function 3: Plant Community functions

Definition

This function is defined as the degree to which a high gradient, headwater riverine ecosystem supports a plant community that is similar in structure and composition to that found on the least disturbed sites in West Virginia. Various approaches have been developed to describe and assess plant community characteristics that might be appropriately applied in developing independent measures of this function. However, none of these approaches alone can supply a "direct independent measure" of plant community function, because they are tools that are employed in more complex analyses that require familiarity with regional vegetation and collection of appropriate sample data.

Rationale for selecting the function

The ability to maintain a characteristic plant community is important in part because of the intrinsic value of the species found there. In the West Virginia landscape, the dominant community type is hardwood forest, and the high gradient, headwater riverine subclass constitutes a small percentage of the overall area. The presence of a characteristic plant community also is critical in maintaining various biotic and abiotic processes occurring in wetlands. For example, plant communities are the source of primary productivity, produce carbon and nutrients that may be exported to other ecosystems, and provide habitats and refugia necessary for various animal species (Harris and Gosselink 1990).

Overview of the plant community

The plant communities of headwater ecosystems are complex and vary across the State and even locally. Except immediately following severe disturbances, forest is the dominant community type in these ecosystems. Sites that have been relatively undisturbed for decades or hundreds of years support trees of various sizes and ages. Depending on the species that initially occupy a site after a major disturbance, succession can progress along different paths, but because of small-scale disturbances (e.g., individual trees dying and creating canopy gaps that may be colonized by different species), eventually an uneven-aged forest with well-developed stratification will be achieved (Hunter 1990). In general, older stands tend to be more stratified than younger ones and forests with several vertical strata have higher species diversity than young or middle-aged stands with few strata (Willson 1974, Hunter 1990). This is important in maintenance of the community over time given that species diversity has been found to be positively related to community stability (Bolen and Robinson 2003).

Factors that influence the plant community

Factors that influence the development and maintenance of a characteristic plant community in most wetlands including high gradient, headwater riverine systems in West Virginia include the physical site characteristics, the hydrologic regime, weather events, anthropogenic disturbances, and various ecological processes such as competition, disease, browsing pressure, shade tolerance, and community succession. Alterations to these factors or processes in the stream channel, adjacent riparian area, or to the surrounding watershed may directly affect the species composition and biodiversity of the site (Askins et al. 1987, Keller et al. 1993, Kilgo et al. 1997).

The moisture regime is one of the most important determinants of the structure and composition of plant communities. In high gradient, headwater riverine ecosystems, water delivery occurs as direct precipitation, overland flow, or groundwater discharge from the surroundings uplands. Overland flow is believed to be the most important of the three in the maintenance of hydrology in these riverine systems.

Activities that degrade the physical nature of a stream, especially its flow regime, have the potential to have deleterious effects on the plant community and, if significant enough, may alter the plant community for extended periods, and even permanently. For example, depositing fill in a stream channel fundamentally changes the substrate and hydrologic regime and, if amounts are substantial, can result in conversion of the area from riverine system to upland.

Some alterations that do not even occur in the stream channels themselves may have serious negative consequences for the plant community. For example, clearing the natural vegetation in the upland watershed and adding impervious surfaces (roads, parking lots, etc.) can result in significantly more water entering a stream and could alter community composition and structure. If mean water depths increase beyond the ability of even these species to survive, the area essentially would become an open water basin with vegetation existing only at the edges.

Except for anthropogenic impacts, high gradient, headwater riverine ecosystems in West Virginia are influenced primarily by small-scale frequent disturbances, especially individual tree mortality which leads to gap-phase regeneration. Forests that develop under such conditions generally are composed of shade-tolerant species of different age (and by inference size) classes (Hunter 1990).

Functional capacity index

The following variables are used in the assessment model for the Plant Community function:

- Channel Alterations (*CHANNELALT*)
- Vegetation composition and diversity (*COMP*)
- Tree Cover (*TREE*)
- Shrub Cover (*SHRUB*)
- Herbaceous Cover (*HERB*)

The assessment models for calculating the FCI for the maintenance of a characteristic plant community in high gradient, headwater riverine ecosystems are given below. The choice of models depends on the characteristics of the dominant vegetation present within the ecosystem. If the site contains a tree or shrub layer ($\geq$10% total tree or shrub cover), then equation 5 is used. If neither trees nor shrubs are common (<10% cover), then equation 6 is used.

$$\left[CHANNELALT \times \left(\frac{TREE + SHRUB + COMP}{3}\right)\right]^{1/2} \qquad (5)$$

$$\left(CHANNELALT \times HERB\right)^{1/2} \qquad (6)$$

These models represent the existing plant community in the wetland and include variables that provide insight into its serial stage, structure, species composition, diversity, and stability. The models assume that the physical environment necessary to maintain the community (e.g., hydrology) is also present. If not, any recent environmental changes that may affect the long-term persistence of the community should be reflected in reduced FCIs for Functions 1 and 2. In the context of this function, Average Percent Cover of Trees (*TREE*) and Average Percent Cover of Shrubs (*SHRUB*) are structural indicators of serial stage and of disturbance. The vegetation composition and diversity variable (*COMP*) reflects floristic quality and diversity, as well as seral stage and disturbance. In a forested system (equation 5), subindices for *TREE*, *SHRUB*, and *COMP* are averaged. In systems without trees or shrubs *HERB* is the only vegetation variable and equation 6 is used. In both equations the vegetative variables are combined with *CHANNELALT* using a geometric mean reflecting the importance of hydrology to the ecosystem. For herbaceous dominated ecosystems, the maximum FCI is 0.32.

Function 4: Wildlife Habitat

Definition

This function is defined as the capacity of a high gradient, headwater riverine ecosystem to provide critical life requisites to selected components of the vertebrate and invertebrate wildlife community. Ecosystems within the subclass provide habitat for numerous species of amphibians, reptiles, birds, and mammals. Birds and amphibians were selected as the focus of this function. Birds were chosen because they are of considerable public and agency interest, and they respond rapidly to changes in the quality and quantity of their habitats. In addition, birds are a diverse group and individual species have strong associations with the different strata of the multi-layered forests that characterize those sites that were considered to be functioning at the highest level (reference standard). Birds have been shown to be sensitive indicators and integrators of environmental change such as that brought about by human use and alteration of landscapes (Morrison 1986, Croonquist and Brooks 1991, O'Connell et al. 2000). Amphibians were chosen because of the importance of wetlands as breeding habitat. Various species of salamanders and frogs breed in shallow streams, temporary ponds, and moist leaf litter or duff. In the adult stages, they often disperse into suitable habitat in the adjacent uplands.

A potential independent, quantitative measure of this function that could be used to validate the assessment model (Wakeley and Smith 2001) is the combined species richness of birds and amphibians that use high gradient, headwater ecosystems in West Virginia throughout the annual cycle. Data requirements for model validation include direct monitoring of wildlife communities using appropriate techniques for each taxon. Ralph et al. (1993) described field methods for monitoring bird populations. Gibbons and Semlitsch (1981) described procedures for sampling small animals including reptiles and amphibians. Heyer et al. (1994) and Dodd (2003) described monitoring procedures for amphibians.

Rationale for selecting the function

Wetlands and the adjacent surrounding upland are recognized as valuable habitats for a diversity of animal species including both vertebrates and invertebrates. In the vicinity of headwater streams, birds and mammals are diverse and abundant. However, amphibians can be particularly important. Burton and Likens (1975) reported that amphibians constitute the single largest source of vertebrate biomass in some ecosystems. Because many amphibians require both wetland and adjacent upland habitats, they serve as a conduit for energy exchange between the two systems (Mitchell et al. 2004). Wharton et al. (1982), Johnson (1987), Whitlock et al. (1994), Crowley et al. (1996), Mitsch and Gosselink (2000), and Bailey et al. (2004) are all good sources of information regarding animal communities of wetlands.

Many wildlife species associated with wetlands have experienced serious population declines. Within the United States, approximately one third of the plant and animal species listed as threatened or endangered are associated with wetlands during some part of their life cycles (Dahl and Johnson 1991). In West Virginia, high gradient, riverine wetlands and the adjacent riparian areas constitute a relatively small percentage of the landscape within the state, therefore, these areas are likely are important for the maintenance of local populations of many species.

Characteristics and processes that influence the function

Hydrologic alteration of high gradient, riverine ecosystems has the potential to impact a number of wildlife species, but the most serious impacts would be to amphibians. Animals with direct dependence on water, such as amphibians that use seasonally ponded micro-depressions within high gradient, riverine ecosystems for reproduction, are highly vulnerable to drainage or filling. Even partial draining or filling could impact breeding activity because of the length of time needed for egg development and maturation of the young. There is considerable variability in development time among species. Most anurans require the presence of water for 2-3 months (Duellman and Trueb 1986). Some species, however, require substantially shorter periods of time. Conversely, artificially increasing the amount of time that surface water is present in a riverine ecosystem by excavating or by augmenting runoff into the wetland can potentially reduce the suitability for amphibians by allowing fish populations to become established. Bailey et al. (2004) noted that predatory fish prey on breeding amphibians, their eggs, and tadpoles. They recommended that wherever ecosystems free of fish exist, efforts should be made to avoid accidental or deliberate introductions.

Besides the direct effects of hydrologic change on animals, indirect effects can occur through changes in the plant community. Sites with unaltered hydrology that have not been subjected to significant disturbance for long periods support a characteristic vegetation composition and structure (i.e., tree size, density, stratification, etc.) as described in the plant community model discussion. Wildlife species have evolved with and adapted to these conditions. Thus, altering the hydroperiod has the potential to change the composition and structure of the wildlife community. Factors other than hydrology, including droughts and catastrophic storms, competition, disease, browsing pressure, shade tolerance, community succession, and natural and anthropogenic disturbances, also affect the plant community directly and wildlife community indirectly. Following is an overview of the relationships between specific characteristics of the plant community and wildlife utilization of forested ecosystems including wetlands. Wharton et al. (1982), Hunter (1990), and Morrison et al. (1992) are all good sources of information on this subject.

Habitat structure is probably the most important determinant of wildlife species composition and diversity (Wiens 1969, Anderson and Shugart 1974). Undisturbed high gradient, riverine ecosystems in West Virginia normally contain multiple strata. This structural complexity provides a myriad of habitat conditions for animals and allows numerous species to coexist in the same area (Schoener 1986). This is especially well documented with birds, which tend to show affinities for habitats based on physical characteristics, such as the size and density of overstory trees, density of shrub and ground cover, number of snags, and other factors. For example, some bird species utilize the forest canopy, whereas others are associated with the understory (Cody 1985, Wakeley and Roberts 1996).

While the structure of the forest in the immediate vicinity of a headwater stream is an important determinant of animal habitat availability, the characteristics of adjacent uplands are equally critical to many species. Although tied to wetlands and other aquatic habitats for breeding, many frogs and some salamanders spend the remainder of the year in terrestrial habitats, often in hardwood forests (Mitchell et al. 2004). Semlitsch and Jensen (2001) noted that suitable terrestrial habitat surrounding the breeding site is critical for feeding, growth, maturation, and maintenance of juvenile and adult populations of pond-breeding salamanders. Bailey et al. (2004) concurred, stating that "a seasonal wetland without appropriate surrounding upland habitat will lose its amphibian and reptile fauna." Semlitsch and Jensen (2001) suggested that the terrestrial habitat be referred to as part of the "core habitat" used by the animals, because it is as essential as the breeding site itself. This is different from the traditional concept of the "buffer zone" commonly recommended around wetlands to protect various wetland functions (Boyd 2001).

Semlitsch and Bodie (2003) reviewed the literature on terrestrial habitats used by amphibians. Habitat features such as leaf litter, coarse woody debris (i.e., logs), boulders, small mammal burrows, cracks in rocks, spring seeps, and rocky pools were important for foraging, refuge, or over-wintering. A well-developed canopy (for shade) and coarse woody debris and litter (for refuge and food) were considered to be essential habitat features. The abundance of litter is related to the age of forest stands. The litter layer in an older forest usually is much thicker than in a younger forest due to the differential amount of foliage produced. Young stands do not begin to contain significant amounts of litter and coarse woody debris until natural thinning begins. Coffey (1998) reported that minimal woody debris was found in bottomland hardwood stands younger than 6 years of age. Such a pattern probably also exists in upland forests. Shade, which is critical to some amphibian species in slowing or preventing dehydration (Spight 1968, Rothermel and Semlitsch 2002), is provided to some extent in all forest stands but likely is not effective until tree canopies begin to close (Rothermel and Semlitsch 2002). Thus total canopy cover is an important consideration in evaluating amphibian habitat in forest ecosystems.

Terrestrial areas immediately adjacent to wetlands also are important to the integrity of the wetland ecosystem itself. Such areas serve to reduce the amounts of silt, contaminants, and pathogens that enter the stream, and to moderate physical parameters such as temperature (Rhode et al. 1980, Young et al. 1980, Hupp et al. 1993, Snyder et al. 1995, Daniels and Gilliam 1996, Semlitsch and Jensen 2001, Semlitsch and Bodie 2003). These functions directly or indirectly affect amphibians through improved water quality and provide benefits to the entire wildlife community. Semlitsch and Bodie (2003) recommended a 30-60 m (100-200 ft) wide "buffer" around the wetland for this purpose alone.

Functional Capacity Index

The following variables are used in the assessment model for the function Provide Characteristic Wildlife Habitat:

- Channel Alterations (*CHANNELALT*)
- Channel Geomorphology (*CHANNELGEO*)
- Large Woody Debris (*LWDEBRIS*)
- Land Cover (*COVER*)
- Stream Sediment Size (*SED*)
- Soil Detritus (*DETRITUS*)
- Tree Cover (*TREE*)
- Herbaceous Cover (*HERB*)

The model used for deriving the functional capacity index for the wildlife habitat function in high gradient, riverine ecosystems depend on the characteristics of the uppermost stratum of vegetation within the wetland. If the site supports a tree layer (≥10% total tree or shrub cover), then equation 7 is used. If neither trees nor shrubs are common (<10% cover), then equation 8 is used.

$$\left[CHANNELALT \times \left(\frac{COVER + CHANNGEO + SED + TREE + DETRITUS + LWDEBRIS}{6}\right)\right]^{1/2} \quad (7)$$

$$\left[CHANNELALT \times \left(\frac{COVER + HERB + SED + CHANNGEO + LWDEBRIS}{5} \right) \right]^{\frac{1}{2}} \quad (8)$$

This model is assumed to reflect the ability of high gradient, riverine ecosystems to provide critical life requisites for wildlife, with an emphasis on amphibians and birds. If the components of this model are similar to those found under reference standard conditions, then it is likely that the entire complement of amphibians and birds characteristic of high gradient, riverine ecosystems within the reference domain will be present.

The first part of each equation is an expression of the hydrologic integrity of the stream channel and only involves the variable *CHANNELALT*. In the context of this function, a characteristic hydrologic regime is essential as a source of water for breeding amphibians and to support the plant community upon which the animal community depends. The second part of each equation contains variables that reflect seral stage, cover potential, food production potential, nest site potential, availability of dispersal habitat, and other factors that depend on stand structure, maturity, and connectivity. *TREE* is used when the ecosystem is dominated by trees and *HERB* is used in wetlands lacking sufficient trees. Other features of forested wetlands such as snags, are also are important habitat requirements for various members of the wildlife community, but are not explicitly included in the model. It was assumed that if the structure of the tree layer is appropriate, then these additional features will be present in the appropriate numbers or amounts. Channel integrity is assumed to be critical to the maintenance of wetland wildlife habitat; therefore, the hydrology component is used as a multiplier in each equation. The other terms in the model, which reflect onsite and offsite habitat conditions, are assumed to be partially compensatory (i.e., a low value for one term will be partially compensated by a high value for the other(s)). In high gradient, headwater riverine ecosystems dominated by trees, the maximum possible FCI is 1.0. In ecosystems containing few trees, the maximum FCI is 0.82.

Models

Hydrology Functions

$$\left[\left(CHANNELALT\times\left\{\frac{CHANNELGEO+LWDEBRIS}{2}\right\}\right)^{1/2}\times\left(\frac{COVER+SLOPE+\left\{\frac{TREE+SHRUB}{2}\right\}}{3}\right)\right]^{1/2} \quad (1)$$

$$\left[\left(CHANNELALT\times\left\{\frac{CHANNELGEO+LWDEBRIS}{2}\right\}\right)^{1/2}\times\left(\frac{COVER+SLOPE+HERB}{3}\right)\right]^{1/2} \quad (2)$$

Biogeochemical Functions

$$\left[\left(CHANNELALT\times CHANNELGEO\right)^{1/2}\times\frac{\left(\frac{COVER+SLOPE}{2}\right)+\left(\frac{TREE+SHRUB}{2}\right)+\left(\frac{DETRITUS+LWDEBRIS}{2}\right)}{3}\right]^{1/2} \quad (3)$$

$$\left[\left(CHANNELALT\times CHANNELGEO\right)^{1/2}\times\left\{\frac{HERB+LWDEBRIS+\left(\frac{COVER+SLOPE}{2}\right)}{3}\right\}\right]^{1/2} \quad (4)$$

Plant Community Functions

$$\left[CHANNELALT\times\left(\frac{TREE+SHRUB+COMP}{3}\right)\right]^{1/2} \quad (5)$$

$$\left(CHANNELALT\times HERB\right)^{1/2} \quad (6)$$

Habitat Functions

$$\left[CHANNELALT\times\left(\frac{COVER+CHANNGEO+SED+TREE+DETRITUS+LWDEBRIS}{6}\right)\right]^{1/2} \quad (7)$$

$$\left[CHANNELALT\times\left(\frac{COVER+HERB+SED+CHANNGEO+LWDEBRIS}{5}\right)\right]^{1/2} \quad (8)$$

References

Anderson, S. H., and Shugart, H. H. Jr. (1974). “Habitat selection of breeding birds in an east Tennessee deciduous forest,” *Ecology* 55, 828-837.

Askins, R. A., Philbrick, M. J., and Sugeno, D. S. (1987). “Relationship between the regional abundance of forest and the composition of forest bird communities,” *Biological Conservation* 39, 129-52.

Bailey, M. A., Holmes, J. N., and Buhlmann, K. A. (2004). “Habitat management guidelines for amphibians and reptiles of the southeastern United States.” Partners in Amphibian and Reptile Conservation Technical Publication HMG-2.

Beaulac, N. M., and Reckhow, K. H. (1982). “An examination of land use nutrient export relationships,” *Water Resources Bulletin* 18(6), 1013-24.

Bolen, E. G., and Robinson, W. L. (2003). *Wildlife ecology and management, 5th ed*. Prentice Hall, Upper Saddle River, NJ. 634 pp.

Bormann, F. H., and Likens, G. E. (1970). “The nutrient cycles of an ecosystem,” *Scientific American* 223, 92-101.

Boyd, L. (2001). “Buffer zones and beyond: wildlife use of wetland buffer zones and their protection under the Massachusetts Wetland Protection Act.” Wetland Conservation Professional Program, Department of Natural Resources Conservation, University of Massachusetts, Amherst, MA.

Burton, T. M., and Likens, G. E. (1975). “Salamander populations and biomass in the Hubbard Brook Experimental Forest, New Hampshire,” *Copeia* 1975, 541-546.

Carpenter, S. R. (1988). *Complex interactions in lake communities*. Springer Verlag, New York, 283 pp.

Cody, M. L. (1985). *Habitat selection in birds*. Academic Press, Inc., Orlando, Florida

Coffey, P. L. (1998). “Evaluation of early successional bottomland hardwood forests.” M. S. Thesis, Tennessee Technological University, Cookeville, TN.

Croonquist, M.J., and Brooks, R. P. (1991). “Use of avian and mammalian guilds as indicators of cumulative impacts in riparian wetland areas,” *Environmental Management* 15(5), 701-714.

Crow, J. H., and MacDonald, K. B. (1978). “Wetland values: Secondary productivity,” *Wetland functions and values: The state of our understanding*. P. E. Greeson, J. R. Clark, and J. E. Clark, ed., American Water Resources Association, Minneapolis, MN.

Dahl, T. E., and Johnson, C. E. (1991). “”Status and trends of wetlands in the coterminous United States, mid-1970s to mid-1980s,” U. S. Fish and Wildlife Service, Washington, DC.

Daniels, R. B., and Gilliam J. W. 1996. “Sediment and chemical load reduction by grass and riparian filters.” *Soil Science Society of America Journal* 60, 246-251.

Dickinson, C. H., and Pugh, G. (1974). *Biology of plant litter decomposition, Vol. 1*. Academic Press, London, England.

Dodd, C. K., Jr. (2003). "Monitoring amphibians in Great Smoky Mountains National Park.," Circular No. 1258, U.S. Geological Survey, Washington, DC, 117 pp.

Duellman, W. E., and Trueb, L. (1986). *Biology of amphibians.* McGraw-Hill, New York.

Federico, A. D. (1977). "Investigations of the relationship between land use, rainfall, and runoff quality in the Taylor Creek watershed," Technical Publication 77-3, South Florida Water Management District, West Palm Beach, FL.

Fredrickson, L. H. (1978). "Lowland hardwood wetlands : Current status and habitat values for wildlife," *Wetland functions and values: The state of our understanding*. P. E. Greeson, J. R. Clark, and J. E. Clark, eds., American Water Resources Association, Minneapolis MN.

Gemborys, S. R., and Hodgkins, E. J. (1971). "Forests of small stream bottoms in the coastal plain of southwestern Alabama," *Ecology* 52, 70-84.

Gibbons, J. W., and R. D. Semlitsch. (1981). "Terrestrial drift fences and pitfall traps: An effective technique for quantitative sampling of animal populations," *Brimleyana* 7, 1-16.

Grubb, H. F., and Ryder, P. D. (1972). "Effects of coal mining on the water resources of the Tradewater River Basin, Kentucky," Geological Survey Water-Supply Paper 1940, U.S. Government Printing Office, Washington, DC.

Harmon, M. E., Franklin, J. F., and Swanson, F. J. (1986). "Ecology of coarse woody debris in temperate ecosystems," *Advances in Ecological Research* 15, 133-302.

Harris, L. D., and Gosselink, J. G. (1990). "Cumulative impacts of bottomland hardwood forest conversion on hydrology, water quality, and terrestrial wildlife." *Ecological processes and cumulative impacts illustrated by bottomland hardwood wetland ecosystems.* J. G. Gosselink, L. C. Lee, and T. A. Muir, ed., Lewis Publishers, Chelsea, MI, 259-322.

Hayes, A. J. (1979). "The microbiology of plant litter decomposition," *Scientific Progress* 66, 25-42.

Heyer, W. R., M. A. Donnelly, R. W. McDiarmid, L. C. Hayek, and M. S. Foster. (1994). *Measuring and monitoring biological diversity: Standard methods for amphibians.* Smithsonian Institution Press, Washington, DC.

Hunter, M. L. (1990). *Wildlife, forests, and forestry: Principles of managing forests for biological diversity.* Prentice Hall, Englewood Cliffs, NJ.

Hupp, C. R., Woodside, M. D., Yanosky, T. M. (1993). "Sediment and trace element trapping in a forested wetland, Chichahominy River, Va," *Wetlands* 13, 95-104.

Johnson, T. R. (1987). "The amphibians and reptiles of Missouri," Missouri Department of Conservation, Jefferson City, Missouri.

Keller, C. M. E., Robbins, C. S., and Hatfield, J. S. (1993). "Avian communities in riparian forests of different widths in Maryland and Delaware," *Wetlands* 13, 137-44.

Kilgo, J. C., Sargent, R. A., Miller, K. V., and Chapman, B. R. (1997). "Landscape influences on breeding bird communities in hardwood fragments in South Carolina," *Wildlife Society Bulletin* 25, 878-85.

Mausbach, M. J., and Richardson, J. L. (1994). "Biogeochemical processes in hydric soils," *Current Topics in Wetland Biogeochemistry* 1, 68-127.

Mitchell, J. C., I. N., Bailey, M. A., Holmes, J. N., and Buhlmann, K. A. (2004). "Habitat management guidelines for amphibians and reptiles of the southeastern United States." Partners in Amphibian and Reptile Conservation Technical Publication HMG-2.

Mitsch, W. J., and Gosselink, J. G. (2000). *Wetlands. 3rd ed*., John Wiley and Sons, New York.

Morrison, M. L. (1986). "Bird populations as indicators of environmental change," *Current Ornithology* 3, 429-451.

Morrison, M. L., Marcot, B. C., and Mannan, R. W. (1992). *Wildlife Habitat Relationships: Concepts and Applications*. University of Wisconsin Press, Madison, Wisconsin.

Nelson, J. B. (1986). "The Natural Communities of South Carolina: Initial Classification and Description." S.C. Wildlife and Marine Resources Dept. Division of Wildlife and Freshwater Fisheries. Columbia, SC.

O'Connell, T. J., L. E. Jackson, and R. P. Brooks. (2000). "Bird guilds as indicators of ecological condition in the central Appalachians," *Ecological Applications* 10, 1706-1721.

Ostry, R. C. (1982). "Relationship of water quality and pollutant loads to land uses in adjoining watersheds," *Water Resources Bulletin* 18 (1), 99-104.

Perry, D. A. (1994). *Forest ecosystems.* Johns Hopkins University Press, Baltimore, MD.

Pugh, G., and Dickinson, C. H. (1974). *Biology of plant litter decomposition, Vol. II.* Academic Press, London, England.

Ralph, C. J., Geupel, G. R., Pyle, P., Martin, T. E., and DeSante, D. F. (1993). "Handbook of field methods for monitoring landbirds," General Technical Report PSW-GTR-144, U.S. Dept. of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA. 41 pp.

Reiners, W. A. (1972). "Terrestrial detritus and the carbon cycle," G. M. Woodwell and E. V. Pecan, ed. *Carbon and the biosphere*. Conference proceedings, United States Atomic Energy Commission.

Rhode, W. A., Asmussen, L. E., Hauser, E. W., Wauchope, R. D., and Allison, H. D. 1980. "Trifluralin movement in runoff from a small agricultural watershed," *Journal of Environmental Quality* 9, 37-42.

Rothermel, B. B., and Semlitsch, R. D. (2002). "An experimental investigation of landscape resistance of forest versus old-field habitats to emigrating juvenile amphibians," *Conservation Biology* 16, 1324-1332.

Schlesinger, W. H. (1977). "Carbon balance in terrestrial detritus," *Annual review of ecology and systematics* 8, 51-81.

Schoener, T. W. (1986). "Resource partitioning." *Community ecology: Patterns and processes*. J. Kikkawa and D. J. Anderson, eds., Blackwell, Melbourne, 91-126.

Rosgen, D. and Silvey, L. (1998). Field Guide for Stream Classification. Wildland Hydrology, Colorado.

Semlitsch, R. D., and Bodie, J. R. (2003). "Biological criteria for buffer zones around wetlands and riparian habitats for amphibians and reptiles," *Conservation Biology* 17, 1219-1227.

Semlitsch, R. D., and Jensen, J. B. (2001). "Core habitat, not buffer zone," *National Wetlands Newsletter* 23, 5-6.

Shahan, A. N. (1982). "Estimation of pre- and post-development nonpoint water quality loadings," *Water Resources Bulletin* 18, 231-237.

Singh, J. S., and Gupta, S. R. (1977). "Plant decomposition and soil respiration in terrestrial ecosystems," *Botanical Review* 43, 449-528.

Snyder, N. J, Mostaghimi, S., Berry, D. F., Reneau, R. B., and Smith, E. P. (1995). "Evaluation of a riparian wetland as a naturally occurring decontamination zone." *Clean water, clean environment – 21st century. Volume III: Practices, systems, and adoption.* Proceedings of a conference March 5-8, 1995, Kansas City, Mo., American Society of Agricultural Engineers, St. Joseph, Michigan, 259-262.

Spight, T. M. (1968). "The water economy of salamanders: evaporative water loss," *Physiological Zoology* 41, 195-203.

Strecker, E. W., Kernar, J. M., Driscoll, E. D., Horner, R. R., and Davenport, T. E. (1992). "The use of wetlands for controlling stormwater pollution," The Terrene Institute, Alexandria, VA.

U.S. Department of Agriculture, Soil Conservation Service. (1993). Soil Survey Manual. USDA Handbook 18. U.S. Government Printing Office, Washington, D.C.

U.S. Department of Agriculture. (2004). "Soil Survey of McDowell County, West Virginina," Natural Resources Conservation Service.

U. S. Fish and Wildlife Service. (1980). "Habitat Evaluation Procedures," Ecological Services Manual 102, Washington, DC.

Vogt, K. A., Grier, C. C., and Vogt, D. J. (1986). "Production, turnover, and nutrient dynamics of above and belowground detritus of world forests," *Advances in Ecological Research* 15, 303-77.

Wakeley, J. S., and Roberts, T. H. (1996). "Bird distribution and forest zonation in a bottomland hardwood wetland," *Wetlands* 16, 296-308.

Wakeley, J. S. and Smith, R. D. (2001). "Hydrogeomorphic Approach to Assessing Wetland Functions: Guidelines for Developing Regional Guidebooks - Chapter 7 Verifying, Field Testing, and Validating Assessment Models," ERDC/EL TR-01-31, U.S. Army Engineer Research and Development Center, Vicksburg, MS (http://el.erdc.usace.army.mil/wetlands/pdfs/trel01-31.pdf).

Wharton, C. H., Kitchens, W. M., Pendleton, E. C., and Sipe, T. W. (1982). "The ecology of bottomland hardwood swamps of the southeast: A community profile," Report FWS/OBS-81/37, U.S. Fish and Wildlife Service, Office of Biological Services, Washington, DC.

Whitlock, A. L., Jarman, N. M., and Larson, J. S. (1994). "WEThings; Wetland Habitat Indicators for Nongame Species, Wetland-Dependent Amphibians, Reptiles and Mammals of New England," Publication 94-1, The Environmental Institute, University of Massachusetts, Amherst, MA.

Whittaker, R. H. (1975). *Communities and ecosystems.* MacMillan Publishing Company, New York.

Wiens, J. A. (1969). "An approach to the study of ecological relationships among grassland birds," *Ornithological Monographs* 8, 1-93.

Willson, M. F. (1974). "Avian community organization and habitat structure," *Ecology* 55, 1017-1029.

Young, R. A., Huntrods, T. and Anderson, W. (1980). "Effectiveness of riparian buffer strips in controlling pollution from feedlot runoff," *Journal of Environmental Quality* 9, 483-487.

Zarbock, H., Janicki, A., Wade, D., Heimbuch, D., and Wilson, H. (1994). "Estimates of total nitrogen, total phosphorus, and total suspended solids loadings to Tampa Bay, Florida," Tampa Bay National Estuary Program, St. Petersburg, FL.

Site Name -

Assessment Date -

Impact Area (acres) -

Impacted Stream Length (feet) -

Stream channel alterations (*CHANNELALT*)	
Type of Alteration	**%**
unaltered	
restored	
incised or excess sediment in channel	
dammed	
channelized/straightened	
dredged	
Channel >50% filled	

Average Percent Slope of Watershed (*SLOPE*)	
Percent Slope	**%**
30 to 45 or unaltered	
(20 to 29) or (46 to 65)	
10 to 19	
(5 to 9) or (66 to 90)	
less than 5	

Average Stream Sediment Size (*SED*)	
USDA Texture	**%**
bolders, stones, and cobbles (>3 in.)	
gravel (3/4 to 3 in.)	
sand	
silt	
clay/pavement	

Land Cover Within Watershed (*COVER*)	
Land cover	**%**
forest	
shrub	
orchards	
pasture or hay	
urban, roads	

Average Percent Cover of Trees (*TREE*) (≥3 in. dbh)	
Percent Cover	**%**
Greater than 90	
70 to 90	
50 to 69	
20 to 49	
10 to 19	
less than 10	

Average Percent Cover of Shrubs (*SHRUB*) (>39 in tall and <3 in. dbh)	
Percent Cover	**%**
Greater than 50	
20 to 50	
10 to 19	
less than 10	

Average Percent Cover of Herbaceous Vegetation (*HERB*)	
Percent Cover	**%**
70 to 100	
less than 70	

Number of Native Species (*COMP*)	
# of species	

Average Percent Cover of Detritus (*DETRITUS*)	
Percent Cover	**%**
Greater than 75	
50 to 75	
25 to 49	
10 to 24	
less than 10	

Large Woody Debris in Channel (*LWDEBRIS*)	
# of logs in channel	

Channel Geomorphology (*CHANNGEO*)	
Slope and Pools	**%**
>4% slope with many step pools (or unaltered)	
2 to 4% slope with common step pools	
1 to 1.9% slope with few step	
Less than 1% slope with no step pools	

Investigator(s):	
County:	
Latitude:	
Longitude:	
Topo Quad:	

Remarks:

Photos

Identifier	Description

A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

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The River Continuum Concept[1]

ROBIN L. VANNOTE

Stroud Water Research Center, Academy of Natural Sciences of Philadelphia, Avondale, PA 19311, USA

G. WAYNE MINSHALL

Department of Biology, Idaho State University, Pocatello, ID 83209, USA

KENNETH W. CUMMINS

Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR 97331, USA

JAMES R. SEDELL

Weyerhauser Corporation, Forestry Research, 505 North Pearl Street, Centralia, WA 98531, USA

AND COLBERT E. CUSHING

Ecosystems Department, Battelle-Pacific Northwest Laboratories, Richland, WA 99352, USA

VANNOTE, R. L., G. W. MINSHALL, K. W. CUMMINS, J. R. SEDELL, AND C. E. CUSHING. 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37: 130–137.

From headwaters to mouth, the physical variables within a river system present a continuous gradient of physical conditions. This gradient should elicit a series of responses within the constituent populations resulting in a continuum of biotic adjustments and consistent patterns of loading, transport, utilization, and storage of organic matter along the length of a river. Based on the energy equilibrium theory of fluvial geomorphologists, we hypothesize that the structural and functional characteristics of stream communities are adapted to conform to the most probable position or mean state of the physical system. We reason that producer and consumer communities characteristic of a given river reach become established in harmony with the dynamic physical conditions of the channel. In natural stream systems, biological communities can be characterized as forming a temporal continuum of synchronized species replacements. This continuous replacement functions to distribute the utilization of energy inputs over time. Thus, the biological system moves towards a balance between a tendency for efficient use of energy inputs through resource partitioning (food, substrate, etc.) and an opposing tendency for a uniform rate of energy processing throughout the year. We theorize that biological communities developed in natural streams assume processing strategies involving minimum energy loss. Downstream communities are fashioned to capitalize on upstream processing inefficiencies. Both the upstream inefficiency (leakage) and the downstream adjustments seem predictable. We propose that this River Continuum Concept provides a framework for integrating predictable and observable biological features of lotic systems. Implications of the concept in the areas of structure, function, and stability of riverine ecosystems are discussed.

Key words: river continuum; stream ecosystems; ecosystem structure, function; resource partitioning; ecosystem stability; community succession; river zonation; stream geomorphology

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De la tête des eaux à l'embouchure, un réseau fluvial offre un gradient continu de conditions physiques. Ce gradient devrait susciter, chez les populations habitant dans le réseau, une série de réponses aboutissant à un continuum d'ajustements biotiques et à des schémas uniformes de charge, transport, utilisation et emmagasinage de la matière organique sur tout le

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parcours d'une rivière. Faisant appel à la théorie de l'équilibre énergétique des spécialistes de la géomorphologie fluviale, nous avançons l'hypothèse que les caractéristiques structurales et fonctionnelles des communautés fluviatiles sont adaptées de façon à se conformer à la position ou condition moyenne la plus probable du système physique. Nous croyons que les communautés de producteurs et de consommateurs caractéristiques d'un segment donné de la rivière se mettent en harmonie avec les conditions physiques dynamiques du chenal. Dans des réseaux fluviaux naturels, on peut dire que les communautés biologiques forment un continuum temporel de remplacements synchronisés d'espèces. Grâce à ce remplacement continu, il y a répartition dans le temps de l'utilisation des apports énergétiques. Ainsi, le système biologique vise à un équilibre entre une tendance vers l'utilisation efficace des apports d'énergie en partageant les ressources (nourriture, substrat, etc.), d'une part, et une tendance opposée vers un taux uniforme de transformation de l'énergie durant l'année, d'autre part. A notre avis, les communautés biologiques habitant dans des cours d'eau naturels adoptent des stratégies de transformation comportant une perte minimale d'énergie. Les communautés d'aval sont organisées de façon à tirer profit de l'inefficacité de transformation des communautés d'amont. On semble pouvoir prédire à la fois l'inefficacité (fuite) d'amont et les ajustements d'aval. Nous suggérons ce concept d'un continuum fluvial comme cadre dans lequel intégrer les caractères biologiques prévisibles et observables des systèmes lotiques. Nous analysons les implications du concept quant à la structure, fonction et stabilité des écosystèmes fluviaux.

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Statement of the Concept

Many communities can be thought of as continua consisting of mosaics of integrading population aggregates (McIntosh 1967; Mills 1969). Such a conceptualization is particularly appropriate to streams. Several workers have visualized streams as possessing assemblages of species which respond by their occurrences and relative abundances to the physical gradients present (Shelford 1911; Thompson and Hunt 1930; Ricker 1934; Ide 1935; Burton and Odum 1945; Van Deusen 1954; Huet 1954, 1959; Slack 1955; Minshall 1968; Ziemer 1973; Swanston et al. 1977; Platts 1979). Expansion of this idea to include functional relationships has allowed development of a framework, the "River Continuum Concept," describing the structure and function of communities along a river system. Basically, the concept proposes that understanding of the biological strategies and dynamics of river systems requires consideration of the gradient of physical factors formed by the drainage network. Thus energy input, and organic matter transport, storage, and use by macroinvertebrate functional feeding groups may be regulated largely by fluvial geomorphic processes. The patterns of organic matter use may be analogous to those of physical energy expenditure proposed by geomorphologists (Leopold and Maddock 1953; Leopold and Langbein 1962; Langbein and Leopold 1966; Curry 1972). Further, the physical structure coupled with the hydrologic cycle form a templet (Southwood 1977) for biological responses and result in consistent patterns of community structure and function and organic matter loading, transport, utilization, and storage along the length of a river.

Derivation of the Concept

As the cyclic theory for explaining the evolution of land forms and streams (young, mature, ancient) proved unsatisfactory, the concepts gradually were replaced by a principle of dynamic equilibrium (Curry 1972). The concept of the physical stream network system and the distribution of watersheds as open systems in dynamic ("quasi") equilibrium was first proposed by Leopold and Maddock (1953) to describe consistent patterns, or adjustments, in the relationships of stream width, depth, velocity, and sediment load. These "steady state" systems are only rarely characterized by exact equilibria and generally the river and its channel tend toward a mean form, definable only in terms of statistical means and extremes (Chorley 1962); hence, the idea of a "dynamic" equilibrium. The equilibrium concept was later expanded to include at least nine physical variables and was progressively developed in terms of energy inputs, efficiency in utilization, and rate of entropy gain (Leopold and Langbein 1962; Leopold et al. 1964; Langbein and Leopold 1966). In this view, equilibration of river morphology and hydraulics is achieved by adjustments between the tendency of the river to maximize the efficiency of energy utilization and the opposing tendency toward a uniform rate of energy use.

Based upon these geomorphological considerations, Vannote initially formulated the hypothesis that structural and functional characteristics of stream communities distributed along river gradients are selected to conform to the most probable position or mean state of the physical system. From our collective experience with a number of streams, we felt it was possible to translate the energy equilibrium theory from the physical system of geomorphologists into a biological analog. In this analysis, producer and consumer communities characteristic of a given reach of the river continuum conform to the manner in which the river system utilizes its kinetic energy in achieving a dynamic equilibrium. Therefore, over extended river reaches, biological communities should become established which approach equilibrium with the dynamic physical conditions of the channel.

Implications of the Concept

It is only possible at present to trace the broad outlines of the ways the concept should apply to stream ecosystems and to illustrate these with a few examples for which reasonably good information is available. From headwaters to downstream extent, the physical variables within a stream system present a continuous gradient of conditions including width, depth, velocity, flow volume, temperature, and entropy gain. In developing a biological analog to the physical system, we hypothesize that the biological organization in rivers conforms structurally and functionally to kinetic energy dissipation patterns of the physical system. Biotic communities rapidly adjust to any changes in the redistribution of use of kinetic energy by the physcial system.

Stream Size and Ecosystem Structure and Function

Based on considerations of stream size, we propose some broad characteristics of lotic communities which can be roughly grouped into headwaters (orders 1–3), medium-sized streams (4–6), and large rivers (>6) (Fig. 1). Many headwater streams are influenced strongly by the riparian vegetation which reduces autotrophic production by shading and contributes large amounts of allochthonous detritus. As stream size increases, the reduced importance of terrestrial organic input coincides with enhanced significance of autochthonous primary production and organic transport from upstream. This transition from headwaters, dependent on terrestrial inputs, to medium-sized rivers, relying on algal or rooted vascular plant production, is thought to be generally reflected by a change in the ratio of gross primary productivity to community respiration (P/R) (Fig. 2). The zone through which the stream shifts from heterotrophic to autotrophic is primarily dependent upon the degree of shading (Minshall 1978). In deciduous forests and some coniferous forests, the transition probably is approximately at order 3 (Fig. 1). At higher elevations and latitudes, and in xeric regions where riparian vegetation is restricted, the transition to autotrophy may be in order 1. Deeply incised streams, even with sparse riparian vegetation, may be heterotrophic due to side slope ("canyon") shading.

Large rivers receive quantities of fine particulate organic matter from upstream processing of dead leaves and woody debris. The effect of riparian vegetation is insignificant, but primary production may often be limited by depth and turbidity. Such light attenuated systems would be characterized by P/R < 1. Streams of lower order entering midsized or larger rivers (e.g. the 3rd order system shown entering the 6th order

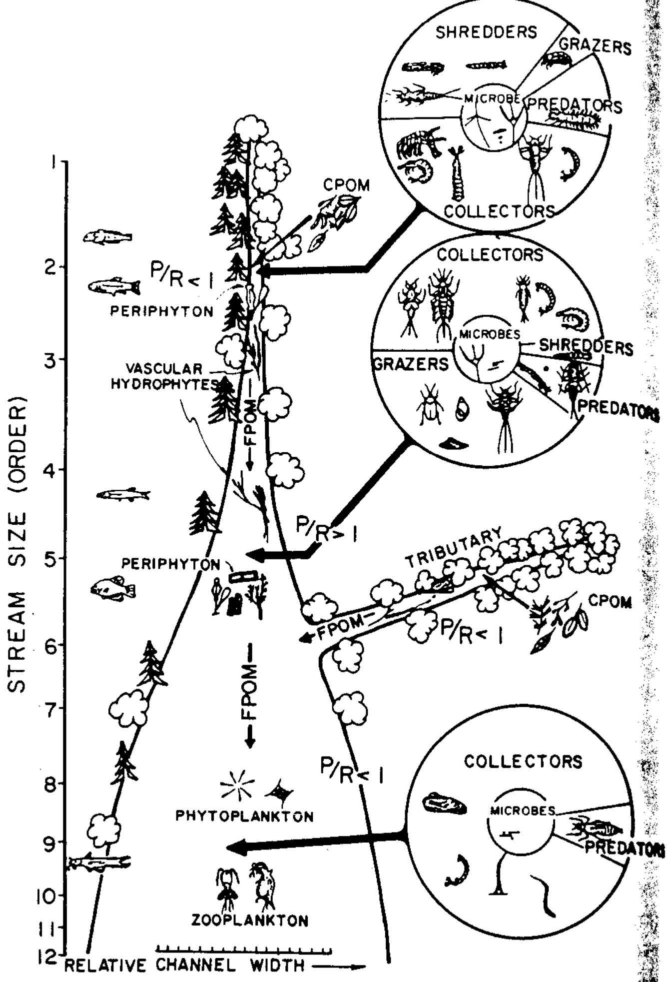

FIG. 1. A proposed relationship between stream size and the progressive shift in structural and functional attributes of lotic communities. See text for fuller explanation.

river in Fig. 1) have localized effects of varying magnitude depending upon the volume and nature of the inputs.

The morphological–behavioral adaptations of running water invertebrates reflect shifts in types and locations of food resources with stream size (Fig. 1). The relative dominance (as biomass) of the general functional groups — shredders, collectors, scrapers (grazers), and predators are depicted in Fig. 1. Shredders utilize coarse particulate organic matter (CPOM, >1 mm), such as leaf litter, with a significant dependence on the associated microbial biomass. Collectors filter from transport, or gather from the sediments, fine and ultrafine particulate organic matter (FPOM, 50 μm–1 mm; UPOM 0.5–50 μm). Like shredders, collectors depend on the microbial biomass associated with the particles (primarily on the surface) and products of microbial metabolism for their nutrition. Scrapers are adapted primarily for shearing attached algae from surfaces. The proposed dominance of scrapers follows shifts in primary production, being maximized in midsized rivers

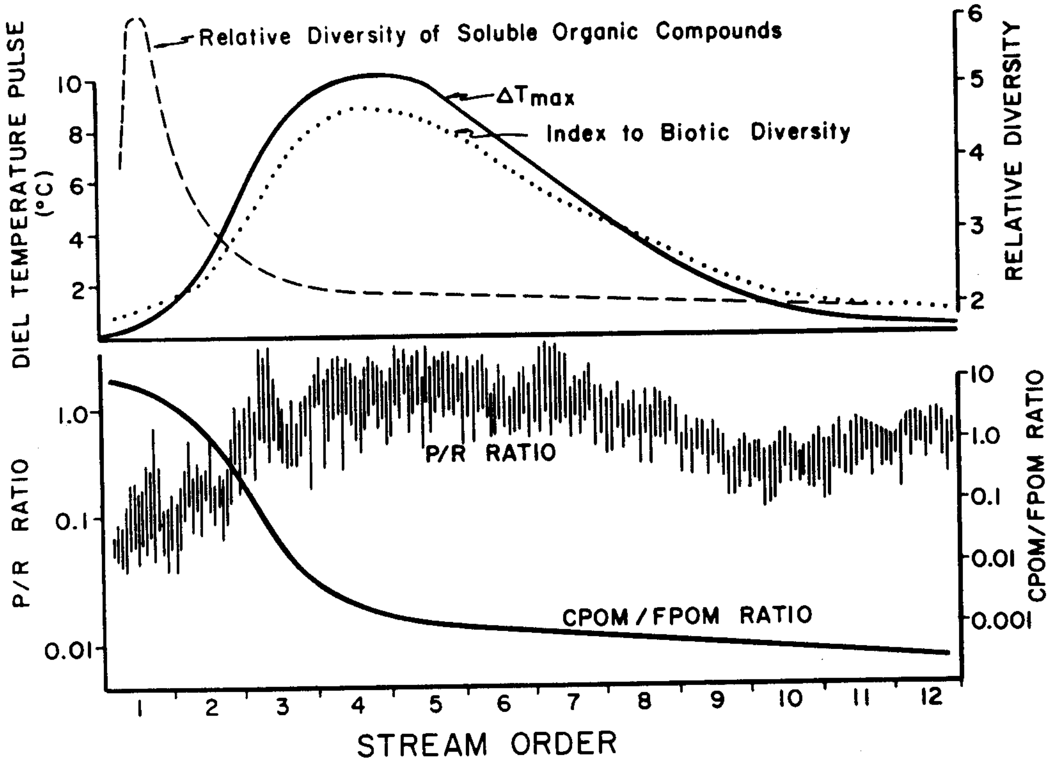

FIG. 2. Hypothetical distribution of selected parameters through the river continuum from headwater seeps to a twelfth order river. Parameters include heterogeneity of soluble organic matter, maximum diel temperature pulse, total biotic diversity within the river channel, coarse to fine particulate organic matter ratio, and the gross photosynthesis/respiration ratio.

with $P/R > 1$. Shredders are hypothesized to be codominant with collectors in the headwaters, reflecting the importance of riparian zone CPOM and FPOM–UPOM derived from it. With increasing stream size and a general reduction in detrital particle size, collectors should increase in importance and dominate the macroinvertebrate assemblages of large rivers (Fig. 1).

The predatory invertebrate component changes little in relative dominance with stream order. Fish populations (Fig. 1) show a shift from cool water species low in diversity to more diverse warm water communities (e.g. Huet 1954). Most headwater species are largely invertivores. Piscivorous and invertivorous species characterize the midsized rivers and in large rivers some planktivorous species are found — reflecting the semi-lentic nature of such waters.

The expected diversity of soluble organic compounds through the continuum is shown in Fig. 2 (dashed line). Headwater streams represent the maximum interface with the landscape and therefore are predominantly accumulators, processors, and transporters of materials from the terrestrial system. Among these inputs are heterogeneous assemblages of labile and refractory dissolved compounds, comprised of short- and long-chain organics. Heterotrophic use and physical absorption of labile organic compounds is rapid, leaving the more refractory and relatively high molecular weight compounds for export downstream. The relative importance of large particle detritus to energy flow in the system is expected to follow a curve similar to that of the diversity of soluble organic compounds; however, its importance may extend further downstream.

Thus the river system, from headwaters to mouth, can be considered as a gradient of conditions from a strongly heterotrophic headwater regime to a seasonal, and in many cases, an annual regime of autotrophy in midreaches, and then a gradual return to heterotrophic processes in downstream waters (Fisher 1977). Major bioenergetic influences along the stream continuum are local inputs (allochthonous litter and light) and transport from upstream reaches and tributaries (Fig. 1). As a consequence of physical and biological processes, the particle size of organic material in transport should become progressively smaller down the continuum (reflected by CPOM:FPOM ratio in Fig. 2, except for localized input of lower order tributaries) and the stream community response reflect progressively more efficient processing of smaller particles.

RIVER ECOSYSTEM STABILITY

Stability of the river ecosystem may be viewed as a tendency for reduced fluctuations in energy flow, while community structure and function are maintained, in the face of environmental variations. This implicitly couples community stability (sensu Ricklefs 1979) to the instability ("noise") of the physical system. In highly stable physical systems, biotic contribution to ecosystem stability may be less critical. However, in widely fluctuating environments (e.g. stream reaches with lage fluctuations in temperature), the biota may assume critical importance in stabilizing the entire system. In this interpretation, ecosystem stability is achieved by a dynamic balance between forces contributing to stabilization (e.g. debris dams, filter feeders, and other retention devices; nutrient cycling) and those contributing to its instability (e.g. floods, temperature fluctuations, microbial epidemics). In systems with a highly stable physical structure, biotic diversity may be low and yet total stability of the stream ecosystem still be maintained. In contrast, systems with a high degree of physical variation may have high species diversity or at least high complexity in species function which acts to maintain stability.

For example, in stream zones experiencing wide diel temperature changes, organisms may be exposed to suboptimum temperatures for significant portions of the day, but over some range in the diel cycle each organism encounters a favorable or optimum temperature range. Under these conditions an optimum temperature will occur for a larger number of species than if the thermal regime displayed minimum variance. Also, in the thermally fluctuating system, many populations have an opportunity to process energy, and as temperatures oscillate around a mean position, various populations may increase or decrease their processing rates. Thus, an important aspect of the predictably fluctuating physical system is that it encompasses optimum conditions for a large number of species. This interplay between physical and biological components can be seen in terms of ecosystem stability by considering the response of total biotic diversity in the river channel as balanced against the maximum diel temperature range (ΔT max) (Fig. 2). Headwater streams in proximity to groundwater supply or infiltration source areas exhibit little variation in ΔT max. With increased distance from subsurface sources and separation of the forest canopy, ΔT max will attain its widest variance because of increased solar input. The ΔT max amplitude is greatly diminished in high order streams due to the buffering effect of the large volume of water in the channel (Ross 1963). In headwater springs and brooks, diversity may be low because biological communities are assembled from those species which can function within a narrow temperature range on a restricted nutritional base; the stability of the system may be maintained by the low amplitude of diel and annual temperature regimes. Total community diversity is greatest in medium-sized (3rd to 5th order in Fig. 2) streams where temperature variations tend to be maximized. The tendency to stabilize energy flow in midsized streams may be aided by high biotic diversity which mitigates the influence of high variance in the physical system as characterized by ΔT max; i.e. variation due to fluctuating thermal regimes should be offset by a high diversity of biota. In large rivers, stability of the system should be correlated with reduction in variance of diel temperature. We wish to emphasize that temperature is not the only factor responsible for the change in community structure; it is simply one of the easiest to visualize. Other factors such as riparian influence, substrate, flow, and food also are important and change in predictable fashion downstream both absolutely and in terms of the relative heterogeneity of each.

Temporal Adjustments in Maintaining an Equilibrium of Energy Flow

Natural stream ecosystems should tend towards uniformity of energy flow on an annual basis. Although the processing rates and efficiencies of energy utilization by consumer organisms are believed to approach equilibrium for the year, the major organic substrates shift seasonally. In natural stream systems, both living and detrital food bases are processed continuously, but there is a seasonal shift in the relative importance of autotrophic production vs. detritus loading and processing. Several studies (Minshall 1967; Coffman et al. 1971; Kaushik and Hynes 1971; MacKay and Kalff 1973; Cummins 1974; Sedell et al. 1974) have shown the importance of detritus in supporting autumn-winter food chains and providing a fine particle base for consumer organisms during other seasons of the year. Autotrophic communities often form the major food base, especially in spring and summer months (Minshall 1978).

Studies on headwater (order 1–3) streams have shown that biological communities in most habitats can be characterized as forming a temporal sequence of synchronized species replacement. As a species completes its growth in a particular microhabitat, it is replaced by other species performing essentially the same function, differing principally by the season of growth (Minshall 1968; Sweeney and Vannote 1978; Vannote 1978; Vannote and Sweeney 1979). It is this continuous species replacement that functions to distribute the utilization of energy inputs over time (e.g. Wallace et al. 1977). Individuals within a species will tend to exploit their environment as efficiently as possible. This results in the biological system (composite species assemblage) tending to maximize energy consumption. Because some species persist through time and because new species become dominant, and these too are exploiting their environment as efficiently as possible, processing of energy by the changing biological system tends to result in uniform energy processing over time. Thus, the biological system moves towards equilibrium by a trade-off between a tendency to make most efficient use of energy inputs through resource partitioning of food, substrate, temperature, etc. and tendency toward a uniform rate of energy processing throughout the year. From strategies observed on small to medium-sized streams (orders 1–5), we propose that biological communities, developed in natural streams in dynamic equilibrium, assume processing strategies involving minimum energy loss (termed maximum "spiraling" by Webster 1975).

Ecosystem Processing Along the Continuum

The dynamic equilibrium resulting from maximization of energy utilization and minimization of variation in its use over the year determines storage or leakage of energy. Storage includes production of new tissue and physical retention of organic material for future processing. In stream ecosystems, unused or partially processed materials will tend to be transported downstream. This energy loss, however, is the energy income, together with local inputs, for communities in downstream reaches. We postulate that downstream communities are structured to capitalize on these inefficiencies of upstream processing. In every reach some material is processed, some stored, and some released. The amount released in this fashion has been used in calculating system efficiency (Fisher 1977). Both the upstream inefficiency (leakage) and the downstream adjustments seem predictable. Communities distributed along the river are structured to process materials (specific detrital sizes, algae, and vascular hydrophytes) thereby minimizing the variance in system structure and function. For example, materials prone to washout, such as flocculant fine-particle detritus, might be most efficiently processed either in transport or after deposition in downstream areas. The resistivity of fine particle detritus to periodic washout is increased by sedimentation in depositional zones or by combination in a matrix with the more cohesive silt and clay sediments. Thus, enhanced retention results in the formation of a distinct community adapted to utilize this material. The minimization of the variance of energy flow is the outcome of seasonal variations of energy input rates (detritus and autotrophic production), coupled with adjustments in species diversity, specialization for food processing, temporal expression of functional groups, and the erosional–depositional transport and storage characteristics of flowing waters.

Time Invariance and the Absence of Succession in Stream Communities

A corollary to the continuum hypothesis, also arising from the geomorphological literature (Langbein and Leopold 1966), is that studies of biological systems established in a dynamically balanced physical setting can be viewed in a time independent fashion. In the context of viewing adaptive strategies and processes as continua along a river system, temporal change becomes the slow process of evolutionary drift (physical and genetic). Incorporation of new functional components into the community over evolutionary time necessitates an efficiency adjustment towards reduced leakage. In natural river systems, community structure gains and loses species in response to low probability cataclysmic events and in response to slow processes of channel development.

The concept of time invariance allows integration of community structure and function along the river without the illusion that successional stages are being observed at a given location in a time-dependent series. The concept of biological succession (Margalef 1960) is of little use for river continua, because the communities in each reach have a continuous heritage rather than an isolated temporal composition within a sequence of discrete successional stages. In fact, the biological subsystems for each reach are in equilibrium with the physical system at that point in the continuum. The concept of heritage implies that in natural river systems total absence of a population is rare, and biological subsystems are simply shifting spatially (visualize a series of overlapping normal species-abundance curves in which all species are present at any point on the spatial axis but their abundance differs from one point to the next) and not in the temporal sense typical of plant succession.

On an evolutionary time scale, the spatial shift has two vectors: a donwstream one involving most of the aquatic insects and an upstream one involving molluscs and crustaceans. The insects are believed to have evolved terrestrially and to be secondarily aquatic. Since the maximum terrestrial–aquatic interface occurs in the headwaters, it is likely that the transition from land to water first occurred here with the aquatic forms then moving progressively downstream. The molluscs and crayfish are thought to have developed in a marine environment and to have moved through estuaries into rivers and thence upstream. The convergence of the two vectors may explain why maximum species diversity occurs in the midreaches.

Conclusion

We propose that the River Continuum Concept provides a framework for integrating predictable and observable biological features of flowing water systems with the physical–geomorphic environment. The model has been developed specifically in reference to natural, unperturbed stream ecosystems as they operate in the context of evolutionary and population time scales. However, the concept should accommodate many unnatural disturbances as well, particularly those which alter the relative degree of autotrophy:heterotrophy (e.g. nutrient enrichment, organic pollution, alteration of riparian vegetation through grazing, clear-cutting, etc.) or affect the quality and quantity of transport (e.g. impoundment, high sediment load). In many cases, these alterations can be thought of as reset mechanisms which cause the overall continuum response to be shifted toward the headwaters or seaward depending on the type of perturbation and its location on the river system.

A concept of dynamic equilibrium for biological communities, despite some difficulties in absolute definition, is useful because it suggests that community structure and function adjust to changes in certain geomorphic, physical, and biotic variables such as stream flow, channel morphology, detritus loading, size of particulate organic material, characteristics of autotrophic production, and thermal responses. In developing a theory of biological strategies along the river continuum, it also should be possible to observe a number of patterns that describe various processing rates, growth strategies, metabolic strategies, and community structures and functions. Collection of extensive data sets over the long profile of rivers are needed to further test and refine these ideas.

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BURTON, G. W., AND E. P. ODUM. 1945. The distribution of stream fish in the vicinity of Mountain Lake, Virginia. Ecology 26: 182–194.

CHORLEY, R. J. 1962. Geomorphology and general systems theory. U.S. Geol. Surv. Prof. Pap. 500-B: 10 p.

COFFMAN, W. P., K. W. CUMMINS, AND J. C. WUYCHECK. 1971. Energy flow in a woodland stream ecosystem. I. Tissue support trophic structure of the autumnal community. Arch. Hydrobiol. 68: 232–276.

CUMMINS, K. W. 1974. Structure and function of stream ecosystems. BioScience 24: 631–641.

CURRY, R. R. 1972. Rivers — a geomorphic and chemical overview, p. 9–31. *In* R. T. Oglesby, C. A. Carlson, and J. A. McCann [ed.] River ecology and man. Academic Press, N.Y. 465 p.

FISHER, S. G. 1977. Organic matter processing by a stream-segment ecosystem: Fort River, Massachusetts, U.S.A. Int. Rev. Hydrobiol. 62: 701–727.

HUET, M. 1954. Biologie, prifils en long et en travers des eaux courantes. Bull. Fr. Piscic. 175: 41–53.

——— 1959. Profiles and biology of Western European streams as related to fish management. Trans. Am. Fish. Soc. 88: 153–163.

IDE, F. P. 1935. The effect of temperature on the distribution of the mayfly fauna of a stream. Publ. Ont. Fish. Res. Lab. 50: 1–76.

KAUSHIK, N. K., AND H. B. N. HYNES. 1971. The fate of dead leaves that fall into streams. Arch. Hydrobiol. 68: 465–515.

LANGBEIN, W. B., AND L. B. LEOPOLD. 1966. River meanders — theory of minimum variance. U.S. Geol. Surv. Prof. Pap. 422-H: 15 p.

LEOPOLD, L. B., AND T. MADDOCK JR. 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geol. Surv. Prof. Pap. 252: 57 p.

LEOPOLD, L. B., AND W. B. LANGBEIN. 1962. The concept of entropy in landscape evolution. U.S. Geol. Surv. Prof. Pap. 500-A: 20 p.

LEOPOLD, L. B., M. G. WOLMAN, AND J. P. MILLER. 1964. Fluvial processes in geomorphology. W. H. Freeman, San Francisco, Calif. 522 p.

MACKAY, R. J., AND J. KALFF. 1973. Ecology of two related species of caddisfly larvae in the organic substrates of a woodland stream. Ecology 54: 499–511.

MCINTOSH, R. P. 1967. The concept of vegetation. Bot. Rev. 33: 130–187.

MARGALEF, R. 1960. Ideas for a synthetic approach to the ecology of running waters. Int. Rev. Gesamten Hydrobiol. 45: 133–153.

MILLS, E. L. 1969. The community concept in marine zoology, with comments on continua and instability in some marine communities: a review. J. Fish. Res. Board Can. 26: 1415–1428.

MINSHALL, G. W. 1967. Role of allochthonous detritus in the trophic structure of a woodland springbrook community. Ecology 48: 139–149.

——— 1968. Community dynamics of the benthic fauna in a woodland springbrook. Hydrobiologia 32: 305–339.

——— 1978. Autotrophy in stream ecosystems. BioScience 28: 767–771.

PLATTS, W. S. 1979. Relationships among stream order, fish populations, and aquatic geomorphology in an Idaho river drainage. Fisheries 4: 5–9.

RICKER, W. E. 1934. An ecological classification of certain Ontario streams. Univ. Toronto Stud. Biol. 37: 1–114.

RICKLEFS, R. E. 1979. Ecology. Chiron Press, Inc. New York, N.Y. 966 p.

ROSS, H. H. 1963. Stream communities and terrestrial biomes. Arch. Hydrobiol. 59: 235–242.

SEDELL, J. R., F. J. TRISKA, J. D. HALL, N. H. ANDERSON, AND J. H. LYFORD JR. 1974. Sources and fate of organic inputs in coniferous forest streams, p. 57–69. *In* R. H. Waring and R. L. Edmonds [ed.] Integrated research in the Coniferous Forest Biome. Bull. Coniferous Forest Biome Ecosystem Analysis Studies. Univ. Washington, Seattle, Wash. 78 p.

SHELFORD, V. E. 1911. Ecological succession. I. Stream fishes and the method of physiographic analysis. Biol. Bull. 21: 9–35.

SLACK, K. V. 1955. A study of the factors affecting stream productivity by the comparative method. Invest. Indiana Lakes Streams 4: 3–47.

SOUTHWOOD, T. R. E. 1977. Habitat, the templet for ecological strategies? J. Anim. Ecol. 46: 337–365.

SWANSTON, D. N., W. R. MEEHAN, AND J. A. MCNUTT. 1977. A quantitative geomorphic approach to predicting productivity of pink and chum salmon in Southeast Alaska. Publ. Pac. N. W. Forest Range Exp. Stn.

SWEENY, B. W., AND R. L. VANNOTE. 1978. Size variation and the distribution of hemimetabolous aquatic insects: two thermal equilibrium hypotheses. Science 200: 444–446.

THOMPSON, D. H., AND F. D. HUNT. 1930. The fishes of Champaign County: a study of the distribution and abundance of fishes in small streams. Bull. Ill. Nat. Hist. Surv. 19: 5–101.

VAN DEUSEN, R. D. 1954. Maryland freshwater stream classification by watersheds. Contr. Chesapeake Biol. Lab. 106: 1–30.

VANNOTE, R. L. 1978. A geometric model describing a quasi-equilibrium of energy flow in populations of stream insects. Proc. Natl. Acad. Sci. U.S.A. 75: 381–384.

VANNOTE, R. L., AND B. W. SWEENEY. 1979. Geographic analysis of thermal equilibria: a conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities. Am. Nat. 14: (In press)

WALLACE, J. B., J. R. WEBSTER, AND W. R. WOODALL. 1977. The role of filter feeders in flowing waters. Arch. Hydrobiol. 79: 506–532.

WEBSTER, J. R. 1975. Analysis of potassium and calcium dynamics in stream ecosystems on three southern Appalachian watersheds of contrasting vegetation. Ph.D. thesis, Univ. Georgia, Athens, Ga. 232 p.

ZIEMER, G. L. 1973. Quantitative geomorphology of drainage basins related to fish production. Alaska Fish Game Dep. Info. Leafl. 162: 1–26.

A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

Prepared by Pamela C. Dodds, Ph.D., Licensed Professional Geologist
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Virginia Stormwater Management Handbook

First Edition
1999

VOLUME I

Virginia Department of Conservation and Recreation
Division of Soil and Water Conservation

COMMONWEALTH of VIRGINIA

Virginia Stormwater Management Handbook

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VOLUME I

Department of Conservation and Recreation
Division of Soil and Water Conservation
203 Governor Street, Suite 206
Richmond, VA 23219-2094
Phone (804) 786-2064

DCR
Department of Conservation & Recreation
CONSERVING VIRGINIA'S NATURAL AND RECREATIONAL RESOURCES

NOAA
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PREFACE

Welcome to the *Working Draft* of the Virginia Stormwater Management Handbook!! This document is in no way intended to be a trailblazer in the way of new technologies and design standards and methodologies. Rather, the focus was on collecting basic hydrologic, hydraulic, and BMP design principles, most of which have been previously documented in other manuals published within the Chesapeake Bay watershed, and through out the country, and publishing them under one cover. Our number one goal is to promote and develop consistent and effective implementation of stormwater management policies.

So here it is!! This Handbook is a dynamic and evolving resource. Four Technical Bulletins have been developed and are included in the back of the manual. You may wish to insert them in the appropriate chapters or keep them in one place. Additional Technical Bulletins will be developed to provide you with the latest technologies, policies, and guidance. These Technical Bulletins help the Department of Conservation and Recreation (DCR) serve as a clearing house of information on local program development, local program funding ideas and experiences, innovative BMP design, BMP pollutant removal efficiencies, BMP maintenance, ongoing studies, and any other information which would be helpful to Handbook users. Future Technical Bulletins, as well as edits and updates to the Manual, will be available on the DCR website. The best news is that the entire handbook will be available in PDF format on our website: www.dcr.state.va.us

The list of Technical Bulletin topics being requested by our clients is beginning to look like the makings of another Handbook. DCR, however, is committed to providing continual guidance on stormwater issues. We are also interested in your comments. If there are issues which have not been addressed, or issues which deserve more attention, please contact us in writing at:

Stormwater Management Handbook
203 Governor Street, Suite 206
Richmond, Virginia 23219

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We take our hats off to all those who have developed technical manuals and handbooks before us. There are as many different opinions regarding style and format as there are people who have an interest in hydrology and hydraulics. To quote a famous philosopher: "What a long strange trip its been".

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CHAPTER 1

VIRGINIA STORMWATER MANAGEMENT PROGRAM

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1-1 INTRODUCTION

This Handbook has been developed by the Virginia Department of Conservation and Recreation (DCR) to provide basic guidance for compliance with the Virginia Stormwater Management Regulations. (4VAC3-20 et seq.) The technical material provided within represents some of the more basic types of hydrologic and hydraulic analysis procedures, mostly derived from SCS sources such as the SCS National Engineering Handbook (NEH), and the SCS Engineering Field Manual (EFM), and others. The science of stormwater management analysis is very broad and in no way are the methods and procedures presented here intended to represent the only acceptable way of preparing a stormwater management plan.

Chapter 1: Virginia Stormwater Management Program, provides an overview of the various State regulations which address water quality and nonpoint source pollution, as well as the interrelationship among the agencies.

Chapter 2: Stormwater Management and Urban BMPs, presents the basic components of stormwater management, as found in the Virginia SWM Regulations, and follows them through the BMP sizing and selection criteria. Most importantly, this Chapter 2 presents the basics of Regional Stormwater Management and Comprehensive Watershed Management.

Chapter 3: Minimum Standards, provides the technical design requirements and specifications, and maintenance requirements for stormwater BMPs defined in the Regulations. These criterion were derived from available sources such as the Northern Virginia BMP Handbook, Hampton Roads BMP Handbook, and various other publications, including those from the Metropolitan Washington Council of Governments and the Center for Watershed Protection. These minimum standards represent current, and in some cases innovative, design information pulled together under one cover in order to promote consistency in the design and construction, and therefore the effectiveness, of stormwater BMPs. These BMPs include:

3.01 Earthen Embankments
3.02 Principal Spillways
3.03 Vegetated Emergency Spillway
3.04 Sediment Forebay
3.05 Landscaping
3.06 Retention Basins
3.07 Extended Detention Basin
3.08 Detention Basin
3.09 Constructed Wetlands
3.10 Infiltration Practices
3.11 Bio-Retention
3.12 Sand Filters
3.13 Grassed Swale
3.14 Vegetated Filter Strip
3.15 Manufactured BMP Systems

Chapter 4: Hydrologic Methods, presents four methods for conducting a hydrologic analysis and determining the peak discharge from a watershed or drainage area. These methods include the Rational Method, Modified Rational Method, SCS TR-55 Graphical Peak Discharge Method and Tabular Hydrograph Method. Also included is a basic overview of various types of design hydrographs used in stormwater modeling.

Chapter 5: Engineering Calculations, provides very detailed calculation procedures for designing an impoundment BMP using standard hydraulic equations. These procedures include storage volume requirements, water quality and channel erosion control volume calculations, extended detention calculations, principal spillway and emergency spillway design, anti-seep collar design, outlet protection, riser floatation calculations, and water quality calculation procedures.

Chapter 6: Example Problems, provides some design examples including hydrologic and hydraulic analyses.

1-2 VIRGINIA STORMWATER MANAGEMENT PROGRAM

The 1998 amendments to the Virginia Stormwater Management (SWM) Regulations (4 VAC 3-20-10 et. seq.) reflect an on-going evolution in the definition and role of stormwater management. The initial goal of the amendment was to develop a more "user friendly" regulation; one which allowed flexibility for local program adoption, while also maintaining a solid framework of technical criteria. During the amendment process, legislative studies on the efficiency and consistency of the stormwater management and permitting policies of the Commonwealth provided additional guidance in the area of regulatory consistency. Providing consistent technical criteria for the water quality related programs in Virginia soon became a goal as well. To satisfy the these two goals, the technical criteria within the amended SWM regulations is divided into components: *Water Quality*, *Stream Channel Erosion*, and *Flooding*.

Water Quality

The water quality component reflects consistency between the Virginia SWM Regulations (DCR), The Chesapeake Bay Preservation Act (CBPA) and regulations (CBLAD), and the Virginia Pollution Discharge Elimination System (VPDES) permit (DEQ).

The reader should note that the land disturbing thresholds for compliance with these other water quality programs are independent of the SWM regulations: A VPDES permit is required for various industrial activities (including construction activities of 5 acres or more) and CBPA local regulatory compliance is required for projects of a certain size and/or in certain locations (refer to the local ordinance). Once it is determined that compliance with one of these water quality related programs is required, then the stormwater management regulations technical criteria for water quality (4 VAC 3-20-11) provides the consistent criteria for compliance.

Stream Channel Erosion

The stream channel erosion component of the SWM Regulations (4 VAC 3-20-81) incorporates the technical provisions of stormwater runoff component of the Erosion and Sediment Control Regulations (Minimum Standard 19, 4 VAC 50-30-40.19) as required by law. This component will be the subject of significant scrutiny as we try to further develop an appropriate technical criteria for stream channel erosion control. The challenge is the variable nature of stream channel hydraulics and hydrologic modeling. As the technical criteria is expanded to define the analysis and required solutions, we lose the emphasis on the engineers' ability and responsibility to determine the appropriate level of design for stream channel protection. An alternative would be to simply require that "downstream channels and properties be protected from erosion and damage due to increase in volume, velocity, and peak flow rate". The engineer would then be responsible for determining what level of control is needed to satisfy the requirement. On the other hand, requiring a full analysis of the channel geomorphology in order to establish the protection criteria would probably be too complex of an analysis, with few people qualified to review it.

The amended SWM regulations provide an alternative design criteria that has been found to be more effective in preventing downstream channel erosion: extended detention of the runoff from the 1-year frequency 24-hour storm. This criteria effectively reduces the runoff flow rate and velocity from a wide range of storms to less than the critical velocity. Further updates and guidance on the channel erosion component will be provided.

Flexible Adoption

The most significant amendment to the regulations is the flexible adoption of the stormwater components. A locality may now adopt individual components for local implementation. During the development of these amendments, this flexible adoption was referred to as a *cafeteria style* approach: choose the desired components from the "menu" of options. **However, any local SWM program adopted pursuant to the Stormwater Management Law (Title 10.1, Chapter 6, Article 1.1) must, at a minimum, contain the Flooding component (4VAC3-20-85).**

Administrative Procedures and Reporting

Other elements within the Regulations which caused concern on the part of localities interested in adopting a program were the Administrative Procedures which address stormwater management plan submission and review, and local program reporting. DCR acknowledged that our intent is not to supersede any local program development review process. State law does mandate a maximum review time of 60 days, with communication of the review to the applicant in writing. A survey of local program administrative procedures indicated that the actual review times, whether as required by local ordinance or by the level of development, were actually much less than the required 60 day maximum.

The issue of local program reporting was evaluated in light of the General Assembly requirement of an annual report on the extent to which local stormwater management programs have reduced nonpoint source pollution and mitigated the effects of localized flooding. Local government officials were wary of a reporting burden draining available staff time. DCR reviewed the type of information which was needed to compile the annual report to the General Assembly and determined the level of reporting to be a simple accounting of stormwater BMPs approved through the development review process or otherwise implemented in the locality. Additional information, such as monitoring studies, regional watershed plan studies and implementation, are certainly considered helpful in compiling a report to the General Assembly, however, not every locality will have such information. Again, a local program survey indicated that most existing local review and approval procedures do contain a simple accounting of what has been approved. Therefore, DCR amended the Reporting section of the Regulations (4VAC3-20-251) to ask local programs to voluntarily submit an annual report to the Department, as well as indicate the type of information which would be appropriate. The basis for this was that if most local programs are already compiling the type of information needed for the annual report, as the local program survey indicated, than the reporting of that information should not be burden. For localities that are just starting a program, DCR will commit to providing a simple record keeping system to help document the stormwater management BMPs and associated information.

In summary, the amendments to the Stormwater Management Regulations have made the adoption of a local program extremely simple and unburdonsome. Consider a local government currently operating, as required by law, an Erosion and Sediment Control Program with MS-19 requirements, and a Chesapeake Bay Preservation Act (CBPA) ordinance. MS-19 requirements satisfy the Stream Channel Erosion component of the Stormwater Management Regulations, and the water quality provisions within the CBPA ordinance satisfy the water quality component of the Stormwater Regulations. If the locality also has a flood control requirement (10-year storm, 25-year storm, etc.), than that locality is in full compliance with the State minimum technical requirements for a local stormwater management program. Without changing any of the actual duties or requirements mandated by the local ordinance, the locality may simply reference the authority for their combined program as the Virginia Stormwater Management Law, and thereby operate under the simple umbrella of enabling authority offered by the Stormwater Management Law. (It may be advisable to consolidate the various components into one section or chapter of the local ordinance for simplicity.)

There are many variations of the above example where localities are currently operating under fragmented enabling authority, and can now amend their ordinance to reference the Stormwater Management Law. The Department will periodically review these programs to insure consistency in implementation. The purpose of the review is to help the Department promote consistency in stormwater management policies across the commonwealth, as directed by the General Assembly, as well as help the local program maintain effective implementation of the technical criteria.

State Agency Compliance with Local Programs

Another incentive for local programs to adopt a State Stormwater Management Program is the ability to require state agency projects to comply with the local requirements. This can be especially important if a regional (watershed-wide) plan has been adopted. The Regulations allow for a local program to request, in writing, that the Department consider the local program requirements when reviewing state agency plans. Further, the regulations require that state agencies, to the maximum extent practicable, comply with any local stormwater management program technical criteria adopted pursuant to the Act, and that it shall be the responsibility of the state agency to demonstrate that the local program requirements are not practical for the project under consideration. (4VAC3-20-210).
Experience has indicated that this cooperation between local programs and state agencies has resulted in a win-win deal for the locality and the state agency, and in most cases resulted in more effective BMP implementation. Localities must notify DCR of their desire to have state agency plans comply with the local program technical requirements or investigate participating in a local regional SWM program.

1-3 VIRGINIA STORMWATER MANAGEMENT LAW and REGULATIONS

The following is the complete, edited text of Title 10.1, Chapter 6, Article 1.1 of the Code of Virginia as amended through 1998. Please refer to the Code of Virginia for an official copy of the Law.

§ 10.1-603.1. Cooperative state-local program.

The General Assembly has determined that the lands and waters of the Commonwealth are great natural resources; that as a result of intensive land development and other land use conversions, degradation of these resources frequently occurs in the form of water pollution, stream channel erosion, depletion of groundwater resources, and more frequent localized flooding; that these impacts adversely affect fish, aquatic life, recreation, shipping, property values and other uses of lands and waters; that existing authorities under the Code of Virginia do not adequately address all of these impacts. Therefore the General Assembly finds it in the public interest to enable the establishment of stormwater management programs.

§ 10.1-603.2. Definitions.

As used in this article, unless the context requires a different meaning:

"Applicant" means any person submitting a stormwater management plan for approval.

"Board" means the Board of Conservation and Recreation.

"Department" means the Department of Conservation and Recreation.

"Flooding" means a volume of water which is too great to be confined within the banks or walls of the stream, water body or conveyance system and which overflows onto adjacent lands, causing or threatening damage.

"Land development" or *"land development project"* means a manmade change to the land surface that potentially changes its runoff characteristics.

"Linear development project" means a land development project that is linear in nature such as, but not limited to, (I) the construction of electric and telephone utility lines, and natural gas pipelines; (ii) construction of tracks, rights-of-way, bridges, communication facilities and other related structures of a railroad company; and (iii) highway construction projects.

"Local stormwater management program" or "local program" means a statement of the various methods employed by a locality to manage the runoff from land development projects and may include such items as local ordinances, policies and guidelines, technical materials, inspection, enforcement, and evaluation.

"Nonpoint source pollution" means pollution whose sources cannot be pinpointed but rather is washed from the land surface in a diffuse manner by stormwater runoff.

"Runoff" means that portion of precipitation that is discharged across the land surface or through conveyances to one or more waterways.

"Stormwater management plan" or *"plan"* means a document containing material for describing how existing runoff characteristics will be maintained by a land development project.

"Subdivision" means the same as defined in §15.1-465.

"Watershed" means a defined land area drained by a river or stream or system of connecting rivers or streams such that all surface water within the area flows through a single outlet.

§ 10.1-603.3. Counties, cities and towns may by ordinance establish stormwater management programs as a local option; effective date

Each locality may, by ordinance, to be effective on or after July 1, 1990, establish a local stormwater management program which shall include, but is not limited to, the following:

1. Consistency with regulations promulgated in accordance with provisions of this article;

2. Provisions for long-term responsibility for and maintenance of stormwater management control devices and other techniques specified to manage the quality and quantity of runoff; and

3. Provisions for the integration of locally adopted stormwater management programs with local erosion and sediment control, flood insurance, flood plain management and other programs requiring compliance prior to authorizing construction in order to make the submission and approval of plans, issuance of permits, payment of fees, and coordination of inspection and enforcement activities more convenient and efficient both for the local governments and those responsible for compliance with the programs.

§ 10.1-603.4. Development of regulations.

The Board is authorized to promulgate regulations which specify minimum technical criteria and administrative procedures for stormwater management programs in Virginia. In order to inhibit the deterioration of existing waters and waterways, the regulations shall:

1. Require that state and local programs maintain after-development runoff rate of flow, as nearly as practicable, as the pre-development runoff characteristics;

2. Establish minimum design criteria for measures to control nonpoint source pollution and

localized flooding, and incorporate the stormwater management regulations promulgated pursuant to the Virginia Erosion and Sediment Control Law, Article 4 (§10.1-560 et seq.) of Chapter 5 of this title, as they relate to the prevention of stream channel erosion. These criteria shall be periodically modified as required in order to reflect current engineering methods;

3. Require the provision of long-term responsibility for and maintenance of stormwater management control devices and other techniques specified to manage the quality and quantity of runoff; and

4. Require as a minimum the inclusion in local programs of certain administrative procedures which include, but are not limited to, specifying the time period within which a local government which has adopted a stormwater management program must grant written approval of a plan, the conditions under which approval shall be granted, the procedures for communicating disapproval, the conditions under which an approved plan may be changed and requirements for inspection of approved projects.

§ 10.1-603.5. State agency projects.

A. After January 1, 1991, a state agency may not undertake any land clearing, soil movement, or construction activity involving soil movement or land development unless the agency has submitted and obtained approval of a stormwater management plan from the Department. In lieu of such a plan, the agency may annually submit stormwater management standards and specifications.

B. Notwithstanding the provisions of this article, all state agencies shall comply with the stormwater management provisions of the Erosion and Sediment Control Law, Article 4 (§10.1-560 et seq.) of Chapter 5 of this title, and related regulations. The Department shall perform random site inspections to assure compliance with this article, the Erosion and Sediment Control Law and regulations promulgated thereunder.

C. The Department shall have thirty days in which to comment on the stormwater management plan, and its recommendations shall be binding on the state agency or the private business hired by the state agency. Individual approval of separate projects is not necessary when annually approved standards and specifications have been approved.

As on-site changes occur, the state agency shall submit changes in the stormwater management plan to the Department.

The state agency responsible for the land-disturbing activity shall ensure compliance with the approved plan or specifications.

§ 10.1-603.6. Involvement of the Department with local programs.

A. The Department shall provide technical assistance, training, research, and coordination in stormwater management technology to the local governments consistent with the purposes of this article.

B. The Department is authorized to review the plan for any project with real or potential interjurisdictional impacts upon the request of one of the involved localities to determine that the plan is consistent with the provisions of this article. Any such review shall be completed and a report submitted to each locality involved within ninety days of such request.

§ 10.1-603.7. Authorization for more stringent regulations.

Localities are authorized to adopt more stringent stormwater management regulations than those necessary to ensure compliance with the Board's minimum regulations, with the exception of regulations related to plan approval, provided that the more stringent regulations are based upon the findings of local comprehensive watershed management studies and that prior to adopting more stringent regulations a public hearing is held after giving due notice.

§ 10.1-603.8. Regulated activities; submission and approval of a control plan; security for performance; exemptions.

A. Except as provided in §10.1-603.5, after the adoption of a local ordinance, a person shall not develop any land for residential, commercial, industrial, or institutional use in that locality until he has submitted a stormwater management plan to the locality that has jurisdiction and has obtained approval of the plan from that locality. The plan may include appropriate maps, mathematical calculations, detail drawings and a listing of all major decisions to assure that the entire unit or units of land will be so treated to achieve the objectives of the local program. Prior to issuance of any permit, the locality may also require an applicant to submit a reasonable performance bond with surety, cash escrow, letter of credit, any combination thereof, or such other legal arrangement acceptable to the locality, to ensure that measures could be taken by the locality at the applicant's expense should he fail, after proper notice, within the time specified to initiate or maintain appropriate actions which may be required of him by the approved stormwater management plan as a result of his land-development project. If the locality takes such action upon such failure by the applicant, the agency may collect from the applicant for the difference should the amount of the reasonable cost of such action exceed the amount of the security held. Within sixty days of the completion of the requirements of the approved stormwater management plan, such bond, cash escrow, letter of credit or other legal arrangement, or the unexpended or unobligated portion thereof, shall be refunded to the applicant or terminated. These requirements are in addition to all other provisions of law relating to the issuance of such plans and are not intended to otherwise affect the requirements for such plans.

B. Notwithstanding any other provisions of this article, the following activities are exempt:

1. Permitted surface or deep mining operations and projects, or oil and gas operations and projects conducted under the provisions of Title 45.1;

2. Tilling, planting or harvesting of agricultural, horticultural, or forest crops;

3. Single-family residences separately built and not part of a subdivision, including additions or modifications to existing single-family detached residential structures;

4. Land development projects that disturb less than one acre of land area; however, the governing body of a locality which has adopted a stormwater management program may reduce this exception to a smaller area of disturbed land or qualify the conditions under which this exception shall apply; and

5. Linear development projects, provided that (I) less than one acre of land will be disturbed per outfall or watershed, (ii) there will be insignificant increases in peak flow rates, and (iii) there are no existing or anticipated flooding or erosion problems downstream of the discharge point.

§ 10.1-603.9. Approved plan required for issuance of grading, building, or other permits.

Upon the adoption of a local ordinance no grading, building or other permit shall be issued for a property unless a stormwater management plan has been approved that is consistent with the local program and this article and unless the applicant has certified that all land clearing, construction, land development and drainage will be done according to the approved plan.

§ 10.1-603.10. Recovery of administrative costs.

Any locality which administers a stormwater management program may charge applicants a reasonable fee to defray the cost of program administration, including costs associated with plan review, issuance of permits, periodic inspection for compliance with approved plans, and necessary enforcement, provided that charges for such costs are not made under any other law, ordinance or program. The fee shall not exceed an amount commensurate with the services rendered and expenses incurred or $1,000, whichever is less.

§ 10.1-603.11. Monitoring, reports and inspections.

A. The plan-approving authority or, if a permit is issued in connection with land-disturbing activities which involve the issuance of a grading, building, or other permit, the permit-issuing authority (I) shall provide for periodic inspections of the installation of stormwater management measures and (ii) may require monitoring and reports from the person responsible for carrying out the plan, to ensure compliance with the approved plan and to determine whether the measures required in the plan provide effective stormwater management. The owner, occupier or operator shall be given notice of the inspection and an opportunity to accompany the inspectors. If the permit-issuing authority or plan-approving authority determines that there is a failure to comply with the plan, notice shall be served upon the permittee or person responsible for carrying out the plan by registered or certified mail to the address specified in the permit application or in the plan certification, or by delivery at the site of the development activities to the agent or employee supervising such activities. Where the plan-approving authority serves notice, a copy of the notice shall also be sent to the issuer of the permit. The notice shall specify the measures needed to comply with the plan and shall specify the time within which such measures shall be completed. Upon failure to comply within the time specified, the permit may be revoked and the permittee or person responsible for carrying out the plan shall be deemed to be in violation of this article and upon conviction shall be subject to the penalties provided by §10.1-603.14.

B. Notwithstanding subsection A of this section, the following may be applied:

1. Where a county, city, or town administers the local control program and the permit-issuing authority and the plan-approving authority are not within the same local government department, the locality may designate one department to inspect, monitor, report and ensure compliance.

2. Where a permit-issuing authority has been established, and such authority is not vested in an employee or officer of local government but in the commissioner of revenue or some other person, the locality shall exercise the responsibilities of the permit-issuing authority with respect to monitoring, reports, inspections, and enforcement unless such responsibilities are transferred as provided for in this section.

§ 10.1-603.12. Department to review local and state agency programs.

A. The Department shall periodically conduct a comprehensive review and evaluation of the effectiveness of each local government's and state agency's stormwater management program. The review shall include an assessment of the extent to which the program has reduced nonpoint source pollution and mitigated the detrimental effects of localized flooding. A summary of these reviews and evaluations shall be submitted annually to the General Assembly.

B. If, after such a review and evaluation, a local government is found to have a program which does not comply with the provisions of this article or regulations promulgated thereunder, the Department may issue an order requiring that necessary corrective action be taken within a reasonably prescribed time.

§ 10.1-603.13. Appeals of decisions of counties, cities or towns.

A. An appeal from a decision of a locality concerning an application for approval or disapproval of a stormwater management plan may be taken by the applicant, or any aggrieved party authorized by law, within thirty days after the rendering of such a decision of the locality, to the circuit court of the jurisdiction in which the land development project is located.

B. Judicial review shall be on the record previously established and shall otherwise be in accordance with the provisions of the Administrative Process Act (§9-6.14:1 et seq.).

§ 10.1-603.14. Penalties, injunctions and other legal actions.

Any person who violates any provision of a local ordinance or program adopted pursuant to the authority of this article shall be guilty of a misdemeanor and shall be subject to a fine not exceeding $1,000 or up to thirty days imprisonment for each violation or both. Such a local ordinance may also include the following sanctions:

1. A locality operating its own program may apply to the circuit court in any jurisdiction wherein the land lies to enjoin a violation or a threatened violation of the provisions of this article or of the local ordinance without the necessity of showing that an adequate remedy at law does not exist.

2. Without limiting the remedies which may be obtained in this section, a locality operating its own program may bring a civil action against any person for violation of any ordinance or any condition of a permit, or any provision of a local program adopted pursuant to this article. The action may seek the imposition of a civil penalty of not more than $2,000 against the person for each violation.

3. With the consent of any person who has violated or failed, neglected or refused to obey any ordinance or any condition of a permit or any provision of a local program adopted pursuant to this article, the administrator of the local program may provide, in an order issued by the administrator against such person, for the payment of civil charges for violations in specific sums, not to exceed the limit specified in subdivision 2 of this section. Such civil charges shall be instead of any appropriate civil penalty which could be imposed under subdivision 2.

§ 10.1-603.15. Cooperation with federal and state agencies.

Localities operating their own programs and the Department are authorized to cooperate and enter into agreements with any federal or state agency in connection with plans for stormwater management.

1-4 VIRGINIA STORMWATER MANAGEMENT REGULATIONS

The following is a complete text of the Virginia Stormwater Management Regulations 4VAC3-20 amended by the Board of Conservation and Recreation, effective March 5, 1998

PART I.
GENERAL.

4 VAC 3-20-10. Definitions.

The following words and terms used in this chapter have the following meanings, unless the context clearly indicates otherwise.

"Act" means Article 1.1 (§ 10.1-603.1 et seq.) of Chapter 6 of Title 10.1 of the Code of Virginia.

"Adequate channel" means a channel that will convey the designated frequency storm event without overtopping the channel banks nor causing erosive damage to the channel bed or banks.

"Applicant" means any person submitting a stormwater management plan for approval.

"Aquatic bench" means a 10- to 15-foot wide bench around the inside perimeter of a permanent pool that ranges in depth from zero to 12 inches. Vegetated with emergent plants, the bench augments pollutant removal, provides habitats, conceals trash and water level fluctuations, and enhances safety.

"Average land cover condition" means a measure of the average amount of impervious surfaces within a watershed, assumed to be 16%. Note that a locality may opt to calculate actual watershed-specific values for the average land cover condition based upon 4 VAC 3-20-101.

"Best management practice (BMP)" means a structural or nonstructural practice which is designed to minimize the impacts of development on surface and groundwater systems.

"Bioretention basin" means a water quality BMP engineered to filter the water quality volume through an engineered planting bed, consisting of a vegetated surface layer (vegetation, mulch, ground cover), planting soil, and sand bed, and into the in-situ material.

"Bioretention filter" means a bioretention basin with the addition of a sand filter collector pipe system beneath the planting bed.

"Board" means the Board of Conservation and Recreation.

"Channel" means a natural or manmade waterway.

"Constructed wetlands" means areas intentionally designed and created to emulate the water quality improvement function of wetlands for the primary purpose of removing pollutants from stormwater.

"Department" means the Department of Conservation and Recreation.

"Development" means a tract of land developed or to be developed as a unit under single ownership or unified control which is to be used for any business or industrial purpose or is to contain three or more residential dwelling units.

"Director" means the Director of the Department of Conservation and Recreation.

"Flooding" means a volume of water that is too great to be confined within the banks or walls of the stream, water body or conveyance system and that overflows onto adjacent lands, causing or threatening damage.

"Grassed swale" means an earthen conveyance system which is broad and shallow with erosion resistant grasses and check dams, engineered to remove pollutants from stormwater runoff by filtration through grass and infiltration into the soil.

"Impervious cover" means a surface composed of any material that significantly impedes or prevents natural infiltration of water into soil. Impervious surfaces include, but are not limited to, roofs, buildings, streets, parking areas, and any concrete, asphalt, or compacted gravel surface.

"Infiltration facility" means a stormwater management facility which temporarily impounds runoff and discharges it via infiltration through the surrounding soil. While an infiltration facility may also be equipped with an outlet structure to discharge impounded runoff, such discharge is normally reserved for overflow and other emergency conditions. Since an infiltration facility impounds runoff only temporarily, it is normally dry during nonrainfall periods. Infiltration basin, infiltration trench, infiltration dry well, and porous pavement shall be considered infiltration facilities.

"Inspection" means an on-site review of the project's compliance with the approved plan, the local stormwater management program, and any applicable design criteria.

"Land development" or *"land development project"* means a manmade change to, or construction on, the land surface, except as exempted in the Stormwater Management Act, § 10.1-603.8 B of the Code of Virginia, that changes its runoff characteristics.

"Linear development project" means a land development project that is linear in nature such as, but not limited to, (i) the construction of electric and telephone utility lines, and natural gas pipelines; (ii) construction of tracks, rights-of-way, bridges, communication facilities and other related structures of a railroad company; and (iii) highway construction projects.

"Local stormwater management program" or *"local program"* means a statement of the various methods adopted pursuant to the Act and implemented by a locality to manage the runoff from land development projects and shall include an ordinance with provisions to require the control of after-development stormwater runoff rate of flow, the proper maintenance of stormwater management facilities, and minimum administrative procedures consistent with this chapter.

"Locality" means a county, city, or town.

"Nonpoint source pollution" means contaminants such as sediment, nitrogen and phosphorous, hydrocarbons, heavy metals, and toxics whose sources cannot be pinpointed but rather are washed from the land surface in a diffuse manner by stormwater runoff.

"Nonpoint source pollutant runoff load" or *"pollutant discharge"* means the average amount of a particular pollutant measured in pounds per year, delivered in a diffuse manner by stormwater runoff.

"Percent impervious" means the impervious area within the site divided by the area of the site multiplied by 100.

"Person" means any individual, partnership, firm, association, joint venture, public or private corporation, trust, estate, commission, board, public or private institution, utility, cooperative, county, city, town or other political subdivision of the Commonwealth, any interstate body or any other legal entity.

"Planning area" means a designated portion of the parcel on which the land development project is located. Planning areas shall be established by delineation on a master plan. Once established, planning areas shall be applied consistently for all future projects.

"Post-development" refers to conditions that reasonably may be expected or anticipated to exist after completion of the land development activity on a specific site or tract of land.

"Pre-development" refers to the conditions that exist at the time that plans for the land development of a tract of land are approved by the plan approval authority. Where phased development or plan approval occurs (preliminary grading, roads and utilities, etc.), the existing conditions at the time *prior to* the first item being approved or permitted shall establish pre-development conditions.

"Regional (watershed-wide) stormwater management facility" or *"regional facility"* means a facility or series of facilities designed to control stormwater runoff from a specific watershed, although only portions of the watershed may experience land development.

"Regional (watershed-wide) stormwater management plan" or *"regional plan"* means a document containing material describing how runoff from open space, existing development and future planned development areas within a watershed will be controlled by coordinated design and implementation of regional stormwater management facilities.

"Runoff" or *"stormwater runoff"* means that portion of precipitation that is discharged across the land surface or through conveyances to one or more waterways.

"Sand filter" means a contained bed of sand which acts to filter the first flush of runoff. The runoff is then collected beneath the sand bed and conveyed to an adequate discharge point or infiltrated into the in-situ soils.

"Shallow marsh" means a zone within a stormwater extended detention basin that exists from the surface of the normal pool to a depth of six to 18 inches, and has a large surface area and, therefore, requires a reliable source of baseflow, groundwater supply, or a sizeable drainage area,

to maintain the desired water surface elevations to support emergent vegetation.

"*Site*" means the parcel of land being developed, or a designated planning area in which the land development project is located.

"State project" means any land development project which is undertaken by any state agency, board, commission, authority or any branch of state government, including state supported institutions of higher learning.

"Stormwater detention basin" or *"detention basin"* means a stormwater management facility which temporarily impounds runoff and discharges it through a hydraulic outlet structure to a downstream conveyance system. While a certain amount of outflow may also occur via infiltration through the surrounding soil, such amounts are negligible when compared to the outlet structure discharge rates and are, therefore, not considered in the facility's design. Since a detention facility impounds runoff only temporarily, it is normally dry during nonrainfall periods.

"Stormwater extended detention basin" or *"extended detention basin"* means a stormwater management facility which temporarily impounds runoff and discharges it through a hydraulic outlet structure over a specified period of time to a downstream conveyance system for the purpose of water quality enhancement or stream channel erosion control. While a certain amount of outflow may also occur via infiltration through the surrounding soil, such amounts are negligible when compared to the outlet structure discharge rates and, therefore, are not considered in the facility's design. Since an extended detention basin impounds runoff only temporarily, it is normally dry during nonrainfall periods.

"*Stormwater extended detention basin-enhanced*" or *"extended detention basin-enhanced"* means an extended detention basin modified to increase pollutant removal by providing a shallow marsh in the lower stage of the basin.

"Stormwater management facility" means a device that controls stormwater runoff and changes the characteristics of that runoff including, but not limited to, the quantity and quality, the period of release or the velocity of flow.

"Stormwater management plan" or *"plan"* means a document containing material for describing how existing runoff characteristics will be affected by a land development project and methods for complying with the requirements of the local program or this chapter.

"Stormwater retention basin" or *"retention basin"* means a stormwater management facility which includes a permanent impoundment, or normal pool of water, for the purpose of enhancing water quality and, therefore, is normally wet, even during nonrainfall periods. Storm runoff inflows are may be temporarily stored above this permanent impoundment for the purpose of reducing flooding, or stream channel erosion.

"*Stormwater retention basin I*" or *"retention basin I"* means a retention basin with the volume of the permanent pool equal to three times the water quality volume.

"Stormwater retention basin II" or *"retention basin II"* means a retention basin with the volume of the permanent pool equal to four times the water quality volume.

"Stormwater retention basin III" or *"retention basin III"* means a retention basin with the volume of the permanent pool equal to four times the water quality volume with the addition of an aquatic bench.

"Subdivision" unless otherwise defined in a local ordinance adopted pursuant to § 15.1-465 of the Code of Virginia, means the division of a parcel of land into three or more lots or parcels of less than five acres each for the purpose of transfer of ownership or building development, or, if a new street is involved in such division, any division of a parcel of land. The term includes resubdivision and, when appropriate to the context, shall relate to the process of subdividing or to the land subdivided.

"Vegetated filter strip" means a densely vegetated section of land engineered to accept runoff as overland sheet flow from upstream development. It shall adopt any natural vegetated form, from grassy meadow to small forest. The vegetative cover facilitates pollutant removal through filtration, sediment deposition, infiltration and absorption, and is dedicated for that purpose.

"Water quality volume" means the volume equal to the first 1/2 inch of runoff multiplied by the impervious surface of the land development project.

"Watershed" means a defined land area drained by a river, stream or drainage ways or system of connecting rivers, streams, or drainage ways such that all surface water within the area flows through a single outlet.

4 VAC 3-20-30. Purposes.

The purposes of this chapter are to provide a framework for the administration, implementation and enforcement of the Act, while at the same time providing flexibility for innovative solutions to stormwater management issues.

4 VAC 3-20-40. Applicability.

This chapter is applicable to:

1. Every locality that establishes a local stormwater management program; and
2. Every state project.

PART II.
TECHNICAL CRITERIA.

4 VAC 3-20-50. Applicability.

This part specifies technical criteria for localities that establish a local stormwater management program and for state projects.

4 VAC 3-20-60. General.

A. Determination of flooding and channel erosion impacts to receiving streams due to land development projects shall be measured at each point of discharge from the development project and such determination shall include any runoff from the balance of the watershed which also contributes to that point of discharge.

B. The specified design storms shall be defined as either a 24-hour storm using the rainfall distribution recommended by the U.S. Soil Conservation Service when using U.S. Soil Conservation Service methods or as the storm of critical duration that produces the greatest required storage volume at the site when using a design method such as the Modified Rational Method.

C. For purposes of computing runoff, all pervious lands in the site shall be assumed prior to development to be in good condition (if the lands are pastures, lawns, or parks), with good cover (if the lands are woods), or with conservation treatment (if the lands are cultivated); regardless of conditions existing at the time of computation.

D. Construction of stormwater management facilities or modifications to channels shall comply with all applicable laws and regulations. Evidence of approval of all necessary permits shall be presented.

E. Impounding structures that are not covered by the Impounding Structure Regulations (4 VAC 50-20-10 et seq.) shall be engineered for structural integrity during the 100-year storm event.

F. Pre-development and post-development runoff rates shall be verified by calculations that are consistent with good engineering practices.

G. Outflows from a stormwater management facility shall be discharged to an adequate channel, and velocity dissipators shall be placed at the outfall of all stormwater management facilities and along the length of any outfall channel as necessary to provide a nonerosive velocity of flow from the basin to a channel.

H. Proposed residential, commercial, or industrial subdivisions shall apply these stormwater management criteria to the land development as a whole. Individual lots in new subdivisions shall not be considered separate land development projects, but rather the entire subdivision shall be considered a single land development project. Hydrologic parameters shall reflect the ultimate land development and shall be used in all engineering calculations.

I. All stormwater management facilities shall have a maintenance plan which identifies the owner and the responsible party for carrying out the maintenance plan.

J. Construction of stormwater management impoundment structures within a Federal Emergency Management Agency (FEMA) designated 100-year floodplain shall be avoided to the extent possible. When this is unavoidable, all stormwater management facility construction shall be in compliance with all applicable regulations under the National Flood Insurance Program, 44 CFR Part 59.

K. Natural channel characteristics shall be preserved to the maximum extent practicable.

L. Land development projects shall comply with the Virginia Erosion and Sediment Control Act and attendant regulations.

4 VAC 3-20-71. Water quality.

A. Compliance with the water quality criteria may be achieved by applying the performance-based criteria or the technology-based criteria to either the site or a planning area.

B. Performance-based criteria. For land development, the calculated post-development nonpoint source pollutant runoff load shall be compared to the calculated pre-development load based upon the average land cover condition or the existing site condition. A BMP shall be located, designed, and maintained to achieve the target pollutant removal efficiencies specified in Table 1 to effectively reduce the pollutant load to the required level based upon the following four applicable land development situations for which the performance criteria apply:

1. Situation 1 consists of land development where the existing percent impervious cover is less than or equal to the average land cover condition and the proposed improvements will create a total percent impervious cover which is less than the average land cover condition.

Requirement: No reduction in the after development pollutant discharge is required.

2. Situation 2 consists of land development where the existing percent impervious cover is less than or equal to the average land cover condition and the proposed improvements will create a total percent impervious cover which is greater than the average land cover condition.

Requirement: The pollutant discharge after development shall not exceed the existing pollutant discharge based on the average land cover condition.

3. Situation 3 consists of land development where the existing percent impervious cover is greater than the average land cover condition.

Requirement: The pollutant discharge after development shall not exceed (i) the pollutant discharge based on existing conditions less 10% or (ii) the pollutant discharge based on the average land cover condition, whichever is greater.

4. Situation 4 consists of land development where the existing percent impervious cover is served by an existing stormwater management BMP that addresses water quality.

Requirement: The pollutant discharge after development shall not exceed the existing pollutant discharge based on the existing percent impervious cover while served by the existing BMP. The existing BMP shall be shown to have been designed and constructed in accordance with proper design standards and specifications, and to be in proper functioning condition.

C. Technology-based criteria. For land development, the post-developed stormwater runoff from the impervious cover shall be treated by an appropriate BMP as required by the post-developed condition percent impervious cover as specified in Table 1. The selected BMP shall be located, designed, and maintained to perform at the target pollutant removal efficiency specified in Table 1. Design standards and specifications for the BMPs in Table 1 which meet the required target pollutant removal efficiencywill be available at the department.

Table 1*

Water Quality BMP	Target Phosphorus Removal Efficiency	Percent Impervious Cover
Vegetated filter strip	10%	16-21%
Grassed swale	15%	
Constructed wetlands	30%	22 -37%
Extended detention (2 x WQ Vol)	35%	
Retention basin I (3 x WQ Vol)	40%	
Bioretention basin	50%	38 -66%
Bioretention filter	50%	
Extended detention-enhanced	50%	
Retention basin II (4 x WQ Vol)	50%	
Infiltration (1 x WQ Vol)	50%	
Sand filter	65%	67 -100%
Infiltration (2 x WQ Vol)	65%	
Retention basin III (4 x WQ Vol with aquatic bench)	65%	

* Innovative or alternate BMPs not included in this table may be allowed at the discretion of the local program administrator or the Department. Innovative or alternate BMPs not included in this table which target appropriate nonpoint source pollution other than phosphorous may be allowed at the discretion of the local program administrator or the Department.

4 VAC 3-20-81. Stream channel erosion.

A. Properties and receiving waterways downstream of any land development project shall be protected from erosion and damage due to increases in volume, velocity and peak flow rate of stormwater runoff in accordance with the minimum design standards set out in this section.

B. The plan approving authority shall require compliance with subdivision 19 of 4 VAC 50-30-40 of the Erosion and Sediment Control Regulations, promulgated pursuant to Article 4 (§ 10.1-560 et seq.) of Chapter 5 of Title 10.1 of the Code of Virginia.

C. The plan approving authority may determine that some watersheds or receiving stream systems require enhanced criteria in order to address the increased frequency of bankfull flow conditions brought on by land development projects. Therefore, in lieu of the reduction of the 2-year post-developed peak rate of runoff as required in subsection B of this section, the land development project being considered shall provide 24-hour extended detention of the runoff generated by the 1-year, 24-hour duration storm.

D. In addition to subsections B and C of this section, localities may, by ordinance, adopt more stringent channel analysis criteria or design standards to ensure that the natural level of channel erosion, to the maximum extent practicable, will not increase due to the land development projects. These criteria may include, but are not limited to, the following:

1. Criteria and procedures for channel analysis and classification.
2. Procedures for channel data collection.
3. Criteria and procedures for the determination of the magnitude and frequency of natural sediment transport loads.
4. Criteria for the selection of proposed natural or man-made channel linings.

4 VAC 3-20-85. Flooding.

A. Downstream properties and waterways shall be protected from damages from localized flooding due to increases in volume, velocity and peak flow rate of stormwater runoff in accordance with the minimum design standards set out in this section

B. The 10-year post-developed peak rate of runoff from the development site shall not exceed the 10-year pre-developed peak rate of runoff.

C. In lieu of subsection B of this section, localities may, by ordinance, adopt alternate design criteria based upon geographic, land use, topographic, geologic factors or other downstream conveyance factors as appropriate.

D. Linear development projects shall not be required to control post-developed stormwater runoff for flooding, except in accordance with a watershed or regional stormwater management plan.

4 VAC 3-20-86. Regional (watershed-wide) stormwater management plans.

This section enables localities to develop regional stormwater management plans. State agencies intending to develop large tracts of land such as campuses or prison compounds are encouraged to develop regional plans where practical.

The objective of a regional stormwater management plan is to address the stormwater management concerns in a given watershed with greater economy and efficiency by installing regional stormwater management facilities versus individual, site-specific facilities. The result will be fewer stormwater management facilities to design, build and maintain in the affected watershed. It is also anticipated that regional stormwater management facilities will not only help mitigate the impacts of new development, but may also provide for the remediation of erosion, flooding or water quality problems caused by existing development within the given watershed.

If developed, a regional plan shall, at a minimum, address the following:

1. The specific stormwater management issues within the targeted watersheds.

2. The technical criteria in 4 VAC 3-20-50 through 4 VAC 3-20-85 as needed based on subdivision 1 of this section.

3. The implications of any local comprehensive plans, zoning requirements and other planning documents.

4. Opportunities for financing a watershed plan through cost sharing with neighboring agencies or localities, implementation of regional stormwater utility fees, etc.

5. Maintenance of the selected stormwater management facilities.

6. Future expansion of the selected stormwater management facilities in the event that development exceeds the anticipated level.

PART III.
LOCAL PROGRAMS.

4 VAC 3-20-90. Applicability.

This part specifies technical criteria, minimum ordinance requirements, and administrative procedures for all localities operating local stormwater management programs.

4 VAC 3-20-101. Technical criteria for local programs.

A. All local stormwater management programs shall comply with the general technical criteria as outlined in 4 VAC 3-20-60.

B. All local stormwater management programs which contain provisions for stormwater runoff quality shall comply with 4 VAC 3-20-71. A locality may establish criteria for selecting either the site or a planning area on which to apply the water quality criteria. A locality may opt to calculate actual watershed specific or locality wide values for the average land cover condition based upon:

1. Existing land use data at time of local Chesapeake Bay Preservation Act Program or Department storm water management program adoption, whichever was adopted first,

2. Watershed or locality size, and

3. Determination of equivalent values of impervious cover for nonurban land uses which contribute nonpoint source pollution, such as agriculture, forest, etc.

C. All local stormwater management programs which contain provisions for stream channel erosion shall comply with 4 VAC 3-20-81.

D. All local stormwater management programs must contain provisions for flooding and shall comply with 4 VAC 3-20-85.

E. All local stormwater management programs which contain provisions for watershed or regional stormwater management plans shall comply with 4 VAC 3-20-101.

F. A locality that has adopted more stringent requirements or implemented a regional (watershed-wide) stormwater management plan may request, in writing, that the department consider these requirements in its review of state projects within that locality.

G. Nothing in this part shall be construed as authorizing a locality to regulate, or to require prior approval by the locality for, a state project.

4 VAC 3-20-111. Requirements for local program and ordinance.

A. At a minimum, the local stormwater management program and implementing ordinance shall meet the following:

1. The ordinance shall identify the plan-approving authority and other positions of authority within the program, and shall include the regulations and technical criteria to be used in the program.

2. The ordinance shall include procedures for submission and approval of plans, issuance of permits, monitoring and inspections of land development projects. The party responsible for conducting inspections shall be identified. The local program authority shall maintain, either on-site or in local program files, a copy of the approved plan and a record of all inspections for each land development project.

B. The department shall periodically review each locality's stormwater management program, implementing ordinance, and amendments. Subsequent to this review, the department shall determine if the program and ordinance are consistent with the state stormwater management regulations and notify the locality of its findings. To the maximum extent practicable the department will coordinate the reviews with other local government program reviews to avoid redundancy. The review of a local program shall consist of the following:

1. A personal interview between department staff and the local program administrator or his designee;

2. A review of the local ordinance and other applicable documents;

3. A review of plans approved by the locality and consistency of application;

4. An inspection of regulated activities; and

5. A review of enforcement actions.

C. Nothing in this chapter shall be construed as limiting the rights of other federal and state agencies from imposing stricter technical criteria or other requirements as allowed by law.

4 VAC 3-20-121. Administrative procedures: stormwater management plans.

A. Localities shall approve or disapprove stormwater management plans according to the following:

1. A maximum of 60 calendar days from the day a complete stormwater management plan is accepted for review will be allowed for the review of the plan. During the 60-day review period, the locality shall either approve or disapprove the plan and communicate its decision to the applicant in writing. Approval or denial shall be based on the plan's compliance with the locality's stormwater management program.

2. A disapproval of a plan shall contain the reasons for disapproval.

B. Each plan approved by a locality shall be subject to the following conditions:

1. The applicant shall comply with all applicable requirements of the approved plan, the local program, this chapter and the Act, and shall certify that all land clearing, construction, land development and drainage will be done according to the approved plan.

2. The land development project shall be conducted only within the area specified in the approved plan.

3. The locality shall be allowed, after giving notice to the owner, occupier or operator of the land development project, to conduct periodic inspections of the project.

4. The person responsible for implementing the approved plan shall conduct monitoring and submit reports as the locality may require to ensure compliance with the approved plan and to determine whether the plan provides effective stormwater management.

5. No changes may be made to an approved plan without review and written approval by the locality.

4 VAC 3-20-131. Administrative procedures: exceptions.

A. A request for an exception shall be submitted, in writing, to the locality. An exception from the stormwater management regulations may be granted, provided that: (i) exceptions to the criteria are the minimum necessary to afford relief and (ii) reasonable and appropriate conditions shall be imposed as necessary upon any exception granted so that the intent of the Act and this chapter are preserved.

B. Economic hardship is not sufficient reason to grant an exception from the requirements of this chapter.

4 VAC 3-20-141. Administrative procedures: maintenance and inspections.

A. Responsibility for the operation and maintenance of stormwater management facilities, unless assumed by a governmental agency, shall remain with the property owner and shall pass to any successor or owner. If portions of the land are to be sold, legally binding arrangements shall be made to pass the basic responsibility to successors in title. These arrangements shall designate for each project the property owner, governmental agency, or other legally established entity to be permanently responsible for maintenance.

B. In the case of developments where lots are to be sold, permanent arrangements satisfactory to the locality shall be made to ensure continued performance of this chapter.

C. A schedule of maintenance inspections shall be incorporated into the local ordinance. Ordinances shall provide that in cases where maintenance or repair is neglected, or the stormwater management facility becomes a danger to public health or safety, the locality has the authority to perform the work and to recover the costs from the owner.

D. Localities may require right-of-entry agreements or easements from the applicant for purposes of inspection and maintenance.

E. Periodic inspections are required for all stormwater management facilities. Localities shall either:

1. Provide for inspection of stormwater management facilities on an annual basis; or

2. Establish an alternative inspection program which ensures that stormwater management facilities are functioning as intended. Any alternative inspection program shall be:

   a. Established in writing;

   b. Based on a system of priorities that, at a minimum, considers the purpose of the facility, the contributing drainage area, and downstream conditions; and

   c. Documented by inspection records.

F. During construction of the stormwater management facilities, localities shall make inspections on a regular basis.

G. Inspection reports shall be maintained as part of a land development project file.

PART IV.
STATE PROJECTS.

4 VAC 3-20-210. Technical criteria and plan requirements for state projects.

A. This part specifies technical criteria and administrative procedures for all state projects.

B. Stormwater management plans prepared for state projects shall comply with the technical criteria outlined in Part II (4 VAC 3-20-50 et seq.) of this chapter and, to the maximum extent practicable, any local stormwater management program technical requirements adopted pursuant to the Act. It shall be the responsibility of the state agency to demonstrate that the local program technical requirements are not practical for the project under consideration.

C. The department may establish criteria for selecting either the site or a planning area on which to apply the water quality criteria.

D. As a minimum, stormwater management plans and computations shall contain the following:

1. The location and the design of the proposed stormwater management facilities.

2. Overall site plan with pre-developed and post-developed condition drainage area maps.

3. Comprehensive hydrologic and hydraulic computations of the pre-development and post-development runoff conditions for the required design storms, considered individually.

4. Calculations verifying compliance with the water quality requirements.

5. A description of the requirements for maintenance of the stormwater management facilities and a recommended schedule of inspection and maintenance.

6. The identification of a person or persons who will be responsible for maintenance.

7. All stormwater management plans shall be appropriately sealed and signed by a professional in adherence to all minimum standards and requirements pertaining to the practice of that profession in accordance with Chapter 4 (§ 54.1-400 et seq.) of Title 54.1 of the Code of Virginia and attendant regulations.

4 VAC 3-20-220. Requirements for stormwater management annual standards and specifications.

A. A request for approval of stormwater management standards and specifications may be submitted to the department by a state agency on an annual basis. At a minimum, the following certifications shall accompany the request:

1. Individual stormwater management plans shall be prepared for each of the state projects.

2. The stormwater management plans shall comply with the technical criteria as outlined in Part II (4 VAC 3-20-50 et seq.) of this chapter and, to the maximum extent practicable, any local stormwater management program technical requirements adopted pursuant to the Stormwater Management Act. It shall be the responsibility of the state agency to demonstrate that the local program technical requirements are not practical for the project under consideration.

3. An inspection and maintenance schedule shall be developed and implemented.

B. Copies of such stormwater management specifications and standards including, but not limited to, design manuals, technical guides and handbooks, shall be submitted.

4 VAC 3-20-230. Administrative procedures: stormwater management plans.

A. Within 30 days after receipt of a complete stormwater management plan submitted by a state agency, the department shall approve or disapprove the plan.

1. The department shall transmit its decision in writing to the state agency which submitted the plan.

2. Disapproved plans shall be revised and resubmitted to the department.

B. Approval of a stormwater management plan for a state project shall be subject to the following conditions:

1. The state agency shall comply with all applicable requirements of the approved plan and this chapter, and shall certify that all land clearing, construction, land development, and drainage will be done according to the approved plan.

2. The land development shall be conducted only within the area specified in the approved plan.

3. No changes may be made to an approved plan without review and written approval by the department.

4. The department shall be notified one week prior to the pre-construction meeting and one week prior to the commencement of land disturbing activity.

5. The department shall conduct periodic inspections of the project to ensure compliance with the plan.

6. The department may require monitoring and reports from the state agency responsible for implementing the plan to ensure compliance with the plan and to determine if the measures required in the plan provide effective stormwater management.

C. Compliance with approved plans shall be subject to the following conditions:

1. Where inspections by department personnel reveal deficiencies in carrying out an approved plan, the responsible state agency shall be issued a notice to comply, with corrective actions specified and the deadline within which the work shall be performed.

2. Whenever the Commonwealth or any of its agencies fail to comply within the time provided in a notice to comply, the director may petition the secretary of a given secretariat or an agency head for a given state agency for compliance. Where the petition does not achieve timely compliance, the director shall bring the matter to the Governor for resolution.

3. Where compliance will require the appropriation of funds, the director shall cooperate with the appropriate agency head in seeking such an appropriation; where the director determines that an emergency exists, he shall petition the Governor for funds from the Civil Contingency Fund or other appropriate source.

4 VAC 3-20-241. Administrative procedures: exceptions.

A. A request for an exception shall be submitted, in writing, to the department. An exception from the stormwater management regulations may be granted, provided that: (i) exceptions to the criteria are the minimum necessary to afford relief and (ii) reasonable and appropriate conditions shall be imposed as necessary upon any exception granted so that the purpose and intent of the Act is preserved.

B. Economic hardship is not sufficient reason to grant an exception from the requirements of this chapter.

4 VAC 3-20-245. Administrative procedures: maintenance and inspections.

A. Responsibility for the operation and maintenance of stormwater management facilities shall remain with the state agency and shall pass to any successor or owner. If portions of the land are to be sold, legally binding arrangements shall be made to pass the basic responsibility to successors in title. These arrangements shall designate for each state project the property owner, governmental agency, or other legally established entity to be permanently responsible for maintenance.

B. At a minimum, a stormwater management facility shall be inspected on an annual basis and after any storm which causes the capacity of the facility principal spillway to be exceeded.

C. During construction of the stormwater management facilities, the department shall make inspections on a regular basis.

D. Inspection reports shall be maintained as part of the land development project file.

PART V.
REPORTING.

4 VAC 3-20-251. Reporting on stormwater management.

The department is required to report to the General Assembly on the extent to which stormwater management programs have reduced nonpoint source pollution to the Commonwealth's waters and mitigated the effects of localized flooding. In order to complete this report, localities with stormwater management programs and state agencies may be asked to voluntarily submit an annual report to the department. Such a request may suggest reporting of data on the number and types of stormwater management facilities installed in the preceding year, the drainage area or watershed size served, the receiving stream or hydrologic unit, a summary of monitoring data, if any, and other data useful in determining the effectiveness of the programs and BMP technologies in current use.

1-5 VIRGINIA EROSION AND SEDIMENT CONTROL REGULATIONS

The following is a complete text of the Virginia Erosion and Sediment Control Regulations 4VAC50-30 amended by the Virginia Soil and Water Conservation Board, Effective March 22, 1995

§4VAC50-30-10 Definitions.

The following words and terms, when used in these regulations, shall have the following meaning, unless the context clearly indicates otherwise. In addition, some terms not defined herein are defined in §10.1-560 of the Erosion and Sediment Control Law.

"Act" means the Erosion and Sediment Control Law, Article 4 (§10.1-560 et seq.) of Chapter 5 of Title 10.1 of the Code of Virginia.

"*Adequate channel*" means a watercourse that will convey the designated frequency storm event without overtopping its banks or causing erosive damage to the bed, banks and overbank sections of the same.

"*Agreement in lieu of a plan*" means a contract between the program authority and the owner which specifies conservation measures which must be implemented in the construction of a single-family residence; this contract may be executed by the program authority in lieu of an erosion and sediment control plan.

"*Applicant*" means any person submitting an erosion and sediment control plan or an agreement in lieu of a plan for approval or requesting the issuance of a permit, when required, authorizing land-disturbing activities to commence.

"*Board*" means the Virginia Soil and Water Conservation Board.

"*Causeway*" means a temporary structural span constructed across a flowing watercourse or wetland to allow construction traffic to access the area without causing erosion damage.

"*Channel*" means a natural stream or manmade waterway.

"*Cofferdam*" means a watertight temporary structure in a river, lake, etc., for keeping the water from an enclosed area that has been pumped dry so that bridge foundations, dams, etc., may be constructed.

"*Dam*" means a barrier to confine or raise water for storage or diversion, to create a hydraulic head, to prevent gully erosion, or to retain soil, rock or other debris.

"*Denuded*" means a term applied to land that has been physically disturbed and no longer supports vegetative cover.

"*Department*" means the Department of Conservation and Recreation.

"*Development*" means a tract or parcel of land developed or to be developed as a single unit under single ownership or unified control which is to be used for any business or industrial purpose or is to contain three or more residential dwelling units.

"*Dike*" means an earthen embankment constructed to confine or control water, especially one built along the banks of a river to prevent overflow of lowlands; levee.

"*Director*" means the Director of the Department of Conservation and Recreation.

"*District*" or "soil and water conservation district" means a political subdivision of the Commonwealth organized in accordance with the provisions of Article 3 (§10.1-506 et seq.) of Chapter 5 of Title 10.1 of the Code of Virginia.

"*Diversion*" means a channel with a supporting earthen ridge on the lower side constructed across or at the bottom of a slope for the purpose of intercepting surface runoff.

"*Dormant*" refers to denuded land that is not actively being brought to a desired grade or condition.

"*Energy dissipator*" means a non-erodible structure which reduces the velocity of concentrated flow to reduce its erosive effects.

"*Erosion and* sediment control plan, *conservation plan*" or "*plan*," means a document containing material for the conservation of soil and water resources of a unit or group of units of land. It may include appropriate maps, an appropriate soil and water plan inventory and management information with needed interpretations, and a record of decisions contributing to conservation treatment. The plan shall contain all major conservation decisions and all information deemed necessary by the plan-approving authority to assure that the entire unit or units of land will be so treated to achieve the conservation objectives.

"*Flume*" means a constructed device lined with erosion-resistant materials intended to convey water on steep grades.

"*Hydraulic outlet structure*" means a control section composed of orifice(s), weir(s) and/or conduit(s) which release impounded runoff at a prescribed flowrate.

"*Hydrologic unit*" means a defined land area drained by a river/stream or system of connecting rivers/streams such that all surface water within the area flows through a single outlet.

"*Live watercourse*" means a definite channel with bed and banks within which concentrated water flows continuously.

"*Locality*" means a county, city or town.

"*Natural stream*" means nontidal waterways that are part of the natural topography. They usually maintain a continuous or seasonal flow during the year and are characterized as being irregular in cross-section with a meandering course. Constructed channels such as drainage ditches or swales shall not be considered natural streams.

"*Nonerodible*" means a material, e.g., riprap, concrete, plastic, etc., that will not experience surface wear due to natural forces.

"*Person*" means any individual, partnership, firm, association, joint venture, public or private corporation, trust, estate, commission, board, public or private institution, utility, cooperative, county, city, town or other political subdivision of the Commonwealth, any interstate body, or any other legal entity.

"*Plan-approving authority*" means the Board, the program authority a department of a program authority, or an agent of the program authority responsible for determining the adequacy of a conservation plan submitted for land-disturbing activities on a unit or units of land and for approving plans.

"*Post-development*" refers to conditions that may be reasonably expected or anticipated to exist after completion of the land development activity on a specific site or tract of land.

"*Program administrator*" means the person or persons responsible for administering and enforcing the erosion and sediment control program of a program authority.

"Program authority" means a district, county, city, or town which has adopted a soil erosion and sediment control program which has been approved by the Board.

"*Pre-development*" refers to conditions at the time the erosion and sediment control plan is submitted to the plan-approving authority. Where phased development or plan approval occurs (preliminary grading, roads and utilities, etc.), the existing conditions at the time the erosion and sediment control plan for the initial phase is submitted for approval shall establish pre-development conditions.

"*Sediment basin*" means a temporary impoundment built to retain sediment and debris with a controlled stormwater release structure.

"*Sediment trap*" means a temporary impoundment built to retain sediment and debris which is formed by constructing an earthen embankment with a stone outlet.

"*Sheet flow*" (also called overland flow) means shallow, unconcentrated and irregular flow down a slope. The length of strip for overland flow usually does not exceed 200 feet under natural conditions.

Shore erosion control project" means an erosion control project approved by local wetlands boards, the Virginia Marine Resources Commission, the Virginia Department of Environmental Quality or the United States Army Corps of Engineers and located on tidal waters and within nonvegetated or vegetated wetlands as defined in Title 28.2 of the Code of Virginia.

"*Slope drain*" means tubing or conduit made of nonerosive material extending from the top to the bottom of a cut or fill slope with an energy dissipator at the outlet end.

"*Stabilized*" means land that has been treated to withstand normal exposure to natural forces without incurring erosion damage.

"*Storm sewer inlet*" means a structure through which stormwater is introduced into an underground conveyance system.

"*Stormwater detention*" means the process of temporarily impounding runoff and discharging it through a hydraulic outlet structure to a downstream conveyance system.

"*Temporary vehicular stream crossing*" means a temporary nonerodible structural span installed across a flowing watercourse for use by construction traffic. Structures may include bridges, round pipes or pipe arches constructed on or through nonerodible material.

"*Ten-year storm*" means a storm that is capable of producing rainfall expected to be equaled or exceeded on the average of once in 10 years. It may also be expressed as an exceedence probability with a 10% chance of being equaled or exceeded in any given year.

"Two-year storm" means a storm that is capable of producing rainfall expected to be equaled or exceeded on the average of once in two years. It may also be expressed as an exceedence probability with a 50% chance of being equaled or exceeded in any given year.

"Twenty-five-year storm" means a storm that is capable of producing rainfall expected to be equaled or exceeded on the average of once in twenty-five years. It may also be expressed as exceedence probability with a 4% chance of being equaled or exceeded in any given year.

§4VAC50-30-20 Purpose.

The purpose of these regulations is to form the basis for the administration, implementation and enforcement of the Act. The intent of these regulations is to establish the framework for compliance with the Act while at the same time providing flexibility for innovative solutions to erosion and sediment control concerns.

§4VAC50-30-30 Scope and Applicability.

A. These regulations set forth minimum standards for the effective control of soil erosion, sediment deposition and nonagricultural runoff that must be met:

   1. In erosion and sediment control programs adopted by districts and localities under §10.1-562 of the Act.

   2. In erosion and sediment control plans that may be submitted directly to the Board pursuant to §10.1-563 A of the Act;

3. In annual general erosion and sediment control specifications that electric and telephone utility companies and railroad companies are required to file with the Board pursuant to §10.1-563 D of the Act;

4. In conservation plans and annual specifications that state agencies are required to file with the Department pursuant to §10.1-564 of the Act; and

5. By federal agencies that enter into agreements with the Board.

B. The submission of annual specifications to the Board or the Department by any agency or company does not eliminate the need for a project specific erosion and sediment control plan.

C. These regulations must be incorporated into the local erosion and sediment control program within one year of their effective date.

§4VAC50-30-40 Minimum Standards.

An erosion and sediment control program adopted by a district or locality must be consistent with the following criteria, techniques and methods:

1. Permanent or temporary soil stabilization shall be applied to denuded areas within seven days after final grade is reached on any portion of the site. Temporary soil stabilization shall be applied within seven days to denuded areas that may not be at final grade but will remain dormant for longer than 30 days. Permanent stabilization shall be applied to areas that are to be left dormant for more than one year.

2. During construction of the project, soil stockpiles and borrow areas shall be stabilized or protected with sediment trapping measures. The applicant is responsible for the temporary protection and permanent stabilization of all soil stockpiles on site as well as borrow areas and soil intentionally transported from the project site.

3. A permanent vegetative cover shall be established on denuded areas not otherwise permanently stabilized. Permanent vegetation shall not be considered established until a ground cover is achieved that, is uniform, mature enough to survive and will inhibit erosion.

4. Sediment basins and traps, perimeter dikes, sediment barriers and other measures intended to trap sediment shall be constructed as a first step in any land-disturbing activity and shall be made functional before upslope land disturbance takes place.

5. Stabilization measures shall be applied to earthen structures such as dams, dikes and diversions immediately after installation.

6. Sediment traps and sediment basins shall be designed and constructed based upon the

total drainage area to be served by the trap or basin.

a. The minimum storage capacity of a sediment trap shall be 134 cubic yards per acre of drainage area and the trap shall only control drainage areas less than three acres.

b. Surface runoff from disturbed areas that is comprised of flow from drainage areas greater than or equal to three acres shall be controlled by a sediment basin. The minimum storage capacity of a sediment basin shall be 134 cubic yards per acre of drainage area. The outfall system shall, at a minimum, maintain the structural integrity of the basin during a twenty-five year storm of 24-hour duration. Runoff coefficients used in runoff calculations shall correspond to a bare earth condition or those conditions expected to exist while the sediment basin is utilized.

7. Cut and fill slopes shall be designed and constructed in a manner that will minimize erosion. Slopes that are found to be eroding excessively within one year of permanent stabilization shall be provided with additional slope stabilizing measures until the problem is corrected.

8. Concentrated runoff shall not flow down cut or fill slopes unless contained within an adequate temporary or permanent channel, flume or slope drain structure.

9. Whenever water seeps from a slope face, adequate drainage or other protection shall be provided.

10. All storm sewer inlets that are made operable during construction shall be protected so that sediment-laden water cannot enter the conveyance system without first being filtered or otherwise treated to remove sediment.

11. Before newly constructed stormwater conveyance channels or pipes are made operational, adequate outlet protection and any required temporary or permanent channel lining shall be installed in both the conveyance channel and receiving channel.

12. When work in a live watercourse is performed, precautions shall be taken to minimize encroachment, control sediment transport and stabilize the work area to the greatest extent possible during construction. Nonerodible material shall be used for the construction of causeways and cofferdams. Earthen fill may be used for these structures if armored by nonerodible cover materials.

13. When a live watercourse must be crossed by construction vehicles more than twice in any six-month period, a temporary vehicular stream crossing constructed of nonerodible material shall be provided.

14. All applicable federal, state and local regulations pertaining to working in or crossing live watercourses shall be met.

15. The bed and banks of a watercourse shall be stabilized immediately after work in the watercourse is completed.

16. Underground utility lines shall be installed in accordance with the following standards in addition to other applicable criteria:

    a. No more than 500 linear feet of trench may be opened at one time.

    b. Excavated material shall be placed on the uphill side of trenches.

    c. Effluent from dewatering operations shall be filtered or passed through an approved sediment trapping device, or both, and discharged in a manner that does not adversely affect flowing streams or off-site property.

    d. Material used for backfilling trenches shall be properly compacted in order to minimize erosion and promote stabilization.

    e. Restabilization shall be accomplished in accordance with these regulations.

    f. Applicable safety regulations shall be complied with.

17. Where construction vehicle access routes intersect paved or public roads, provisions shall be made to minimize the transport of sediment by vehicular tracking onto the paved surface. Where sediment is transported onto a paved or public road surface, the road surface shall be cleaned thoroughly at the end of each day. Sediment shall be removed from the roads by shoveling or sweeping and transported to a sediment control disposal area. Street washing shall be allowed only after sediment is removed in this manner. This provision shall apply to individual development lots as well as to larger land-disturbing activities.

18. All temporary erosion and sediment control measures shall be removed within 30 days after final site stabilization or after the temporary measures are no longer needed, unless otherwise authorized by the local program authority. Trapped sediment and the disturbed soil areas resulting from the disposition of temporary measures shall be permanently stabilized to prevent further erosion and sedimentation.

19. Properties and waterways downstream from development sites shall be protected from sediment deposition, erosion and damage due to increases in volume, velocity and peak flow rate of stormwater runoff for the stated frequency storm of 24-hour duration in accordance with the following standards and criteria:

    a. Concentrated stormwater runoff leaving a development site shall be discharged directly into an adequate natural or man-made receiving channel, pipe or storm sewer system. For those sites where runoff is discharged into a pipe or pipe system, downstream stability analyses at the outfall of the pipe or pipe system shall be performed.

b. Adequacy of all channels and pipes shall be verified in the following manner:

(1) The applicant shall demonstrate that the total drainage area to the point of analysis within the channel is one hundred times greater than the contributing drainage area of the project in question; or

(2) (a) Natural channels shall be analyzed by the use of a two-year storm to verify that stormwater will not overtop channel banks nor cause erosion of channel bed or banks; and

(b) All previously constructed man-made channels shall be analyzed by the use of a ten-year storm to verify that stormwater will not overtop its banks and by the use of a two-year storm to demonstrate that stormwater will not cause erosion of channel bed or banks; and

(c) Pipes and storm sewer systems shall be analyzed by the use of a ten-year storm to verify that stormwater will be contained within the pipe or system.

c. If existing natural receiving channels or previously constructed man-made channels or pipes are not adequate, the applicant shall:

(1) Improve the channel to a condition where a ten-year storm will not overtop the banks and a two-year storm will not cause erosion to the channel bed or banks; or

(2) Improve the pipe or pipe system to a condition where the ten-year storm is contained within the appurtenances; or

(3) Develop a site design that will not cause the pre-development peak runoff rate from a two-year storm to increase when runoff outfalls into a natural channel or will not cause the pre-development peak runoff rate from a ten-year storm to increase when runoff outfalls into a man-made channel; or

(4) Provide a combination of channel improvement, stormwater detention or other measures which is satisfactory to the plan-approving authority to prevent downstream erosion.

d. The applicant shall provide evidence of permission to make the improvements.

e. All hydrologic analyses shall be based on the existing watershed characteristics and the ultimate development of the subject project.

f. If the applicant chooses an option that includes stormwater detention he shall obtain approval from the locality of a plan for maintenance of the detention facilities. The plan shall set forth the maintenance requirements of the facility and the person responsible for performing the maintenance.

g. Outfall from a detention facility shall be discharged to a receiving channel, and energy dissipators shall be placed at the outfall of all detention facilities as necessary to provide a stabilized transition from the facility to the receiving channel.

h. All on-site channels must be verified to be adequate.

I. Increased volumes of sheet flows that may cause erosion or sedimentation on adjacent property shall be diverted to a stable outlet, adequate channel, pipe or pipe system, or to a detention facility.

j. In applying these stormwater runoff criteria, individual lots or parcels in a residential, commercial or industrial development shall not be considered to be separate development projects. Instead, the development, as a whole, shall be considered to be a single development project. Hydrologic parameters that reflect the ultimate development condition shall be used in all engineering calculations.

k. All measures used to protect properties and waterways shall be employed in a manner which minimizes impacts on the physical, chemical and biological integrity of rivers, streams and other waters of the state.

§4VAC50-30-50 Variances.

The plan-approving authority may waive or modify any of the regulations that are deemed inappropriate or too restrictive for site conditions, by granting a variance. A variance may be granted under these conditions:

1. At the time of plan submission, an applicant may request a variance to become part of the approved erosion and sediment control plan. The applicant shall explain the reasons for requesting variances in writing. Specific variances which are allowed by the plan-approving authority shall be documented in the plan.

2. During construction, the person responsible for implementing the approved plan may request a variance in writing from the plan-approving authority.
The plan-approving authority shall respond in writing either approving or disapproving such a request. If the plan-approving authority does not approve a variance within 10 days of receipt of the request, the request shall be considered to be disapproved. Following disapproval, the applicant may resubmit a variance request with additional documentation.

3. The plan-approving authority shall consider variance requests judiciously, keeping in

mind both the need of the applicant to maximize cost effectiveness and the need to protect off-site properties and resources from damage.

§4VAC50-30-60 Maintenance and Inspections.

A. All erosion and sediment control structures and systems shall be maintained, inspected and repaired as needed to insure continued performance of their intended function. A statement describing the maintenance responsibilities of the permittee shall be included in the approved erosion and sediment control plan.

B. Periodic inspections are required on all projects by the program authority. The program authority shall either:

a. provide for an inspection during or immediately following initial installation of erosion and sediment controls, at least once in every two-week period, within 48 hours following any runoff producing storm event, and at the completion of the project prior to the release of any performance bonds; or

b. Establish an alternative inspection program which ensures compliance with the approved erosion and sediment control plan. Any alternative inspection program shall be:

(1) Approved by the Board prior to implementation;

(2) Established in writing;

(3) Based upon a system of priorities that, at a minimum, address the amount of disturbed project area, site conditions and stage of construction; and
(4) Documented by inspection records.

§4VAC50-30-70 Developments.

A. An erosion and sediment control plan shall be filed for a development and the buildings constructed within, regardless of the phasing of construction.

B. If individual lots or sections in a residential development are being developed by different property owners, all land-disturbing activities related to the building construction shall be covered by an erosion and sediment control plan or an "Agreement in Lieu of a Plan" signed by the property owner.

C. Land-disturbing activity of less than 10,000 square feet on individual lots in a residential development shall not be considered exempt from the provisions of the act and these regulations if the total land-disturbing activity in the development is equal to or greater than 10,000 square feet.

§4VAC50-30-80 Criteria for Determining Status of Land-disturbing Activity.

A. The program administrator shall determine the validity of a claim of exempt status by a property owner who disturbs 10,000 square feet or more. As soon as a nonexempt status is determined, the requirements of the Act shall be immediately enforced.

B. Should a land-disturbing activity not begin during the 180-day period following plan approval or cease for more than 180 days, the plan-approval authority or the permit-issuing authority may evaluate the existing approved erosion and sediment control plan to determine whether the plan still satisfies local and state erosion and sediment control criteria and to verify that all design factors are still valid. If the authority finds the previously filed plan to be inadequate, a modified plan shall be submitted and approved prior to the resumption of land-disturbing activity.

C. Shore erosion control projects are not subject to these regulations. However, land-disturbing activity immediately outside the limits of the shore erosion project is subject to the Act and these regulations.

D. Whenever land-disturbing activity involves activity at a separate location (including but not limited to borrow and disposal areas), the program authority may either:

1. Consider the off-site activity as being part of the proposed land-disturbing activity; or,

2. If the off-site activity is already covered by an approved erosion and sediment control plan, the program authority may require the applicant to provide proof of the approval and to certify that the plan will be implemented in accordance with the Act and these regulations.

§4VAC50-30-90 Review and Evaluation of Local Programs: Minimum Program Standards

A. This section sets forth the criteria that will be used by the Department to determine whether a local program operating under authority of the Act, satisfies minimum standards of effectiveness, as follows.

Each local program must contain an ordinance or other appropriate document(s) adopted by the governing body. Such document(s) must be consistent with the Act and 4VAC50-30 and 4VAC50-50, including the following criteria:

1. The document(s) shall include or reference the definition of land-disturbing activity including exemptions, as well as any other significant terms, as necessary to produce an effective local program.

2. The document(s) shall identify the plan-approving authority and other positions of authority within the program, and must include the regulations and design standards to be used in the program.

3. The document(s) shall include procedures for submission and approval of plans, issuance of permits, monitoring and inspections of land-disturbing activities. The position, agency, department, or other party responsible for conducting inspections shall be identified. The local program authority shall maintain, either on-site or in local program files, a copy of the approved plan and a record of inspections for each active land-disturbing activity.

4. The local program authority must take appropriate enforcement actions to achieve compliance with the program and maintain a record of enforcement actions for all active land-disturbing activities.

B. The Department staff, under authority of the Board, shall periodically conduct a comprehensive review and evaluation of local programs. The review of a local program shall consist of the following: (1) personal interview between the Department staff and the local program administrator or designee(s); (2) review of the local ordinance and other applicable documents; (3) review of plans approved by the program; (4) inspection of regulated activities; (5) review of enforcement actions.

C. Local programs shall be reviewed and evaluated for effectiveness in carrying out the Act using the criteria in this section. However, the Director is not limited to the consideration of only these items when assessing the overall effectiveness of a local program.

D. If the Director determines that the deficiencies noted in the review will cause the local erosion and sediment control program to be inconsistent with the state program and regulations, the Director shall notify the local program authority concerning the deficiencies and provide a reasonable period of time for corrective action to be taken. If the program authority fails to take the corrective action within the specified time, the Director may formally request Board action pursuant to Code of Virginia §10.1-562.

E. Review and evaluation of local programs shall be conducted according to a schedule adopted by the Board.

§4VAC50-30-100 State Agency Projects

A. All state agency land-disturbing activities that are not exempt and that have commenced without an approved erosion and sediment control plan shall immediately cease until an erosion and sediment control plan has been submitted to and approved by the Department. A formal "Notice of Plan Requirement" will be sent to the state agency under whose purview the project lies since that agency is responsible for compliance with the Act.

B. Where inspections by Department personnel reveal deficiencies in carrying out an approved plan, the person responsible for carrying out the plan, as well as the state agency responsible, will be issued a notice to comply with specific actions and the deadlines that shall be met. Failure to meet the prescribed deadlines can result in the issuance of a stop work order for all land-disturbing activities on the project at the discretion of the Director of the Department or his designee who is authorized to sign such an order. The stop work order will be lifted once the required erosion and sediment control measures are in place and inspected by department staff.

C. Whenever the Commonwealth or any of its agencies fails to comply within the time provided in an appropriate final order, the Director of the Department may petition for compliance as follows: For violations in the Natural Resources Secretariat, to the Secretary of Natural Resources; for violations in other secretariats, to the appropriate secretary; for violations in other state agencies, to the head of such agency. Where the petition does not achieve timely compliance, the Director shall bring the matter to the Governor for resolution.

D. Where compliance will require the appropriation of funds, the Director shall cooperate with the appropriate agency head in seeking such an appropriation; where the Director determines that an emergency exists, he shall petition the Governor for funds from the Civil Contingency Fund or other appropriate source.

§4VAC50-30-110 Board Adopted Local Erosion and Sediment Control Programs

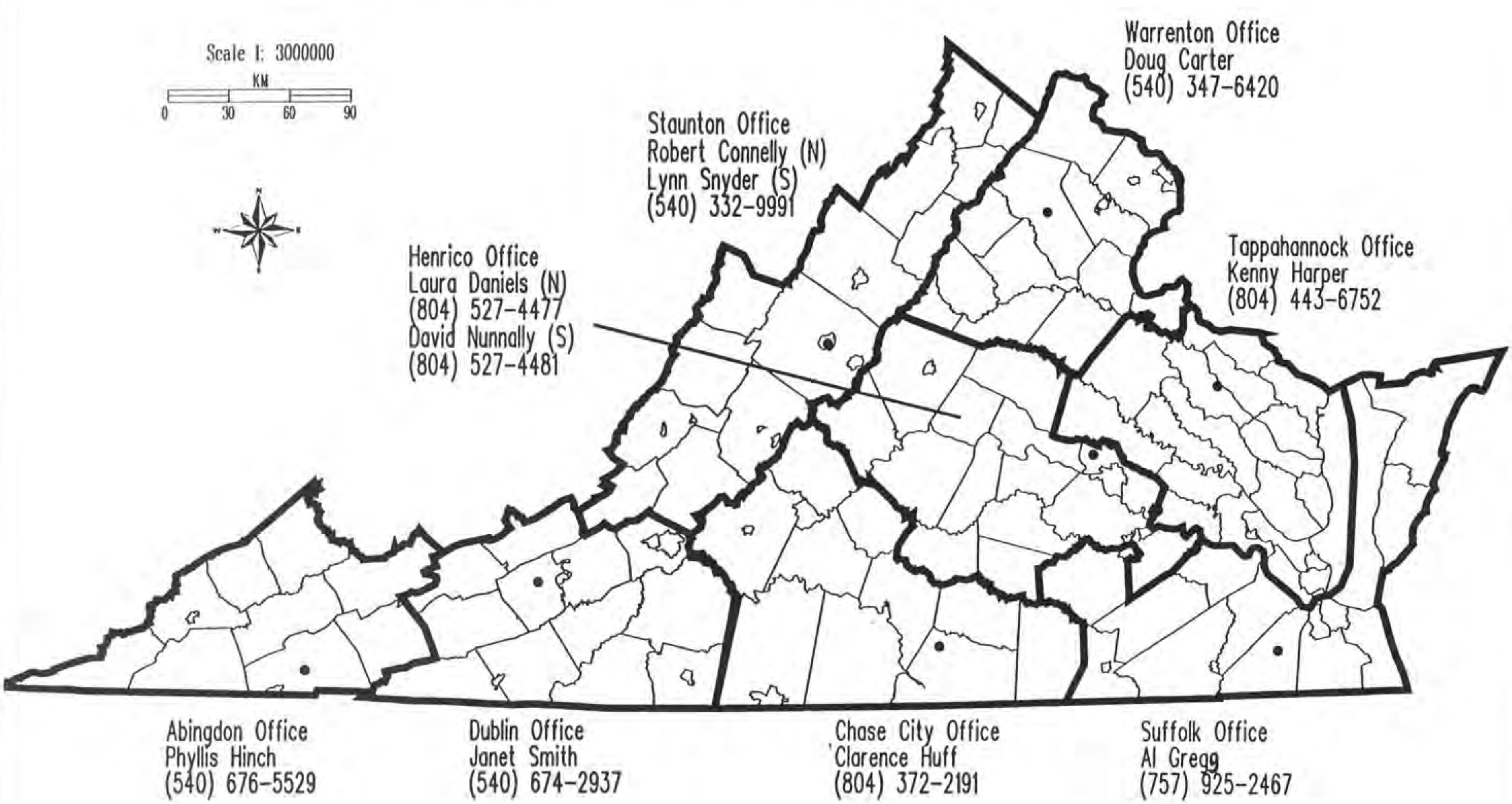
A. To carry out its duties under §10.1-562, the Board shall develop, adopt, and administer an appropriate local erosion and sediment control program for the locality under consideration. In fulfilling these duties, the Board shall assume the full powers of the local erosion and sediment control program granted by law.

B. The Board shall develop, adopt and administer a local erosion and sediment control program based on the minimum program standards established by these regulations and, as deemed appropriate by the Board, may include any or all of the provisions provided by law and regulations including administrative fees and performance securities.

C. Upon adoption of a local erosion and sediment control program by the Board, payment of monies including fees, securities, and penalties shall be made to the state treasury.

D. When administering a local erosion and sediment control program the Board may delegate to the Director such operational activities as necessary. Further, the Board may enter into agreements with other public or private entities to accomplish certain program responsibilities as it deems necessary to administer the local program.

DCR-DSWC REGIONAL
EROSION AND SEDIMENT CONTROL SPECIALISTS



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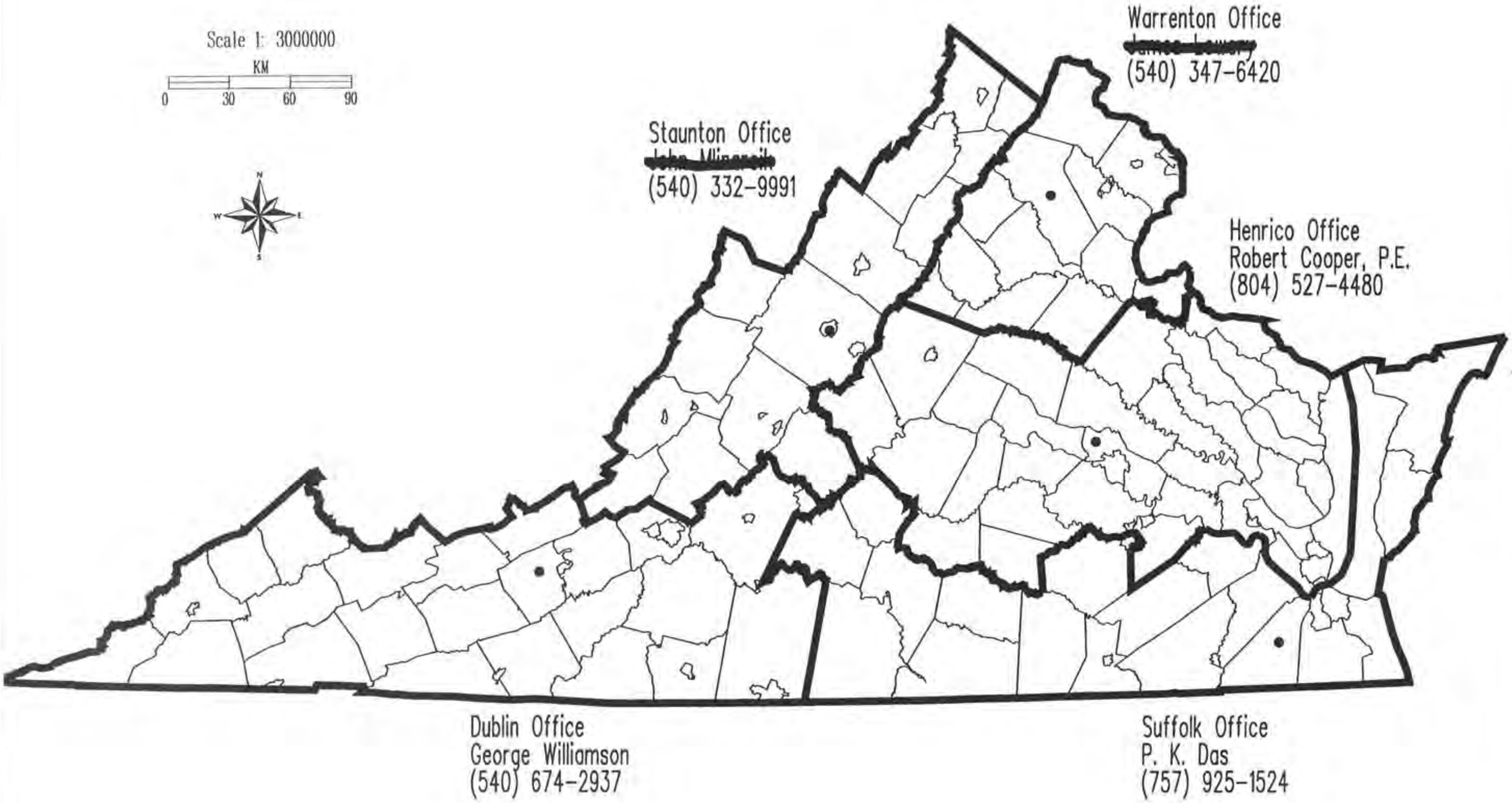
STORMWATER MANAGEMENT ENGINEERS



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CHAPTER 2

STORMWATER MANAGEMENT and URBAN BMPs

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2-1 COMPONENTS OF STORMWATER MANAGEMENT

The goal of storm water management is to mitigate the impact on the hydrologic cycle resulting from changes to the land surface. Urban development has been identified as having a direct impact on the hydrologic cycle by reducing or even eliminating the natural storage capacity of the land. This impact is the result of a decrease in tree cover, loose organic surface soils, and natural depressions, all of which provide natural storage capacity. These natural storage areas are then replaced with impervious and managed pervious surfaces. Impervious cover prevents the percolation of the runoff into the soil, which means that most, if not all of the rainfall is converted to runoff. In addition, managed pervious areas, such as courtyards and lawn areas typically do not provide opportunities for infiltration due to compaction of the surface soil profile and improved drainage conveyances. (The impact of development on the hydrologic cycle is discussed in detail in **Chapter 4; Hydrologic Methods**.) The results of increased stormwater runoff can be classified by its impact on *water quality*, *stream channel erosion*, and *localized flooding*. These components are identified in the Virginia Stormwater Management (SWM) Regulations.

2-1.1 Water Quality

One of the impacts of stormwater runoff is that of the quality of the runoff on the aquatic ecosystem. Various soluble and particulate pollutants are found in stormwater runoff. Studies have shown that the source of these pollutants are atmospheric deposition, urban and agricultural lands, and natural spaces. The focus of this document is on the urban land sources. The impervious surfaces, such as parking lots, roof tops, roads, etc., which are associated with land development serve to accumulate and transport these pollutants to receiving stream channels. It should be noted that pervious areas associated with development, such as golf courses, parks, open space, etc., also contribute pollutants.

The following presents a basic overview of the typical urban pollutants. Additional discussion of urban pollutants associated with certain ultra-urban development environments, referred to as *stormwater hotspots* (Claytor, 1996) is discussed in **Section 2-3: BMP Selection Criteria**.

Nutrients. Concentrations of nutrients, such as nitrogen and phosphorus, found in urban runoff can cause eutrophication of receiving streams, lakes, and rivers, and estuaries. As these nutrients collect in slower moving water bodies, they promote the growth of algae, which in turn blocks sunlight to bottom grasses, and eventually leads to a depletion of available dissolved oxygen (DO). Nutrients in urban runoff have been identified as being a significant contributor to the decline of the Chesapeake Bay. The Virginia Tributary Strategy initiative calls for a 40% reduction in nutrients reaching the Chesapeake Bay by the year 2000.

Suspended solids. All natural drainage channels have a natural sediment bed load which helps maintain a state of equilibrium within the channels of undeveloped watersheds. Increases in the peak rates of flow through the channel or stream system will disrupt the equilibrium by increasing the amount of sediment removed from the channel bed and banks. Suspended solids which result from excessive erosion and scour of the stream channel, the transport of sediments from impervious and managed pervious surfaces, and construction site runoff can have many adverse impacts on aquatic life throughout the water column. Further, these sediments will eventually settle in slower waters and smother the benthic habitat.

The "shock loading" which results from construction site runoff is most damaging to the aquatic habitat. The Virginia Erosion and Sediment Control Program addresses construction site runoff with the implementation of temporary erosion and sediment control measures specifically designed to inhibit sediment from leaving the site, as well as specifications for stabilization of the site once construction is complete. Even after final stabilization, however, loose soil or worn areas will continue to be a source of sediment to the receiving streams.

Bacteria. Varying levels of bacteria found in surface stormwater runoff can create public health concerns in receiving streams and lakes. The source of bacteria in stormwater runoff includes livestock operations, failing septic systems, unusually high concentrations of pet and wildlife droppings, leaking sewer lines, illicit connections between storm and sanitary lines, combined sewer overflows, etc. High concentrations of bacteria often result in the closure of public recreational uses of water resources, and may increase the cost of treatment for domestic water use.

Hydrocarbons. Hydrocarbon loading in urban runoff is often associated with automobile engine oil, lubricants, and other compounds. Hydrocarbon levels have been found to be highest in the runoff from parking lots, roads, and service stations.

Trace metals. Trace metals found in urban runoff, such as cadmium, copper, lead, and zinc, originate from a wide variety of sources such as roofing materials, down spouts, galvanized pipes, catalytic converters, brake linings, etc. Over time these surfaces wear down, enabling the metals to wash away in urban runoff.

Biological Oxygen Demand (BOD). Decomposition of organic matter in slow moving receiving water bodies such as lakes and estuaries increases the biological oxygen demand. High BOD depletes the available dissolved oxygen (DO) necessary to sustain aquatic life.

Thermal Impacts. Runoff from urban impervious surfaces can significantly increase ambient temperatures in receiving streams. Paved surfaces transfer significant amounts of thermal energy to runoff passing over it. When this warmed runoff reaches the receiving stream, a rise in temperature of just a few degrees can have a adverse impact on aquatic life.

2-1.2 Stream Channel Erosion

The impact of increased stormwater runoff can be easily observed in an urbanized stream system. Most of the drainage network is developed or improved to convey increased volumes and rates of runoff to the receiving stream channel. The stream channel then responds to the increase in flow by eroding to form a larger cross sectional flow area which, theoretically, should result in reduced flow velocities. An eroded channel, however, is quite often a very efficient conveyance system and promotes an even faster velocity of flow, which in turn, accelerates the channel erosion process. Once this process has begun, it is very difficult to stop because typical stream channel soils are highly erodible once the protective lining of cobble or vegetation is eroded away.

2-1.3 Flooding

When the rate of stormwater runoff exceeds the capacity of the various manmade or natural conveyance systems, the result is localized flooding. The conveyance system gradually catches up and drains the flood waters as the rainfall subsides. In some cases debris or other materials dislodged by the rising flood waters will clog the drainage system and cause longer periods of flooding. In either case, pockets of standing water which do not drain will remain for periods of time and eventually percolate into the ground or evaporate.

In the pre-developed condition, most stream channels have an adequate floodplain or flood fringe to convey and store the out of bank flows with minimal damage. With urbanization, however, these floodplain areas are often eliminated or developed with improvements. The periodic ponding of water in developed areas often results in damage. Pavement will fail or be undermined, structures will be water damaged, landscaping and other improvements not used to inundation will be damaged.

2-1.4 Regional (watershed-wide) Stormwater Plans

The cumulative effect of sedimentation, scouring, increased flooding, lower summer flows, higher water temperature, and pollution contribute to the overall degradation of the stream ecosystem. Many studies have documented the decline of fish diversity in urbanized watersheds. The aquatic insects which are a major food resource for fish are impacted by the increased sediment load, trace metals, nutrients, and flow velocities. Less noticeable impacts to the stream systems are changes in water temperature, oxygen levels, and substrate composition.

A regional or watershed-wide stormwater plan provides the framework needed to evaluate the impacts of changes to the land on water resources. A comprehensive watershed management plan considers all of the impacts of increased stormwater runoff: water quality, channel erosion, and flooding. The plan is the result of studying the environmental features of the watershed to identify those areas that should be protected and preserved. The plan identifies and strategically locates stormwater management measures and design criteria to be utilized to protect the watershed. The plan also aims to utilize and protect ecological processes to lessen the need for structural control methods that require capital costs and maintenance.

2-2 BMP SIZING CRITERIA

Stormwater management policies have been developed over the years in an attempt to mitigate the impact of land development on aquatic systems as discussed previously. Increased flash flooding and the associated flood damage in urbanizing areas gave rise to stormwater management policies based on controlling peak discharge. In addition to the structural damage, significant erosion of the channel bed and banks was considered to be a detriment to the value of property. Detention basins sized to reduce the post-development peak discharge to the pre-developed rates became an acceptable and commonly used method of mitigating these impacts of urbanization. As channels eroded, more and more localities developed peak rate control policies aimed at controlling channel erosion and localized flooding. These policies, however, were still based on a peak rate of discharge and did not address the increased *volume* and *frequency* of the peak discharge.

Both theory and experience indicates that, while detention basins designed to control peak discharge are effective in controlling peak rates, the basins are ineffective in controlling the degradation of erodible channels downstream of the basin. (McCuen, Moglen, 1988). Similarly, detention basin design must incorporate methods for improving water quality. The following discussion provides a discussion of various sizing criterion for stormwater quality, stream channel erosion, and flood control BMPs.

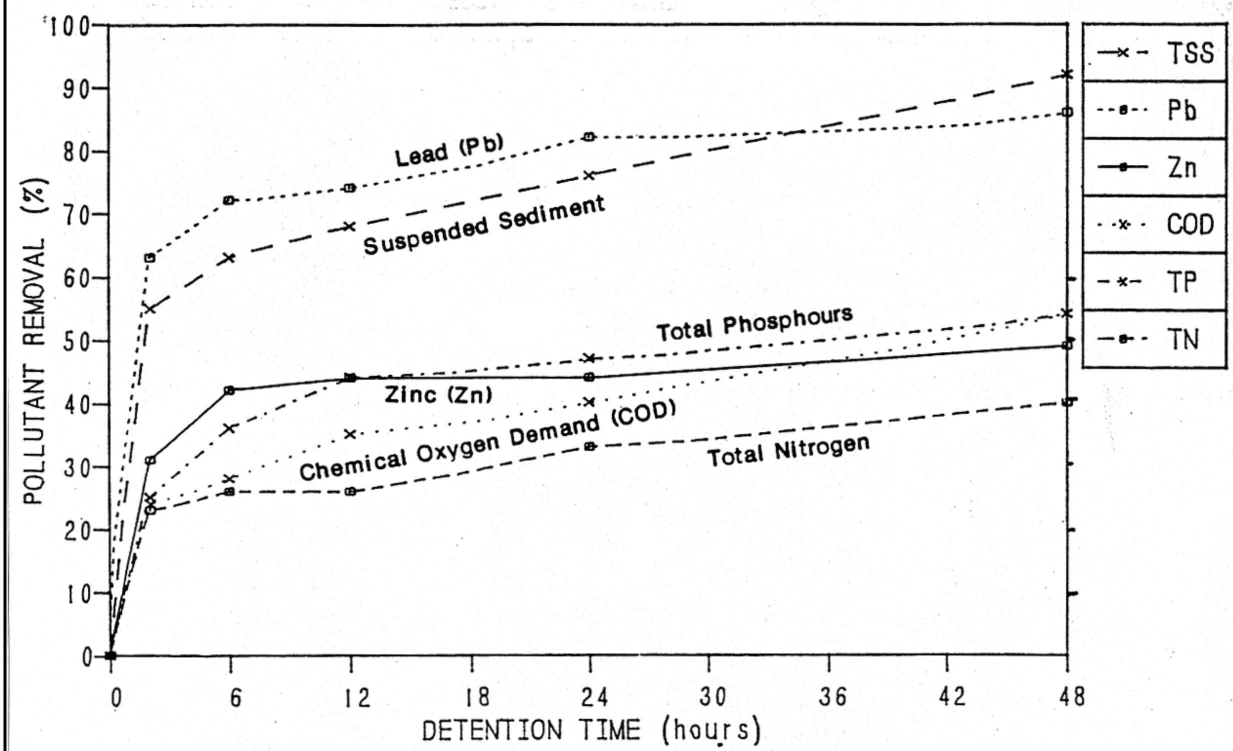
2-2.1 Water Quality

Pollutant Removal Mechanisms

Pollutant removal mechanisms employed by urban BMPs include *settling*, *filtering*, and *biological processes*.

Settling or *sedimentation* is limited to particulate pollutants which drop out of the water column by way of gravitational settling. In some cases, pollutants will attach themselves to heavier sediment particles or suspended solids and drop out of the water column. Laboratory and field studies indicated that significant settling of urban pollutants occurs in the first 6 to 12 hours of detention. **Figure 2-1** provides removal rate vs detention time for selected pollutants. The brim draw down requirement for water quality extended detention design is 30 hours, rather than the minimum of 6 to 12 hours. The additional time is required to allow for ideal settling conditions to develop within the stormwater facility. In addition, the added time will allow for settling of smaller particle sizes and nutrients, as well as increasing the opportunity for biological processes. Stormwater BMPs which utilize settling are usually suited for dual purposes, that is they can also provide storage volume for peak rate control, channel erosion, and/or flood control. These impoundment water quality BMPs are generally sized based on a volume of runoff, commonly referred to as the *water quality volume* (WQV), or “first flush” of runoff. The water quality volume is discussed in detail later in this section.

FIGURE 2-1
Removal Rate vs. Detention Time for Selected Pollutants



Source: Schueler, Controlling Urban Runoff, 1987

Stormwater filtering or *filtration* is typically limited to BMPs which address water quality. These facilities utilize a filter media, such as sand, peat, grass, compost, or various types of fabrics or other material to strain pollutants out of the stormwater. Since the stormwater must pass through the filter media in order to be treated, these structures are limited to small drainage areas (less than 5 acres) and low flow rates. A drawback to these structures is the overflow or bypass of large flows from high intensity storms. The current sizing criteria for these BMPs is the water quality volume. The Department is currently evaluating the option of designating a flow rate or return frequency intensity for design purposes. In most cases a bypass or diversion structure is needed to allow large flows to bypass the BMP without flushing previously deposited pollutants out of the BMP. Guidance on this issue will be provided in the future.

Biological processes are the most effective removal mechanisms for soluble pollutants, such as nutrients. A combination of shallow permanent pool depths and abundant vegetation help to create conditions which allow a natural food chain to develop. Marsh plants, algae and bacteria that grow on the shallow organic rich sediments can take up soluble forms of nutrients needed for their growth. BMPs suited for this pollutant removal mechanism include enhanced extended detention, retention, constructed stormwater wetlands, and in some cases bioretention. The sizing criteria for these BMPs is generally based on permanent pool volume defined as a multiple of the water quality volume, IE: 2.0 or 3.0 times the WQV. (Bioretention utilizes filtering as the primary pollutant removal mechanism.)

Table 2-1 identifies the pollutant removal mechanism utilized by each of the BMPs listed in Table 1 of the Virginia SWM Regulations. It should be noted that the Manufactured BMP Systems are not itemized in **Table 2-1**. For further discussion of Manufactured BMP Systems, refer to **Minimum Standard 3.15**.

TABLE 2-1
Pollutant Removal Mechanisms

Water Quality BMP	Settling	Filtering	Biological
Vegetated filter strip		U	
Grassed swale (w/ check dams)	U	U	
Constructed wetlands	U	U	U
Extended detention	U		
Extended detention enhanced	U	U	U
Bioretention		U	U
Retention basin I, II	U		U
Retention III	U		U
Sand filter		U	
Infiltration		U	

Many stormwater BMPs will utilize a combination of these pollutant removal mechanisms. In some cases, after a BMP has been in operation for a period of time, a layer of organic matter will develop within the BMP, thereby increasing the adsorption potential of the BMP. *Adsorption* is the chemical or molecular attraction which enhances the removal of soluble pollutants. BMPs which include plants and grasses also display increased pollutant removal efficiency over time as the biomass increases. As the vegetation thickens, it serves to slow the velocity of the runoff through the BMP. This allows for increased gravitational settling and filtering of pollutants, as well as decreased export of sediment and attached pollutants via erosion.

Water Quality Volume (WQV)

Ideally, the pollutant removal mechanism should dictate the treatment volume or frequency storm for water quality BMPs. The sizing of BMPs which utilize gravitational settling of pollutants as the removal mechanism can be based on a volume of runoff, while BMPs which utilize filtering should probably be based on a flow rate or frequency. Design criteria provided in **Chapter 3: BMP Minimum Standards**, specifies maximum flow velocities for grass swales and filter strips, as well as the need for a flow splitter or bypass structure for sand filters and other flow through structures.

The Virginia Stormwater Management Regulations require that the *first flush* of runoff be captured and "treated" to remove pollutants. The first flush, or water quality volume (WQV) is generally defined as the first ½" to 1" of runoff from impervious surfaces. Other methods of defining this first flush have been developed. One method in particular, developed by The Center for Watershed Protection, utilizes the Runoff Frequency Spectrum (RFS) for the Washington D.C. area and surrounding Chesapeake Bay watershed. The RFS is based on the fact that 90% of the annual runoff is generated by storms of 1" of rainfall or less. Therefore, the goal of treating at least 90% of the annual runoff results in a treatment volume based on a 1" rainfall. The volume of runoff is determined by multiplying a volumetric runoff coefficient (R_v), based on site imperviousness, by the 1" of rainfall. This method generates a water quality volume of close to 1" for highly impervious sites and gradually decreasing volumes for gradually decreasing levels of imperviousness.

As noted in the Virginia Stormwater Management Regulations, water quality BMPs which are dependent on volume, such as extended detention, constructed stormwater wetlands, and in some cases infiltration, have a required treatment volume of 2.0 x WQV (or 2.0 x 0.5" = 1.0" per impervious acre). This will result in a very similar volume as that based on the RFS method described above. As these methods are studied and BMPs are monitored, the design criteria for determining the WQV may be refined to achieve a greater overall level of treatment.

While the first flush from a storm event is considered to contain the highest concentration of pollutants, there is considerable debate over the intensity of rain needed to wash the pollutants from the urban landscape. Studies have shown that intensity is the critical wash off factor for most storm events, and many people can intuitively comprehend that higher intensity rains leave impervious surfaces cleaner than lower intensity rains. (Adams, 1997). The typical SCS rainfall hyetograph starts with a low rainfall intensity which gradually rises to a peak and then declines. This may indicate that in some cases the designated water quality volume provided in a stormwater basin may fill up with the relatively clean water at the onset of a rain event, consequently allowing the larger flows associated with the high intensity rain and pollutant wash off to pass through the facility.

A similar discussion on the design criteria for water quality structures focuses on the "volume" of runoff verses the "rate", or even the return frequency, of runoff. The water quality volume or first flush is detained in a basin or impoundment structure to allow the pollutants to settle out. Whether that specific volume of runoff enters the basin gradually, or as the result of a sudden high intensity rain, it is still detained for a period of time. Filtering structures, on the other hand, can handle only a certain design flow rate. Sudden high intensity rain will typically generate too much runoff too fast and therefore bypass the treatment facility.

A new category of water quality BMPs: Manufactured BMP Systems (**Minimum Standard 3.15**), utilizes combinations of settling, swirl concentration, and filtering to separate pollutants from the runoff. These structures vary in how they respond to high flows. Some will bypass large flows with little or no treatment, while others will continue to separate and treat the runoff at a reduced efficiency. Further study of these manufactured systems and the appropriate design criteria for flow through or hydro-dynamic structures is warranted and will be provided at a future time.

2-2.2 Stream Channel Erosion

Stream channel erosion results primarily from high scour velocities over extended durations of time. Studies show that natural channels are shaped by the 1½- to 2-year frequency storm event. (Leopold et al., 1964; Anderson, 1970). This frequency allows the channel to maintain a state of equilibrium with regard to the natural sediment load transport and natural vegetation which helps to stabilize channel banks. Therefore, local ordinances have traditionally regulated the 2-year storm, specifying that the post-developed peak rate of runoff may not exceed the pre-developed rate. Note, however, that this requirement does not address the increase in the *frequency* of that peak runoff rate. Urbanization usually increases the amount of impervious cover, resulting in less infiltration, less initial abstraction and less depression storage. Consequently, it takes less rainfall to produce the same *volume* of runoff. Therefore, the *peak rate of runoff* that normally occurs on a 2-year frequency before development, may occur several times a year following development.

To compound the problem, a detention basin stores the increased *volume* of runoff from a developed area and releases it at the pre-developed rate. The *duration* of this discharge is much longer than the pre-developed condition. The peak rate and velocity may be at pre-developed levels, but by receiving the pre-developed rate for a longer *duration*, coupled with the increase in *frequency*, a stable earth-lined channel can quickly degrade.

The increased frequency of a specific discharge can be illustrated by considering an undeveloped watershed which, during a 2-year frequency storm (3.2 inches of rain), generates a theoretical peak rate of runoff of 15 cfs, and a corresponding volume of runoff of 0.52 watershed inches. We will assume that this 2-year frequency flow represents the channel forming, bankfull discharge. After the watershed has experienced development (32% imperviousness) along with the associated improved drainage conveyance systems, the same watershed requires only 1.6 inches of rainfall to generate that same theoretical bankfull discharge of 15 cfs. This means that the channel will now experience bankfull flows at an approximate increased *frequency* of every three to six months rather than two years. In addition, for the 2-year storm, the *volume* of runoff has increased to 1.15 watershed inches, more than double the pre-developed volume, which means a significant increase in the *duration* of the peak flow can be expected. Under this scenario, the receiving stream will experience a significant increase in erosive flows.

The solution to designing for stream channel erosion is evolving into a study of stream channel geomorphology. Several studies have indicated that the level of erosion (or bed-material load) is a function of the difference between the flow velocity and the *critical* velocity.(McCuen, 1987). The critical velocity is a function of the type of soil of which the channel bed is composed. The studies indicate that the amount of bed sediment moved is a function of the time duration over which the velocity is greater than the critical velocity. According to McCuen, this explains from a conceptual standpoint why the duration of flow is just as important as the rate of flow. Further, it may explain why detention basins may actually increase the erosion compared to providing no control of the post-developed flows. When no control is provided, the flow tends to exceed the channel capacity and extend out into the floodplain; thus the velocity within the channel banks may not increase significantly even though the peak flow rate does increase significantly.

This should not be interpreted as justification for no control of stormwater runoff. Rather, it highlights the need for a design criteria that replicates the pre-development sediment load transport characteristics of the channel. Several methodologies have been recommended, some of which are very subjective as they are based upon the ability of the designer to analyze and interpret the stream sediment characteristics. This could easily become an expensive and cumbersome methodology, especially in localities that do not experience significant development pressure. The review and approval process could become bogged down in the analysis of field data and trying to verify the channel characteristics, especially when the requirements of the field work may be different for every project.

The Virginia Stormwater Management Regulations address stream channel erosion by requiring compliance with Minimum Standard 19 of the Virginia Erosion and Sediment Control Regulations (4VAC50-30-40.19). This standard requires that **properties downstream from development sites be protected from sediment deposition, erosion, damage due to increases in volume, velocity, and peak flow rate of stormwater runoff**. The specific design criteria specifies that downstream *natural channels* by analyzed for adequacy to convey the developed condition 2-year peak discharge within the channel banks and at a non-erosive velocity. In addition, *man made channels* are analyzed for adequacy to convey the 10-year peak discharge within the channel banks and the 2-year peak discharge at a non-erosive velocity.

When a channel is determined to be not adequate, the use of a stormwater detention BMP sized to discharge the 2-year and 10-year frequency developed-condition peak discharge at the respective pre-developed rates is one of the available options. (Refer to **Chapter 1** for the complete language of Minimum Standard 19.) As we discussed above, this criteria may not be adequate for natural channels due to the increase in the frequency, duration, and volume of the “pre-developed” discharge.

An alternative is to identify a design frequency storm and control the discharge such that it does not exceed that of the critical velocity for the channel. Recent studies have shown a significant reduction in stream channel erosion below facilities designed to provide 24-hour extended-detention of the runoff from the 1-year frequency storm. (Galli MWCOG, 1992). This criteria results in significantly lowered discharge rates and velocities considered to be non-erosive, despite the longer impact time and increased frequency. The Virginia SWM Regulations allow this criteria as an alternative to the 2-year peak discharge control requirement in cases where natural channels are experiencing erosion resulting from existing conditions, or where channels are considered to be sensitive to any increase in flow rate or duration.

Further guidance on the analysis of the adequacy of natural channels, consistent with the Erosion and Sediment Control Regulations will be provided by the DCR in the near future.

2-2.3 Flooding

Control of the 10-year frequency design storm to the pre-developed rate is considered to provide control over a wide range of storms for control of localized or out of bank flooding. This should not be confused with out of bank flooding as it pertains to the 100-year floodplain which is mapped by the Federal Emergency Management Agency (FEMA), and based on the 100-year frequency design storm. The mapped 100-year floodplain is important because it is used to designate and implement the National Flood Insurance Program. Most localities in Virginia have a Floodplain Management Ordinance which controls development within the 100-year floodplain.

2-2.4 More Stringent Criteria

Local programs are authorized under the Virginia Stormwater Management Act to require more stringent technical criteria than the state minimum criteria found in the regulations (4VAC3-20). The more stringent criteria must be based on a watershed plan or study which justifies the criteria, and must be passed into local ordinance through the local ordinance adoption process. The scope of an acceptable watershed plan or study is somewhat subjective and, at a minimum, must stand up to the scrutiny of the local adoption process. Some basic watershed plan concepts are provided in **Section 2-4**.

2-3 BMP SELECTION CRITERIA

The following discussion provides a general outline for choosing the appropriate BMPS for a development site. The order of presentation **does not** imply a decision making process that will systematically progress towards an acceptable BMP. On the contrary, any one of the criteria can render a preferred BMP unacceptable. **In some cases**, the designer may be able to accommodate certain limiting feasibility factors by providing an innovative design which addresses or remedies the constraint. **In all cases**, once a BMP is selected, we strongly recommend that the selection, along with the supporting criteria and any compromises or design features, be presented to the various review or permitting agencies to ensure proper evaluation and review. This will help avoid extensive changes to the stormwater management strategy during the review process.

One of the first considerations in selecting a stormwater BMP is the functional goal of the BMP. Previously, we discussed the components of SWM: *stormwater quality*, *stream channel erosion*, and *flooding*. Any one or combination of these components may be addressed by the local ordinance and will dictate the functional goal of the BMPs. (State agency projects, are required to comply with all three of these regulatory components). In general, stormwater BMPs can be categorized into water *quality* BMPs and water *quantity* (stream channel erosion and flooding) BMPs. **Table 2-2** provides a general categorization of BMPs by functional goal. Note, that some BMPS can be designed to satisfy both quality and quantity goals while others are specifically suited for only one.

The use of some BMPS are limited by site or watershed feasibility factors such as environmental impacts, drainage area or watershed size, and topographic constraints.

Finally, the BMPS designed for water quality control provide varying levels of pollutant removal and are suited for specific development densities. **Table 2-3** presents a generic list of water quality BMPS, their target phosphorus removal efficiency, and appropriate percent impervious cover.

The decision making process of choosing a stormwater BMP must weigh the goals of the proposed facility against the limiting site feasibility factors of the proposed site or BMP location. The limiting *site feasibility* factors include:

1. Topographic and geologic constraints,
2. Contributing drainage area size, and
3. Environmental impacts.
4. Access for maintenance

The possible stormwater management requirements or goals which influence BMP selection include:

1. Multiple Criterion: Stormwater quality, stream channel erosion, flooding, and environmental mitigation,
2. Multiple discharge points,

3. Pollutant removal capability, and
4. Performance-based vs technology-based water quality criteria.

2-3.1 Site Feasibility

1. Topographic and Geologic Constraints

The physical characteristics of the site must be compatible with the performance of the BMP. Reviewing the **Minimum Standards** found in **Chapter 3**, you will note that BMPs are restricted in certain areas based on the geologic or underlying conditions. This can be as simple as determining if the hydrologic soil group is appropriate for the BMP (such as infiltration in permeable soils) or may require a vigorous geotechnical investigation.

a. *Karst topography:* Karst topography consists of geologic formation underlain by carbonate rock and typified by the presence of limestone caverns and sink holes. These areas present very difficult challenges since any BMP which impounds water may cause underlying caverns or sink holes to expand and open at the surface. The use of liners may help the BMP hold the runoff as intended, however, the conveyance to the BMP, as well as the conveyance from the BMP to the receiving channel must also be considered since the overall volume of runoff is increasing and possibly being directed to areas previously not impacted by runoff.

   In addition, the presence of karst may allow a direct path for the stormwater runoff to enter the water table with little or no filtering of pollutants. Any design in regions suspected to include karst topography should be supported by a thorough subsurface geotechnical or geological investigation. Further guidance on geotechnical methods for karst topography will be provided by the Department in the near future.

b. *High water table*: A high water table can impact the proper functioning of a BMP. Infiltration BMPs are restricted since a high water table will prevent the percolation of the stormwater into the sub soils. A high water table may cause dry detention BMPs to evolve into wet facilities. While this may enhance pollutant removal by encouraging a marsh environment, it may not be the choice of design based on maintenance, aesthetics, etc. A high water table may also impact the construction of the embankment or impoundment facilities by making it difficult to achieve the proper compaction of the underlying foundation. Special geotechnical recommendations may be necessary to address impacts associated with a high water table.

c. *Bedrock:* The presence of bedrock close to the surface can have a significant impact on a development project. The cost of excavation increases considerably, especially if blasting is required. Blasting rock in the area of a proposed embankment is not acceptable unless a liner system is proposed for the basin. Blasting can open seams in the bedrock which may allow stormwater to drain out of (or under) the proposed facility.

A thorough geotechnical investigation and report should verify the subsurface conditions for the presence of any of the above features. The scope and requirements of a geotechnical investigation may vary from site to site. Refer to **Minimum Standard 3.10: General Infiltration Practices** for additional information on geotechnical investigations.

d. *Proximity to structures, steep slopes, and water supply wells.* One of the goals of stormwater facilities is to provide recharge of the groundwater. This tends to saturate the adjacent ground during, and for a period of time, after, a storm event. Building foundations, basements, and other structures may be impacted by the wet/dry cycle of the surrounding soils.

Saturating the soils on or adjacent to steep slopes (6 to 10 percent or greater) can cause a failure of the slope and adjacent structures.

The proximity to water supply wells raises concern over the introduction of pollutants into the water supply aquifer. Minimum distances from these features are presented in **Chapter 3: Minimum Standards**.

2. Contributing Drainage Area Size

Some BMPs are restricted based upon the size of the contributing drainage area. The recommended maximum and minimum sizes are considered guidelines and some flexibility should be allowed. The exceptions, however, are the Manufactured BMP Systems (**Minimum Standard 3.15**) The manufacturers design criteria should be adjusted or modified **by the manufacturer only**. The proper operation of these BMPs is dependent on the proper sizing of the structure.

3. Environmental Impacts

It is extremely important for the designer to asses the environmental impacts associated with the site development and the placement of the stormwater BMP. Local, State, and Federal regulations may restrict the disturbance, or encroachment upon any of the following: wetlands, Waters of the United States, stream or wetland buffers, floodplains, conservation easements, and other sensitive resources.

Virginia Water Protection Permit Program: The Virginia Department of Environmental Quality implements the Virginia Water Protection Permit (VWPP) Program. This program regulates all activities in Virginia which result in discharge or dredge or fill material into state waters. This can include wetlands, perennial streams, and other aquatic resources. The VWPP program is in conjunction with the U.S. Corps. of Engineers Federal Permit authorized by the Clear Water Act. Some projects may require one or both permits. The permit typically requires that the developer investigate alternatives to the proposed impacts. If no alternatives are viable, then possible design modifications may be needed, such as pre-treatment of stormwater prior to discharging into wetlands, thermal and dissolved oxygen impacts to the receiving stream be addressed, etc. The designer should contact the appropriate state or federal agencies prior to the design to identify such permit requirements.

Chesapeake Bay Preservation Act: The Chesapeake Bay Preservation Act (CBPA) and regulations, implemented by local governments, contain restrictions on development within certain buffer areas of wetlands, streams and other sensitive water resources. The designer should contact the Chesapeake Bay Local Assistance Department or the local government prior to the design to identify the restricted buffer areas and other requirements of the CBPA and regulations.

National Flood Insurance Program: The Department of Conservation and Recreation (DCR) coordinates the Federal Emergency Management Agency (FEMA) National Flood Insurance Program (NFIP) in Virginia. Local governments implement local floodplain management ordinances consistent with the state and federal statutes. The designer should contact DCR or the local government prior to design in order to identify any mapped 100-year foodplain located on the project.

2-3.2 Site or Watershed Stormwater Management Requirements

1. Multiple Criterion: Quality, Stream Channel Erosion, and Flooding

The functional goal of the stormwater BMP will be determined by the regulatory requirements imposed on the site. In some cases the downstream receiving waters will influence the regulatory requirements. Where multiple controls are required (quality and quantity), ideally these controls can be satisfied in one BMP strategically located on the site. This is usually accomplished with an impoundment BMP such as *extended detention* or *retention*.

On small sites, however, the use of impoundment facilities is limited by the available space, and their inability to adequately serve small areas for water quality. (The small orifice diameter required for adequate extended detention time can easily become a maintenance burden for a small site, and the contributing drainage area size should be at least 25 acres or contain a base flow when considering a retention basin.) Therefore, it may become necessary to utilize more than one BMP: one which addresses quantity and another which addresses quality. Reducing the stormwater quantity requirements through non-structural BMPs or innovating site design techniques will help to reduce the need for structural quantity control BMPs which typically are land intensive.

2. Multiple Discharge Points

The simplest site design includes a stormwater management strategy that consists of one discharge point from the site. Large developments, however, often contain multiple discharge locations as dictated by the topography. Traditionally, this situation has been addressed one of two ways: 1) Provide a Stormwater BMP at each location as required by the size of the contributing drainage area and associated increase in peak discharge, percent imperviousness, etc; or 2) overcompensate at one discharge point in order to allow the other discharge point(s) to go uncontrolled.

Overcompensation of Peak Discharge should be subject to the following conditions:

1. The drainage channels which leave the site must be part of the same stream or tributary network and the confluence should occur at some reasonable distance from the site.

2. The uncontrolled discharge is still subject to the requirements of MS-19, that is the receiving channel is adequate to convey the increased flow.

3. The overall peak rate of discharge leaving the site must not exceed that of the pre-developed condition.

Overcompensation of Water Quality is covered in more detail in the next section which discusses the use of the Performance-based Water Quality Criteria. However, as it applies to multiple discharge points, the following conditions should apply:

1. The drainage channels which leave the site must be part of the same stream or tributary network and the confluence should occur at some reasonable distance from the site.

2. Every effort should be made to provide water quality enhancement through the use of vegetated buffers, open grass/vegetated swales, bioretention, or other low maintenance water quality BMPs.

3. Every effort should be made to minimize the impacts in the uncontrolled drainage area through non-structural means as discussed previously.

4. The overall site water quality compliance must be determined using the performance-based water quality criteria.

Another alternative which may be considered is the control of existing development in lieu of the proposed development. This trade off should be considered only if specific site, watershed, or environmental considerations hinder the successful incorporation of on-site BMPs.

3. Pollutant Removal Efficiency

Years of pollutant removal monitoring of stormwater BMPs has provided us with a basic understanding of how efficient various BMPs are at removing urban pollutants. Most of this knowledge is limited to the older and more traditional impoundment BMP structures such as *retention* and *extended detention*. Recent regulatory requirements focused on reducing the export of nonpoint source pollution have given rise to new BMPs, some of which have had very limited monitoring with which to verify removal efficiencies. The pollutant removal efficiencies provided in the stormwater regulations and this handbook are derived from the best available information. We recognize that these values are subject to change as we learn more about the practical application and maintenance of these new BMPs.

Keystone Pollutant

The pollutant removal efficiencies presented in **Table 2-4** are removal efficiencies for phosphorus. This target or keystone pollutant was selected by the Chesapeake Bay Local Assistance Department in order to evaluate the performance of site design and BMPs at reducing pollutant export from a development site. The selection of one pollutant allows a consistent application of a performance based water quality criteria. Phosphorous was selected because it exhibits some of the characteristics of particulate pollutants, as well as those of soluble pollutants, making it a good indicator of urban pollutants in general. This is not meant to exclude other pollutants from being targeted. The performance-based water quality calculation procedure was originally adopted as guidance in the Chesapeake Bay Local Assistance Department's *Local Assistance Manual* for localities implementing Chesapeake Bay Preservation Act (CBPA) programs. In situations where other pollutants are identified as a problem, such as from "stormwater hotspots", those other pollutants should be addressed.

Stormwater Hotspots

Stormwater hotspots are defined as a land use or activity that generates higher concentrations of a particular pollutant or pollutants, such as sediment, hydro-carbons, trace metals, or toxicants, than are found in typical stormwater runoff, based on monitoring studies. (Center for Watershed Protection, 1997). The use of some BMPs are limited on sites considered to be stormwater hotspots. This is due to the potential for the contamination of groundwater. *Infiltration facilities* are not recomended for hotspots for this reason. Further, the use of impoundment type structures for hotspots should be qualified by an adequate separation from the seasonal groundwater table (four foot separation is desirable, and a two foot separation minimum), or an impermeable liner used to prevent leachate infiltration

TABLE 2-2
Functional Goal of Stormwater BMPs

Stormwater BMP	Quality	Stream Channel Erosion	Flooding
Vegetated filter strip	U++		
Grassed Swale (w/ check dams)	U++	U	
Constructed wetlands	U++	U	
Extended detention	U+	U++	U
Extended detention enhanced	U++	U+	U
Bioretention	U++		
Retention basin	U++	U+	U
Sand filter	U++		
Infiltration	U++		
Infiltration Basin	U+	U	U
Detention		U+	U++
Manufactured BMPs	U++		

Legend: U++ = Primary functional goal

U+ = Potential secondary functional goal

U = Potential secondary functional goal with design modifications or additional storage

NOTE: *Some BMPs, when properly designed, can provide secondary goals. Table 2-2 indicates several water quality BMPs with potential secondary goals. This is not meant to restrict the designer from incorporating design modifications or additional storage as appropriate for the particular site. Care must be taken to ensure that the the design modifications do not diminish the primary goal capabilities of the BMP.*

TABLE 2-3
Target Phosphorus Removal Efficiency*

Water Quality BMP	Target Phosphorus Removal Efficiency	Percent Impervious Cover
Vegetated filter strip Grassed swale	10% 15%	16-21%
Constructed wetlands Extended detention (2 x WQ Vol) Retention basin I (3 x WQ Vol)	30% 35% 40%	22 -37%
Bioretention basin Bioretention filter Extended detention-enhanced Retention basin II (4 x WQ Vol) Infiltration (1 x WQ Vol)	50% 50% 50% 50% 50%	38 -66%
Sand filter Infiltration (2 x WQ Vol) Retention basin III (4 x WQ Vol with aquatic bench)	65% 65% 65%	67 -100%

** Innovative or alternate BMPs not included in this table may be allowed at the discretion of the local program administrator or the Department. Innovative or alternate BMPs not included in this table which target appropriate nonpoint source pollution other than phosphorous may be allowed at the discretion of the local program administrator or the Department.*

TABLE 2-4
Classification of Stormwater Hotspots

The following land uses and activities are deemed *stormwater hotspots*

< vehicle salvage yards and recycling facilities #
< vehicle fueling stations
< vehicle service and maintenance facilities
< vehicle and equipment cleaning facilities #
< fleet storage areas (bus, truck, etc.) #
< industrial sites (for SIC codes contact Virginia Dept. Of Environmental Quality)
< marinas (service and maintenance) #
< outdoor liquid container storage
< outdoor loading/unloading facilities
< public works storage areas
< facilities that generate or store hazardous materials #
< commercial container nursery

# indicates that the land use or activity is required to prepare a stormwater pollution prevention plan in accordance with the Virginia Pollution Discharge Elimination System program permit as required by the Virginia Department of Environmental Quality.

Source: Center for Watershed Protection, 1997

2-3.3 *Technology-Based* and *Performance-Based* Water Quality Criteria

The *Technology-based* and *Performance-based* water quality criterion represent a consolidation of the water quality technical criteria of three state agencies charged with the responsibility of monitoring and improving the water resources of the Commonwealth: The Department of Conservation and Recreation (DCR), the Department of Environmental Quality (DEQ), and the Chesapeake Bay Local Assistance Department (CBLAD). The specific responsibilities of these agencies are presented in **Chapter 1**. The stormwater management water quality regulations require compliance by **either** a *performance-based water quality criteria* **or** a *technology-based water quality criteria*.

The *performance-based* water quality criteria states that for land development, the calculated post-development nonpoint source pollutant runoff load shall be compared to the calculated pre-development load based upon the average land cover condition or the existing site condition. This approach requires the designer to calculate the pollutant load to be removed, implement a BMP strategy, and then calculate the performance of that strategy, based on the effectiveness or pollutant removal efficiency of the selected BMP(s), (**Table 2-3**) .

The calculation procedure for verifying compliance with the performance-based water quality criteria is based on the Simple Method. The *Simple Method* is empirical in nature and utilizes the extensive data base obtained in the Washington D. C. National Urban Runoff Pollution (N.U.R.P.) study, as well as the national N.U.R.P. data analysis (MWCOG, 1983) to establish pollutant loading values for various land uses. The derivation of the Simple Method can be found in Appendix A of Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs, published by The Metropolitan Washington Council of Governments.

The *technology-based* water quality criteria states that for land development, the post-developed stormwater runoff from the impervious cover shall be treated by an appropriate BMP as required by the post-developed condition percent impervious cover as specified in **Table 2-3**. The selected BMP shall be located, designed, and maintained to perform at the target pollutant removal efficiency specified in **Table 2-3**.

These two criterion are considered to be equivalent when implemented as described in this handbook. The design criteria found in **Chapter 3** establishes the minimum design elements which should result in the expected pollutant removal performance of the BMP.

1. Performance-Based Water Quality Criteria

The *performance-based water quality criteria* states that for land development, the calculated post-development nonpoint source pollutant runoff load shall be compared to the calculated pre-development load based upon the average land cover condition or the existing site condition. A BMP shall be located, designed, and maintained to achieve the target pollutant removal efficiencies specified in **Table 2-3** to effectively reduce the pollutant load to the required level based upon the following four applicable land development situations for which the performance criteria apply:

1. *Situation 1* consists of land development where the existing percent impervious cover is less than or equal to the average land cover condition and the proposed improvements will create a total percent impervious cover which is less than the average land cover condition.

    Requirement: No reduction in the after development pollutant discharge is required.

2. *Situation 2* consists of land development where the existing percent impervious cover is less than or equal to the average land cover condition and the proposed improvements will create a total percent impervious cover which is greater than the average land cover condition.

    Requirement: The pollutant discharge after development shall not exceed the existing pollutant discharge based on the average land cover condition.

3. *Situation 3* consists of land development where the existing percent impervious cover is greater than the average land cover condition.

> Requirement: The pollutant discharge after development shall not exceed (i) the pollutant discharge based on existing conditions less 10% or (ii) the pollutant discharge based on the average land cover condition, whichever is greater.

("...which ever is greater" refers to the calculated pollutant discharge to which the after development pollutant discharge is compared. Additional explanation is provided in the discussion following this section.)

4. *Situation 4* consists of land development where the existing percent impervious cover is served by an existing stormwater management BMP that addresses water quality.

> Requirement: The pollutant discharge after development shall not exceed the existing pollutant discharge based on the existing percent impervious cover while served by the existing BMP. The existing BMP shall be shown to have been designed and constructed in accordance with proper design standards and specifications, and to be in proper functioning condition.

The definition of the average land cover condition is important to the successful implementation of the performance-based water quality criteria. An analysis of the Chesapeake Bay watershed identified the average land cover condition using the following categories: urban land use, forest cover, pasture land, conservation till acreage, and conventional till acreage. Using the pollutant load values from the N.U.R.P. studies, the average land cover condition was then used to establish a baseline existing land use condition pollutant load value of 0.45 lb/ac/yr of phosphorous. Since the Simple Method is based on impervious cover, an equivalent percent impervious cover is needed. 16% impervious cover has been determined to be an equivalent pollutant load source for all of the urban and non-urban land uses which contribute nonpoint source pollution. These values (16% impervious cover and 0.45 lb/ac/yr of phosphorous) represent the average land cover conditions for the Chesapeake Bay watershed. (Keep in mind that these values may be adjusted based on actual land use conditions within the locality or individual watersheds within the locality at the time of DCR or CBLAD program adoption, whichever occurred first.) This allows the designer to calculate, using the Simple Method, the pre-developed pollutant load using average land cover conditions, and the post-developed pollutant load using the project post-developed impervious cover. The difference between the pre- and post-developed pollutant load represents the increase in pollutant load which must then be controlled by an appropriate BMP.

Since this methodology is based on impervious cover, there may be some developments such as golf courses, cemetaries, etc. which would be calculated as having no increase in pollutant load. Depending on the pre-developed land cover, this may or may not be the case. Unmanaged meadow which is graded into a golf course fairway will probably experience an increase in pollutant discharge. Since this is not accounted for in the calculation procedure, the designer and reviewer are encouraged to use sound engineering judgement in applying the water quality criteria. Site feasibility factors should be evaluated and an appropriate BMP selected in situations where the calculation procedures do not accurately reflect the post developed condition impact on water quality.

The designation of an average land cover condition helps to prevent extreme compliance situations. Without such a provision, a site in its natural state with very little runoff and NPS pollution, e.g. a forested site, might become impossible to develop simply because currently available BMPs may not be able to satisfy the pollutant removal requirement of *post* back to *pre*. Conversely, a development of open land with sparse vegetation may generate a significant pre-development load such that careful development of the site, without the use of BMPs, may satisfy the rpollutant removal standard. The concept of average land cover condition attempts to provide a balance in implementing the performance-based and technology-based water quality criteria regulations.

The following presents a brief discussion of the four development situations and the application of the performance based criteria:

Development Situation 1 describes new low density development with a percent imperious cover of less than the average land cover condition (16% Chesapeake Bay watershed default value or a watershed specific value pre-determined by the locality).

Note that the designation of the 16% impervious cover value is not intended to be a threshold for water quality compliance. Simply stated, a development with less than 16% impervious cover should be reviewed for the type and distribution of the impervious cover prior to determining that no water quality measures are required.

A low density development with scattered disconnected impervious cover (such as lots sized at 1 acre or more) can easily be considered to have negligible impacts on water quality if the clearing and grading is limited to the minimum needed to build the road and site the houses (other considerations such as maintaining the natural stream buffers, avoiding steep slopes, and minimizing wetland impacts and tree removal should also be evaluated).

Some low impact development (LID) strategies recommend the clustering of development and the associated impervious cover and preserving open space. This strategy allows the overall impervious cover to be kept low while allowing for the preservation of high priority open space such as stream buffers and unmanaged open space. However, the clustered development represents a significant source of increased runoff and pollutant load when directly connected to the drainage system. Guidance on mitigating these impacts within the LID strategy can be found in the references provided at the end of this chapter.

If, on the other hand, the development consists of commercial or industrial development and associated infrastructure (parking lots, roads, and other impervious surfaces), located on a sufficiently large parcel such that the total area of impervious cover is less than 16%, and the improvements include a directly connected drainage network, then water quality controls should be provided. This type of development poses a very difficult development situation to regulate using the performance-based water quality criteria since the overall percent impervious cover is low. Initial efforts to define the impervious cover as connected or disconnected led to very awkward and subjective regulatory language. Another option considered revising the definition of *percent impervious* to read "the impervious area divided by the drainage area within the site multiplied by 100." Again, various development situations were presented which led to subjective interpretations of these definitions. The preferred method of dealing with this issue was determined to be clear guidance on the intent of the 16% impervious cover "average land cover condition," and a case by case evaluation of the application of the performance-based water quality criteria.

When improvements on a site are concentrated such that the impervious area is collected and drained to a single receiving channel (connected impervious cover), it is reasonable to expect that the developed condition runoff will have an impact on the receiving system in terms of water quality impairments, regardless of the overall "site" percent imperviousness, and therefore should be considered in the water quality strategy. In such cases, DCR recommends that the percent impervious cover calculation be based on the drainage area being collected by the improved drainage system.

Development Situation 2 describes new development which results in impervious cover greater than the average land cover condition. The selection and location of a BMP to satisfy the pollutant removal requirement is verified using the Simple Method.

Development Situation 3 describes development of a site with existing development already present. This development situation is provided to help create an incentive for development, or "redevelopment" of existing infrastructure as opposed to developing a raw piece of land. Clearly redevelopment contains more challenges with regard to existing utilities, building locations, entrances, drainage systems, etc. The requirement of 10% reduction in calculated pollutant load from the site allows flexibility in siting a BMP at the most advantageous location with regard to existing site restrictions. If the amount of impervious surface does not change significantly, the designer has the choice of several BMPs to achieve the 10% reduction including the Manufactured BMP Systems (**Minimum Standard 3.15**) which can be easily located on an existing storm system.

Development situation 4 accounts for redevelopment where the existing development is served by an existing water quality BMP. This implies that the BMP was specifically designed to serve as a water quality BMP. In order for the existing BMP to satisfy the criteria it must be shown to have been designed and constructed properly and be in good working condition. New maintenance agreements may be necessary for continued operation of the BMP, as well as design enhancements, to ensure continued successful operation in the new development or redevelopment condition.

The performance-based water quality criteria allows the designer to locate the BMP at the most advantageous location on the site relative to the post-developed drainage divides, topography, etc, in order to meet the "pollutant removal" requirements of the four development situations. The pollutant removal requirements are based on the anticipated pollutant load from the site. Since a "site" may consist of several distinct drainage areas and discharge points, the designer must apply the removal efficiency of the BMP to the area draining to the BMP only. If this does not meet the removal requirement for the site, additional BMPs must be located in other drainage areas until the total pollutant removal satisfies the requirements, or a more efficient BMP should be selected. (All drainage discharges **are** subject to Erosion and Sediment Control Minimum Standard MS-19 - Channel Adequacy).

BMPs with the same pollutant removal mechanisms should not be located in series (runoff flowing from one BMP to the next) with removal efficiencies simply summed together. Consideration should be given to the form of pollutant which is targeted for removal. Sources cite that approximately 40% of phosphorus is bound to sediment or in particulate form. Thus BMPs added in series which serve to remove only particulates (settling) will not significantly increase the pollutant removal efficiency. While there may be some additional removal efficiency, the increase is certainly less than the algebraic sum of the two individual efficiencies.

The performance-based water quality criteria and calculation procedures should generally be applied to subdivision developments on a whole, and not to individual lots. This is not a contradiction to the previous discussion, however, there does appear to be a certain amount of judgement required to effectively comply with the intent of the water quality criteria. Many subdivision type developments can be effectively controlled with several BMPs serving individual lots or concentrated areas of impervious cover. The calculation procedure accounting for several BMPs may still be applied to the whole parcel or development in order to calculate the total pollutant removal achieved by the BMP strategy (the BMP strategy in this case includes multiple BMPs).

2. Technology-Based Water Quality Criteria

The selection of a BMP using the technology-based water quality criteria is based on the imperviousness and size of the drainage area. Review of **Table 2-3** reveals that each BMP is associated with a range of impervious cover. The development of a highly impervious land use such as an office park, in the range of 38 - 66% impervious cover, would indicate that an appropriate selection of BMP should be bio-retention basin or filter, extended detention-enhanced, retention basin II, or infiltration (or any of the BMPs listed for an imperviousness range of 67 - 100%).

Likewise the development of a low density subdivision in the range of 16 -21% imperviousness would indicate the selection of a vegetated filter strip or grassed swale (or any of the more efficient BMPs). The designer need only verify using the performance-based calculation procedure that the required removal efficiency would dictate a similar selection, thus indicating the equality of the two methodologies.

The difference in the two methodologies is the ability to incorporate a combination of BMPs using the performance-based criteria. Consider the just mentioned office park. If an extended detention-enhanced basin is selected, yet does not capture the runoff from the entire site to the effect that the calculated pollutant removal of the BMP does not satisfy the site or planning area pollutant removal requirement, then an additional BMP or a more efficient BMP must be designed.

Consider, as part of the office park, a two acre parking area along the edge of the office park which does not drain to the extended detention-enhanced facility. The designer may choose to incorporate a grassed swale with check dams to control the two acre drainage area. Since the two acre drainage area is almost entirely impervious, strict application of the technology-based criteria would preclude the use of anything but the most efficient BMPs (sand filter, infiltration, etc.) The performance-based criteria, on the other hand, allows for a total pollutant removal to be calculated to measure the combined effectiveness of the more efficient extended detention-enhanced facility on the majority of the site along with the lower efficiency grassed swale serving the small portion of the site.

The use of sound judgement in the application of multiple BMPs should dictate. If the designer is using the technology approach to control a majority of the site, and proposes a less efficient BMP to control the small area draining in the other direction, the requirement to calculate the total site pollutant removal using the performance-based calculation procedure is at the discretion of the plan approving authority. On the other hand, if a portion of the development site is being left uncontrolled, the plan approving authority may certainly require the performance-based calculation procedure to verify compliance.

Several examples will be provided by DCR as guidance in these types of review decisions.

2-4 REGIONAL STORMWATER MANAGEMENT PLANS

The development of a regional stormwater management plan allows a local government to strategically locate stormwater facilities to provide the most efficient control of localized flooding, stream channel erosion, and water quality. In addition, a regional plan provides the added benefit of mitigating the impacts of existing development to allow for restoration of urbanized stream systems.

The objective of a regional stormwater management plan is to address the stormwater management concerns in a given watershed with greater economy and efficiency by installing regional stormwater management facilities versus individual, site-specific facilities. The result will be fewer stormwater management facilities to design, build and maintain in the affected watershed. It is also anticipated that regional stormwater management facilities will not only help mitigate the impacts of new development, buy may also provide for the remediation of erosion, flooding or water quality problems caused by existing development within the given watershed.

If developed, a regional plan shall, at a minimum, address the following:

1. The specific stormwater management issues within the targeted watershed.
2. The technical criteria in 4VAC3-20-50 through 4 VAC 3-20-85 as needed based on number 1 above.
3. The implications of any local comprehensive plans, zoning requirements and other planning documents.
4. Opportunities for financing a watershed plan through cost sharing with neighboring agencies or localities, implementation of regional stormwater utility fees, etc.
5. Maintenance of the selected stormwater management facilities.
6. Future expansion of the selected stormwater management facilities in the event that development exceeds the anticipated level.

The benefits of regional stormwater management plans are well documented by those localities which have implemented them. Likewise, adverse impacts are also documented. The debate over the merits of regional facilities versus the impacts is different in each watershed. The following provides a list of some of the more common issues frequently surrounding the decision making process. Future guidance, in conjunction with the Corps of Engineers and the Department of Environmental Quality, will be provided by DCR.

Asserted problems with on-site facilities:

1. Not as efficient at pollutant removal as larger facilities.

2. More land is disturbed because of need for a number of smaller facilities; an additional 5 to 10 acres will not be available for development out of every 1, 000 acres served by stormwater management facilities.

3. Not well maintained, reducing pollutant removal efficiency.

4. More complicated for localities to maintain a large number of small facilities.

5. Access may be more difficult.

6. Do not typically have maintenance features such as forebays, access roads, and sediment disposal areas. Difficulty in access and maintenance often results in maintenance responsibility being shifted to homeowner's associations, which experience has shown, are not generally capable of coordinating the public works function required to effectively maintain stormwater management facilities. Uncertainty of maintenance puts long- term reliability of the facility in question.

7. Pose a greater public safety hazard.

8. Have more potential to become "eyesores."

9. Can only be sited to address stormwater discharges from future development since they are implemented for individual development projects only.

10. More expensive.

11. May result in a haphazard siting pattern for stormwater management facilities; with only limited control of down stream erosion and flooding.

Asserted benefits of regional facilities:

1. More efficient and ensure the highest possible efficiencies for the entire watershed, rather than one small site.

2. Offer the ability to control temperature of outflow which is not possible with small facilities.

3. Can be strategically located within a watershed and designed for coincident stormwater releases,

resulting in a coordinated system of controls.[1]

4. Can be located to control some existing, as well as future, development and can compensate for pre-existing development that does not have adequate (or any) stormwater control to help reduce stream bank erosion and negative impacts to downstream floodplains and wetlands.

5. More likely to be adequately maintained.

6. Lower lifetime maintenance cost; more easily accessed and maintained.

7. Provide a recreational amenity.

Asserted adverse consequences that may result from regional facilities:

1. Reaches of a stream above an instream facility receive untreated stormwater containing a variety of pollutants that adversely impact water quality and stream habitat.

2. Upstream inundation from the pond's impounded water destroys floodplains, wetlands and stream habitats.

3. Changes in water depth and frequency and duration of flooding can change the plant communities above and below the pond.

4. Wet ponds block the passage of fish and other aquatic life that normally move up and down the stream and disrupt the downstream movement of food particles, which are the base of the food chain for stream ecosystems.

5. The hydrologic change caused by the impoundment will eliminate species that thrive on flowing stream conditions, but cannot tolerate ponded conditions.

6. Water temperature increases in the pond, as well as downstream, due to incoming runoff can eliminate certain species of fish and aquatic insects.

7. Are more likely to be located in and adversely impact wetlands.

8. Large regional facilities are more difficult to administer because the locality must (1) prepare

[1] Peak flow reductions are only localized in nature because of several factors: The small drainage area controlled by each facility; the extended duration over which the facility releases stormwater flows; the relatively high peak release rates from the on-site facilities (compared to regional facilities which can be sized to achieve release rates that are much less than pre-development conditions); and interactions among releases from on-site facilities which are not coordinated.

a master plan specifying the sites and design criteria, (2) implement a phased construction program so that facilities are in place when new development occurs, and (3) recover pro-rata charges from new development or establish a stormwater utility with which to offset the costs for the regional facilities.

2-5 COMPREHENSIVE WATERSHED MANAGEMENT

The 1994 General Assembly passed Senate Joint Resolution (SJR) No. 44 which allowed for the continued study of the efficiency and consistency of the stormwater management and permitting policies of the Commonwealth. The resolution included, among other elements, the study of approaches to watershed management of stormwater. The following incorporates the findings of the Technical Task Force of the SJR 44 Joint Study Committee.

A comprehensive watershed management plan is the result of studying the environmental and land use features of a watershed to identify those areas that should be protected and preserved and stormwater management measures and design criteria to be utilized to protect such areas so that development, when it does occur, will not negatively impact water resources. In so doing, watershed planning uses and protects ecological processes to lessen the need for structural control methods that require capital costs and maintenance. By including consideration of the watershed and its characteristics, cumulative impacts and inter-jurisdictional issues are more effectively managed than when solely relying on a single site permit approach. Watershed planning can be an important tool for maintaining environmental integrity and economic development.

The Stormwater Management Act (§10.1 - 603.1 et. seq. of the Code of Virginia) enables localities to adopt more stringent stormwater management criteria than those promulgated in the Stormwater Management Regulations (4VAC3-20), provided that the more stringent regulations are based upon the findings of local comprehensive watershed management studies.

Historically, a watershed or regional plan simply focused on the implementation of regional stormwater management facilities within a designated watershed. As our understanding of the dynamic relationship between development and water resources grows, so should the goals of a watershed plan. A watershed plan should provide:

- guidance as to the areas and resources to avoid and protect,
- development guidelines to minimize the impacts of new development on water resources,
- identification of retrofit opportunities such as BMP retrofits, stream restoration, etc. to mitigate impacts resulting from existing development, and
- appropriate stormwater management options (structural and non-structural) including design criteria and locations.

To accomplish these goals, a watershed plan should consist of three components: **Inventory, Planning, and Implementation.**

These three components include the following:

A. Inventory

1. **Define the watershed boundary.**
2. **Conduct a watershed inventory of natural resource features** (wetlands, floodplains, stream corridors, greenways, rare and endangered species, steep slopes, erodible soils, karst bedrock areas, sensitive habitats, fish and wildlife resources, recreational areas, sources of water supply).
3. **Conduct a stream inventory** (size, order, water and habitat quality, flow regime).
4. **Identify significant environmental features in neighboring watersheds** (large pollution sources, wildlife refuges, sources of water supply).
5. **Identify and quantify existing sources of point and nonpoint source pollution.**
6. **Model the existing hydrology and hydraulics of the watershed** (understand the impact of land use, conveyances, land cover, stormwater management facilities, stream cross sections, roadway crossings, flooding and drainage problems).

B. Planning

1. **Define the goals of the watershed management plan** (what is envisioned for the watershed and who is going to lead the implementation efforts).
2. **Identify and quantify future sources of point and nonpoint source pollution.**
3. **Model the future hydrology and hydraulics of the watershed.**
4. **Develop and evaluate alternatives to meet the goals and manage water quality** (point and nonpoint source pollution) **and quantity** (hydrology and hydraulics).
5. **Identify opportunities to restore natural resources.**
6. **Develop the watershed management plan** (include specific recommendations on development and land use evaluation, selection of structural and non-structural BMPs, public education needs, regulatory requirements, and funding).

C. Implementation

1. **Identify the stakeholders responsible for developing, implementing and updating the plan to ensure long-term accountability.**
2. **Define the implementation costs** (capital costs and annual administrative, operations and maintenance costs) **and who will pay for the implementation of the watershed management plan** (provide incentives and secure commitments).
3. **Develop a watershed monitoring program.**
4. **Develop an evaluation and revision process for the watershed management plan.**
5. **Establish and implementation schedule.**

The process described in the following sections is based on the above mentioned steps and can be used to develop a watershed management plan for any watershed. The amount of effort expended on each step depends on the specific goals of the project, the data available, and the people involved in preparing and implementing the plan. Some of the steps need to be conducted concurrently to facilitate a successful implementation of the plan.

2-5.1 Inventory of Watershed Characteristics

The inventory of the watershed characteristics will serve as the basis for the design and location of BMPs at the regional (watershed) level and flood/erosion controls. The inventory data will be integrated with information from the planning and implementation components to develop the watershed management plan.

1. Define the Watershed Boundary

In order to develop a meaningful and implementable watershed management plan, an appropriate watershed or subwatershed needs to be selected. Watershed plans often end up on the shelf because the size of the watershed was too large (greater than 60 square miles) and the focus of the plans became too fuzzy (Center for Watershed Protection, 1996). In addition, the impacts of different land uses on the watershed hydrology, stream health and water quality is difficult to evaluate, unless very detailed models are developed.

Municipalities can be subdivided into watersheds or subwatersheds ranging from 2 to 20 square miles in drainage area. When these watershed or subwatersheds extend beyond the municipality's corporate limits, efforts should be made to develop memoranda of understanding with adjacent jurisdictions to facilitate and promote implementation of watershed management plans. Once the watershed or subwatersheds are delineated, the municipality can prioritize the development of watershed management plans based on local needs and water quality and quantity criteria.

2. Conduct a Watershed Inventory of Natural Resource Features

Successful implementation of a watershed management plan will also depend on the ability to obtain the appropriate permits from state and federal agencies. An inventory of natural resource features in the watershed will promote the development of a BMP siting approach that minimizes or avoids impacts on environmental resources to the maximum extent practicable. This BMP siting approach will facilitate permitting.

The natural resource features to be inventoried would depend on the characteristics of the watershed being studied and could include:

- Wetlands
- Floodplains
- Stream corridors and greenways
- Steep slopes
- Erodible soils
- Karst bedrock areas
- Rare and endangered species
- Sensitive habitats
- Cultural resources
- Fish and wildlife resources
- Recreational areas
- Sources of water supply

Wetlands

Wetlands provide unique habitats for both plants and wildlife, including many threatened and endangered species. As a consequence, wetlands are valued for aesthetic and recreational reasons. Wetlands also provide valuable flood storage, groundwater recharge, and pollutant-filtering functions.

Wetlands are widely scattered throughout Virginia and commonly are encountered on development sites and throughout watersheds. Protecting the natural functions of wetlands is a critical element of the site development process and watershed management planning. For moderate- to high-quality wetlands, which are very difficult to replace, avoidance is recommended. If the watershed contains scattered, small, low-quality wetlands, which are more readily replaced, mitigating the wetlands at a central location may be more appropriate, thereby enhancing wetland functions and reducing a potential constraint to development. Early coordination with resource agencies is recommended.

Floodplains and Stream Corridors

Floodplains and stream corridors include waterways and adjacent riparian lands that may be subject to flooding. Natural waterways provide habitat for fish, aquatic plants, and benthic (bottom dwelling) organisms. Development in waterways may destroy aquatic organisms and introduce large loads of sediment and pollutants into the waterways. Modifying waterways to accommodate development also may destroy the physical features essential to a good habitat, including: stable stream banks and bottom substrates, pools and riffles, meanders, and spawning areas.

Vegetated riparian land adjacent to streams stabilizes the stream bank, filters pollutants from storms and floods, and provides habitats for a variety of amphibians, aquatic birds, and mammals that depend on the proximity to water for their life functions. Development in floodplains and riparian corridors can impair the functions and subject structures to damage from flooding and the meandering of natural streams.

A filter strip or riparian-forested buffer should be preserved or created along the banks of streams, where possible. Furthermore, consideration should be given to establishing setbacks for intensive development (e.g., buildings, parking lots, roadways). This will minimize the potential for sediment releases to the streams, as well as maintain the corridor to achieve flood control, water quality, and habitat enhancement objectives. If a development site contains a highly channelized stream, the best interest of both the developer and the aquatic resource may be served by restoring the stream corridor.

Shorelines of ponds, lakes, and wetlands provide many of the same functions as riparian stream corridors provide for streams. Stable vegetated shorelines are particularly valuable in preventing erosion caused by wave action. Protection of shorelines should be considered when developing water dependent development, such as piers and marinas (CH2M HILL, 1998).

Steep Slopes and Highly Erodible Soils

From an erodibility standpoint, the definition of steep can vary depending on surface soil type and underlying geology. In general, extra caution is warranted on a slope exceeding 10 percent (1 foot of vertical drop per 10 feet of horizontal distance). However, even flatter slopes that have soil classified as highly erodible should be identified as steep.

Disturbing steep slopes with development causes instability of the soil on the slopes. Inappropriate development destroys vegetation, root systems, and soil structures. High runoff velocities from exposed steep slopes result in destructive and unsightly erosion, denuded slopes that may be difficult to revegetate, and sediment deposition in sensitive areas both on and off the site.

A general rule to be followed in site development is to minimize the area and time of disturbance and to fit the development to the natural terrain. Stabilizing vegetation should be protected to the maximum extent practicable and disturbed areas should be immediately revegetated. Extending this general rule to the entire watershed will promote preservation of natural resource features.

Karst Bedrock Areas

Karst bedrock areas are underlain by bedrock containing soluble minerals. Karst areas develop voids and solution channels as groundwater gradually dissolves the bedrock. In these terrains groundwater flow can be extremely rapid and unpredictable. Furthermore, the concentration of runoff may stimulate the formation of sinkholes. Sinkholes can develop as flowing water exposes and then washes into the mouths of the near surface openings of subterrain channels and caverns. Rapid degradation of groundwater resources can result when sediment or pollutant laden runoff percolates into karst bedrock aquifers.

Several areas of Virginia are underlain by limestone, dolomite, or marl carbonate rocks which are potentially susceptible to the development of karst conditions. Before introducing site alterations that could concentrate or pond runoff, the presence or absence of carbonate bedrock should be established. If carbonate rocks do occur a professional geologist or civil engineer should be consulted to determine whether sink hole activity is likely. The United States Geological Survey is a good source of information on karst bedrock in Virginia. If an area is prone to sink hole development, site drainage should be planned to minimize the concentration of runoff. This can be accomplished by reducing the hydraulic connectivity of impervious surfaces and by the use of filter strips. Where they are required, channels or ponds should be lined.

Certain BMPs can be used in karst areas to provide infiltration opportunities over a very large area. Examples are filter strips, large bioretention facilities, and permeable pavement. These practices mimic the natural process by which rainfall enters the subsurface. Point sources of infiltration, such infiltration trenches or dry wells should be avoided (CH2M HILL, 1998).

Threatened and Endangered Species

Existing information can be obtained from surveys conducted by the Division of Natural Heritage (DNH) of the Virginia Department of Conservation and Recreation. For portions of the watershed that have not been previously surveyed, DNH's Element List can be compared to plant community information derived from previous investigations in the watershed, as well as from wetlands identification efforts. The inventory should include a list of potential threatened or endangered species.

Cultural Resources

Existing information can be obtained from the Virginia Department of Historic Resources. For potential regional (watershed) BMP sites, background research to characterize the cultural resource potential of the project area can be conducted. This research will provide a historic context for evaluating any cultural resources that might be located in the project area.

Fish and Wildlife Resources

Existing information can be obtained from the Virginia Department of Game and Inland Fisheries. This information will be useful when defining watershed goals and selecting BMPs to protect sensitive areas. In addition, fish can be a good indicator of stream health and can be used during the evaluation of effectiveness of the watershed management plan, as part of a watershed monitoring program.

Recreational Areas and Sources of Water Supply

An inventory of recreational areas and sources of water supply will also facilitate, and in some cases mandate, the goals of the watershed. This information will also be important in the selection of models that will be needed to identify sources of pollution, understand the hydrologic and hydraulic characteristics of the watershed, and evaluate alternatives to meet the watershed goals and manage water quality.

3. Conduct a Stream Inventory

Classifying the stream system within a watershed will further the understanding of its characteristics and will provide a framework for evaluating alternatives. Streams within a watershed can be inventoried based on size, order, water and habitat quality, or flow regime.

4. Identify significant environmental features in neighboring watersheds

Each subwatershed is nested within many larger watersheds. Therefore, watershed management plans for smaller watershed have to be developed within the context of the larger watershed in which they are located. Once the larger and neighboring watersheds are identified, the goals of those watersheds can be incorporated in the watershed management plan. Some of the goals that typically are incorporated in local watershed management plans include nutrient and toxic targets, such as the Tributary Strategy targets, water supply, flood protection, and waste water requirements or effluent limits (Center for Watershed Protection, 1996). In addition, large pollution sources, wildlife refuges, and sources of water supply in neighboring watersheds may also provide additional goals for the watershed management plan.

5. Identify and Quantify Existing Sources of Point and Nonpoint Source Pollution

Existing information on point sources of pollution can be obtained from the Virginia Department of Environmental Quality (DEQ). Typically, the NPDES permits for point sources will also include some monitoring requirements that can provide additional information for the watershed management efforts. Nonpoint source data can be obtained from DCR and from the local Soil and Water Conservation Districts. The local public works or engineering office can also be good sources of information on previous studies and monitoring efforts.

Watershed models are tools used to understand the cause-and-effect relationships within a watershed. Specifically, water quality models provide information on pollutant loads (from point and nonpoint sources) and their movement throughout the watershed.

Model selection is a function of the following variables:

- The goals and objectives of the watershed management plan
- The data available to describe the hydrologic and hydraulic characteristics and water quality problems in the watershed
- The regulatory requirements and other watershed specific environmental and water quality issues (including time and space scales of the issues or problems)
- The resources (cost, time, hardware and software, modeling expertise, funds) available for applying the model and implementing the recommendations developed with the model

The objectives of the model application for a watershed management plan may range from simple screening of environmental problems that require minimum data input to detailed analysis of water quantity and quality in the watershed. Detailed analysis requires more input data and usually provides information needed for the design of a specific project or for the analysis and solution of specific environmental problems. Detailed analyses are used to represent the watershed processes that affect pollution generation. However, it is not always true that detailed analyses, based on sophisticated models, provide the most accurate representation of the watershed and its environmental problems; it is best to use the least complicated model that will produce the results for appropriate decision making.

Model selection also depends significantly on the data available in the watershed. The precision of the model predictions is affected by dynamic and transient conditions, high spatial variability (mainly related to rainfall variability and land use), and differences in event conditions (such as antecedent moisture conditions, infiltration potential, local pipe or stream conditions, etc.). The data availability and the simulation complexities affect model selection by tempering the decision towards acceptance of a model that is accurate but not as precise as other more sophisticated models.
In addition to data availability issues, monitoring data and watershed responses can be highly variable. Selecting a simpler model, and accepting results that are not as precise as desired but remain accurate, is an appropriate strategy.

6. Model the Existing Hydrology and Hydraulics of the Watershed

The model selection strategy presented in the previous section also applies to hydrologic and hydraulic models.

Hydrologic models provide information on the amount of runoff that will reach the outlet of the watershed and any receiving waters. Hydraulic models estimate water surface elevations and velocities of surface water. These models are also used to characterize the drainage system in the watershed. Groundwater models represent the movement of groundwater.

The focus of the modeling of the existing characteristics of the watershed is to develop baseline information that will be used to evaluate BMP siting and sizing alternatives for meeting the watershed goals and solving drainage and flooding problems. The hydrologic and hydraulic models will also facilitate the understanding of the impact of land use, conveyances, land cover, stormwater management facilities, stream cross sections, roadway crossings, and flooding and drainage problems.

Accurate land use data will ensure accurate modeling results. Developing an updating land use and impervious cover information will facilitate the implementation of the watershed plan.

2-5.2 Planning and Developing the Watershed Management Plan

This second component will define the goals for the watershed management plan; will model future characteristics of the watershed; will develop alternatives to restore resources and meet the goals, including BMPs at the regional (watershed) level; and will produce the watershed management plan. The inventory data developed in the first component will be used as part of the decision-making process illustrated in this component.

1. Define the Goals of the Watershed Management Plan

The first step of the planning component is to define the goals that are most important to the watershed to be protected and to the stakeholder group that will be defined as part of the third component, implementation. As previously mentioned, some of the steps of the three components (inventory, planning, and implementation) need to be conducted concurrently.

A stakeholder group beginning a watershed effort needs to determine what it wants to accomplish and how it wants to use the water body being protected (water quality enhancements and quantity control). The clearer the goals, the easier it is to track progress towards meeting those goals. The goals tend to become clearer as the stakeholders proceed in their efforts. Therefore, the planning process should allow for a systematic re-evaluation of the goals at least every 3 to 5 years.

If possible, express the goals of the watershed management plan in terms of the condition of the waterbody relative to its beneficial uses, not in terms of achieving a certain level of pollutant reduction or applying a certain technology.

2. Identify and Quantify Future Sources of Point and Nonpoint Source Pollution

This step involves using the water quality models developed in the inventory component (**Section 2-5.1, step 5**) and modifying them to include future development conditions in the watershed. It is important to use future land-use information from the comprehensive plan of the municipality and any amendments or recent rezoning cases.

3. Model the Future Hydrology and Hydraulics of the Watershed

This step involves using the hydrologic and hydraulic models described in the inventory component (**Section 2-5.1, step 5**) and modifying them to include future development conditions in the watershed. It is important to use future-land use information from the comprehensive plan of the municipality and any amendments or recent rezoning cases.

4. Develop and Evaluate Alternatives to Meet the Goals and Manage Water Quality and Quantity

In order to meet the watershed goals and to solve the watershed's problems effectively, the watershed master plan should consider all feasible alternatives. These alternatives will manage water quantity and quality in the watershed. Therefore, the alternatives will address flooding, drainage, erosion, and stormwater pollution problems.

Generally, alternative solutions mitigate **flooding and drainage damages** by providing additional storage of flows, by increasing the conveyance capacity of the drainage and stream system, or by floodproofing structures at risk of flooding. Alternative solutions mitigate **erosion damages** by stabilizing stream banks using non-erosive materials and/or by redefining the meandering pattern and using the channel and floodplain to dissipate the flow energy. Alternative solutions mitigate **stormwater pollution** problems by providing structural and non-structural BMPs.

Alternatives should be evaluated by using the existing and future condition models and the information from the inventory component described in **Section 2-5.1**. A map of the watershed showing the recommended alternatives should be prepared and distributed to all stakeholders.

Each alternative, or combination of alternatives, also could be evaluated according to screening criteria that address technical, practical, environmental, economic, and political feasibility. Alternatives can be investigated in detail when they appeared to have potential to be cost-effective and satisfy all project criteria.

Selecting sites for regional (watershed-level) BMPs or flood/erosion controls involves balancing pollutant removal, runoff attenuation, environmental permitting constraints, and cost issues. The following is a typical sequence of the iterative process to be completed for each of the potential sites:

A. Identify potential regional BMP sites and sites for flood/erosion controls.

B. Field screen the sites taking into account the following:
   - drainage area
   - topography
   - existing development and projected future development
   - access and construction issues
   - wetlands constraints
   - other regulatory constraints
   - land ownership/value issues

C. Use the previously described watershed models to analyze pollutant reduction (phosphorous and total suspended solids management), flood/erosion control, and resource protection.

D. Use the inventory and models to identify performance standards for the selection, design, and location of BMPs and for the establishment of erosion, sedimentation, and flood control requirements.

5. Identify Opportunities to Restore Natural Resources

Protecting natural resources and drainage features, particularly vegetated drainage swales and channels, is desirable because of their ability to infiltrate and attenuate flows and to filter pollutants. However, this goal is often not accomplished in most developments. In fact, commonly held drainage philosophy encourages just the opposite pattern. Streets and adjacent storm sewers typically are located in the natural headwater valleys and swales, thereby replacing natural drainage functions with a completely impervious system. Runoff and pollutants generated from impervious surfaces flow directly into storm sewers with no opportunity for attenuation, infiltration, or filtration.
One method of preserving natural drainage features is to use *cluster development* to avoid disturbing major swales. Another recommended approach is to develop site plans that keep roads and parking areas higher in the landscape and *locate existing swales along back lot lines* within drainage easements.

6. Develop the Watershed Management Plan

The watershed management plan will integrate and summarize the different steps described in **Sections 2.5.1** and **2-5.2**. The plan needs to be succinct and simple to ensure that people read it. The plan needs to address the goals and problems of the watershed and should provide recommendations that are specific and implementable. Finally, the plan should include a budget and an implementation schedule, as described in **Section 2-5.3**, below.

2-5.3 Implementation of the Watershed Management Plan

A watershed management plan is effective if it is implemented. Implementation depends on the level of buy-in of the plan from the stakeholders. Stakeholders will remain interested if they are involved from the beginning and they have ways of monitoring the success of the plan.

1. Identify the stakeholders responsible for developing, implementing and updating the plan

Assemble stakeholders who are most affected early in the process. Specifically include those who use, impact and regulate the affected waterbody, and allow them to shape key decisions. Early and effective stakeholder involvement will ensure long-term accountability.

2. **Define the implementation costs and who will pay for the implementation of the watershed management plan**

Use uniform and consistent procedures to estimate project costs for the alternatives developed to solve the problems in each watershed. The cost should include capital costs and annual administrative, operations and maintenance costs for all the elements of the plan.

Identify the funding sources for implementation of the watershed management plan. Below is a summary of the possible funding sources:

- General obligation and revenue bonds
- Stormwater utility fees
- Land development fees
- Pro-rata share contributions
- General fund resources
- Loans and grant programs
- Special service districts and watershed improvement districts

3. **Develop a watershed monitoring program**

Develop a monitoring program that enables the stakeholders to objectively measure and track indicators of the watershed management plan's success. The indicators should focus on water quantity and quality issues, programmatic and socioeconomic needs, and physical and hydrologic measures.

Stormwater chemistry is fairly well understood. Therefore, chemical monitoring of stormwater outfalls will not necessarily provide valuable data. On the other hand, physical and biological monitoring and selected long-term stream monitoring stations will provide valuable information to "measure" the successful implementation of the watershed plan. If success is not achieved, the monitoring program will provide the data to make revisions to the plan. The monitoring program also will provide information to re-evaluate the watershed goals and the implementation schedule.

4. **Develop an evaluation and revision process for the watershed management plan**

During the implementation of the watershed management plan, it is likely that at least one of the following problems will occur:

- Monitoring indicates that the wrong problem is being solved.
- Solving one problem unmasks another problem that is more difficult to control.
- The program reaches some program or activity goals but may not be effective enough to reach the water

quality goals.

- Quantifiable objectives (e.g., pollutant load reduction or flood protection for specific storms) were set too low to solve the problem.

These unpleasant realizations typically occur because of data gaps during the development of the plan. Therefore, the watershed plan needs to include evaluation periods where aspects of the program can be revised if necessary. Watershed plan evaluations can take place every 3 to 5 years.

5. Establish and implementation schedule

Each of the steps presented in the previous sections represent groups of specific activities that make up the watershed plan. Because of the complex and developing nature of the plan, the implementation of the individual steps will occur over differing time frames and will not necessarily follow in a linear sequence but rather be in a parallel sequence.

Some activities need to be implemented quickly to ensure protection of the watershed others will take more time. Therefore, an implementation schedule typically includes a combination of immediate, short-term, and longer-term actions.

Implementation schedules need to be updated and distributed to all stakeholders regularly.

REFERENCES

CH2M HILL, Pennsylvania Handbook of Best Management Practices for Development Areas, Spring 1998.

Center for Watershed Protection, Ellicott City MD. 1998. Better Site Design: A Handbook for Changing Development Rules in Your Community.

Center for Watershed Protection, Ellicott City, MD, 1995. Site Planning for Urban Stream Protection. Prepared for: Metropolitan Washington Council of Governments, Washington D.C.

Center for Watershed Protection, Ellicott City, MD, Watershed Protection Techniques, Volume 2, No. 2, Spring 1996.

Center for Watershed Protection. Ellicott City, MD, 1998. Nutrient Loading from Conventional and Innovative Site Development. Prepared for: Chesapeake Research Consortium.

Chesapeake Bay Local Assistance Department, Richmond, VA, 1999. Chesapeake Bay Preservation Act Implementation: Case Studies on Techniques to Minimize Land Disturbance and Impervious Surfaces and Preserve Vegetation.

Chesapeake Bay Local Assistance Department, Richmond, VA, 1989, Local Assistance Manual

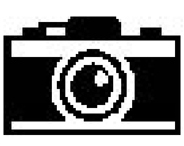
Delaware Department of Natural Resources and Environmental Control (DE DNREC), Dover, DE.1997. Conservation Design for Stormwater Management

Metropolitan Washington Council of Governments, 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs

Prince George County Department of Environmental Resources (PGDER), Laurel, MD. 1997. Low-Impact Development Design Manual

MINIMUM STANDARD 3.01

EARTHEN EMBANKMENT



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MINIMUM STANDARD 3.01

EARTHEN EMBANKMENT

Definition

An earthen embankment is a raised impounding structure made from compacted soil.

Purpose

The purpose of an earthen embankment is to impound stormwater runoff.

Conditions Where Practice Applies

An earthen embankment is appropriate for use with infiltration, detention, extended-detention or retention facilities.

The design procedures presented in this section **may not** apply to small embankments or to storm drainage outfall structures with less than 3 feet of embankment height. The review and approval of such structures should be based on sound engineering practices and supporting calculations that verify a stable outfall for the 10-year storm, at a minimum.

Similarly, this section **does not** apply to embankments with a height of 25 feet or more and a maximum storage capacity of 50 acre-feet or more, as measured from the top of the embankment. Such structures may be regulated under the Virginia Dam Safety Act and the Virginia Dam Safety Regulations (VR 625-01-00).

The *height of an earthen embankment* is the vertical distance from the natural bed of the stream or watercourse, measured at the downstream toe of the embankment, to the top of the embankment. If the embankment does not span a stream or watercourse, the height is the vertical distance between the lowest elevation, measured at the outside limit of the embankment, and the top of the embankment.

Planning Considerations

Earthen embankments are complex structures that must be designed and constructed with consideration given to the following: a) *specific site and foundation conditions*, b) *construction material characteristics*, c) *purpose of the impoundment*, and d) *hazard potential associated with the particular site and/or impoundment*.

The *hazard potential* associated with an impoundment is defined in the Virginia Dam Safety Regulations. It is based on the potential for loss of life and/or economic loss due to facility failure. While stormwater management embankments are typically much smaller than those regulated under the Virginia Dam Safety Program, the potential for significant property damage and loss of life may still be present. The engineer is responsible for analyzing potential downstream impacts and for determining if more stringent analyses are required. **Minimum** guidelines for those facilities **not covered** under Virginia's Dam Safety Regulations are provided in this handbook.

Embankment Types

The type of embankment selected will depend on the purpose of the stormwater facility (detention, extended-detention, retention, etc.) and the available soil material for construction. The two general types are listed below:

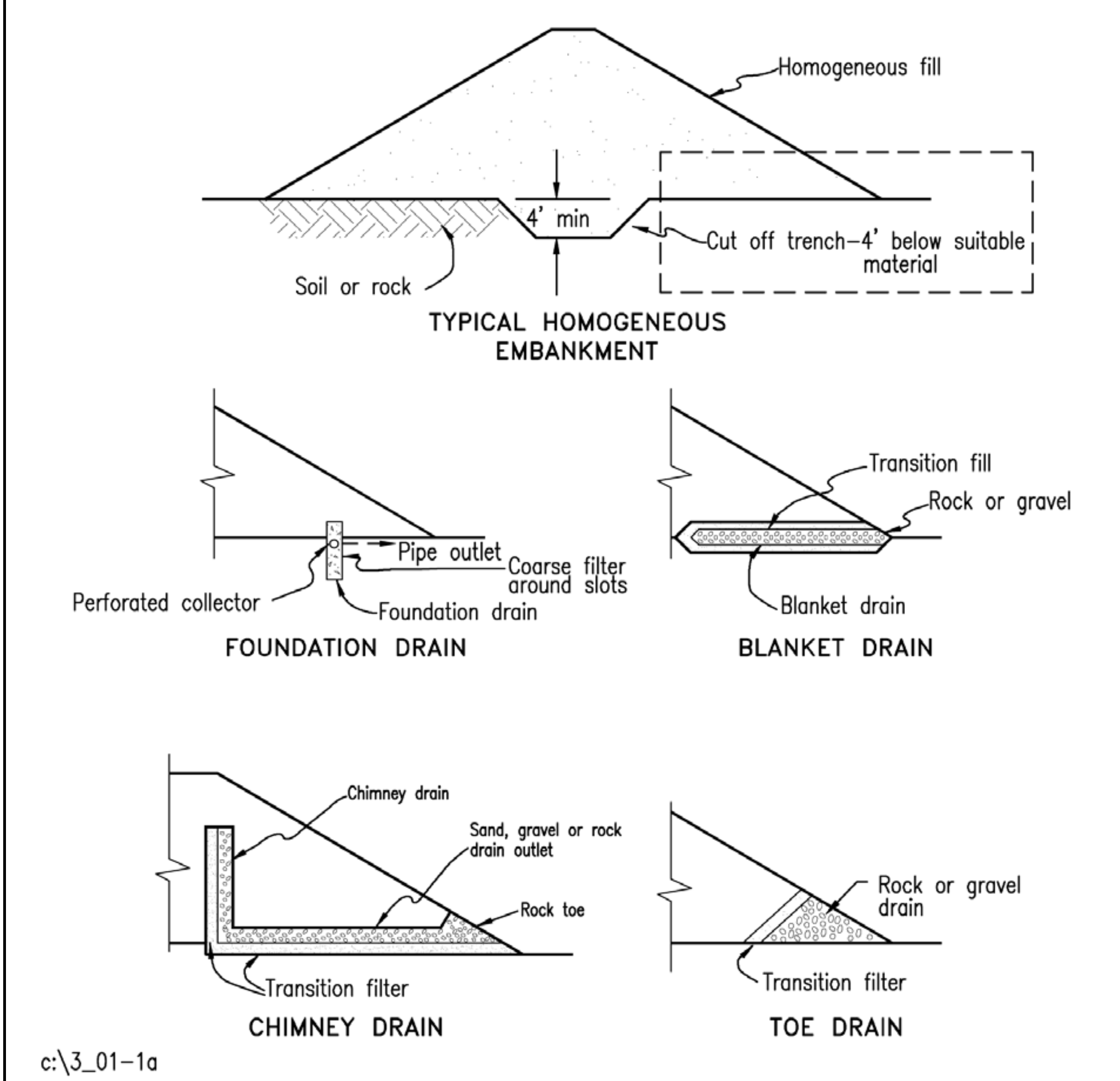
1. A *homogeneous embankment* is composed of one kind of material (excluding slope protection). The material used must be sufficiently impervious to provide an adequate water barrier, and the slopes must be moderately flat for stability and ease of maintenance (see **Figure 3.01-1a**).

2. A *zoned embankment* contains a central impervious core, flanked by zones of more pervious material, called shells. These pervious zones or shells enclose, support, and protect the impervious core. Typically, a zoned embankment requires an internal drain, or filter, between the impervious zone and the downstream shell and between the shell and the foundation (see **Figure 3.01-1b**.

Soils Investigation

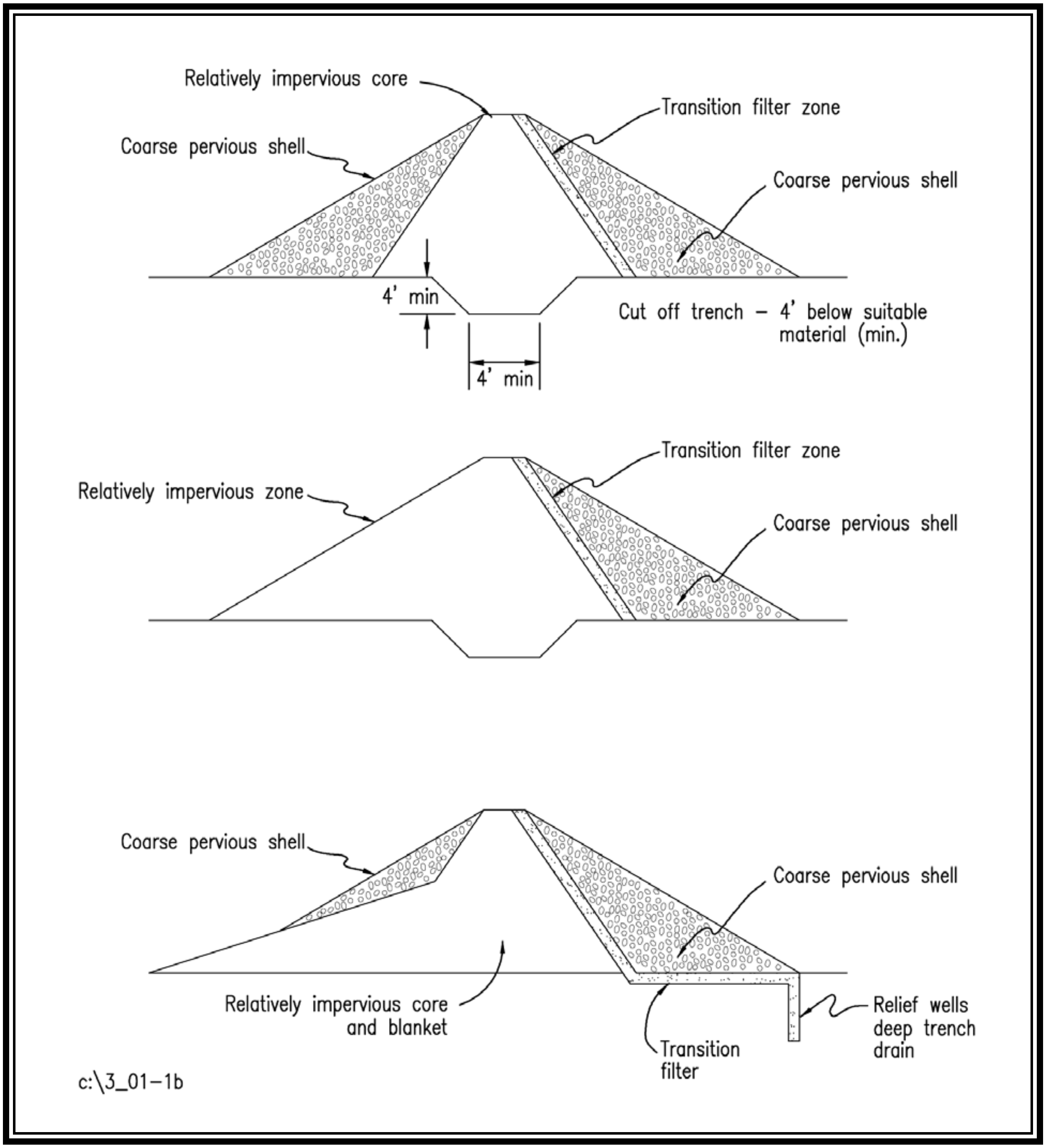
A soils investigation, or geotechnical study, should be completed before designing any earthen embankment covered in this section. The scope of such a study will vary from site to site based upon the size of each project. Recommended minimum guidelines for a geotechnical study are provided below. Refer to U.S. Department of Interior (USDI), Design of Small Dams, latest edition, for additional information.

FIGURE 3.01 - 1a
Homogeneous Embankments w/ Seepage Controls



Source: SCS Engineering Field Manual

FIGURE 3.01 - 1b
Zoned Embankment



Geotechnical Guidelines

The following discussion presents minimum recommended criteria for the planning and design of earthen embankments. The designer is responsible for determining which of the guidelines are applicable to the specific project and for determining if any additional investigations are required.

The validity of the design depends on the thoroughness of the site investigation, the adequacy of the testing program, and the soundness of the designer's judgment. Design components based on quantitative soil tests, such as analyses of slope stability, seepage, and settlement, are not discussed herein, but they are necessary to design large dams. Such analyses will logically follow the selection of a preliminary design. Even for small earth dams that have a low hazard potential, the following criteria should be considered in a geotechnical report.

A geotechnical engineering study should evaluate the stability of the proposed embankment.

A geotechnical engineering study should consist of 1) *a site investigation*, 2) *laboratory testing*, and 3) *an engineering analysis*.

1. A field investigation should include the review of available soils information and a subsurface exploration. Test borings, test pits, or both, should be used to evaluate the foundations, abutments, borrow materials, reservoir area, embankment design and any other pertinent geological considerations. In areas underlain by Karst limestone, a subsurface profile using seismic or sonar technology should be considered to verify that subsurface anomalies do not exist. This type of subsurface investigation may also be recommended in areas known to have been previously mined for mineral extractions.

2. Laboratory testing should be completed to evaluate the various soils. At a minimum, an *index property test* should be completed to classify the soils following the Unified Soil Classification System. Shear strength, compressibility, and permeability testing may be required depending upon the size and complexity of the embankment and the nature of the site's subsurface conditions.

3. A geotechnical engineer should do an engineering analysis and present his or her findings, recommendations and comments on items such as: foundation materials and preparation; design of interior drainage features and filters; and geotechnical design of conduits/structures through the embankment, including seepage and stability analyses. The engineer should also provide a summary describing the soil types and rock strata encountered and explaining the laboratory tests and their results.

Stream Diversions

The design of some earthen embankments will require provisions for stream diversions around or through the embankment site during construction. A stream diversion can be accomplished by a variety of acceptable means, including open channels, conduits, coffer dams, and pumping. Occasionally, stream diversions may be required to meet additional requirements and/or to be permitted by agencies such as the U.S. Army Corps of Engineers, the Virginia Department of Environmental Quality, and/or the Virginia Marine Resources Commission. Refer to the Virginia Erosion and Sediment Control Handbook (VESCH), 1992 edition, for additional guidance on stream diversions.

Design Criteria

To establish *design water surface elevations* and *spillway capacity* for earthen embankments, various hydrologic design methods and spillway storm frequencies may be used. Factors that affect their selection include: a) *the purpose of the stormwater facility: flood control, water quality enhancement, and/or channel erosion control,* b) *the contributing watershed size,* and c) *local regulations*. Despite the design method selected or the frequency storm is used, **the embankment should always be analyzed to ensure safe passage of the maximum spillway design storm while maintaining its structural integrity and stability**. Furthermore, the embankment height should be set such that runoff from the spillway design storm can safely pass through one of the following spillways without overtopping the embankment:

- a natural or constructed spillway,
- a principal spillway, or
- a combination of a principal spillway and an emergency spillway.

Hydrologic and hydraulic methods are described in **Chapters 4** and **5**, respectively.

Local ordinances or watershed conditions may require a more stringent analysis of the embankment concerning overtopping or spillway capacity. The Soil Conservation Service's (SCS) National Engineering Handbook and the Virginia Dam Safety Regulations provide a classification of dams based on the *potential hazard* from failure. A dam failure analysis, or *breach analysis*, may be required to learn the extent of the potential hazard. Any dam breach analysis should use a method similar to the Army Corps of Engineers, SCS (TR-60), National Weather Service, or that specified by the local authority.

Embankment Stability

An earthen embankment must be designed to be stable against any *force condition* or combination of *force conditions* that may develop during the life of the structure. Other than overtopping caused by inadequate spillway capacity, the three most critical conditions that may cause failure of the embankment are:

1. *Differential settlement* within the embankment or its foundation due to a variation in materials, a variation in embankment height, or compression of the foundation strata. Differential settlement may, subsequently, cause the formation of cracks through the embankment that are roughly parallel to the abutments. These cracks may concentrate seepage through the dam and lead to failure by internal erosion.

2. S*eepage* through the embankment and foundation. This condition may cause piping within the embankment or the foundation, or both.

3. S*hearing stresses* within the embankment and foundation due to the weight of the fill. If the shearing stress force exceeds the strength of the materials, sliding of the embankment or its foundation may occur, resulting in the displacement of large portions of the embankment.

The stability of an embankment and its side slopes is dependent on the following: 1) *construction materials*, 2) *foundation conditions*, 3) *embankment height and cross-section geometry*, 4) *normal and maximum pool levels*, and 5) *purpose of BMP: retention, detention, or extended-detention*. The embankment cross-section should be designed to provide an adequate factor of safety to protect against sliding, sloughing, or rotation in the embankment or foundation. SCS's TR-60 publication provides guidelines for slope stability analysis when required. The most important factors in determining the stability of an embankment are:

1. **Physical characteristics of the fill materials**. Soil classification for engineering uses can be found in the SCS Engineering Field Manual, Chapter 4, and other references listed at the end of this section.

2. **Configuration of the site**. The height of the embankment may vary considerably throughout its length, so the total settlement of any given section of the embankment may differ from that of adjacent sections. The length of the embankment and slope of the abutments profoundly influence the degree of differential settlement between adjacent sections of the embankment. As the length shortens and the abutments become more steep, differential settlement becomes more likely. (**Minimum Standard 3.02**, **Principal Spillway** discusses the use of a concrete cradle to protect the spillway barrel sections from separating due to the forces of differential settlement.)

3. **Foundation materials**. The character and distribution of the foundation material must be considered for its *shear strength*, *compressibility*, and *permeability*. Occasionally, the shear strength of the foundation may govern the choice of embankment slopes. Permeability and stratification of the foundation may dictate the need for a *zoned embankment*. Quite often, foundations contain compressible soils that settle under the weight of the embankment, although the shear strength of these soils is satisfactory. When such settlement occurs in the foundation, the embankment settles. This settlement is rarely uniform over the basal area of the embankment. Therefore, fill materials used on such sites must be sufficiently plastic to deform without cracking. (**Minimum Standard 3.02**, **Principal Spillway** discusses the use of a concrete cradle to protect the spillway barrel sections from separating due to the forces of differential settlement.)

A foundation composed of homogeneous soil is simple to evaluate; however, this condition rarely occurs in natural soil deposits. Most often, a stratified deposit composed of layers of several soil types is encountered. To determine the suitability of such a foundation, the following information becomes very important: 1) *the geologic history of the site*, 2) *the degree of stratification*, and 3) *the order in which materials occur within the stratification*. A complex, stratified foundation containing plastic or compressible soil should be investigated by an experienced engineer or geologist.

Foundation cutoff - A foundation cutoff trench of moderately impervious material should be provided under the embankment. The cutoff trench should be installed at or upstream of the dam's centerline, and should extend up the abutments to the 10-year water surface elevation.

The bottom of the cutoff trench should be wide enough to accommodate excavation, backfill and compaction equipment. The trench's minimum width and depth should be 4 feet and the side slopes should be no steeper than 1H:1V (refer to **Figures 3.01-1a,b** and **3.01-2**).

Rock foundations - The presence of rock in the embankment foundation area requires specific design and construction recommendations (provided in the geotechnical engineering analysis) to insure a proper bond between the foundation and the embankment.

Generally, no blasting should be permitted within 100 feet of the foundation and abutment area. If blasting is essential, it should be carried out under controlled conditions to reduce adverse effects on the rock foundation, such as over-blasting and opening fractures. This is especially critical in areas of Karst topography.

Embankment zoning and seepage - The stability of an embankment slope and the seepage pattern through it are greatly influenced by the *zoning of the embankment*. (Refer to **Embankment Types** in the **Planning Considerations** section of this standard.) The position of the saturation line within a homogeneous embankment is theoretically independent of the type of soil used in it. Although soils vary greatly in regard to permeability, even the tightest clays are porous and cannot prevent water from seeping through them. **The rate of seepage through an embankment is dependent on the consistency of the reservoir level and the permeability of the embankment or core material**.

The upper surface of seepage is called the *phreatic surface* (zero pressure). In a cross-section, it is called the *phreatic line*. The position of the phreatic line in a retention basin embankment can be assumed to begin at the normal pool elevation on the upstream slope and extend at a 4H:1V slope downward through the embankment. **This assumption is based on the presence of a permanent pool**. For detention and extended-detention facilities with no permanent pool, many designers assume that the embankment will not impound water long enough for a phreatic surface to occur. This assumption, however, is based on a properly designed, constructed, and maintained embankment. Many jurisdictions, therefore, have chosen a conservative design approach by requiring that the phreatic line start at the 10-year design storm water surface elevation, regardless of the presence of a permanent pool.

For most stormwater management facilities, determining the location of the phreatic surface will often suggest the need to install seepage collars on the barrel. (Refer to **Minimum Standard 3.02, Principal Spillway**, for a discussion on seepage control along conduits.) For larger stormwater facilities, especially those with a permanent pool, the location of the phreatic surface may require additional design considerations such as an internal drain.

If the saturation line intersects the downstream slope of the embankment at a point above the toe, then seepage will exit the embankment along the downstream face and toe. Typically, the quantity of seepage is so slight that it does not affect the slope's stability. However, sometimes the saturation of the toe will cause sloughing or serious reduction of the shear strength in the downstream section of the embankment. Seepage control should be included in the design if the following conditions exist:

- pervious layers in the foundation are not intercepted by the cutoff,
- possible seepage from the abutments may create a wet embankment,
- the phreatic line intersects the downstream slope, or
- special conditions exist which require drainage to insure a stable embankment.

For *seepage collar design*, it is recommended that the phreatic line start at the 10-year design storm water surface elevation and extend through the embankment at a 4H:1V slope. **If the phreatic line intersects the downstream slope, a qualified soil scientist should be consulted to decide if additional controls are needed**. The location of the phreatic surface, therefore, may have a significant impact on the design of the embankment.

Seepage may be controlled by:

- foundation, abutment or embankment drains,

- a downstream drainage blanket,
- a downstream toe drain, or
- a combination of these measures (see **Figure 3.01-1b**).

Seepage encountered in the cutoff trench during construction may be controlled by *foundation drains*. These drains must be downstream of the embankment centerline and outside the limits of the proposed cutoff trench.

Including a toe drain in the design of most homogeneous embankments may be desirable. Embankments built on pervious foundations or constructed of materials that exhibit susceptibility to piping and cracking should always be protected by adequate toe drainage. Toe drains may be constructed of sand, gravel, or rock, depending on the nature of the embankment fill material. Whenever a rock toe drain is installed, a graded filter should be placed between the fill and the drain. Often, a 12-inch layer of well-graded, stream-run, sandy gravel will satisfy this requirement. Filter and drainage diaphragm design criteria are presented in the references listed as USDA-SCS Soil Mechanics Notes No. 1 and No. 3 at the end of this section, and provided in **Chapter 5 Appendix 5B**.

<u>Piping</u>

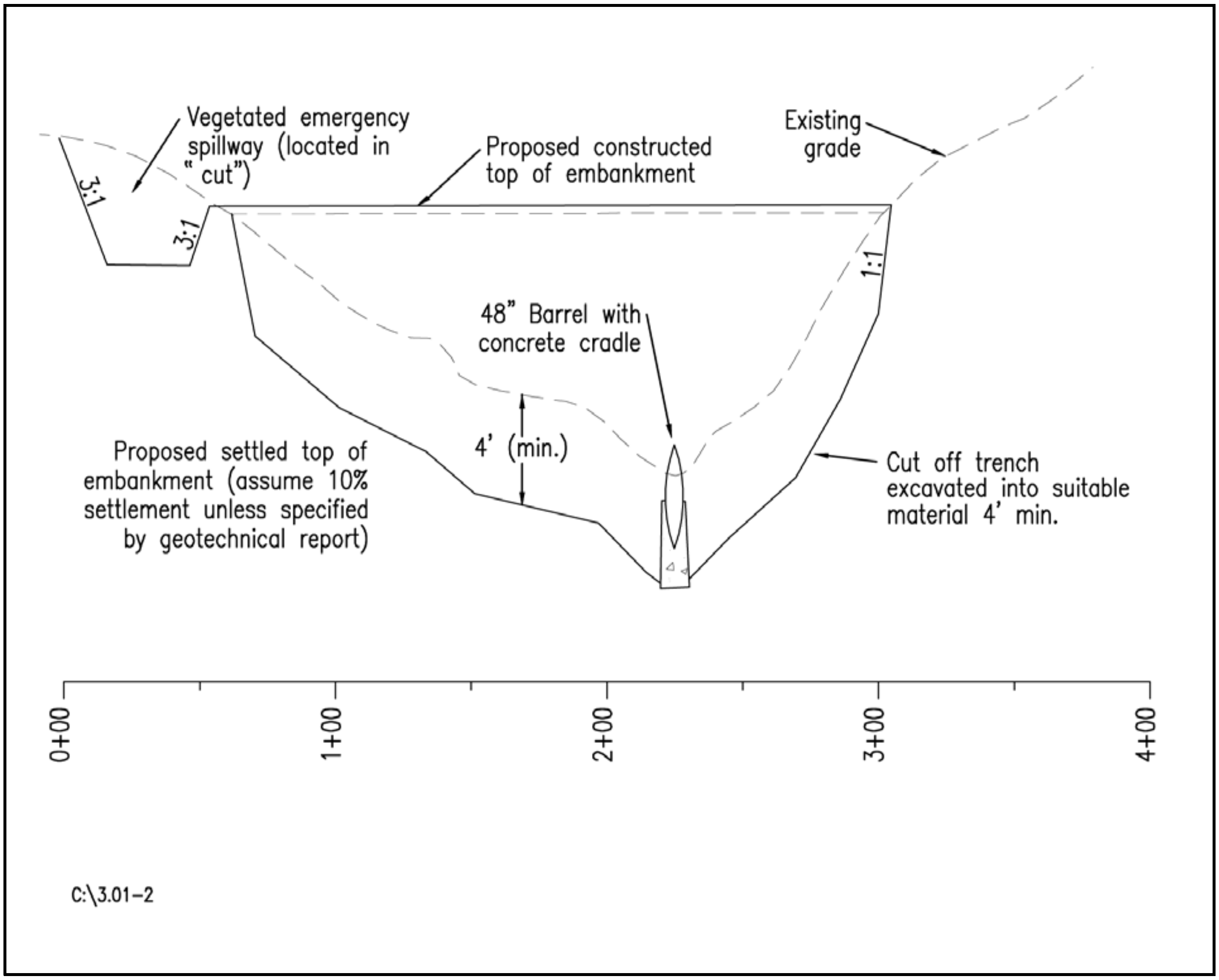
The contact areas between the embankment soils, foundation material, abutments, and conduits are the most susceptible locations for *piping failures.* Piping occurs due to the variation in materials at contact points and the difficulty in compacting the soil in these areas. Compaction is especially difficult next to and under conduits and seepage collars. Therefore, it is highly recommended that all utility conduits, except the principal spillway, be installed away from the embankment. When utility conduits through the embankment cannot be avoided, they should meet the requirements for spillways, i.e., water tight joints, no gravel bedding, restrained to prevent joint separation due to settlement, etc.

Seepage along pipe conduits that extend through an embankment should be controlled by use of the following:

- anti-seep collars, or
- filter and drainage diaphragms.

Refer to **Minimum Standard 3.02, Principal Spillway** for additional information on the use of anti-seep collars. Filter and drainage diaphragms are presented in USDA-SCS Soil Mechanics Notes No. 1 and No. 3, available upon request from DCR or USDA-SCS. When filter and drainage diaphragms are used, their design and construction should be supervised by a registered professional engineer.

FIGURE 3.01 - 2
Profile Along Centerline of Embankment



<u>Embankment Geometry</u>

1. **Height** - The height of an earthen embankment is based upon the freeboard requirements relative to the maximum water surface elevation during the 100-year frequency storm event. **An embankment <u>with</u> an emergency spillway must provide at least 1 foot of freeboard from the maximum 100-year storm water surface elevation (WSE) to the lowest point on the top of the embankment (excluding the emergency spillway)**. (Note that the *spillway design storm W.S.E*, if specified, may be used instead of the 100-year elevation.)

An embankment <u>without</u> an emergency spillway must provide at least 2 feet of freeboard from the maximum 100-year storm WSE to the lowest point on the top of the embankment. (Note that the *spillway design storm WSE*, if specified, may be used instead of the 100-year elevation.)

2. ***Top Width*** - The top of an earthen embankment should be shaped to provide positive drainage. The top width is based on the following table:

TABLE 3.01 - 1
Embankment Top Widths

Total Height of Embankment (*ft.*)	**Minimum Top Width (*ft.*)**
14 or less	8
15-19	10
20-24	12
25 or more	15

<u>Compacted Fill</u>

The soil types, as covered in the geotechnical analysis, should be specified by using the Unified Soil Classification System.

The compaction requirements should include the percent of maximum dry density for the specified density standard, allowable range of moisture content, and maximum loose lift thickness. Refer to **Construction Specifications for Earthen Embankments** later in this standard. In general, the design of an embankment should account for approximately 10% settlement unless otherwise specified by a geotechnical report based on the embankment foundation and fill material. The top of the embankment must be level in order to avoid possible overtopping in one location in cases of extreme storms or spillway failure.

Compaction tests should be performed regularly throughout the embankment construction; typically, one test per 5,000 square feet on each layer of fill or as directed by the geotechnical engineer. Generally, one of two compaction tests will be specified for embankment construction: the *Standard Proctor Test* (ASTM D698) or the *Modified Proctor Test* (ASTM D1557). For the construction of earth dams, the Modified Proctor Test is likely to be more appropriate (Terzaghi, Peck, 1948).This is due in part to the unconfined nature of the earth fill for dam construction. A new Proctor test is required if the material changes from that previously tested.

Embankment Construction

A geotechnical or construction inspector should be on site during embankment construction. Inspectors should be required to do more than just test fill compaction, i.e., observe foundation preparation, pipe installation, riser construction, filter installation, etc. (Refer to inspection checklist for impoundment structures, **Appendix 3**).

> *A vertical trench through the embankment material to place the spillway pipe should not be allowed under any circumstances. Trench side slopes should be laid back in steps at a 2:1 slope, minimum.*

Maintenance and Safety

Embankment slopes should be no steeper than 3H:1V if possible, with a maximum combined upstream and downstream slope of 5:1 (3:1 downstream face and 2:1 upstream face). For embankments exceeding 15 feet in height, a 6 to 10 foot wide bench should be provided at intervals of 10 to 15 feet of height, particularly if slopes are steeper than 3H:1V.

The following design considerations are provided to help reduce the long-term maintenance burden on the owner(s):

1. *Internal drainage systems in embankments (e.g., drainage blankets, toe drains)* should be designed such that the collection conduits discharge downstream of the embankment at a location where access for observation is possible by maintenance personnel.

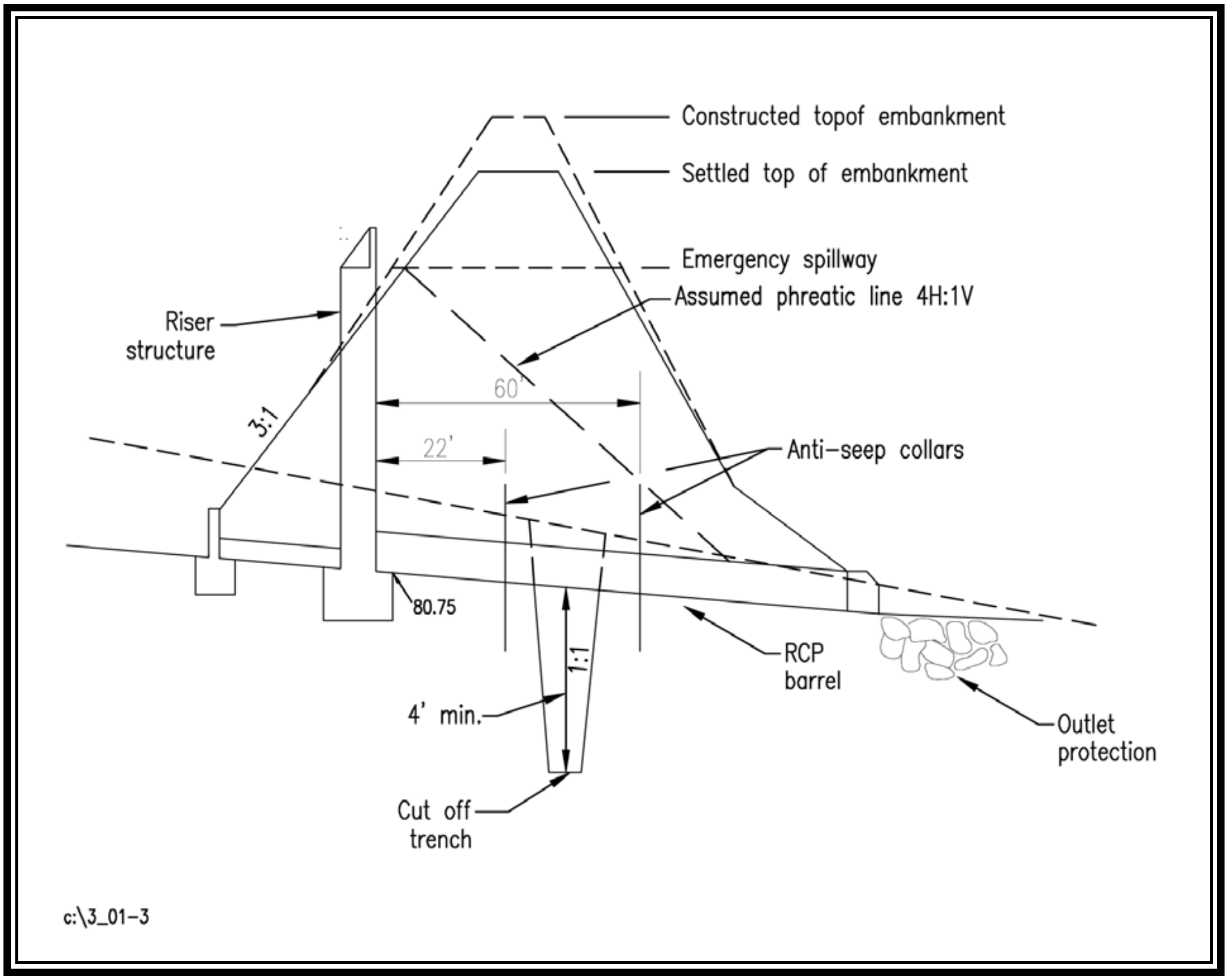
2. *Adequate erosion protection* is recommended along the contact point between the face of the embankment and the abutments. Runoff from rainfall concentrates in these areas and may reach erosive velocities depending on the gutter slope and embankment height. Although a sod gutter will be satisfactory for most small embankments, an evaluation should be made to decide if another type of gutter protection is required. For most embankments, a riprap gutter is preferred to a paved concrete gutter.

3. *Trees, shrubs, or any other woody plants should not be planted on the embankment* or adjacent areas extending at least 25 feet beyond the embankment toe and abutment contacts.

4. *Access should be provided to all areas of an impoundment that require observation or regular maintenance*. These areas include the embankment, emergency spillway, basin shoreline, principal spillway outlet, stilling basin, toe drains, riser structure, extended-drawdown device, and likely sediment accumulation areas.

FIGURE 3.01 - 3

Profile Along Centerline of Principal Spillway



Construction Specifications

The construction specifications for earthen embankments outlined below should be considered as minimum guidelines, with the understanding that more stringent specifications may be required depending upon individual site conditions, as evaluated by the geotechnical engineer. Final construction specifications should be included on the construction plans. In general, widely accepted construction standards and specifications for embankments, such as those developed by the USDA Soil Conservation Service or the U. S. Army Corps of Engineers, should be followed.

Further guidance can be found in the SCS Engineering Field Manual and National Engineering Handbook. Specifications for the embankment work should conform to the methods and procedures indicated for installing earthwork, concrete, reinforcing steel, pipe, water gates, metal work, woodwork and masonry, as they apply to the site and the purpose of the structure. The specifications should also satisfy all requirements of the local government.

Site Preparation

Areas designated for borrow sites, embankment construction, and structural work should be cleared, grubbed and stripped of topsoil. All trees, vegetation, roots and other objectional material should be removed.

All cleared and grubbed material should be disposed of outside and below the limits of the embankment and reservoir, as directed by the owner or his representative. When specified, a sufficient quantity of topsoil should be stockpiled in a suitable location for use on the embankment and other designated areas.

Earth Fill

1. **Material** - Fill material should be taken from an approved, designated borrow area. It should be free of roots, stumps, wood, rubbish, stones greater than 6 inches, and frozen or other objectionable materials. Fill material for the center of the embankment and the cutoff trench should conform to Unified Soil Classification GC, SC, or CL. Consideration may be given to the use of other materials in the embankment if the design and construction are supervised by a geotechnical engineer.

2. **Placement** - Areas on which fill is to be placed should be scarified before its placement. Fill material should be placed in layers a maximum of 8 inches thick (before compaction), which should be continuous over the entire length of the fill. The most permeable borrow material should be placed in the downstream portions of the embankment. The principal spillway must be installed concurrently with fill placement and **not excavated** into the embankment.

3. **Compaction** - Fill material should be compacted with appropriate compaction equipment such as a sheepsfoot, rubber-tired or vibratory roller. The number of required passes by the compaction equipment over the fill material may vary with soil conditions. Fill material should contain sufficient moisture such that the required degree of compaction will be obtained with the equipment used.

   The minimum required density is 95% of maximum dry density with a moisture content within ± 2% of the optimum, unless otherwise specified by the engineer. Each layer of the fill should be compacted as necessary to obtain minimum density and the engineer should certify, at the time of construction, that each fill layer meets the minimum density requirement. All compaction is to be determined by either Standard Proctor Test (ASTM D698) or the Modified Proctor Test (ASTM D1557) as directed by the geotechnical enginer based on site and soil conditions and the size and type of structure being built.

4. **Cutoff Trench** - The cutoff trench should be excavated into impervious material along or parallel to the centerline of the embankment as shown on the plans. The bottom width of the trench should be governed by the equipment used for excavation, with the minimum width being 4 feet. The depth should be at least 4 feet below existing grade or as shown on the plans. The side slopes of the trench should be 1H:1V or flatter. The backfill should be compacted with construction equipment, rollers, or hand tampers to assure maximum density and minimum permeability.

5. **Top Soil** - The surface layer of compacted fill should be scarified prior to placement of at least 6 inches of top soil. The top soil shall be stabilized with in accordance with the Virginia Erosion and Sediement Control Handbook, latest edition.

<u>Structure and Conduit Backfill</u>

Backfill that is beside pipes or structures should be of the same type and quality as specified for the adjoining fill material. The fill should be placed in horizontal layers not to exceed 4 inches in thickness and compacted by hand tampers or other manually directed compaction equipment. The material should completely fill all spaces under and beside the pipe. During the backfilling operation, equipment should not be driven closer than 4 feet, as measured horizontally, to any part of a structure. Also, equipment should **NEVER** be driven over any part of a structure or pipe, unless compacted fill has been placed to a depth specified by the structural live load capacity of the structure or pipe in order to adequately distribute the load.

<u>Filters and Drainage Layers</u>

In order to achieve maximum density of clean sands, filter layers should be flooded with clean water and vibrated just after the water drops below the sand surface. The filter material should be placed in lifts of no more than 12 inches.

Up to four feet of embankment material may be placed over a filter material layer before excavating back down to expose the previous layer. After removing any unsuitable materials, the trench may be filled with additional 12 inch lifts of filter material, flooded, and vibrated as described above, until the top of adjacent fill is reached.

Filter fabrics should not be used in lieu of sands and gravel layers within the embankment.

Maintenance and Inspection Guidelines

A thick, healthy grass cover, free of trees and brush, should be maintained on the embankment. Such a cover will help stabilize the surfaces of the embankment and will simplify inspections.

The maintenance and inspection guidelines presented below are **NOT** all-inclusive. Specific facilities may require other measures not discussed here. It is the designer's responsibility to decide if additional measures are necessary.

1. The embankment should be mowed periodically during the growing season, ensuring that the last cutting occurs at the end of the season. The grass should not be cut less than 6 to 8 inches in height.

2. If necessary, the embankment should be limed, fertilized and seeded in the fall, after the growing season. Lime and fertilizer application rates should be based on soil test results. The type of seed should be consistent with that originally specified on the construction plans.

3. All erosion gullies noted during the growing season should be backfilled with topsoil, reseeded and protected (mulched) until vegetation is established.

4. All bare areas and pathways on the embankment should be properly seeded and protected (mulched) or otherwise stabilized to eliminate the potential for erosion.

5. All animal burrows should be backfilled and compacted and burrowing animals should be removed from the area.

6. All trees, woody vegetation and other deep-rooted growth, including stumps and associated root systems, should be removed from the embankment and adjacent areas extending to at least 25 feet beyond the embankment toe and abutment contacts. The root systems should be extracted and the excavated volume replaced and compacted with material similar to the surrounding area. All seedlings should be removed at the first

opportunity. Similarly, any vine cover and brush should be removed from the embankment to allow for inspections.

7. Any repairs made to the princpal spillway (riser or barrel) should be reviewed by a professional engineer. Vertical trenching to expose the barrel should not be allowed under any circumstances. The trench side slopes should be stepped back at a 2:1 slope, minimum.

REFERENCES

ASTM D-2487. Classification of Soils for Engineering Purposes.

ASTM D-2488. Description and Identification of Soils (visual-manual procedure).

Maryland Department of the Environment-Dam Safety Division. Dos and Don’ts for Pond Construction. May 1997.

Sowers, George F. Introductory Soil Mechanics and Foundations: Geotechnical Engineering.

Terzaghi and Peck. Soil Mechanics in Engineering Practice.

USDA Soil Conservation Service. Engineering Field Manual.

USDA Soil Conservation Service. National Engineering Handbooks.

USDA Soil Conservation Service, Soil Mechanics Notes:

SM Note No. 1, Guide for Determining the Gradation of Sand and Gravel Filters.
SM Note No. 2, Light Weight Piston Sampler for Soft Soils and Loose Sands.
SM Note No. 3, Soil Mechanics Considerations for Embankment Drains.
SM Note No. 4, Preparation and Shipment of Undisturbed Core Samples.
SM Note No. 5, Flow Net Construction and Use.
SM Note No. 6, Glossary, Symbols, Abbreviations, and Conservation Factors.
SM Note No. 7, The Mechanics of Seepage Analysis.
SM Note No. 8, Soil Mechanics Testing Standards.
SM Note No. 9, Permeability of Selected Clean Sands and Gravels.
SM Note No. 10, The Static Cone Penatrometer: The Equipment and Using the Data.

USDA Soil Conservation Service, Technical Releases:

TR 709. Dimensioning of Filter-Drainage Diaphragms for Conduits According to TR-60.
TR 026. The Use of Soils Containing More Than 5% Rock Larger Than the No.4 Sieve.
TR 027. Laboratory and Field Test Procedures for Control of Density and Moisture of Compacted Earth Embankments.
TR 028. Clay Minerals.
TR 071. Rock Materials Field Classification Procedure.
TR 60. Earth Dams and Reservoirs

U.S. Department of the Interior. Design of Small Dams. 1987.

U.S. Department of the Interior, Bureau of Reclamation. Guidelines for Controlling Seepage Conduits through Embankments.

Virginia Department of Conservation and Recreation. Virginia Erosion and Sediment Control Handbook. Richmond, Virginia: 1992.

Chapter 3.01

Typical Earthen Embankment

Stabiliazation of newly constructed Earthen Embankment

Earthen Embankment

MINIMUM STANDARD 3.02

PRINCIPAL SPILLWAY

View BMP Images

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MINIMUM STANDARD 3.02

PRINCIPAL SPILLWAY

Definition

A principal spillway is the primary outlet device for a stormwater impoundment. It usually consists of either a *riser structure in combination with an outlet conduit*, which extends through the embankment, or *a weir control section* cut through the embankment.

Purpose

The purpose of a principal spillway is to provide a primary outlet for storm flows, usually up to the 10- or 25-year frequency storm event. The principal spillway is designed and sized to regulate the allowable discharge from the impoundment facility.

Conditions Where Practice Applies

A principal spillway is used on any impoundment BMP, including retention, extended-detention, and detention facilities. It may also be used with constructed wetlands and infiltration measures.

Planning Considerations

A principal spillway typically consists of a *multistage riser structure* and an outlet conduit or a *weir* that allows flow to pass over a *control section* of the embankment. The shape and geometry of the weir as well as that of the riser structure can be manipulated to meet the needs of the specific facility. The use of a weir as the principal spillway eliminates the barrel projecting through the embankment. The barrel through the embankment and the associated piping and seepage control represent not only significant material and construction costs, but also the potential trouble spots for long term maintenance and possible repair.

The most common type of riser structure is a *drop inlet spillway*. A drop inlet spillway usually consists of a rectangular or other shaped riser structure containing one or several openings sized to control one or more discharge rates. For aesthetic or safety concerns, the drop inlet riser structure may be installed in the embankment with only its top showing. The discharge openings may be extended to the design water surface elevations with pipe. See **Figures 3-02.1(a-f)** for typical riser structures and locations.

The barrel shape or geometry and size through the embankment is based upon the required flow capacities and availability of materials.

Design Criteria

The purpose of this section is to provide minimum design recommendations and guidelines for principal spillway systems (riser structure and barrel). The designer is responsible for determining those aspects that are applicable to the particular facility being designed, and for determining if any additional design elements are required to insure the long-term functioning of the system.

The crest elevation of the principal spillway must be at least 1.0 ft. below the crest of the emergency spillway.

Drop Inlet Spillways

Drop inlet spillways (riser and barrel system) should be designed such that a) *full flow is established in the outlet conduit and riser at the lowest head over the riser crest as is practical,* and b) *the facility operates without excessive surging, noise, vibration, or vortex action at any stage*. To meet these two requirements, the riser must have a larger cross-sectional area than the outlet conduit. **Chapter 5** provides the basic hydraulic calculation procedures needed to design the spillway riser and barrel system.

Headwall/Conduit Spillways

Headwall spillways consist of a pipe extending through an embankment with a headwall at the upstream end. The headwall is typically oversized to provide an adequate surface against which to compact the embankment fill.

Weir Spillways

A weir spillway, when used as a principal spillway, should be armored with concrete or other non-erosive material, since it usually carries water during every storm event. At the spillway, armoring should extend from the upstream face of the embankment to a point downstream of the spillway toe.

In general, all principal spillways should be constructed of a nonerosive material. The selected material should have an anticipated life expectancy similar to that of the stormwater management facility. Precast riser structures can not be substituted if plans call for a cast in place structure, unless approved by the design engineer and the plan approving authority. Sections of precast structures must be anchored together for stability and flotation requirements. A structural engineer should evaluate shop drawings for pipe, precast structures, or other fabricated appurtenances before fabrication or installation. **Cinder block and masonry block structures should not be used**.

Vegetated spillways designed to carry flow during the 100-year frequency storm or greater are discussed in **Minimum Standard 3.03**, **Vegetated Emergency Spillway**.

Combined Principal and Emergency Spillways

An *emergency spillway*, separated from the principal spillway, is generally recommended. However, using an overland emergency spillway at the embankment abutments may not be practical due to site limitations, such as the following:

- topographic conditions (e.g., abutments are too steep)
- land use conditions (e.g., existing or proposed development imposes constraints)
- other factors (e.g., roadway embankments are used as a dam, basins are excavated, etc.).

In these instances, a *combined principal/emergency spillway* may be considered. A combined principal/emergency spillway is simply a single spillway structure that conveys both low flows and extreme flows (such as the 100-year frequency flow). The combined spillway may take the form of a drop inlet spillway, a weir spillway, a headwall/conduit spillway or any other spillway type.

A primary design consideration for a combined principal/emergency spillway, particularly if it is a drop inlet spillway, is protection against clogging.

FIGURE 3.02 - 1a
Typical Principal Spillway Structures

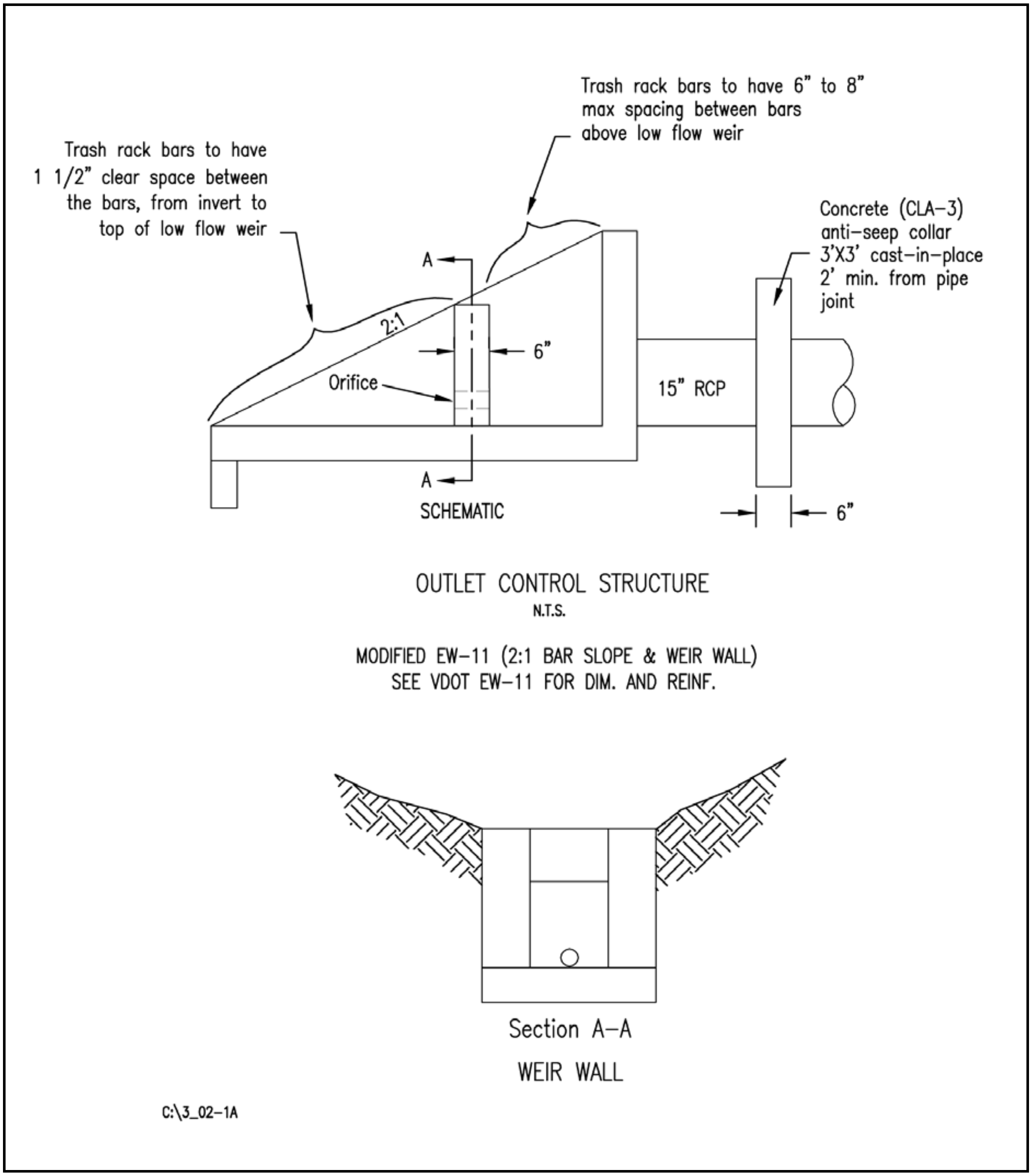


FIGURE 3.02 - 1b
Typical Principal Spillway Structures

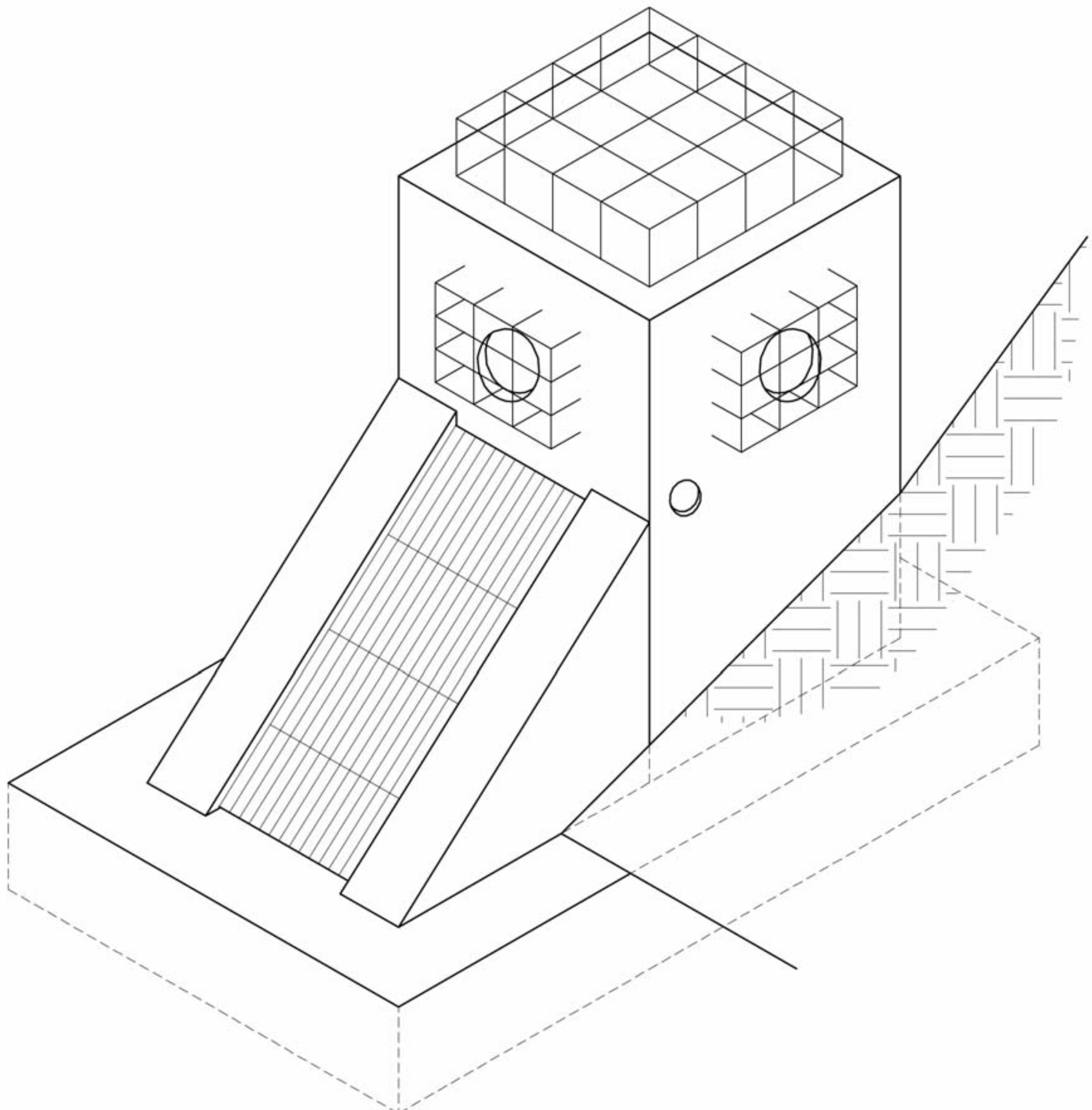


FIGURE 3.02 - 1c
Typical Principal Spillway Structures

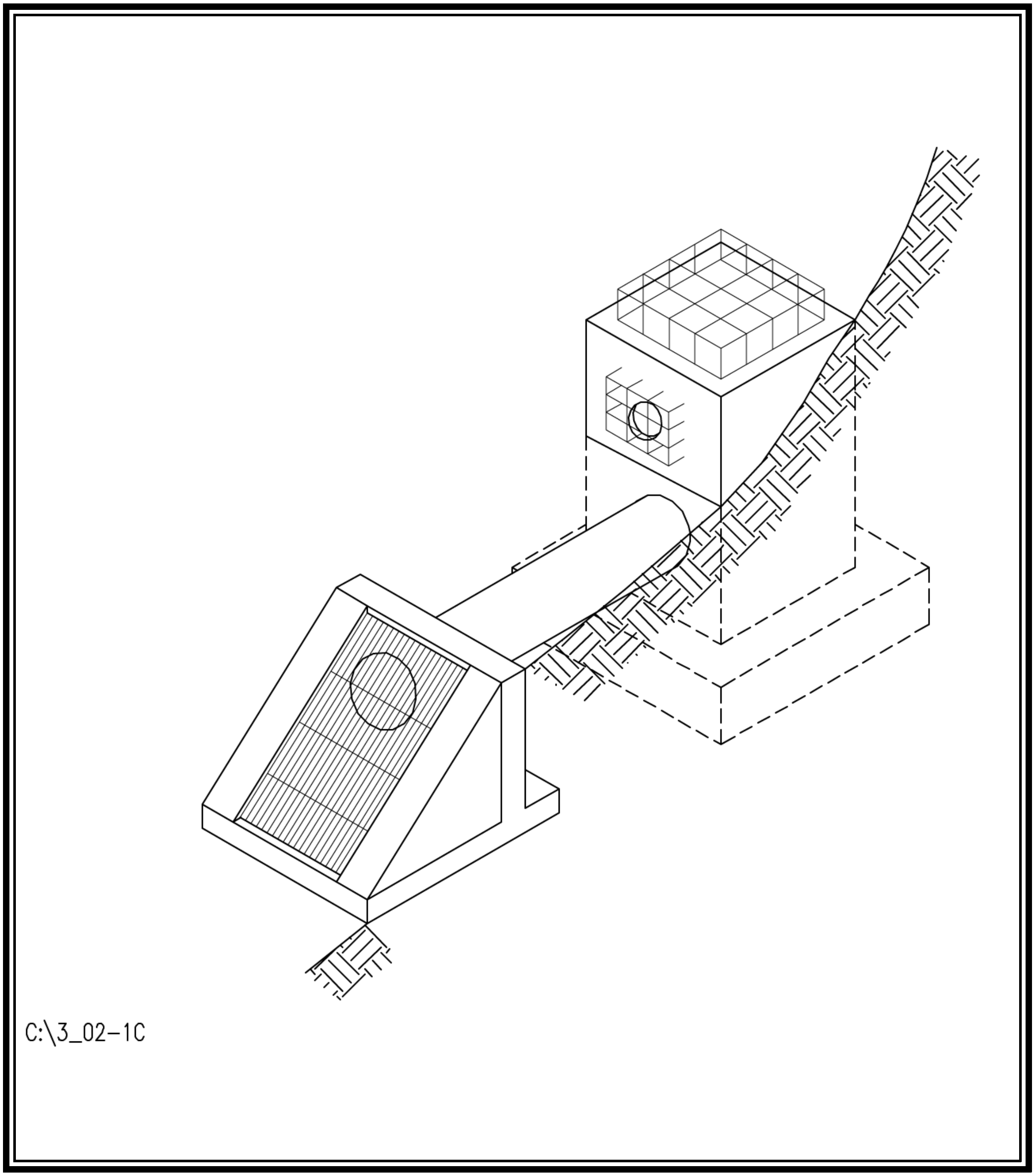


FIGURE 3.02 - 1d
Typical Principal Spillway Structures

FIGURE 3.02 - 1e
Typical Principal Spillway Structures

FIGURE 3.02 - 1f
Typical Principal Spillway Structures

FIGURE 3.02 - 1g
Typical Principal Spillway Structures

<u>Conduits/Structures through Embankments</u>

The *contact point* between the embankment soil, the foundation material, and the conduit is the most likely location for *piping* to occur due to the discontinuity in materials and the difficulty in compacting the soil around the pipe. Therefore, special attention must be given to the design of any conduit that penetrates an embankment.

It is highly recommended that the designer limit the number of conduits that penetrate through an embankment. Whenever possible, utility or other secondary conduits should be located outside of and away from the embankment. When additional conduits cannot be avoided, they should meet the requirements for spillways i.e., water tight joints, no gravel bedding, encasement in concrete or flowable fill, restrained to prevent joint separation due to settlement, etc.

Many embankment failures occur along the principal spillway because of the difficulty in compacting soil along a pipe. To help alleviate this concern, designers should consider the use of a weir as an control structure.

An additional cause of embankment failure is the separation of pipe joints due to differential settlement and pipe deflection. Corrugated metal pipe (CMP) must meet or exceed the minimum required thickness specified in **Table 3.02-1**. The contractor and project inspector should verify the metal thickness (compare manufacturer's certification which accompanies the pipe shipment with the plan specifications), corrugation size, proper connecting bands, and gasket type. Maximum allowable deflection of CMP conduits is 5% of the pipe diameter. However, with larger pipe sizes, it may be difficult to get water tight joints even if the deflection is less than that which is allowed. For increased design life, the engineer may choose to specify a heavier gage than indicated in **Table 3.02-1**.

Water tight joints are necessary to prevent infiltration of embankment soils into the conduit. All joints must be constructed as specified by the pipe manufacturer. "Field joints" where the ends of the pipes are cut off in the field should not be accepted. In addition, six inch hugger bands and "dimple bands" should not be accepted for CMP conduits. The construction specifications (found later in this Standard) specify 12-inch bands with 12-inch O-ring or flat neoprene gaskets for pipes 24 inches or less in diameter. Larger pipes require 24-inch wide bands with 24-inch wide flat gaskets and four "rod and lug" type connectors. Flanged pipe with gaskets is also permitted. Refer to the Construction Specifications in this standard for more information.

All pipe gaskets should be propely lubricated with the material provided by the pipe manufacturer.

Use of an incorrect lubricant may cause deterioration of gasket material.

Conduit Piping and Seepage Control – *Seepage* or *piping* along a pipe conduit, which extends through an embankment, should be controlled by use of one of the following: 1) *anti-seep collars*, as shown in **Figure 3.02-2**, or 2) *filter or drainage diaphragms* as shown in **Figure 3.02-3**. Concrete cradles, as discussed in item 3 below, may also be used.

***Seepage control will not be required on pipes less than 6 inches in diameter*.**

1. *Anti-Seep Collars* - These collars lengthen the percolation path along the conduit, subsequently reducing the *exit gradient*, which helps to reduce the potential for piping. While this works well in theory, the required quality of compaction around the collars is very difficult to achieve in the field.

The Bureau of Reclamation, the U.S. Army Corps of Engineers, and the Soil Conservation Service no longer recommend the use of anti-seep collars. The Bureau of Reclamation issued Technical Memorandum No. 9 in 1987 that states:

> *"When a conduit is selected for a waterway through an earth or rockfill embankment, cutoff collars will not be selected as the seepage control measure."*

Alternative measures have been developed and used in the designs of major structures. These measures include *graded filters* or *filter diaphragms*, and *drainage blankets*. These devices are not only less complicated and more cost-effective to construct than the cutoff collars, but also allow for easier placement of the embankment fill.

Designers and engineers, however, continue to use anti-seep collars as the sole method of seepage control for small dams. This may be due to the complexity of the design procedure for graded filters. It may also be due to the designer's concern that little engineering supervision and/or inspection will occur during construction, which is generally necessary for the successful installation of graded filters.

Anti-seep collars, when used, should be installed around all conduits through earth fills according to the following criteria:

a. Enough collars should be placed to increase the seepage length along the conduit by a minimum of 15%. This percentage is based on the length of pipe in the saturation zone.

b. The assumed normal saturation zone should be determined by projecting a line through the embankment, with a 4H:1V slope, from the point where the normal water elevation meets the upstream slope to a point where it intersects the invert of the conduit. This line, referred to as the *phreatic line*, represents the upper surface of the zone of saturation within the embankment. For stormwater management basins, the phreatic line starting elevation should be the 10-year storm pool elevation. (See **Minimum Standard 3.01**, **Earthen Embankment**.)

c. Maximum collar spacing should be 14 times the minimum projection above the pipe. The minimum collar spacing should be 5 times the minimum projection.

d. Anti-seep collars should be placed within the saturation zone. In cases where the spacing limit will not allow this, at least one collar should be in the saturation zone.

e. All anti-seep collars and their connections to the conduit should be watertight and made of material compatible with the conduit.

f. Collar dimensions should extend a minimum of 2 feet in all directions around the pipe.

g. Anti-seep collars should be placed a minimum of 2 feet from pipe joints unless flanged joints are used.

The calculation procedure for sizing anti-seep collars is presented in Chapter 5: Multi-Stage Riser Design, STEP 15.

FIGURE 3.02 - 2
Anti-Seep Collar

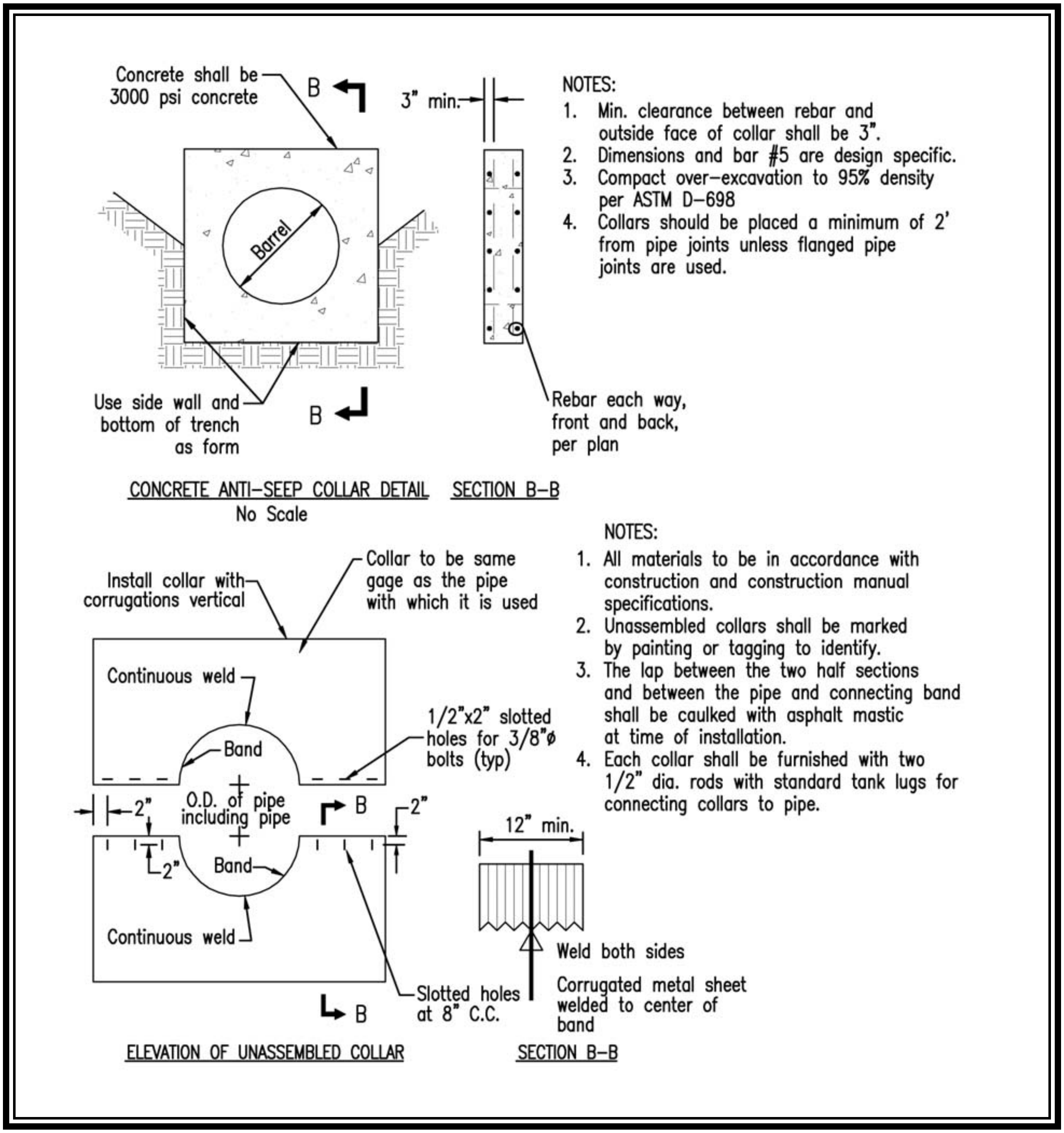
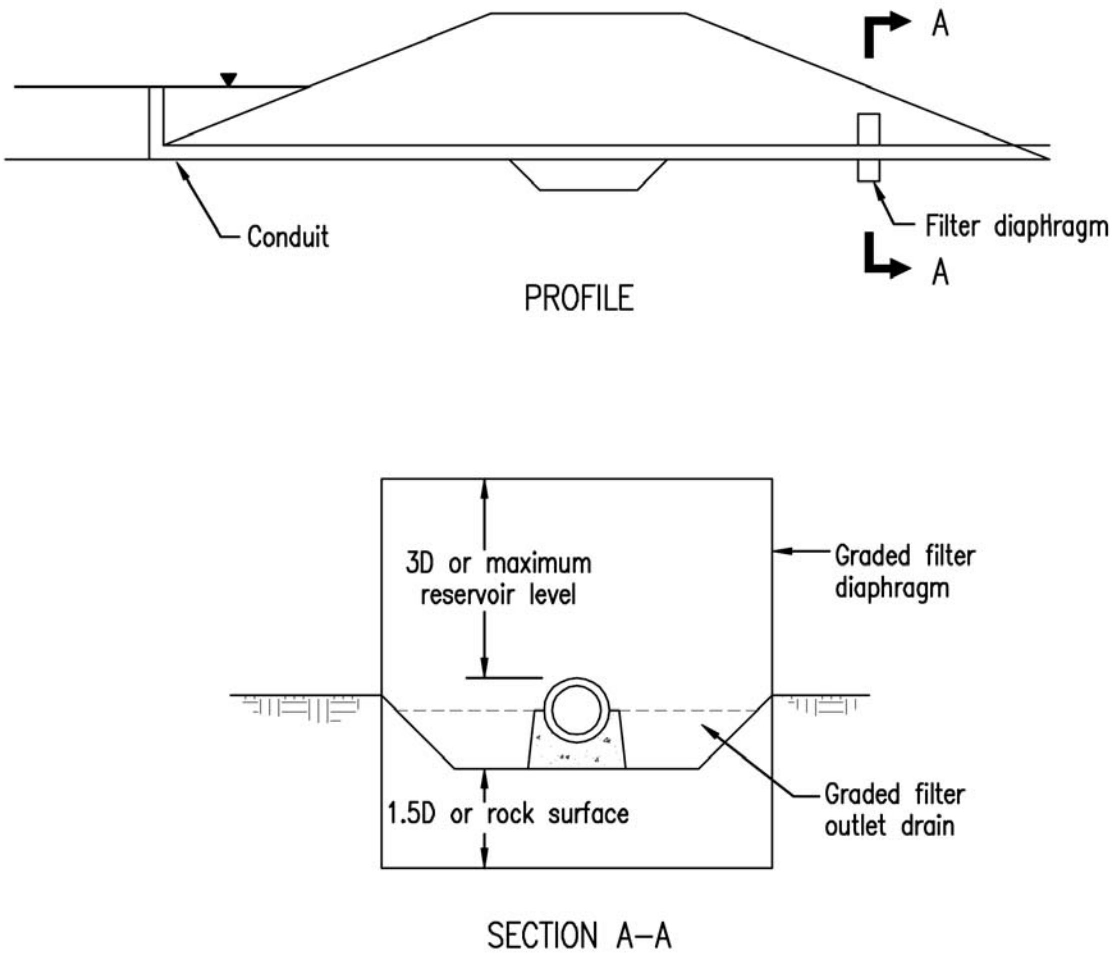


FIGURE 3.02 - 3
Graded Filter Diaphragm for Seepage Control Around Conduit



NOTES:
1. Delete filter diaphragm when conduit passes through chimney drain.
2. Delete outlet drain when filter diaphragm is connected to foundation drainage blanket.

c:\3_02–3

Source: Seepage Control Along Conduits Penetrating Embankment Dams, Ray E. Martin, Ph.D., P.E.

2. *Filter and Drainage Diaphragms* - Anti-seep collars extend the flow path along the conduit and, therefore, discourage piping. In contrast, filter and drainage diaphragms do not eliminate or discourage piping, rather they control the transport of embankment fines, which is the major concern in piping and seepage. Rather than trying to prevent seepage or increase its flow length, these devices channel the flow through a filter of fine graded material, such as sand, which traps any embankment material being transported. The flow is then conveyed out of the embankment through a perforated toe drain or other acceptable technique.

While filter and drainage diaphragms require careful design, the procedure is straightforward. The *grain size distribution* of the embankment fill and foundation material must be determined so that the filter material grain size distribution can be specified. If the specified filter material is not available on the site, it must be imported. The design procedure for filter and drainage diaphragms can be found in the following references:

Ë SCS TR-60
Ë SCS Technical Note No. 709
Ë SCS Soil Mechanics Notes 1 and 3 (Available upon request from DCR or NRCS)

There are some distinct advantages to using filter diaphragms over anti-seep collars:

¢ By eliminating the obstructions created by anti-seep collars, heavy compaction equipment can more thoroughly compact the embankment fill material adjacent to the conduit.

¢ The labor intensive formwork associated with anti-seep collar construction is eliminated.

¢ Cracks that form in the fill along the conduit will be terminated by the filter and will not propogate completely through the dam.

The design of filter and drainage diaphragms should be supervised by a geotechnical engineer. The critical design element is the grain size distribution of the filter material compared with that of the embankment fill and foundation material.

Overall, the following criteria apply to the use of filter and drainage diaphragms:

a. The diaphragm should consist of sand, meeting fine concrete aggregate requirements (at least 15% passing the No. 40 sieve but no more than 10% passing the No. 100 sieve). If unusual soil conditions exist, a special analysis should be completed.

b. The diaphragm should be a minimum of 3 feet thick and should extend vertically **upward** and **horizontally** at least 3 times the pipe diameter and vertically **downward** at least 24 inches beneath the barrel invert, or to rock, whichever is encountered first (SCS Tech. Note 709).

c. The diaphragm should be placed immediately downstream of the cutoff trench, approximately parallel to the centerline of the dam.

d. In order to achieve maximum density of clean sands, filter layers should be flooded with clean water and vibrated just after the water drops below the sand surface. The filter material should be placed in lifts of no more than 12 inches.

   Up to four feet of embankment material may be placed over a filter material layer before excavating back down to expose the previous layer. After removing any unsuitable materials, the trench may be filled with additional 12-inch lifts of filter material, flooded and vibrated as described above, until the top of adjacent fill is reached.

e. The diaphragm should be discharged at the downstream toe of the embankment. The opening sizes for slotted and perforated pipes in drains must be designed using the filter criteria. A second filter layer may be required around the drain pipe in order to alleviate the need for many very small openings. Fabric should not be used around the perforated pipe as it may clog rendering the perforations impenetrable by water.

The construction specifications for a filter diaphragm should include provisions to prevent settlement of the filter material upon saturation. This is usually accomplished by flooding the filter upon installation and compacting with vibratory equipment as soon as the water drops below the surface (Van Aller, 1990).

Whatever measures are taken to control seepage, proper construction techniques and inspection are critical to a successful project. The contractor should ensure that backfill material meets the specifications for *quality, lift thickness, placement, moisture content,* and *dry unit weight*. In addition, special care should be taken in the placement and compaction of the embankment material beside the barrel. Compaction along this conduit must extend away from the pipe enough to overlap with the compaction of the embankment. The use of filter and drainage diaphragms will ease this effort while providing greater protection against the damaging effects of piping and seepage.

During construction, it is recommended that filter and drainage diaphragms be inspected by a qualified professional. Inspection logs should be submitted along with any as-built plans.

3. *Concrete Pipe Bedding* - If the embankment fill material under the spring line of the conduit is **inadequately** compacted, *piping* may result. This problem is magnified if the conduit is not designed with flexible watertight joints; differential settlement of the embankment and foundation materials may pull the conduit joints apart, allowing the stormwater to escape into the surrounding soil, greatly adding to the piping condition. Installation of a concrete cradle will help to reduce the risk of piping under the barrel and the subsequent failure of the embankment, resulting from differential settlement.

Cradles not only provide conduit support, but also provide a better condition for the placement and compaction of backfill.

> Concrete cradles serve two distinctly different, yet related functions: 1) *they help to prevent piping along the conduit*, and 2) *they provide a 90E* ***bedding angle*** *for the loading support of the conduit. See* ***Figure 3.02 - 4****.*

The concrete cradle may not be necessary along the entire length of the conduit to prevent piping, but it is recommended. This will eliminate a sudden change in the support provided under the conduit. The load distribution of the conduit is assumed to be the same as the typical load distribution characteristics of reinforced concrete pipe (*RCP*). The external loading capacity of *RCP* depends upon a bedding condition that provides equal support around the base of the pipe. General pipe culvert installation specifications call for the placement of gravel under the pipe to distribute the load evenly. However, g**ravel bedding under an embankment conduit is <u>never</u> appropriate unless it is designed as a filter or drainage diaphragm.** Therefore, if the external load on the barrel is enough to warrant provision for its ***maximum supporting strength***, then a concrete cradle should be installed along the conduit's entire length. Note that external loads on the barrel may be due to the height of the embankment fill, the anticipated construction traffic, or the weight of the compaction equipment.

Single Conduits – All conduits penetrating dam embankments should be designed using the following criteria:

a. Conduits and structures penetrating an embankment should have a smooth surface without protrusions or indentations that will hinder compaction of embankment materials.

b. All conduits should be circular in cross-section except cast-in-place reinforced concrete box culverts.

c. Conduits should be designed to withstand the external loading from the proposed embankment without yielding, buckling or cracking, all of which will result in joint seperation.

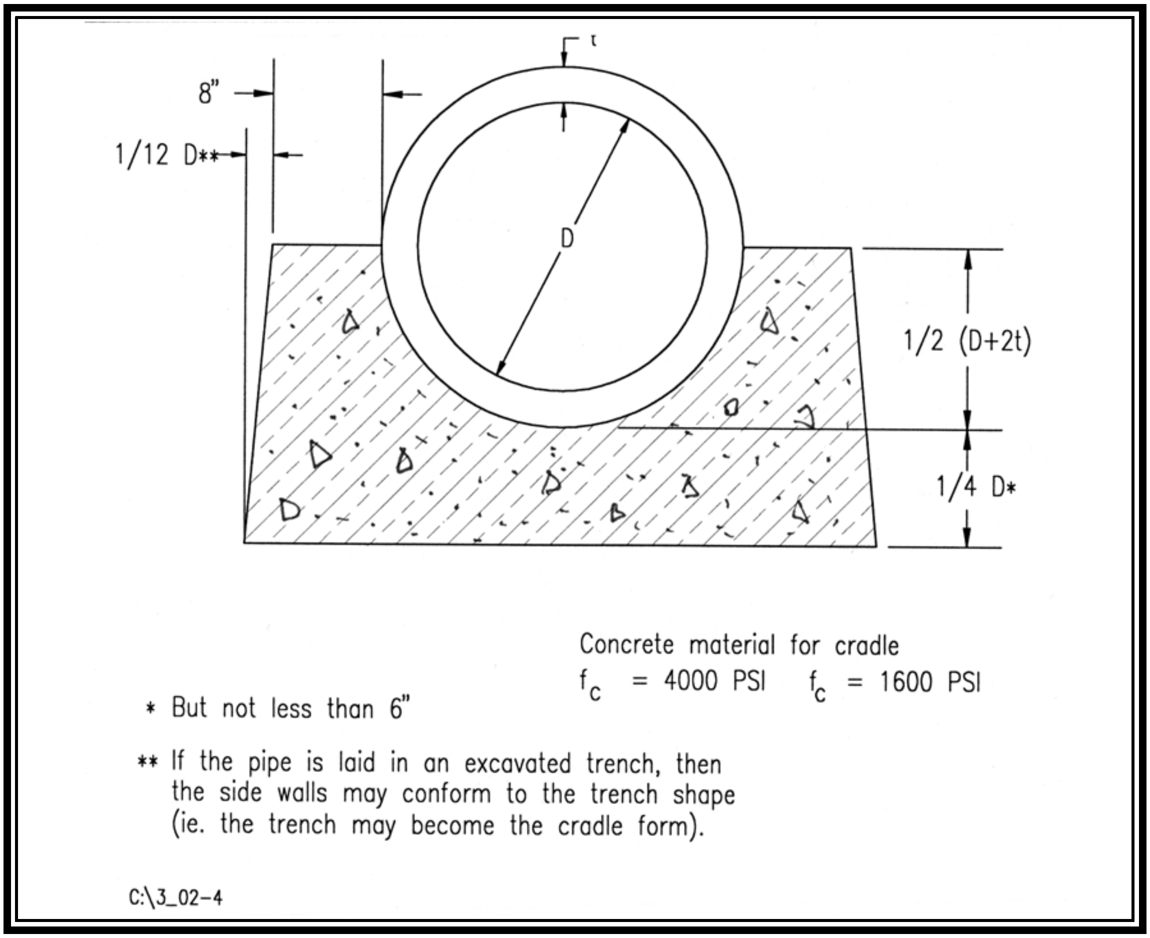
d. Conduit strength should not be less than the values shown in **Tables 3.02-1** and **3.02-2** for corrugated steel, aluminum, and PVC pipes, and the applicable ASTM standards for other materials. The manufacturer should submit certification that the pipe meets plan requirements for design load, pipe thickness, joint design, etc.

e. Inlet and outlet flared-end sections should be made from materials that are compatible with the pipe.

f. All pipe joints should be made watertight by using flanges with gaskets, coupling bands with gaskets, bell and spigot ends with gaskets, or by welding. See **Construction Specifications** later in this standard.

Multiple Conduits – Where multiple conduits are used, each conduit should conform to the requirements in item (b), above. In addition, sufficient space between the conduits and the installed anti-seep collars should be provided to allow for backfill material to be placed between the conduits with earth moving equipment and to allow for easy access by hand-operated compaction equipment. The distance between conduits should be equal to or greater than one-half of the pipe diameter, but not less than 2 feet.

FIGURE 3.02 - 4
Concrete Cradle



Cathodic Protection

In some areas of Virginia, sedimentary layers may be very acidic. This is particularly common in the coastal and piedmont regions east of the fall line, or roughly east of Interstate 95. Cathodic protection should be provided for *coated welded steel* and *galvanized corrugated metal* pipe when soil and resistivity studies indicate the need for a protective coating. Cathodic protection may also be provided when additional protection and longevity are warranted.

Outlet Protection

Outlet protection should be used on the downstream toe of a spillway structure to help dissipate the high energy flow through the spillway and to prevent excessive erosion in the receiving channel.

Various types of outlet protection can be used including: *riprap at the endwall or end-section of an outlet conduit* or a *designed hydraulic jump with impact blocks*. The type of outlet protection depends on the flow velocities associated with the spillway design flood and energy dissipation required. Riprap is the preferred form of outlet protection when designed according to **Chapter 5** of this handbook and the Virginia Erosion and Sediment Control Handbook (VESCH), 1992 edition. Gabion baskets are also an acceptable outlet protection material. Other references for designing outlet protection include publications by the Federal Highway Administration, the Soil Conservation Service, the Bureau of Reclamation and the U.S. Army Corps of Engineers.

The following general criteria are recommended for the placement of riprap at the outfall of a stormwater impoundment:

1. The bottom of the riprap apron should be constructed at 0% slope along its length. The end of the apron should match the grade and alignment of the receiving channel.

2. If the receiving channel is well-defined, the riprap should be placed on the channel bottom and side slopes (no steeper than 2:1) for the entire length, L_a, required per **Chapter 5** and the VESCH, 1992 edition. Riprap placement should not alter the channel's geometry. Excavation of the channel bed and banks may be required to construct the full thickness of the apron.

3. If the barrel discharges into the receiving channel at an angle, the opposite bank must be protected up to the 10-year storm elevation. In no instance should the total length of outlet protection be shortened. If a permit requires that no work may be performed in the stream or channel, then the outlet structure should be moved back to allow for adequate protection.

4. The horizontal alignment of the apron should have no bends within the design length, La. Additional rip rapshould be placed if a significant change in grade occurs at the downstream end of the outfall apron.

5. Filter fabric should be placed between the riprap and the underlying soil to prevent soil movement into and through the riprap.

Trash Racks and Debris Control Devices

Most basins will collect a certain amount of trash and debris from incoming flows. Floating debris such as grass clippings, tree limbs, leaves, trash, construction debris, and sediment bed load from upstream watersheds are common. Therefore, all control structures, including detention, extended-detention and retention basin low-flow weirs and orifices should have a trash rack or debris control device. The following are recommended design criteria for trash racks and debris control devices:

1. Openings for trash racks should be no larger than one-half of the minimum conduit dimension, and to discourage child access, bar spacing should be no greater than 1 foot apart. The clear distance between the bars on large storm discharge openings should generally be no less than 6 inches.

2. **Flat grates for trash racks are not acceptable**. Inlet structures that have flow over the top should have a non-clogging trash rack such as a hood-type inlet that allows passage of water from underneath the trash rack into the riser, or a vertical or sloped grate. The designer should verify that the surface area of the vertical perimeter of a raised grate equals the area of the horizontal top opening. This will allow adequate flow passage should the top horizontal surface become clogged. Examples are shown in **Figure 3.02-5**.

3. Metal trash racks and monitoring hardware should be constructed of galvanized or stainless steel metal.

4. Methods to prevent clogging of extended detention orifices in dry extended detention basins should be carefully designed since these orifices are usually very small and located at the invert or bottom of the basin (refer to **Minimum Standard 3:07, Extended Detention Basin**).

<u>Anti-vortex Device</u>

All drop inlet spillways designed for pressure flow should have adequate anti-vortex devices. An anti-vortex device is not required if weir control is maintained in the riser through all flow stages, including the maximum design storm or safety storm.

An anti-vortex device may be a baffle or plate installed on top of the riser, or a headwall set on one side of the riser. Examples of anti-vortex devices are shown in **Figure 3.02-6**.

<u>Drain Pipes and Valves</u>

Stormwater management facilities having permanent impoundments may be designed so that the permanent pool can be drained to simplify maintenance and sediment removal. The draining mechanism will usually consist of a valve or gate attached to the spillway structure and an inlet pipe projecting into the reservoir area with a trash rack or debris control device. The typical configuration of a drainpipe will place the valve inside the riser structure with the pipe extending out to the pool area. This configuration results in the drain pipe being pressurized by the hydraulic head associated with the permanent pool. Pressurized drain pipes should consist of mechanical joints in order to avoid possible leaks and seepage resulting from this condition. In all cases, valves should be secured to prevent unauthorized draining of the facility.

Basin drains should be designed with sufficient capacity to pass the 1-year frequency design storm with limited ponding in the reservoir area, such that sediment removal or other maintenance functions are not hampered.

An uncontrolled or rapid drawdown of a stormwater basin could cause a slide in the saturated upstream slope of the dam embankment or shoreline area. Therefore, the design of a basin drain system should include specific operating instructions for the owner. **Generally, drawdown rates should not exceed 6 inches per day**. For embankments or shoreline slopes of clay or silt, drawdown rates as low as *1 inch per week* may be required to ensure slope stability. (FPFM, 1994).

<u>Antiflotation</u>

The design of a principal spillway riser structure should include a *flotation* or *buoyancy* calculation.

When the ground around the riser is saturated and the water surface elevation in the basin is higher than the riser footing, then the riser structure behaves like a “vessel” floating in water. Such flotation forces on the riser can lead to failure of the connection between the riser and barrel, and any other rigid connections.

The downward force of the riser and footing (assuming the riser is attached firmly to the footing) is the *structure weight.* To maintain adequate stability, this weight must be at least 1.25 times greater than the upward force, or buoyant force, acting on the riser.

An *anti-flotation* calculation procedure is presented in Chapter 5.

<u>Maintenance and Safety</u>

As mentioned previously, trash racks and debris control structures should be sized to prevent entry by children. Fencing or other barriers should be considered around spillway structures having open or accessible drops more than 3 feet. A locking manhole cover on the riser may also be prudent to prevent unauthorized access.

FIGURE 3.02 - 5
Trash Rack

FIGURE 3.02 - 6
Anti-Vortex Device

Construction Specifications

The construction specifications for principal spillways outlined below should be considered as minimum guidelines. More stringent requirements may be needed depending upon individual site conditions. Overall, widely accepted construction standards and specifications, such as those developed by the USDA Soil Conservation Service or the U.S. Army Corps of Engineers, should be followed.

Further guidance can be found in the SCS Engineering Field Manual. Specifications for the work should conform to the methods and procedures specified for installing earthwork, concrete, reinforcing steel, pipe water gates, metal work, woodwork, and masonry, as they apply to the site and the purpose of the structure. The specifications should also satisfy all requirements of the local government. Final construction specifications should be included on the construction plans.

Corrugated Metal Pipe - The following criteria apply:

1. **Materials –** Corrugated metal pipe may be steel, aluminum coated steel or aluminum.

   a. *Steel Pipe* - This pipe and its appurtenances should be galvanized and fully bituminous coated and should conform to the requirements of AASHTO Specification M-190 Type A with watertight coupling bands. Any bituminous coating damaged or otherwise removed should be replaced with cold applied bituminous coating compound. Steel pipes with polymeric coatings should have a minimum coating thickness of 0.01 inches (10 *mils*) on both sides of the pipe. The following coatings or an approved equal may be used: Nexon, Plasti-Cote, Blac-Clad, and Beth-Cu-Loy. Coated corrugated steel pipe should meet the requirements of AASHTO M-245 and M-246.

   b. *Aluminum Coated Steel Pipe* - This pipe and its appurtenances should conform to the requirements of AASHTO Specification M-274 with watertight coupling bands or flanges. Any aluminum coating damaged or otherwise removed should be replaced with cold applied bituminous coating compound.

   c. *Aluminum Pipe* - This pipe and its appurtenances should conform to the requirements of AASHTO Specification M-196 or M-211 with watertight coupling bands or flanges. Aluminum surfaces that are to be in contact with concrete should be painted with one coat of zinc chromate primer. Hot dipped galvanized bolts may be used for connections. The pH of the surrounding soils should be between 4 and 9.

2. **Coupling bands, anti-seep collars, end-sections, etc.** - All connectors must be composed of the same material as the pipe. Metals must be shielded from dissimilar materials with rubber or plastic insulation at least 24 mils thick.

3. **Connections** - All connections to pipes must be completely watertight. The drain pipe (or barrel) connection to the riser should be welded all around when both are metal. Anti-seep collars should be connected to the pipe so that they are completely watertight. **Dimple bands are not considered watertight**.

   A rubber or neoprene gasket should be used when joining pipe sections. The end of each pipe should be re-rolled by enough corrugations to fit the band width. The following connection types are acceptable for pipes less than 24 inches in diameter: flanges with gaskets on both ends of the pipe, a 12-inch wide standard lap type band with a 12-inch wide by ½-inch thick closed cell circular neoprene gaskets, and a 12-inch wide hugger type band with 0-ring gaskets having a minimum diameter of 3/8 inches greater than the corrugation depth. Pipes 24 inches in diameter and larger should be connected by a 24-inch long annular corrugated band using rods and lugs and a 24 inch wide by 3/8 inch thick closed cell circular neoprene gasket. Helically corrugated pipe should have either continuous welded seams or lock seams with internal caulking or a neoprene bead.

   All pipe gaskets must be properly lubricated with the material provided by the pipe manufacturer, and tensioned. Flat gaskets must be factory welded or solvent glued into a circular ring, with no overlaps or gaps.

4. **Bedding** - The pipe should be firmly and uniformly bedded throughout its length. Where rock or soft, spongy or other unstable soil is encountered, it should be removed and replaced with suitable earth that is subsequently compacted to provide adequate support. Under no conditions should gravel bedding be placed under a conduit through the embankment.

5. **Backfill** - All backfill material and placement should conform to Structure Backfill specifications in **Minimum Standard 3.01, Earthen Embankment**.

Reinforced Concrete Pipe - The following criteria apply:

1. **Materials** - Reinforced concrete pipe should have bell and singular spigot joints with rubber gaskets and should equal or exceed ASTM Designation C-361.

2. **Bedding** - All reinforced concrete pipe conduits should be laid in a **concrete** bedding for their entire length. This bedding should consist of high slump concrete placed under the pipe and up the sides of the pipe at least 25% of its outside diameter, and preferrably to the spring line, with a minimum thickness of 3 inches, or as shown on the drawings.

3. **Laying pipe** - Bell and spigot pipe should be placed with the bell end upstream. Joints should be made per recommendations from the manufacturer. After the joints are sealed for the entire run of pipe, the bedding should be placed so that all spaces under the pipe are filled. Care should be taken to prevent any deviation from the original line and grade of the pipe.

4. **Backfill** - All backfill material and placement should conform to Structure Backfill specifications in **Minimum Standard 3.01, Earthen Embankment**.

Polyvinyl Chloride (PVC) Pipe - The following criteria apply:

1. **Materials** - PVC pipe should be PVC-1120 or PVC-1220 conforming to ASTM D-1785 or ASTM D-2241.

2. **Connections** - Joints and connections to anti-seep collars should be completely watertight.

3. **Bedding** - The pipe should be firmly and uniformly bedded throughout its length. Where rock or soft, spongy or other unstable soil is encountered, it should be removed and replaced with suitable earth that is subsequently compacted to provide adequate support.

4. **Backfill** - All backfill material and placement should conform to Structure Backfill specifications in **Minimum Standard 3.01, Earthen Embankment**.

Filters and Drainage Layers

In order to achieve maximum density of clean sands, filter layers should be flooded with clean water and vibrated just after the water drops below the sand surface. The filter material should be placed in lifts of no more than 12 inches.

Up to four feet of embankment material may placed over a filter material layer before excavating back down to expose the previous layer. After removing any unsuitable materials, the trench may be filled with additional 12-inch lifts of filter material, flooded, and vibrated as described above, until the top of adjacent fill is reached.

Filter fabrics should not be used in lieu of sands and gravel layers within the embankment.

TABLE 3.02 - 1
Minimum Gages for Metal Pipes

CORRUGATED STEEL PIPE *2-2/3" x ½" Corrugations*

Fill Height Over Pipe *(ft.)*	**Pipe Diameter *(in.)* 24 & Less**	**30**	**36**	**42**	**48**
1 - 15	16	16	14	10	8
16 - 20	16	12	8	*	*
21 - 25	16	10	*	*	*

CORRUGATED ALUMINUM PIPE *2-2/3" x ½" Corrugations*

Fill Height Over Pipe *(ft.)*	**Pipe Diameter *(in.)* 24 & Less**	**24**	**30**	**36**
1 - 15	16	14	10	8
16 - 20	12	10	*	*
21 - 25	10	*	*	*

CORRUGATED STEEL PIPE *3" x 1" or 5" x 1" Corrugations*

Fill Height Over Pipe *(ft.)*	**Pipe Diameter *(in.)* 36**	**42**	**48**	**54**	**60**	**66**	**72**
1 - 15	16	16	16	16	14	12	10
16 - 20	16	16	14	10	8	*	*
21 - 25	16	14	10	8	*	*	*

* Not permitted
Coatings for corrugated steel should be as specified in this handbook, or equivalent.

CORRUGATED ALUMINUM PIPE *3" x 1" Corrugations*

Fill Height Over Pipe *(ft.)*	**Pipe Diameter *(in.)* 30**	**36**	**42**	**48**	**54**
1 - 15	16	16	14	10	8
16 - 20	16	12	8	*	*
21 - 25	12	8	*	*	*

* Not permitted

Source: SCS Standards and Specifications for Ponds - Code 378

TABLE 3.02 - 2
Acceptable PVC Pipe for Use in Earth Dams[1]

Nominal Pipe Size *(in.)*	Schedule or Standard Dimension Ration *(SDR)*	Maximum Depth of Fill Over Pipe *(ft.)*
6 - 24	Schedule 40 Schedule 80 SDR 26	10 15 10

[1]Polyvinyl chloride pipe, PVC 1120 or PVC 1220, conforming to ASTM D-1785 or ASTM D-2241.

Source: SCS Standards and Specifications for Ponds - Code 378

Concrete

Concrete should meet the requirements of the Virginia Department of Transportation (VDOT) Road and Bridge Specifications, latest edition.

Outlet Protection

Outlet protection should meet the requirements and construction specifications of the VESCH, 1992 edition, Std. & Spec. 3.18, Outlet Protection, and 3.19, Riprap, latest edition. Materials should conform to the following:

1. Filter fabric should meet or exceed the requirements in Standard & Specification 3.18 and 3.19 in the VESCH, 1992 edition.

2. Riprap should meet or exceed the requirements in Standard & Specification 3.18 and 3.19 in the VESCH, 1992 edition.

3. Gabion baskets should be made of hexagonal triple-twist mesh, PVC coated, heavily galvanized steel wire. The maximum linear dimension of the mesh opening should not exceed 4 1/2 inches and the area of the mesh opening should not exceed 10 square inches.

Stone or riprap for the baskets should be sized according to the following criteria:

TABLE 3.02 - 3
Gabion Basket Criteria

BASKET THICKNESS		STONE SIZE
inches	*millimeters*	*inches*
6	150	3 - 5
9	225	4 - 7
12	300	4 - 7
18	460	4 - 7
36	910	4 - 12

The stone or riprap should consist of field stone or rough, unhewn quarry stone. The stone should be hard and angular and of a quality that will not disintegrate from exposure to water or weather. The specific gravity of the individual stones should be at least 2.5.

Recycled concrete may be used and will be considered equivalent if it has a density of at least 150 pounds per cubic foot and no exposed steel or reinforcing bars.

Trash Rack and Debris Control Devices

All trash rack and debris control components should be stainless steel or galvanized metal per the Virginia Department of Transportation (VDOT) specifications. Trash racks attached to a concrete spillway structure should be secured with stainless steel anchor bolts.

Maintenance and Inspection Guidelines

This section presents general operation, maintenance and inspection guidelines for principal spillways and components. However, these guidelines are not intended to be all-inclusive. Specific structures may require special measures not discussed here. The engineer is responsible for determining what, if any, additional items are necessary.

1. Spillway structures should be cleared of debris periodically and after any significant rainfall event where inspection reveals a significant blockage.

2. During low water conditions, concrete spillway structures should be inspected to decide if water is passing through any joints or other structure contacts and to identify any cracks, spalling, broken or loose sections. Any cracked, spalled, broken or loose sections should be cleaned and refilled with an appropriate concrete patching material. A professional engineer should be consulted to repair extensive leakage, spalls or fractures.

3. Outlet protection (stilling basins) and discharge channels should be cleared of brush at least once per year.

4. Trash racks and locking mechanisms should be inspected and tested periodically to make sure they are intact and operative.

5. All sluice gates (or other types of gates or valves used to drain an impoundment) should be operated periodically to insure proper function. The gate and stem should be periodically lubricated and all exposed metal should be painted to protect it from corrosion.

6. Any repairs made to the principal spillway (riser or barrel) should be reviewed by a professional engineer. Vertical trenching to expose the barrel should not be allowed under any circumstances. The trench side slopes should be stepped back at a 2:1 slope, minimum.

REFERENCES

American Society of Civil Engineers. Stormwater Detention Outlet Control Structures. Task Commission On the Design of Outlet Control Structures, ASCE. New York, NY: 1985.

Brater, E.F., and H.W. King. Handbook of Hydraulics. 6th ed. New York: McGraw Hill Book Company, 1976.

Debo, T.N., and A.J. Reese. Municipal Stormwater Management. 1995.

Federal Highway Administration. Debris-Control Structures. Hydraulic Engineering Circular No. 9, 1971.

Federal Highway Administration. Hydraulic Design of Highway Culverts. Hydraulic Design Series No. 5, 1985.

Maryland Department of the Environment-Dam Safety Division, DOs and DON'Ts for Pond Construction, May 1997.

Rossmiller, R.L. Outlet Structure Hydraulics for Detention Facilities. Proc. Int. Symp. On Urban Hydrology, Hydraulics and Sediment Control. University of Kentucky, KY: 1982.

Sandvik, A. "Proportional Weirs for Stormwater Pond Outlets." Civil Engineering. ASCE. pp. 54- 56. March, 1985.

U.S. Department of the Interior Bureau of Reclamation. ACER Technical Memorandum No. 9, Guidelines for Controlling Seepage Along Conduits Through Embankment. 1987.

USDA Soil Conservation Service T.R. 5, Appendix C. Evaluation of the Settlement Ratio for Positive Projecting Conduits.

USDA Soil Conservation Service. Technical Note Series No. 709, Dimensioning of Filter-Drainage Diaphragms for Conduits According to TR-60. April, 1985.

U. S. Department of the Interior, Bureau of Reclamation. Design of Small Dams. 1987.

USDA Soil Conservation Service. Engineering Field Manual, National Engineering Handbook.

Virginia Department of Conservation and Recreation. Virginia Erosion and Sediment Control Handbook (VESCH) 1992 edition.

Principal Spillway multi-stage riser. Note bird-cage type trash rack to prevent clogging.

Principal Spillway multi-stage riser configured for temporary sediment basin function. Note anti-vortex plate and inclined trash rack to prevent clogging.

Principal Spillway

Principal Spillway multi-stage riser – “V” shaped weir protected by trash rack.

Principal Spillway multi-stage weir. Note low flow/extended detention orifice protected by “hood” draws water from approximately 18” below pool surface.

Principal Spillway

MINIMUM STANDARD 3.03

VEGETATED EMERGENCY SPILLWAY

View BMP Images

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MINIMUM STANDARD 3.03

VEGETATED EMERGENCY SPILLWAY

Definition

A vegetated emergency spillway is an open channel, usually trapezoidal in cross-section, that is constructed beside an embankment. It consists of an *inlet channel*, a *control section*, and an *exit channel*, and is lined with erosion-resistant vegetation.

Purpose

The purpose of a vegetated emergency spillway is to convey flows that are greater than the principal spillway's design discharge at a *non-erosive velocity* to an *adequate channel*.

Conditions Where Practice

A vegetated emergency spillway is appropriate to use when the required maximum design flood volume exceeds the capacity of the principal spillway system. A vegetated emergency spillway may also be used as a safety feature to pass flood flows when or if the principal spillway becomes clogged.

Planning Considerations

The *adjacent topography* (steepness of the abutments), the *existing or proposed land* use, and *other factors* (such as a roadway over the embankment) influence the design and construction of a vegetated emergency spillway.

Vegetated emergency spillways must be built in existing ground or "cut." Therefore, additional land disturbance beside the embankment must be accounted for during the planning stages of a project. Sometimes, an emergency spillway may not be practical due to this or other considerations.

Remember, even though an emergency spillway helps to extend the life expectancy of an impoundment and lowers the associated downstream hazard conditions, it should not be located on any portion of the embankment fill.

If site topography or other constraints preclude the use of a vegetated emergency spillway in "cut," the principal spillway can be oversized to pass the additional flows or an *armored* emergency spillway may be provided. A cost analysis may be helpful to aid in the selection of the spillway type. If armoring is chosen, riprap, concrete or any other permanent, nonerodible surface may be used. Note, however, that **an armored emergency spillway over the top of an embankment should be designed by a qualified professional**.

Vegetated emergency spillways should be used only where the soils and topography will permit safe discharge of the peak flow at a point downstream from the embankment and at a velocity that will not cause appreciable erosion. Additional flood storage in the reservoir may be provided to reduce the design flow or the frequency with which the spillway is used.

Design Criteria

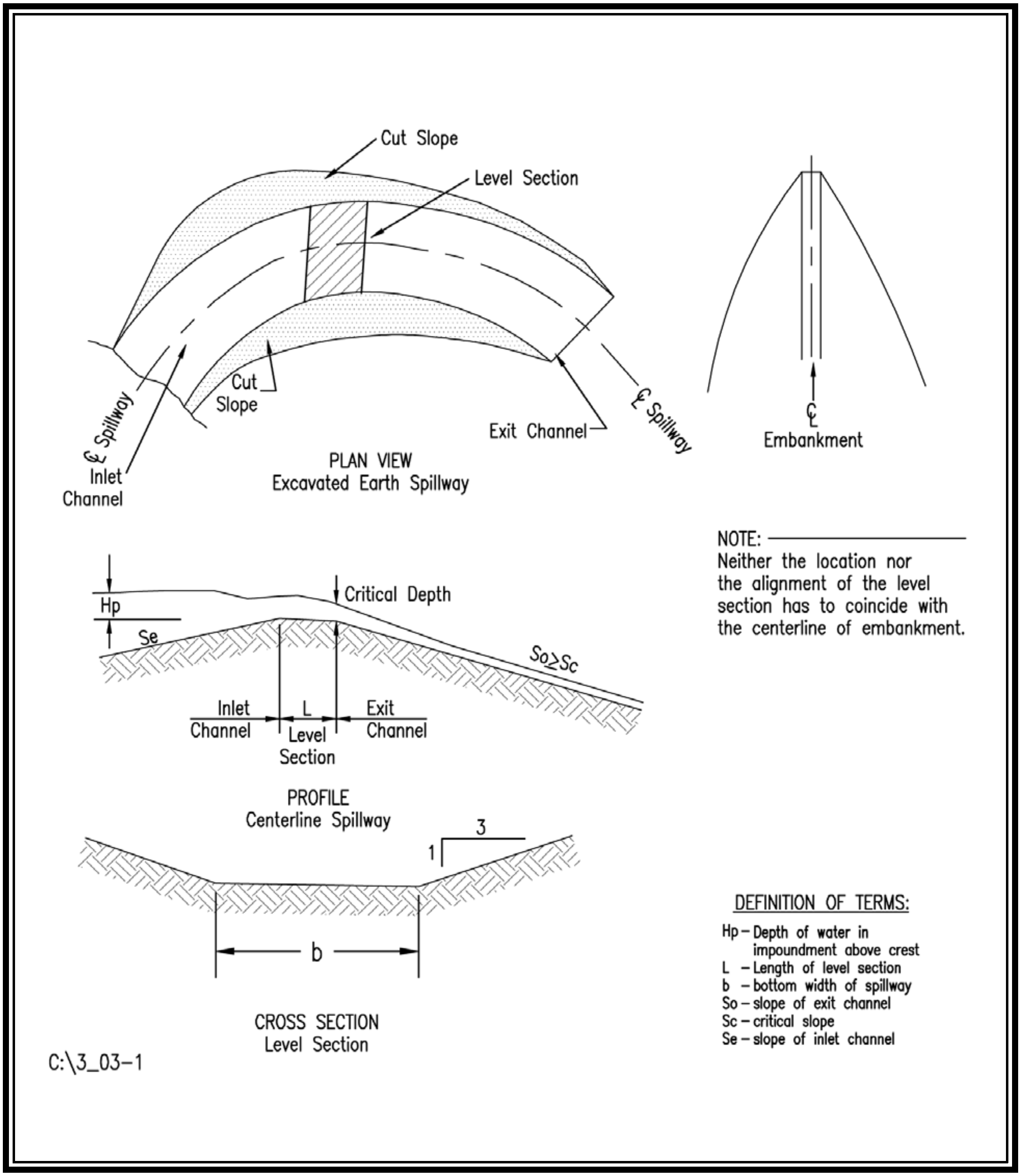
A vegetated emergency spillway is designed to convey a pre-determined design flood discharge without excessive velocities and without overtopping the embankment. **The maximum design water surface elevation through the emergency spillway should be at least 1 foot lower than the settled top of the embankment**.

Layout

Vegetated spillways should be constructed in undisturbed earth in the abutments at one or both ends of an earthen embankment or over a topographic saddle anywhere on the periphery of the basin. **The channel should be excavated into undisturbed earth or rock and the water surface, under maximum design flood discharge, should be confined by undisturbed earth or rock**.

Excavated spillways consist of three elements: 1) an *inlet channel*, 2) a *level section*, and 3) an *exit channel*. (See **Figure 3.03-1**.) Flow enters the spillway through the inlet channel. The depth of flow, H_p, located upstream from the level section, is controlled in the level section and then discharged through the exit channel. Flow in the inlet channel is *sub-critical*. Flow in the exit channel can be either *critical* or *supercritical*. **The control section is, therefore, the point on the spillway where the flow passes through critical depth**. It is recommended that the control section be installed close to the intersection of the earthen embankment and the emergency spillway centerlines.

FIGURE 3.03 - 1
Typical Plan and Profiles Along the Centerline of an Earth Spillway



The topography must be carefully considered when constructing an emergency spillway. The alignment of the exit channel must be straight to a point far enough below the embankment to insure that any flow escaping the exit channel cannot damage the embankment. This may result in additional clearing and/or grading requirements beside the abutments, property line, etc.

Figure 3.03-1 shows profiles along the centerline of a typical vegetated spillway. To reduce losses through the inlet channel, the cross-sectional area of flow in the inlet channel should be large in comparison to the flow area at the control section. Where the depth of the channel changes to provide for the increased flow area, the bottom width should be altered gradually to avoid abrupt changes in the shape of the sloping channel banks.

The exit channel must have an adequate slope to discharge the peak flow within the channel. However, the slope must be no greater than that which will produce maximum permissible velocities for the soil type or the planned grass cover.

Soil Types and Vegetative Cover

The type of soil and vegetative cover used in an emergency spillway can be used to establish the spillway design dimensions (Procedure 2 - **Chapter 5-8**). Soil types are classified as *erosion resistant* and *easily erodible*. ***Erosion resistant soils*** are those with a high clay content and high plasticity. Typical soil textures for erosion resistant soils are silty clay, sandy clay, and clay. ***Easily erodible soils*** are those with a high content of fine sand or silt, and a low plasticity or non-plastic. Typical soil textures for easily erodible soils are fine sand, silt, sandy loam, and silty loam. **Table 3.03-1** provides permissible velocities for a vegetated spillway based on its soil type, vegetated cover, and exit channel slope. The maximum permissible velocity may be increased by 25% when the anticipated average use is less than once in 10 years.

In general, it is recommended that a vegetated emergency spillway be designed to operate during the 100-year frequency storm or greater.

The *type* and *length of vegetative cover* affect the design of a vegetated spillway. Vegetation provides a *degree of retardance* to the flow through the spillway. **Table 3.03-2** gives retardance values for various heights of vegetative cover. Retardance for a given spillway will depend mostly upon the *height* and *density* of the cover chosen. Generally, after the cover is selected, “retardance with a good, uncut condition” should be used to find the capacity. Since a condition offering less protection and less retardance exists during the establishment period and after mowing, a lower degree of retardance should be used when designing for stability. Refer to the sample exercises for the design of vegetated spillways found in **Chapter 5**.

Hydraulic Design

The hydraulic design of earthen spillways can be simplified if the effects of *spillway storage* are ignored. Stormwater facilities designed for compliance with state or local stormwater management regulations are typically small, resulting in minimal storage effects on the flood routing.

Two design calculation procedures are presented in **Chapter 5-8**. The first (Procedure 1) is a conservative design procedure which is also found in the Virginia Erosion & Sediment Control Handbook (VESCH) 1992 edition, (Std., & Spec. 3.14). This procedure is typically acceptable for stormwater management basins. The second method (Procedure 2) utilizes the roughness, or retardance, and durability of the vegetation and soils within the vegetated spillway. This second design is appropriate for larger or regional stormwater facilities where the construction inspection and permanent maintenance are more readily enforced. These larger facilities typically control relatively large watersheds and are located such that the stability of the emergency spillway is essential to safeguard downstream features.

If the inflow is known (from the post-developed condition hydrology) and either the desired maximum water surface elevation, or the approximate width of the proposed emergency spillway (established by the embankment geometry and the adjacent topography), then the relationship between H_p, the depth of flow through the emergency spillway, and b, the emergency spillway bottom width, can be established using design Procedure 1 (**Chapter 5-8**) and **Table 5-12**.

If the required discharge capacity, *Q*, permissible velocity, *V* (see **Table 3.03-1**), degree of retardance, *C* (see **Table 3.03-2**), and the natural slope of the exit channel, s_o , are known, then the bottom width, *b*, of the level and exit sections and the depth of flow, H_p , may be computed using design Procedure 2 (**Chapter 5-8**) and **Table 5-13**.

Table 5-13(a-d) is not appropriate for bottom widths less than 8 feet.

The hydraulic design of a vegetated emergency spillway should comply with the following:

1. The maximum permissible velocity for vegetated spillways should be selected using **Table 3.03-1**.

2. The slope range of the exit channel provided in **Table 5-11**, **Chapter 5**, is a minimum slope range needed to insure ***supercritical*** flow in the exit channel.

3. Spillway side slopes should be no steeper than 3H:1V unless the spillway is excavated into rock.

4. For a given H_p , a decrease in the exit slope from s_o, as given in **Table 5-11** of **Chapter 5**, decreases the spillway discharge, but increasing the exit slope from s_o does not increase discharge.

5. The exit channel should have a straight alignment and grade and, at a minimum, the same cross-section as the control section.

6. The inlet channel should have a straight alignment and grade.

7. The selected bottom width of the spillway should not exceed 35 times the design depth of flow. Where this ratio of bottom width to depth is exceeded, the spillway is likely to be damaged by meandering flow and accumulated debris. Whenever the required bottom width of the spillway is excessive, consideration should be given to the use of a spillway at each end of the dam. The two spillways do not need to be of equal width if their total capacity meets design requirements. If the required discharge capacity exceeds the ranges shown in the referenced tables, or topographic conditions preclude the construction of the exit channel bottom using a slope that falls within the designated ranges, alternate design procedures should be used.

8. Vegetated emergency spillways should be designed for use with the 100-year frequency storm or greater.

Construction Specifications

Overall, widely acceptable construction standards and specifications for a vegetated emergency spillway on an embankment, such as those developed by the USDA Soil Conservation Service or the U. S. Army Corps of Engineers, should be followed. Further guidance can be found in the SCS Engineering Field Manual and the National Engineering Handbook. Specifications for all earthwork and any other related work should conform to the methods and procedures that apply to the site and the purpose of the structure. The specifications should also satisfy any requirements of the local government.

Installation of a vegetated emergency spillway consists of the following: a) *excavating the proper bottom width and side slopes according to the approved plan*, b) *backfilling with 12 inches of topsoil (minimum)*, and c) *stabilizing the area* following the VESCH, 1992 edition.

Maintenance and Inspection Guidelines

The following maintenance and inspection guidelines are recommendations. The engineer must decide if additional criteria are needed based upon the size and scope of the facility.

1. Vegetated emergency spillway channels should be mowed concurrently with the embankment and should not be cut to less than 6 to 8 inches in height.

2. The emergency spillway approach and discharge channels should be cleared of brush and other woody growth periodically.

3. After any flow has passed through the emergency spillway, the spillway crest (control section) and exit channel should be inspected for erosion. All eroded areas should be repaired and stabilized.

TABLE 3.03 - 1
Permissible Velocities for Vegetated Spillways [1]

Vegetative Cover	Permissible Velocity [2] *(ft/s)*			
	Erosion Resistant Soils [3]		Easily Erodible Soils [4]	
	Slope of Exit Channel		Slope of Exit Channel	
	0-5%	*5-10%*	*0-5%*	*5-10%*
Bermuda Grass Bahiagrass	8	7	6	5
Buffalograss Kentucky Bluegrass Smooth Bromegrass Tall Fescue Reed Canary Grass	7	6	5	4
Sod Forming Grass-Legume Mixtures	5	4	4	3
Lespedeza Weeping Lovegrass Yellow Bluestem Native Grass Mixtures	3.5	3.5	2.5	2.5

[1] SCS-TP-61
[2] Increase values 25 percent when the anticipated average use of the spillway is not more frequent than once in 10 years.
[3] Those with a high clay content and high plasticity. Typical soil textures are silty clay, sandy clay, and clay.
[4] Those with a high content of fine sand or silty and lower plasticity or non-plastic. Typical soil textures are fine sand, silt, sandy loam, and silty loam.

Source - USDA-SCS Engineering Field Manual

TABLE 3.03 - 2
Retardance Classifications for Vegetative Channel Linings

Retardance	Vegetative Cover	Stand	Condition
B	Tall Fescue	Good	Unmowed - 18"
	Sericea Lespedeza	Good	Unmowed - 18"
	Grass-Legume Mixture	Good	Unmowed - 20"
	Small Grains, Mature	Good	Uncut - 19"
	Bermuda Grass	Good	Tall - 12"
	Reed Canary Grass	Good	Mowed - 14"
C	Bermuda Grass	Good	Mowed - 6"
	Redtop	Good	Headed - 18"
	Grass-Legume Mixture - Summer	Good	Unmowed - 7"
	Kentucky Bluegrass	Good	Headed - 9"
	Small Grains, Mature	Poor	Uncut - 19"
	Tall Fescue	Good	Mowed - 6"
D	Bermuda Grass	Good	Mowed - 2.5"
	Red Fescue	Good	Headed - 15"
	Grass-Legume Mixture, Spring and Fall	Good	Unmowed - 5"
	Sericea Lespedeza	Good	Mowed - 2"

Source: USDA-SCS

REFERENCES

USDA Soil Conservation Service. Engineering Field Manual.

USDA Soil Conservation Service. National Engineering Handbook.

USDA Soil Conservation Service. Technical Release No. 60, Earth Dams and Reservoirs.

U. S. Department of the Interior. Design of Small Dams. 1987.

Virginia Department of Conservation and Recreation. Virginia Erosion and Sediment Control Handbook (VESCH) 1992 edition.

Emergency Spillway “cut” into existing grade.

Emergency Spillway draining into concrete channel to protect embankment from erosion.

Vegetated Emergency Spillway

MINIMUM STANDARD 3.04

SEDIMENT FOREBAY

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MINIMUM STANDARD 3.04

SEDIMENT FOREBAY

Definition

A sediment forebay is a settling basin or plunge pool constructed at the incoming discharge points of a stormwater BMP.

Purpose

The purpose of a sediment forebay is to allow sediment to settle from the incoming stormwater runoff before it is delivered to the balance of the BMP. A sediment forebay helps to isolate the sediment deposition in an accessible area, which facilitates BMP maintenance efforts.

Condition Where Practice Applies

A sediment forebay is an essential component of most impoundment and infiltration BMPs including retention, detention, extended-detention, constructed wetlands, and infiltration basins.

Planning Considerations

A sediment forebay should be located at each inflow point in the stormwater BMP. Storm drain piping or other conveyances may be aligned to discharge into one forebay or several, as appropriate for the particular site. Forebays should be installed in a location which is accessible by maintenance equipment.

Water Quality

A sediment forebay not only serves as a maintenance feature in a stormwater BMP, it also enhances the pollutant removal capabilities of the BMP. The volume and depth of the forebay work in concert with the outlet protection at the inflow points to dissipate the energy of incoming stormwater flows. This allows the heavier, course-grained sediments and particulate pollutants to settle out of the runoff. **Note that for the BMPs listed in this handbook, the target pollutant removal efficiencies have been established assuming sediment forebays are included in the design**. Therefore, no additional pollutant removal efficiency is warranted for using a sediment forebay.

Channel Erosion Control and Flood Control

An "on line" BMP designed for flood control and channel erosion control is subject to the natural bed material (sediment) load, plus any bed load increases due to higher velocities in the upstream channels. This is especially true for regional facilities where the upstream channel is used to convey the increased developed condition flows. In such cases, the sediment forebay becomes an essential facility maintenance component since it serves to simplify clean-out operations.

Studies indicate that a well-designed retention basin will function for 20 to 25 years before it needs dredging. This implies a gradual sediment accumulation process. A concern regarding stormwater basins is that the landowners will probably change at least once during that 20 to 25-year period. The new owners may not be aware of the maintenance requirements and, may therefore, neglect to maintain the facility. Sediment will then continue to accumulate and will eventually fill the BMP pool volume.

A sediment forebay, however, is designed to trap the sediments within a confined area. This causes a more rapid sediment accumulation. Studies indicate that for a typical mixed-use watershed, sediment removal from the forebay should occur every 3 to 5 years. Despite this frequency, removal of sediment from the forebay should be less costly over the same time period than a one time cleaning of the entire basin. This is due in part to the fact that removing sediment from the forebay is a much simpler operation than that of an entire stormwater basin or pond. The sediment is confined to strategic forebay locations with easy access. Furthermore, the more frequent and less expensive schedule will likely become a regular part of the operation and maintenance efforts of the owners.

Design Criteria

The most attractive aspect of a sediment forebay is its isolation from the rest of the facility. To create this separation, an earthen berm, or a gabion, concrete, or riprap wall can be constructed along the outlet side of the forebay. A designed overflow section should be constructed on the top of the separation to allow flow to exit the forebay at non-erosive velocities during the 2-year and 10-year frequency design storms. The overflow section may be set at the permanent pool elevation or the extended-detention volume elevation. It may also be designed to serve as a spillover for the forebay if the forebay is set at a higher elevation than the second or remaining cell.

The use of an aquatic bench with emergent vegetation around the perimeter will help with water quality as well as provide a safety feature for large forebays (used on large lake BMPs or retrofits).

Volume

The sediment forebay should be sized to hold 0.25 inches of runoff per impervious acre of contributing drainage area, with an absolute minimum of 0.1 inches per impervious acre. The volume of the sediment forebay is not in addition to the required volume of the retention basin permanent pool, but rather as part of the required pool volume. For dry facilities, the forebay does not represent available storage volume if it remains full of water. A dry forebay must be carefully designed to avoid the resuspension of previously deposited sediments. The 0.1 to 0.25 impervious watershed inches is guidance for ideal performance. For smaller stormwater facilities, a more appropriate sizing criteria of 10% of the total required pool or detention volume may be more practical. This volume should be 4 to 6 feet deep to adequately dissipate turbulent inflow without resuspending previously deposited sediment (Center for Watershed Protection, 1995).

Maintenance

Direct access to the forebay should be provided to simplify maintenance. Provision of a hardened access or staging pad adjacent to the forebay is also beneficial. Such an area helps protect the forebay and basin from excessive erosion resulting from operation of the heavy equipment used for maintenance. The pad area can be hardened by installing block pavers or similar material. Also, a hardened bottom to the forebay will help avoid over excavation during clean out operations.

In addition, a fixed, vertical, sediment depth marker should be installed in each sediment forebay to measure the sediment deposition. The sediment depth marker will allow the owner to monitor the accumulation and anticipate maintenance needs. Clean out frequency will vary depending on the conditions of the upstream watershed and the given site.

In general, sediment should be removed from the forebay every 3 to 5 years, or when 6 to 12 inches have accumulated, whichever comes first. To clean the forebay, draining or pumping and a possible temporary partial drawdown of the pool area may be required. Refer to the VESCH, 1992 edition for proper dewatering methods.

To reduce costs associated with hauling and disposing of dredged material, a designated spoil area should be approved and identified on the site during initial design and development of the project.

FIGURE 3.04 - 1
Typical Sediment Forebay Plan and Section

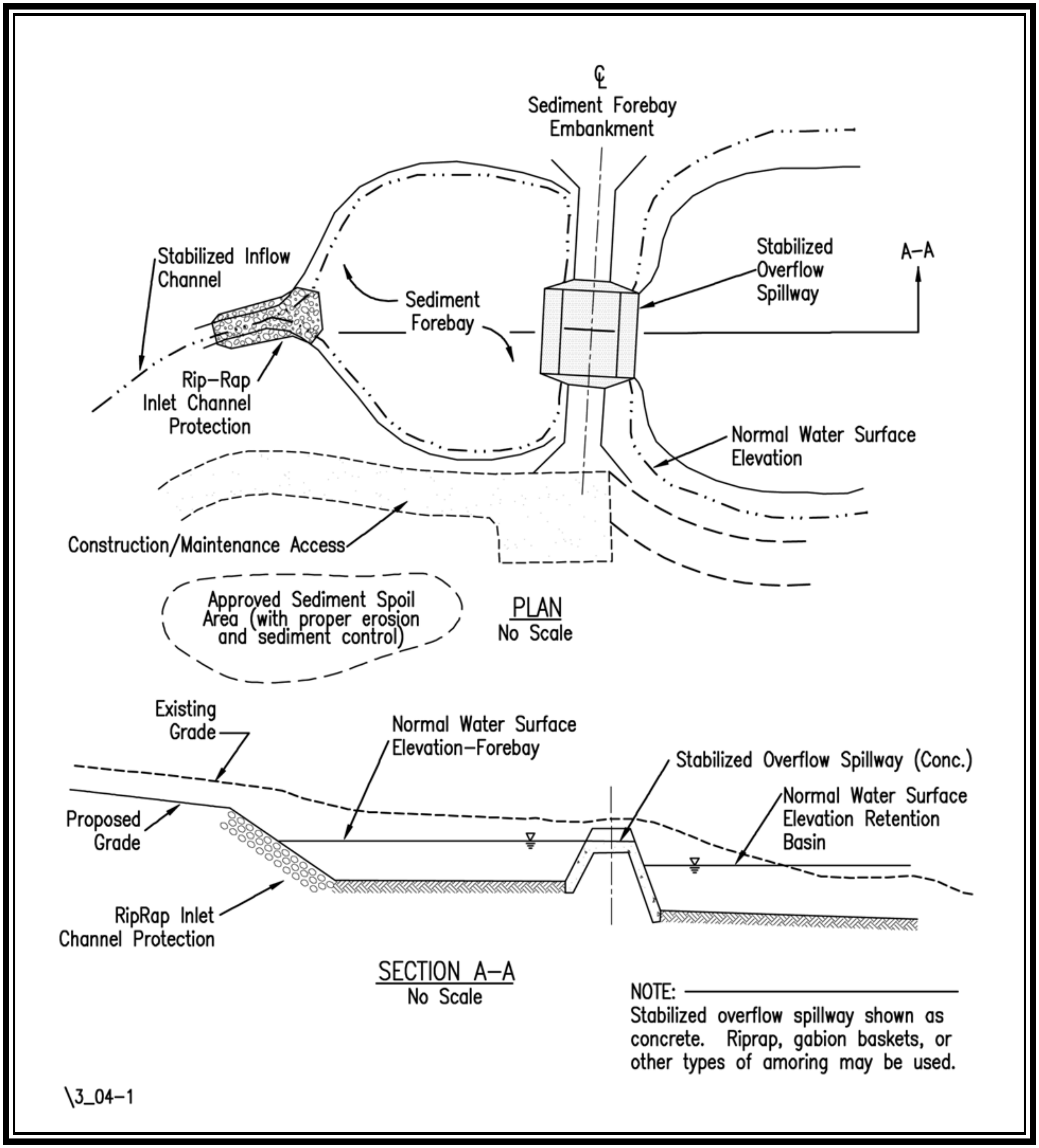
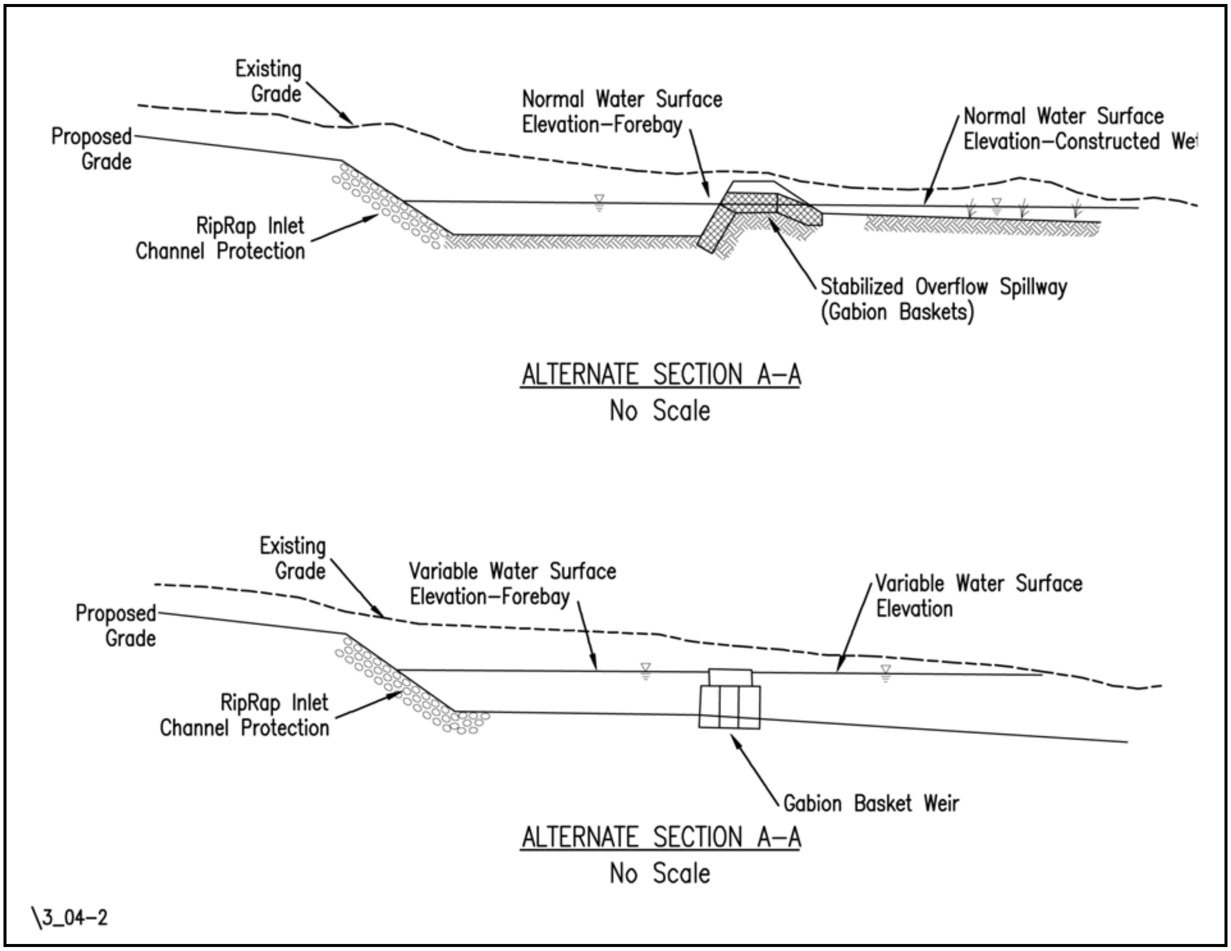


FIGURE 3.04 - 2
Typical Sediment Forebay Sections



Sediment Forebay constructed with earthen embankment and rip-rap overflow.

Sediment Forebay constructed with submerged rip-rap weir.

Sediment Forebay

MINIMUM STANDARD 3.05

LANDSCAPING

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MINIMUM STANDARD 3.05

LANDSCAPING

Definition

Landscaping is the placement of vegetation in and around stormwater management BMPs.

Purpose

The purpose of landscaping is to help stabilize disturbed areas, enhance the pollutant removal capabilities of a stormwater BMP and improve the overall aesthetics of a stormwater BMP.

Conditions Where Practice Applies

A landscape plan is an integral part of any land development project. It provides guidance and specifications for the type, location, and number of planting units according to the various requirements of the development project. A landscape plan may need one or all of the following:

1. Minimum green space or other requirements per local zoning or stabilization ordinances.

2. Natural and manmade vegetative buffer requirements between differing land uses or between developed land and natural resources.

3. Landscaping and stabilization requirements for stormwater management BMPs.

This minimum standard focuses on landscaping and stabilization requirements for stormwater management BMPs and their associated buffer areas. This standard may also be appropriate for other landscaping applications used in plan and specification preparation.

Certain BMPs, such as constructed wetlands, retention basins with an aquatic bench, *enhanced* extended detention basins with a shallow marsh, bioretention facilities, etc., require very specific plant materials and handling specifications. Refer to the minimum standards found in this chapter for additional criteria applicable to specific BMP designs.

Landscaped areas can provide significant reductions in pollutant export from developed sites through biological uptake of nutrients, sediment trapping, filtering, and infiltration.

For stormwater management purposes, landscaping is considered an integral component of a structural BMP. While the benefit realized from landscaping may be difficult to measure, it is widely accepted that the biological processes occurring in detention and retention BMPs are greatly enhanced by using vegetation. **The target pollutant removal efficiencies assigned to the BMPs in this handbook are based on the use of vegetative practices within the BMP buffer areas and the various BMP planting zones**. The vegetative practices should be specified in a landscape plan as part of the overall BMP and site construction documents.

Planning Considerations

Plant selection should be based on the planting zones within the BMP. Various zones exist within a stormwater impoundment and each represents a different inundation frequency and soil moisture condition. The planting zones can be classified as follows:

Zone 1: Deep Water Areas: This zone is submerged beneath 18 inches to 6 feet of water. It supports submerged aquatic vegetation such as pondweed, coontail, wild celery, etc., and floating vegetation such as duckweed. Plants can actively remove metals from the water and provide food and habitat for invertebrates at the bottom of the food cycle. This zone may be present in retention basins, constructed wetlands, and in sediment forebays and micro-pools of extended-detention and *enhanced* extended-detention basins.

Zone 2: Shallow Water Area: This zone is 0 to 18 inches in normal depth and is the primary area for the establishment of emergent wetland plants. It may be present in retention basins, constructed wetlands, and *enhanced* extended-detention basins. This zone is divided into **low-marsh** and **high-marsh** sub-zones. The low-marsh extends from 6 to 18 inches in depth below the normal water surface. The high-marsh ranges from 6 inches below the normal water surface and up to the normal water surface. Vegetation in this zone can serve the following purposes:

- enhances nutrient uptake,
- reduces flow velocities to increase the rate of sediment deposition,
- reduces resuspension of bottom sediments,
- provides food and cover for wildlife,
- provides habitat for predatory insects and to serve as a check for mosquitoes,
- reduces shoreline erosion, and
- improves aesthetics

Suggested plants for this zone include common three-square, soft-stem bulrush, pickerelweed, arrow arrum, sedges, and others.

Zone 3: Shoreline Fringe: This zone is regularly inundated during runoff-producing storm events and may remain saturated due to the proximity of the permanent pool. However, plants must be tolerant of periodic drying, especially during the summer months. This zone extends from the normal water surface to about 1 foot above the normal water surface for retention basins and constructed wetlands. It also continues up to the maximum extended-detention volume elevation for extended-detention and *enhanced* extended-detention basins. The vegetation in this zone may serve the following purposes:

- stabilizes the shoreline,
- improves aesthetics,
- limits shoreline access by people and animals (geese),
- provides food, cover, and nesting for wildlife, and
- provides shade

Recommended species for this zone include herbaceous vegetation such as soft-stem bulrush, pickerelweed, rice cutgrass, sedges, and others. It also includes trees such as black willow and river birch and shrubs such as chokeberry.

Zone 4: Riparian Fringe Area: This zone is only briefly inundated during storms. It generally includes the upper storage areas of extended-detention basins (above the water quality or channel erosion control volume) and the lower basin areas of dry detention basins. It experiences both wet and dry soil conditions and periodic inundation. The vegetation in this zone may serve the following purposes:

- reduce resuspension of newly deposited sediments,
- prevent erosion, and
- provide habitat and food for wildlife,

A variety of trees, shrubs, and ground covers can be used in this zone, including black willow, river birch, red chokeberry, green ash, sweetgum and others.

Zone 5: Floodplain Terrace: This zone experiences inundation only during large storms. It is generally between the 2-year and 100-year water surface elevations. Plant species native to floodplains usually grow well in this zone. Plants selected for the floodplain terrace should have the following traits:

- ability to provide erosion control on steep slopes,
- ability to survive periodic mowing,
- ability to withstand exposure and compacted soil, and
- require minimal maintenance

Zone 6: Upland Areas: This zone seldom, if ever, experiences inundation and may include any buffer areas required for stormwater basins. Selection of plant species in this zone typically depends on local soil conditions and the intended secondary uses of the area. Refer to **Table 3.05-4** for a plant guide.

Figure 3.05-1 shows a schematic cross-section of the six planting zones. Designers should select appropriate plant and tree species based on the characteristics of each zone, local soil conditions, sun and wind exposure levels, and intended secondary uses of the buffer area.

Preservation of Existing Vegetation

Although there are many reasons to minimize land disturbance associated with development, one of the greatest benefits may be the reduced runoff associated with undisturbed ground. Existing vegetation helps prevent erosion, filters runoff, and allows stormwater to filter into the ground, which ultimately results in lower stormwater management costs. As for the economics of site development, planning for the selective preservation of vegetation on a site **before land disturbance** is much less costly than trying to reestablish it once it has been removed. This holds true for both labor and replacement costs. In addition, studies conducted by the U.S. Forest Service and others indicate that preserving mature vegetation on residential sites can increase property values by 30% (NVPDC, 1996).

For guidance on non-structural BMPs and vegetative practices in general, refer to the following references:

- *Piedmont Provinces Vegetative Practices Guide, NVPDC, 1996.*
- *Nonstructural BMP Handbook: A Guide to Nonpoint Source Pollution Prevention Measures, NVPDC, 1996.*
- *Vegetative Practices Guide for Nonpoint Source Pollution Management, HRPDC, 1992.*
- *Chesapeake Bay Local Assistance Manual, CBLAD, 1989.*
- *Virginia Erosion & Sediment Control Handbook (VESCH), DCR, 1992.**

* The VESCH, 1992 edition, also provides details for tree preservation during construction.

Design Criteria

The landscape plan for a stormwater BMP depends on the BMP being used. However, there are key components to any landscape plan which help assure its overall success. The following section describes these components.

A landscape plan for a stormwater management BMP should contain the following, at a minimum:

Plant Species Selection

Plants selected for a stormwater BMP must tolerate urban stresses such as pollutants, along with variable soil moisture and ponding fluctuations, climate, soils, and topography. Virginia has three distinct physiographic regions that reflect changes in soils and topography: Coastal Plain, Piedmont, and Appalachian and Blue Ridge regions. See **Figure 3.05-2**.

When selecting plants, native plant species should be used, if possible. Nonnative plants may require more care to adapt to the hydrology, climate, exposure, soil and other conditions. Also, some nonnative plants can become invasive, especially those used for stabilization, and may ultimately choke out the native plant population.

Newly constructed stormwater BMPs will be fully exposed for several years before the buffer vegetation becomes adequately established. Therefore, plants which require full shade, are susceptible to winter kill, or are prone to wind damage, should be avoided.

The plant material should conform to the American Standard for Nursery Stock, current issue, as published by the American Association of Nurserymen. The botanical (scientific) name of the plant species should be in accordance with the landscape industry's standard nomenclature. All plant material specified should be suited for USDA Plant Hardiness zones 6 or 7. See **Figure 3.05- 3**.

Transport and Storage of Plant Material

Specifications may be required for the handling and storage of certain plant materials. Aquatic or emergent plants, for example, require very precise instructions for the contractor. Depending on the time of year and the sequence of construction, it may not be prudent to deliver the plants to the site until the project is ready for landscaping.

Sequence of Construction

The *sequence of construction* describes the site preparation activities such as grading, addition of soil amendments, and any preplanting requirements. It also addresses the installation of erosion and sediment control measures, which should be in place until the entire landscape plan is implemented and the site is stabilized.

Installation of Plant Material

The success of any landscape plan depends on the selection of the proper specifications that are subsequently implemented by the contractor. The specifications should include procedures for installing the plants. They should also provide details for the steps to be taken before and after installation, such as any special instructions for the preparation of the planting pit and fertilization requirements. Any seasonal requirements for installation should also be specified. Typically, containerized or balled and burlapped trees or shrubs should be planted between March 15 and June 30, or between September 15 and November 15.

The placement of trees or shrubs on an embankment is prohibited. The root system of large trees and shrubs can threaten the structural integrity of the embankment and possibly cause its failure.

The side slopes of detention and retention BMPs are usually compacted during the construction process to ensure stability. The density of these compacted soils is often such that plant roots cannot penetrate to an adequate depth, leading to premature mortality or loss of vigor. Therefore, it is advisable to excavate oversized holes around the proposed planting sites and backfill with uncompacted topsoil. In general, planting holes should be 3 times deeper and wider than the diameter of the root ball (B&B stock) and 5 times deeper and wider for container-grown stock (MWCOG, 1992).

Contractor Responsibilities

The contractor should conform to any specifications that directly affect his aspect of the work. He should be aware that there may be penalties for unnecessarily delayed work, minimum success rate of plantings, etc.

For projects involving bio-retention basins or constructed wetlands, it may be advisable to utilize a subcontractor who specializes in aquatic landscaping. The plant specifications, handling, and installation procedures can be unusual compared to traditional landscaping requirements.

Maintenance

A maintenance schedule should be provided in the project plans and/or specifications. This is particularly important for BMPs that have a vegetative component that is integral to the pollutant removal efficiency. The schedule should include guidance regarding methods, frequency, and time of year for landscape maintenance and fertilization.

Specific plant communities may require different levels of maintenance. Upland and floodplain terrace areas, grown as meadows or forests, require very little maintenance, while aquatic or emergent vegetation may need periodic thinning or reinforcement plantings. Note that after the first growing season it should be obvious if reinforcement plantings are needed. If they are, they should be installed at the onset of the second growing season after construction.

Research indicates that for most aquatic plants the uptake of pollutants are stored in the roots, not the stems and leaves (Lepp 1981). Therefore, aquatic plants should not require harvesting before winter plant die-back. There are still many unanswered questions about the long term pollutant storage capacity of plants. It is possible that aquatic and emergent plant maintenance recommendations may be presented in the future.

FIGURE 3.05 - 1
Planting Zones for Typical Stormwater BMPS

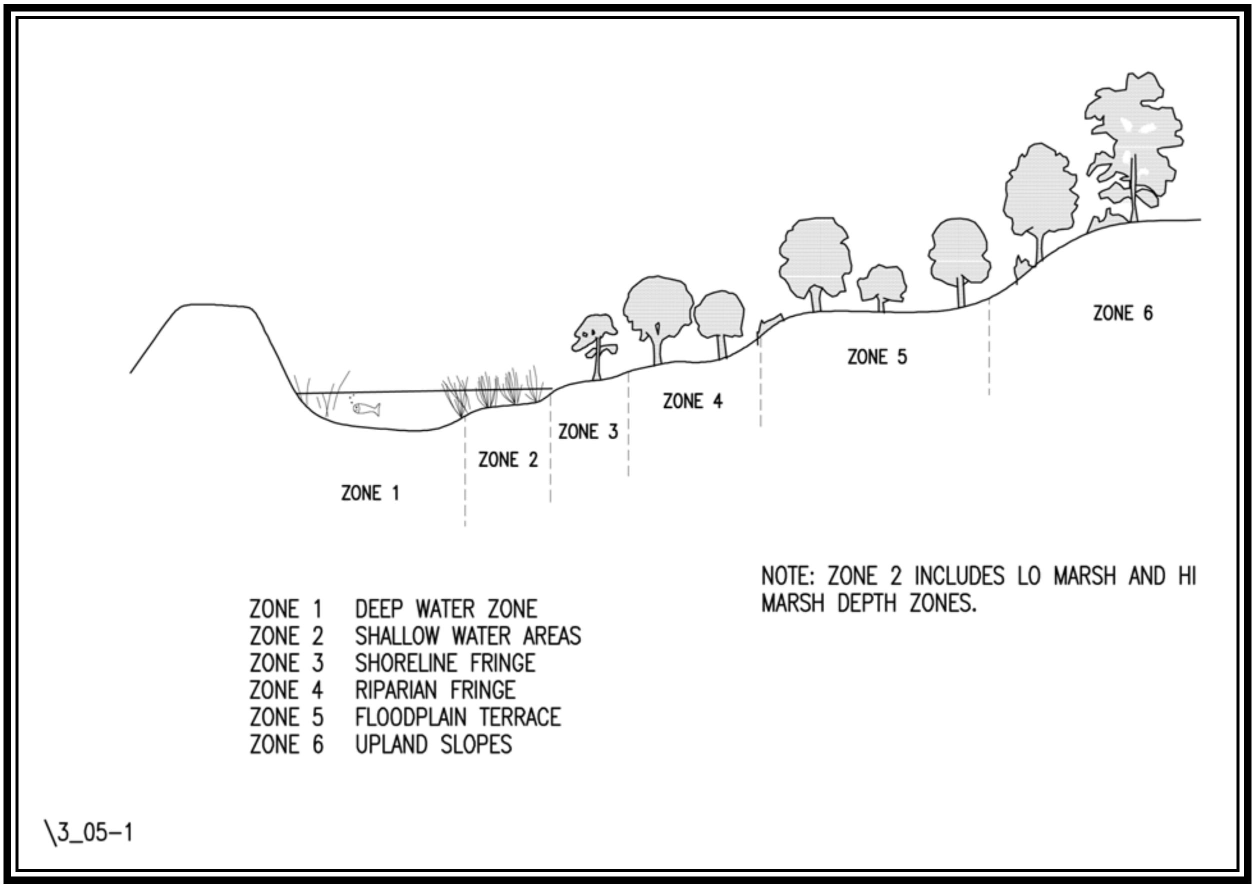

FIGURE 3.05 - 2
Virginia Physiographic Regions

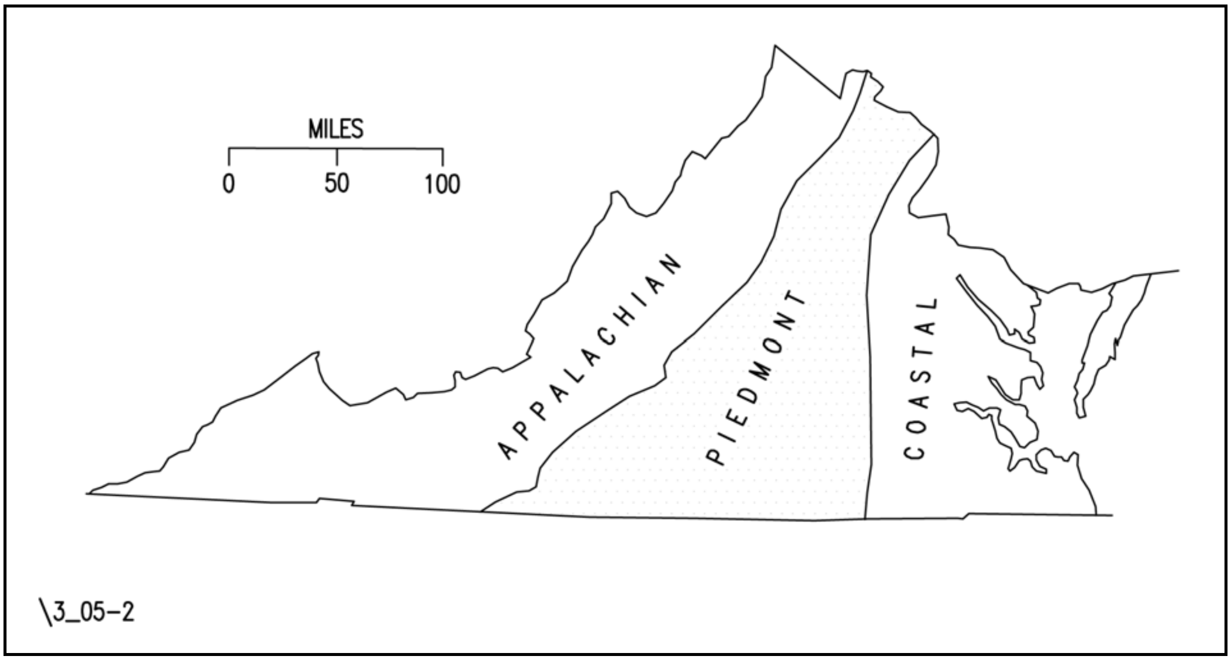

FIGURE 3.05 - 3
USDA Plant Hardiness Zones

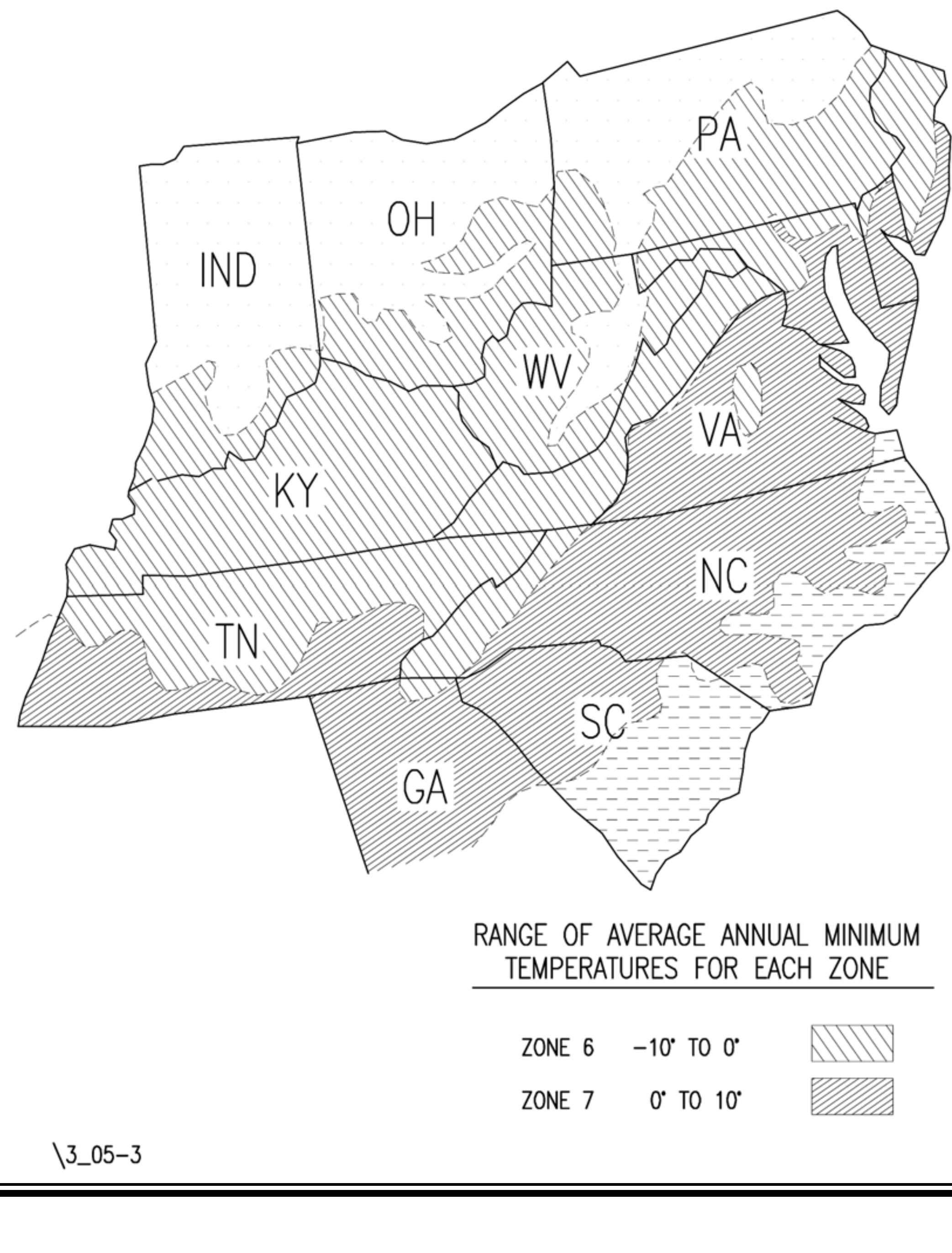

FIGURE 3.05 - 4a

Native Plant Guide for Stormwater Management Areas in the Mid-Atlantic, USA

Trees and Shrubs

Tree/Shrub	*Zone	Form	Available	Inundation Tolerance	Wildlife Value	Notes
American Beech *(Fagus grandifolia)*	5,6	Dec. Tree	no	no	High, mammals and birds.	Prefers shade and rich, well-drained soils.
American Holly *(Ilex opaca)*	5,6	Dec. Tree	yes	some	High,songbirds, food, cover, nesting.	Coastal plain only. Prefers shade and rich soils.
American Hornbeam *(Carpinus caroliniana)*	4,5	Dec. Tree	yes	yes	Moderate, food, browsing.	Most common in flood plains and bottom land of Piedmont and mountains.
Arrowwood Viburnum *(Viburnum dentatum)*	2,3,4	Dec. Shrub	yes	no	High, songbirds and mammals.	Grows best in sun to partial shade.
Bald Cypress *(Taxodium distichum)*	3,4	Dec. Tree	yes	yes	Little food value but good perching site for waterfowl.	Forested Coastal Plain wetlands. North of normal range. Tolerates drought.
Bayberry *(Myricia pensylvanica)*	4,5,6	Dec. Shrub	yes	no	High, nesting, food cover. Berries last into winter.	Coastal Plain only. Roots fix N. Tolerates slightly acidic soil.
Bitternut Hickory *(Carya cordiformis)*	3,4,5	Dec. Tree	no	yes	High, food.	Moist soils or wet bottom land areas.
Black Cherry *(Prunus serotina)*	5,6	Dec. Tree	yes	yes	High, fruit is eaten by many birds.	Temporarily flooded forested areas. Possible fungus infestation.
Black Walnut *(Juglans nigra)*	5,6	Dec. Tree	yes	yes	High, food.	Temporarily flooded wetlands along flood plains. Well drained, rich soils.
Blackgum or Sourgum *(Nyssa sylvatica)*	4,5,6	Dec. Tree	yes	yes	High, songbirds, egrets, herons, raccoons, owls.	Can be difficult to transplant. Prefers sun to partial shade.
Black Willow *(Salix nigra)*	3,4,5	Dec. Tree	yes	yes	High, browsing and cavity nesters.	Rapid growth, stabilizes stream banks. Full sun.
Buttonbush *(Cephalanthus occidentalis)*	2,3,4,5	Dec. Shrub	yes	yes	High, ducks and shorebirds. Seeds, nectar and nesting.	Full sun to partial shade. Will grow in dry areas.
Chestnut Oak *(Quercus prinus)*	5,6	Dec. Tree	no	no	High. Cover, browse and food.	Gypsy moth target. Dry soils.

FIGURE 3.05 - 4a (cont.)

Tree/Shrub	*Zone	Form	Available	Inundation Tolerance	Wildlife Value	Notes
Common Choke Cherry *(Prunus virginiana)*	5,6	Dec. Tree	no	some	High, birds, mammals. Fruit and cover.	Prefers drier conditions.
Common Spicebush *(Lindera benzoin)*	4,5	Dec. Shrub	yes	no	Very high, songbirds.	Shade and rich soils. Tolerates acidic soils. Good understory species.
Eastern Cottonwood *(Populus deltoides)*	4,5	Dec. Tree	yes	yes	Moderate, cover, food.	Shallow rooted, subject to windthrow. Invasive roots. Rapid growth.
Eastern Hemlock *(Tsuga conadensis)*	5,6	Conif. Tree	yes	yes	Moderate. Mostly cover and some food.	Tolerates all sun/shade conditions. Tolerates acidic soil.
Eastern Red Cedar *(Juniperus virginiana)*	4,5,6	Conif. Tree	yes	no	High. Fruit for birds. Some cover.	Full sun to partial shade. Common in wetlands, shrub bogs and edge of streams.
Elderberry *(Sambucus canadensis)*	4,5,6	Dec. Shrub	yes	yes	Extremely high for food and cover, for birds and mammals.	Full sun to partial shade.
Flowering Dogwood *(Cornus florida)*	4,5,6	Dec. Tree	no	yes	High, birds, food.	Prefers rich, moist soils. Dogwood anthracnose possible problem.
Fringe Tree *(Chionanthus viginicus)*	3,4,5	Dec. Shrub or small tree	yes	some	Moderate. Food and cover.	Full sun to partial shade. Tolerates acidic soil.
Green Ash, Red Ash *(Fraxinus pennysylvanica)*	4,5	Dec. Tree	yes	yes	Moderate, songbirds.	Rapid growing stream bank stabilizer. Full sun to partial shade.
Hackberry *(Celtis occidentalis)*	5,6	Dec. Tree	yes	yes	High, food and cover.	Full sun to partial shade.
Ironwood/ Hophornbeam *(Ostrya virginiana)*	5,6	Dec. Tree	yes	yes	Moderate, food and browse.	Tolerant of all sunlight conditions.
Larch, Tamarack *(Larix laricina)*	3,4	Conif. Tree	no	yes	Low, nest tree and seeds.	Rapid initial growth. Full sun, acidic boggy soils.
Loblolly Pine *(Pinus taeda)*	5,6	Conif. Tree	yes	yes	Moderate, food, nesting, squirrels.	Coastal Plain only. Tolerant of extreme soil conditions.

FIGURE 3.05 - 4a (cont.)

Tree/Shrub	*Zone	Form	Available	Inundation Tolerance	Wildlife Value	Notes
Mountain Laurel *(Kalmia latifolia)*	6	Evergreen	no	some	Low, cover, and nectar. Foliage is toxic to cattle and deer.	Partial shade, acidic soils.
Persimmon *(Diospyros virginiana)*	4,5,6	Dec. Tree	yes	no	Extremely high, birds, mammals.	Not shade tolerant. Well-drained soils.
Pin Oak *(Quercus palustris)*	4,5,6	Dec. Tree	yes	yes	High, mast. Tolerates acidic soil.	Gypsy moth target. Prefers sun to partial shade.
Red Chokeberry *(Pyrus arbutifolia)*	3,4,5	Dec. Shrub	no	yes	Moderate, songbirds.	Bank stabilizer. Partial sun.
Red Maple *(Acer rubrum)*	4,5,6	Dec. Tree	yes	yes	High, seeds and browse. Tolerates acidic soil.	Rapid growth.
Red Oak *(Quercus rubra)*	5,6	Dec. Tree	yes	no	High, food and cover.	Gypsy moth target. Prefers well drained, sandy soils.
River Birch *(Betula nigra)*	3,4	Dec. Tree	yes	yes	Low, but good for cavity nesters.	Bank erosion control. Full sun.
Scarlet Oak *(Quercus coccinea)*	3,4	Dec. Tree	no	no	High, food and cover.	Gypsy moth target. Difficult to transplant.
Shadbush, Serviceberry *(Amelanchier canadensis)*	5,6	Dec. Tree	yes	yes	High, nesting, cover and food. Birds and mammals.	Prefers partial shade. Common in forested wetlands and upland woods.
Silky Dogwood *(Cornus amomum)*	5,6	Dec. Shrub	yes	yes	High, songbirds, mammals.	Shade and drought tolerant. Good bank stabilizer.

Source: Native Plant Pondscaping Guide - Watershed Restoration Sourcebook, Natalie Karouna, MWCOG

***Zone 1: Submergent Aquatic Vegetation**
***Zone 2: Shallow Water Bench - 6-12 inches Deep**
***Zone 3: Shoreline Fringe - Regularly Inundated Area**
***Zone 4: Riparian Fringe - Periodically Inundated Area, Wet Soils**
***Zone 5: Floodplain Terrace - Infrequently Inundated, Moist Soils**
***Zone 6: Upland Slopes - Seldom or Never Inundated, Moist To Dry Soils**

FIGURE 3.05 - 4b

Native Plant Guide for Stormwater Management Areas in the Mid-Atlantic, USA

Wetland Plants

Wetland Plants	*Zone	Form	Available	Inundation Tolerance	Wildlife Value	Notes
Arrow arum *(Peltandra virginica)*	2	Emergent	yes	up to 1 ft.	High, berries are eaten by wood ducks.	Full sun to partial shade.
Arrowhead/Duck potato *(Saggitaria latifolia)*	2	Emergent	yes	up to 1 ft.	Moderate, tubers and seeds eaten by ducks.	Aggressive colonizer.
Broomsedge *(Andropogon virginianus)*	2,3	Perimeter	yes	up to 3 in.	High, songbirds and browsers. Winter food and cover.	Tolerant of fluctuating water levels and partial shade.
Cattail *(Typha spp.)*	2,3	Emergent	yes	up to 1 ft.	Low, except as cover.	Aggressive. May eliminate other species. Volunteer. High pollutant treatment.
Coontail *(Ceratophyllum demersum)*	1	Submergent	no	yes	Low, food, good habitat and shelter for fish and invertebrates.	Free floating SAV. Shade tolerant. Rapid growth.
Common Three Square *(Scipus pungens)*	2	Emergent	yes	up to 6 in.	High, seeds, cover, waterfowl, songbirds.	Fast colonizer. Can tolerate periods of dryness. Full sun. High metal removal.
Duckweed *(Lemna sp.)*	1,2	Submergent /Emergent	yes	yes	High, food for waterfowl and fish.	May biomagnify metals beyond concentrations found in water.
Lizard's Tail *(Saururus cernuus)*	2	Emergent	yes	up to 1 ft.	Low, except wood ducks.	Rapid growth. Shade tolerant.
Marsh Hibiscus *(Hibiscus moscheutos)*	2,3	Emergent	yes	up to 3 in.	Low, nectar.	Full sun. Can tolerate periodic dryness.
Pickerelweed *(Pontederia cordata)*	2,3	Emergent	yes	up to 1 ft.	Moderate, ducks, nectar for butterflies.	Full sun to partial shade.
Pond Weed *(Potamogeton pectinatus)*	1	Submergent	yes	yes	Extremely high, waterfowl, marsh and shore-birds.	Removes heavy metals.
Rice Cutgrass *(Leersia oryzoides)*	2,3	Emergent	yes	up to 3 in.	High, food and cover.	Full sun, although tolerant of shade. Shoreline stabilization.

FIGURE 3.05 - 4b (cont.)

Wetland Plants	*Zone	Form	Available	Inundation Tolerance	Wildlife Value	Notes
Sedges *(Carex spp.)*	2,3	Emergent	yes	up to 3 in.	High, waterfowl, songbirds.	Many wetland and several upland species.
Soft-stem Bulrush *(Scipus validus)*	2,3	Emergent	yes	up to 1 ft.	Moderate, good cover and food.	Full sun. Aggressive colonizer. High pollutant removal.
Smartweed (Polygonum spp.)	2	Emergent	yes	up to 1 ft.	High, waterfowl, songbirds, seeds and cover.	Fast colonizer. Avoid weedy aliens such as P. Perfoliatum.
Spatterdock (Nuphar luteum)	2	Emergent	yes	up to 1.5 ft.	Moderate, for food but high for cover.	Fast colonizer. Tolerant of fluctuating water levels.
Switchgrass *(Panicum virgatum)*	2,3,4, 5,6	Perimeter	yes	up to 3 in.	High, seeds, cover. Waterfowl, songbirds.	Tolerates wet/dry conditions.
Sweet Flag *(Acorus calamus)*	2,3	Perimeter	yes	up to 3 in.	Low, tolerant of dry periods.	Tolerates acidic conditions. Not a rapid colonizer.
Waterweed *(Elodea canadensis)*	1	Submergent	yes	yes	Low.	Good water oxygenator. High nutrient, copper, manganese and chromium removal.
Wild Celery *(Valisneria americana)*	1	Submergent	yes	yes	High, food for waterfowl. Habitat for fish and invertebrates.	Tolerant of murkey water and high nutrient loads.
Wild Rice *(Zizania aquatica)*	2	Emergent	yes	up to 1 ft.	High, food. Birds.	Prefers full sun.

Source: Native Plant Pondscaping Guide - Watershed Restoration Sourcebook, Natalie Karouna, MWCOG

****Zone 1:Submergent Aquatic Vegetation***
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REFERENCES

Arnold, J.A., ed., D.E. Line, S.W. Coffey, and J. Spooner. Stormwater Management Guidance Manual. Raleigh, North Carolina: North Carolina Cooperative Extension Service and North Carolina Division of Environmental Management, 1993.

Brady, N.C. The Nature and Properties of Soils. New York: MacMillan Publishing Co., 1984.

Chesapeake Bay Local Assistance Department. Chesapeake Bay Local Assistance Manual. Richmond, Virginia: 1989.

Chesapeake Bay Program. Water Quality Functions of Riparian Forest Buffer Systems in the Chesapeake Bay Watershed. Technology Transfer Report CBP/TRS 134/95. Annapolis, Maryland: 1995.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. "Vegetative Filter Strips for Agricultural Nonpoint Source Pollution Control." Transactions of the American Society of Agricultural Engineers. Blacksburg, Virginia: 1989.

Fernald, M. L. Gray's Manual of Botany. 8th ed. Portland, Oregon: Dioscorides Press, 1950.

Galli, John. Analysis of Urban BMP Performance and Longevity. Washington, D. C.: Metropolitan Washington Council of Governments, 1992.

Hampton Roads Planning District Commission. Vegetative Practices Guide for Nonpoint Source Pollution Management. Chesapeake, Virginia: 1992.

Hightshoe, G. L. Native Trees, Shrubs, and Vines for Urban and Rural America. New York: Van Nostrand Reinhold, 1988.

Karouna, Natalie. Native Plant Pondscaping Guide. Anacostia Watershed Restoration Source Book. Washington, D. C.: Metropolitan Washington Council of Governments, 1991.

Metropolitan Washington Council of Governments. Guidance Report 1: Riparian Buffer Programs, A Guide to Developing and Implementing a Riparian Buffer Program as an Urban Stormwater Best Management Practice. Washington, District of Columbia: 1993.

Northern Virginia Planning District Commission and Engineers and Surveyors Institute. Northern Virginia BMP Handbook. Annandale, Virginia: 1992.

Reed, P. B., Jr. National List of Species That Occur in Wetlands: Northeast. St. Petersburg, Florida: United States Fish and Wildlife Service, 1988.

Schlesinger, W. H. and Waring, R. H. Forest Ecosystems: Concepts and Management. Orlando, Florida: Academic Press, 1985.

Schueler, T. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Washington, D. C.: Metropolitan Washington Council of Governments, 1987.

Schueler, T. Level Spreader/Filter Strip System Assessed in Virginia. Watershed Protection Techniques, Vol. 1, No. 1. Silver Spring, Maryland: Center for Watershed Protection, 1994.

Schueler, T.R., P.A. Kumble, and M.A. Heraty. A Current Assessment of Urban Best Management Practices. Washington, D.C.: Metropolitan Washington Council of Governments, 1992.

Schueler, T. The Architecture of Urban Stream Buffers. Watershed Protection Techniques, Vol. 1, No. 4. Silver Spring, Maryland: Center for Watershed Protection, 1995.

Tisdale, S. L. and Nelson, W. L. Soil Fertility and Fertilizers. 3rd. ed. New York: MacMillan Publishing Co., Inc., 1975.

Virginia Department of Forestry. Interim Report to the Chesapeake Bay Executive Council, EC Directive #94-1 Riparian Forest Buffers. Charlottesville, Virginia: 1995.

Virginia Department of Conservation and Recreation. Virginia Erosion and Sediment Control Handbook (VESCH). Richmond, Virginia: 1992.

Wong, S.L. and R.H. McCuen. The Design of Vegetative Buffer Strips for Runoff and Sediment Control. Tidewater Administration, Maryland Department of Natural Resources, Annapolis, Maryland: 1982.

Landscaping – “rough” shoreline edge and aquatic bench provides improved pollutant removal and shoreline stabilization.

Landscaping – “manicured” landscape plan. Note brick bulkhead to control shoreline erosion.

Landscaping

MINIMUM STANDARD 3.06

RETENTION BASIN

View BMP Images

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MINIMUM STANDARD 3.06

RETENTION BASIN

Definition

A retention basin is a stormwater facility which includes a permanent impoundment, or pool of water, and, therefore, is normally wet, even during non-rainfall periods. Inflows from stormwater runoff may be temporarily stored above this permanent pool.

Purpose

A retention basin provides for long-term water quality enhancement of stormwater runoff. Stormwater inflows may also be temporarily stored above the permanent pool for downstream flood control and channel erosion control. A retention basin is considered one of the most reliable and versatile BMPs available.

Water Quality Enhancement

High removal rates of particulate and soluble pollutants (nutrients) can be achieved in retention basins through *gravitational settling*, *biological uptake* and *decomposition*. When an even higher degree of pollutant removal efficiency is required, the basin can be ***enhanced*** by using various modifications relating to the size and design of the permanent pool.

Monitoring studies have shown sediment removal efficiencies to range from 50-90%, total phosphorus removal efficiencies to range from 30-90% and soluble nutrient removal efficiencies to range from 40-80%. (MWCOG, 1992). The design elements, physical characteristics, and monitoring techniques varied for each basin studied, which explains the wide range of efficiencies. The target pollutant removal efficiencies assigned to the different design options are presented in **Table 3.06-1**.

FIGURE 3.06 - 1
Retention Basin - Plan & Section

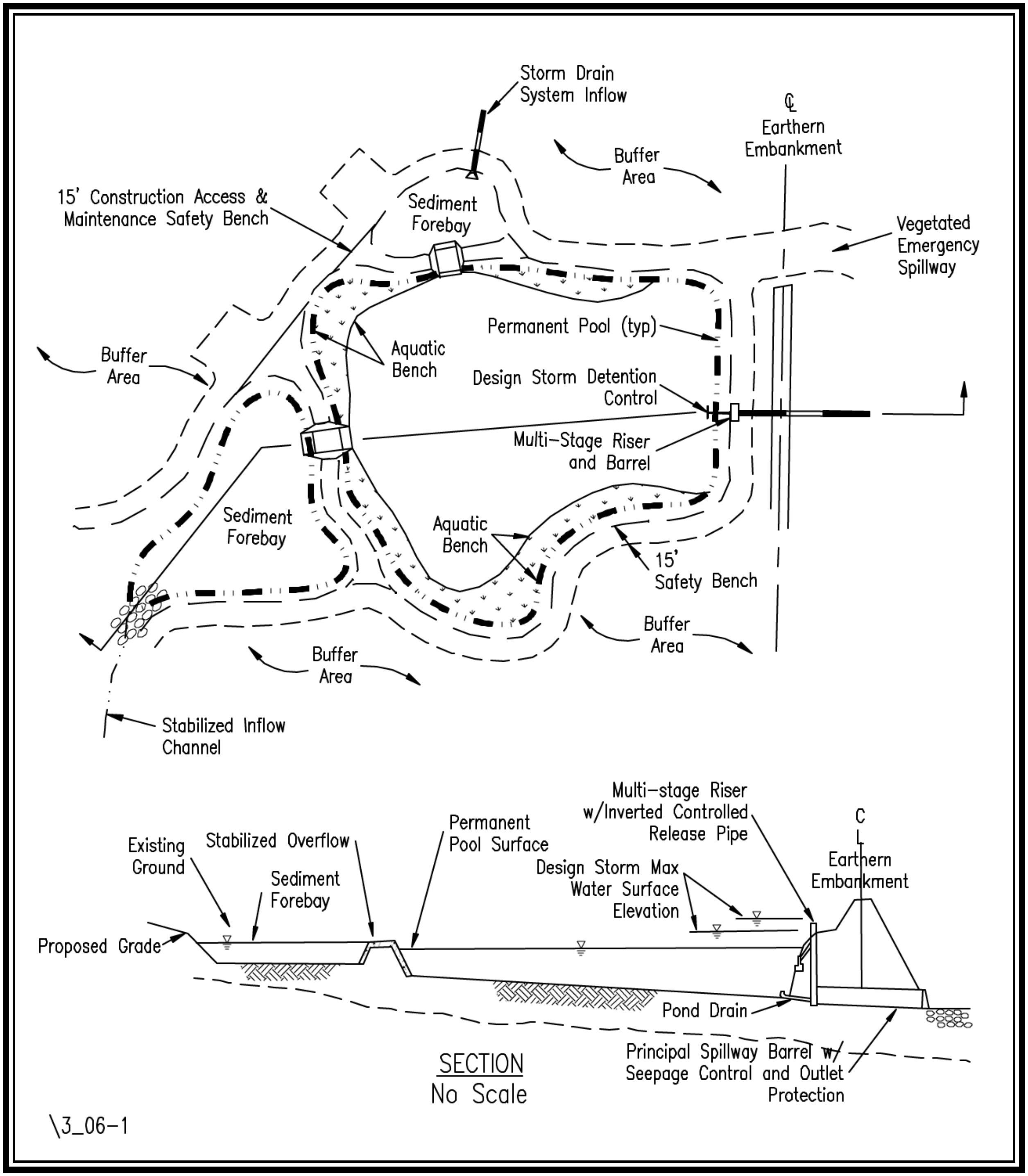

TABLE 3.06 - 1
Pollutant Removal Efficiencies for Retention Basins

Type	Sizing Rule	Target Phosphorus Removal Efficiency	Impervious Cover
Retention Basin I	3.0 x WQ Volume	40%	22-37%
Retention Basin II	4.0 x WQ Volume	50%	38-66%
Retention Basin III	4.0 x WQ Volume with Aquatic Bench	65%	67-100%

<u>Flood Control</u>

Retention basins which provide flood control are designed with "dry" storage above the permanent pool. This dry storage works in concert with a riser or control structure to reduce the peak rate of runoff from a drainage area. Typically, the design storms selected for flood control (i.e., 2-year, 10-year frequency, etc.) are specified by state and local ordinances, or are based on specific watershed conditions. In either case, the required volume to be stored above the permanent pool can be readily determined using the hydrologic methods discussed in **Chapter 4**. Similarly, a control or spillway structure can be designed using the engineering calculation procedures presented in **Chapter 5**.

<u>Channel Erosion Control</u>

The storage volume above the permanent pool can also be used to control or reduce channel erosion. Channel erosion protection can be accomplished by reducing the peak rate of discharge, similar to flood control, or by controlling the time over which the peak volume of discharge is released (extended detention), similar to water quality enhancement. **Chapter 5-11** provides a discussion on the design criteria for channel erosion control.

Conditions Where Practice Applies

<u>Drainage Area</u>

A contributing watershed of at least 10 acres and/or a good source of baseflow should be present for a retention basin to be feasible. Even with 10 acres of contributing watershed, the permanent pool may be susceptible to dry weather drawdowns due to infiltration and evaporation.

(Refer to **Chapter 5, Appendix 5C** for water balance calculation procedures.) Dry weather stagnation may result in aesthetic and odor problems for adjacent property owners. Therefore, for residential or high visibility applications, a minimum of 15 to 20 acres of contributing watershed may be more appropriate. Infiltration basins, trenches or extended-detention basins are more suitable for smaller sites.

A retention basin is recommended for use as a regional or watershed-wide stormwater management facility since its cost per acre treated is inversely proportional to the watershed size. Studies confirm that the most cost-effective application of a retention basin is on larger, more intensely developed sites (Schueler, et. al., 1985).

Note that excavated retention basins in areas of high groundwater, such as in Tidewater, Virginia, may be feasible with very small drainage areas. The groundwater elevation should be carefully monitored, however, to verify the design permanent pool elevation.

Development Conditions

Retention basins have the potential for removing high levels of soluble and particulate pollutants which makes them suitable for most types of development. They are appropriate for both high- and low- visibility sites. However, for high-visibility sites, care must be taken to avoid the aesthetic problems associated with stagnation or excessive infiltration of the permanent pool. Maintenance of the permanent pool is not necessarily critical to the retention basin's ability to remove pollutants, but maintenance **is critical** to ensure the BMP's acceptance by adjacent landowners. If adequate space is available, retention basins may also be used for both high and low density residential or commercial developments.

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A minimum 20-foot wide vegetated buffer should be provided around a retention basin to help filter out pollutants before they enter the basin. This requirement results in the need for more land, especially for those basins that may already be oversized to enhance their pollutant removal capabilities. It is for this reason that the use of large retention basins may not be a feasible option in developing watersheds where land is at a premium. This strengthens the argument for a regional or watershed approach to stormwater management. A regional retention or extended-detention basin is not only more cost-effective, it is also more likely to be installed on land that is not suitable for development. (It should be noted, however, that the environmental impacts and appropriate permits must still be considered for such an application.)

Planning Considerations

The success of a retention basin is dependent on the designer's ability to identify any site or downstream conditions that may affect the design and function of the basin. Above all, the facility should be compatible with both upstream and downstream stormwater systems, thus promoting a *watershed approach* in providing stormwater management.

Site Conditions

Existing site conditions should be considered in the design and location of a retention basin. Features such as topography, wetlands, structures, utilities, property lines, easements, etc., may impose constraints on the location or construction of the basin. Local government land use and zoning ordinances may also designate certain requirements.

All retention basins should be a minimum of 20 feet from any structure or property line (as required by local ordinances), and 100 feet from any septic tank/drainfield. (The designer should be aware that an impoundment of water may elevate the local water table which could adversely effect drainfields and structures.) Retention basins should be a minimum of 50 feet from any steep slope (greater than 15%). Alternatively, a geotechnical report must address the potential impact of any retention basin that is to be constructed on or near such a slope.

Additional considerations are as follows:

1. **Soils –**

   In the past, many designs were accepted based upon soils information compiled from available data, such as SCS soil surveys. While such a source may be appropriate for a pre-engineering feasibility study, final design and acceptance **should be based on an actual subsurface analysis and a permeability test**, accompanied by appropriate engineering recommenda- tions. The references listed at the end of this standard and at the end of **Minimum Standard 3.10, Infiltration Practices** provide more detailed information regarding the feasibility analysis of subsurface conditions for various soil types. Due to its complexity, this topic is not covered here. Note that the geotechnical study required for the embankment design (reference **Minimum Standard 3.01, Earthen Embankment**) will often provide adequate data to verify the soil's suitability for a retention basin.

   The goal of a subsurface analysis is to determine if the soils are suitable for a retention basin. The textural character of the soil horizons and/or strata units within the subsoil profile should be identified to at least 3 feet below the facility bottom. This information is used to verify the infiltration rate or permeability of the soil. For a retention basin, water inflow (base flow and groundwater) must be greater than water losses (infiltration and evaporation). If the infiltration rate of the soil is too high, then a retention basin may not be an appropriate BMP.

   Permeable soils are not suited for retention basins. The depth of the permanent pool can influence the rate at which water will infiltrate through the existing soil. The soil permeability may be such that the basin can support a shallow marsh or constructed wetland. However, as the depth of the permanent pool increases, the increased head or pressure on the soil may increase the infiltration rate. If necessary, a liner of clay, geosynthetic fabric, or other suitable material may be used in the basin (as specified by a geotechnical engineer). Refer to the design criteria for basin liners.

2. **Rock –**

A subsurface investigation should also identify the presence of rock or bedrock. Excavation of rock may be too expensive or difficult with conventional earth moving equipment, precluding the use of a basin. Blasting the rock for removal may be possible, but blasting may open seams or create cracks in the underlying rock, resulting in an unwanted drawdown of the permanent pool. Blasting of rock is not recommended unless a liner, as described above, is installed.

3. **Karst –**

In regions where Karst topography is prevalent, projects may require thorough soils investigations and specialized design and construction techniques. The presence of karst should be determined **during the planning phase of the project** since it may affect BMP selection, design, and cost.

4. **Existing Utilities–**

Most utility companies will not allow a permanent or temporary pool to be installed over their underground utility lines or right-of-ways. However, if such a site must be used, the designer should obtain permission from the utility company **before designing** the basin. The relocation of any existing utilities should be researched and the costs included in the overall basin cost estimate.

Environmental Impacts

1. **Wetlands –**

Large facilities and/or regional facilities naturally lend themselves to being placed in low lying, and usually environmentally sensitive, areas. Such locations often contain wetlands, shallow marshes, perennial streams, wildlife habitat, etc., and may be protected by state or federal laws. The owner or designer should investigate regional wetland maps and contact appropriate local, state, and federal agencies to verify the presence of wetlands, their protected status, and suitability for a retention basin at the location in question.

With careful planning, it may be possible to incorporate wetland mitigation into a retention basin design. This assumes that the functional value of the existing or impacted wetland can be identified and included, reconstructed, or mitigated for, in the basin. The Virginia Department of Environmental Quality should be contacted for more information regarding wetland mitigation.

2. **Downstream Impacts –**

A retention basin may have an adverse impact on downstream water quality by altering the biological oxygen demand (BOD), dissolved oxygen (DO), temperature, etc., of the water body. This is of special concern in cold water trout streams. The release depth of the control structure, overall pond depth, hydraulic residence time, and other design features can be manipulated to help meet the site specific needs of the downstream channel.

Urban detention and retention basin design should be coordinated with a watershed or regional plan for managing stormwater runoff, if available. In a localized situation, an individual basin can provide effective stream protection for the downstream property if no other areas contribute runoff in a detrimental way to that property. However, an uncontrolled increase in the number of impoundments within a watershed can severely alter natural flow conditions, causing combined flow peaks or increased flow duration. This can ultimately lead to downstream flooding and degradation.

3. **Upstream Impacts –**

The upstream channel must also be considered, especially when the retention basin is to be used to control downstream channel erosion. Erosive upstream flows will not only degrade the upstream channel, but will also significantly increase the maintenance requirements in the basin by depositing large amounts of sediment eroded from the channel bottom.

<u>Water Quality Enhancement</u>

A retention basin is typically selected for its water quality enhancement abilities and/or aesthetic value. The flexibility of providing for additional control components (channel erosion control, flood control, habitat, etc.) increases their value. The permanent pool of a retention basin serves to enhance the quality of the stormwater within it. Studies show that providing a larger permanent pool, and/or adding modifications such as an aquatic bench, sediment forebay, etc., will provide greater and more consistent pollutant removal benefits (refer to the **Design Criteria** section in this standard). Currently, no credit is given for any additional pollutant removal efficiency that may occur with an extended-detention volume stacked on top of the permanent pool of a retention basin. However, significant improvements in channel erosion control have been reported using extended-detention for the 1-year frequency design storm (Galli, MWCOG, 1992). Refer to **Minimum Standard 3.07, Extended Detention Basins**.

A concern in specifying a retention basin is how much land it will occupy. The size of the permanent pool will be based on the desired pollutant removal efficiency. The "dry" storage volume above the permanent pool will be sized for downstream channel erosion and/or flood control. The size of these two components together will determine the size of the basin.

Preliminary sizing estimates for the permanent pool and "dry" storage volume are recommended during the planning stages to evaluate the feasibility of using a retention basin.

If a retention basin is used to remove pollutants, the water quality within the basin will be lowered, thus possibly reducing its desirability for water supply, recreation, and aesthetic purposes. Therefore, the engineer should be aware of the site's specific runoff components and understand their possible effects on the quality of the stored water. Runoff from highways and streets can be expected to carry significant concentrations of heavy metals such as lead, zinc, and copper. These and other heavy metals may accumulate in the bottom of a facility, creating a potential health and environmental hazard. If a basin is in a watershed where a significant portion of the runoff is from highways, streets or parking areas, then access to the facility should be limited and warning signs should be posted. Proper disposal of the bottom sediments from these basins may require that they be hauled to an approved facility.

Further, retention basins in residential areas are subject to nutrients from lawn fertilizers and other urban sources. Excess nutrients can lead to algae and other undesirable vegetation which can diminish the aesthetic and recreational value of the basin.

Flooding and Channel Erosion Control

Flood control and downstream channel erosion are managed by providing additional storage volume, referred to as dry storage, above the permanent pool, and properly sizing a discharge opening in the riser structure.

When a retention basin is designed for channel erosion control and/or flood control, but **not** water quality enhancement, the permanent pool volume should be sized to address maintenance, aesthetic, and feasibility concerns (adequate drainage area, etc.).

Sediment Control

A stormwater retention basin may initially serve as a sediment control basin during the project's construction. A sediment basin is designed for the maximum drainage area expected to contribute to the basin during the construction process, while a permanent stormwater basin is designed based on post-developed land use conditions. When designing a facility to do both, the basin should be sized using the most stringent criteria, sediment control or stormwater management, which will result in the largest storage volume. The design elevations should be set with final clean out and conversion in mind. The bottom elevation of the permanent SWM basin should be lower than the design bottom of the temporary E&S basin. This allows for the establishment of a solid permanent bottom after sediment is removed from the facility.

The riser and barrel hydraulics and materials should be designed as the permanent stormwater control structure. However, the permanent riser may be temporarily modified to provide a sediment basin with wet and dry storage as required by the Virginia Erosion and Sediment Control Handbook, (VESCH), 1992 edition.

Safety

Basins that are readily accessible to populated areas should include all possible safety precautions. Steep side slopes (steeper than 3H:1V) at the perimeter should be avoided and dangerous outlet structures should be protected by enclosures. Warning signs for deep water and potential health risks should be used wherever appropriate. Signs should be placed so that at least one is clearly visible and legible from all adjacent streets, sidewalks or paths. A notice should be posted warning residents of potential waterborne disease that may be contracted by swimming or diving in these facilities.

If the basin's surface area exceeds 20,000 square feet, an aquatic bench should be provided. (Refer to the **Design Criteria for Aquatic Bench**.)

A fence is **required** at or above the maximum water surface elevation **when a basin slope is a vertical wall**. Local governments and homeowner associations may also require appropriate fencing without regard for the steepness of the basin side slopes.

Maintenance

Retention basins have shown an ability to function as designed for long periods without routine maintenance. However, some maintenance is essential to protect the aesthetic and wildlife properties of these facilities.

Vehicular access to the permanent pool area and release structure must be provided to allow for long-term maintenance operations (such as sediment removal) and repairs, as needed. The incorporation of a *sediment forebay* at the inflow points into the basin will help to localize disturbance during sediment removal operations. An onsite area designated for sediment dewatering and disposal should also be included in the design. Care must be taken in the disposal of sediment that may contain an accumulation of heavy metals. **Sediment testing is recommended prior to sediment removal to assure proper disposal**.

A sign should be posted near the basin that clearly identifies the person or organization responsible for basin maintenance. Allowing participation by adjacent landowners or visitors is very helpful, especially if the facility serves as a recreational facility. Maintenance needs that are observed and addressed early will help to lower the overall maintenance costs. Routine maintenance inspections, however, should be conducted by authorized personnel. In all cases, access easements should be provided to facilitate inspection and maintenance operation.

Design Criteria

This section provides recommendations and minimum criteria for the design of stormwater retention basins intended to comply with the Virginia Stormwater Management program. It is the designer's responsibility to decide which aspects of the program apply to the particular facility being designed and if any additional design elements are required. The designer should also consider the long-term functioning of the facility in the selection of materials for the structural components.

Hydrology and Hydraulics

Chapter 4, **Hydrologic Methods** and **Chapter 5**, **Engineering Calculations** should be used to develop the pre- and post-developed hydrology for a basin's contributing watershed, to design and analyze the hydraulics of the riser and barrel system, and to design the emergency spillway.

The design of the riser and barrel system should take into account any additional storage provided above the permanent pool for peak discharge control. Generally, the 2-year storm should be used in *receiving channel adequacy* calculations and the 10-year storm should be used for *flood control* calculations. Alternative requirements such as 1-year extended detention for channel erosion control may be imposed by local ordinances.

The contributing drainage area should be a minimum of 10 acres with an adequate base flow. Fifteen to 20 acres is more appropriate to sustain a healthy permanent pool. Note that this requirement may preclude the use of the Modified Rational Method for the basin's design.

Embankment

The design of the earthen embankment for a retention basin should comply with **Minimum Standard 3.01, Earthen Embankment**. The requirements for geotechnical analysis, seepage control, maximum slopes and freeboard are particularly appropriate.

Principal Spillways

The design of the principal spillway and barrel system, anti-vortex device, and trash racks should comply with **Minimum Standard 3.02, Principal Spillway**.

Emergency Spillway

An emergency spillway that complies with **Minimum Standard 3.03, Vegetated Emergency Spillway** should be provided when possible, or appropriate.

Sediment Basin Conversion

When a proposed stormwater facility is used as a temporary sediment basin, the conversion to the permanent facility should be completed after final stabilization and approval from the appropriate erosion and sediment control authority.

In most cases the design criteria for the temporary sediment basin will require more storage volume (combined wet and dry) than that of a stormwater basin. In such cases, the extra volume should be allocated to the component of the facility that would derive the greatest benefit from the increased storage. This will depend on the primary function of the facility (i.e., water quality enhancement, flood control, or channel erosion control).

If modifications to the riser structure are required as part of the conversion to a permanent stormwater facility, they should be designed so that a) *the structural integrity of the riser is not threatened*, and b) *large construction equipment is not needed within the basin*. Any heavy construction work required on the riser should be completed during its initial installation. It is **NOT** recommended to install a temporary riser structure in the sediment basin and then replace it with a permanent riser after final stabilization. This may affect the structural integrity of the existing embankment and barrel.

The following additional criteria should be considered for a conversion:

1. Final elevations and a complete description of any modifications to the riser structure's geometry should be shown in the approved plans.

2. The wet storage area must be dewatered following the methods outlined in the VESCH, 1992 edition.

3. Sediment and other debris should be removed to a contained spoil area. Regrading of the basin may be necessary to achieve the final design grades and to provide an adequate topsoil layer to promote final stabilization.

4. Final modifications to the riser structure should be carefully inspected for watertight connections and compliance with the approved plans.

5. Final landscaping and stabilization should be per the VESCH, 1992 edition, and **Minimum Standard 3.05, Landscaping** in this handbook.

Permanent Pool

When designing a permanent pool for water quality benefits, certain physical and hydraulic factors can be manipulated to achieve a desired *pollutant removal efficiency*. These factors, which also influence the downstream water quality, include the permanent pool's *volume*, *depth*, *geometry*, *hydraulic residence time*, and *release depth*.

1. **Volume –**

Increasing the *volume* of the permanent pool increases the *residence time*, resulting in an increase in the pollutant removal efficiency of the permanent pool. **Table 3.06-1** provides the target pollutant removal efficiencies associated with different sizing rules.

2. **Depth –**

The *depth* of the permanent pool will affect several features of a retention basin including a) *aquatic plant selection*, b) *fish and wildlife habitat selection*, and c) *the rate at which nutrients are cycled*. Retention basins and artificial marshes built too shallow will not support fish populations year round. Basins built too deep may stratify, creating anaerobic conditions that may result in the resolubilizing of pollutants that are normally bound in the sediment. The release of such pollutants back into the water column can seriously reduce the effectivenes of the BMP and may cause nuisance conditions.

The depth of a stormwater management basin should vary to include as much diversity as possible, with an average depth of 3 to 6 feet. Approximately 15% of the basin area should be less than 18 inches deep. (Schueler, 1987). This can be accomplished by using an aquatic bench along the perimeter of the permanent pool as shown in **Figure 3.06-2**. **Table 3.06-2** below provides recommended surface area - pool depth relationships.

TABLE 3.06 - 2
Recommended Surface Area - Pool Depth Relationships for Retention Basins

BMP	**Pool Depth (*ft.*)**	**Surface Area (*as % of total BMP surface area*)**
Retention Basin	0 - 1.5 1.5 - 2 2 - 6	15% 15% 70%

Source: Washington State D.O.E.

3. **Geometry –**

The geometry of a stormwater basin and the associated drainage patterns are usually dictated by site topography and development conditions. However, the alignment of the incoming pipes should be manipulated relative to the release structure to the greatest extent possible to avoid *short-circuiting* of the incoming runoff. *Short-circuiting* is the condition where incoming runoff passes through the basin without displacing the old water. This can be avoided by maximizing the distance between the inlet and outlet structures. It can also be avoided by designing a *meandering* flow path through the basin, rather than a straight line flow path. In either case, a length-to-width ratio of 2:1 should be maintained. If site conditions prevent using the proper ratio, then baffles made from gabion baskets, earthen berms or other suitable materials may be used to lengthen the flow path (see **Figure 3.06-3**).

A retention basin should be multi-celled with at least two cells and preferably three. The first cell can be used as a sediment forebay to trap coarse sediments and reduce turbulence that may cause resuspension of sediments. This first cell should be easily accessible for maintenance purposes. The second (and third) cell provides for the further settling of pollutants and any biological processes.

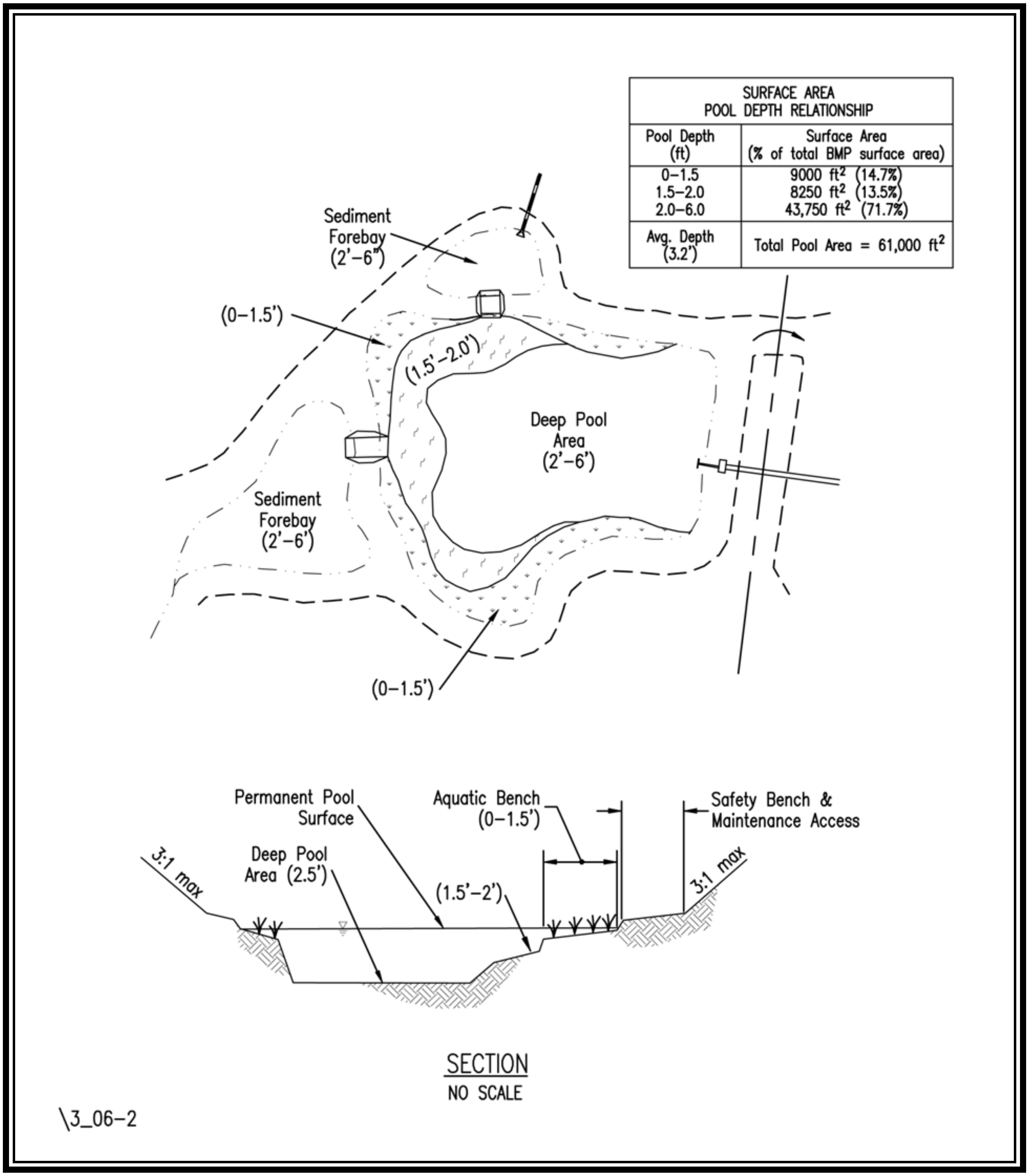
4. **Hydraulic Residence Time –**

Hydraulic residence time is the permanent pool volume divided by the average outflow discharge rate. The longer the residence time, the higher the pollutant removal efficiency (Driscoll, 1983, Kulzer, 1989). A retention basin used for channel erosion control and flood control will usually achieve higher pollutant removal rates. This is due to the increased residence time associated with the peak discharge control above the permanent pool. The hydraulic residence time would be a factor in the design of a retention basin with a permanent pool volume based on an impervious area which is relatively small when compared to the contributory drainage area. In this case, the total drainage area discharge will turn over, or replace, the volume of the "undersized" pool volume before it has achieved an adequate residence time. Optimal pollutant removal efficiency is generally associated with a *mean annual hydraulic residence* time of 14 to 30 days (Driscoll, 1988; Kulzer, 1989; Schueler, 1987).

5. **Release Depth –**

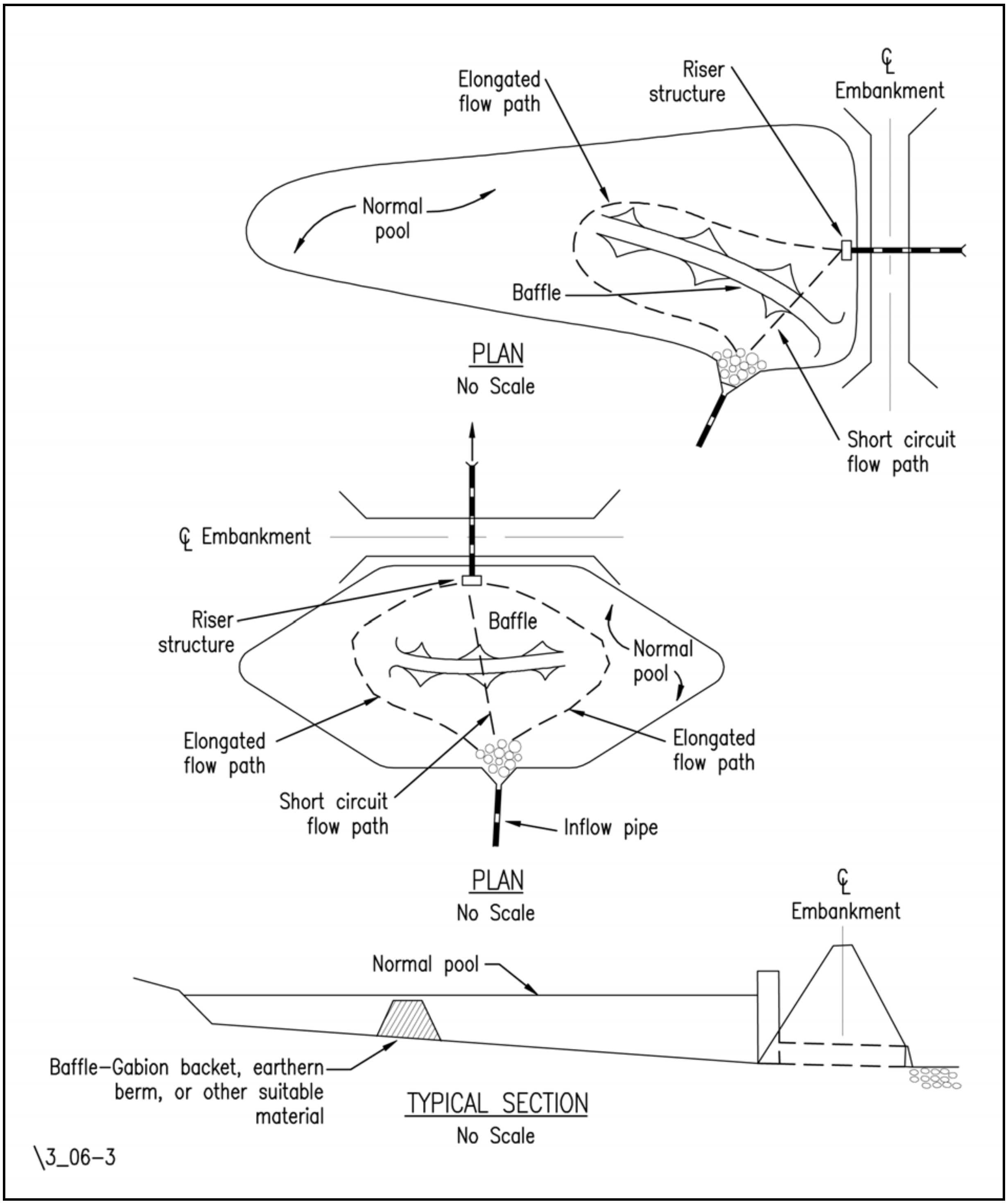
The best water quality in a retention basin's permanent pool is usually at or near the surface (Galli, 1988; Redfield, 1983). Under normal dry weather conditions, the concentrations of total dissolved solids, phosphorus, and nitrogen generally decrease in the upper portions of the water column due to physical settling and algal and biological assimilation (Galli, 1992). This suggests that <u>subsurface</u> releases have high levels of nutrients and suspended solids. In addition, deeper basins usually have very low levels of dissolved oxygen in the bottom portions of the water column.

FIGURE 3.06 - 2
Varying Depth of Permanent Pool



SURFACE AREA POOL DEPTH RELATIONSHIP	
Pool Depth (ft)	Surface Area (% of total BMP surface area)
0–1.5 1.5–2.0 2.0–6.0	9000 ft² (14.7%) 8250 ft² (13.5%) 43,750 ft² (71.7%)
Avg. Depth (3.2')	Total Pool Area = 61,000 ft²

FIGURE 3.06 - 3
Short-Circuiting

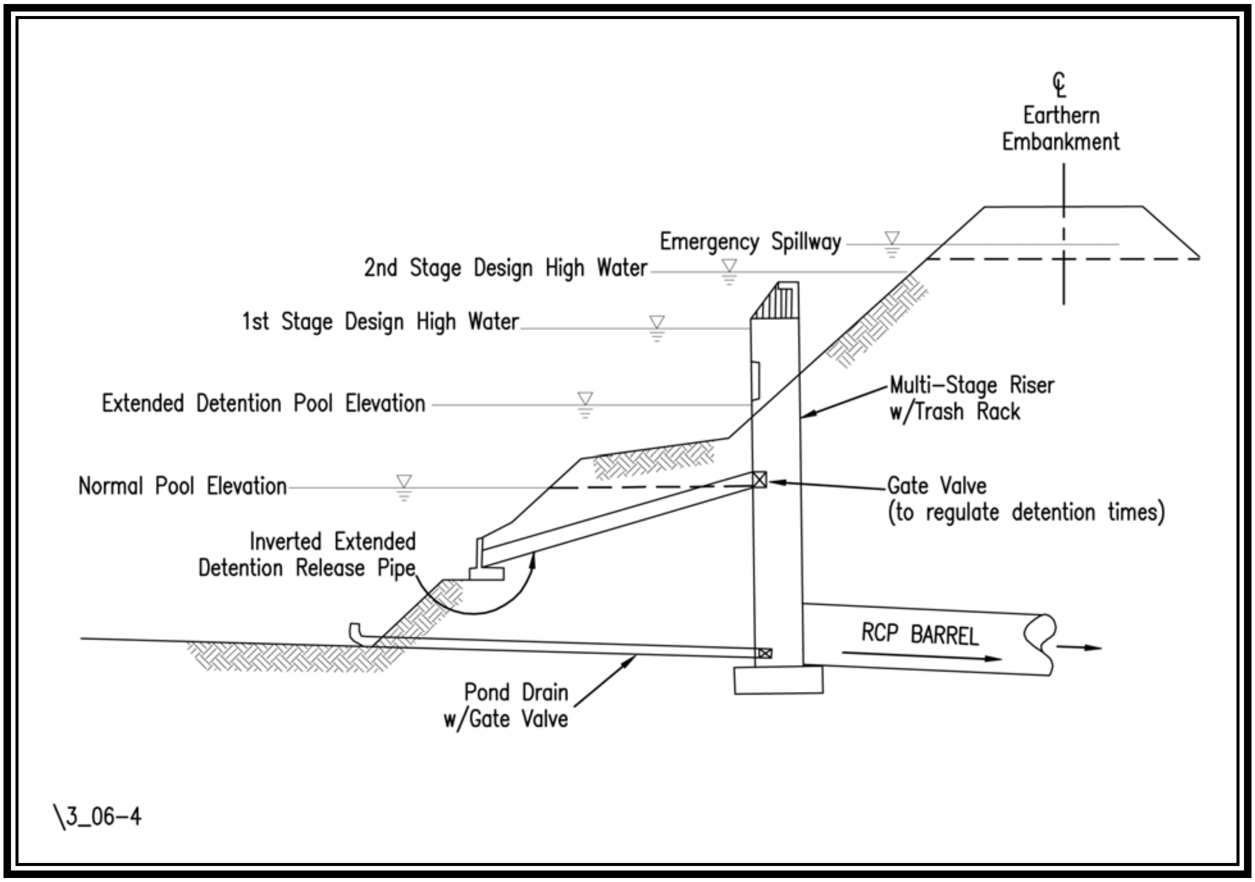


In contrast, the water at or near the surface of a retention basin is warmer because of solar heating of the basin and heated stormwater inflow. This resembles the cycling process of water in natural lakes and water bodies. However, the proximity of a retention basin to development (i.e., impervious surfaces) may lead to an excessive heat buildup from the incoming runoff during the warmer months. Therefore, a release depth of approximately 18 inches from the water surface is recommended (Galli, 1992) to avoid extremes in temperature, nutrient levels, and dissolved oxygen (see **Figure 3.06-4**).

It should be noted that inexpensive design modifications can be incorporated into the design of a retention facility to mitigate downstream impacts such as: a) *oversizing the barrel and adding surgestone or rip rap to the invert to help re-aerate the basin discharge* (Schueler, 1987), and b) *providing shade by planting (or saving) trees around the perimeter of the basin to help lower surface water temperature*.

If the receiving stream supports a trout population, the designer should contact the Department of Game and Inland Fisheries for additional measures to protect the downstream habitat.

FIGURE 3.06 - 4
Typical Retention Basin Control Structure



Aquatic Bench

The pollutant removal efficiency of a retention basin can be further enhanced by adding an *aquatic bench*. An aquatic bench is a 10 to 15 foot wide area that slopes from zero inches at the shoreline to between 12 and 18 inches deep in the basin (see **Figure 3.06-5**). This bench provides suitable conditions for a variety of aquatic plants and emergent vegetation. Specific landscaping requirements for an aquatic bench should be provided on the landscaping plan per **Minimum Standard 3.05, Landscaping**.

Most important, an aquatic bench augments the pollutant removal capabilities of a retention basin by providing an environment for aquatic vegetation and associated algae, bacteria and other microorganisms that reduce organic matter and nutrients (Schueler, 1987). In addition, aquatic bench vegetation provides an ideal habitat for wildlife, such as waterfowl and fish, and for predator insects that feed on mosquitoes and other nuisance insects.

An aquatic bench also serves to stabilize and protect the shoreline from erosion resulting from fluctuating water levels, and provides a safety feature by eliminating the presence of a steep submerged slope next to the shoreline.

The increase in pollutant removal efficiency associated with the establishment of an aquatic bench is **approximated** based on available information. Note that discharge monitoring may indicate much higher or lower values since many variables exist in any given stormwater basin design and the efficiencies are estimated.

Sediment Forebay

A *sediment forebay* will help to postpone overall basin maintenance by trapping incoming sediments at a specified location. The forebay should be situated and designed per **Minimum Standard 3.04, Sediment Forebays**. Usually, a sediment forebay is placed at the outfall of the incoming storm drain pipes or channels directed toward the basin and is situated to provide access for maintenance equipment.

A sediment forebay enhances the pollutant removal efficiency of a basin by trapping the incoming sediment load in one area, where it can be easily monitored and removed. The *target pollutant removal efficiency* of a retention basin, as listed in **Table 3.06-1**, is predicated on the use of sediment forebays at the inflow points to the basin.

Liner to Prevent Infiltration

A retention basin should have negligible infiltration through its bottom. Infiltration may impair the proper functioning of the basin and may contaminate groundwater. Where infiltration is anticipated, or in areas underlain by karst topography then a retention or detention facility should **not** be used unless an impervious liner is installed. When using a liner, the specifications provided in **Table**

3.06-3 for clay liners and the following recommendations apply:

1. A clay liner should have a minimum thickness of 12 inches.

2. A layer of compacted topsoil (minimum thickness 6 to 12 inches) should be placed over the liner before seeding with an appropriate seed mixture (refer to the VESCH, 1992 edition.)

3. Other liners may be used provided the engineer can supply supporting documentation that the material will achieve the required performance.

In many cases, the fine particulates and suspended solids in the water column of a new retention basin will settle out and quickly clog the the pores of the bottom soil. However, a geotechnical analysis should address the potential for infiltration and, if needed, specify liner materials.

Safety

The side slopes of a retention basin should be no steeper than 3H:1V and should be stabilized with permanent vegetation. If the basin surface exceeds 20,000 square feet, an aquatic bench should be provided to serve as a safety feature. Fencing may also be required by local ordinance.

Access

A 10 to 12-foot-wide access road with a maximum grade of 12% should be provided to allow vehicular access to both the outlet structure area and at least one side of the basin. The road's surface material should be selected to support the anticipated frequency of use and the anticipated vehicular load without excessive erosion or damage.

TABLE 3.06 - 3
Clay Liner Specifications

Property	Test Method (or equal)	Unit	Specification
Permeability	ASTM D-2434	*cm/sec*	1×10^{-6}
Plasticity Index of Clay	ASTM D-423 & D-424	%	Not less than 15
Liquid Limit of Clay	ASTM D-2216	%	Not less than 30
Clay Particles Passing	ASTM D-422	%	Not less than 30
Clay Compaction	ASTM D-2216	%	95% of Standard Proctor Density

Source: City of Austin, 1988

Landscaping

A qualified individual should prepare the landscape plan for a retention basin. Appropriate *shoreline fringe*, *riparian fringe* and *floodplain terrace vegetation* must be selected to correspond with the expected frequency and duration of inundation. Selection and installation guidelines should be per **Minimum Standard 3.05, Landscaping**.

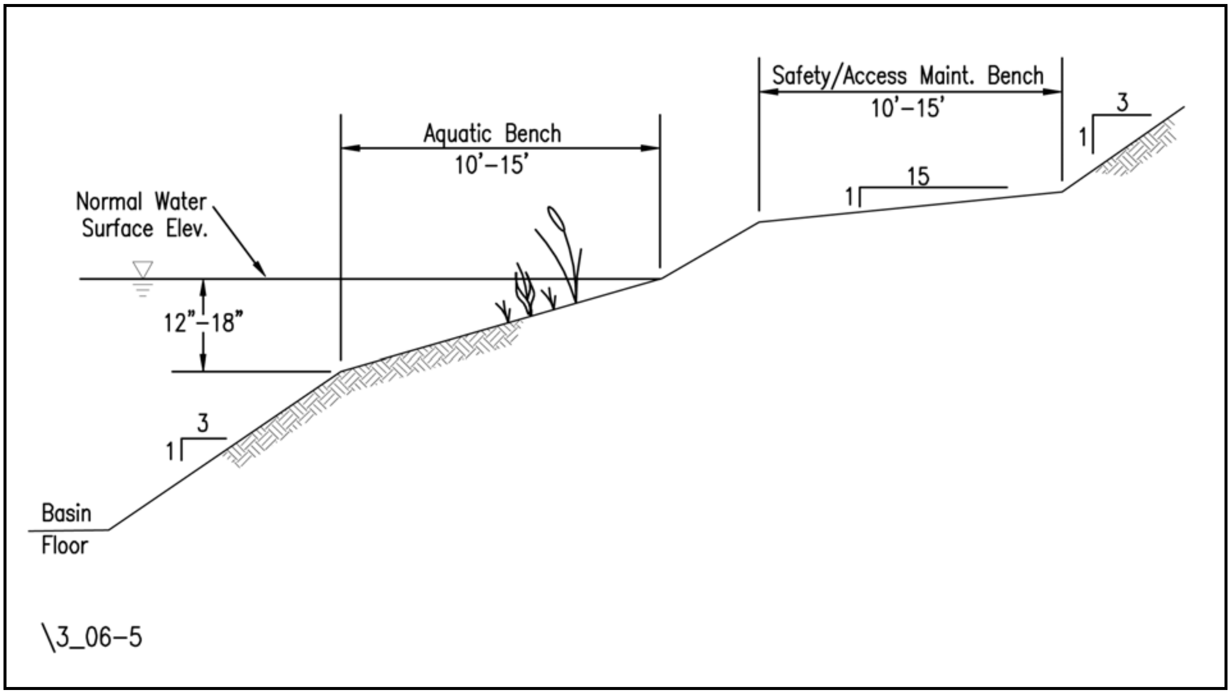
Vegetation should be planted in soil that is appropriate for the plants selected. Soil tests showing the adequacy of the soil or a soil enhancement plan should be submitted with the overall basin design.

The soil substrate must be soft enough to permit easy installation of the plants. If the basin soil has been compacted or vegetation has formed a dense root mat, the upper 6 inches of soil should be disked before planting. If soil is imported, it should be laid at least 6 inches deep to provide sufficient depth for plant rooting to occur.

Buffer Zones

A vegetated buffer strip should be maintained beside the basin. The strip should be a minimum of 20 feet wide, as measured from the maximum water surface elevation. Refer to **Minimum Standard 3.05, Landscaping**.

FIGURE 3.06 - 5
Typical Retention Basin Aquatic Bench - Section



Construction Specifications

The construction specifications for stormwater retention basins outlined below should be considered minimum guidelines. More stringent or additional specifications may be required based on individual site conditions.

Overall, widely accepted construction standards and specifications for embankment ponds and reservoirs, such as those developed by the USDA Soil Conservation Service or the U.S. Army Corps of Engineers, should be followed to build an impoundment.

Further guidance can be found in Chapter 17 of the Soil Conservation Service's Engineering Field Manual. Specifications for the work should conform to methods and procedures indicated for installing earthwork, concrete, reinforcing steel, pipe, water gates, metal work, woodwork and masonry and any other items that are apply to the site and the purpose of the structure. The specifications should also satisfy any requirements of the local plan approving authority.

The following minimum standards contain guidance and construction specifications for various components of retention basins: **3.01, Earthen Embankment**; **3.02, Principal Spillway**; **3.03, Vegetated Emergency Spillway**; **3.04, Sediment Forebay**; and **3.05, Landscaping**.

Maintenance and Inspections

The following maintenance and inspection guidelines are not intended to be all-inclusive. Specific facilities may require other measures not discussed here. The engineer is responsible for determining if any additional items are necessary.

Inspecting and maintaining the structures and the impoundment area should be the responsibility of either the local government, a designated group such as a homeowner's association or an individual. A specific maintenance plan should be formulated outlining the schedule and scope of maintenance operations.

Any standing water pumped during the maintenance operation must be disposed of per the VESCH, 1992 edition and any local requirements.

General Maintenance

Maintenance and inspection guidelines found in the following minimum standards apply: **3.01, Earthen Embankment**; **3.02, Principal Spillway**; **3.03, Vegetated Emergency Spillway**; **3.04, Sediment Forebay**; and **3.05: Landscaping**.

Vegetation

The basin's side slopes, embankment and emergency spillway should be mowed at least twice a year to discourage woody growth. For aesthetic purposes, more frequent mowing may be necessary in residential areas

Specific plant communities may require different levels of maintenance. Upland and floodplain terrace areas, grown as meadows or forests, require very little maintenance, while aquatic or emergent vegetation may need periodic thinning or reinforcement plantings. Note that after the first growing season, it should be obvious if reinforcement plantings are needed. If they are, they should be installed at the onset of the second growing season after construction.

Research indicates that for most aquatic plants the uptake of pollutants is stored in the roots, not the stems and leaves (Lepp 1981). Therefore, aquatic plants should not require harvesting before winter plant die-back. There are still many unanswered questions about the long term pollutant storage capacity of plants. It is possible that aquatic and emergent plant maintenance recommendations may be presented in the future.

Debris and Litter Removal

Debris and litter will accumulate near the inflow points and around the outlet control structure. Such material should be removed periodically. Also, as the water level rises during storm events, floatables accumulate around the grate or trash rack of the control structure. If a flat horizontal trash rack is used, floating debris will become lodged on the trash rack, which will remain clogged until it is manually cleaned. A significant accumulation can clog the riser structure. The use of an angled trash rack is recommended to allow any accumulated debris to slide off as the water level drops.

Sediment Removal

Sediment deposition should be continually monitored in the basin. Removal of any accumulated sediment, in the sediment forebay or elsewhere, is extremely important. A significant accumulation of sediment impairs the pollutant removal capabilities of the basin by reducing the permanent pool volume. The deposited sediment also becomes prone to resuspension during heavy flow periods. Unless unusual conditions exist, accumulated sediment should be removed from the sediment forebay and possibly other deep areas within the permanent pool every 5 to 10 years. The use of a sediment forebay with access for heavy equipment will greatly simplify the removal process. **During maintenance procedures, ensure that any pumping of standing water or dewatering of dredged sediments complies with the VESCH, 1992 edition, and any local requirements**.

Owners, operators, and maintenance authorities should be aware that significant concentrations of heavy metals (e.g., lead, zinc and cadmium) and some organics, such as pesticides, may be expected to accumulate at the bottom of a retention basin. Testing of sediment, especially near points of inflow, should be conducted regularly and **before disposal** to establish the leaching potential and level of accumulation of hazardous materials. Disposal methods must comply with applicable state and local regulations (e.g., for special waste).

<u>Inspections</u>

A retention basin and its components should be inspected annually, at a minimum, to ensure that they operate in the manner originally intended. Items in need of repair should be addressed promptly and as specified in the comprehensive maintenance program. Detailed inspections by qualified person(s) should address the following areas/concerns:

- Dam settling, woody growth, and signs of piping
- Signs of seepage on the downstream face of the embankment
- Condition of grass cover on the embankment, basin floor and perimeter
- Riprap displacement or failure
- Principal and emergency spillway meet design plans for operation
- Outlet controls, debris racks and mechanical and electrical equipment
- Outlet channel conditions
- Inlet pipe conditions
- Safety features of the facility
- Access for maintenance equipment
- Sediment accumulation
- Debris and trash accumulation
- Erosion of the embankment or side slopes

Design Procedures

1. Determine if the anticipated development conditions and drainage area are appropriate for a stormwater retention basin BMP.

   C Minimum drainage area of 10 acres and/or base flow

2. Determine if the soils (permeability, bedrock, Karst, embankment foundation, etc.) and topographic conditions (slopes, existing utilities, environmental restrictions) are appropriate for a stormwater retention basin BMP.

3. Determine any additional stormwater management requirements (channel erosion, flooding) for the project.

4. Locate the stormwater retention basin on the site.

5. Determine the hydrology and peak discharges of the contributory drainage area for each of the required design storms (**Chapter 4, Hydrologic Methods**).

6. Calculate the permanent pool volume and approximate storage volume requirements (**Chapter 5, Engineering Calculations**).

7. Design the embankment (**Min. Std. 3.01**), principal spillway (**Min. Std. 3.02**), emergency spillway (**Min. Std. 3.03**), sediment forebay (**Min. Std. 3.04**), landscaping plan (**Min. Std. 3.05**), and the permanent pool and other components of a stormwater retention basin BMP (**Min. Std. 3.06**) using **Chapter 5, Engineering Calculations**, and the Minimum Standards listed.

   - permanent pool depth
   - Permanent pool geometry
   - release depth
   - aquatic bench
   - pond drain

8. Design final grading of basin.

   - landscape plan
   - 20-foot buffer area
   - safety (3:1 slopes with bench)
   - access

9. Establish specifications for sediment control and sediment basin conversion (if required).

10. Establish construction sequence and construction specifications.

11. Establish maintenance and inspection requirements.

Checklists

Refer to **Appendix-3A** for **Design and Plan Review**, **Construction Inspection**, and **Operation and Maintenance** Checklists.

REFERENCES

American Society of Civil Engineers. "Stormwater Detention Outlet Control Structures." Task Commission on the Design of Outlet Control Structures. New York, NY:ASCE, 1985.

Brater, E.F. and H.W. King. Handbook of Hydraulics. 6th ed. New York: McGraw Hill Book Company, 1976.

Chesapeake Bay Local Assistance Department (CBLAD). Local Assistance Manual: A Guide for the Development of Local Programs in Order to Comply with the Chesapeake Bay Preservation Act. Richmond, Virginia: November 1989.

Debo, T.N. and Reese, A. J. Municipal Stormwater Management. 1995.

Federal Highway Administration. "Debris-Control Structures." Hydraulic Engineering Circular No. 9, 1971.

Federal Highway Administration. Retention, Detention and Overland Flow for Pollutant Removal from Highway Stormwater Runoff: Interim Guidelines for Management Measures. Pub. No. FHWA/RD-87/056. McLean, Virginia: March, 1988.

Galli, J. Analysis of Urban BMP Performance and Longevity in Prince George's County, Maryland. Washington, D.C.: Metropolitan Washington Council of Governments (MWCOG), August, 1992.

Maryland Department of Natural Resources (Md. DNR). Guidelines for Constructing Wetland Stormwater Basins. Annapolis, Maryland: Water Resources Administration, March, 1987.

Maryland Department of Natural Resources (Md. DNR). Wetland Basins for Stormwater Treatment; Discussion and Background. Annapolis, Maryland: Water Resources Administration, undated.

McCuen, R.H. "Design Accuracy of Stormwater Detention Basins." Technical Report, Department of Civil Engineering, University of Maryland, 1983.

Northern Virginia Planning District Commission. Northern Virginia BMP Handbook. 1992.

Perham, R.E. "Floating Debris Control: A Literature Review." Hanover, NH: U.S. Army CREL, 13, 1987.

Poertner, H.G. "Practices in the Detention of Urban Stormwater Runoff." American Public Works Association, OWWR Proj. C-3380, 1974.

Schueler, T.R., P.A. Kumble, and M.A. Heraty, A Current Assessment of Urban Best Management Practices. Washington, D.C.: Metropolitan Washington Council of Governments (MWCOG), March 1992.

Schueler, T.R. Design of Stormwater Wetland Systems: Guidelines for Creating Diverse and Effective Stormwater Wetland Systems in the Mid-Atlantic Region. Washington, D.C.: Metropolitan Washington Council of Governments, October, 1992.

Schueler, T.R. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Washington, D.C.: Metropolitan Washington Council of Governments, July, 1987.

Smith, P.H. and J.S. Cook, "Stormwater Management Detention Pond Design Within Floodplain Areas." Trans., Res. Record 1017, 1987.

Stahre, P. and B.Urbonas. "Stormwater Detention." Prentice Hall, 1990.

State of Maryland. "Design Procedures for Stormwater Management Detention Structures." Department of the Environment, Sediment and Stormwater Division, 1987.

U. S. Department of the Interior, Bureau of Reclamation. Design of Small Dams. 1987.

USDA Soil Conservation Service. Engineering Field Manual.

USDA Soil Conservation Service. National Engineering Handbook.

Virginia Department of Conservation and Recreation (DCR). Virginia Erosion and Sediment Control Handbook (VESCH). 3rd. ed. Richmond, Virginia: 1992.

Washington State Department of Ecology. "Stormwater Management Manual for the Puget Sound Basin." 1992.

Retention basin with small island.

Retention basin in ultra-urban setting (under construction).

Retention Basin

Chapter 3.06

Retention basin – Note flat slopes with “rough” edge and aquatic bench provided as safety and pollutant removal features.

Retention Basin

MINIMUM STANDARD 3.07

EXTENDED-DETENTION BASIN
&
ENHANCED EXTENDED-DETENTION BASIN

View BMP Images

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MINIMUM STANDARD 3.07

EXTENDED-DETENTION BASIN & *ENHANCED* EXTENDED-DETENTION BASIN

Definition

An extended-detention basin is an impoundment that temporarily stores runoff for a specified period and discharges it through a hydraulic outlet structure to a downstream conveyance system. An extended-detention basin is usually dry during non-rainfall periods.

Purpose

An extended-detention basin can be designed to provide for one, or all, of the following: a) *water quality enhancement*, b) *downstream flood control*, and c) *channel erosion control*.

Water Quality Enhancement

An **extended-detention basin** improves the quality of stormwater runoff through gravitational settling. However, due to frequent high inflow velocities, settled pollutants often get resuspended.

An ***enhanced*** **extended-detention basin** has a higher efficiency than an extended-detention basin because it incorporates a shallow marsh in its bottom. The shallow marsh provides additional pollutant removal through *wetland plant uptake*, *absorption*, *physical filtration*, and *decomposition*. The shallow marsh vegetation also helps to reduce the resuspension of settled pollutants by trapping them.

The target pollutant removal efficiencies for both extended-detention and *enhanced* extended-detention basins are presented in **Table 3.07-1**. The target pollutant removal efficiencies are based on certain design criteria associated with the physical characteristics of the basin, and shallow marsh, when used.

FIGURE 3.07 - 1a
Extended-Detention Basin - Plan

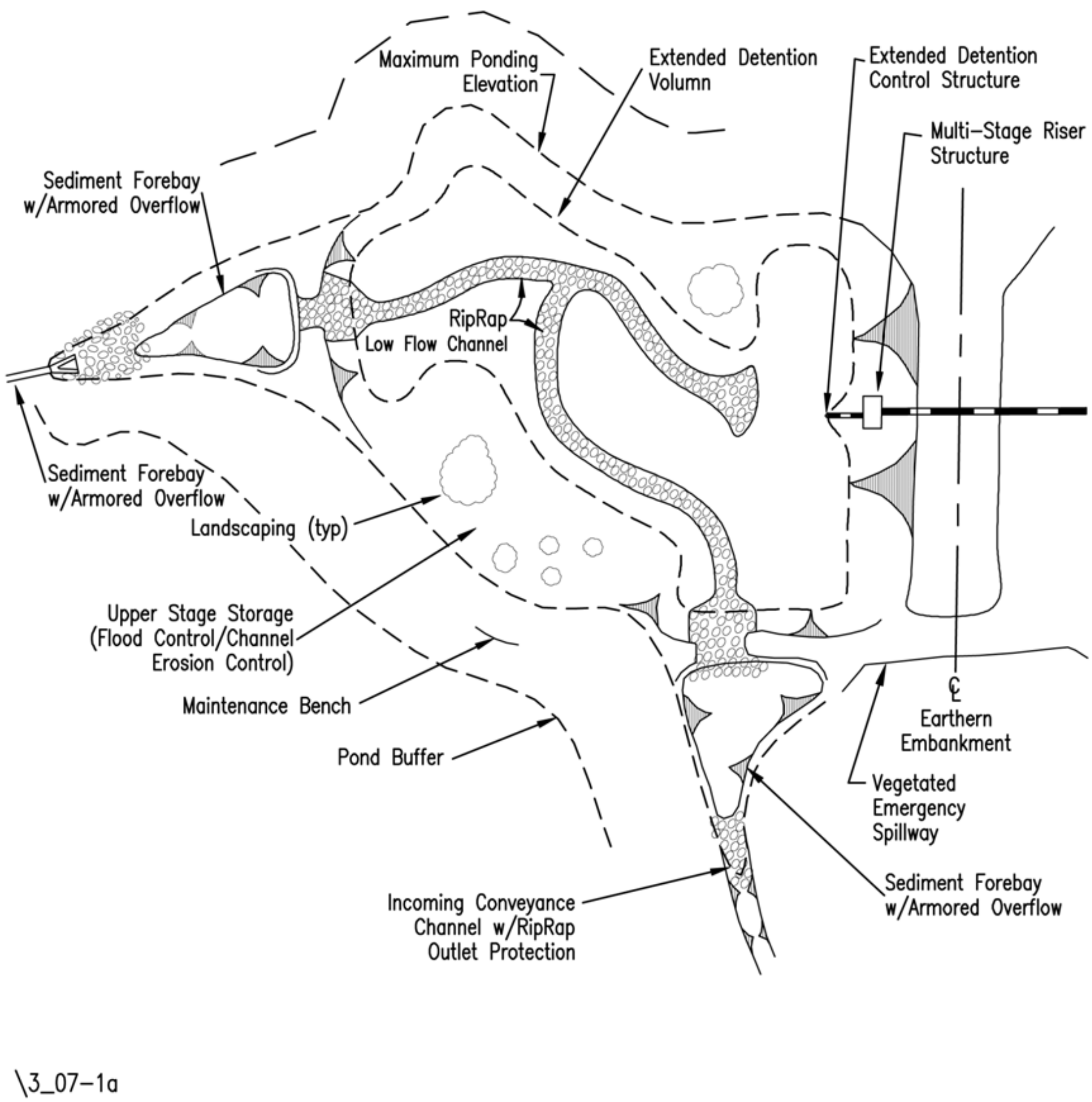
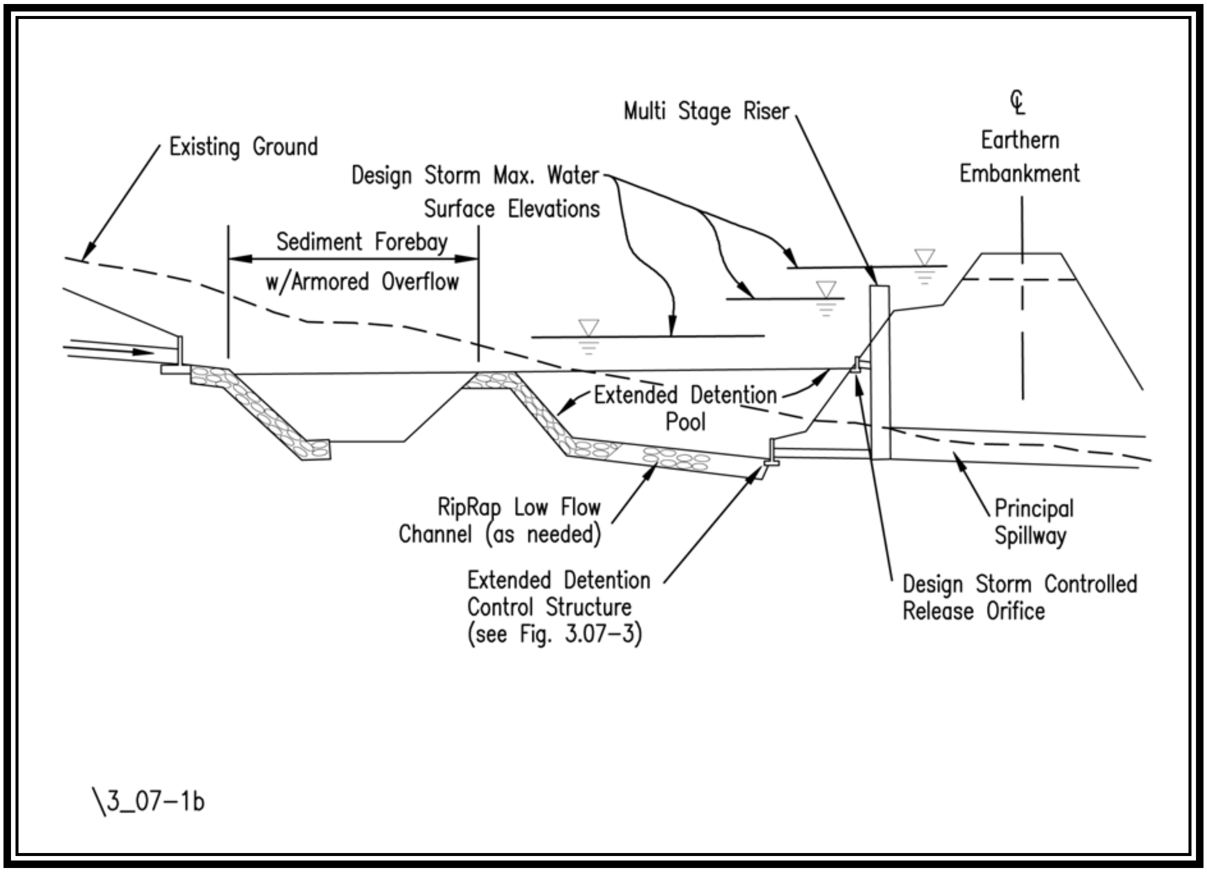


FIGURE 3.07-1b
Extended-Detention Basin - Section

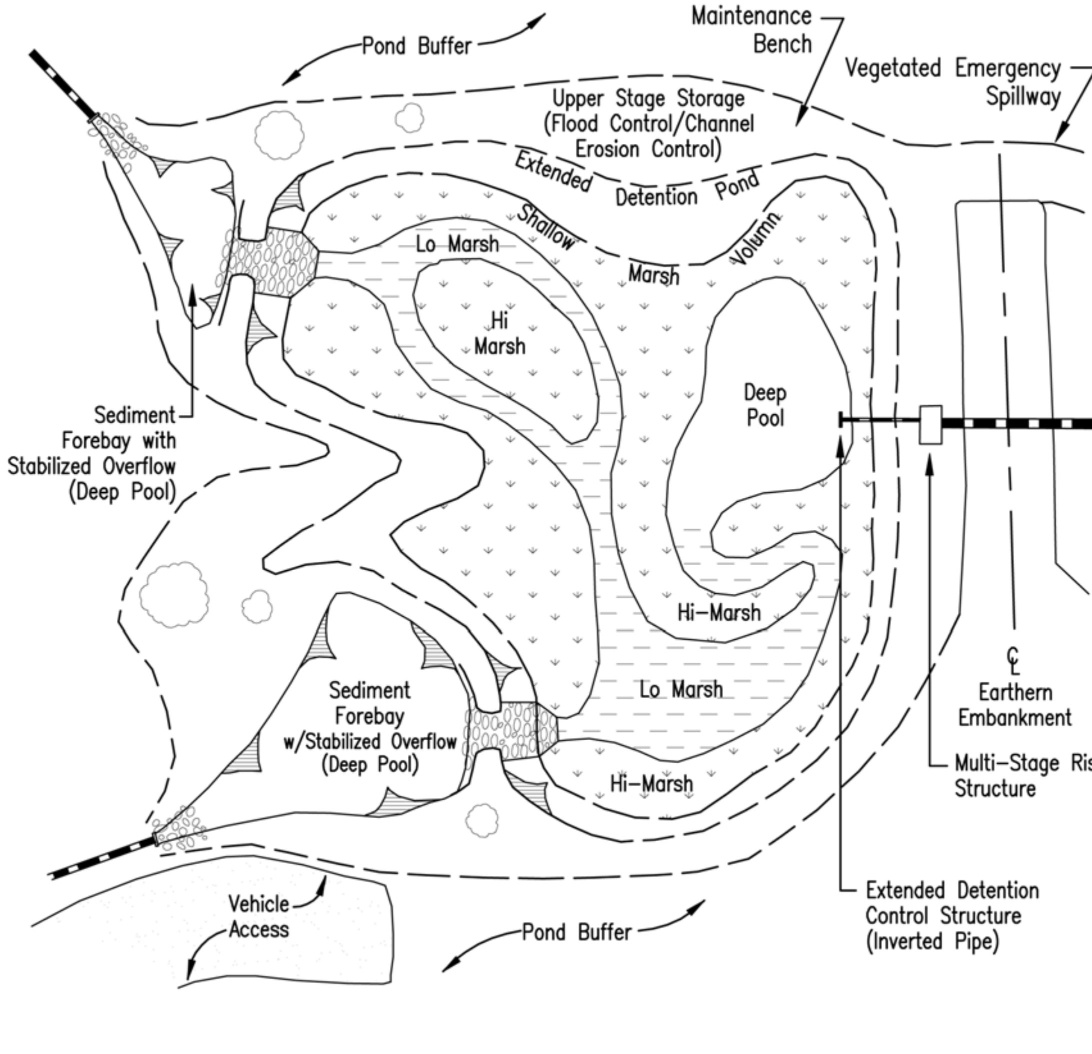


Flood Control

Extended-detention basins can be designed for flood control by providing additional storage above the extended-detention volume, and by reducing the peak rate of runoff from the drainage area. The design storms chosen for flood control are usually specified by ordinance, or are based on specific watershed conditions. By managing multiple storms, such as the 2- and 10-year storms, adequate flood control may be provided for a broad range of storm events.

The additional volume required for storage above the extended-detention volume can be readily determined using the hydrologic methods discussed in **Chapter 4, Hydrologic Methods**. Once this volume is known, a control or spillway structure can be designed and the reservoir routing and channel capacity design techniques discussed in **Chapter 5, Engineering Calculations**.

FIGURE 3.07 - 2a
Enhanced Extended-Detention Basin - Plan



Depth Zone	% of Surface Areas
Deep Pool	20%
Lo Marsh	35%
Hi Marsh	45%

FIGURE 3.07 - 2b
Enhanced Extended-Detention Basin - Section

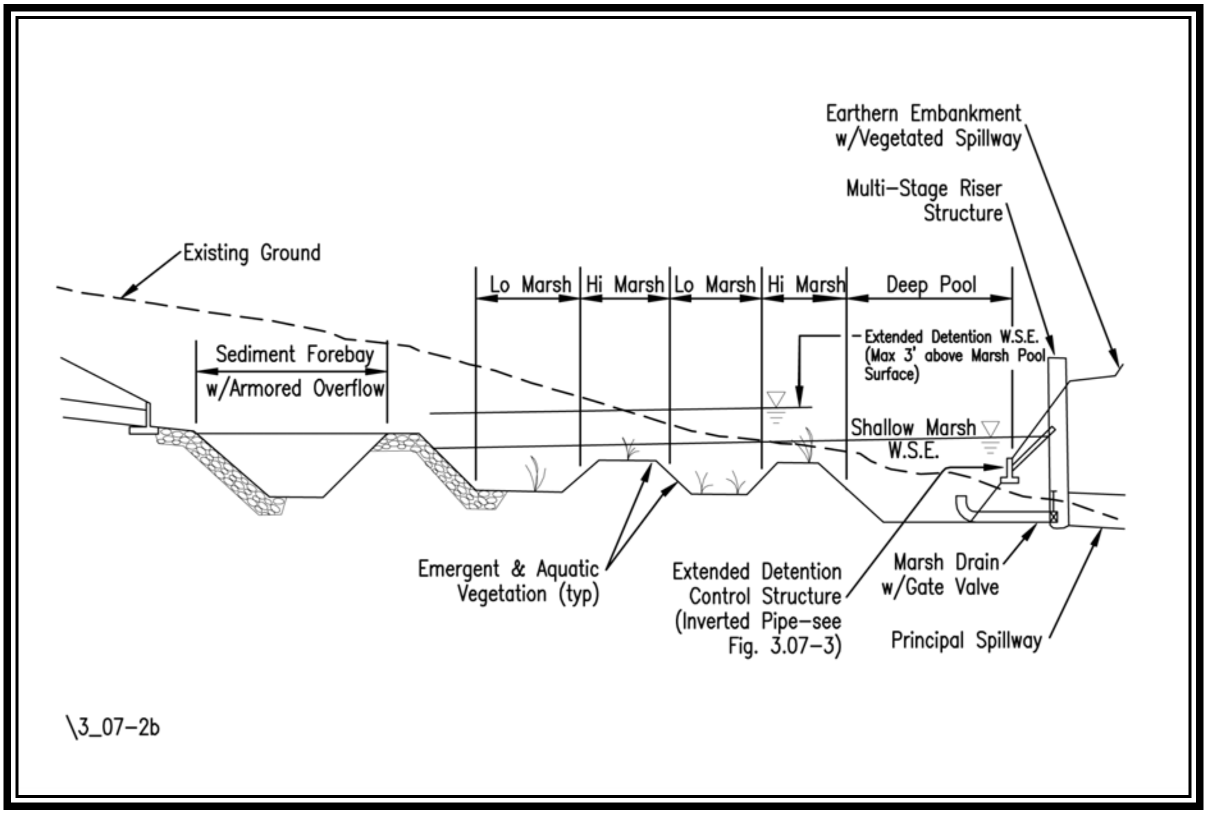


TABLE 3.07 - 1
Pollutant Removal Efficiencies for
Extended-Detention & Enhanced Extended-Detention Basins

Type	Target Phosphorus Removal Efficiency	Impervious Cover
Extended-detention (30 *hr*. Drawdown of 2 × WQ Volume)	35%	22 - 37%
Enhanced extended-detention (30-*hr*. Drawdown of 1 × WQ Volume, and 1 × WQ Volume Shallow Marsh)	50%	38 - 66%

Channel Erosion Control

The objective in controlling channel erosion is to reduce the rate of discharge from a designated frequency storm to below the critical velocity of the downstream channel. The critical velocity of a channel is the velocity that, when exceeded, causes the channel bed or banks to erode. The Virginia Erosion and Sediment Control Handbook, 1992 edition, provides the theoretical critical velocities for various natural channel linings. This critical velocity approach, however, does not consider the frequency or the duration of the critical velocity flow. An increase in impervious cover will increase the frequency of occurance of the "pre-developed" design storm discharge by raising the rainfall to runoff response characteristics of the drainage area. A detention basin will increase the duration of the "pre-developed" design storm discharge by releasing the runoff over time. (A detention basin lowers the peak by spreading it out over a longer period of time.) An extended-detention basin, on the other hand, reduces the discharge based on an extended period of time rather than a peak rate of discharge. Extended-detention of a specific design storm will typically result in lower rates of discharge than the "pre-developed" rate (or critical velocity), thereby compensating for the effects of increased frequency and duration.

The selection of an design storm and a extended-detention period is not a scientific process and is currently determined to be the runoff from the 1-year frequency storm, detained and released over a 24 hour period. Studies show a significant reduction in stream channel erosion below extended-detention facilities designed to this criteria (Galli MWCOG, 1992). Extended-detention of the 1-year storm lowers the discharge velocities from a broad range of storm frequencies to non-erosive levels.

Conditions Where Practice Applies

Drainage Area

The **minimum** contributing drainage area for an extended-detention basin varies with the required extended-detention volume and draw down period and the resulting orifice size. The orifice configuration for small drainage areas should be selected carefully since small openings (less than 3 inches) are prone to clogging. Several different configurations for effective trash, debris, and sediment control are presented in **Figure 3.07-3**. The engineer is free to choose any of these, or to select from other innovative designs.

The **maximum** drainage area served by an extended-detention basin will vary from watershed to watershed. Drainage areas above 50 to 75 acres may require provisions for *base flow*. (Refer to **Design Criteria**). Care should be taken when sizing the water quality orifice if base flow is present.

An undersized orifice may create an undersized permanent pool within the extended-detention volume, leaving inadequate volume above it to provide the required extended-detention. An oversized orifice will result in little extended-detention of the water quality volume.

Development Conditions

Lacking a permanent pool of water, a detention facility is rarely considered aesthetically pleasing. It is, therefore, recommended for *low-visibility* sites. In certain situations, an extended-detention basin may be used on a *high-visibility* site, but the designer must be careful to avoid stagnation or excessive infiltration of the shallow marsh. Maintenance of the basin's shallow marsh is not necessarily critical to its ability to remove pollution, but maintenance **is critical** to ensure the BMP's acceptance by adjacent landowners.

Extended-detention basins can be used for low- to medium-density residential or commercial projects, as classified by their impervious cover. (see **Table 3.07-1**). Along with the storage and shallow marsh volumes required in the basin, a minimum 20-foot vegetated buffer should also be provided. This requirement results in the need for more land. It is for this reason that the use of extended-detention basins may not be the best choice of water quality BMP in developing watersheds where land is at a premium. This strengthens the argument for a regional or watershed approach to stormwater management. A regional extended-detention basin is not only more cost-effective, but is also more likely to be installed on land that is not suitable for development. (It should be noted, however,that the environmental impacts and appropriate permits must still be considered for such an application.)

FIGURE 3.07 - 3a
Trash and Debris Rack Configurations for Extended-Detention Control Structures

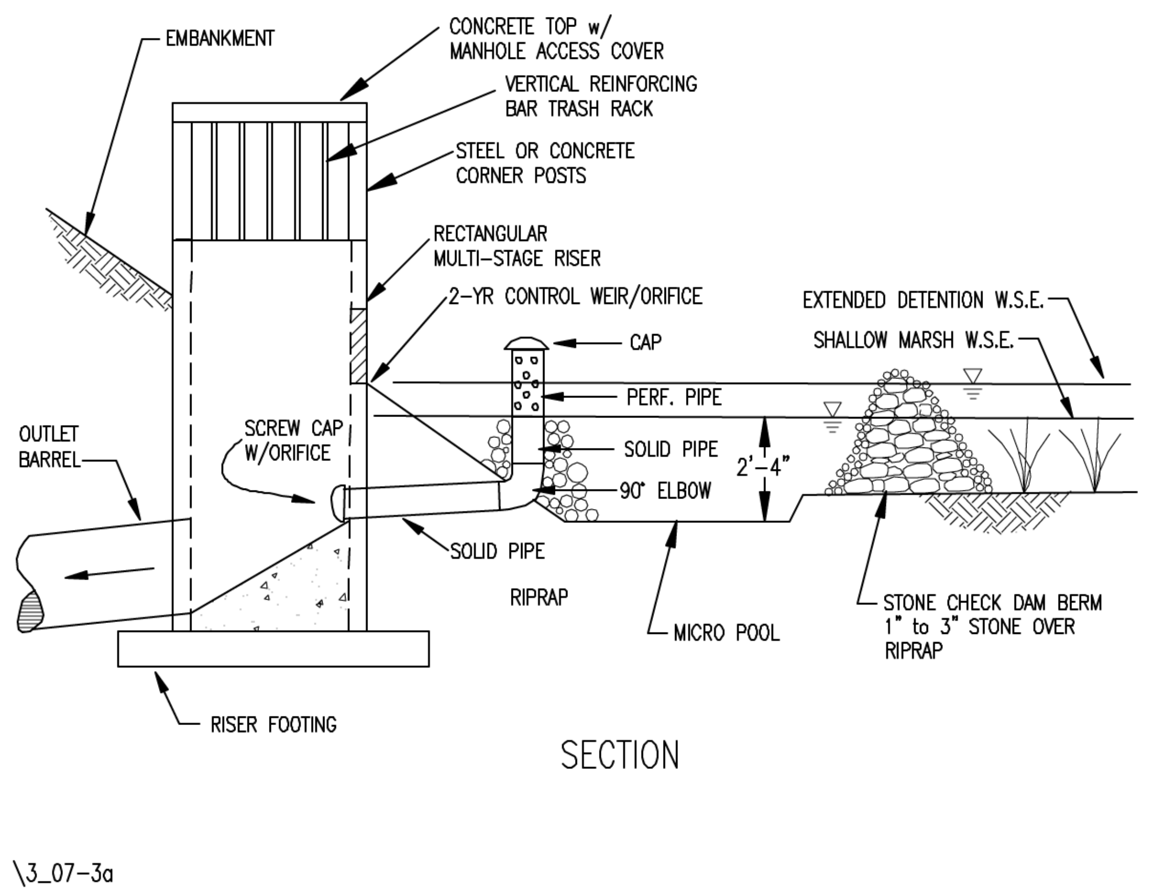


FIGURE 3.07 - 3b
Trash and Debris Rack Configurations for Extended-Detention Control Structures

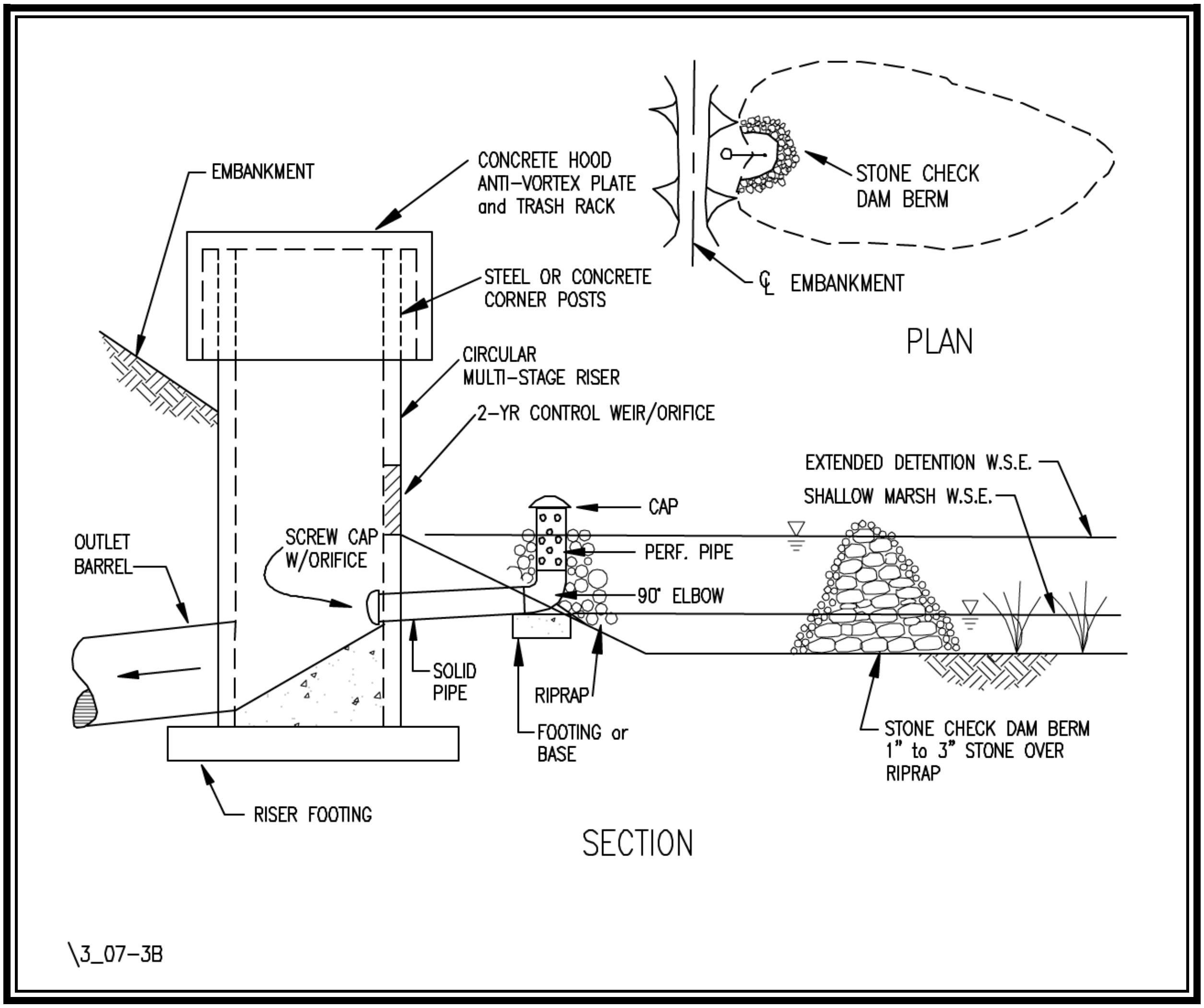
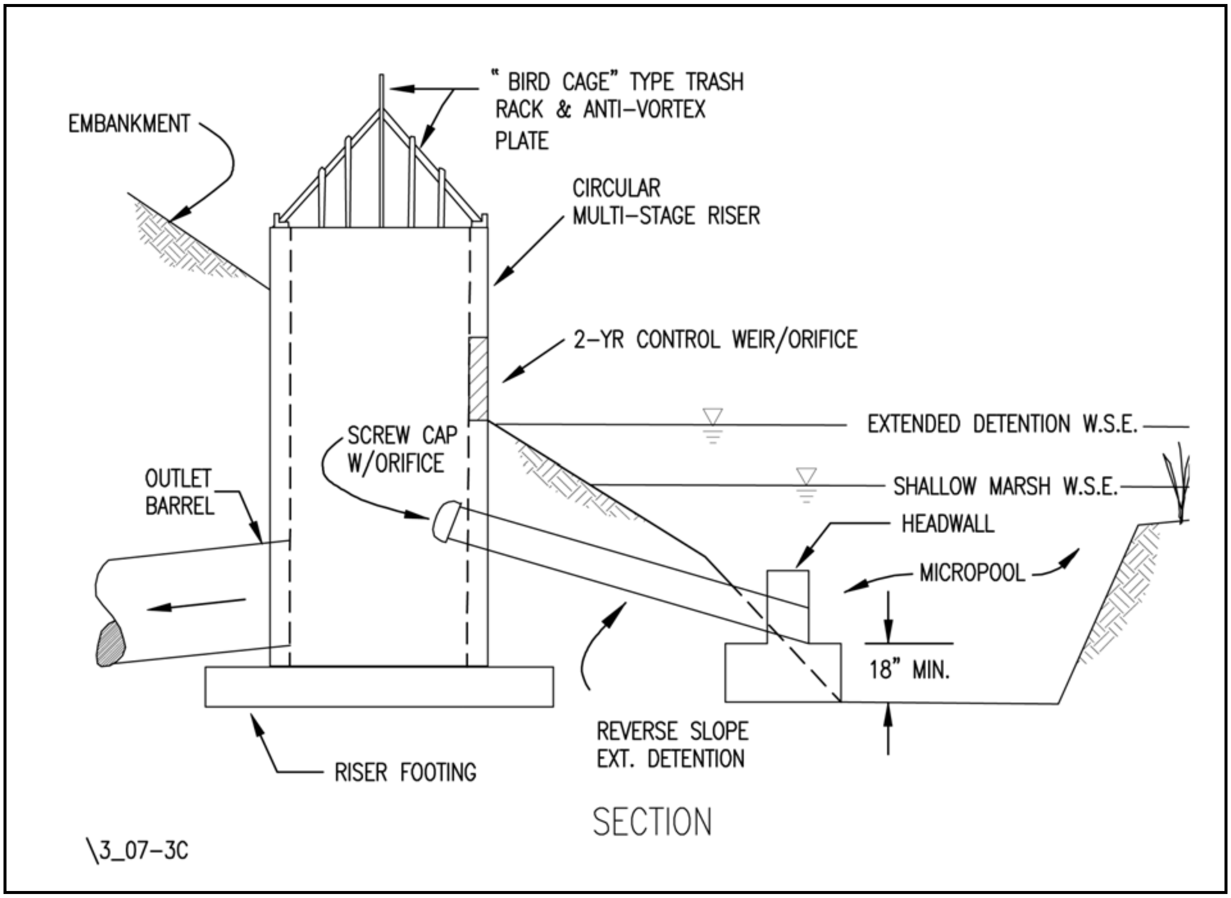


FIGURE 3.07 - 3c
Trash and Debris Rack Configurations for Extended-Detention Control Structures



Planning Considerations

The success of an extended-detention basin is dependent on the designer's ability to identify any site and downstream conditions that may affect the design and function of the basin. Above all, the facility should be compatible with both upstream and downstream stormwater systems to promote a *watershed approach* in providing stormwater management.

The planning considerations for designing the shallow marsh of an *enhanced* extended-detention basin are very similar to those of a constructed wetland (refer to **Minimum Standard 3.09, Constructed Stormwater Wetland; Planning Considerations**).

Site conditions

Existing site conditions should be considered in the design and location of an extended-detention basin. Features such as topography, wetlands, structures, utilities, property lines, easements, etc., may impose constraints on the development. Local government land use and zoning ordinances may also specify certain requirements.

All extended-detention basins should be a minimum of 20 feet from any structure or property line, and 100 feet from any septic tank/drainfield. Extended-detention basins should also be a minimum of 50 feet from any steep slope (greater than 15%). Otherwise, a geotechnical report will be required to address the potential impact of any basin that must be constructed on or near such a slope.

Additional considerations are as follows:

1. **Soils –**

   In the past, many designs were accepted based upon soils information compiled from available data, such as SCS soil surveys. While such a source may be appropriate for a pre-engineering feasibility study, final design and acceptance **should be based on an actual subsurface analysis and a permeability test**, accompanied by appropriate engineering recommendations. The references listed at the end of this standard and at the end of **Minimum Standard 3.10, Infiltration Practices** provide more detailed information regarding the feasibility analysis of subsurface conditions for various soil types. Due to its complexity, this topic is not covered here.

   Highly permeable soils are not suited for extended-detention basins. A basin with highly permeable soils will act as an infiltration facility until the soils become clogged. Although this phenomenon is not always considered a negative impact, it does change the function and design of the basin. For an *enhanced* extended-detention basin, the soils must support the shallow marsh **at the time of stabilization and planting**.

A thorough analysis of the soil strata should be conducted to verify its suitability for use with an extended-detention basin. The geotechnical study required for the embankment design (refer to **Minimum Standard 3.01, Earthen Embankment**) will often provide adequate data for this purpose. The soil permeability may be such that the basin can support a shallow marsh. However, as the depth of the temporary storage increases, the increased head or pressure on the soil may increase the rate of infiltration. If necessary, a liner of clay, geosynthetic fabric, or other suitable material may be used in the basin (as specified by a geotechnical engineer). Refer to the design criteria for basin liners.

2. **Rock –**

The subsurface investigation should also identify the presence of rock or bedrock. Excavation of rock may be too expensive or difficult with conventional earth moving equipment.Blasting the rock for removal may be possible, but it may also open seams or create cracks in the underlying rock, resulting in an unwanted drawdown of the shallow marsh. Blasting of rock is not recommended unless a liner, as described above, is used.

3. **Karst –**

In regions where Karst topography is prevalent, projects may require thorough soils investigation and specialized design and construction techniques. Since the presence of karst may affect BMP selection, design, and cost, a site should be evaluated **during the planning phase of the project**.

4. **Existing Utilities –**

Most utility companies will not allow a permanent or temporary pool to be installed over their underground lines or right-of-ways. If such a site must be used, the designer should obtain permission from the utility company **before designing the basin**. The relocation of any existing utilities should be researched and the costs included in the overall basin cost estimate.

Environmental Impacts

1. **Wetlands–**

Large facilities and/or regional facilities lend themselves to being placed in low lying, and usually environmentally sensitive, areas. Such locations often contain wetlands, shallow marshes, perennial streams, wildlife habitat, etc., and may be protected by state or federal laws. The owner or designer should investigate the regional wetland maps and contact appropriate local, state, and federal agencies to verify the presence of wetlands, their protected status, and the suitability for an extended-detention basin at the location in question.

With careful planning, it may be possible to incorporate wetland mitigation into an extended-detention basin design. This assumes that the functional value of the existing or impacted wetland can be identified and included, reconstructed, or mitigated for, in the basin. Contact the Virginia Department of Environmental Quality for more information regarding wetland mitigation.

2. **Downstream Impacts–**

Urban detention and retention basin design should be coordinated with a watershed or regional plan for managing stormwater runoff, if available. In a localized situation, an individual basin can provide effective protection for the downstream channel if no other areas contribute runoff in a detrimental way to the channel. However, an uncontrolled increase in the number of impoundments within a watershed can severely alter natural flow conditions, causing combined flow peaks or increased flow duration. This can ultimately lead to flooding downstream degradation.

3. **Upstream Impacts–**

The upstream channel must also be considered, especially when the extended-detention basin is used to control downstream channel erosion. Erosive upstream flows will not only degrade the upstream channel, but will also significantly increase the maintenance requirements in the basin by depositing large amounts of sediment eroded from the channel bottom.

Water Quality Enhancement

In an extended-detention basin, the quality of the incoming stormwater is improved through *gravitational settling* of pollutants from the water quality volume. The pollutant removal efficiency for *soluble* pollutants is usually much **lower** than for *particulate pollutants*. Therefore, the efficiency of an extended-detention basin can be **enhanced** by adding a *shallow marsh* to the lower stage of the basin. The shallow marsh creates physical and biological characteristics that are more conducive to the removal process for soluble pollutants.

Settling column studies suggest a maximum upper limit of approximately 40 to 50% removal for total phosphorous after 48 hours, with most of the removal occurring within the first 6 to 12 hours (MWCOG, 1987). However, field studies show a much broader range in removing phosphorous (15-70%) and in removing sediment (65%). Since the soluble form of phosphorous comprises nearly half the phosphorous found in urban runoff, the lower efficiency of 35% (**Table 3.07-1**) is deemed appropriate. The increase in efficiency of *enhanced* extended-detention is attributed to the ability of the shallow marsh to reduce the soluble pollutant levels.

Providing a larger extended-detention volume (similar to providing a larger permanent pool for a retention basin) may not increase the pollutant removal efficiency. **Increasing the volume without increasing the detention time results in a larger orifice size and, therefore, less control of the smaller "first flush" storms**. Simply increasing the detention time will not provide additional efficiency either, since the 30-hour drawdown period exceeds the *probable settling time* associated with most particulate pollutants.

The pollutant removal efficiency in an *enhanced* extended-detention basin **can** be increased, however, by enlarging the volume of the shallow marsh. As the volume of the marsh is increased, with respect to the contributing drainage area, the *hydraulic residence time* is increased. This longer residence time provides more opportunity for further biological uptake and decomposition of pollutants.

Flooding and Channel Erosion Control

Flood control and downstream channel erosion are managed by storing additional runoff above the extended-detention pool (and shallow marsh) and by properly sizing the discharge opening in the riser structure.

When selecting an extended-detention basin, the biggest concern is how much land it requires. The storage volume needed above the extended-detention pool (and shallow marsh) must be approximated and its availability verified on the preliminary site plan.

> *A preliminary sizing estimate is recommended* ***during the planning stage*** *to verify the feasibility of using an extended-detention basin. (See* ***Chapter 5, Engineering Calculations*** *for Storage Volume Requirement Estimates).*

Sediment Control

An extended-detention basin may be used as a *temporary sediment control basin* during construction. The design of a temporary sediment basin is based on the *maximum drainage area* and *rate of runoff* expected anytime during the site construction process. In contrast, the design of the permanent stormwater basin is based on *post-developed land use conditions*. When designing a basin to provide both temporary sediment control and permanent stormwater management, the criteria that produces the largest storage volume should be used to size the basin. The discharge structure should be designed as a permanent stormwater facility with respect to its riser and barrel hydraulics and materials. The riser's geometry may then be temporarily modified to provide the wet and dry storage for the temporary sediment basin, as required by VESCH, 1992 edition.

Safety

Basins that are readily accessible to populated areas should include all possible safety precautions. Steep side slopes (steeper than 3H:1V) at the perimeter should be avoided and dangerous outlet facilities should be protected by enclosures. Warning signs for temporary deep water conditions and potential health risks should be used wherever appropriate. Signs should be placed so that at least one is clearly visible and legible from all adjacent streets, sidewalks or paths. A dry basin may hold a significant amount of soft sediment in the bottom, posing a danger to small children.

A fence is required at or above the maximum water surface elevation when a basin slope is a vertical wall. Local governments and homeowners associations may also require appropriate fencing despite the steepness of the basin side slopes.

Maintenance

Extended-detention basins have shown an ability to function as designed for long periods without routine maintenance. However, some maintenance is essential to protect the aesthetic properties of these facilities.

Vehicular access to the sediment forebay and the release structure should be provided to allow for long-term maintenance (such as sediment removal) and repairs, as needed. The use of a sediment forebay at the upstream end of the basin will help to localize the disturbance during routine sediment removal operations. An onsite area designated for sediment dewatering and disposal should also be included in the design. Care must be taken in the disposal of sediment that may contain an accumulation of heavy metals. **Sediment testing is recommended prior to sediment removal to assure proper disposal**.

A sign should be posted near the basin that clearly identifies the person or organization responsible for basin maintenance. Allowing participation by adjacent landowners or visitors is very helpful, especially if the facility is used for recreation. Maintenance items observed and addressed early will

help to limit overall maintenance costs. Routine maintenance inspections, however, should be conducted by authorized personnel
.

Design Criteria

This section provides recommendations and minimum criteria for the design of extended-detention and *enhanced* extended-detention basins intended to comply with the Virginia Stormwater Management program. It is the designer's responsibility to decide which aspects of the program are applicable to the particular facility being designed and to decide if any additional design elements are required. The designer should also consider the long-term functioning of the facility when selecting materials for the structural components.

<u>Hydrology and Hydraulics</u>

The pre- and post-developed hydrology for a basin's contributing watershed, the hydraulic analysis of the riser and barrel system, and the emergency spillway design should be developed using **Chapter 4, Hydrologic Methods** and **Chapter 5, Engineering Calculations**.

Generally, the 2-year storm should be used in *receiving channel adequacy* calculations and the 10-year storm should be used for *flood control* calculations. Alternate requirements, such as 1-year extended detention for channel erosion control may be imposed by local ordinances.

<u>Embankment</u>

The design of the earthen embankment for an extended-detention and *enhanced* extended-detention basin should comply with **Minimum Standard 3.01, Earthen Embankment**. The requirements for geotechnical, seepage control, maximum slope, and freeboard are particularly appropriate.

<u>Principal Spillway</u>

The design of the principal spillway and barrel system, anti-vortex device, and trash racks should comply with **Minimum Standard 3.02, Principal Spillway**.

Emergency Spillway

An emergency spillway that complies with **Minimum Standard 3.03, Vegetated Emergency Spillway** should be provided when possible, or appropriate.

Sediment Basin Conversion

When a proposed stormwater facility is used initially as a temporary sediment basin, conversion to the permanent facility should be completed after final stabilization and approval from the appropriate erosion and sediment control authority.

Sometimes, the temporary sediment basin design criteria will require more storage volume than that of a stormwater basin. In such cases, the extra volume may be allocated to the component of the facility that would derive the greatest benefit from increased storage. This will depend on the primary function of the facility (i.e., water quality enhancement, flood control, or channel erosion control).

If modifications to the riser structure are required as part of the conversion to a permanent basin, they should be designed so that a) *the structural integrity of the riser is not threatened*, and b) *large construction equipment is not needed within the basin*. Any heavy construction work required on the riser should be completed during its initial installation. It is **NOT** recommended to install a temporary sediment basin riser structure in the basin and then replace it with a permanent riser after final stabilization. This may affect the structural integrity of the existing embankment and barrel.

The following additional criteria should be considered for a conversion:

1. Final elevations and a complete description of any modifications to the riser structure geometry should be shown on the approved plans.

2. The wet storage area must be dewatered following the approved methods in VESCH, 1992 edition.

3. Sediment and other debris should be removed to a contained spoil area. Regrading of the basin may be necessary to achieve the final design grades and to provide an adequate topsoil layer to promote final stabilization.

4. Final modifications to the riser structure should be carefully inspected for water tight connections and compliance with the approved plans.

5. Final landscaping and stabilization should be per VESCH, 1992 edition, and **Minimum Standard 3.05, Landscaping** in this manual. Establishing vegetation may prove difficult if flow is routed through the facility prior to germination. In such cases, specifying sod or other reinforcements for the basin bottom and low flow channels may be appropriate.

Extended-Detention Volume

Water quality extended-detention basins are designed to allow particulate pollutants to settle out of water quality volume. **Chapter 5, Engineering Calculations** provides calculation procedures for determining the *water quality volume* for a particular watershed, and for sizing the release orifice to provide the required 30-hour draw down. **The water quality volume is the first one-half inch of runoff from the impervious surfaces**.

Channel erosion control extended-detention basins are designed to reduce the rate of discharge such that the velocity is below the critical velocity for the downstream channel. **Chapter 5, Engineering Calculations** provides the calculation procedures for calculating the *channel erosion control volume* for a particular watershed, and for sizing the release structure to provide the required 24-hour draw down. **The channel erosion control volume is the runoff generated from the drainage area or watershed by the 1-year frequency design storm.**

The orifice sizing procedure for extended detention is based on a "*brim*" drawdown. The full design volume is assumed to be in the basin, and the drawdown period is the time it takes to drain that entire volume. In reality, this technique ignores the *routing effect* that occurs in the basin: as the runoff volume accumulates, stormwater is draining into the basin while simultaneously draining out of it. For small storms, the extended-detention volume will never fill to the "brim" and will, therefore, never achieve the maximum drawdown time.

The calculation procedure used to verify the draw down time is presented in **Chapter 5.** The extended-detention volume (in cubic feet) is divided by the <u>maximum</u> release rate (in cubic feet per second), which is based on the maximum hydraulic head associated with the water quality volume, to give the *detention time*, in seconds. Using the maximum release rate, rather than the average release rate, results in a smaller orifice, which helps to compensate for ignoring the routing effect, as discussed above.

Enhanced Extended-Detention Basin: Shallow Marsh

When a higher pollutant removal efficiency is needed, a water quality extended-detention basin can be enhanced by providing a *shallow marsh* in the bottom of the facility. The use of a shallow marsh limits the maximum range of vertical storage in the extended-detention pool to 3 feet above the marsh's water surface elevation. However, the surface area requirements for the shallow marsh will likely force the basin's geometry to broaden at the lower stages, which will compensate for the reduced vertical storage. Extended-detention water surface elevations greater than 3 feet, and the frequency at which those elevations can be expected, are not conducive to the growth of dense or diverse stands of emergent wetland plants.

Similar to the permanent pool of a constructed wetland, the shallow marsh in the bottom of an extended-detention basin should be designed to maximize pollutant removal efficiency. The physical and hydraulic factors that can influence the pollutant removal efficiency of a shallow marsh are: 1) *volume*, 2) *depth*, 3) *surface area*, 4) *geometry*, and 5) *hydraulic residence time*. In addition, careful attention should be given to the landscaping plan (refer to **Minimum Standard 3.09, Constructed Wetland** for design criteria regarding the establishment of vegetation in a shallow marsh.

The following criteria are general guidelines. The depth of the treatment volume and amount of surface area varies with each site and the intended secondary functions of the facility (i.e., providing habitat, aesthetics, etc.).

1. **Volume–**

The pool volume of an extended-detention shallow marsh varies with the water quality volume. The water quality volume (WQV), as defined by Virginia Stormwater Management regulations, is the **first one-half inch of runoff, multiplied by the area of impervious surface**. The target pollutant removal efficiency of an *enhanced* extended-detention basin, as presented in **Table 3.07-1**, is based on 2.0 times the WQV. The shallow marsh pool volume represents 1.0 × WQV and the extended-detention volume represents an additional 1.0 × WQV. The pollutant removal efficiency is directly related to the percentage of runoff available to be treated. If it is assumed that all of the rainfall that hits impervious surfaces turns into runoff (ignoring minor losses such as evaporation, depression storage, etc.), then a design volume of 2.0 × WQV represents a design storm of 1 inch of rainfall. Based upon available rainfall data from the Washington, D.C. area, 1 inch of rainfall represents approximately 85% of all runoff producing storm events (MWCOG, 1992). Therefore, 2.0 × WQV (or 1 inch of rainfall from impervious surfaces) represents a significant percentage of runoff producing events.

2. **Depth–**

The treatment volume of a shallow marsh should occupy different depth zones, as shown in **Table 3.07-2**, to maximize the physical and biological processes that occur within the marsh. Three basic depth zones should be used: a) *deep pools*, b) *low-marsh*, and c) *high-marsh*.

a. Deep pool areas should be 1.5 to 4 feet deep and may consist of 1) *sediment forebays*, 2) *micro-pools*, and 3) *deep water channels*.

1. A sediment forebay is highly recommended in a shallow marsh. It should be constructed near incoming pipes or channels to reduce the velocity of incoming runoff, trap course sediments, and spread the runoff evenly over the marsh area. The forebay should be constructed as a separate cell from the rest of the marsh, with maintenance access provided to simplify cleaning with heavy equipment (refer to **Minimum Standard 3.04, Sediment Forebay**).

2. A micro-pool should be a standard component of the extended-detention shallow marsh. The purpose of a micro-pool is to create sufficient depth near

the outlet to help reduce clogging of the extended detention orifice. This will allow for a reverse-sloped pipe to extend into the marsh below the pool surface elevation but above the pool bottom which helps to prevent clogging, since a typical marsh environment consists of floating plant debris and possible sediment and organic accumulation on the bottom. Micro-pools also provide open water areas to attract plant and wildlife diversity (refer to the **Overflow** discussion later in this section).

3. Deep water channels provide an opportunity to lengthen the flow path to avoid seasonal short-circuiting (refer to the **Geometry** discussion later in this standard.)

b. Low-marsh zones range in depth from 6 to 18 inches.

c. High-marsh zones range in depth from 0 to 6 inches. The high-marsh zone will typically support the greatest density and diversity of emergent plant species.

3. **Surface Area–**

At a minimum, the surface area of an extended-detention shallow marsh should be sized to equal 1% of the contributing drainage area. The recommended surface area allocation for the different depth zones is presented in **Table 3.07-2** (MWCOG, 1992). Note that the surface area criteria may create a conflict with the volume allocations. If this happens, the designer is reminded that these are recommendations. **The criteria that establish the largest permanent pool should be used**.

4. **Geometry–**

The geometry of the shallow marsh must be carefully designed to avoid *short-circuiting*. Meandering, rather than straight line flow is desirable. Maximum pollutant removal efficiencies will be achieved due to the increased contact time associated with the longest possible flow path through the marsh. A length-to-width ratio of 2:1 through the marsh should be maintained (see **Figure 3.07-4**). The length-to-width ratio is calculated by dividing the straight line distance from the inlet to the outlet by the marsh's average width.

TABLE 3.07 - 2
Recommended Allocation of Surface Area and Treatment Volume for Depth Zones

Depth Zone	% of Surface Area	% of Treatment Volume
Deep Water 1.5 to 4 feet in depth (forebay and micro-pool)	20	40
Low Marsh 0.5 to 1.5 feet in depth	40	40
High Marsh 0 to 0.5 feet	40	20

(Adapted from MWCOG, 1992)

5. **Hydraulic Residence Time–**

The *hydraulic residence time* is the shallow marsh pool volume divided by the average outflow discharge rate. The longer the residence time, the higher the pollutant removal efficiency (Driscoll, 1983, Kulzer, 1989).

In theory, by using 1.0 x WQV in sizing the shallow marsh volume, the smaller storms (those producing ½ inch of runoff or less) will displace the pool volume of the marsh. However, larger treatment volumes (such as 2 or 3 x WQV), compared with the watershed size, will provide longer residence times and greater efficiencies. In certain situations, increasing the target pollutant removal efficiency by using a higher water quality volume multiplier to size the marsh volume may be acceptable. However, the challenge will be to provide the recommended depth zone allocations for the allocated percentages of surface area and treatment volumes, as previously discussed.

Base Flow

The presence of a *base flow* makes the design of an extended-detention control structure difficult. If the extended-detention orifice is sized for the *wet weather base flow*, then the dry weather control is compromised because the release rate is too high. If the orifice is undersized to maintain the *dry weather control*, then the extended-detention pool may remain full of water during the wet weather season; this essentially eliminates the extended-detention volume by creating an undersized permanent pool (1.0 x WQV). When seasonal base flow is present, an adjustable orifice should be provided in the control structure to maintain the marsh volume.

The presence of a base flow and the associated potential for erosion within the basin should be considered in the design. Ideally, base flow, or *low flows*, should be spread out so that they *sheet flow* across the bottom of the basin. Due to maintenance difficulties and undesirable insect breeding associated with standing water, some localities may have ordinances that require *low-flow channels* (or *trickle ditches*) to carry base flows. If an *impervious* ditch is used to convey base flows, it should be designed to overflow during storm events and spread the runoff across the basin floor. The use of gabion baskets or riprap, instead of concrete, may provide the advantage of slowing the flow, encouraging spillover onto the basin floor. **Generally, an impervious low-flow channel is <u>NOT</u> recommended in a stormwater management water quality basin, as its use is contrary to the basin's water quality function**.

Local ordinances should be reviewed for specific requirements relating to low-flow or base-flow channels in dry detention basins.

<u>Overflow</u>

Similar to a constructed stormwater wetland, an extended-detention overflow system should be designed to provide adequate overflow or bypass for a full range of design storms. For an *enhanced* extended-detention basin, the overflow system should pass the full range of design storms with no more than 3 feet of hydraulic head above the shallow marsh.

<u>Sediment Forebay</u>

A sediment forebay will help to postpone overall basin maintenance by trapping incoming sediments at a specified location. The forebay should be situated and designed per **Minimum Standard 3.04, Sediment Forebay**. Usually, a sediment forebay is placed at the outfall of the incoming storm drain pipes and positioned to ensure access for maintenance equipment.

A sediment forebay enhances the pollutant removal efficiency of a basin by trapping the incoming sediment load in one area where it can be easily monitored and removed. For an *enhanced* extended-detention basin, the sediment forebay is included in the deep pool allocations of the surface area and storage volume. The target pollutant removal efficiency of an extended-detention basin, as listed in **Table 3.07-1**, is predicated on using a sediment forebay at the inflow points of the basin.

<u>Liner to Prevent Infiltration</u>

Extended-detention basins should have negligible infiltration rates through the bottom of the basin. Infiltration will impair the proper functioning of the basin and may contaminate groundwater, and in areas of Karst, may cause collapse. For an *enhanced* extended-detention basin, excessive infiltration may prevent the shallow marsh from holding water. If infiltration is anticipated, and the area is not suspected to be underlain by Karst, than an infiltration facility, rather than a detention water quality BMP, should be used **<u>or</u>** a liner should be installed in the basin to prevent infiltration.

When using a liner, the following recommendations apply:

1. A clay liner should have a minimum thickness of 12 inches and should comply with the specifications provided in **Table 3.07-3**.

2. A layer of compacted topsoil (minimum 6 to 12 inches thick) should be placed over the liner before seeding with an appropriate seed mixture (refer to VESCH, 1992 edition)

3. Other liner types may be used if supporting documentation is provided verifying the liner material's performance.

TABLE 3.07 - 3
Clay Liner Specifications

Property	Test Method (or equal)	Unit	Specification
Permeability	ASTM D-2434	*cm/sec*	1×10^{-6}
Plasticity Index of Clay	ASTM D-423 & D-424	%	Not less than 15
Liquid Limit of Clay	ASTM D-2216	%	Not less than 30
Clay Particles Passing	ASTM D-422	%	Not less than 30
Clay Compaction	ASTM D-2216	%	95% of Standard Proctor Density

Source: City of Austin, 1988

Access

A 10 to 12 foot wide access road with a maximum grade of 12% should be provided to allow vehicular access to both the outlet structure area and at least one side of the basin. The road's surface material should be selected to support the anticipated frequency of use and vehicular load without excessive erosion or damage.

Landscaping

A qualified individual should prepare the landscape plan for an extended-detention basin. Appropriate shoreline fringe, riparian fringe and floodplain terrace vegetation must be selected to correspond with the expected frequency and duration of inundation. Additional criteria for landscaping may be found in **Minimum Standard 3.05, Landscaping**. For establishment of vegetation in the marsh area, refer to **Minimum Standard 3.09, Constructed Wetland**.

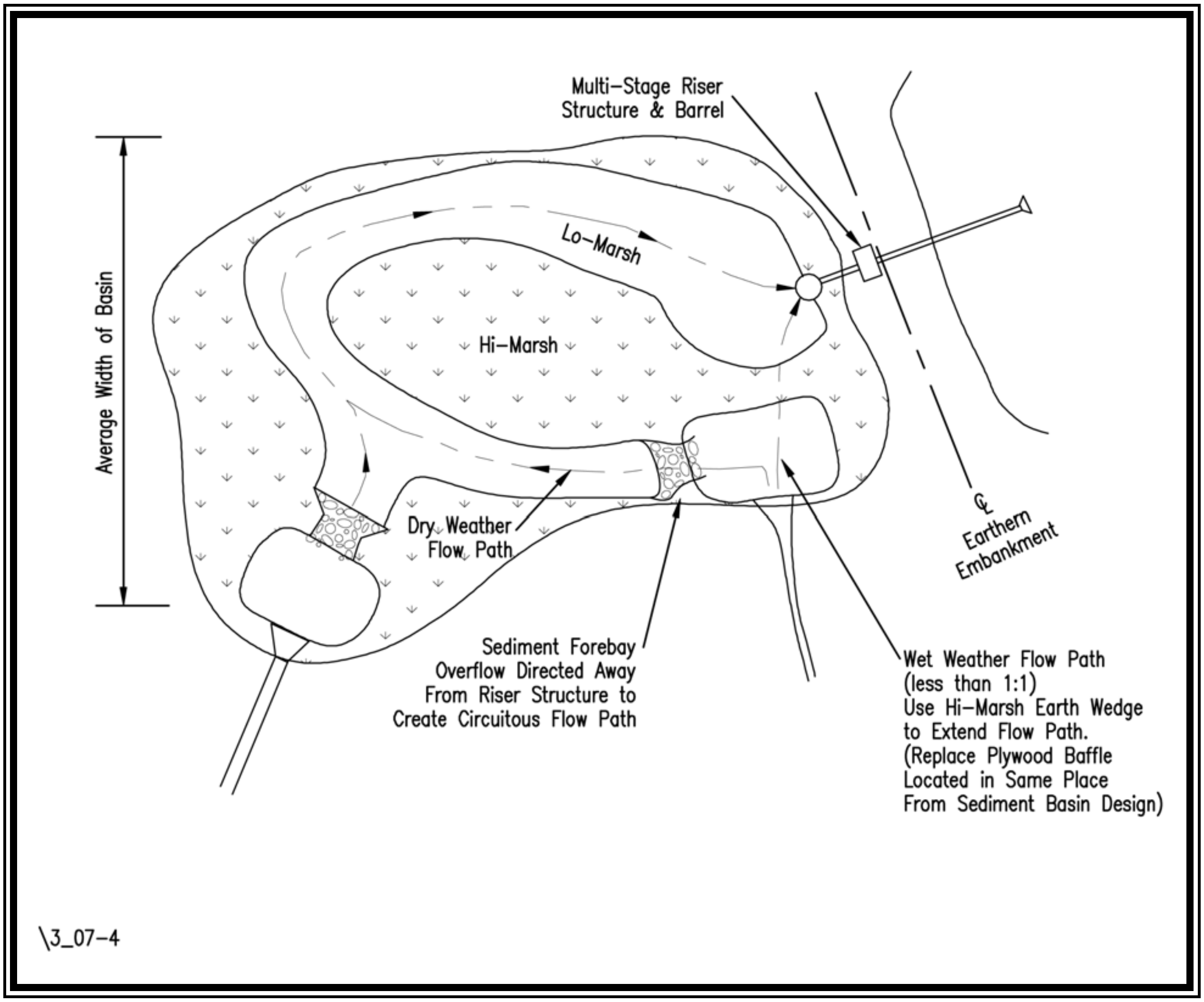
The vegetation should be planted in soil that is appropriate for the plants selected. Soil tests showing the adequacy of the soil or a soil enhancement plan should be submitted with the overall basin design.

The soil substrate must be soft enough to permit easy installation of the plants. If the basin soil has been compacted or vegetation has formed a dense root mat, the upper 6 inches of soil should be disked before planting. If soil is imported, it should be laid at least 6 inches deep to provide sufficient depth for plant rooting to occur.

<u>Buffer Zone</u>

A vegetated buffer strip should be maintained beside the basin. The strip should be a minimum of 20 feet wide, as measured from the maximum water surface elevation. Refer to **Minimum Standard 3.05, Landscaping**.

FIGURE 3.07 - 4
Flow Path/Short-Circuiting



Construction Specifications

The construction specifications for stormwater extended-detention and *enhanced* extended-detention basins outlined below should be considered minimum guidelines. More stringent or additional specifications may be required based on individual site conditions.

Overall, widely accepted construction standards and specifications for embankment ponds, such as those developed by the USDA Soil Conservation Service or the U.S. Army Corps of Engineers, should be followed to build an impoundment.

Further guidance can be found in Chapter 17 of the Soil Conservation Service's Engineering Field Manual. Specifications for the work should conform to methods and procedures specified for installing earthwork, concrete, reinforcing steel, pipe, water gates, metal work, woodwork and masonry and any other items that apply to the site and the purpose of the structure. The specifications should also satisfy any requirements of the local plan approving authority.

The following minimum standards contain guidance and construction specifications for various components of these facilities: **3.01, Earthen Embankment**; **3.02, Principal Spillway**; **3.03, Vegetated Emergency Spillway**; **3.04, Sediment Forebay**; **3.05, Landscaping**, and **3:09, Constructed Wetland**.

Maintenance and Inspections

The following maintenance and inspection guidelines are not intended to be all-inclusive. Specific facilities may require other measures not discussed here. The engineer is responsible for determining if any additional items are necessary.

Inspecting and maintaining the structures and the impoundment area should be the responsibility of the local government, a designated group such as a homeowner association, or an individual. A specific maintenance plan should be formulated outlining the schedule and scope of maintenance operations.

General Maintenance

Maintenance and inspection guidelines found in the following minimum standards also apply: **3.01, Earthen Embankment**; **3.02, Principal Spillway**; **3.03, Vegetated Emergency Spillway**; **3.04, Sediment Forebay**, and **3.05, Landscaping**.

Vegetation

The basin's side slopes, embankment and emergency spillway should be mowed at least twice a year to discourage woody growth. More frequent mowing may be necessary in residential areas for aesthetic purposes.

Dry extended-detention basins may have soggy bottoms, making mowing costly and difficult. The use of water-tolerant, hardy, and slow growing grass is recommended for the bottom of these basins. **Vegetation is preferred to an impervious low-flow channel since the channel may interfere with the pollution removal capabilities of the basin**. The designer should be aware of local program requirements, as some localities require low-flow channels.

Specific plant communities may require different levels of maintenance. Upland and floodplain terrace areas, grown as meadows or forests, require very little maintenance, while aquatic or emergent vegetation may need periodic thinning or reinforcement plantings. Note that after the first growing season it should be obvious if reinforcement plantings are needed. If they are, they should be installed at the onset of the second growing season after construction.

Research indicates that for most aquatic plants the uptake of pollutants is stored in the roots, not the stems and leaves (Lepp 1981). Therefore, aquatic plants should not require harvesting before winter plant die-back. There are still many unanswered questions about the long term pollutant storage capacity of plants. Possible aquatic and emergent plant maintenance recommendations may be presented in the future.

Debris and Litter Removal

Debris and litter will accumulate near the inflow points and around the outlet control structure. Such material should be removed periodically. Significant accumulation can clog the low-flow outlet and the upper control openings.

Sediment Removal

Sediment deposition should be continually monitored in the basin. Removal of accumulated sediment is extremely important. A significant accumulation of sediment impairs the pollutant removal capabilities of the basin by reducing the available storage for the water quality volume and/or reducing the available volume for the shallow marsh. In addition, accumulated sediment in the bottom of a basin creates unsightly conditions and chokes out established vegetation.

Unless unusual conditions exist, it is anticipated that accumulated sediment will need to be removed from the basin every 5 to 10 years (MWCOG, 1987). More frequent cleaning of the area around the low flow or extended-detention orifice may be required. The use of a sediment forebay with access for heavy equipment will greatly simplify the removal process. **During maintenance procedures,**

ensure that any pumping of standing water or dewatering of dredged sediments complies with the VESCH, 1992 edition, and any local requirements.

Owners, operators, and maintenance authorities should be aware that significant concentrations of heavy metals (e.g., lead, zinc and cadmium) and some organics, such as pesticides, may be expected to accumulate at the bottom of a basin. Testing of sediment, especially near points of inflow, should be conducted regularly and **before disposal** to find the leaching potential and level of accumulation of hazardous materials. Disposal methods must comply with the health department requirements of the local government.

Inspections

An extended-detention basin and its components should be inspected annually to ensure that they operate in the manner originally intended. If possible, inspections should be conducted during wet weather to determine if the extended-detention time is being achieved. Inspections should be conducted by a qualified individual following the checklist provided in **Chapter 3 Appendix**.

REFERENCES

American Society of Civil Engineers. “Stormwater Detention Outlet Control Structures.” Task Commission on the Design of Outlet Control Structures. New York, NY:ASCE, 1985.

Brater, E.F. and H.W. King. Handbook of Hydraulics. 6th ed. New York: McGraw Hill Book Company, 1976.

Chesapeake Bay Local Assistance Department (CBLAD). Local Assistance Manual: A Guide for the Development of Local Programs in Order to Comply with the Chesapeake Bay Preservation Act. Richmond, Virginia: November 1989.

Debo, T.N. and A.J. Reese. “Determining Downstream Analysis Limits for Detention Facilities.” Proceedings for NOVATECH 92, International Conference of Innovative Technologies in The Domain of Urban Storm Water Drainage. Lyon, France, 1992.

Debo, T.N. and Reese, A. J. Municipal Stormwater Management. 1995.

Federal Highway Administration. “Debris-Control Structures.” Hydraulic Engineering Circular No. 9, 1971.

Federal Highway Administration. Retention, Detention and Overland Flow for Pollutant Removal from Highway Stormwater Runoff: Interim Guidelines for Management Measures. Pub. No FHWA/RD-87/056. McLean, Virginia: March, 1988.

Galli, J. Analysis of Urban BMP Performance and Longevity in Prince George’s County, Maryland. Washington, D.C.: Metropolitan Washington Council of Governments (MWCOG), August, 1992.

James, W.P., J.F. Bell and D.L. Leslie. “Size and Location of Detention Storage,” ASCEJ of Water Resources Planning and Management, Vol. 113, No. 1, 1987.

Jones, J.E. “Multipurpose Stormwater Detention Ponds.” Public Works, 1990.

Maryland Department of Natural Resources (Md. DNR). Guidelines for Constructing Wetland Stormwater Basins. Annapolis, Maryland: Water Resources Administration, March, 1987.

Maryland Department of Natural Resources (Md. DNR). Wetland Basins for Stormwater Treatment; Discussion and Background. Annapolis, Maryland: Water Resources Administration, undated.

McCuen, R.H. “Design Accuracy of Stormwater Detention Basins.” Technical Report, Department of Civil Engineering, University of Maryland, 1983.

Northern Virginia Planning District Commission. Northern Virginia BMP Handbook. 1992.

Perham, R.E. “Floating Debris Control: A Literature Review.” Hanover, NH: U.S. Army CREL, 13, 1987.

Poertner, H.G. “Practices in the Detention of Urban Stormwater Runoff.” American Public Works Association, OWWR Proj. C-3380, 1974.

Schueler, T.R., P.A. Kumble, and M.A. Heraty, A Current Assessment of Urban Best Management Practices. Washington, D.C.: Metropolitan Washington Council of Governments (MWCOG), March 1992.

Schueler, T.R. Design of Stormwater Wetland Systems: Guidelines for Creating Diverse and Effective Stormwater Wetland Systems in the Mid-Atlantic Region. Washington, D.C.: Metropolitan Washington Council of Governments, October, 1992.

Schueler, T.R. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Washington, D.C.: Metropolitan Washington Council of Governments, July, 1987.

Smith, P.H. and J.S. Cook, “Stormwater Management Detention Pond Design Within Floodplain Areas.” Trans., Res. Record 1017, 1987.

Stahre, P. and B.Urbonas. “Stormwater Detention.” Prentice Hall, 1990.

State of Maryland. “Design Procedures for Stormwater Management Detention Structures.” Department of the Environment, Sediment and Stormwater Division, 1987.

The Virginia Department of Conservation and Recreation (DCR). Virginia Erosion and Sediment Control Handbook (VESCH). 3rd. ed. Richmond, Virginia: 1992.

U. S. Department of the Interior, Bureau of Reclamation. Design of Small Dams. 1987.

USDA Soil Conservation Service. Engineering Field Manual.

USDA Soil Conservation Service. National Engineering Handbook.

Washington State Department of Ecology. “Stormwater Management Manual for the Puget Sound Basin.” 1992.

Extended Detention Basin – full. Note circuitous flow path.

Enhanced Extended Detention Basin – Shallow Marsh. Note multi-stage weir principal spillway and deep water pool (18” – 48” depth).

Extended-Detention Basin & Enhanced Extended-Detention Basin

Extended Detention Basin – empty.

Extended Detention Basin – full.

Extended-Detention Basin & Enhanced Extended-Detention Basin

MINIMUM STANDARD 3.09

CONSTRUCTED STORMWATER WETLAND

View BMP Images

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MINIMUM STANDARD 3.09

CONSTRUCTED STORMWATER WETLAND

Definition

Constructed stormwater wetlands are manmade shallow pools that create growing conditions suitable for both emergent and aquatic vegetation.

Purpose

Constructed wetlands are intentionally installed on non-wetland sites to enhance the quality of stormwater runoff.

In contrast, *created wetlands* are also intentionally installed on non-wetland sites, but are designed to produce or replace natural functional wetlands and wetland habitats (e.g., for compensatory mitigation projects).

This handbook deals primarily with *constructed wetlands*. Sometimes, a constructed wetland may provide some of the benefits of a created wetland. However, understanding the differences in these two manmade systems is important. For a *natural* or *created wetland*, pre-treatment BMPs, such as erosion controls, presettling basins, biofilters, etc., are used to reduce pollutants entering the wetland to prevent its degradation and clogging. The primary function of a *constructed wetland*, on the other hand, is to provide those same types of pre-treatment functions within the wetland itself. The constructed wetland, therefore, will require maintenance to assure long-term pollutant removal. **It should be noted that the pre-treatment BMPs mentioned above will often simplify or reduce maintenance requirements, as well as enhance and prolong the useful life of a constructed stormwater wetland.**

<u>Water Quality Enhancement</u>

A constructed stormwater wetland can achieve high removal rates of particulate and soluble pollutants (nutrients) through gravitational settling, wetland plant uptake, absorption, physical filtration, and biological decomposition. The pollutant removal efficiency of a constructed wetland is dependent on various design criteria relating to the size and design of the pool area. Other site-specific design features and variations in environmental conditions such as soils, climate, hydrology, etc. make it difficult to predict the actual pollutant removal efficiency. Monitoring of many stormwater wetland facilities has confirmed the wide range of pollutant removal efficiencies associated with such systems.

Constructed stormwater wetlands operate similar to retention basins, yet their overall performance is expected to be more variable. This may be due to any of the following:

1. The decrease in biological activity associated with seasonal cold weather.

2. The conversion of plant species and densities as the wetland matures and becomes acclimated to various environmental factors such as soils, hydrology, climate, and sediment and pollutant load.

3. The uncertainty of the biological cycling processes of phosphorous in the wetland environment.

The expected pollutant removal rate of constructed stormwater wetlands is provided in **Table 3.09-1**. While the rate may appear low, it reflects the uncertainty of their long-term viability.

TABLE 3.09 - 1
Pollutant Removal Efficiency for Constructed Stormwater Wetlands

Water Quality BMP	Target Phosphorus Removal Efficiency	Impervious Cover
Constructed Wetlands 2.0 x WQ Volume	30%	22 - 37%

Flood Control & Channel Erosion Control

Constructed stormwater wetlands should generally not be used for flood control or stream channel erosion control. This is due to the anticipated water level fluctuations associated with quantity controls. The clearing of vegetation and the addition of impervious surfaces may cause large and sudden surges of runoff during rain events, and may cause less than normal base flows due to lack of groundwater during dry periods. Large, sudden fluctuations in water levels can stress emergent wetland and upland edge vegetation. Most edge vegetation cannot survive drought or saturation extremes, leaving wetland banks exposed to potential erosion. It should be noted that the large surface area requirement for constructed stormwater wetlands will help to minimize the “extreme” water level fluctuations during all but the larger storm events. Also, certain plants can be specified for the upland banks which may be more tolerant to the wet and dry extremes. Therefore, preventing surges whenever possible and designing for gradual increases and decreases in water level is important for successful constructed wetland design. See **Design Criteria** for further discussion.

(Wetland vegetation can be used to enhance the pollutant removal efficiency of extended-detention flood control and stream channel erosion control facilities by constructing a shallow marsh in their bottoms. See **Minimum Standard 3.07, Extended-Detention and *Enhanced* Extended-Detention Basin**.)

Conditions Where Practice Applies

Drainage Area

The drainage area criteria for a constructed stormwater wetland is similar to that of a retention basin. However, because of their shallow depth, constructed stormwater wetlands may consume two to three times the site area compared with other stormwater quality BMPs (MWCOG, 1992). Vertical (depth) storage is usually not possible in constructed wetlands due to the needs of aquatic plants. Therefore, the maximum watershed size depends on the available area on the site that is suitable for a constructed wetland system.

The minimum watershed drainage area for constructed stormwater wetlands should be 10 acres. However, this minimum should be confirmed based on the watershed's hydrology and the presence of an adequate base flow to support the selected vegetation. Similar to retention basins, a drainage area of 15 to 20 acres or the presence of a dependable base flow is most desirable to maintain a healthy wetland. A clay liner may be necessary to prevent infiltration if losses are expected to be high.

Development Conditions

Constructed stormwater wetlands are suited for both low- and high-visibility sites. However, the aesthetic problems associated with having a natural and free growing landscape feature in an otherwise manicured development setting should be avoided for high-visibility sites. Additional concerns regarding stagnation or excessive infiltration during the dry summer months may also influence the choice of location. Proper planning, design, and maintenance are critical to ensure the pollutant removal capabilities of a constructed wetland and to insure its acceptance by adjacent landowners.

Like retention basins, constructed wetlands are also suited for low- and medium-density residential or commercial developments. However, the land area required for this BMP may limit its use.

Planning Considerations

Constructed stormwater wetlands should be designed to duplicate the functions of natural wetlands, while allowing for ongoing maintenance. The designer faces the difficult task of replicating natural wetland hydrology in a constructed setting, while ensuring easy access for maintenance.

Hydrology

The hydrology of a constructed stormwater wetland is largely influenced by surface runoff. The hydrology, in turn, affects several key characteristics of a stormwater wetland, such as:

1. *Water level fluctuations*. A *constructed stormwater* wetland will experience rapid inundation and drawdown periods with each runoff-producing event.

2. *Permanent pool*. A *natural* wetland may experience seasonal standing water and/or periodic drawdowns. However, a constructed stormwater wetland is engineered to permanently hold a specific volume of water, or at a minimum, maintain pools of water of varying depths. This stored water supports the aquatic and emergent plant regime and maintains the pollutant removal efficiency of the BMP.

3. *Vegetation*. The vegetation diversity in a constructed wetland is established by the landscape plan or volunteer vegetation. The selection of vegetation should be limited to native plant species suitable for the pool depths expected within the different depth zones. Care should be taken to avoid the introduction of exotic or invasive species. The use of appropriate donor soil and wetland mulch will help prevent this problem.

   In contrast, a natural wetland vegetates itself through natural selection based on the growing conditions within it. The existing source of seeds, which is usually enhanced by wildlife, allows for the constant renewal of plant life.

4. *Sediment and pollutant load*. A stormwater wetland is subject to sediment loads, especially from upland pervious areas during the first growing season. During this period, permanent vegetation in the developing watershed is still growing. Without a well-established ground cover, surface sediments can be easily transported by rainfall and resulting runoff. Accumulation of this sediment in the constructed stormwater wetland during the first growing season alone can dramatically alter the topography of the facility, affecting water levels and flow paths. Furthermore, the pollutant load (nutrients and organics) associated with urban runoff and sediments entering a constructed wetland is usually higher than that which enters a natural or undisturbed wetland in undeveloped watershed. Therefore, if the constructed wetland is used to remove pollutants, the water quality within the wetland itself will be decreased. During the planning stage of a facility, the designer should have a good understanding of site-specific runoff constituents and an understanding of their possible effects on the selected vegetation.

Site Conditions

Site conditions, such as property lines, easements, utilities, structures, etc., that may impose constraints on development should be considered when designing a constructed wetland. Local government land use and zoning ordinances may also specify certain requirements.

All facilities should be a minimum of 20 feet from any structure, property line, or vegetative buffer, and 100 feet from any septic tank/drainfield. Local landuse setbacks and other restrictions may apply.

All facilities should be a minimum of 50 feet from any steep slope (greater than 10%). Alternatively, a site-specific geotechnical report must address the potential impact of a constructed stormwater wetland that is to be installed on, or near, such a slope.

Additional considerations are as follows:

1. **Soils–**

   Permeable soils are not suited for constructed stormwater wetlands. A thorough analysis of the soil strata should be conducted to verify its suitability for holding water. In the past, many BMP designs were accepted based upon soils information compiled from available data, such as SCS soil surveys. While such a source may be appropriate for a pre-engineering feasibility study, final design and acceptance **should be based on an actual subsurface analysis and permeability tests**, accompanied by appropriate engineering recommendations. Refer to the references listed at the end of **Minimum Standard 3.10, Infiltration Practices** for additional information on soil analysis techniques.

   The goal of a subsurface analysis is to determine if the soils are suitable for a constructed stormwater wetland. The textural character of the soil horizons and/or strata units within the subsoil profile should be identified to at least 3 feet below the bottom of the facility. This information is used to verify the infiltration rate or permeability of the soil. For constructed stormwater wetlands, water inflow (base flow and groundwater) must be greater than water losses (infiltration and evaporation). If the infiltration rate of the soil is too great, then a constructed wetland may not be an appropriate BMP, or a liner may be required. The soil permeability may be such that the shallow depths of a constructed wetland can be maintained. However, as the depth of the permanent pool increases, the increased head or pressure on the soil may increase the infiltration rate.

   For discussions regarding the appropriate soils for landscaping, see the Landscape section in this standard and **Minimum Standard 3.05, Landscaping**.

2. **Rock–**

The subsurface investigation should also identify the presence of any rock or bedrock layers. The excavation of rock to achieve the proper wetland dimensions and hydrology may be too expensive or difficult with conventional earth moving equipment. However, blasting may open seams or create cracks in the underlying rock that may result in unwanted drawdown of the permanent pool. Blasting of rock is not recommended unless a liner is used.

3. **Karst–**

In regions where Karst topography is prevalent, projects may require a thorough soils investigation and specialized design and construction techniques. Since the presence of karst may affect BMP selection, design, and cost, a site should be evaluated **during the planning phase of the project**.

4. **Existing Utilities–**

Most utility companies will not allow their underground lines and right-of-ways to be submerged under a permanent pool. If such a site must be used, the designer should obtain permission **before designing the BMP**. Note that if the utilities ever require maintenance or repair, the characteristics of the constructed wetland may be irreparably changed or damaged. The cost to move any existing utilities during initial wetland construction should be determined and included in the project's overall construction costs.

Environmental Impacts

Constructed stormwater wetlands are generally located in areas with favorable hydrology. These locations are prone to being environmentally sensitive (low-lying) as well, and may contain existing wetlands, shallow marshes, perennial streams, wildlife habitat, etc., which may be protected by state or federal laws. The owner or designer should review local wetland maps and contact local, state, and federal permitting agencies to verify the presence of wetlands, their protected status, and the suitability of the location for a constructed wetland.

With careful planning, it may be possible to incorporate wetland mitigation into a constructed stormwater wetland. This assumes that the functional value of the existing or impacted wetland can be identified and included, reconstructed, or mitigated for, in the stormwater wetland. The Virginia Department of Environmental Quality should be contacted for more information regarding wetland mitigation.

Sediment Control

A constructed stormwater wetland should not be used as a sediment control facility during site construction. A presettling basin, or forebay, may be constructed above the proposed constructed wetland facility, however, any planting or preparation of the constructed wetland site should occur after the site construction has been completed. This will eliminate any forseeable impact from sediment loads that overwhelm temporary erosion and sediment control measures during storm events.

Maintenance

Constructed stormwater wetlands require periodic maintenance, as does any stormwater BMP. In addition, a constructed wetland will require active management of the hydrology and vegetation during the first few years or growing seasons in order for it to achieve the performance and functions for which it was designed.

Vehicular access and manuvering room in the vicinity of a constructed wetland (and sediment forebay) is necessary to allow for long-term maintenance. In addition, the establishment of an on-site sediment disposal area, properly located and contained, will significantly reduce the cost of routine maintenance and sediment removal. Care must be taken in the disposal of sediment that may contain an accumulation of heavy metals. **Sediment testing is recommended prior to sediment removal to assure proper disposal**.

Design Criteria

This section provides minimum criteria and recommendations for the design of a constructed stormwater wetland intended to comply with the runoff quality requirements of the Virginia Stormwater Management program. It is the designer's responsibility to decide which aspects of the program apply to the particular facility being designed and if any additional design elements are required to insure the long-term functioning of the wetland.

Hydrology and Hydraulics

Chapter 4, Hydrologic Methods and **Chapter 5, Engineering Calculations** should be used to develop the post-developed hydrology of the wetland's contributing watershed, to analyze the hydraulics of the riser and barrel system (if used) and to design the emergency spillway.

The contributing watershed's area should be a minimum of 10 acres and/or there should be an adequate base flow to support the hydrology.

Embankment

The design of the earthen embankment for any impoundmant BMP should comply with **Minimum Standard 3.01, Earthen Embankment**. Specific requirements for geotechnical analysis, seepage control, maximum slopes, and freeboard are particularly appropriate.

Principal Spillway

The design of the principal spillway and barrel system, or weir overflow system, anti-vortex device, and trash racks should comply with **Minimum Standard 3.02, Principal Spillway**. Weir spillways have a large cross-sectional area that can pass a considerable flow rate at low head conditions. Since reducing the depth of ponding in a constructed wetland helps to avoid stressing plant communities, an armored, weir-type spillway may be the most desirable overflow device for a constructed stormwater wetland. Further, the use of an adjustable weir will help maintain the proper water surface elevation during seasonal extremes.

Emergency Spillway

An emergency spillway that complies with **Minimum Standard 3.03, Vegetated Emergency Spillway** should be provided when possible.

Permanent Pool

Sizing a constructed stormwater wetland is based on maximizing its pollutant removal efficiency. The physical and hydraulic factors that influence the wetland's pollutant removal efficiency are the permanent pool *volume*, *depth*, *surface area*, *geometry*, and *hydraulic residence time*. Minimum design criteria are presented below for each of these factors:

1. **Volume –**

The required permanent pool volume of a constructed stormwater wetland is **2 times the water quality volume** (2 ×WQV). The target pollutant removal efficiency shown in **Table 3.09-1** is based on this sizing criteria.

2. **Depth –**

Four depth zones are needed within the permanent pool of a constructed stormwater wetland: a) *deep pool*, b) *low marsh*, c) *high marsh*, and d) *semi-wet* (see **Figure 3.09-2**).

a. The *deep pool* areas of a constructed wetland should be 18 *inches* to 6 *feet* in depth and may consist of 1) *sediment forebays*, 2) *micro-pools*, and/or 3) *deep-water channels*.

    1. *Sediment forebays* are highly recommended in constructed stormwater wetlands. They should be installed at stormwater inflow points to reduce the velocity of

incoming runoff and trap course sediments, and to spread the runoff evenly over the wetland area. The forebay should be constructed as a separate cell from the rest of the wetland and provide easy access for maintenance with heavy equipment. Refer to **Minimum Standard 3.04, Sediment Forebay** for further information.

2. *Micro-pools* offer open water areas to attract plant and wildlife diversity. If a low-flow discharge pipe is used, it should be constructed on a reverse slope and extended into the wetland below the pool surface elevation but above the bottom elevation. This helps to prevent clogging, since a typical wetland environment consists of floating plant debris and possible sediment and organic accumulation at the bottom. (Refer to the **Overflow** discussion later in this section.)

3. *Deep-water channels* provide an opportunity to lengthen the flow path to avoid seasonal short-circuiting (see pool geometry).

b. The *low-marsh zone* ranges in depth from 6 to 18 inches.

c. The *high-marsh zone* ranges in depth from 0 to 6 inches. Usually, this zone will support the greatest density and diversity of emergent plant species.

d. The *semi-wet zone* refers to the area that, during normal, non-rainfall periods, is above the pool, but is inundated during storm events for a period of time, depending on the amount of rainfall, and the hydraulics of the overflow device.

Note: The low-marsh, high-marsh, and semi-wet zones are useful as a perimeter shelf 10 to 15 feet wide. This shelf, or aquatic bench, can serve as a safety feature to keep children away from the open water deep pool areas. Also, as a secondary benefit, a heavily vegetated perimeter will help to discourage geese from using the facility as a permanent habitat.

The recommended surface area allocation for these depth zones is presented in **Table 3.09-2.**

3. **Surface Area–**

At a minimum, the pool surface area of a constructed stormwater wetland should equal 2% of the size of the contributing watershed. Recommended surface area allocations for different depth zones are shown in **Table 3.09-2** (MWCOG, 1992). Note that if the surface area criteria conflict with the volume allocations, the surface area allocations are more critical to an effective design.

4. **Geometry–**

The geometry of the constructed stormwater wetland must be designed to avoid short-circuiting. Maximum pollutant removal efficiency is achieved with the longest possible flow path, since this increases the contact time over the wetland area. The minimum length-to-width ratio of the pool should be 1:1 in wet weather and 2:1 during dry weather (see **Figure 3.09-3**).

TABLE 3.09-2
Recommended Allocation of Surface Area and Treatment Volume for Various Depth Zones

Depth Zone	% of Surface Area	% of Treatment Volume
Deep Water 1.5 to 6 feet deep	10	20
Low Marsh 0.5 to 1.5 feet deep	40	*
High Marsh 0 to 0.5 feet deep	50	*
		* combined marsh area = 80% of treatment volume

Adapted from MWCOG, 1992

The **wet weather** *length-to-width ratio* is calculated by dividing the straight line distance from the inlet to the outlet by the wetland's average width. The **dry weather** *length-to-width ratio* is calculated by dividing the dry weather flow path length by the wetland's average width. Note that the dry weather flow path is created by constructing high marsh areas perpendicular to the straight line flow path described above. These marsh areas act as submerged berms and lengthen the effective flow path.

5. **Hydraulic Residence Time–**

The hydraulic residence time is the permanent pool volume, divided by the average outflow discharge rate. The longer the residence time, the higher the pollutant removal efficiency (Driscoll, 1983, Kulzer, 1989).

Using *2 × WQV* to size the permanent pool means that smaller storms (*1 × WQV* or *½-in.*) will displace only half of the pool volume of the wetland, thus providing for extended residence times. Larger treatment volumes with respect to the watershed size (*3 × WQV*) will provide longer residence times and, therefore, greater efficiencies. In certain situations, using these larger volumes and efficiencies may be acceptable, but the decision should be made carefully. The associated challenge is to provide the recommended surface area allocations for the different depth zones as previously discussed.

<u>Overflow</u>

Providing flood control and/or channel erosion control within a constructed stormwater wetland creates a hydrologic regime that is very difficult to adapt to in the landscaping plan, due to extreme water depth fluctuations. If a constructed wetland is to serve as a quantity control BMP, it should be designed to provide adequate overflow or bypass for the full range of design storms with as little vertical ponding depth as possible. The hydraulic head needed to pass a design storm is a function of the relationship between the constructed wetland surface area, the geometry of the overflow structure, and the allowable discharge (refer to **Chapter 5, Engineering Calculations**). Outlet structures should be sized to pass the design storms (up to the 10-year storm) with a maximum of 2 feet of water ponded above the wetland pool.

In a stormwater wetland designed for water quality enhancement only, a bypass or diversion structure may be used to prevent sudden surges of runoff from flushing through the wetland (see **Figure 3.09-4**). This establishes the constructed wetland as an off-line facility. If site constraints prevent the use of an off-line facility, then the overflow should be designed to pass the full range of design storms with as little head as possible. An oversized riser and barrel system or a weir structure installed along the berm at the outlet may be used. Refer to **Minimum Standard 3.02, Principal Spillway** for outlet structure design criteria.

Sediment Forebay

Sediment forebays should be installed and designed per **Minimum Standard 3.04, Sediment Forebay**. Generally, they should be constructed at the outfall of incoming storm drain pipes or channels and should be made accessible for maintenance equipment. To lower maintenance costs, an on-site disposal area should be included in the design. Sediment forebays enhance the pollutant removal efficiency of BMPs by containing incoming sediment in one area, which also simplifies monitoring and removal. Therefore, the target pollutant removal efficiency of a constructed stormwater wetland, as presented in **Table 3.09-1**, is predicated on the use of sediment forebays at all inflow points.

Liner to Prevent Infiltration

Constructed stormwater wetlands should have negligible infiltration rates through their bottom. Infiltration impairs the proper functioning of any retention facility by lowering its pool elevation. If infiltration is expected, then a retention BMP must **not** be used, **or** a liner should be installed to prevent infiltration. If a clay liner is used, the specifications provided in **Table 3.09-3** apply and the following are recommended:

1. A clay liner should have a minimum thickness of 12 inches.

2. A layer of compacted topsoil (6 to 12 inches thick, minimum) should be placed over the liner.

3. Other liners may be used if adequate documentation exists to show that the material will provide the required performance.

Safety

The side slopes of a constructed stormwater wetland should be no steeper than 3H:1V. Also, local ordinances may require fencing of deep pool areas next to the shoreline as an additional safety measure. Dense plantings of shoreline fringe vegetation can serve as a safety feature by discouraging access to the pool areas.

TABLE 3.09 - 3
Clay Liner Specifications

Property	Test Method (or equal)	Unit	Specification
Permeability	ASTM D-2434	*cm/sec*	1 x 10^{-6}
Clay Plasticity Index	ASTM D-423 & D-424	%	Not less than 15
Liquid Limit of Clay	ASTM D-2216	%	Not less than 30
Clay Particles Passing	ASTM D-422	%	Not less than 30
Clay Compaction	ASTM D-2216	%	95% of Standard Proctor Density

Source: City of Austin, 1988

Access

A 10 to 12-foot wide access road with a maximum grade of 12% should be provided to allow vehicular access to the outlet structure area, at least one side of the basin, and the sediment forebay(s). The road’s surface should be selected to support the anticipated frequency of use and vehicular load without excessive erosion or damage.

Landscaping

A qualified individual should prepare the landscape plan for a constructed stormwater wetland. Appropriate aquatic, emergent, shoreline fringe, transitional, and floodplain terrace vegetation must be selected to correspond with the expected frequency, duration, and depth of inundation.

The landscaping plan for a constructed wetland is based on the projected depth zones and onsite soil analysis, and should contain the following:

1. **The location, quantity, and propagation methods of plant species and grasses for the stormwater wetland and its buffer.**

The location of plants is based on the depth zones in the wetland and the innundation tolerance of the plant species. Planting zones of uniform depth should be identified for each species selected.

Only one-half of the low- and-high marsh depth zones need to be planted. If the appropriate planting depths are achieved, the entire wetland should be colonized within three years. At least 5 to 7 emergent wetland species, including a minimum of two species for each of the marsh depth zones (high and low), should be used. Selections should be based on wildlife food value, depth tolerance, price, commercial availability and/or shade limitations. Certain species, such as cattails, should be selected with caution. Although they may provide excellent pollutant removal characteristics, they can be invasive and may eventually crowd out other species.

A constructed stormwater wetland does not contain a seed bank, nor does it have an existing natural seed transport cycle as found in native wetlands. While the use of donor soil from disturbed or dredged sites may provide a seed bank, these opportunities may not be readily available. Therefore, the most common and convenient technique for establishing wetland vegetation in a constructed system is to transplant nursery-grown stock. Other propagation techniques (which are outside the scope of this manual) may also prove successful, but special growing conditions must exist.

2. **Instructions for site preparation**.

The soil in which the vegetation is planted should be appropriate for the wetland plants selected. Soil tests showing the adequacy of the soil, or a soil enhancement plan should be submitted with the wetland design.

The soil substrate must be soft enough to permit easy insertion of the plants. If the basin soil is compacted or vegetation has formed a dense root mat, the upper 6 inches of soil should be disked before planting. If soil is imported, it should be laid at least 4 inches deep to provide sufficient depth for plant rooting.

3. **A schedule for transplanting emergent wetland stock**.

The window for transplanting emergent stock extends from early April to mid-June. Dormant rhizomes can be planted in fall or winter. To insure availability, ordering stock 3 to 6 months in advance may be necessary.

4. **Planting procedures**.

A landscape plan should describe any special procedures for planting nursery stock. Most emergent plants may be planted in flooded or dry conditions. If planting is done in dry conditions, then instructions should be included for flooding the wetland immediately following installation.

Proper handling of nursery stock is crucial. The roots must be kept moist to prevent damage. Plants received from the nursery will be in peat pots or bare-rooted. Bare-rooted plants will have some form of protection to keep the roots moist and may be kept for several days, but out of direct sunlight. For the maximum chance of success, all nursery stock should be planted as soon as possible. A minimum acceptable success rate of the plantings should be specified in the plan.

5. **A maintenance and vegetation reinforcement schedule for the first three years after construction**.

Sometimes additional stabilization of the basin area may be necessary to ensure that the vegetation becomes established and mature prior to the erosion of the planting soil. Annual grasses may be used for this purpose. However, the specified application rates in the Virginia Erosion and Sediment Control Handbook (VESCH), 1992 edition: Temporary Seeding Spec. 3.31 should be reduced to help prevent these grasses from competing with other plants, particularly those emerging from bulbs and rhizomes. Overall, permanent seeding (VESCH Spec. 3.32) should be prohibited in zones 1 through 4, as the grasses will indefinitely compete with the wetland plants. Refer to the Maintenance and Inspection section in this standard for more information.

Additional considerations and criteria for developing a landscape plan can be found in **Minimum Standard 3.05, Landscaping**.

Buffer Zones

A minimum 20-foot wide vegetated buffer, measured from the maximum water surface elevation, should be maintained beside the wetland. Refer to **Minimum Standard 3.05, Landscaping**.

Construction Specifications

Overall, widely accepted construction standards and specifications, such as those developed by the USDA Soil Conservation Service or the U.S. Army Corps of Engineers for embankment ponds and reservoirs, should be followed to build the impoundment.

Further guidance can be found in Chapter 17 of the Soil Conservation Service's Engineering Field Manual. Specifications for the work should conform to methods and procedures specified for earthwork, concrete, reinforcing steel, pipe water gates, metal work, woodwork and masonry and any other items that apply to the site and the purpose of the structure. The specifications should also satisfy any requirements of the local government.

Guidance and construction specifications in the following minimum standards also apply for various components of the facility: **3.01, Earthen Embankment**; **3.02, Principal Spillway**; **3.03, Vegetated Emergency Spillway**; **3.04, Sediment Forebay**; and **3.05, Landscaping**.

Maintenance and Inspections

A constructed stormwater wetland may be maintained without a permit from the U. S. Army Corps of Engineers or the Virginia Department of Environmental Quality (Va. DEQ).

Any pre-treatment facility or diversion structure should be inspected and maintained regularly to remove floatables and any large debris. Sediment should be removed from the forebay every 3 to 5 years, or when 6 to 12 inches have accumulated, whichever comes first. To clean the forebay, draining or pumping and a possible temporary partial drawdown of the pool area may be required. Refer to the VESCH, 1992 edition for proper dewatering methods. A predesignated spoil area, away from the wetlands, should be used.

The constructed stormwater wetland should be inspected at least twice a year in the first three years after construction, during both the growing and non-growing seasons,for vegetative establishment. Inspectors should document plant species distribution and fatality rates and verify compliance with the landscaping specifications. Also, sediment accumulation, water elevations, and the condition of the outlet should be documented. Records should be kept to track the wetland's health over time.

Management of Wetland Vegetation

The constructed wetland and its buffer may need a *reinforcement planting* at the onset of the second growing season after construction. The size and species of plants to be used should be based on the growth and survival rate of the existing plants at the end of their first growing season. Controlling the growth of certain invasive species, such as cattail and phragmites, may also be necessary. These plants can be very hard to contain if they are allowed to spread unchecked. The best strategy may be to design for a wide range of distinct depth zones.

Research shows that for most aquatic plants the bulk of the pollutants is stored in the roots, not the stems and leaves (Lepp 1981). Therefore, harvesting before winter dieback is unnecessary. Many unanswered questions remain concerning the long-term pollutant storage capacity of plants. Additional plant maintenance recommendations may be presented in the future, as such information becomes available.

The embankment and BMP access road should be mowed biannually, at a maximum, to prevent the growth of trees. Otherwise, the buffer and upland areas should be allowed to grow in meadow conditions.

FIGURE 3.09 - 1
Constructed Stormwater Wetlands - Plan

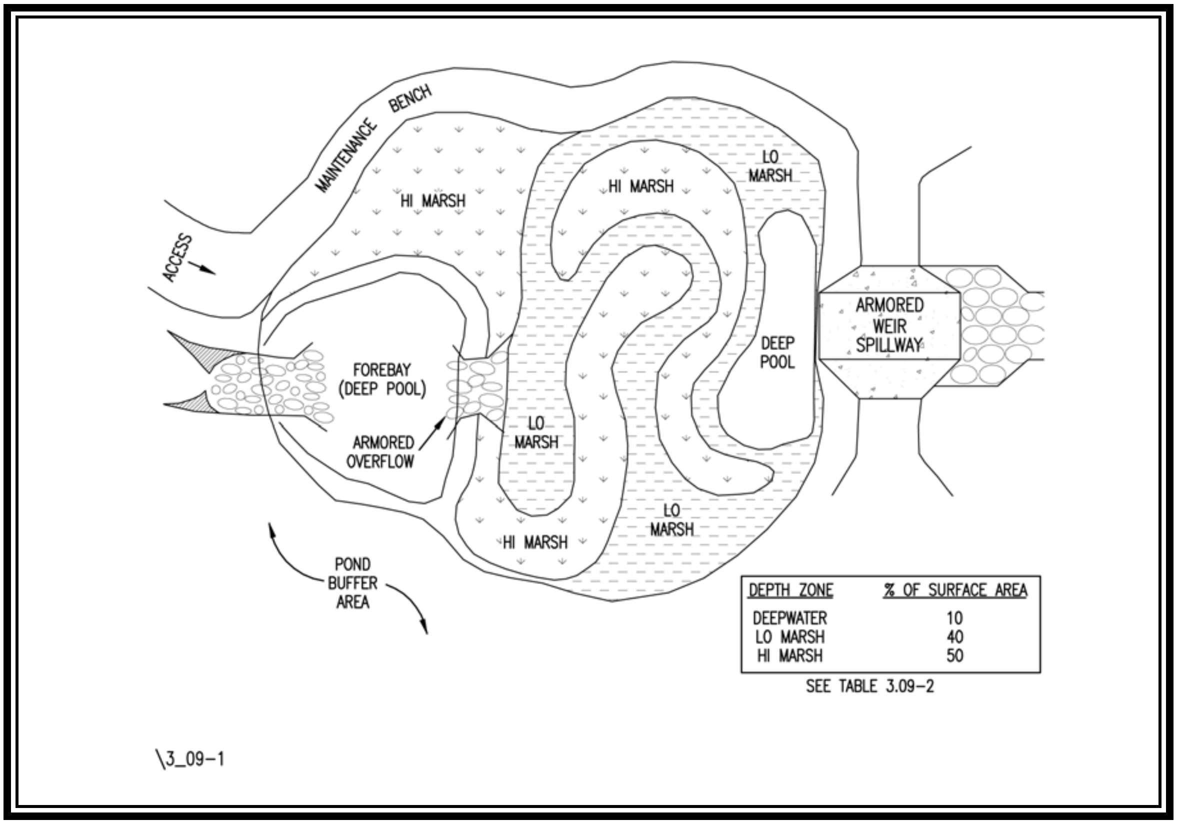


FIGURE 3.09 - 2
Constructed Stormwater Wetlands - Depth Zones

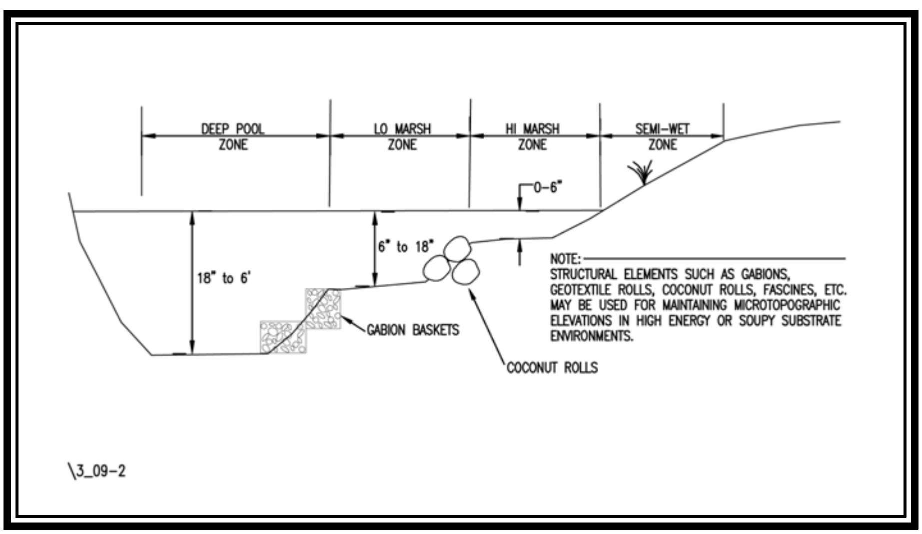


FIGURE 3.09 - 3
Dry Weather and Wet Weather Flow Paths

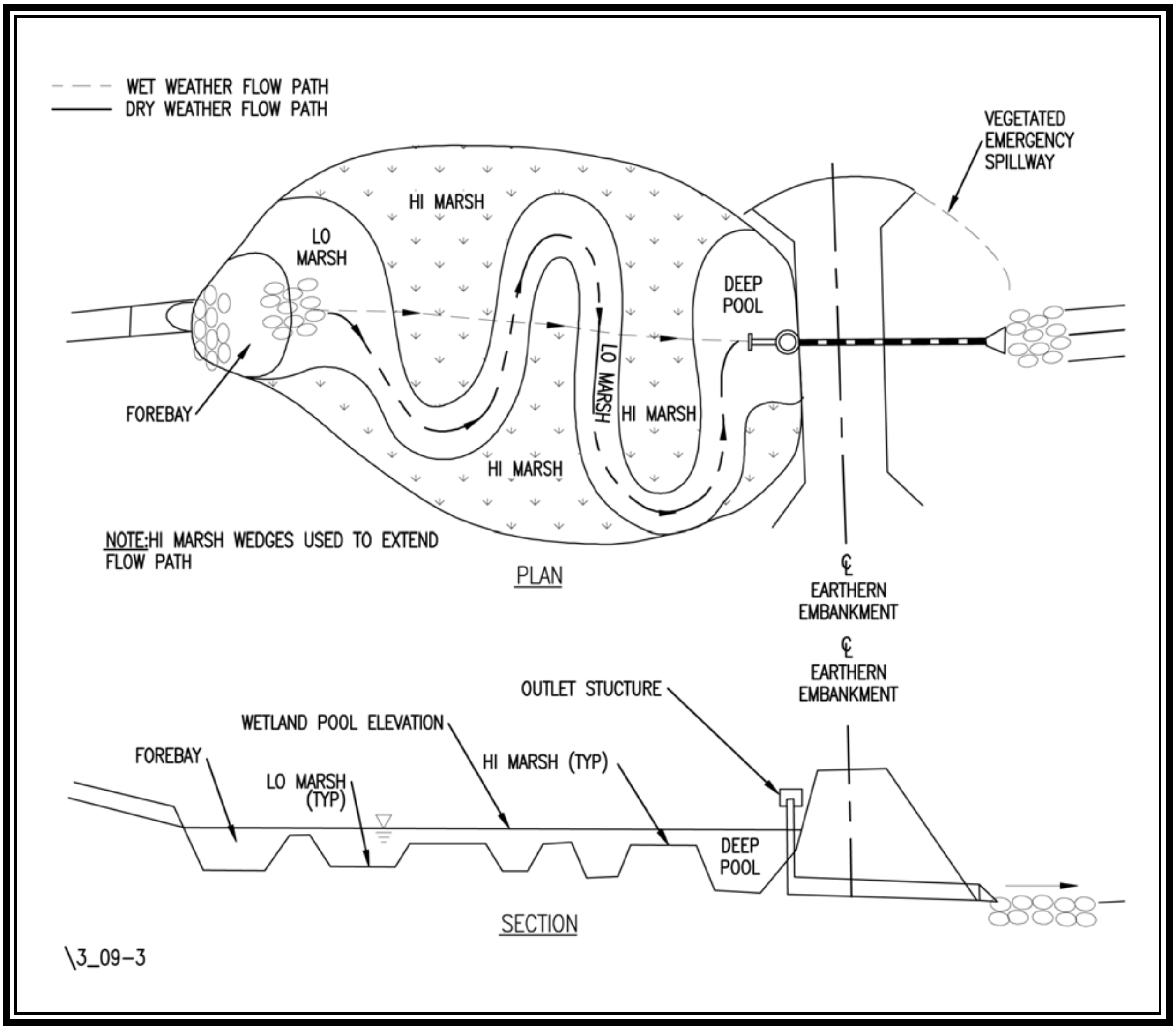
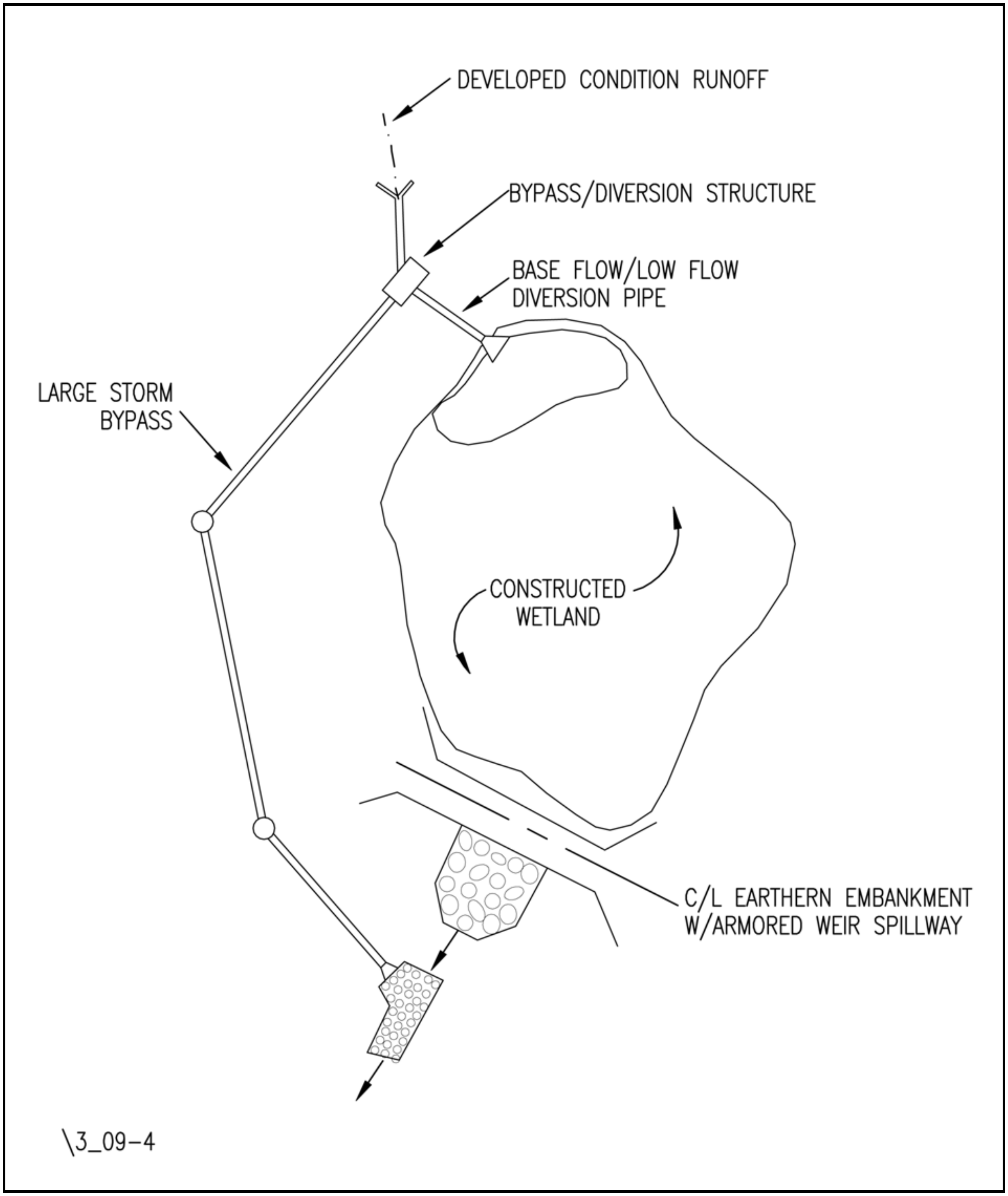


FIGURE 3.09 - 4
Off-line Bypass Structure



REFERENCES

Chesapeake Bay Local Assistance Department (CBLAD). Local Assistance Manual: A Guide for the Development of Local Programs in Order to Comply with the Chesapeake Bay Preservation Act. Richmond, Virginia: November 1989.

Galli, J. Analysis of Urban BMP Performance and Longevity in Prince George's County, Maryland. Washington, D.C.: Metropolitan Washington Council of Governments (MWCOG), August, 1992.

Maryland Department of Natural Resources (Md. DNR), Water Resources Administration. Guidelines for Constructing Wetland Stormwater Basins. Annapolis, Maryland: March, 1987.

Maryland Department of Natural Resources (Md. DNR), Water Resources Administration. Wetland Basins for Stormwater Treatment; Discussion and Background. Annapolis, Maryland: undated.

Northern Virginia Planning District Commission (NVPDC). Northern Virginia BMP Handbook. Annandale, Virginia: November, 1992.

Schueler, T.R. Design of Stormwater Wetland Systems: Guidelines for Creating Diverse and Effective Stormwater Wetland Systems in the Mid-Atlantic Region. Washington, D.C.: Metropolitan Washington Council of Governments (MWCOG), October, 1992.

Schueler, T.R., P.A. Kumble, and M.A. Heraty. A Current Assessment of Urban Best Management Practices. Washington, D.C.: Metropolitan Washington Council of Governments (MWCOG), March 1992.

Schueler, T. R. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Washington, D.C.: Metropolitan Washington Council of Governments (MWCOG), July, 1987.

Virginia Department of Conservation and Recreation (DCR). Virginia Erosion and Sediment Control Handbook (VESCH). 3rd ed. Richmond, Virginia: 1992.

Washington State Department of Ecology. Stormwater Management Manual for the Puget Sound Basin (The Technical Manual). Olympia, Washington: February, 1992.

Constructed Stormwater Wetland – recently completed.

Constructed Stormwater Wetland – becoming stabilized, emergent vegetation barely visible.

Constructed Stormwater Wetland

Constructed Stormwater Wetland. Note vegetation protected from waterfowl by netting system.

Forebay and Constructed Stormwater Wetland incorporated into regional retention basin design.

Constructed Stormwater Wetland

MINIMUM STANDARD 3.10

GENERAL INFILTRATION PRACTICES

3.10A	Infiltration Basin
3.10B	Infiltration Trench
3.10C	Roof Downspout System
3.10D	Porous Pavement

View BMP Images

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MINIMUM STANDARD 3.10

GENERAL INFILTRATION PRACTICES

Definition

Infiltration facilities temporarily impound stormwater runoff and discharge it via infiltration into the surrounding soil.

Purpose

Infiltration facilities are primarily used for water quality enhancement. Their use to control large volumes of runoff for flooding and channel erosion control is often impractical. Therefore, the infiltration facilities presented in this handbook should generally be used to control the water quality volume and up to the 2-year design storm only. Infiltration practices that capture all of the runoff from the "first flush" (i.e., the water quality volume) may utilize dry storage above the water quality volume to provide sufficient reductions in the 1- or 2-year peak discharge as required. The 10-year and 100-year flows will usually exceed the capacity of an infiltration facility. **Table 3.10-1** contains the target pollutant removal efficiencies based on the runoff volume to be controlled.

Infiltration practices are appealing in that they help to reverse the hydrologic consequences of urban development by reducing peak discharge and providing groundwater recharge.

TABLE 3.10 - 1
Pollutant Removal Efficiency for Infiltration Facilities

BMP Description	Target Phosphorus Removal Efficiency
Infiltration facility with storage volume equivalent to 0.5 inches of runoff from the impervious Area.	50%
Infiltration facility with storage volume equivalent to 1.0 inch of runoff from the impervious area.	65%

FIGURE 3.10 - 1a
Infiltration Basin - Plan and Section

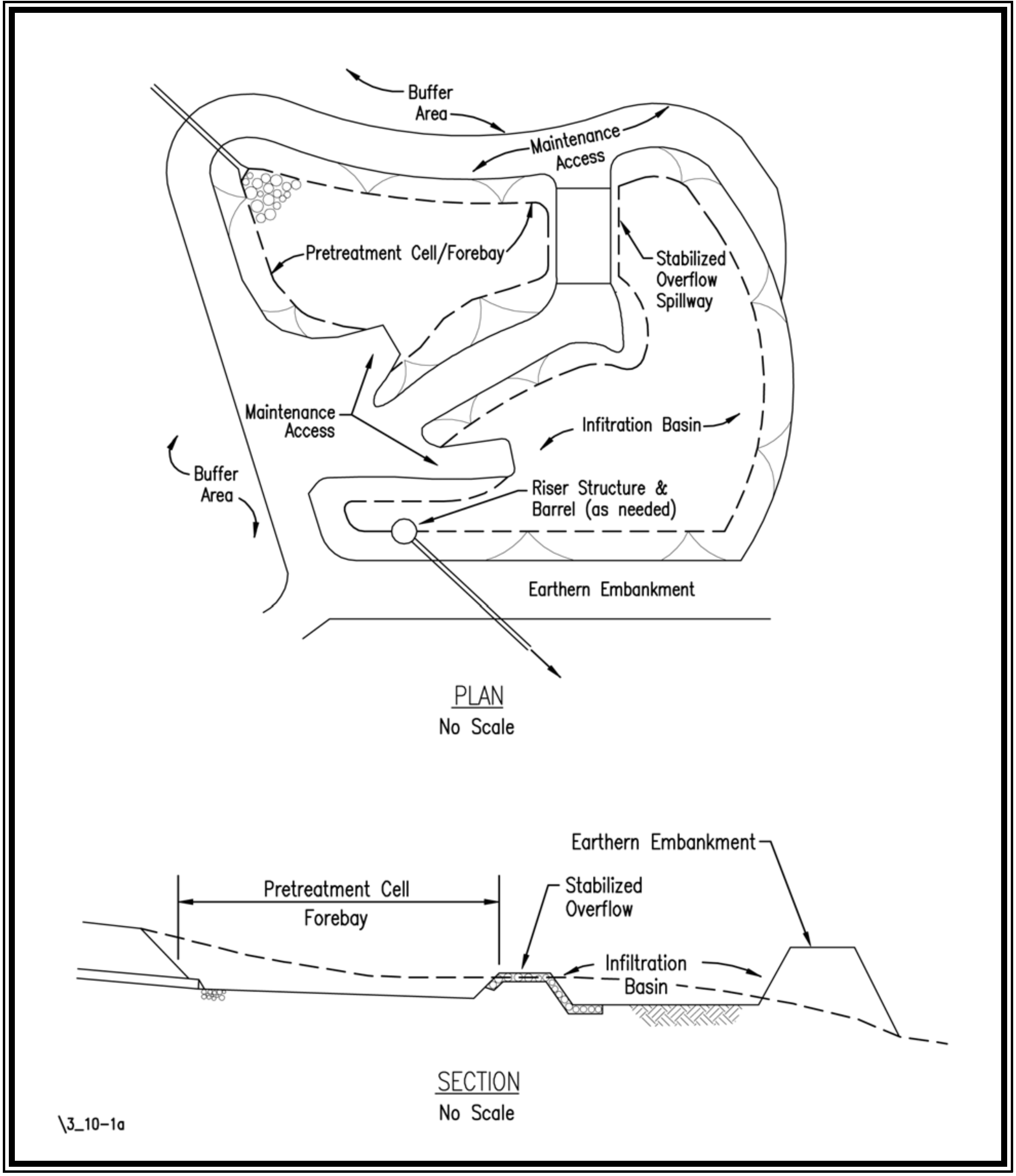
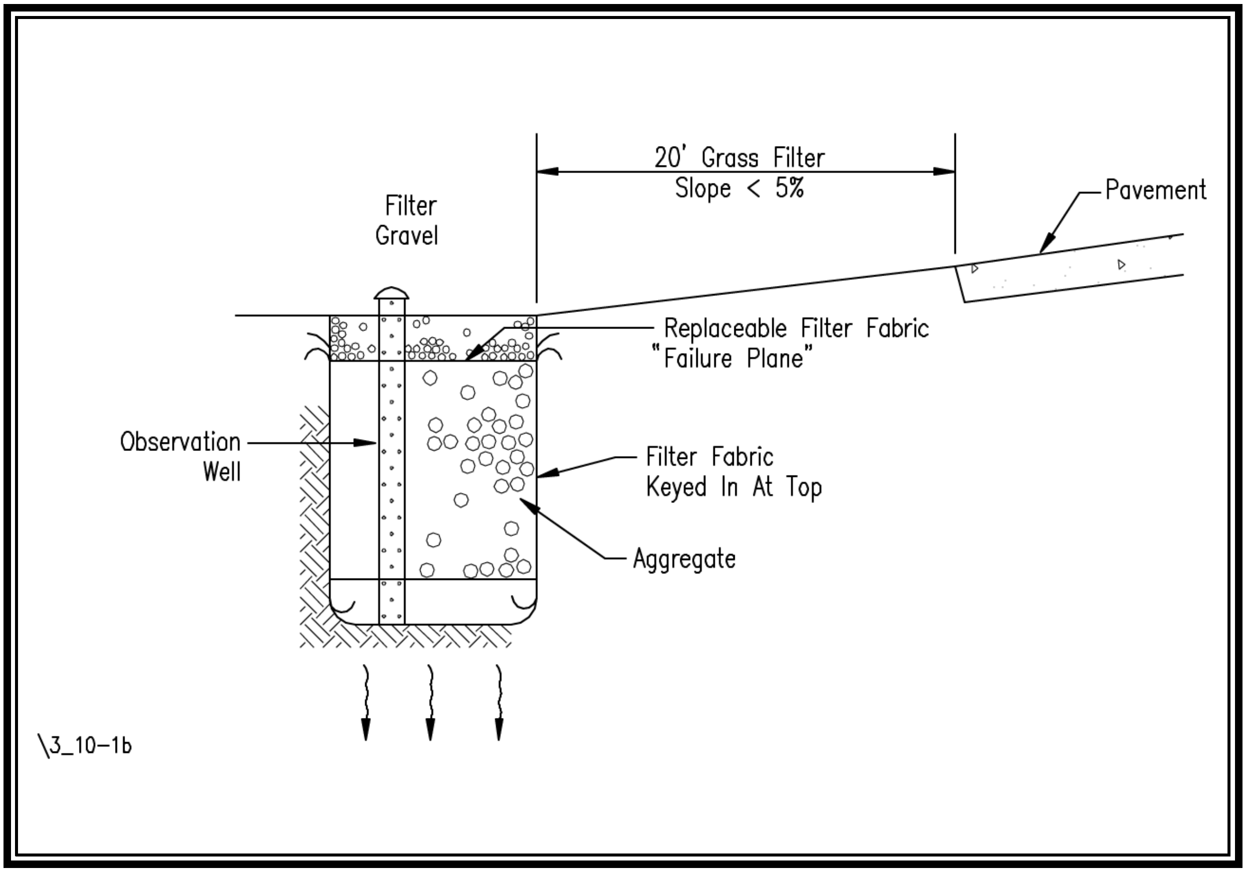


FIGURE 3.10 - 1b
Infiltration Trench - Section



Conditions Where Practice Applies

Infiltration facilities are suitable for use where the subsoil is sufficiently permeable to provide a reasonable rate of infiltration. They are also practical where the water table is sufficiently lower than the design depth of the facility to prevent pollution of the groundwater. Infiltration is not recomended for areas underlain by karst topography. Concentrating runoff into an infiltration facility may cause solution channels to develop or cause karst collapse.

Infiltration practices are generally suited for low- to medium-density development (38% to 66% impervious cover). Specific conditions such as drainage area size and development conditions for each infiltration practice are discussed in the appropriate section of this Standard.

Infiltration facilities are subject to clogging and, therefore, are not recommended for areas where sediment, grease, or oil loadings may be high. Such areas include roadways, parking lots, car service facilities, etc. To increase the life expectancy of an infiltration facility, a pretreatment facility such as a settling basin or "cell", or additional BMP in series should be used to remove sediments or other substances from the stormwater runoff **before** it enters the infiltration facility. Refer to **Minimum Standard 3.15, Manufactured BMP Systems** for additional pretreatment BMPs.

Planning Considerations

The following planning considerations are provided for infiltration practices overall. More specific considerations that may be applicable are presented with each infiltration practice.

Site Conditions

In the past, many designs were accepted based on soils information compiled from available data, such as SCS soil surveys. While these sources may be appropriate for a pre-engineering feasibility study, final design and acceptance should be based on an actual subsurface analysis and permeability tests.

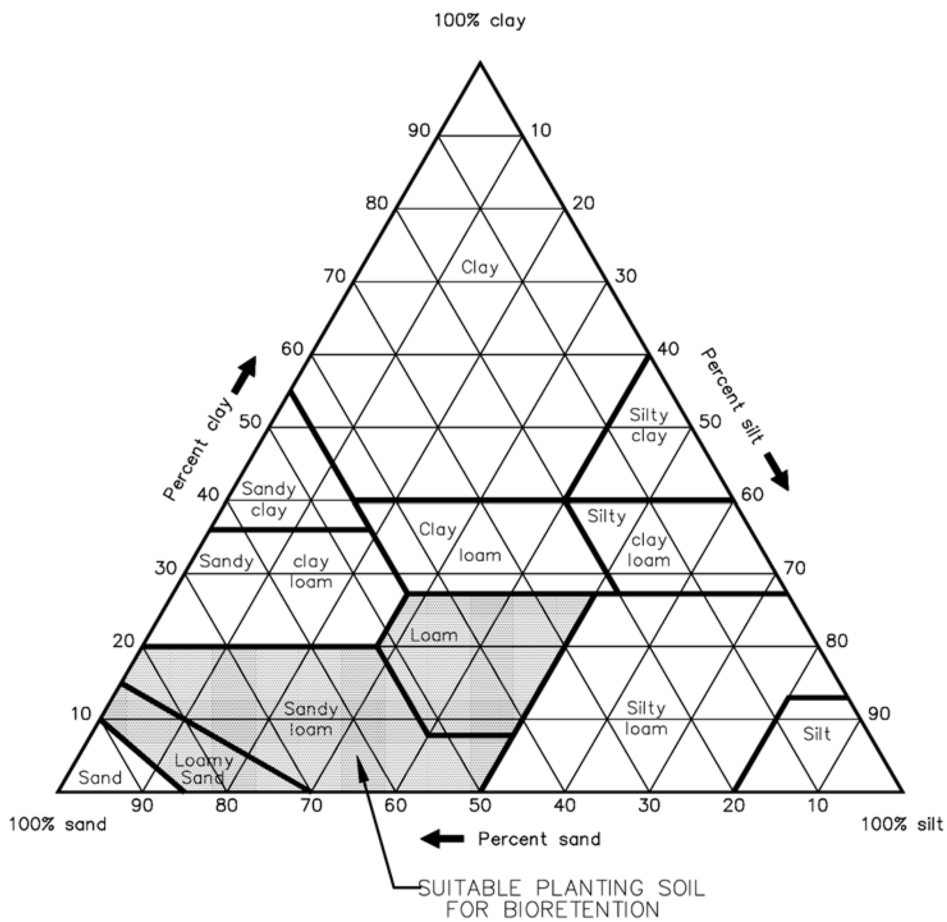
The high failure rates of infiltration facilities, as presented in recent studies (MWCOG), suggest that site-specific soil borings should be required to support the use of infiltration practices. The suitability of the soil for use with the desired infiltration practice can be determined from the soil boring analysis. Details for appropriate geotechnical techniques can be found in the references listed at the end of this section (MD WRA). In general, the following information should be included in a site-specific subsurface or geotechnical study:

1. **Soil permeability**

   The soil types within the subsoil profile, extending a minimum of 3 feet below the bottom of the facility, should be identified to verify the ***infiltration rate*** or ***permeability*** of the soil. The infiltration rate, or permeability, measured in inches per hour, is the rate at which water passes through the soil profile during saturated conditions. Minimum and maximum infiltration rates establish the suitability of various soil textural classes for infiltration. Each soil texture and corresponding hydrologic properties within the soil profile are identified through analysis of a gradation test of the soil boring material. **Soil textures acceptable for use with infiltration systems include those with infiltration rates between 0.52 inches per hour and 8.27inches per hour, and include loam, sandy loam, and loamy sand**.

Soil textures with infiltration rates ***less than 0.52 inches per hour*** *or greater than* ***8.27 inches per hour*** *are* ***<u>not</u> <u>suitable</u>*** *for infiltration practices.*

FIGURE 3.10 - 2
USDA Textural Triangle



SOURCE: U.S. SOIL CONSERVATION SERVICE, 1967.

Soils that have a 30% clay content are unacceptable for use with infiltration facilities since they are structurally unstable and susceptible to frost heaving. Similarly, soils that have poor percolation capabilities or excessively drained soils, such as sand, should not be used for infiltration purposes. The soil textures presented in **Table 3.10-2** correspond to the soil textures of the U.S. Department of Agriculture (USDA) Textural Triangle presented in **Figure 3.10-2**. It should be noted that the difference in soil textures of sand and loamy sand are the percentages of clay found in the soil. While the actual percent of difference is small, a significant difference in infiltration rates can be expected. Note that actual permeability tests may indicate infiltration rates different from those in **Table 3.10-2**.

Predicting the exfiltration of water from an infiltration facility is difficult, especially over an extended period, such as the desired life expectancy of the facility. A factor of safety should be applied in the design to ensure that the facility is sized to function even when partially clogged. (This is discussed further in the **General Design Criteria** presented later in this section.)

TABLE 3.10 - 2
Hydrologic Soil Properties Classified by Soil Texture

Texture Class	Effective Water Capacity (C_w) (inch per inch)	Minimum Infiltration Rate (*f*) (inch per hour)	Hydrologic Soil Grouping
Sand	0.35	8.27	A
Loamy Sand	0.31	2.41	A
Sandy Loam	0.25	1.02	B
Loam	0.19	0.52	B
Silt Loam	0.17	0.27	C
Sandy Clay Loam	0.14	0.17	C
Clay Loam	0.14	0.09	D
Silty Clay Loam	0.11	0.06	D
Sandy Clay	0.09	0.05	D
Silty Clay	0.09	0.04	D
Clay	0.08	0.02	D

2. **Depth to the seasonal high groundwater table and bedrock**.

Typically, infiltration facilities are not recommended in areas with a high groundwater table due to the inability of the soil to adequately filter out pollutants before the stormwater enters the water table. A distance of **2** to **4** feet is required between the bottom of an infiltration facility and the existing water table or bedrock. Similarly, infiltration facilities are not recommended for areas where karst topography is present (in Virginia, west of the Blue Ridge Mountains) due to the possibility of causing subsurface collapse and sink hole formation.

Determination of the seasonal high groundwater table elevation should be given a high priority because flooding of an infiltration facility will render it inoperable during periods of high precipitation. Occasionally, based on the hydraulic conductivity of the soil and the physical dimensions of the trench, a greater separation than 2 to 4 feet may be necessary. Since some soils do not always contain the low chroma (gray) mottles indicative of seasonal saturation, an observation well may be used to locate the seasonal high groundwater table to verify the soil analysis.

Subsurface analysis techniques and related engineering recommendations are too broad and complex for the scope of this handbook. The references listed at the end of this section are recommended for further reading if more detailed information regarding the feasibility analysis of subsurface conditions is needed.

Selecting the optimum depth of an infiltration facility is a process of analyzing constraints. It includes seeking those soil horizons which have a permeability rate that will allow the structure to empty within 48 hours after a design storm event. The design elements of this process are covered in **General Design Criteria**, presented later in this section.

3. **Topographic conditions**

The topographic conditions of a development site represent feasibility factors that should be examined before designing an infiltration system. These factors include the slope of the land, the nature of the soil (natural or fill), and the proximity of building foundations and water supply wells.

The use of a particular BMP is restricted by the allowable slope for that practice. Porous asphalt pavement, for example, requires a relatively level or gently sloping area less than or equal to 3% (20H:1V). All other infiltration practices should be located in areas in which the slope does not exceed 20% (5H:1V). Using infiltration practices on a steep grade increases the chance of water seepage from the subgrade to the lower areas of the site and reduces the amount which infiltrates.

Developments occurring on sloping and rolling sites often require extensive cut and fill operations. The use of stormwater management infiltration systems on fill material is not recommended due to the possibility of creating an unstable subgrade. Fill areas can be very susceptible to slope failure due to slippage along the interface of the in-situ and fill material. This condition could be aggravated if the fill material is allowed to become saturated by using infiltration practices.

Nearby building foundations should be at least 10 feet up-gradient of the infiltration system to prevent the possibility of flooding basements. Proximity to septic systems is also a concern and local health officials should be consulted for guidance on minimum setbacks. Additionally, the location of infiltration practices should be a minimum of 100 feet from any water supply well where the runoff is from commercial or industrial impervious parking areas.

Sediment Control

It has been reported that many infiltration BMPs have failed because adequate precautions to prevent sediment contamination were not implemented (NVPDC, MWCOG). Provisions for long-term sediment control, or pretreatment of the stormwater runoff, must be incorporated into the design, along with precautions taken during onsite construction activities. Advance consideration should be given to the potential impacts that construction techniques, work sequence, and equipment could have on the future maintenance requirements of the BMP. Serious maintenance problems can be averted, or reduced, by the adoption of relatively simple measures during construction.

1. **Construction Runoff**

> ***Infiltration BMPs should be constructed AFTER the site work is completed and stabilization measures have been implemented.***

Infiltration facilities built prior to the completion of site construction activities often become choked with sediment, rendering them inoperable from the outset. Simply providing inlet protection or some other filtering mechanism during site construction may not adequately control the sediment. One large storm can overload protection devices and completely clog the infiltration facility.

To protect an infiltration facility **during** construction, provisions for sediment control should be included in the design. The following references provide technical guidance on sediment control designs:

¢ Virginia Erosion and Sediment Control Handbook (VESCH), DCR, 1992,
¢ Standards and Specifications for Infiltration Practices, Md. DNR, 1984, and
¢ Controlling Urban Runoff (MWCOG, 1987).

> ***Experience with infiltration practices in other states has shown that stormwater management infiltration facilities must be protected until their contributing drainage areas have been adequately stabilized*** *(Maryland,1987).*

The definition of the term "adequately stabilized" when describing the contributing drainage area of an infiltration BMP is critical to the success of the facility. An approved erosion and sediment control plan will specify various devices for trapping sediment during construction, such as silt fences, diversions, sediment traps, etc. It will also specify measures and provide specifications for site stabilization. Following construction activities, the temporary sediment control measures should be removed at the direction of the erosion control inspector when, at a minimum, stabilization measures, such as seed and mulch, are in place. This does not mean, however, that stabilization has occurred. Often, it may take one or more full growing seasons before the pervious areas are fully stabilized, and the construction-related sediment load is controlled. **Therefore, provisions to bypass the stormwater around, or away from, the infiltration facility during the stabilization period should be implemented.**

2. **Urban Runoff**

A fully stabilized site will generate a particulate pollutant load resulting from natural erosion, lawn and garden debris such as leaves, grass clippings, mulch, roadway sand, etc. Various measures can be incorporated into the design to protect the facility and facilitate regular maintenance. The following discussion on pretreatment systems for infiltration facilities is adapted from the Northern Virginia BMP Handbook (NVPDC 1992) and Standards and Specifications for Infiltration Practices (Md. DNR, 1984).

Urban and ultra-urban development projects are usually limited to the use of infiltration trenches, which include ***dry wells***, ***porous pavement***, and ***roof downspout systems***. Runoff to any infiltration trench must be filtered to remove sediment prior to entering the structure.

Runoff to an infiltration trench is usually ***concentrated input***, which is conveyed by gutters, inlets, or pipes, and enters the facility at one or more points. Sediment control devices for *concentrated input* include in-line structures such as water quality inlets (Refer to **Minimum Standard 3.15, Manufactured BMP Systems**), sediment collection sumps or similar structures, provided there is an assured means of regular inspection and maintenance. Any pretreatment BMP which allows sediment- laden water to enter the infiltration facility upon failure of the pretreatment BMP should be avoided. Ideally, a clogged or failed pretreatment BMP should create a noticeable amount of overland flow bypassing the infiltration facility, which indicates that it is time to maintain the pretreatment decvice. Prompt maintenance of the pretreatment BMP will ensure that the infiltration facility remains intact.

The design of sediment control systems for concentrated input facilities invites innovation. Redundant controls or backup systems should be employed wherever there is an opportunity. One type of backup sediment control measure used for trenches with large diameter CMP pipe storage consists of lining the interior surface of the pipe with a geotextile fabric as shown in **Figure 3.10-3**. This continuous liner is held against the interior metal surface of the pipe by expandable rings. If routine monitoring reveals that the water is not being released from the pipe, the filter should be inspected and replaced as necessary. Note that the diameter of the pipe must be such that access for maintenance is possible.

Any sediment collection structure must be adequate to handle the expected flows. Therefore, filter systems should be designed with an additional capacity to account for eventual, partial clogging.

Runoff to an infiltration BMP may also be in the form of ***sheet flow***, entering the top of the storage reservoir over a wide area. **Figure 3.10-1b** portrays one such infiltration trench where overland sheet flow is directed across a gently sloping grassed filter strip to the surface of the infiltration trench. The grassed filter strip is the primary pretreatment control and must be at least **20 feet wide** and have a **5% slope or less** to be effective. The entry berm must be parallel to the contour to maintain uniform flow to the trench.

The choice of vegetative cover should be made with respect to its tolerance to water, growth rate, climatic preference, stabilization capacity, and maintenance considerations. Refer to the VESCH DCR, 1992, and any local ordinances for specific vegetative recommendations. It is essential that a complete cover of dense turf be established **BEFORE** stormwater flows are allowed to enter the facility.

The trench itself is protected from sediment entry by a layer of geotextile filter fabric (called a *sediment barrier*). The sediment barrier is separate from the filter fabric which lines the trench sides so it can be replaced as part of routine maintenance. It is installed over the top of the crushed stone storage chamber and covered with one-half to one foot of 3/4-inch crushed stone. The edges of the filter fabric must be placed so that runoff cannot bypass the sediment barrier. All input water must flow over the grassed filter strip and enter the trench through the sediment barrier at the top.

Unlike the other trench types, porous pavement may be difficult to maintain because the pollutant load is carried by other means, such as vehicle traffic, rather than runoff. Porous pavement, therefore, requires a strict maintenance program to ensure that the design flow can pass through the pavement. Specific maintenance requirements, along with construction methods and specifications for porous pavement and various other infiltration BMPs, are provided later in this chapter.

FIGURE 3.10 - 3
Concentrated Input Pretreatment

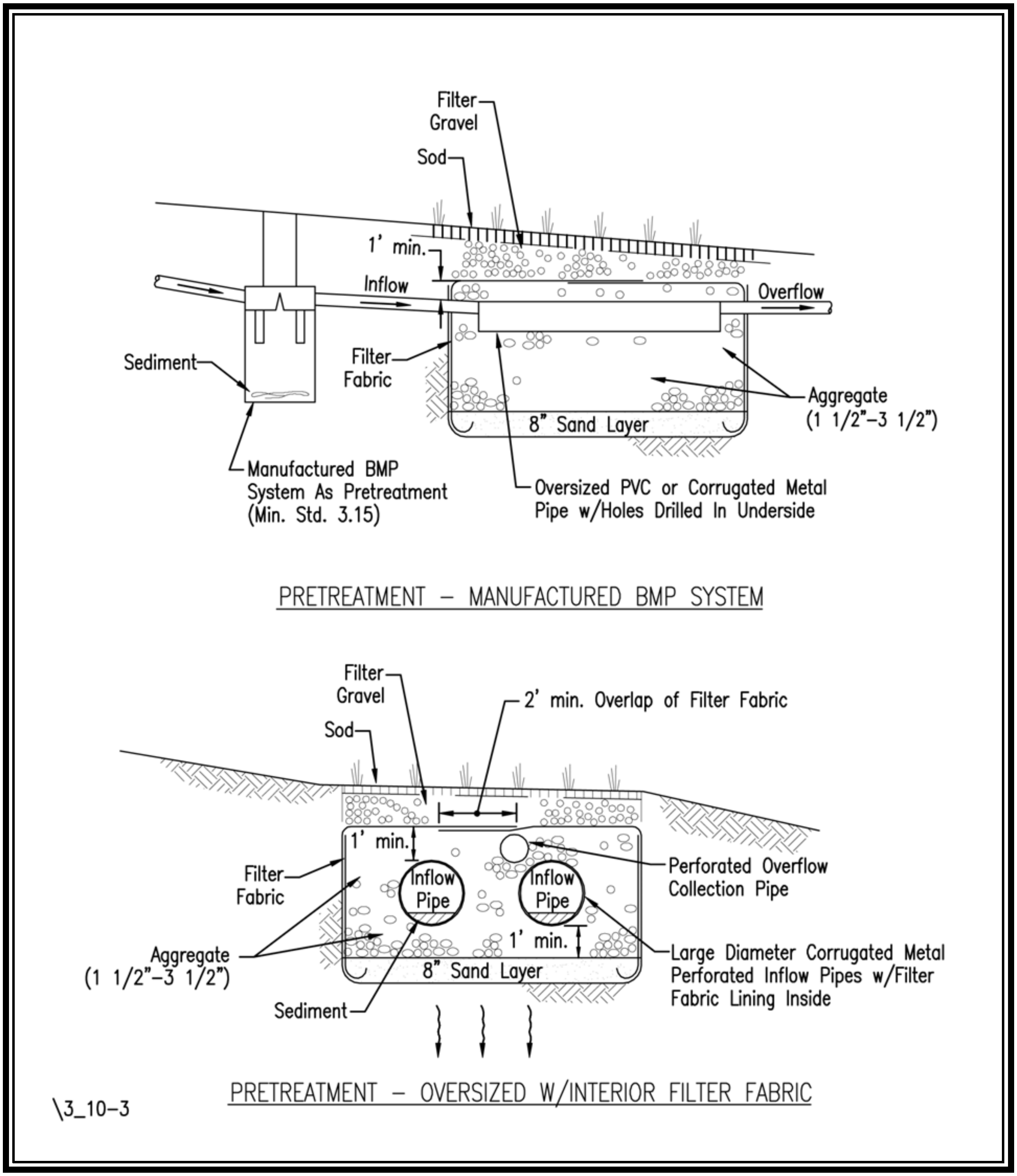
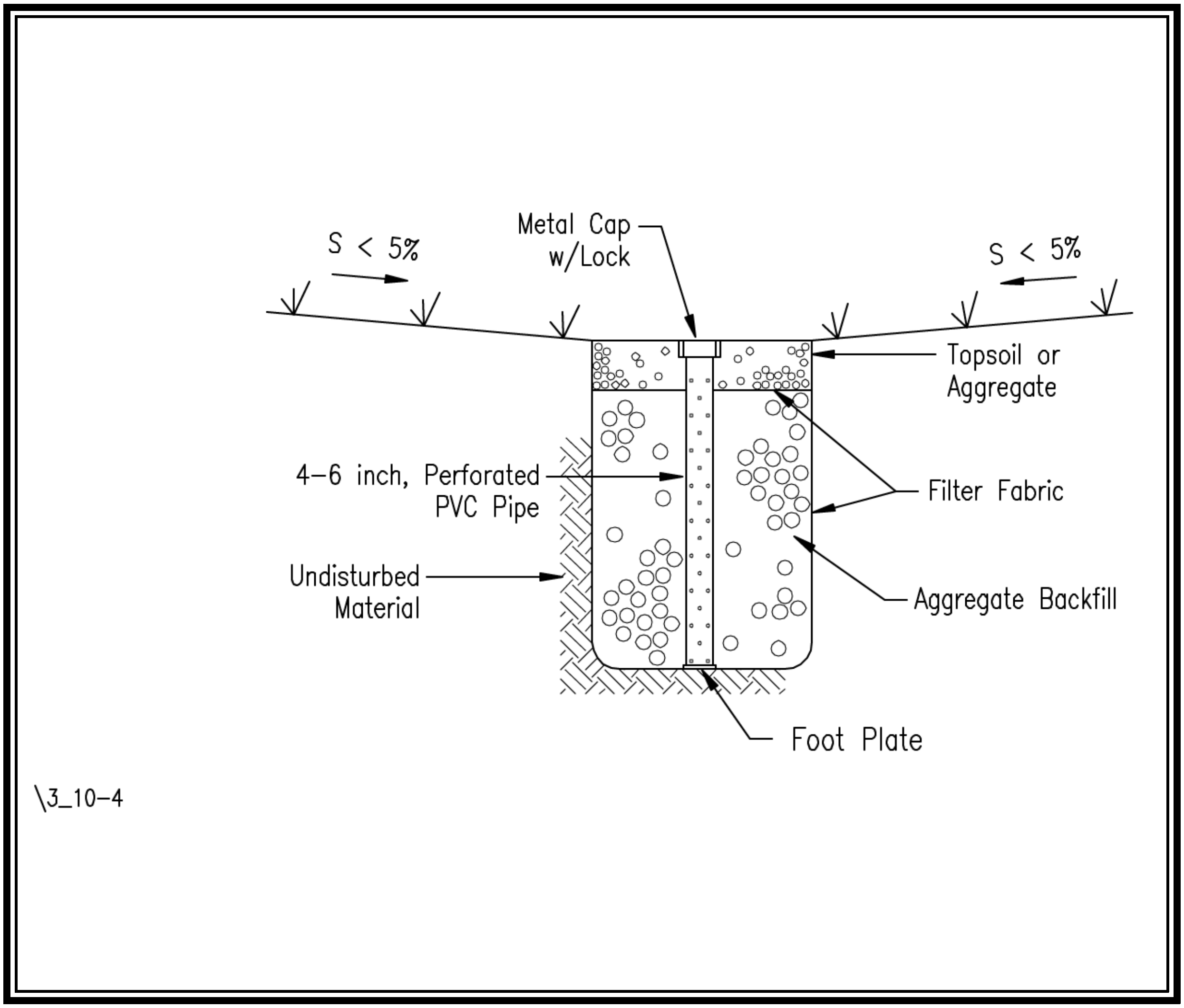


FIGURE 3.10 - 4
Observation Well



Maintenance

The maintenance requirements for a selected infiltration practice must be considered during the planning and design of the facility. Surface facilities such as basins and swales can be visually inspected and easily maintained. The surface of an infiltration trench or dry well can also be visually inspected and maintained if they are constructed at grade. Since their subsurface storage areas cannot be inspected above ground, **observation wells must be required** (refer to **Figure 3.10-4**). Maintenance of the subsurface storage area, however, short of excavating the facility, is very difficult. Therefore, many landowners, developers and local program administrators have been discouraged from using infiltration facilities.

Recent studies indicated that slightly more than half of the surveyed infiltration facilities had failed within the first five years of operation (MWCOG, 1992; Md. DOE, 1987). Often, failure was due to poor subsurface investigations and/or sediment control. Since repair or rehabilitation of underground facilities (infiltration trenches) is limited, design criteria, subsurface exploration, and maintenance requirements should be strictly enforced. In addition, pretreatment of the stormwater runoff will likely extend the life of an infiltration facility by trapping sediments and debris before they enter, and by allowing for the removal of the accumulated material without excavating the structure. To reduce the potential for costly maintenance and/or system reconstruction, it is strongly recommended that the stone reservoir portion of infiltration trenches be located in a lawn area and as close to the ground surface as possible.

Infiltration trenches should not be located beneath paved surfaces, such as parking lots.

General Design

The purpose of this section is to provide recommendations and minimum criteria for the design of infiltration practices intended to comply with the runoff quality requirements of the Virginia Stormwater Management program.

The types of infiltration facilities which are recognized for stormwater management purposes are ***infiltration basins*** and ***infiltration trenches***. The design, construction, and maintenance criteria for infiltration trenches is also applied to the design of the storage volume for ***porous pavement*** and ***roof downspout systems*** (or *dry wells*).

The criteria presented below apply to the design of infiltration basins and trenches for ***water quality enhancement***. This means that the runoff volume to be treated is determined by the water quality volume and the desired pollutant removal efficiency.

Hydrology and Hydraulics

The procedures outlined in **Chapter 4, Hydrologic Methods**, should be used to determine the post-developed hydrology of the drainage area being served by the infiltration BMP. Provisions for large storm bypass must be provided, even when a stormwater BMP is being utilized for water quality enhancement only and not peak discharge control. Ideally, large storms should be diverted around infiltration facilities, or through the facility with a minimum of disruption and/or turbulence

<u>Sizing Procedure</u>

The storage volume required for infiltration facilities designed for water quality enhancement is determined by the water quality volume - ½ to 1 inch of runoff, determined by the desired pollutant removal efficiency (refer to **Table 3.10-1**).

A Darcy's Law approach is recommended for sizing water quality infiltration BMPs. This will assume that the drain time of the facility is controlled by one-dimensional flow through the bottom surface.

$$Q = f\ I\ SA$$

Equation 3.10-1
Darcy's Law

where:
- Q = rate of exfiltration into soil, cfs
- f = infiltration rate of the soil in ft/hr
- I = hydraulic gradient
- SA = bottom surface area of facility in ft^2

1. **Infiltration Rate –**

Over the life of an infiltration facility, the rate of infiltration into the soil, *f*, may gradually decrease due to clogging of the surface layer of soil. The documented high failure rate of infiltration facilities (MWCOG) suggests that a safety factor be built into the design of the facility to allow for future clogging. Therefore, ***a safety factor of 2*** should be applied to the infiltration rate determined from the soil analysis. The design soil infiltration rate, f_d , therefore, is equal to one-half of the actual rate:

$$f_d = 0.5f$$

2. **Hydraulic Gradient –**

In areas with a shallow water table or impermeable layer, the hydraulic gradient may have an impact on the allowable design depth. The hydraulic gradient is given by the equation:

$$I = \frac{h + L}{L}$$

Equation 3.10-2
Hydraulic Gradient

where: I = hydraulic gradient

h = height of the water column over the infiltrating surface, ft.
L = distance from the top surface of the BMP to the water table, bedrock, impermeable layer, or other soil layer of a different infiltration rate, ft.

The hydraulic gradient will be asummed to be equal to one in all infiltration designs since the gradient approaches unity as the facility drains. Therefore,

$$I=1$$

3. **Maximum Ponding or Storage Time, T_{max} –**

A water quality infiltration facility should be designed with a maximum drain time, T_{max}, of 48 hours for the total volume.

The maximum drain time, along with the minimum design soil infiltration rate, f_d, as verified through a subsurface investigation and analysis, will dictate the maximum allowable design depth, d_{max}, of the structure. The maximum depth for an infiltration basin and trench is covered in the following minimum standards.

MINIMUM STANDARD 3.10A

INFILTRATION BASIN

Definition

An infiltration basin is a vegetated, open impoundment where incoming stormwater runoff is stored until it gradually infiltrates into the soil strata.

Purpose

Infiltration basins are used primarily for water quality enhancement. However, flooding and channel erosion control may also be achieved within an infiltration basin by utilizing a multi-stage riser and barrel spillway to provide controlled release of the required design storms above the water quality (infiltration) volume (refer to **Figure 3.10-1**).

Conditions Where Practice Applies

Infiltration basins may be used where the subsoil is sufficiently permeable to provide a reasonable infiltration rate and where the water table is low enough to prevent pollution of groundwater.

Drainage Area

Drainage areas served by infiltration basins should be limited to less than 50 acres. Drainage areas which are greater than 50 acres typically generate such large volumes of runoff that other detention or retention BMPs are more practical and cost-effective.

Development Conditions

Infiltration basins are generally suitable BMPs in low- to medium-density residential and commercial developments (38% to 66% impervious cover).

Planning Considerations

Appropriate soil conditions and protection of the groundwater are among the important considerations when planning an infiltration basin. Refer to the **Planning Considerations** for **General Infiltration Practices** previously discussed in this standard.

An infiltration basin has relatively large surface area requirements, when compared with an infiltration trench or dry well, and ranges from 3 to 12 feet in depth. The seasonal high groundwater table or bedrock should be located at least 2 to 4 feet below the bottom of the basin. Infiltration facilities are not recommended for areas where karst topography is present (in Virginia, west of the Blue Ridge Mountains) due to the possibility of causing subsurface collapse and sink hole formation.

Maintenance

Like all stormwater BMPs, access to an infiltration basin should be considered in the planning stage. Access (as well as maneuvering room) should be provided to at least one side of the facility and the control structure or spillway. In addition, identifying a location and designing for on-site sediment disposal will greatly reduce long-term maintenance costs.

Design Criteria

The purpose of this section is to provide recommendations and minimum criteria for the design of infiltration basins intended to comply with the runoff quality requirements of the Virginia Stormwater Management program.

General

The design of infiltration basins should be according to the following Minimum Standards where applicable: **3.01, Earthen Embankment**; **3.02, Principal Spillway**; **3.03, Vegetated Emergency Spillway**; **3.04, Sediment Forebay**; **3.05, Landscaping**, and **3.10, General Infiltration Practices**, along with additional criteria set forth below. The designer is not only responsible for selecting the appropriate components for his or her particular design but also for ensuring their long-term operation by specifying appropriate structural materials.

The design of the overflow vegetated spillway must consider the frequency of flow. The spillway may require an armored bottom if it is to function during every storm which exceeds the water quality volume (refer to **Minimum Standard 3.03**).

Hydrology and Hydraulics

Chapter 4, **Hydrologic Methods** should be used to develop the pre- and post-developed hydrology for a basin's contributing watershed. An infiltration basin designed for water quality enhancement still must provide an overflow or spillway for the bypass of large storms. **Chapter 5**, **Engineering Calculations** provides the procedures for the design of the riser and barrel system and the emergency spillway design procedures.

Soils Investigation

A minimum of one soil boring log should be required for each 5,000 square feet of infiltration basin area (plan view area) and under no circumstances should there be less than three soil boring logs per basin (Washington State DOE, 1992). Refer also to the **Planning Considerations** and **Design Criteria** of **General Infiltration Practices**, discussed at the beginning of this standard.

Topographic Conditions

Infiltration basins should be a minimum of 50 feet from any slope greater than 15%. If unavoidable, a geotechnical report should address the potential impact of infiltration on or near the steep slope. Developments on sloping sites often require extensive cut and fill operations. **The use of infiltration basins on fill sites is not permitted**. Also, infiltration basins should be a minimum of 100 feet up-slope and 20 feet down-slope from any buildings.

Design Infiltration Rate

The design infiltration rate, f_d, should be set to equal one-half the infiltration rate, f, determined from the soil analysis. Therefore:

$$f_d = 0.5\,f$$

Maximum Ponding Time and Depth

All infiltration basins should be designed to completely drain stored runoff within 2 days following the occurrence of a storm event. Thus, an allowable maximum ponding time, T_{max} , of 48 hours should be used.The maximum ponding depth for an infiltration **basin** is:

$$d_{max} = f_d T_{max}$$

Equation 3.10-3
Maximum Ponding Depth for Infiltration Basin

where: d_{max} = maximum depth of the facility, in ft.
f_d = design infiltration rate of the basin area soils, in ft/hr (f_d = ½ f)
T_{max} = maximum allowable drain time = 48 hrs.

The ponding depth should not be so great as to contribute to the compaction of the soil surface. Depending on the specific soil characteristics, a maximum ponding depth of 2 feet is generally recommended (MWCOG, 1992).

The minimum surface area of the facility bottom is:

$$SA_{min} = \frac{Vol_{wq}}{f_d T_{max}}$$

Equation 3.10-4
Minimum Bottom Surface Area for infiltration Basin

where:
SA_{min} = minimum basin bottom surface area, in ft^2;
Vol_{wq} = water quality volume requirements, in ft^3;
f_d = design infiltration rate of the basin area soils, in ft/hr;
T_{max} = maximum allowable drain time, in hours

Runoff Pretreatment

Infiltration basins should always be preceded by a pretreatment facility. Grease, oil, floatable organic materials, and settleable solids should be removed from the runoff before it enters the infiltration basin. Vegetated filters, sediment traps and/or forebays, water quality inlets (refer to **Minimum Standard 3.15, Manufactured BMP Systems**) are just a few of the available pretreatment strategies. Refer to the discussion on **Sediment Control** in the **General Infiltration Practices** portion of this section.

At a minimum, the layout and design of the basin should include a sediment forebay or pretreatment cell, as shown in **Figure 3.10-1**, to enhance and prolong the infiltration capacity. Any pretreatment facility should be included in the design of the basin and should include maintenance and inspection requirements. It is recommended that a grass strip or other vegetated buffer at least 20 feet wide be maintained around the basin to filter surface runoff.

Principal and Emergency Spillways

A diversion structure upstream of an ***off-line*** basin will regulate the rate of flow into the basin, but not the volume. Therefore, infiltration basins should have a spillway to convey flows from storm events which are larger than the design capacity. The primary outlet should be located above the required infiltration volume. Additionally, a riser and barrel system is advantageous for future conversion to an extended-detention or retention facility if the infiltration capacity of the soil becomes impaired. All design elements of a principal spillway should be per **Minimum Standard 3.02, Principal Spillways**.

An emergency spillway is recommended for all impounding structures, including infiltration basins. If a vegetated spillway is to be used as the primary outlet above the water quality volume, care should be taken to design for the increased frequency of use. This is especially critical between maintenance operations when the infiltration capacity is decreased due to sediment loads. If a spillway is to be used for all storms which generate more runoff than the water quality volume, then a nonerodible surface should be provided. All design elements of a *vegetated* emergency spillway should be per **Minimum Standard 3.03, Vegetated Emergency Spillways**.

Stabilization

As with all stormwater structures, all disturbed areas associated with the construction of the facility, including spoil and borrow areas, should be stabilized immediately according to the VESCH 1992 edition. The basin floor area, emergency spillway, and any vegetative buffer around the facility are critical areas and should be addressed with a specific stabilization measure.

The choice of vegetative cover should be made with respect to its tolerance to water, growth rate, climatic preference, stabilization capacity, and maintenance requirtements. Refer to the VESCH 1992 edition and any local ordinances for specific vegetative recommendations. It is essential that a complete cover of dense turf be established **BEFORE** stormwater flows are allowed to enter the facility.

Fencing

Fencing may be provided where deemed necessary by the developer, land owner, or locality for the purposes of public safety or protection of vegetation.

Construction Specifications

In general, widely accepted construction standards and specifications, such as those developed by the USDA Soil Conservation Service or the U.S. Army Corps of Engineers, should be followed where applicable. Further guidance can be found in the Soil Conservation Service's Engineering Field Manual. Specifications for the work should conform to the methods and procedures indicated for installing earthwork, concrete, reinforcing steel, pipe, water gates, metal work, woodwork and masonry as they apply to the site and the purpose of the structure. The specifications should also satisfy all requirements of the local government.

The construction of infiltration basins should also be in accordance with the following Minimum Standards and Specifications where applicable: **3.01, Earthen Embankment**; **3.02, Principal Spillway**; **3.03, Vegetated Emergency Spillway**; **3.04, Sediment Forebays**; **3.05, Landscaping**; along with the criteria set forth below. These specifications have been adapted from Standards & Specifications for Infiltration Practices (Md. DNR, 1984 and Washington State DOE, 1992).

Sequence of Construction

The sequence of various phases of basin construction should be coordinated with the overall project construction schedule. Rough excavation of the basin may be scheduled with the rough grading phase of the project to permit use of the material as fill in earthwork areas. Otherwise, **infiltration measures should not be constructed or placed into service until the entire contributing drainage area has been stabilized**. Runoff from untreated, recently constructed areas within the drainage area may load the newly formed basin with a large volume of fine sediment. This could seriously impair the natural infiltration ability of the basin floor.

The specifications for construction of a basin should state the following: 1) *the earliest point at which storm drainage may be directed to the basin*, and 2) *the means by which this delay in basin use is to be accomplished*. Due to the wide variety of conditions encountered among projects, each project should be evaluated separately to postpone basin use for as long as possible.

Excavation

Initially, the basin floor should be excavated to within one foot of its final elevation. Excavation to the finished grade should be delayed until all disturbed areas in the watershed have been stabilized or protected. The final phase of excavation should remove all accumulated sediment. Relatively light, tracked-equipment is recommended for this operation to avoid compaction of the basin floor. After the final grading is completed, the basin floor should be deeply tilled by means of rotary tillers or disc harrows to provide a well-aerated, highly porous surface texture.

Lining Material

Establishing dense vegetation on the basin side slopes and floor is recommended. A dense vegetative cover will not only prevent erosion and sloughing, but will also provide a natural means to maintain relatively high infiltration rates. Inflow points to the basin should also be protected with erosion controls (e.g., riprap, flow spreaders, energy dissipators, etc.), as well as a sediment forebay.

Selection of suitable vegetative materials and application of required fertilizer and mulch should be per the VESCH 1992 edition.

Maintenance / Inspection Guidelines

The following maintenance and inspection guidelines are not intended to be all-inclusive. Specific facilities may require other measures not discussed here.

Inspection Schedule

When infiltration basins are first made functional they should be inspected monthly and after any large storm event. Thereafter, once the basin is functioning satisfactorily and without potential sediment problems, inspections may be made semi-annually and after any large storm events. All inspections should include investigation for potential sources of contamination.

Sediment Control

The basin should be designed to allow for maintenance. Access should be provided for vehicles to easily maintain the forebay (pre-settling basin) without disturbing vegetation or sediment any more than what is absolutely necessary.

Grass bottoms in infiltration basins seldom need replacement since grass serves as a good filter material. If silty water is allowed to trickle through the turf, most of the suspended material is strained out within a few yards of surface travel. Well-established turf on a basin floor will grow up through sediment deposits forming a porous turf and preventing the formation of an impenetrable layer. Grass planted on basin side slopes should also prevent erosion.

Vegetation Maintenance

Maintenance of the vegetation on the basin floor and side slopes is necessary to promote a dense turf with extensive root growth, which subsequently enhances infiltration, prevents erosion and sedimentation, and deters invasive weed growth. Bare spots should be immediately stabilized and revegetated.

The use of low-growing, stoloniferous grasses will permit long intervals between mowings. Mowing twice a year is generally satisfactory. Fertilizers should be applied only as necessary and in limited amounts to avoid contributing to pollution problems, including groundwater pollution, for which the infiltration basin helps mitigate. Consult the VESCH, 1992 edition for appropriate fertilizer types and application rates.

Design Procedures

The following design procedure represents a generic list of the steps typically required for the design of an infiltration basin.

1. Determine if the anticipated development conditions and drainage area are appropriate for an infiltration basin application.

2. Determine if the soils (permeability, bedrock, water table, Karst, embankment foundation, etc.) and topographic conditions (slopes, building foundations, etc.) are appropriate for an infiltration basin application.

3. Locate the infiltration basin on the site within topographic constraints.

4. Determine the drainage area to the infiltration basin and calculate the required water quality volume.

5. Evaluate the hydrology of the contributing drainage area to determine peak rates of runoff.

6. Design the infiltration basin:
    - Design infiltration rate, $f_d = 0.5\, f$.
    - Max. Storage time T_{max} = 48 hours
    - Max. Storage depth, d_{max}
    - Runoff pretreatment - concentrated input, sheet flow input, sediment forebay
    - Vegetated buffer around basin to filter surface runoff
    - Vegetated emergency spillway and/or riser and barrel design
    - Earthen Embankment design

7. Provide material specifications.

8. Provide sequence of construction.

9. Provide maintenance and inspection requirements.

MINIMUM STANDARD 3.10B

INFILTRATION TRENCH

Definition

An infiltration trench is a shallow, excavated trench backfilled with a coarse stone aggregate to create an underground reservoir. Stormwater runoff diverted into the trench gradually infiltrates into the surrounding soils from the bottom and sides of the trench. The trench can be either an open surface trench or an underground facility.

Purpose

Infiltration trenches are used primarily as water quality BMPs. Trenches are generally 2 to 10 feet deep and are backfilled with a coarse stone aggregate, allowing for temporary storage of storm runoff in the voids between the aggregate material. Stored runoff gradually infiltrates into the surrounding soil. The surface of the trench can be covered with grating and/or consist of stone, gabion, sand, or a grassed area with a surface inlet. Utilizing underground pipes within the trench can increase the temporary storage capacity of the trench and can sometimes provide enough storage for flooding and/or stream channel erosion control (see **Figure 3.10-3**).

Conditions Where Practice Applies

An infiltration trench may be used where the subsoil is sufficiently permeable to provide a reasonable infiltration rate and where the water table is low enough to prevent pollution of groundwater.
Infiltration facilities are not recommended for areas where karst topography is present (in Virginia, west of the Blue Ridge Mountains) due to the possibility of causing subsurface collapse and sink hole formation.

<u>Drainage Area</u>

Infiltration trenches are not practical for large drainage areas. Generally, the drainage area for infiltration trenches should be limited to 5 acres. Multiple trenches may be considered to control the runoff from a large site, but this also increases the associated maintenance responsibilities.

Development Conditions

Infiltration trenches are generally suited for low- to medium-density residential and commercial developments. They can be installed in multi-use areas, such as along parking lot perimeters, or in small areas that cannot readily support retention basins or similar structures. Infiltration trenches can be used in residential areas, commercial areas, parking lots and open space areas. Unlike most BMPs, trenches can easily fit into the margin, perimeter, or other unused areas of developed sites, making them particularly suitable for retrofitting in existing developments or in conjunction with other BMPs. A trench may also be installed under a swale to increase the storage of the related infiltration system. In all cases, pretreatment of the stormwater runoff to remove course sediment and particulate pollutants prior to entering the infiltration trench should be provided.

Planning Considerations

Appropriate soil conditions and protection of groundwater are two important considerations when planning for an infiltration trench. For further discussion, refer to the **Planning Considerations** previously discussed in **General Infiltration Practices, Minimum Standard 3.10**.

Design Criteria

The purpose of this section is to provide recommendations and minimum criteria for the design of infiltration trenches intended to comply with the runoff quality requirements of the Virginia Stormwater Management program.

General

Infiltration trenches are assumed to have rectangular cross-sections. Thus, the infiltration surface area (trench bottom) can be readily calculated from the trench geometry. The storage volume of the trench must be calculated using the void ratio of the backfill material that will be placed in it.

The same general criteria presented for the design of infiltration basins apply to trenches; the following information is provided for additional guidance.

Soils Investigation

A minimum of one soil boring log should be required for every 50 feet of trench length. A minimum of two soil boring logs should be required for each proposed trench location (Washington State DOE, 1992).

Topographic Conditions

Infiltration trenches should be located 20 feet down-slope and 100 feet up-slope from building foundations. An analysis should be completed to identify any possible adverse effects of seepage zones if there are nearby building foundations, basements, roads, parking lots or sloping sites. Developments on sloping sites often require the use of extensive cut and fill operations. **The use of infiltration trenches on fill sites is not permitted**.

Design Infiltration Rate

The design infiltration rate, f_d, should be set to equal one-half the infiltration rate obtained from the soil analysis. Therefore,

$$f_d = 0.5\,f$$

Maximum Storage Time and Trench Depth

All infiltration trenches should be designed to empty within 2 days following the occurrence of a storm event. Thus, a maximum allowable storage time, T_{max}, of 48 hours should be used.

The maximum depth for an infiltration **trench** may be defined as:

$$d_{max} = \frac{f_d T_{max}}{V_r}$$

Equation 3.10-5
Maximum Depth for Infiltration Trench

where: d_{max} = maximum allowable depth of the facility, in ft;
f_d = design infiltration rate of the trench area soils, in ft/hr ($f_d = 0.5f$);
T_{max} = maximum allowable drain time = 48 hrs.;
V_r = void ratio of the stone reservoir expressed in terms of the percentage of porosity divided by 100 (0.4 typ.).

Refer to the Virginia Department of Transportation's Road and Bridge Specifications, latest edition, for information and specifications for coarse aggregates. A void ratio of 0.40 is assumed for stone reservoirs using 1.5 to 3.5 inch stone - VDOT No. 1 Coarse-graded Aggregate.

The minimum surface area of the facility bottom may be defined as:

$$SA_{min} = \frac{Vol_{wq}}{f_d T_{max}}$$

Equation 3.10-6
Infiltration Trench Minimum Bottom Surface Area

where: SA_{min} = minimum trench bottom surface area, in ft^2;
Vol_{wq} = water quality volume requirements, in ft^3;
f_d = design infiltration rate of the trench area soils, in ft/hr ($f_d = 0.5f$);
T_{max} = maximum allowable drain time = 48 hrs.

Runoff Pretreatment

Infiltration trenches should always be preceded by a pretreatment facility. Grease, oil, floatable organic materials, and settleable solids should be removed from the runoff before it enters the trench. Vegetated filters, sediment traps or forbays, water quality inlets (refer to **Minimum Standard 3.15, Manufactured BMP Systems**) are just a few of the available pretreatment strategies. To reduce both the frequency of turbulent flow-through and the associated scour and/or resuspension of residual material, infiltration trenches and associated pretreatment facilities should be installed off-line (MWCOG, 1992). Additional pretreatment arrangements are illustrated in **Figure 3.10-3**. Refer to the discussion on **Sediment Control** in **General Infiltration Practices**, **Minimum Standard - 3.10**.

A grass strip or other type of vegetated buffer at least 20 feet wide should be maintained around trenches that accept surface runoff as sheet flow. The slope of the filter strip should be approximately 1% along its entire length and 0% across its width. A recent study by MWCOG (Galli, 1992) concluded that for areas receiving high suspended solid loads, a minimum filter length of 50 feet is desirable.

All trenches with surface inlets should be engineered to capture sediment from the runoff before it enters the stone reservoir. Any pretreatment facility design should be included in the design of the trench, complete with maintenance and inspection requirements.

Backfill Material

Backfill material for the infiltration trench should be clean aggregate with a maximum diameter of 3.5 inches and a minimum diameter of 1.5 inches (i.e., VDOT No. 1 Open-graded Coarse Aggregate or equivalent). The aggregate should contain few aggregates smaller than the selected size. Void spaces for VDOT No. 1 aggregate is assumed to be 40 percent.

An 8 inch deep bottom sand layer (VDOT Fine Aggregate, Grading A or B) is required for all trenches to promote better drainage and reduce the risk of soil compaction when the trench is backfilled with stone (MWCOG, 1992).

Filter Fabric

The aggregate fill material should be surrounded with an engineering filter fabric as shown in **Figure 3.10-5**. For an aggregate surface trench, filter fabric should surround all of the aggregate fill material except the top one foot. A separate piece of fabric should be used for the top layer to act as a failure plane. This top piece can then be removed and replaced upon clogging. Note, however, that filter fabric should **not** be placed on the trench bottom. Refer to the VESCH 1992 edition, for filter fabric specifications.

Overflow Channel

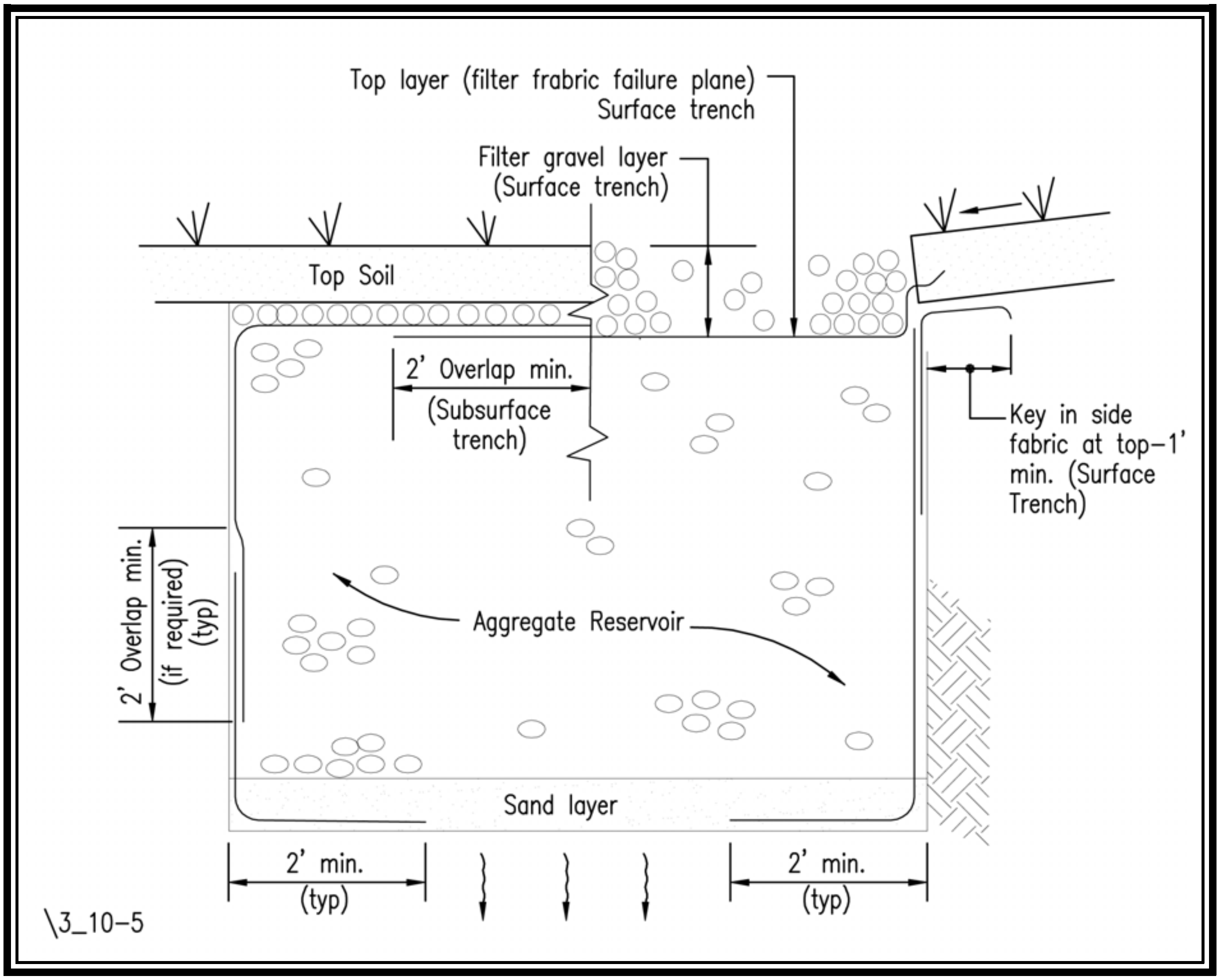
Usually, because of the small drainage areas controlled by an infiltration trench, an emergency spillway is not necessary. However, the overland flow path taken by the surface runoff, when the capacity of the trench is exceeded, should always be evaluated. A nonerosive overflow channel leading to a stabilized watercourse should be provided, as necessary, to insure that uncontrolled, erosive, concentrated flow does not develop.

Observation Well

An observation well should be installed for every 50 feet of infiltration trench length. The observation well will show how quickly the trench dewaters following a storm, as well as providing a means of determining when the filter fabric is clogged and maintenance is needed (refer to **Figure 3.10-4**).

The observation well should consist of perforated PVC pipe, 4 to 6 inches in diameter. It should be installed in the center of the structure, flush with the ground elevation of the trench. Putting the observation well in a non-parking or traffic area to simplify inspections is best. The top of the well should be capped to discourage vandalism and tampering.

FIGURE 3.10 - 5
Filter Fabric Placement



Construction Specifications

Overall, widely accepted construction standards and specifications, such as those developed by the USDA Soil Conservation Service or the U.S. Army Corps of Engineers, should be followed where applicable. Further guidance can be found in the Soil Conservation Service's Engineering Field Manual. Specifications for the work should conform to the methods and procedures indicated for installing earthwork, concrete, reinforcing steel, pipe, water gates, metal work, woodwork and masonry, as they apply to the site and the purpose of the structure. The specifications should also satisfy any requirements of the local government.

Construction of an infiltration trench should also be in conformance with the following:

Sequence of Construction

An infiltration trench should not be constructed or placed into service until all of the contributing drainage area has been stabilized. Runoff from untreated, recently constructed areas within the drainage area may load the newly formed trench and/or pretreatment facility with a large volume of fine sediment.

The specifications for the construction of an infiltration trench should state the following: 1) *the earliest point at which storm drainage may be directed to the trench*, and 2) *the means by which this delay in use is to be accomplished*. Due to the wide variety of conditions encountered among development projects, each project should be evaluated separately to postpone trench use for as long as possible.

Trench Preparation

Trench excavation should be limited to the specific trench dimensions. Excavated materials should be placed away from the trench sides to avoid impacting the trench wall stability.

The trench should be excavated with a backhoe or similar device that allows the equipment to stand away from the trench bottom. This bottom surface should be scarified with the excavator bucket teeth on the final pass to eliminate any smearing or shearing of the soil surface. Similarly, the sand filter material should be placed on the trench bottom so that it does not compact or smear the soil surface. The sand must be deposited ahead of the loader so the equipment is always supported by a minimum of 8 inches of sand.

Large tree roots must be trimmed flush with the trench sides to prevent the fabric from puncturing or tearing during subsequent installation procedures. No voids between the filter fabric and the excavation walls should be present. If boulders or similar obstacles are removed from the excavated walls, natural soils should be placed in these voids before the filter fabric is installed. The side walls of the trench should be roughened where sheared and sealed by heavy equipment.

Vertically excavated walls may be difficult to maintain in areas where the soil moisture is high or where soft cohesive or cohesionless soils predominate. These conditions may require that the side slopes be laid back to maintain stability; trapezoidal rather than rectangular cross sections may result.

Fabric Laydown

The roll of filter fabric should be cut to the proper width before installation. The width should allow for perimeter irregularities plus a minimum 12-inch overlap at the top. When a fabric overlap is required elsewhere, the upstream section should overlap the downstream section by a minimum of 2 feet to ensure that the fabric conforms to the excavation surface during aggregate placement. Note that filter fabric should **not** be placed on the trench bottom.

Stone Aggregate Placement Compaction

The crushed stone aggregate should be placed in the trench in loose lifts of about 12 inches using a backhoe or front-end loader with a drop height near the bottom of the trench, and should be lightly compacted with plate compactors. Aggregate should not be dumped into the trench by a truck.

Backfill material for the infiltration trench should be clean, washed aggregate *1.5* to *3.5* inches in diameter (VDOT No. 1 Open-graded Coarse Aggregate or equivalent). The aggregate should contain few aggregates smaller than the selected size.

The 8 inch deep bottom sand layer should consist of VDOT Fine Aggregate, Grading A or B.

Overlapping and Covering

Following the stone aggregate placement, the filter fabric should be folded over the stone aggregate to form a 12-inch minimum longitudinal overlap. The desired fill soil or stone aggregate should be placed over the lap at sufficient intervals to maintain the lap during subsequent backfilling.

Potential Contamination

Clean aggregate **should not** be mixed with natural or fill soils. All contaminated aggregate should be removed and replaced with clean aggregate.

Traffic Control

To prevent or reduce compaction of the soil, heavy equipment and traffic should not travel over the infiltration trench.

Observation Well

Observation wells should be provided as specified in the design criteria. The depth of the well at the time of installation should be clearly marked on the well cap.

Maintenance / Inspection Guidelines

The following maintenance and inspection guidelines are not intended to be all-inclusive. Specific facilities may require other measures not discussed here.

Inspection Schedule

The observation well and pretreatment facility should be monitored quarterly and after every large storm event. It is recommended that a log book be maintained showing the depth of water in the well at each observation in order to determine the rate at which the facility dewaters after runoff producing storm events. Once the performance characteristics of the structure have been verified, the monitoring schedule can be reduced to an annual basis, unless the performance data suggest that a more frequent schedule is required.

Sediment Control

Sediment buildup in the top foot of stone aggregate or the surface inlet should be monitored on the same schedule as the observation well. A monitoring well in the top foot of stone aggregate should be provided when the trench has a stone surface. Sediment deposited should not be allowed to build up to the point where it will reduce the infiltration rate into the trench.

It is recognized that infiltration facilities are subject to clogging. Once a trench facility has clogged, very little can be done to correct it, short of excavating the facility. Maintenance efforts, therefore, should focus on the measures used for pretreatment of runoff, in addition to the facility itself.

Vegetation Maintenance

Any vegetated buffers associated with an infiltration trench should be inspected regularly and maintained as needed. Regular maintenance of the buffer is necessary to promote dense turf with extensive root growth, which subsequently enhances runoff filtering, prevents erosion and sedimentation, and deters invasive weed growth. Bare spots should be immediately stabilized and revegetated. Fertilizers should be applied only as necessary and in limited amounts to avoid contributing to pollution problems which the infiltration basin helps to mitigate. Consult the VESCH 1992 edition for appropriate fertilizer types and application rates.

Design Procedures

The following design procedure represents a generic list of the steps typically required for the design of an infiltration trench.

1. Determine if the anticipated development conditions and drainage area are appropriate for an infiltration trench application.

2. Determine if the soils (permeability, bedrock, water table, Karst, etc.) and topographic conditions (slopes, building foundations, etc.) are appropriate for an infiltration trench application.

3. Locate the infiltration trench on the site within topographic constraints.

4. Determine the drainage area for each infiltration trench and calculate the required water quality volume.

5. Evaluate the hydrology of the contributing drainage area to determine peak rates of runoff.

6. Design the infiltration trench:
   - design infiltration rate, $f_d = 0.5\ f$
   - max. storage time T_{max} = 48 hours
   - max. storage depth, d_{max}
   - stone backfill of clean aggregate (1.5" to 3.5") VDOT No. 1 Open-Graded Course Aggregate
   - sand layer on trench bottom (8 inches)
   - runoff pretreatment - concentrated input, sheet flow input
   - vegetated buffer around trench to filter surface runoff
   - filter fabric on trench sides and top (not on trench bottom) keyed into trench
   - overflow channel or large storm bypass
   - observation well

7. Provide material specifications.

8. Provide sequence of construction.

9. Provide maintenance and inspection requirements.

MINIMUM STANDARD 3.10C

ROOF DOWNSPOUT SYSTEM

Definition

A roof downspout system is an infiltration trench practice intended only for infiltrating rooftop runoff transported to the trench via roof downspout drains.

Purpose

The purpose of a roof downspout system is to provide water quality enhancement of rooftop runoff via infiltration of the water quality volume into the surrounding soils. This facility is not designed to infiltrate other surface water that could transport sediment or pollutants, such as from paved areas.

Conditions Where Practice Applies

Roof downspout systems may be used in any situation where disposing of rooftop runoff without direct connections to existing drainage systems or BMPs is acceptable and advantageous. Because of their small size, they are well suited for retrofitting in areas where runoff control of existing or new rooftop areas associated with building additions becomes necessary. As part of a low impact development strategy, roof downspout systems effectively disconnect the rooftop imperviousness from the drainage system which helps reduce the stormwater impact of the development. Use of roof downspout systems (or infiltration trenches in general) in residential areas should be used with caution due to concern for the potential lack of inspections and maintenance, and ultimate failure and abandonment of the facility.

Planning Considerations

The planning considerations for roof downspout systems are the same as those for infiltration trenches (**Minimum Standard 3.10B**). The drainage area is limited to the rooftop areas of residential and/or commercial structures.

Design Criteria

This section provides recommendations and minimum criteria for the design of roof downspout systems intended to comply with the runoff quality requirements of the Virginia Stormwater Management program.

The design criteria for roof downspout systems are the same as those for infiltration trenches with the following exceptions and/or additions:

Distance from Structures

Roof downspout systems should be a minimum of 10 feet down-slope from any structure or property line, and 30 feet from any septic tank or drain field.

Runoff Pre-Treatment

Gutters should be fitted with mesh screens to prevent leaf litter and other debris from entering the system in areas where there is tree cover. The expected growth of newly planted trees should be considered.

A pretreatment settling basin as shown in **Figure 3.10-6** should be provided on all roof downspout systems.

Overflow

An overflow outlet should be provided on the downspout at the surface elevation to allow flow to bypass the infiltration facility when it is full or clogged. (See **Figure 3.10-6**.)

Adequate surface drainage away from the structure should be provided according to appropriate building codes.

Construction Specifications

The construction specifications for roof downspout systems are the same as those for infiltration trenches.

Maintenance and Inspection Guidelines

Maintenance procedures are identical for those of an infiltration trench. Since these facilities are installed on individual buildings and other structures, provisions need to be made for their maintenance, especially when they are installed on single family dwellings. When flow is observed to be bypassing the facility, the system has clogged and should be evaluated for rehabilitation.

Design Procedures

The following design procedure represents a generic list of the steps typically required for the design of a roof downspout system.

1. Determine if the anticipated development conditions and rooftop areas are appropriate for a roof downspout system.

2. Determine if the soils (permeability, bedrock, water table, Karst, etc.) and topographic conditions (slopes, building foundations, etc.) are appropriate for a roof downspout system.

3. Locate the roof downspout system on the site within site topographic constraints.

4. Determine the roof area for each roof downspout system and calculate the required water quality volume.

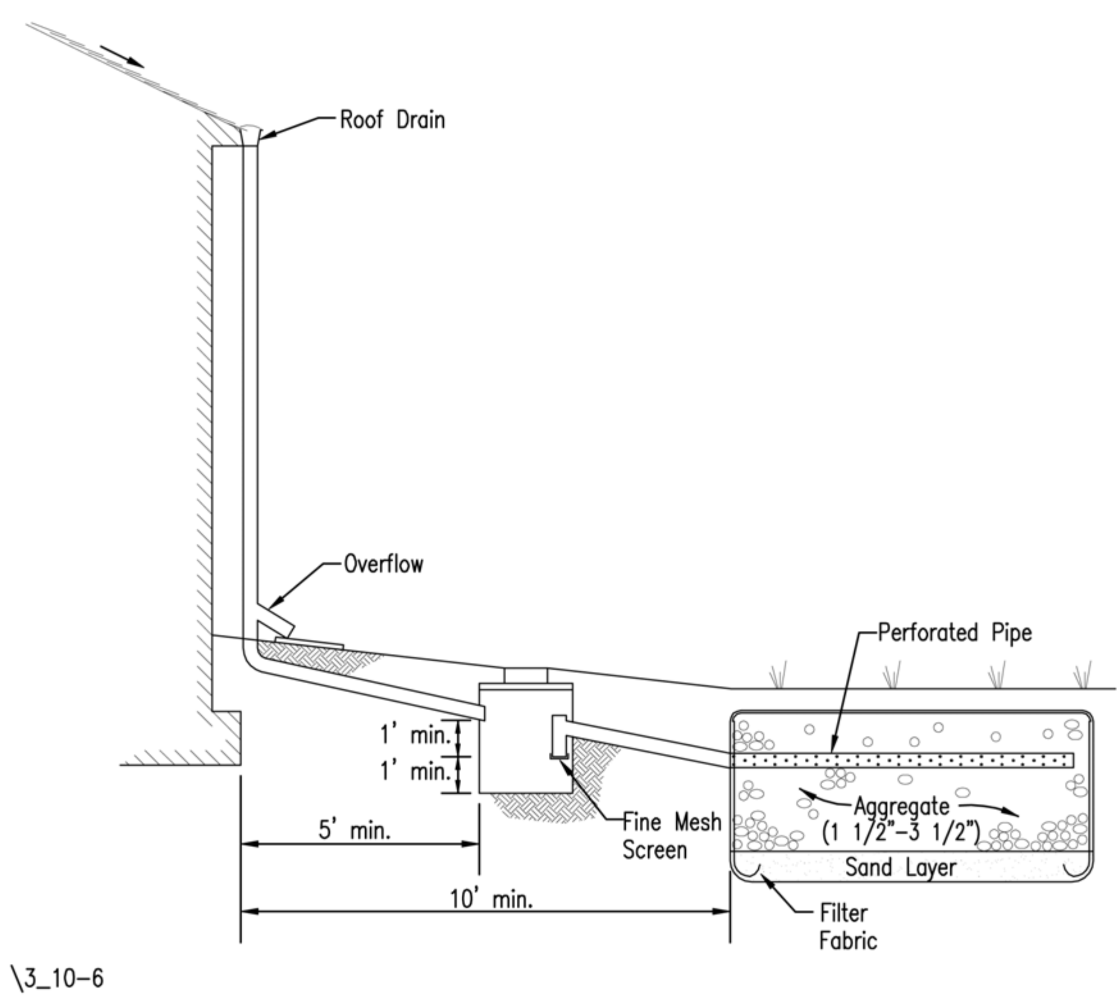
5. Design the roof downspout system:
    - design infiltration rate, $f_d = 0.5\, f$
    - max. Storage time $T_{max} = 48$ hours
    - max. Storage depth, d_{max}
    - stone backfill of clean aggregate (*1.5*" to *3.5*" diameter) - VDOT No. 1 Open-graded Course Aggregate
    - sand layer on trench bottom (*8* inches
    - runoff pretreatment - concentrated input: gutter screens, settling basin
    - filter fabric on trench sides and top (not on trench bottom) keyed into trench
    - overflow channel or large storm bypass
    - observation well

6. Provide material specifications.

7. Provide sequence of construction.

8. Provide maintenance and inspection requirements.

FIGURE 3.10 - 6
Roof Downspout System with a Pretreatment Sump Basin



MINIMUM STANDARD 3.10D

POROUS PAVEMENT

Definition

Porous pavement is a pervious pavement placed over a stone reservoir that is installed above a permeable soil.

The two pavements discussed in this section are ***porous asphalt pavement*** and ***porous concrete pavement***. *Porous asphalt pavement* is an open-graded coarse aggregate, bound together by asphalt cement into a coherent mass, with sufficient interconnected voids to provide a high rate of permeability to water. A typical porous asphalt pavement cross-section is presented in **Figure 3.10-11**. *Pourous concrete pavement* consists of specially formulated mixtures of Portland Cement, uniform, open-graded coarse aggregate and potable water.

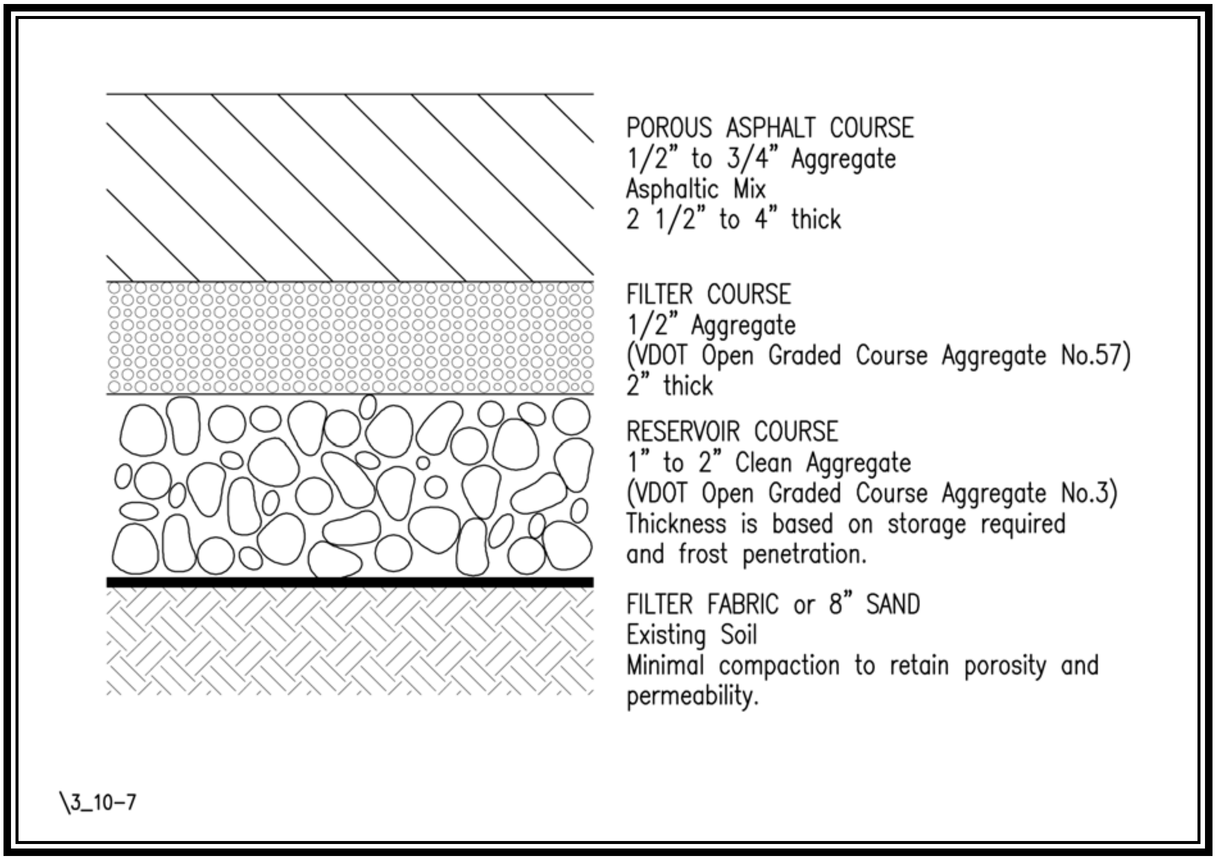
Purpose

The purpose of porous pavement is to provide water quality enhancement by infiltrating water through the paved surface and stone reservoir and into the underlying soils.

Conditions Where Practice Applies

Porous pavement is applicable as a substitute for conventional asphalt pavement on parking areas and low-traffic roadways if the grades, subsoil drainage characteristics and groundwater table conditions are suitable. Usually, the grades should be very gentle to flat, subsoil should have moderately rapid permeability ($f > 0.52$ *in/hr*) and the depth to the water table or bedrock should be at least 3 feet below the bottom of the stone reservoir. Parking lots, especially fringe or overflow parking areas, are suited for use with this paving material. Porous pavement should generally be installed on sites from 1/4 to 10 acres.

FIGURE 3.10 - 7
Porous Pavement Section



Planning Considerations

Porous pavement functions similar to infiltration trenches and, therefore, has similar planning considerations. Appropriate soil conditions and the protection of groundwater are among the important considerations which may limit its use. Refer to the **Planning Considerations** in **General Infiltration Practices**, **Minimum Standard 3.10** for additional discussion.

Generally, groundwater recharge rates are slightly higher under a porous pavement than under natural conditions, as vegetation is absent and water is not transpired during the summer months. Between 60% and 90% of the annual rainfall volume deposited on a porous pavement percolates into the ground (Washington DOE, 1992.)

It has been shown that porous pavement is more skid-resistant than conventional pavement in rainy weather and that the markings on a porous pavement are easier to see on rainy nights. In addition, studies have suggested that porous asphalt pavement is sufficiently strong and able to withstand freeze-thaw cycles and will last as long, structurally, as conventional pavement.

Typically, porous pavement is slightly more expensive than regular pavement. Additional costs associated with critical installation procedures and the availability of the asphalt mix may be offset by eliminating the need for curb and gutter, inlets, and conveyance systems. Availability is a consideration, since asphalt producers may not be willing to provide porous asphalt for small projects due to the demand for conventional asphalt mixes. For the production of a porous pavement mixture, the asphalt plant must be cleaned out to remove the fines not wanted in the porous mix. The cost of the stone reservoir and filter fabric associated with porous pavement is offset by the amount that would be spent on a stormwater facility elsewhere on the site.

Installation requires a very high level of workmanship throughout the construction process; porous pavement must be handled with great care in order for it to retain its porous qualities. Many pavement contractors and pavement engineers have limited experience in designing and constructing porous pavement. Improper installation can render a porous pavement design inoperative from the outset.

The biggest drawback to porous pavement is its tendency to clog if improperly maintained. Once it is clogged, it may have to be completely replaced since rehabilitating it is difficult and costly. On going maintenance of the pavement surface and specific limitations on the methods of snow and ice removal are often ignored and/or forgotten over time and with transfers of ownership. Clogging of the pavement surface from construction-related erosion can be prevented by waiting until all other phases of construction are complete and vegetation is stabilized before installing the pavement. Clogging of the pavement surface from natural circumstances is best prevented by installing it in areas that do not have highly erodible soils or steep slopes adjacent to the paved area.

Certain features can be incorporated into the design of porous pavement facilities to prolong the effective life of the system. One such feature is to “daylight” the aggregate base along the downslope edge of the pavement, forming a chimney drain into the stone storage under the pavement. The runoff can flow into the stone storage through the chimney drain if the pavement clogs.

If slow infiltration rates in the subgrade exist, porous pavement systems can be designed with an underdrain or collector system. When the collector system has a restriction plate on the outlet that controls the discharge, the stone reservoir can be designed as an underground stone-storage detention facility.

Evidence suggests that pollutants adsorb to the aggregate material, while particulates settle to the bottom of the aggregate layer. However, the target removal efficiency of 50% to 65%, as presented in **Table 3.10-1** for infiltration facilities, is too high for a stone-storage facility. **Therefore, a**

porous pavement facility with a stone storage underdrain system that provides positive drainage will be considered an extended-detention or detention facility. Its target pollutant removal efficiency will be based on the storage and release rate characteristics of these facilities as presented in **Minimum Standards 3.07, Extended-Detention**; and **3.08, Detention Basins**, until more information is collected to support the use of a higher pollutant removal efficiency.

Design Criteria

The purpose of this section is to provide recommendations and minimum criteria for the design of porous pavement intended to comply with the runoff quality requirements of theVirginia Stormwater Management programs.

The general design criteria for the porous pavement stone reservoir area and the underlying soils are the same as for infiltration trenches. Additional design is required for determining the porous pavement thickness. The design of the pavement is dependent on the strength of the sub-base soil, the projected traffic intensities, and the storage capacity of the reservoir and base.

A thorough examination of the site is of primary importance to the proper design and functioning of porous pavement. Soil and climate conditions, expected surface wear, and the use objectives of the porous surface should all be considered before designing the pavement.

The following represents a general list of design elements that should be considered in any porous pavement design:

1. Anticipated traffic intensities, defined by the ***average daily equivalent axle load*** (*EAL*).
2. ***California Bearing Ratio*** (CBR) of the soils.
3. Susceptibility of the soils to frost heave.

Due to the complexity of its design, a step-by-step procedure to engineer a porous pavement section will not be presented in this manual. **A professional engineer, with training and experience in porous pavement design and construction, should design the pavement section and supervise during the paving operation**.

Specific design requirements for a satisfactory ***porous asphalt pavement*** section equivalent to a conventional pavement design are available through the U. S. Department of Transportation's Federal Highway Administration and through other references listed at the end of this standard.

Specific design requirements for a satisfactory ***porous concrete pavement*** section are available through the Florida Concrete and Products Association, 649 Vassar Street, Orlando, Florida 32804. Other references are also listed at the end of this standard.

Porous Concrete Pavement Construction Specifications

The design criteria and material specifications for ***porous concrete pavement*** are **NOT INCLUDED** in this manual due their extreme complexity. Note that the methods of handling and placing porous concrete are different from other types of concrete. **Only concrete firms and contractors familiar with the intricacies of porous concrete should be used**. For further discussion, refer to **General Pavement Design Criteria** above.

Porous Asphalt Pavement Construction Specifications

The following construction specifications are general and typically represent aspects of design that require fine-tuning based on site conditions. A professional with experience in porous asphalt design should supervise construction to insure proper methods are used.

Overall, widely accepted construction standards and specifications, such as those developed by the USDA Soil Conservation Service or the U.S. Army Corps of Engineers, should be followed where applicable. Further guidance can be found in the Soil Conservation Service's Engineering Field Manual. Specifications for the work should conform to the methods and procedures specified for installing earthwork, concrete, reinforcing steel, pipe, water gates, metal work, woodwork and masonry, as they apply to the site and the purpose of the structure. The specifications should also satisfy any requirements of the local government.

The specifications for the asphalt mix should include:

1. Calculation of void space in the asphalt section.
2. Aggregate type, quality and gradation.
3. Asphalt cement grade in mix.
4. Asphalt content in mix.
5. Mixing temperature.

Construction of a porous asphalt pavement should also be in conformance with the following (adapted from Construction Sspecifications for the City of Rockville, Maryland:

Stabilization

To preclude premature clogging and/or failure, porous asphalt pavement should not be placed into service until all of the surface drainage areas contributing to the paved area have been effectively stabilized. Refer to the VESCH 1992 edition, for stabilization requirements.

Subgrade Preparation

1. Alter and refine the grades as needed to bring subgrade to required grades and sections as shown in the drawings.

2. The type of equipment used in subgrade preparation should not cause undue subgrade compaction. (Use tracked-equipment or equipment with oversized rubber tires **Do Not use standard rubber tire equipment**.) Traffic over the subgrade should be kept to a minimum. Where fill material is required, it should be compacted to a density equal to the undisturbed subgrade. Inherent soft spots should be corrected.

Trench Bottom

The trench bottom may be lined with filter fabric or an *8* inch layer of sand (VDOT Fine Aggregate, Grading A or B), based on the geotechnical and pavement design recomendations.

Reservoir course

1. The stone reservoir course aggregate should be 1 to 2 inch diameter clean, washed, crushed stone meeting VDOT specifications (Open Graded Course Aggregate No. 3).

2. The stone reservoir thickness (depth) is dependent on the storage volume requirements (water quality volume, quantity control volumes, etc.).

Filter Course

1. The filter course aggregate should be 1/2-inch diameter clean, washed, crushed stone, meeting VDOT specifications (Open-graded Course Aggregate No. 57).

2. The filter course thickness should be 2 inchs.

Porous Asphalt Surface Course

1. The surface course should be laid directly over the aggregate base course and should be laid in one lift.

2. The laying temperature should be between 230EF and 260EF, with a minimum air

temperature of 50EF, to make sure that the surface does not stiffen before compaction.

3. Compaction of the surface course should be completed while the surface is cool enough to resist a 10-ton roller. One or two passes of the roller are required for proper compaction. More rolling could cause a reduction in the surface course porosity.

4. The mixing plant should certify to the aggregate mix, the abrasion loss factor, and the asphalt content in the mix. The asphalt mix should be tested for its resistance to stripping by water using ASTD 1664. If the estimated coating area is not above 95%, antistripping agents should be added to the asphalt.

5. The mix should be transported to the site in a clean vehicle with smooth dump beds sprayed with a non-petroleum release agent. The mix should be covered during transportation to control cooling.

6. The asphalt mix should be 5.5 to 6% of dry aggregate by7 weight.

7. The asphalt's grade should meet AASHTO Specification M-20; 85 to 100% penetration road asphalt as a binder in the western part of the state, 65 to 80% in the piedmont area, and 50 to 65% in southeastern Virginia.

8. The aggregate grading should be as specified in **Table 3.10-3**.

<u>Protection</u>

After final rolling, no vehicular traffic of any kind should be permitted on the pavement until cooling and hardening has taken place, and never less than 6 hours (preferably 24 to 48 hours). All construction related traffic should be routed around or away from the porous pavement.

<u>Workmanship</u>

1. Work should be completed with expertise throughout the process and without staining or damage to other permanent work.

2. The transition between existing and new paving work should be neat and flush.

3. Finished paving should be even, without pockets, and graded to elevations shown.

4. All minor surface projections and edges adjoining other materials should be ironed smoothly to grade.

Certification

An appropriate professional should certify that these specifications were followed.

TABLE 3.10 - 3
Porous (Open-graded) Asphalt Concrete Formulation*

PROBABLE PARTICLE DATA						
Material	**Screen**	**Weight** *%*	**Volume** *%*	**Width** *mm*	**Weight** *g*	**No. In 100g of Asphalt Concrete**
Aggregate	**Through ½**	**2.8**	**2.2**	**10.7**	**1.667**	**1.7**
	Through 3/8	**59.6**	**46.3**	**8.0**	**.697**	**85.5**
	Through #4	**17.0**	**13.3**	**4.0**	**.087**	**195.4**
Sub-Total Coarse Aggregate		**79.4**	**61.8**			**282.6**
	Through # 8	**2.8**	**2.2**	**2.0**	**.0109**	**255.6**
	Through #16	**10.4**	**8.0**	**1.0**	**.00136**	**7647.**
	Through 200	**1.9**	**1.5**	**.06**	**.000294**	**6462.**
Asphalt		**5.5**	**10.5**			
Air		**0**	**16.0**			
TOTAL		**100.0**	**100.0**			

** Source: City of Rockville, Maryland (1982).*

Maintenance and Inspections

The following maintenance and inspection guidelines are not intended to be all-inclusive. Specific applications may require other measures not discussed here.

Inspection Schedule

The observation well should be checked quarterly and after every large storm event. It is recommended that a log book be maintained showing the depth of water in the well during each inspection in order to determine the rate at which the facility dewaters after runoff producing storms events. Once the performance characteristics of the structure have been verified, the monitoring schedule can be reduced to an annual basis, unless the performance data suggest that a more frequent schedule is required.

Maintenance

The surface of porous asphalt pavement must be cleaned regularly to prevent it from becoming clogged by fine material. This cleaning is best accomplished through the use of a vacuum cleaning street sweeper, followed by high pressure water washing. Outside of regular cleaning, porous pavement requires maintenance similar to that of regular pavement. In times of heavy snowfall, however, application of abrasive material should be closely monitored to avoid clogging problems once the snow and ice has melted. There are no maintenance measures designed to repair fully clogged porous pavement, other than replacement.

Design Procedures

The following design procedure represents a generic list of the steps typically required for the design of an infiltration trench.

1. Determine if the anticipated development conditions and drainage area are appropriate for a porous pavement application.

2. Determine if the soils (permeability, bedrock, water table, Karst, etc.) and site topographic conditions (slopes, etc.) are appropriate for a porous pavement application.

3. Locate the porous pavement section on the site within the topographic constraints.

4. Determine the drainage area for the porous pavement and calculate the required water quality volume.

5. Evaluate the hydrology of the contributing drainage area to determine peak rates of runoff.

6. Design the porous pavement stone reservoir:
   - C design infiltration rate, $f_d = 0.5 f$
   - C max. storage time T_{max} = 48 hours
   - C max. storage depth, d_{max}
   - C stone backfill of clean aggregate (1.5" to 3.5") VDOT No. 1 Open-graded Course Aggregate
   - C filter gravel layer - two inches of clean aggregate (1/2") VDOT No. 57 Open-graded Course Aggregate
   - C sand layer on trench bottom (8 inche), or filter fabric, per geotechnical and pavement design recommendations
   - C Filter fabric on trench sides and top (not on trench bottom) keyed into trench
   - C Overflow channel or large storm bypass
   - C Observation well

7. Provide pavement section design and material specifications.

8. Provide sequence of construction.

9. Provide maintenance and inspection requirements.

REFERENCES

(Compiled from Standards and Specifications for Infiltration Practices, Maryland Department of Natural Resources, 1987)

Bentall, R. Methods of Collecting and Interpreting Ground Water Data. U.S. Geological Survey, Water Supply Paper 1544-H, 1963, 97 pp.

Bianchi, W. C., and D. C. Muckel. Ground Water Recharge Hydrology. ARS 41-161, U.S. Department of Agriculture, 1970, 62 pp.

Cedergreen, H. R. Seepage, Drainage, and Flow Nets. New York: John Wiley and Sons, Inc., 1967.

Davis, S. N., and R. J. DeWiest. Hydrogeology. New York: John Wiley and Sons, Inc., 1966.

Ferris, J. G., D. B. Knowles, R. H. Brown, and R. W. Stallman. Theory of Aquifer Tests. U.S. Geological Survey, Water Supply Paper No. 1536-E.

Florida Concrete and Products Association. Design Manual. Orlando, FL.

Galli, John. Analysis of Urban BMP Performance and Longevity. Metropolitan Washington Council of Governments, 1992.

Hannon, J. B. Underground Disposal of Storm Water Runoff, Design Guidelines Manual. The California Department of Transportation in cooperation with the Federal Highway Administration, U.S. Department of Transportation, Washington, DC (FHWA-TS-80-218), February 1980.

Maryland Department of Natural Resources. Standards & Specifications for Infiltration Practices. 1987.

Northern Virginia Planning District Commission. Northern Virginia BMP Handbook. 1992.

Pettyjohn, W. A. Introduction to Artificial Ground Water Recharge. Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency. Worthington, Ohio: National Waterwell Association, 1981, 44 pp.

Rawls, W. J., D. L. Brakensiek, and K. E. Saxton. "Estimation of Soil Properties." Transactions of the American Society of Agricultural Engineers, Vol. 25, No. 5. 1982. p. 1316-1320.

Scheuler, T. R. Controlling Urban Runoff. Metropolitan Washington Council of Governments, 1987.

Scheuler, T. R., P. A. Kumble, and M. A. Heraty. A Current Assessment of Urban Best Management Practices. Metropolitan Washington Council of Governments, 1987.

Schmidt, C. J., and E.V. Clements. Reuse of Municipal Wastewater for Ground Water Recharge. U. S. Environmental Protection Agency, 1977, 183 pp.

Smith, R. W., J. M. Rice, and S. R. Spelman. Design of Open Graded Asphalt Friction Courses. Federal Highway Administration, U. S. Department of Transportation, FHWA-RD-74-2, 1974.

Soil Conservation Service, Engineering Division. Technical Release No. 36. Ground Water Recharge. U. S. Department of Agriculture, 1967, 22 pp.

Soil Conservation Service. National Engineering Handbook, Section 18 Ground Water. U. S. Department of Agriculture, 1968.

Soil Conservation Service. National Engineering Handbook, Section 8, Engineering Geology. U. S. Department of Agriculture, 1978.

Thelen, E., and L. F. Howe. Porous Pavement. Philadelphia, PA: The Franklin Institute Press, 1978.

Thelen, E., et al. Investigation of Porous Pavements for Urban Runoff Control. Franklin Institute Research Laboratories for the U.S. Environmental Protection Agency, NTIS PB-227-5. Springfield, VA, 1972.

Todd, D. K. Ground Water Hydrology. New York: John Wiley and Sons, Inc., 1959.

U. S. Environmental Protection Agency, Office of Water Programs Operations. Design Manual: Onsite Wastewater Treatment and Disposal Systems. U.S. EPA 20460, October 1980.

Virginia Department of Conservation and Recreation. Virginia Erosion and Sediment Control Handbook (VESCH). Richmond, Virginia: 1992.

Virginia State Water Control Board. Best Management Practices Handbook: Urban: Planning Bulletin 321. Richmond, Virginia, 1979.

Washington State Department of Ecology. Stormwater Management Manual for the Puget Sound Basin. 1992.

Wenzel, L. K. Methods of Determining Permeability of Water Bearing Materials. U. S. Geological Survey, Water Supply Paper 887, 1942.

Surface Infiltration Trench. Note grass strip pre-treatment holds heavier particulate pollutants within paved area.

Porous Pavement Infiltration. Testing new pavement installation. Note: steady flow passes through pavement and into stone storage below with minimal spread.

General Infiltration Practices

Chapter 3.10

Infiltration Basin serves as landscaped pedestrian area during dry periods.

Infiltration Trench with concrete parking pavers in office park setting.

General Infiltration Practices

MINIMUM STANDARD 3.11

BIORETENTION BASIN PRACTICES

3.11A **Bioretention Filters**

3.11B **Green Alleys**

View BMP Images

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MINIMUM STANDARD 3.11

BIORETENTION BASINS

Definition

Bioretention is an innovative BMP developed by the Prince George's County, Maryland Department of Environmental protection. The following information is drawn from their ***Design Manual for Use of Bioretention in Stormwater Management*** (P.G. County, 1993) unless otherwise noted. This technology is also referred to as "Rain Gardens."

Figure 3.11-1 illustrates the Maryland bioretention (Rain Garden) concept as adapted for use in Virginia. There are seven major components to the bioretention area (Rain Garden): 1) the grass buffer strip; 2) the ponding area; 3) the surface mulch and planting soil; 4) the sand bed (optional); 5) the organic layer; 6) the plant material, and 7) the infiltration chambers. Each component is critical to sustaining a properly functioning BMP.

Purpose

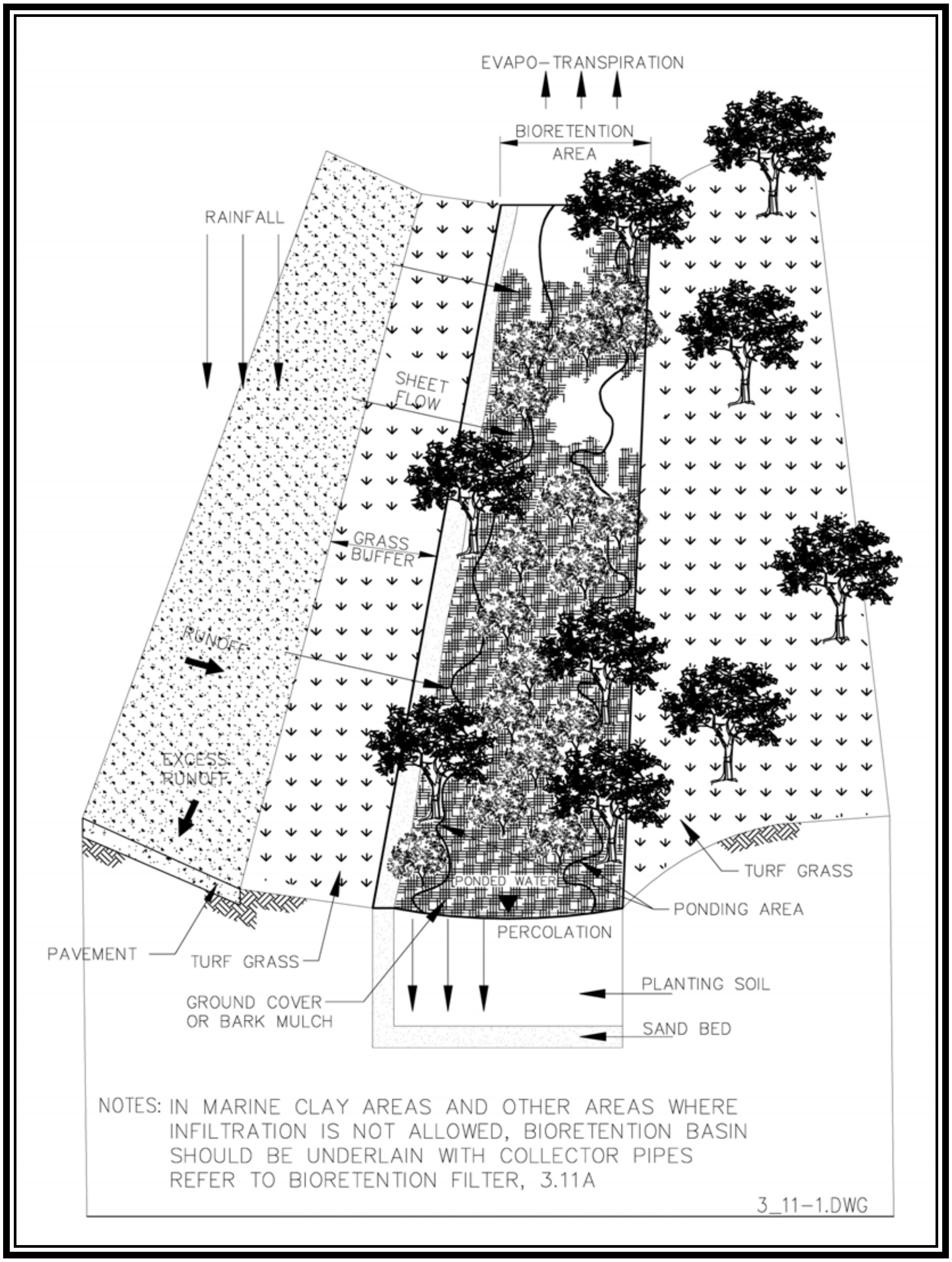
Bioretention basins are used primarily for water quality control. However, since they capture and infilter part of the stormwater from the drainage shed, they may provide partial or complete control of streambank erosion and partial protection from flooding (depending on the volume of water being captured and infiltered).

Bioretention facilities (Rain Gardens) are planting areas installed in shallow basins in which the stormwater runoff is treated by filtering through the bed components, biological and biochemical reactions within the soil matrix and around the root zones of the plants, and infiltration into the underlying soil strata. Properly constructed bioretention areas replicate the ecosystem of an upland forest floor through the use of specific shrubs, trees, ground covers, mulches and deep, rich soils. Since almost all bioretention basins are intended to be visual landscape amenities as well as stormwater BMPs, aesthetic considerations may be equally as important in their use as proper engineering. Bioretention design requires participation by a person with appropriate design skills and a working knowledge of indigenous horticultural practices, preferably a Landscape Architect.

Water Quality Enhancement

Bioretention basins enhance the quality of stormwater runoff through the processes of adsorption, filtration, volitization, ion exchange, microbial and decomposition prior to exfiltration into the surrounding soil mass. Microbial soil processes, evapotranspiration, and nutrient uptake in plants also come into play (Bitter and Bowers, 1995).

FIGURE 3.11 - 1
Bioretention Basin



The **grass buffer strip** filters particles from the runoff and reduces its velocity. The **sand bed** further slows the velocity of the runoff, spreads the runoff over the basin, filters part of the water, provides for positive drainage to prevent anaerobic conditions in the planting soil and enhances exfiltration from the basin. The **ponding area** functions as storage of runoff awaiting treatment and as a presettling basin for particulates that have not been filtered out by the grass buffer. The **organic or mulch layer** acts as a filter for pollutants in the runoff, protects the soil from eroding , and provides an environment for microorganisms to degrade petroleum-based solvents and other pollutants. The **planting soil layer** nurtures the plants with stored water and nutrients. Clay particles in the soil adsorb heavy metals, nutrients, hydrocarbons, and other pollutants. The **plant species** are selected based on their documented ability to cycle and assimilate nutrients, pollutants, and metals through the interactions among plants, soil, and the organic layer (*ibid*). By providing a variety of plants, monoculture susceptibilities to insect and disease infestation are avoided, and evapotranspiration is enhanced. The **vented infiltration chambers** provide unobstructed exfiltration through the open-bottomed cavities, decrease the ponding time above the basin, and aerate the filter media between storms through the open chamber cavities and vents to grade, preventing the development of anaerobic conditions. By providing a valve equipped drawdown drain to daylight, the basin can be converted into a soil media filter should exfiltration surface failures occur.

Perforated underdrain systems are recommended for facilities placed in residential areas and in all areas where the in-situ soils are questionable. Refer to **3.11A - Bioretention Filter**.

The minimum width for a bioretention area is usually 10 feet, although widths as narrow as 4 feet may be used if the runoff arrives as dispersed sheet flow along the length of the facility from a properly sized vegetated strip. The minimum length should be 15 feet (for lengths greater than 20 feet, the length should be at least twice the width to allow dispersed sheet flow). As an infiltration BMP, the maximum ponding depth is restricted to six inches to restrict maximum ponding time to preclude development of anaerobic conditions in the planting soil (which will kill the plants) and to prevent the breeding of mosquitoes and other undesirable insects in the ponded water. The planting soil must have sufficient depth to provide appropriate moisture capacity, create space for the root systems, and provide resistance from windthrow (Minimum depth equal to the diameter of the largest plant root ball plus 4 inches).

Table 3.11-1 contains the target removal efficiencies once a **mature** plant community is created in the bioretention areas based on the volume of runoff to be captured and infiltered.

Flood Control and Channel Erosion

The amount of flood and channel erosion control provided by bioretention basins depends on the local rainfall frequency spectrum, the amount of pre-development (or pre-redevelopment) impervious cover, the amount of post-development impervious cover, and the volume of runoff captured and infiltered by the basin(s). The effect of the BMPs on peak flow rates from the drainage shed must be examined. As with other infiltration practices, bioretention basins tend to reverse the consequences of urban development by reducing peak flow rates and providing groundwater discharge.

TABLE 3.11-1
Pollutant Removal Efficiencies for Bioretention Basins

BMP Description	Target Phosphorus Removal Efficiency
Bioretention basin with capture and treatment volume equal to 0.5 inches of runoff from the impervious area.	50%
Bioretention basin with capture and treatment volume equal to 1.0 inches of runoff from the impervious area.	65%

Conditions Where Practice Applies

Bioretention basins are suitable for use on any project where the subsoil is sufficiently permeable to provide a reasonable rate of infiltration and where the water table is sufficiently lower than the design depth of the facility to prevent pollution of the groundwater. Bioretention basins are generally suited for almost all types of development, from single-family residential to fairly high density commercial projects. They are attractive for higher density projects because of their relatively high removal efficiency. **Figures 3.11-2** through **3.11- 5** illustrate several applications. Bioretention basins may also be installed in off-line pockets along the drainage swales adjacent to highways or other linear projects, as illustrated in **Figure 3.11-6**. For large applications, several bioretention basins connected by an underground infiltration trench (“Green Alleys”) are preferable to a single, massive basin. Such a system is especially desirable along the landward boundary of reduced Chesapeake Bay Resource Protection Areas. **Minimum Standard 3.11B** discusses this system. Considering the character of bioretention basins, some jurisdictions may qualify them as buffer restoration.

FIGURE 3.11 - 2
Bioretention Basin at Edge of Parking Lot With Curb

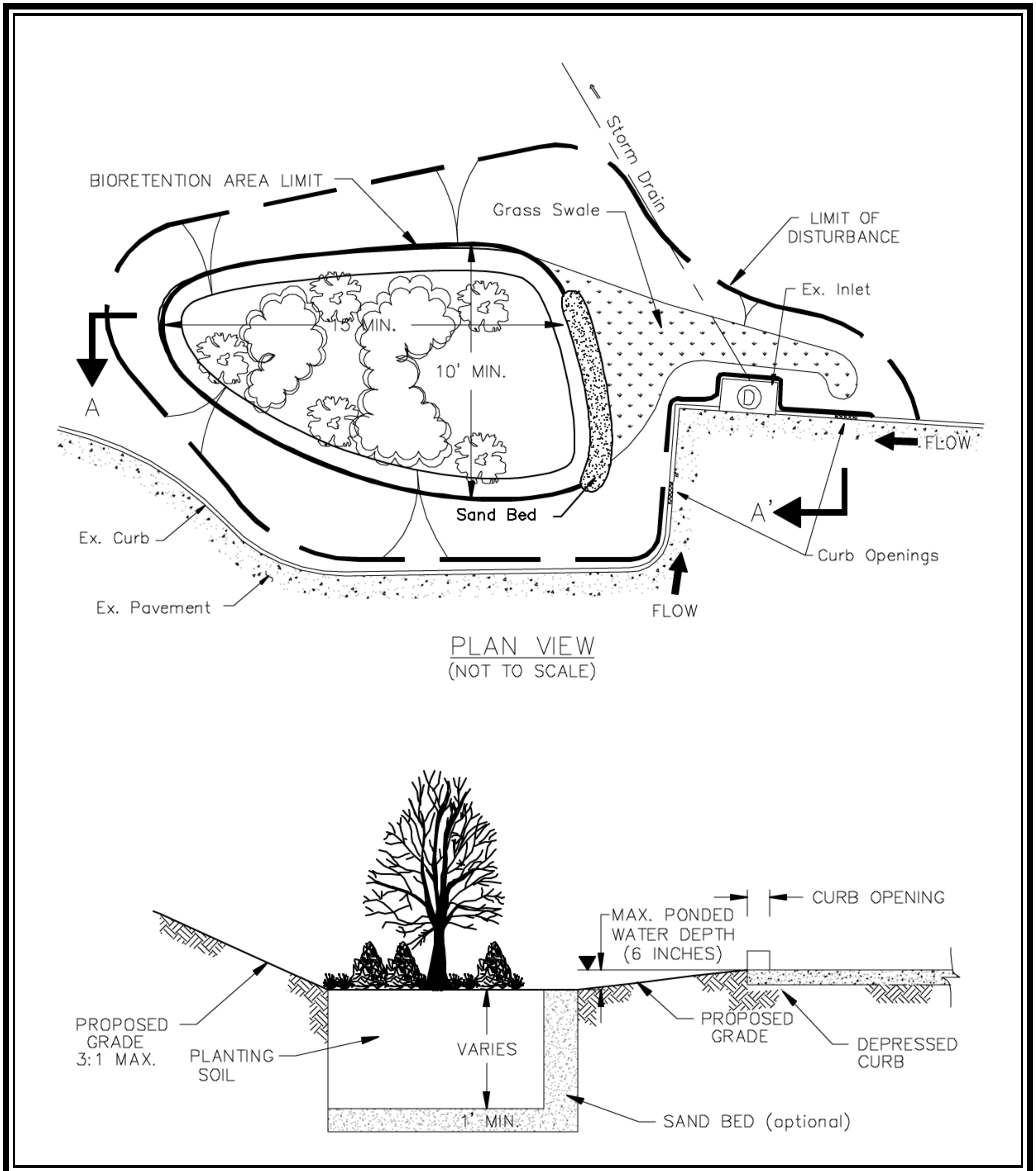


FIGURE 3.11 - 3
Bioretention Basin in a Planting Island in a Parking Lot

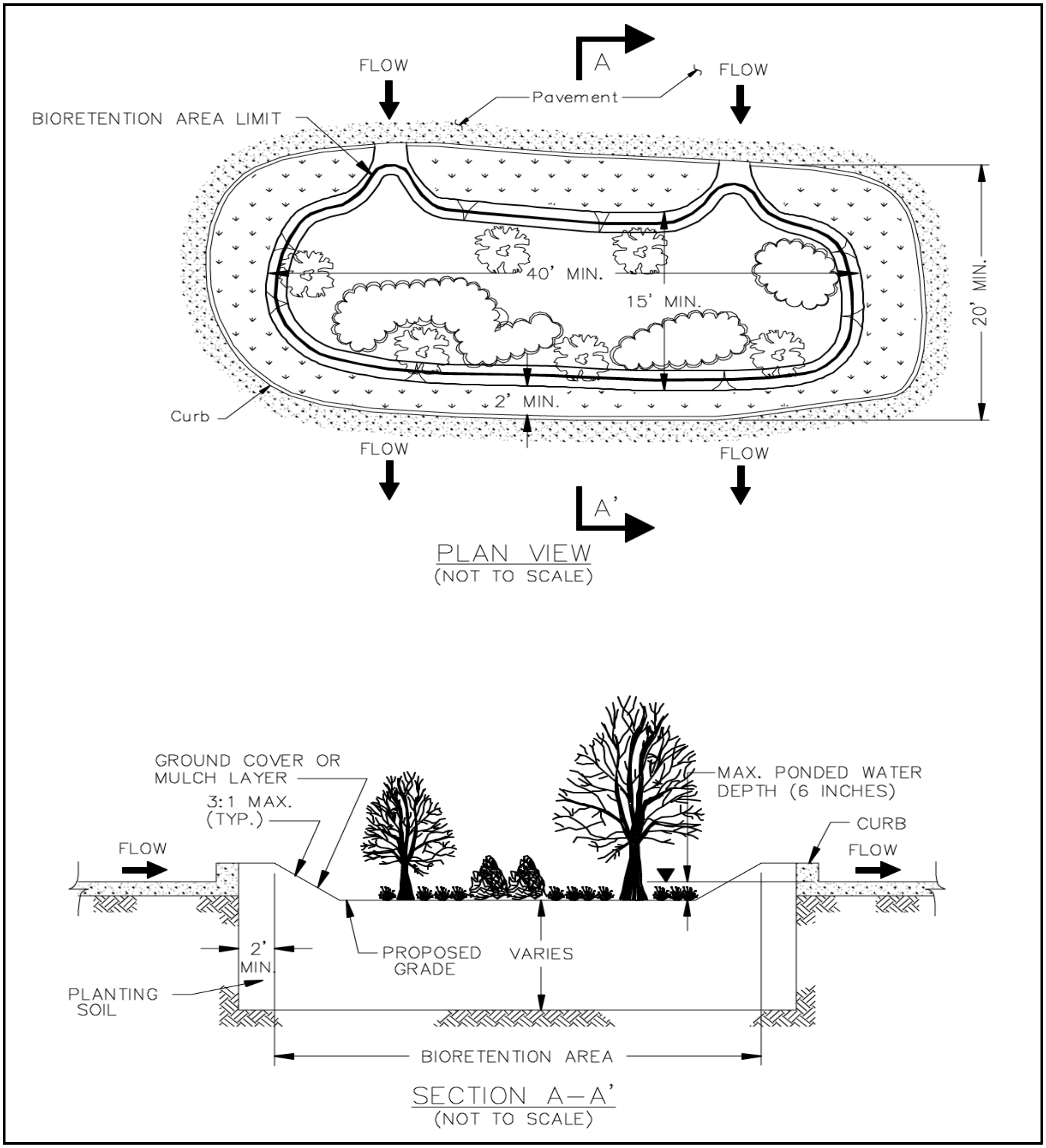


FIGURE 3.11-4
Bioretention Basin Adjacent to a Drainage Swale

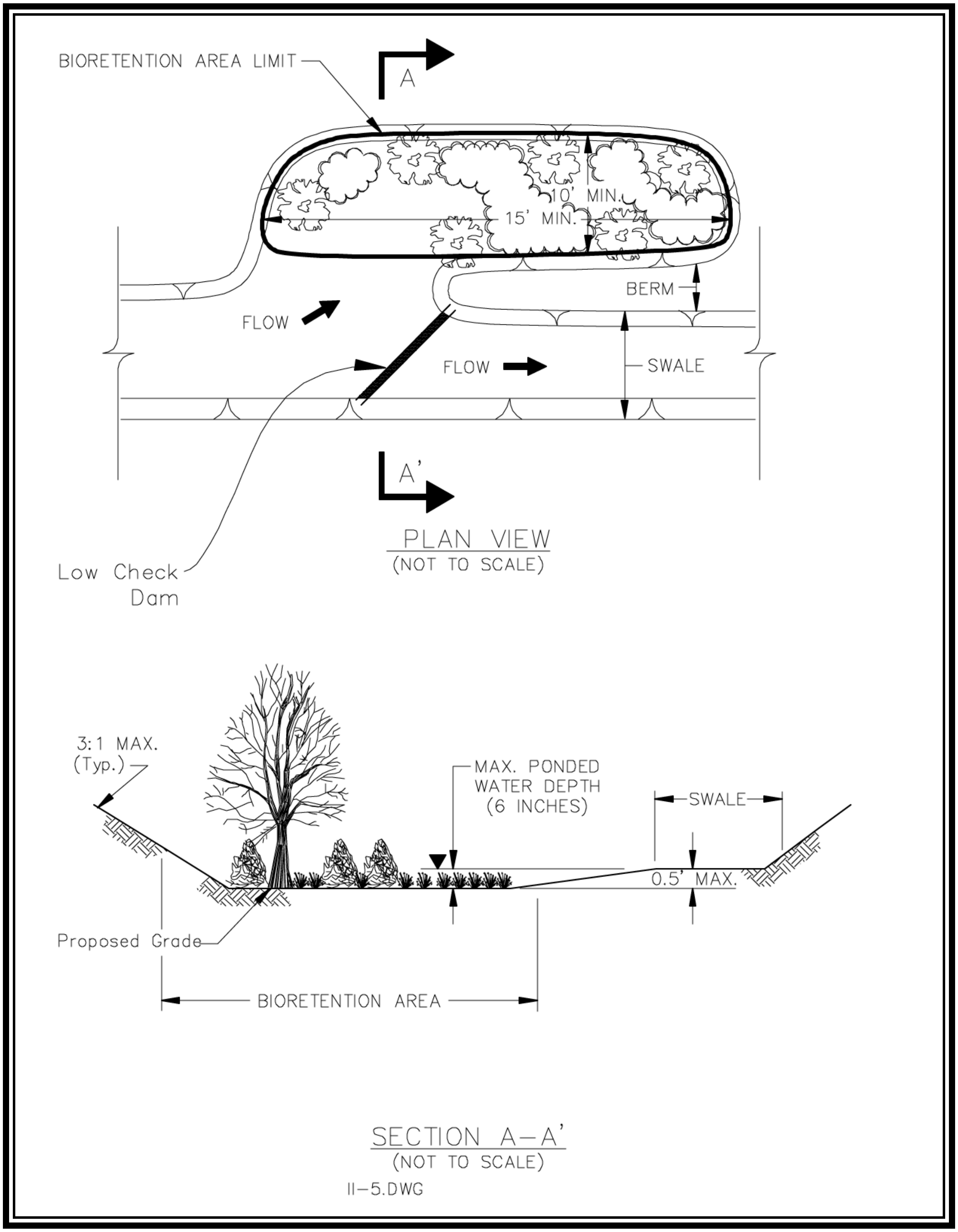
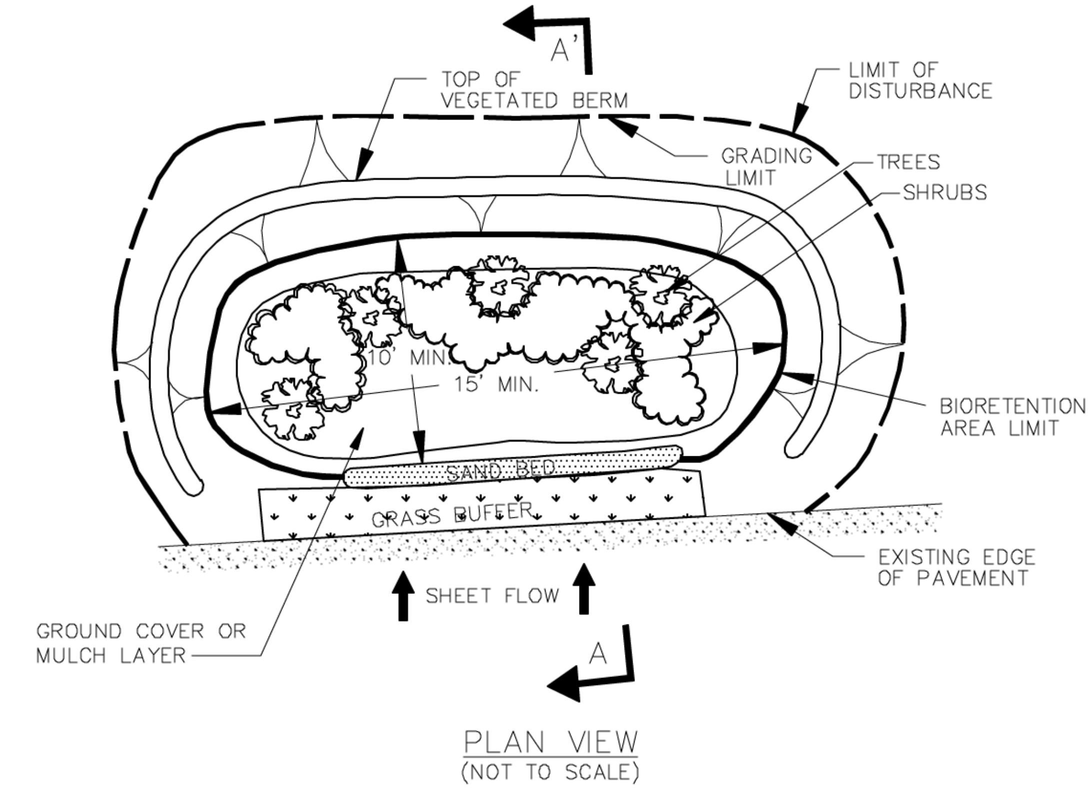
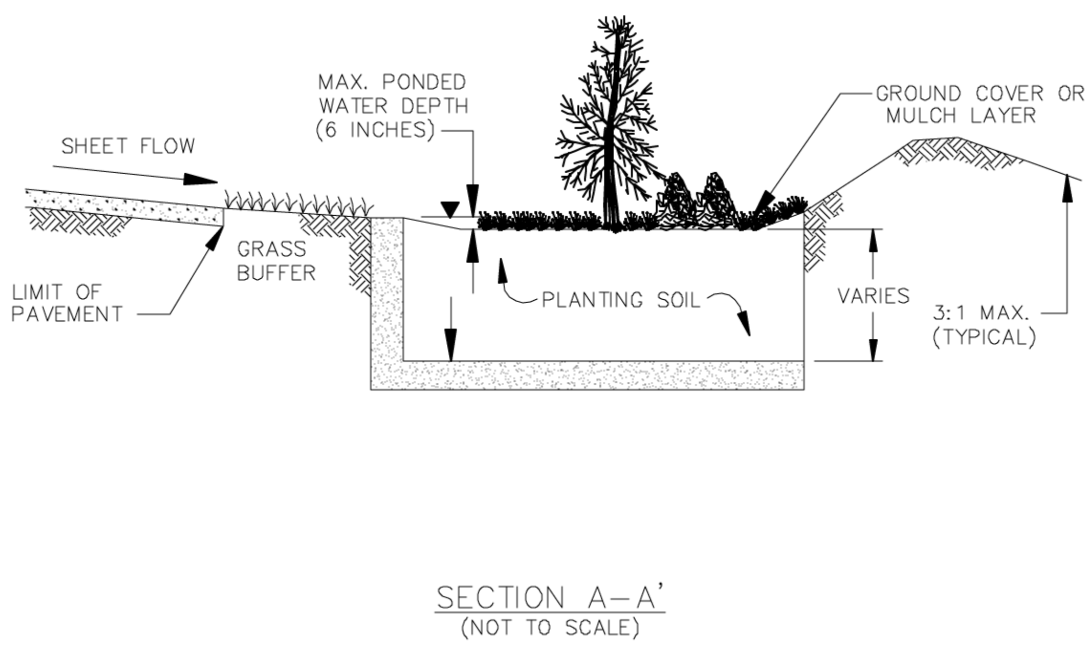


FIGURE 3.11-5
Bioretention Basin at Edge of Parking Lot Without Curbs





Planning Considerations

Site Conditions

All of the Site Conditions considerations for general infiltration practices contained in **MINIMUM STANDARD 3.10** also apply to bioretention basins. Designers should also be mindful of local requirements for soil studies for infiltration practices such as those in the ***Northern Virginia BMP Handbook***. In addition to site conditions affecting infiltration practices in general, the following apply specifically to bioretention basins. The application of individual bioretention basins will usually be limited to drainage areas from 0.25 to 1 acre. Generally, commercial or residential drainage areas exceeding 1 acre in size will discharge sheet flows greater than 5 cfs.

1. Location Guidelines

Preferable locations for bioretention basins include 1) areas upland from inlets or outfalls that receive sheet flow from graded areas, and 2) areas of the site that will be excavated or cut. When available, areas of loamy sand soils should be used since these types of soils comprise the planting soils for bioretention basins. Locating the BMP in such natural locations would eliminate the cost of importing planting soils (see soil and organic specification under **Design Considerations**). BMP location should be integral with preliminary planning studies.

The following areas would be **undesirable** for bioretention basins: 1) areas that have mature trees which would have to be removed for construction of the bioretention basin, 2) areas that have existing slopes of 20% or greater, and 3) areas above or inclose proximity to an unstable soil strata such as marine clay.

2. Sizing Guidelines

For planning purposes, assume that the floor area of the bioretention basin will be a minimum of 2.5% of the impervious area draining to the basin if the first 0.5 inches of runoff is to be treated and a minimum of 4.0% of the impervious area on the drainage shed if the first 1.0 inches of runoff is to be treated. Derivation of these values is discussed below under **Design Considerations**. Note that small projects such as single family residences will likely default to the minimum 150 square foot area (10' X 15').

3. Aesthetic Considerations

Aesthetic considerations of the bioretention basin must be considered early in the site planning process. While topography and hydraulic considerations may dictate the general placement of such facilities, overall aesthetics of the site and the bioretention basins must be integrated into the site plan and stormwater concept plan from their inception. Both the stormwater engineer and the Landscape Architect must participate during the layout of facilities and infrastructure to be placed on the site. Bioretention design must be an integral part of the site planning process.

Sediment Control

Like other infiltration practices, provisions for long-term sediment control must be incorporated into the design, **as well as precautions during on-site construction activities.** Careful consideration must be given **in advance of construction** to the effects of work sequencing, techniques, and equipment employed on the future maintenance of the practice. Serious maintenance problems can be averted, or in large part, mitigated, by the adoption of relatively simple measures during construction.

1. Construction Runoff

Bioretention basin BMPs should be constructed AFTER the site work is complete and stabilization measures have been implemented. If this is not possible, strict implementation of E&S protective measures must be installed and maintained in order to protect the bioretention facility from premature clogging and failure.

Like other infiltration BMPs, bioretention basins constructed prior to full site stabilization will become choked with sediment from upland construction operations, rendering them inoperable from the outset. Simply providing inlet protection or some other filtering mechanism during construction will not adequately control the sediment. One large storm may completely clog the bioretention basin, requiring complete **reconstruction**.

Experience with infiltration practices has also demonstrated that the bioretention basin site should **NOT** be used as the site of sedimentation basins during construction. Such use tends to clog the underlying strata and diminish their capacity to accept infiltration below that indicated in preconstruction soil studies.

Bioretention basins are landscape amenities and should be installed with other landscaping as the last stage of project construction.

A detailed sediment control design to protect the bioretention basin **during** its construction should be included with the facility design. The ***Virginia Erosion and Control Handbook*** (VDCR, 1992), ***Standards and Specifications for infiltration Practices*** (Md. DNR, 1984), and ***Controlling Urban Runoff*** (MWCOG, 1987) provide technical guidance on sediment control designs.

Experience with bioretention basins in Maryland has demonstrated that they must be protected until the drainage areas contributing to the practice have been adequately stabilized (P.G. Co., 1993).

The definition of the term "adequately stabilized" is critical to the success of the facility. At the conclusion of construction activity, the temporary erosion and sediment control measures are usually removed at the direction of the erosion and sediment control inspector when, at a minimum, stabilization measures such as seed and mulch are in place. This does not mean, however, that stabilization has actually occurred. Bioretention basins must be protected until stabilization of the upland site is functioning to control the sediment load from denuded areas. Provisions to bypass the stormwater away from the bioretention basin during the stabilization period should be implemented.

2. Urban Runoff

A fully stabilized site will generate particulate pollutant load resulting from natural erosion, lawn and garden debris such as leaves, grass clippings, mulch, roadway sand, etc. Pretreatment of runoff to remove sediments prior to entering the bioretention basin is usually provided by a grass filter strip or grass channel. When runoff from sheet flow from such areas as parking lots, residential yards, etc., is involved, a grass filter strip, often enhanced with a pea gravel diaphragm, is usually employed. **Table 3.11-2** provides sizing guidelines as a function of inflow approach length, land use, and slope. The minimum filter strip length (flow path) should be 10 feet.

TABLE 3.11-2
Pretreatment Filter Strip Sizing Guidance
(Source: Claytor and Schueler, 1996)

Parameter	Impervious Parking Lots				Residential Lawns				Notes
Maximum Inflow Approach Length (feet)	35		75		75		150		
Filter Strip Slope	≤ 2%	≥2%	≤2%	≥2%	≤2%	≥2%	≤2%	≥2%	Maximum = 6%
Filter Strip Minimum Length	10'	15'	20'	25'	10'	12'	15'	18'	

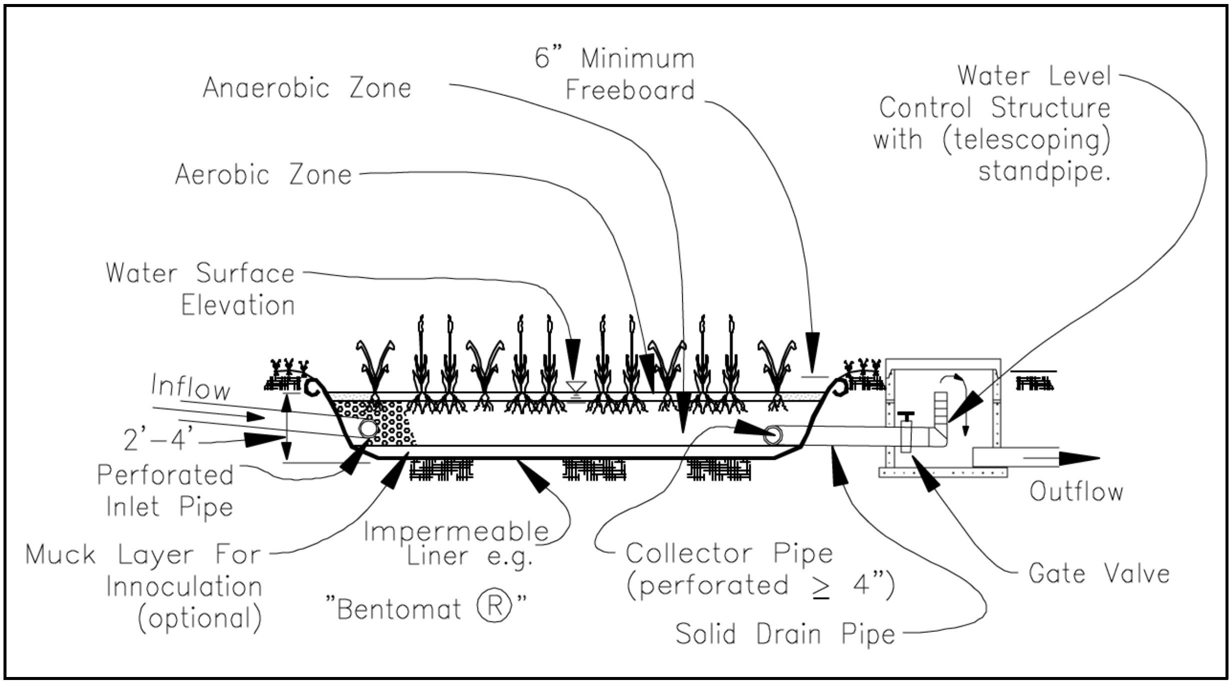
For applications where concentrated runoff enters the bioretention basin by surface flow, such as through a slotted curb opening, a grassed channel, often equipped with a pea gravel diaphragm to slow the velocity and spread out the flow entering the basin, is the usual pretreatment method. The length of the grassed channel depends on the drainage area, land use, and channel slope. **Table 3.11-3** provides recommendations on sizing for grass channels leading into a bioretention basin for a one acre drainage area. The minimum grassed channel length should be 20 feet.

"Grassed filter strips, grassed channels, and side-slopes of the basin should be **sodded with mature sod** prior to placement of the bioretention basin into operation. Simply seeding these areas will likely result in conveyance of sediments into the basin and premature failure. Wrapping of the planting soil mixture up the side slopes beneath the sod is also recommended."

TABLE 3.11-3
Pretreatment Grass Channel Sizing Guidance for a 1.0-Acre Drainage Area
(Source: Claytor and Schueler, 1996)

Parameter	**≤ 33% Impervious**		**Between 34% and 66% Impervious**		**≥ 67% Impervious**		**Notes**
Slope	≤2%	≥2%	≤2%	≥2%	≤2%	≥2%	Maximum slope = 4%
Grassed channel minimum length (feet)	25	40	30	45	35	50	Assumes a 2' wide bottom width

FIGURE 3.11-6
Upflow Inlet for Bioretention Basin
(Source: City of Alexandria)



When concentrated piped flow from impervious areas such as parking lots is routed to a bioretention basin, an energy absorbing and sedimentation structure in which the flow rises into the basin like a tide is usually advisable. Since sediments must usually be removed from such structures on a regular basis, they must be placed in locations where the extension booms on vacuum trucks may easily reach them. **Figure 3.11-6** illustrates an upflow inlet structure for a bioretention basin. Maintenance requirements for pretreatment measures are discussed **Maintenance/Inspection Guidelines**.

General Design Criteria

The purpose of this section is to provide minimum criteria for the design of bioretention basin BMPs intended to comply with the Virginia Stormwater Management program's runoff quality requirements. Bioretention basins which capture and infilter the first 1 inch of runoff from impervious surfaces may also provide streambank erosion protection.

General

The design of bioretention basins should be in accordance with the following Minimum Standards where applicable: **3.1: Earthen Embankments, 3.2: Principal Spillways, 3.3: Vegetated Emergency Spillways, 3.4: Sediment Forebay, 3.10: General Infiltration Practices, and 3.10A: Infiltration Basin,** as well as the additional criteria set forth below. The designer is not only responsible for selecting the appropriate components for the particular design but also for ensuring long-term operation.

Soils Investigation

Refer to the **Planning Considerations** and **Design Criteria** of **General Infiltration Practices, MS-3.10**, and to local jurisdiction soil study requirements such as Chapter 5, Section V. of the ***Northern Virginia BMP Handbook***. As with infiltration basins (**MS3.10A**), a minimum of one soil boring log should be required for each 5,000 square feet of bioretention basin area (plan view area) and in no case less than three soil boring logs per basin.

Topographic Conditions

Like other infiltration facilities, bioretention basins should be a minimum of 50 feet from any slope greater than 15 percent. A geotechnical report should address the impact of the basin upon the steep slope (especially in marine clay areas). Also, bioretention basins should be a minimum of 100 feet up-slope and 20 feet downslope from any buildings.

Basin Sizing Methodology

In Virginia, bioretention basins are designed to exfilter the treatment quantity into the underlying soil strata, or into an underlying perforated underdrain system connected to a storm drain system or other outfall when the underlying soils, proximity to building foundation, or other such restrictions preclude the use of infiltration. When such an underdrain system is used, the facility is referred to as a **Bioretention Filter - Minimum Standard 3.11A**.

Recent research at the University of Maryland has supported a reduction in overall depth of the planting soil to 2.5 feet. Generally, the soil depth can be designed to a minimum depth equal to the diameter of the largest plant root ball plus 4 inches. The recommended soil composition was revised to reduce the clay and increase the sand content (Refer to Soil Texture and Structure later in this standard). This revised soil composition also eliminated the 12" sand layer at the bottom of the facility. The researchers concluded that significant pollutant reductions are achieved in the mulch layer and the first 2 to 2.5 feet of soil.

The elevation of the overflow structure should be 0.5 feet above the mulch layer of the bioretention bed. When an underdrain system is used (Min. Std. 3.11A), the overflow can be as much as 1.0 feet above the mulch layer.

The size of the bioretention facility is dictated by the amount of impervious surface in the contributing drainage area. For facilities capturing the first 0.5 inches of runoff from the impervious areas in the drainage shed, the surface area of the bioretention bed should be a minimum of 2.5% of the impervious area, or 1,090 square feet per impervious acre. For facilities capturing the first 1.0 inch of runoff, the bioretention bed should be a minimum of 5.0% of the impervious area, or 2,180 square feet per impervious acre.

The minimum width and length is recommended at 10 feet and 15 feet respectively. (Widths as narrow as 4 feet may be used if the runoff arrives as dispersed sheet flow along the length of the facility from a properly sized vegetated strip).

The elevation of the overflow structure should be 0.5 feet above the mulch elevation of the bioretention bed.

Note that small projects such as single family residences may default to the minimum (10' X 15') **150 square foot area.**

TABLE 3.11-4
Basin Sizing Summary

Treatment Volume	**Basin Surface Area** (Expressed as percentage of impervious area)
0.5" per impervious acre	2.5%
1.0" per impervious acre	5.0%

Runoff Pretreatment

Like other infiltration basins, bioretention basins must always be preceded by a pretreatment facility to remove grease, oil, floatable organic material, and settleable solids (see Urban Runoff section of **Sediment Control** under **Planning Considerations** above). Where space constraints allow, runoff should be filtered by a grass buffer strip and sand bed. The buffer strip and sand bed will reduce the amount of fine material entering the bioretention area and minimize the potential for clogging of the planting soil. The sand bed also increases the infiltration capacity and provides aeration for the plant roots in the bioretention area. For basins for which high sediment loadings are expected (treating largely pervious areas, etc.), the design can be modified to include a sediment forebay (see **MS 3.04**). Any pretreatment facility should be included in the design of the basin and should include maintenance and inspection requirements.

Drainage Considerations

The grading design must shape the site so that all runoff from impervious areas is routed through the bioretention basins. The basins must be sited so as to accept the design runoff quantity before bypassing any excess flow to the storm drainage system. Bioretention basin locations must therefore be integrated into the basic site design from its inception. Most of the **Planning Considerations** delineated above must come into play at this early stage in the design process. The overall site and impervious surfaces must be contoured to direct the runoff to the basins. **Bioretention basins cannot usually be successfully integrated into a site design that does not take stormwater management into account from its inception.** Elevations must be carefully worked out to assure that the desired amount runoff will flow into the basins and pool at no more that the maximum design depth. This requires a much higher degree of vertical control during construction that is normal with most landscaping work.

Preferably, bioretention basins should be placed “off-line,” i.e. the design should provide for runoff to be diverted into the basin until it fills with the treatment volume and then bypass the remaining flow around the BMP to the storm drainage system. The drainage system is normally designed to handle a specific storm event (the 10-year storm in most of Virginia). To prevent flood damage , however, the bioretention basin design must take into account how the runoff will be processed when larger events occur. This may require, at a minimum, that a vegetated emergency spillway be provided (see **MS-3.03**), and that a path for overland flow to an acceptable channel be incorporated into the design. The designer should provide for relief from the storm event specified by local development approval authority or for the 25-year storm event, whichever is the most stringent.

Figure 3.11-2 illustrates an “off-line” application at the edge of a parking lot with curb and gutter. The inlet deflectors divert runoff into the bioretention basin until the basin fills and backs up. Subsequent runoff then bypasses to the adjacent, down gradient storm inlet. **Figure 3.11-3** illustrates an “off-line” application in a planting island in a parking lot, while **Figure 3.11-4** illustrates an “off-line application adjacent to a drainage swale (such highway drainage). Again, runoff flows into the bioretention basin until it fills, then bypasses down the swale. Placement of a flow diversion check dam in the swale will facilitate filling the basin. In some situations, an “off-line” configuration may not be practical or economical. Figure **3.11-1** and **3.11-5** illustrate applications where sheet flow enters the bioretention basin.

Figure 3.11-7 illustrates a grading plan for a bioretention basin. The grading plan was created for a double-cell bioretention area. There is a seven-foot buffer between cells which allow for the planting of upland trees. As indicated in the grading plan, sheet and gutter flow is diverted into the bioretention areas through openings in the curb. The elevation of the invert of the bioretention area is set by the curb opening elevation. The curb opening elevation is 0.5 ft. higher than the invert of the bioretention area, so water is allowed to pond to a maximum depth of one-half foot before runoff bypasses the bioretention area and flows into the storm drain system.

Precise grading of the basin is critical to capturing the water quality volume and operation of the facility. The plan should have a contour interval of no more than one-foot, and spot elevations should be shown throughout the basin. The perimeter contour elevation should contain the design storm without over topping anywhere except at the outflow structure.

Exclusion of Continuous Flows and Chlorinated Flows

Bioretention and bioretention filter BMPs will **NOT** function properly if subjected to continuous or frequent flows. The basic principles upon which they operate assume that the sand filter will dry out and reaerate between storms. If the sand is kept continually wet by such flows as basement sump pumps, anaerobic conditions will develop, creating a situation under which previously captured iron phosphates degrade, leading to **export** of phosphates rather than the intended high phosphorous removal (Bell, Stokes, Gavan, and Nguyen, 1995). Anaerobic conditions will also kill most of the plants in the basin, stopping the biochemical pollutant removal processes and negating the aesthetic landscaping amenity aspects. It is also essential to **exclude flows containing chlorine and other swimming pool and sauna chemicals** since these will kill the bacteria upon which the principle nitrogen removal mechanisms depend.

Continuous or frequent flows (such as basement sump pump discharges, cooling water, condensate water, artesian wells, etc.) and flows containing swimming pool and sauna chemicals MUST BE EXCLUDED from routing through bioretention or bioretention filter BMPs since such flows will cause the BMP to MALFUNCTION!

Planting Plan

Selection of plantings must include coordination with overall site planning and aesthetic considerations for designing the bioretention plant community. Tables listing suitable species of trees, shrubs, and ground cover are provided at the end of this section. This listing is not intended to be all-inclusive due to the continual introduction of new horticultural varieties ans species in the nursery industry.

1. Planting Concept

The use of plantings in bioretention areas is modeled from the properties of a terrestrial forest community ecosystem. The terrestrial forest community ecosystem is an upland community dominated by trees, typically with a mature canopy, having a distinct sub-canopy of understory trees, a shrub layer, and herbaceous layer. In addition, the terrestrial forest ecosystem typically has a well-developed soil horizon with an organic layer and a mesic moisture regime. A terrestrial forest community model for stormwater management was selected based upon a forest's documented ability to cycle and assimilate nutrients, pollutants, and metals through the interactions among plants, soil, and the organic layer. These three elements are the major elements of the bioretention concept.

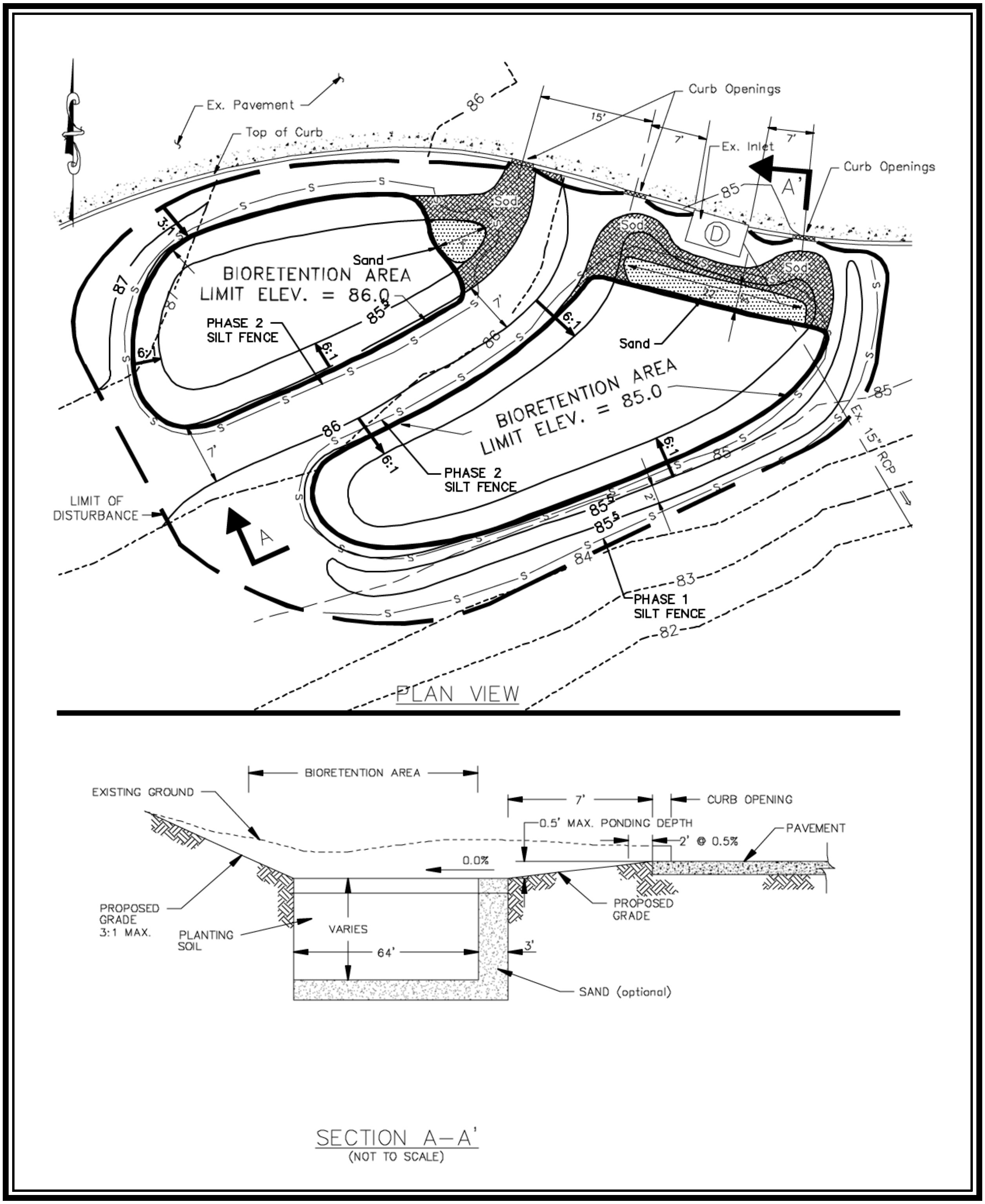
Key elements of the terrestrial forest ecosystem that have been incorporated into bioretention design include species diversity, density, and morphology, and use of native plant species. Species diversity protects the system against collapse from insect and disease infestations and other urban stresses such as temperature and exposure. Typically, indigenous plant species demonstrate a greater ability of adapting and tolerating physical, climatic, and biological stresses.

2. Plant Species Selection

Plant species appropriate for use in bioretention areas are presented in **Tables 3.11-7A** through **3.11-7C** , provided at the end of this section. These species have been selected based on the ability to tolerate urban stresses such as pollutants, variable soil moisture and ponding fluctuations. Important design considerations such as form, character, massing, texture, culture, growth habits/rates, maintenance requirements, hardiness, size, and type of root system are also included. A key factor in designating a species as suitable is its ability to tolerate the soil moisture regime and ponding fluctuations associated with bioretention. The plant indicator status (Reed, 1988) of listed species are predominantly facultative (i.e., they are adapted to stresses associated with both wet and dry conditions); however, facultative upland and wetland species have also been included. This is important because plants in bioretention areas will be exposed to varying levels of soil moisture and ponding throughout the year, ranging from high levels in the spring to potential drought conditions in the summer. All of the species listed in **Tables 3.11-7A - 3.11-7C** are commonly found growing in the Piedmont or Coastal Plain regions of Virginia as either native or ornamental species.

Recent research suggests an increase in the importance of the mulch layer and groundcover plant species in pollutant removal. The plant list in this standard will be expanded to include perennial flowering plants. A robust groundcover species with a thick mulch layer is recommended.

FIGURE 3.11 - 7
Grading Plan for Bioretention Basin



Designers considering species other than ones listed in **Tables 3.11-7A - 3.11-7C** should consult the following reference material on plant habitat requirements, and consider site conditions to ensure that alternative plant material will survive.

American Association of Nurserymen, Latest Edition. American Standard for Nursery Stock ASNI Z60, Washington, D.C.

Dirr, Michael A., 1975. Manual of Woody Landscape Plants, Stripes Publishing Company, Champagne, Illinois.

Hightshoe, G.L., 1988. Native Trees, Shrubs, and Vines for Urban and Rural America. Van Nostrand Reinhold, New York, New York.

Reed, P.B.Jr., 1988. National List of Species That Occur in Wetlands: Northeast. United States Fish and Wildlife Service, St. Petersburg Florida.

Reasons for exclusion of certain plants from bioretention areas include inability to meet the criteria outlined in **Tables 3.11-7A - 3.11-7C** (pollutant and metals tolerance, soil moisture and structure, ponding fluctuations, morphology, etc.). In addition, species that are considered invasive or not recommended by the Urban Design Section of the Maryland-National Capital Park and Planning Commission are not recommended (Prince George's County, 1989).

3. Site and Ecological Considerations

Each site is unique and may contain factors that should be considered before selecting plant species. An example **Plant Material Checklist** is provided in **Appendix 3E**. The checklist has been developed to assist the designer in identifying critical factors about a site that may affect both the plant material layout and the species selection.

Selection of plant species should also be based on site conditions and ecological factors. Site considerations include microclimate (light, temperature, wind), the importance of aesthetics, overall site development design and the extent of maintenance requirements, and proposed or existing buildings . Of particular concern is the increase in reflection of solar radiation from buildings upon bioretention areas. Aesthetics are critical in projects of high visibility. Species that require regular maintenance (shed fruit or are prone to storm damage) should be restricted to areas of limited visibility and pedestrian and vehicular traffic.

Interactions with adjacent plant communities are also critical. Nearby existing vegetated areas dominated by non-native invasive species pose a threat to adjacent bioretention areas. Proposed bioretention area species should be evaluated for compatibility with adjacent plant communities. Invasive species typically develop into monocultures by out competing other species . Mechanisms to avoid encroachment of undesirable species include increased maintenance, providing a soil breach between the invasive community for those species that spread through rhizomes, and providing annual removal of seedlings from wind borne seed dispersal. Existing disease or insect infestations associated with existing site conditions or in the general area that may effect the bioretention plantings.

4. Number of Species

A minimum of three species of trees and three species of shrubs should be selected to insure diversity. In addition to reducing the potential for monoculture mortality concerns, a diversity of trees and shrubs with differing rates of transpiration may ensure a more constant rate of evapotranspiration and nutrient and pollutant uptake throughout the growing season.

Herbaceous ground covers are important to prevent erosion of the mulch and the soil layers. Suitable herbaceous ground covers are identified in **Table 3.11-7C**.

5. Number and Size of Plants

The requisite number of plantings varies, and should be determined on an individual site basis. On average, 1000 trees and shrubs should be planted per acre. For example, a bioretention area measuring 15' x 40' would contain a combination of trees and shrubs totaling 14 individuals. The Prince Georges County recommended minimum and maximum number of individual plants and spacing are given in **Table 3.11-4.** Virginia jurisdictions with significant experience with bioretention prefer the simpler specification of 10 trees and shrubs per 1,000 square feet of basin area, with placement specified by a landscape professional to simulate natural conditions. Two to three shrubs should be specified for each tree (2:1 to 3:1 ratio of shrubs to trees).

At installation, trees should be 1.0 inches minimum in caliper, and shrubs 3 to 4 feet in height or 18 to 24 inches in spread per ASNI Z60. Ground cover may be as seed or, preferably, plugs. The relatively mature size requirements for trees and shrubs are important to ensure that the installation of plants are readily contributing to the bioretention process (i.e., evapotranspiration, pollutant uptake).

TABLE 3.11-5
Recommended Tree and Shrub Spacing

	Tree Spacing (feet)	Shrub Spacing (feet)	Total Density (stems/acre)
Maximum	19	12	400
Average	12	8	1000
Minimum	11	7	1250

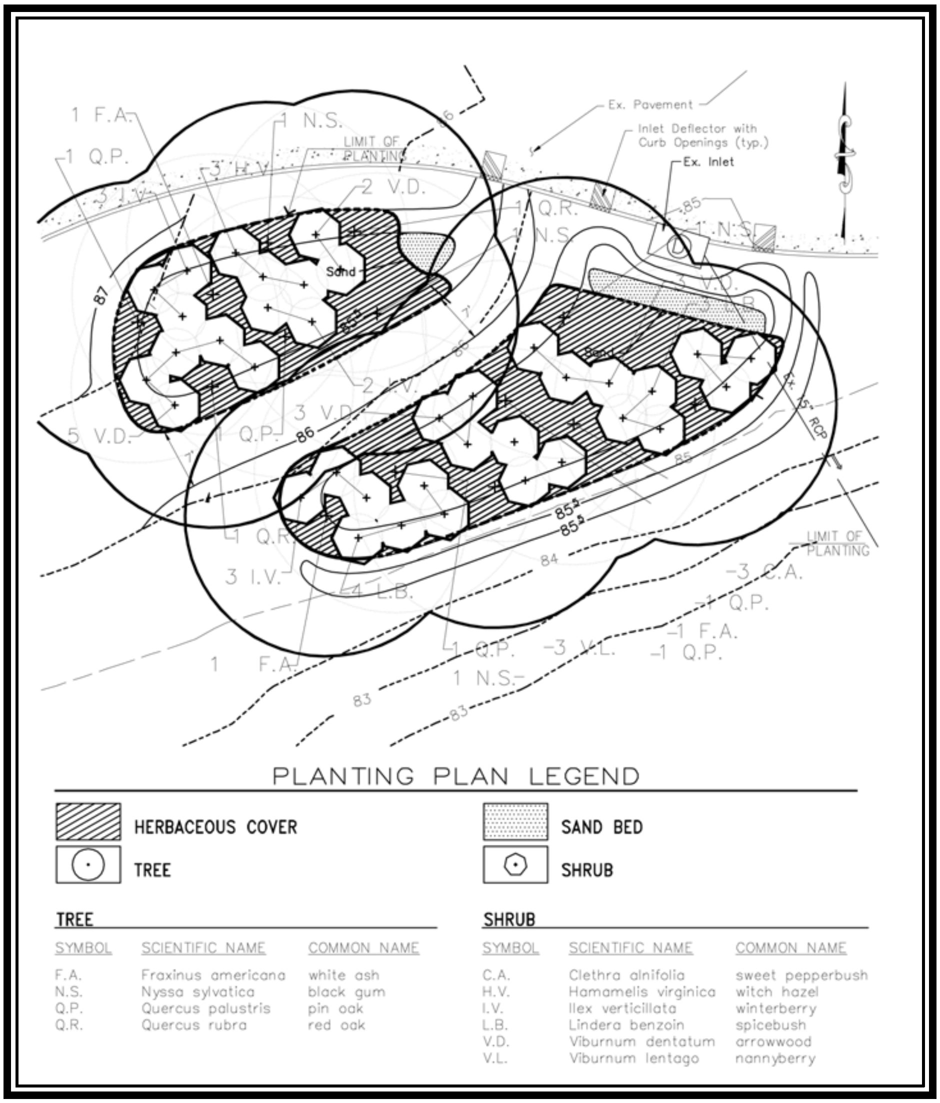
6. Plant Layout

The layout of plant material can be a flexible process; however, the designer should follow some basic guidelines. As discussed above, the designer should first review the Plant Checklist (Appendix D). The checklist table can help expose any constraints that may limit the use of a particular species and/or where a species can be installed.

There are two guidelines that should apply to all bioretention areas. First, woody plant material should not be placed within the immediate areas of where flow will be entering the bioretention area.

Besides possibly concentrating flows, trees and shrubs can be damaged as a result of the flow. Secondly, it is recommended that trees be planted primarily on the perimeter of bioretention areas, to maximize the shading and sheltering of bioretention areas to create a microclimate which will limit the extreme exposure from summer solar radiation and winter freezes and winds. An example planting plan is shown in **Figure 3.11-8**.

FIGURE 3.11 - 8
Sample Planting Plan



Planting Soil Guidelines

The characteristics of the soil play an important role in the improvement of water quality through the use of bioretention systems. The soil is a three-phase system composed of gas, liquid, and solid, each of which in the proper balance is essential to the pollutant removal achieved through bioretention. The soil anchors the plants and provides nutrients and moisture for plant growth. Microorganisms inhabit and proliferate within the soil solution, and the unsaturated pore space provides plant roots with the oxygen necessary for metabolism and growth.

A desirable planting soil would 1) be permeable to allow infiltration of runoff and 2) provide adsorption of organic nitrogen and phosphorus.

The recommended planting soil for bioretention would have the following properties:

1. Soil Texture and Structure

It is recommended that the planting soils for bioretention have a sandy loam, loamy sand, or loam texture. Experience in both Maryland and Virginia has indicated that the original soil specification contained in the Prince Georges County manual must be modified to decrease the clay content to **no more than five percent** to preclude premature failure of the basins due to clogging. Prince Georges County issued a design update in June 1998 in which the total depth of the facility is reduced to 2.5 feet by the elimination of the sand bed and the use of a soil media consisting of 50 percent sand, 20 percent leaf compost, and 30 percent topsoil. Virginia engineers with bioretention experience recommend using either the new Maryland media specification or a media of 50 percent sand and 50 percent hemic or fibric peat, using the Virginia topsoil thickness criteria in both cases, while retaining the sand bed. This could result in an overall thickness somewhat comparable to that specified in Maryland.

2. Soil Acidity

In a bioretention scheme, the desired soil pH would lie between 5.5 and 6.5 (Tisdale and Nelson, 1975). The soil acidity affects the ability of the soil to adsorb and desorb nutrients, and also affects the microbiological activity in the soil.

3. Soil Testing

The planting soil for bioretention areas must be tested prior to installation for pH, organic matter, and other chemical constituents. The soil should meet the following criteria (Landscape Contractors Association, 4th Addition, 1993):

pH range:	5.0 - 7.0
Organic matter:	Greater than 1.5
Magnesium (Mg):	100+ Units
Phosphorus (P_2O_5):	150+ Units
Potassium (K_2O):	120+ Units
Soluble salts:	not to exceed 900 ppm/.9 MMHOS/cm (soil)
	not to exceed 3,000 ppm/2.5 MMHOS/cm (organic mix)

It is recommended that one test for magnesium, phosphorus, potassium, and soluble salts be performed per borrow source or for every 500 cubic yards of soil material. It is recommended that a sieve analysis, pH, and organic matter test be performed per bioretention area.

4. Soil Placement

Placement of the planting soil in the bioretention area should be in lifts of 18 inches or less and lightly compacted. Minimal compaction effort can be applied to the soil by tamping.

Specifications for the planting soil are outlined below under **Construction Specifications**.

Mulch Layer Guidelines

Recent results of bioretention monitoring in Maryland has confirmed that the mulch layer plays a crucial role in the pollutant removal capabilities of the facility. This layer serves to prevent erosion and to protect the soil from excessive drying. Soil biota existing within the organic and soil layer are important in the filtering of nutrients and pollutants and assisting in maintaining soil fertility. Bioretention areas can be designed either with or without a mulch layer. If a herbaceous layer or ground cover (70 to 80% coverage) is provided, a mulch layer is not necessary. Areas should be mulched once trees and shrubs have been planted. Any ground cover specified as plugs may be installed once mulch has been applied.

The mulch layer recommended for bioretention may consist of either a standard landscape fine shredded hardwood mulch or shredded hardwood chips. Both types of mulch are commercially available and provide excellent protection from erosion.

Mulch shall be free of weed seeds, soil, roots, or any other substance not consisting of either bole or branch wood and bark. The mulch shall be uniformly applied approximately 2 to 3 inches in depth. Mulch applied any deeper than three inches reduces proper oxygen and carbon dioxide cycling between the soil and the atmosphere.

Grass clippings are unsuitable for mulch, primarily due to the excessive quantities of nitrogen built up in the material. Adding large sources of nitrogen would limit the capability of bioretention areas to filter the nitrogen associated with runoff.

Plant Material Guidelines

1. Plant Material Source

The plant material should conform to the current issue of the American Standard for Nursery Stock published by the American Association of Nurserymen. Plant material should be selected from certified nurseries that have been inspected by state or federal agencies. The botanical (scientific) name of the plant species should be in accordance with a standard nomenclature source such as Birr, 1975.

Some of the plant species listed in **Tables 3.11-7A - 3.11-7C**, Recommended Plant Species For Use in Bioretention may be unavailable from standard nursery sources. These are typically species native to Virginia and may not be commonly used in standard practices. Designers may need to contact nurseries specializing in native plants propagation.

2. Installation

The success of bioretention areas is dependent on the proper installation specifications that are developed by the designer and subsequently followed by the contractor. The specifications include the procedures for installing the plants and the necessary steps taken before and after installation. Specifications designed for bioretention should include the following considerations:

- Sequence of Construction
- Contractors Responsibilities
- Planting Schedule and Specifications
- Maintenance
- Warranty

The sequence of construction describes site preparation activities such as grading, soil amendments, and any pre-planting structure installation. It also should address erosion and sediment control procedures. Erosion and sediment control practices should be in place until the entire bioretention area is completed. The contractors responsibilities should include all the specifications that directly effect the contractor in the performance of his or her work. The responsibilities include any penalties for unnecessarily delayed work, requests for changes to the design or contract, and exclusions from the contract specifications such as vandalism to the site, etc.

The planting schedule and specifications include type of material to be installed (e.g., ball and burlap, bare root, or containerized material), timing of installation, and post installation procedures. Balled and burlapped and containerized trees and shrubs should be planted during the following periods: March 15 through June 30 and September 15 through November 15. Ground cover excluding grasses and legumes can follow tree and shrub planting dates. Grasses and legumes typically should be planted in the spring of the year. The planting of trees and shrubs should be performed by following the planting specifications set forth in **MS 3.05, Landscaping. MS 3.05** specifications provide guidelines that insure the proper placement and installation of plant material. Designers may choose to use other specifications or to modify the jurisdiction specifications. However, any deviations from the jurisdiction specifications need to address the following:

- transport of plant material
- preparation of the planting pit
- installation of plant material
- stabilization seeding (if applicable)
- maintenance

An example of general planting specification for trees and shrubs and ground cover is given under **Construction Specifications** below.

3. Warranties

Typically, a warranty is established as a part of any plant installation project. The warranty covers all components of the installation that the contractor is responsible for. The plant and mulch installation for bioretention should be performed by a professional landscape contractor. An example of standard guidelines for landscape contract work is provided below:

- The contractor shall maintain a one (1) calendar year 80% care and replacement warranty for all planting.
- The period of care and replacement shall begin after inspection and approval of the complete installation of all plants and continue for one calendar year.
- Plant replacements shall be in accordance with the maintenance schedule.

Plant Growth and Soil Fertility

A discussion of plant growth and soil fertility development over time is important to for estimating the success and lifespan of bioretention areas. The physical, chemical, and biological factors influencing plant growth and development will vary over time as well as for each bioretention area. However, there are certain plant and soil processes that will be the same for all bioretention areas.

1. Plant Growth

The role of plants in bioretention includes uptake of nutrients and pollutants and evapotranspiration of stormwater runoff. The plant material, especially ground covers, are expected to contribute to the evapotranspiration process within the first year of planting. However, trees and shrubs that have been recently planted demonstrate slower rates of growth for the first season due to the initial shock of transplanting. The relative rate of growth is expected to increase to normal rates after the second growth season.

The growth rate for plants in bioretention areas will follow a similar pattern to that of other tree and shrub plantings (reforestation projects, landscaping). For the first two years, the majority of tree and shrub growth occurs with the expansion of the plant root system. By the third or fourth year the growth of the stem and branch system dominates increasing the height and width of the plant. The comparative rate of growth between the root and stem and branch system remains relatively the same throughout the lifespan of the plant. The reproductive system (flowers, fruit) of the plants is initiated last.

The growth rates and time for ground covers to become acclimated to bioretention conditions is much faster than for trees and shrubs. The rate of growth of a typical ground cover can often exceed 100 percent in the first year. Ground covers are considered essentially mature after the first year of growth. The longevity of ground covers will be influenced by the soil fertility and chemistry as well as physical factors, such as shading and overcrowding from trees and shrubs and other ecological and physical factors.

Plants are expected to increase their contribution to the bioretention concept over time, assuming that growing conditions are suitable. The rate of plant growth is directly proportional to the environment in which the plant is established. Plants grown in optimal environments experience greater rates of growth. One of the primary factors determining this is soil fertility.

2. Soil Fertility

Initially, soil in bioretention areas will lack a mature soil profile. It is expected that over time discrete soil zones referred to as horizons will develop. The development of a soil profile and the individual horizons is determined by the influence of the surrounding environment including physical, chemical, and biological processes. Two primary processes important to horizon development is microbial action and the percolation of runoff in the soil.

Horizons expected to develop in bioretention areas include an organic layer, followed by two horizons where active leaching (eluviation) and accumulation (illuvation) of minerals and other substances occur. The time frame for the development of soil horizons will vary greatly. As an average, soil horizons may develop within three to ten years. The exception to this is the formation of the organic layer often within the first or second year (Brady, 1984).

The evaluation of soil fertility in bioretention may be more dependent on the soil interactions relative to plant growth than horizon development. The soil specified for bioretention is important in filtering pollutants and nutrients as well as supply plants with water, nutrients, and support. Unlike plants that will become increasingly beneficial over time, the soil will begin to filter the storm water runoff immediately. It is expected that the ability to filter pollutants and nutrients may decrease over time, reducing the soil fertility accordingly. Substances from runoff such as salt and heavy metals eventually disrupt normal soil functions by lowering the cation exchange capacity (CEC). The CEC, the ability to allow for binding of particles by ion attraction, decreases to the point that the transfer of nutrients for plant uptake can not occur. However, the environmental factors influencing each bioretention area will vary enough that it is difficult to predict for the lifespan of soils. Findings from other stormwater management systems suggest an accumulation of substances eliminating soil fertility within five years. The monitoring of soil development in bioretention areas will help develop better predictions on soil fertility and development.

Construction Specifications

The construction of bioretention basins should be in accordance with the following Minimum Specifications and Standards where applicable: **3.1: Earthen Embankments; 3.2: Principal Spillways; 3.3: Vegetated Emergency Spillways; 3.4: Sediment Forebays; 3.5: Landscaping; 3.10: General Infiltration Practices**, as well as the additional criteria set forth below. These specifications have been adapted from the Prince George's County, Maryland publication, ***Design Manual for Use of Bioretention in Stormwater Management***.

Sequence of Construction

The sequence of various phases of basin construction must be coordinated with the overall project construction. As with other infiltration practices, rough excavation of the basin may be scheduled with the rough grading of the project to permit use of the excavated material as fill elsewhere on the site. However, the bioretention basin must not be constructed or placed in service until the entire contributing drainage area has been stabilized. Runoff from untreated, recently constructed areas within the drainage area may otherwise load the newly formed basin with a large load of fine sediment, seriously impairing the natural infiltration ability of the basin floor. For these reasons, **the locations of infiltration bioretention basins must NOT be used for sediment basins for erosion and sediment protection during site construction.** The sequence of construction shall be as follows:

1. Install Phase I erosion and sediment control measures for the site.

2. Grade each site to elevations shown on plan. Initially, the basin floor may be excavated to within one foot of its final elevation. Excavation to finished grade shall be deferred until all disturbed areas within the watershed have been stabilized and protected. Construct curb openings, and/or remove and replace existing concrete as specified on the plan. Curb openings shall be blocked or other measures taken to prohibit drainage from entering construction area.

3. Complete construction on the watershed and stabilize all areas draining to the Bioretention basin.

4. Remove Phase I sediment control devices at direction of designated inspector.

5. Install Phase II erosion and sediment control measures for bioretention area.

6. Remove all accumulated sediment and excavate Bioretention Area to proposed depth. Use relatively light, tracked equipment to avoid compaction of the basin floor. After final grading is completed, deeply till the basin floor with rotary tillers or disc harrows to provide a well-aerated, highly porous surface texture.

7. Install the infiltration chambers, piping, manifolds, drains, vents, and infiltration stone in accordance in with the specifications and directions of the chamber manufacturer. Install a six-inch layer of washed, 1/4-inch pea gravel above the stone. Install a 1-foot layer of ASTM C-33 concrete sand on top of the pea gravel. Lightly compact with a landscaping roller.

8. After confirmation that soil meets specs by performing the requisite gradation and chemical tests (see below), fill Bioretention Area with planting soil and sand, as shown in the plans and detailed in the specifications.

9. Install vegetation and ground cover specified in the planting plan for Bioretention Area.

Install mulch layer if called for in the design.

10. Place sod, EC fabric, or non erosive lining (depending on inflow velocities) in the inlet channel and/or filter strips.

11. Upon authorization from designated inspector, remove all sediment controls and stabilize all disturbed areas. Unblock curb openings, and provide drainage to the Bioretention Areas.

Bioretention Area Soil Specifications

1. Planting Soil

The bioretention areas shall contain a planting soil mixture of 50% sand, 30% leaf compost (fully composted, NOT partially rotted leaves), and 20% topsoil. Topsoil shall be sandy loam or loamy sand of uniform composition, containing no more than 5% clay, free of stones, stumps, roots, or similar objects greater than one inch, brush, or any other material or substance which may be harmful to plant growth, or a hindrance to plant growth or maintenance.

The top soil shall be free of plants or plant parts of Bermuda grass, Quack grass, Johnson grass, Mugwort, Nutsedge, Poison Ivy, Canadian Thistle or others as specified. It shall not contain toxic substances harmful to plant growth.

The top soil shall be tested and meet the following criteria:

pH range:	5.0 - 7.0
Organic matter:	Greater than 1.5
Magnesium (Mg):	100+ Units
Phosphorus (P_2O_5):	150+ Units
Potassium (K_2O):	120+ Units
Soluble salts:	not to exceed 900 ppm/.9 MMHOS/cm (soil) not to exceed 3,000 ppm/2.5 MMHOS/cm (organic mix)

The following testing frequencies shall apply to the above soil constituents:

pH, Organic Matter: 1 test per 90 cubic yards, but no more than 1 test per Bioretention Area

Magnesium, Phosphorus, Potassium, Soluble Salts:

1 test per 500 cubic yards, but no less than 1 test per borrow source

One grain size analysis shall per performed per 90 cubic yards of planting soil, but no less than 1 test per Bioretention Area. Soil tests must be verified by a qualified professional.

2. Mulch

A mulch layer shall be provided on top of the planting soil. An acceptable mulch layer shall include shredded hardwood or shredded wood chips or other similar product.

Of the approved mulch products all must be well aged, uniform in color, and free of foreign material including plant material.

3. Sand

The sand for bioretention basins when utilized, shall be ASTM C-33 Concrete Sand and free of deleterious material.

4. Compaction

Soil shall be placed in lifts less than 18 inches and lightly compacted (minimal compactive effort) by tamping or rolled with a hand-operated landscape roller.

Bioretention Area Planting Specifications

1. Root stock of the plant material shall be kept moist during transport from the source to the job site and until planted.

2. Walls of planting pit shall be dug so that they are vertical.

3. The diameter of the planting pit must be a minimum of six inches (6") larger than the diameter of the ball of the tree.

4. The planting pit shall be deep enough to allow 1/8 of the overall dimension of the root ball to be above grade. Loose soil at the bottom of the pit shall be tamped by hand.

5. The appropriate amount of fertilizer is to be placed at the bottom of the pit (see below for fertilization rates).

6. The plant shall be removed from the container and placed in the planting pit by lifting and carrying the plant by its' ball (never lift by branches or trunk).

7. Set the plant straight and in the center of the pit so that approximately 1/8 of the diameter of the root ball is above the final grade.

8. Backfill planting pit with existing soil.

9. Make sure plant remains straight during backfilling procedure.

10. Never cover the top of the ball with soil. Mound soil around the exposed ball.

11. Trees shall be braced by using 2" by 2" white oak stakes. Stakes shall be placed parallel to walkways and buildings. Stakes are to be equally spaced on the outside of the tree ball. Utilizing hose and wire the tree is braced to the stakes.

12. Because of the high levels of nutrients in stormwater runoff to be treated, bioretention basin plants should not require chemical fertilization.

Maintenance/Inspection Guidelines

The following maintenance and inspection guidelines are not intended to be all inclusive. Specific Facilities may require additional measures not discussed here.

A schedule of recommended maintenance for bioretention areas is given in **Table 3.11-5**. The table gives general guidance regarding methods, frequency, and time of year for maintenance.

Planting Soil

Urban plant communities tend to become very acidic due to precipitation as well as the influences of storm water runoff. For this reason, it is recommended that the application of alkaline, such as limestone, be considered once to twice a year. Testing of the pH of the organic layer and soil, should precede the limestone application to determine the amount of limestone required.

Soil testing should be conducted annually so that the accumulation of toxins and heavy metals can be detected or prevented. Over a period of time, heavy metals and other toxic substances will tend to accumulate in the soil and the plants. Data from other environs such as forest buffers and grass swales suggest accumulation of toxins and heavy metals within five years of installation. However, there is no methodology to estimate the level of toxic materials in the bioretention areas since runoff, soil, and plant characteristics will vary from site to site.

As the toxic substances accumulate, the plant biologic functions may become impaired, and the plant may experience dwarfed growth followed by mortality. The biota within the soil can also become void and the natural soil chemistry may be altered. The preventative measures would include the removal of the contaminated soil. In some cases, removal and disposal of the entire soil base as well as the plant material may be required.

Mulch

Bioretention areas should be mulched once the planting of trees and shrubs has occurred. Any ground cover specified as plugs may be installed once the area has been mulched. Ground cover established by seeding and\or consisting of grass should not be covered with mulch.

Plant Materials

An important aspect of landscape architecture is to design areas that require little maintenance. Certain plant species involve maintenance problems due to dropping of fruit or other portions of the plant. Another problem includes plants, primarily trees, that are susceptible to windthrow, which creates a potential hazard to people and property (parked cars). As a result, some plant species will be limited to use in low-traffic areas.

Ongoing monitoring and maintenance is vital to the overall success of bioretention areas. Annual maintenance will be required for plant material, mulch layer, and soil layer. A maintenance schedule should include all of the main considerations discussed below. The maintenance schedule usually includes maintenance as part of the construction phase of the project and for life of the design. A example maintenance schedule is shown in **Table 3.11-6**.

Maintenance requirements will vary depending on the importance of aesthetics. Soil and mulch layer maintenance will be most likely limited to correcting areas of erosion. Replacement of mulch layers may be necessary every two to three years. Mulch should be replaced in the spring. When the mulch layer is replaced, the previous layer should be removed first. Plant material upkeep will include addressing problems associated with disease or insect infestations, replacing dead plant material, and any necessary pruning.

Control of Sediments on the Drainage Shed

Care must be taken to protect the bioretention basin from excessive sediments from the drainage shed. Whenever additional land disturbing activity takes place in the area draining to the basin, effective erosion and sediment control measures must first be put in place to exclude sediments from the basin. Performance based special measures over and above those specified in the ***Virginia Erosion and Sediment Control Handbook***, latest edition, may be required to assure that the bioretention basin is not damaged by such land disturbance. When sand or other street abrasives are used during the snow or icing conditions to provide traction on roadways or parking lots draining to bioretention basins, the pavement should be power/vacuum swept as soon as freezing weather abates to prevent damage to the basins.

Checklists

The Construction Inspection and As-Built Checklist provided in **Appendix 3E** is for use in inspecting bioretention basins during construction, and where required by local jurisdiction, engineering certification of the basin construction. The Operation and Maintenance Inspection Checklist, also found in **Appendix 3E**, is for use in conducting maintenance inspections of bioretention basins.

TABLE 3.11 - 6
Example Maintenance Schedule for Bioretention Basin

Description	**Method**	**Frequency**	**Time of the year**
SOIL			
Inspect and Repair Erosion	Visual	Monthly	Monthly
ORGANIC LAYER			
Remulch any void areas	By hand	Whenever needed	Whenever needed
Remove previous mulch layer before applying new layer (optional)	By hand	Once every two to three years	Spring
Any additional mulch added (optional)	By hand	Once a year	Spring
PLANTS			
Removal and replacement of all dead and diseased vegetation considered beyond treatment	See planting specifications	Twice a year	3/15 to 4/30 and 10/1 to 11/30
Treat all diseased trees and shrubs	Mechanical or by hand	N/A	Varies, depends on insect or disease infestation
Watering of plant material shall take place at the end of each day for fourteen consecutive days after planting has been completed	By hand	Immediately after completion of project	N/A
Replace stakes after one year	By hand	Once a year	Only remove stakes In the spring
Replace any deficient stakes or wires	By hand	N/A	Whenever needed
Check for accumulated sediments	Visual	Monthly	Monthly

TABLE 3.11-7A RECOMMENDED PLANT SPECIES FOR USE IN BIORETENTION --- TREE SPECIES

Species	Moisture Regime		Tolerance						Morphology			General Characteristics			Comments
Scientific Name Common Name	Indicator Status	Habitat	Ponding (days)	Salt	Oil/ Grease	Metals	Insects Disease	Exposure	Form	Height	Root System	Native	Non-native	Wildlife	
Acer rubrum red maple	FAC	Mesic - Hydric	4-6	H	H	H	H	Partial Sun	Single to multi-stem tree	50-70'	Shallow	Yes	-	High	-
Amelanchier canadensis shadbush	FAC	Mesic	2-4	H	M	-	H	Partial Sun	Single to multi-stem tree	35-50'	Shallow	Yes	-	High	Not recommended for full sun.
Betula nigra river birch	FACW	Mesic - Hydric	4-6	-	M	M	H	Partial Sun	Single to multi-stem tree	50-75'	Shallow	Yes	-	High	Not susceptible to bronze birch borer.
Betula populifolia gray birch	FAC	Xeric - Hydric	4-6	H	H	M	H	Partial Sun	Single to multi-stem tree	35-50'	Shallow to deep	-	Yes	High	Native to New England area.
Fraxinus americana white ash	FAC	Mesic	2-4	M	H	H	H	Sun	Large tree	50-80'	Deep	Yes	-	Low	-
Fraxinus pennsylvanica green ash	FACW	Mesic	4-6	M	H	H	H	Partial Sun	Large tree	40-65'	Shallow to deep	Yes	-	Low	-
Ginkgo biloba Maidenhair tree	FAC	Mesic	2-4	H	H	H	H	Sun	Large tree	50-80'	Shallow to deep	-	Yes	Low	Avoid female species-offensive odor from fruit.
Gleditsia triacanthos honeylocust	FAC	Mesic	2-4	H	M	-	M	Sun	Small canopied large tree	50-75'	Shallow to deep variable taproot	Yes	-	Low	Select thornless variety.
Juniperus virginiana eastern red cedar	FACU	Mesic - Xeric	2-4	H	H	-	H	Sun	Dense single stem tree	50-75'	Taproot	Yes	-	Very High	Evergreen
Koelreuteria paniculata golden-rain tree	FACU	Mesic	2-4	H	H	H	H	Sun	Round, dense shade tree	20-30'	Shallow	-	Yes	No	-
Liquidambar styraciflua sweet gum	FAC	Mesic	4-6	H	H	H	M	Sun	Large tree	50-70'	Deep taproot	Yes	-	High	Edge and perimeter; fruit is a maintenance problem.
Nyssa sylvatica black gum	FACW	Mesic - Hydric	4-6	H	H	H	H	Sun	Large tree	40-70'	Shallow to deep taproot	Yes	-	High	-

H High Tolerance
M Medium Tolerance
L Low Tolerance

FAC Facultative - Equally likely to occur in wetlands or non-wetlands.
FACU Facultative Upland - Usually occur in non-wetlands, but occasionally found in wetlands.
FACW Facultative Wetland - Usually occur in wetlands, but occasionally found in non-wetlands.

NOTE: Heights shown in table are under ideal conditions in rural settings. They do not reflect urban conditions, under which plants do not commonly survive to such maturity.

TABLE 3.11-7A RECOMMENDED PLANT SPECIES FOR USE IN BIORETENTION --- TREE SPECIES

Species	Moisture Regime		Tolerance						Morphology			General Characteristics			Comments
Scientific Name Common Name	Indicator Status	Habitat	Ponding (days)	Salt	Oil/ Grease	Metals	Insects Disease	Exposure	Form	Height	Root System	Native	Non-native	Wildlife	
Platanus acerifolia London plane-tree	FACW	Mesic	2-4	H	-	-	M	Sun	Large tree	70-80'	Shallow	-	Yes	Low	Tree roots can heave sidewalks.
Platanus occidentalis sycamore	FACW	Mesic - Hydric	4-6	M	M	M	M	Sun	Large tree	70-80'	Shallow	Yes	-	Med.	Edge and perimeter; fruit is a maintenance problem; tree is also prone to windthrow.
Populus deltoides eastern cottonwood	FAC	Xeric - Mesic	4-6	H	H	H	L	Sun	Large tree with spreading branches	75-100'	Shallow	Yes	-	High	Short lived.
Quercus bicolor swamp white oak	FACW	Mesic to wet Mesic	4-6	H	-	H	H	Sun to partial sun	Large tree	75-100'	Shallow	Yes	-	High	One of the faster growing oaks.
Quercus coccinea scarlet oak	FAC	Mesic	1-2	H	M	M	M	Sun	Large tree	50-75'	Shallow to deep	Yes	-	High	-
Quercus macrocarpa bur oak	FAC	Mesic to wet Mesic	2-4	H	H	H	M	Sun	Large spreading tree	75-100'	Taproot	-	Yes	High	Native to midwest.
Quercus palustris pin oak	FACW	Mesic - Hydric	4-6	H	H	H	M	Sun	Large tree	60-80'	Shallow to deep taproot	Yes	-	High	-
Quercus phellos willow oak	FACW	Mesic to wet Mesic	4-6	H	-	-	H	Sun	Large tree	55-75'	Shallow	Yes	-	High	Fast growing oak.
Quercus rubra red oak	FAC	Mesic	2-4	M	H	M	M	Sun to partial sun	Large spreading tree	60-80'	Deep taproot	Yes	-	High	-

H High Tolerance
M Medium Tolerance
L Low Tolerance

FAC Facultative - Equally likely to occur in wetlands or non-wetlands.
FACU Facultative Upland - Usually occur in non-wetlands, but occasionally found in wetlands.
FACW Facultative Wetland - Usually occur in wetlands, but occasionally found in non-wetlands.

NOTE: Heights shown in table are under ideal conditions in rural settings. They do not reflect urban conditions, under which plants do not commonly survive to such maturity.

TABLE 3.11-7A RECOMMENDED PLANT SPECIES FOR USE IN BIORETENTION --- TREE SPECIES

Species	Moisture Regime		Tolerance						Morphology			General Characteristics			Comments
Scientific Name Common Name	Indicator Status	Habitat	Ponding (days)	Salt	Oil/ Grease	Metals	Insects Disease	Exposure	Form	Height	Root System	Native	Non-native	Wildlife	
Robinia pseudo-acacia black locust	FAC	Mesic - Xeric	2-4	H	H	H	M	Sun	Typically tall and slender	30-50'	Shallow	Yes	-	Low	Edge and perimeter; fruit is a maintenance problem; tree is also prone to windthrow.
Sophora japonica Japanese pagoda tree	FAC	Mesic	1-2	M	M	-	M	Sun	Shade tree	40-70'	Shallow	-	Yes	Low	Fruit stains sidewalks etc.
Taxodium distichum bald cypress	FACW	Mesic - Hydric	4-6	-	-	M	H	Sun to partial sun	Typically single stem tree	75-100'	Shallow	Yes	-	Low	Not well documented for planting in urban areas.
Zelkova serrata Japanese zelkova	FACU	Mesic	1-2	M	M	-	H	Sun	Dense shade tree	60-70'	Shallow	-	Yes	Low	Branches can split easily in storms.

H High Tolerance
M Medium Tolerance
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FACU Facultative Upland - Usually occur in non-wetlands, but occasionally found in wetlands.
FACW Facultative Wetland - Usually occur in wetlands, but occasionally found in non-wetlands.

NOTE: Heights shown in table are under ideal conditions in rural settings. They do not reflect urban conditions, under which plants do not commonly survive to such maturity.

TABLE 3.11-7B RECOMMENDED PLANT SPECIES FOR USE IN BIORETENTION --- SHRUB SPECIES

Species	Moisture Regime		Tolerance						Morphology			General Characteristics			Comments
Scientific Name Common Name	Indicator Status	Habitat	Ponding (days)	Salt	Oil/ Grease	Metals	Insects Disease	Exposure	Form	Height	Root System	Native	Non-native	Wildlife	
Berberis koreana barberry	FAC	Mesic	2-4	H	H	H	M	Sun to partial sun	Oval shrub	4-6'	Shallow	-	Yes	Low	-
Berberis thunbergii Japanese barberry	FAC	Mesic	2-4	H	H	H	M	Sun	Rounded, broad dense shrub	5-7'	Shallow	-	Yes	Med.	-
Clethra alnifolia sweet pepperbush	FAC	Mesic to wet Mesic	2-4	H	-	-	H	Sun to partial sun	Ovoid shrub	6-12'	Shallow	Yes	-	Med.	Coastal plain species
Cornus Stolonifera red osier dogwood	FACW	Mesic - Hydric	2-4	H	H	H	M	Sun or shade	Arching, spreading shrub	8-10'	Shallow	Yes	-	High	Needs more consistant moisture levels.
Euonymus alatus winged euonymous	FAC	Mesic	1-2	H	H	H	M	Sun or shade	Flat, dense horizontal branching shrub	5-7'	Shallow	-	Yes	No	-
Euonymus europaeus spindle-tree	FAC	Mesic	1-2	M	M	M	M	Sun to partial sun	Upright dense oval shrub	10-12'	Shallow	-	Yes	No	-
Hamamelis virginiana witch-hazel	FAC	Mesic	2-4	M	M	M	M	Sun or shade	Vase-like compact shrub	4-6'	Shallow	Yes	-	Low	-
Hypericum densiflorum common St. John's wort	FAC	Mesic	2-4	H	M	M	H	Sun	Ovoid shrub	3-6'	Shallow	Yes	-	Med.	-
Ilex glabra inkberry	FACW	Mesic to wet Mesic	2-4	H	H	-	H	Sun to partial sun	Upright dense shrub	6-12'	Shallow	Yes	-	High	Coastal plain species
Ilex verticillata winterberry	FACW	Mesic to wet Mesic	2-4	L	M	-	H	Sun to partial sun	Spreading shrub	6-12'	Shallow	Yes	-	High	-
Juniperus communis "compressa" common juniper	FAC	Dry Mesic - Mesic	1-2	M	H	H	M - H	Sun	Mounded shrub	3-6'	Deep taproot	-	Yes	High	Evergreen

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M Medium Tolerance
L Low Tolerance

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FACU Facultative Upland - Usually occur in non-wetlands, but occasionally found in wetlands.
FACW Facultative Wetland - Usually occur in wetlands, but occasionally found in non-wetlands.

TABLE 3.11-7B RECOMMENDED PLANT SPECIES FOR USE IN BIORETENTION --- SHRUB SPECIES

Species	Moisture Regime		Tolerance						Morphology			General Characteristics			Comments
Scientific Name Common Name	Indicator Status	Habitat	Ponding (days)	Salt	Oil/ Grease	Metals	Insects Disease	Exposure	Form	Height	Root System	Native	Non-native	Wildlife	
Juniperus horizontalis "Bar Harbor" creeping juniper	FAC	Dry Mesic - Mesic	1-2	M	H	H	M - H	Sun	Matted shrub	0-3'	Deep taproot	-	Yes	High	Evergreen
Lindera benzoin spicebush	FACW	Mesic to wet Mesic	2-4	H	-	-	H	Sun	Upright shrub	6-12'	Deep	Yes	-	High	-
Myrica pennsylvanica bayberry	FAC	Mesic	2-4	H	M	M	H	Sun to partial sun	Rounded, compacted shrub	6-8'	Shallow	Yes	-	High	Coastal plain species
Physocarpus opulifolius ninebark	FAC	Dry Mesic to wet Mesic	2-4	M	-	-	H	Sun	Upright shrub	6-12'	Shallow	Yes	-	Med.	May be difficult to locate.
Viburnum cassinoides northern wild raisin	FACW	Mesic	2-4	H	H	H	H	Sun to partial sun	Rounded, compacted shrub	6-8'	Shallow	Yes	-	High	-
Viburnum dentatum arrow-wood	FAC	Mesic	2-4	H	H	H	H	Sun to partial sun	Upright, multi-stemmed shrub	8-10'	Shallow	Yes	-	High	-
Viburnum lentago nannyberry	FAC	Mesic	2-4	H	H	H	H	Sun to partial sun	Upright, multi-stemmed shrub	8-10'	Shallow	Yes	-	High	-

H High Tolerance
M Medium Tolerance
L Low Tolerance

FAC Facultative - Equally likely to occur in wetlands or non-wetlands.
FACU Facultative Upland - Usually occur in non-wetlands, but occasionally found in wetlands.
FACW Facultative Wetland - Usually occur in wetlands, but occasionally found in non-wetlands.

TABLE 3.11-7C RECOMMENDED PLANT SPECIES FOR USE IN BIORETENTION --- HERBACEOUS SPECIES

Species	Moisture Regime		Tolerance						Morphology			General Characteristics			Comments
Scientific Name Common Name	Indicator Status	Habitat	Ponding (days)	Salt	Oil/ Grease	Metals	Insects Disease	Exposure	Form	Height	Root System	Native	Non-native	Wildlife	
Agrostis alba redtop	FAC	Mesic - Xeric	1-2	H	-	H	H	Shade	Grass	2-3'	Fiberous Shallow	Yes	-	High	-
Andropogon gerardi bluejoint	FAC	Dry Mesic - Mesic	1-2	-	-	-	-	Sun	Grass	2-3'	Fiberous Shallow	Yes	-	High	-
Deschampsia caespitosa tufted hairgrass	FACW	Mesic to wet Mesic	2-4	H	-	H	H	Sun	Grass	2-3'	Fiberous Shallow	Yes	-	High	May become invasive.
Hedera helix English ivy	FACU	Mesic	1-2	-	-	-	H	Sun	Evergreen ground cover	-	Fiberous Shallow	-	Yes	Low	-
Lotus Corniculatus birdsfoot-trefoil	FAC	Mesic - Xeric	1-2	H	L	H	H	Sun	Grass	2-3'	Fiberous Shallow	Yes	-	High	Member of the legume family.
Pachysandra terminalis Japanese pachysandra	FACU	Mesic	1-2	-	-	-	M	Shade	Evergreen ground cover	-	Fiberous Shallow	-	Yes	Low	-
Panicum virgatum switch grass	FAC to FACU	Mesic	2-4	H	-	-	H	Sun or Shade	Grass	4-5'	Fiberous Shallow	Yes	-	High	Can spread fast and reach height of 6'.
Parthenocissus Tricuspida Boston ivy	FACU	Mesic	1-2	-	-	-	H	Shade	Evergreen ground cover		Fiberous Shallow	-	Yes	Low	May need to be trimmed back often.
Vinca major large periwinkle	FACU	Mesic	1-2	-	-	-	H	Shade	Evergreen ground cover	-	Fiberous Shallow	-	Yes	Low	Sensitive to soil compaction and pH changes.

H High Tolerance
M Medium Tolerance
L Low Tolerance

FAC Facultative - Equally likely to occur in wetlands or non-wetlands.
FACU Facultative Upland - Usually occur in non-wetlands, but occasionally found in wetlands.
FACW Facultative Wetland - Usually occur in wetlands, but occasionally found in non-wetlands.

MINIMUM STANDARD 3.11A

BIORETENTION FILTERS

Definition

Bioretention basins that rely on infiltration (**MINIMUM STANDARD 3.11: BIORETENTION BASINS**) may not be feasible in many ultra-urban settings because of the proximity of building foundations or because soils are not conducive to exfiltration from the basin. **Bioretention Filters** were developed for use in such circumstances.

Bioretention soil media filters are essentially bioretention basins with the infiltration chamber gallery equipped with a permanent and continuous connection to the storm sewer system. The bioretention basin shown in **Figure 3.11A-1** illustrates a bioretention basin equipped to function as a filter.

When used in areas underlain by marine clays or in proximity to building foundations, the entire basin must be provided with a dense clay or geomembrane liner. When the filter concept must be used simply because of low percolation rates of the soil, the liner may be omitted. The vertical sand column is also optional on a bioretention filter.

Purpose

Water Quality Enhancement

Like bioretention basins, bioretention filters are used primarily for water quality control. Bioretention filters enhance the quality of stormwater runoff through the processes of adsorption, filtration, volitization, ion exchange, microbial and decomposition prior to collection of the treated effluent in the collector pipe system. Microbial soil processes, evapotranspiration, and nutrient uptake in plants also come into play (Bitter and Bowers, 1995). The manner in which these processes work is discussed under **MINIMUM STANDARD 3.11, BIORETENTION BASINS**. The minimum widths and lengths for bioretention basins (10' and 15', respectively) also apply to bioretention filters. However, since runoff will be treated faster in a bioretention filter, it may be pooled to a maximum depth of 1 foot above the basin floor rather than the 0.5 feet allowed in a bioretention basin. **Table 3.11A-1** contains the target removal efficiencies for bioretention filters in which a **mature** forest community has been created, based on the volume of runoff to be filtered.

FIGURE 3.11A-1
Bioretention Filter

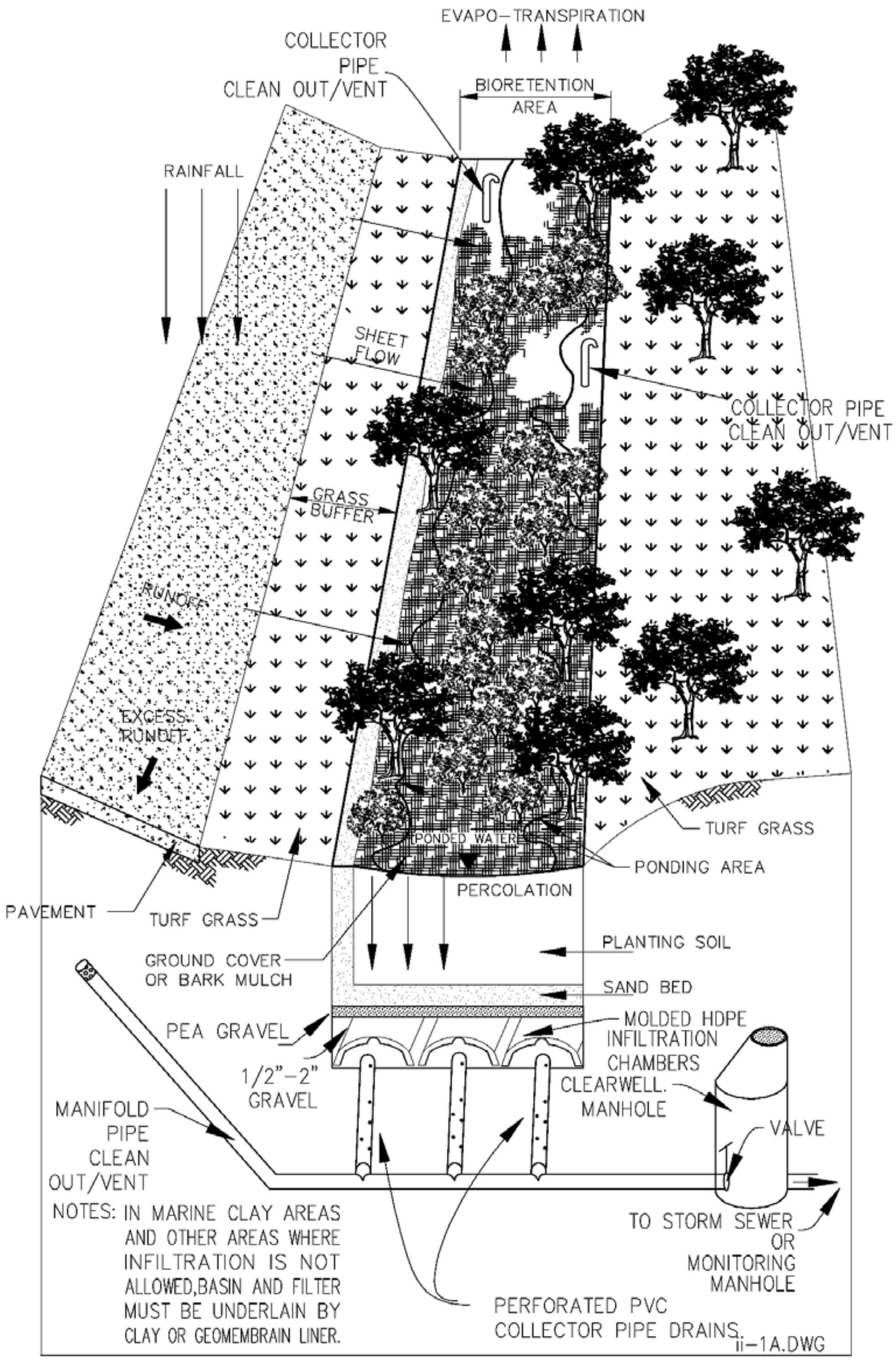

TABLE 3.11A - 1
Pollutant Removal Efficiencies for Bioretention Filters

BMP Description	Target Pollutant Removal Efficiency (Phosphorous)
Bioretention filter with capture and treatment volume equal to 0.5 inches of runoff from the impervious area.	50%
Bioretention filter with capture and treatment volume equal to 1.0 inches of runoff from the impervious area.	65%

Flood Control and Channel Erosion Control

The amount of flood and channel erosion control protection provided by bioretention basins depends on the local rainfall frequency spectrum, the amount of pre-development (or pre-redevelopment) impervious cover, the amount of post-development impervious cover, and the volume of runoff captured and infiltered by the basin(s). The effect of the BMPs on peak flow rates from the drainage shed must be examined As with other infiltration practices, bioretention basins tend to reverse the consequences of urban development by reducing peak flow rates and providing groundwater discharge.

Conditions Where Practice Applies

Bioretention Filters are generally suited for almost all types of development, from single-family residential to fairly high density commercial projects. They are attractive for higher density projects because of their relatively high removal efficiency. The critical prerequisite is the existence of a deep enough storm sewer to accept drainage from the collector pipe system by gravity flow. All of the applications shown in **Figures 3.11-2** through **3.11-6** under **MS 3.11** may be built as bioretention filters. As with bioretention basins, for large applications, several connected bioretention filters (another type of "Green Alleys") are preferable to a single, massive filter. Such systems are especially desirable along the landward boundary of reduced Chesapeake Bay Resource Protection Areas. **MS 3.11B** discusses this system. Considering the character of bioretention basins, some jurisdictions may qualify them as buffer restoration.

Planning Considerations

Site Conditions

Except for those dealing with proper soils to accept infiltration and sizing of the filters, all of the **Site Conditions** considerations for bioretention basins contained in **MINIMUM STANDARD 3.11: BIORETENTION BASINS** also apply to bioretention filters. The same drainage area range applies, as do the same **Location Considerations.** In addition to site conditions, the following apply specifically to bioretention filters.

1. Sizing Guidelines

For planning purposes, assume that the floor area of a bioretention filter will be 2.5% of the impervious area draining to the filter if 0.5 inches of runoff are to be treated and 5.0% of the impervious area on the drainage shed if the first 1.0 inches of runoff are to be treated.

2. Aesthetic Considerations

All of the discussion of aesthetics under **MINIMUM STANDARD 3.11: BIORETENTION BASINS** apply equally to bioretention filters. Overall aesthetics of the bioretention filters must be integrated into the site plan and stormwater concept plan from their inception. Biomorphic shapes which follow the ground contours should be used rather than angular shapes. The bioretention filter should be essentially almost invisible upon completion, blending in with the other landscaping of the site. Both the stormwater engineer and the landscaping planner must participate in the layout of the facilities and infrastructure to be placed on the site.

Sediment Control

All of the **Sediment Control** considerations for bioretention basins under **MS 3.11: Bioretention Basins** also apply to bioretention filters.

Like bioretention basins, bioretention filters should be constructed only AFTER the site work is complete and stabilization measures have been implemented. Experience with bioretention basins and soil media filters has demonstrated that bioretention filters must be protected from all sediment loads.

Bioretention filters must retain sediment control protection until stabilization of the upland site is functional to control the sediment load from denuded areas. Provisions to bypass the stormwater away from the bioretention filter during the stabilization period must be implemented.

General Design Criteria

The purpose of this section is to provide minimum criteria for the design of bioretention filter BMPs intended to comply with the Virginia Stormwater Management program's runoff quality requirements. Bioretention filters which capture and treat the first one inch of runoff from impervious surfaces may also provide streambank erosion protection.

General

The design of bioretention filters should be in accordance with the following Minimum Standards where applicable: **3.1: Earthen Embankments, 3.2: Principal Spillways, 3.3: Vegetated Emergency Spillways, 3.4: Sediment Forebay,** as well as the additional criteria set forth below. The designer is not only responsible for selecting the appropriate components for the particular design but also for ensuring long-term operation.

Integration of the bioretention filters into the general landscaping scheme of the project must be coordinated with the landscaping professional at the inception of the design process. Use of such techniques as biomorphic shapes to present a pleasing aesthetic appearance is of equal importance with hydrological and hydraulic functioning of the basins. Properly designed bioretention filters should not be readily identifiable as stormwater BMPs by the lay observer.

Basin Sizing Methodology

In Virginia, bioretention filters are designed to filter the treatment quantity into the underlying gravel bed and collector pipe system. **Bioretention filters are sized using the same sizing methodology as that of bioretention basins**.

The elevation of the overflow structure should be 1.0 feet above the elevation of the bioretention bed.

The **Runoff Pretreatment, Drainage Considerations**, and **Exclusion of Continuous Flows and Chlorinated Flows** considerations of **MINIMUM STANDARD 3.11: BIORETENTION BASINS**, are also applicable to bioretention filters. If the filter soil remains constantly wet, anaerobic conditions will develop, which will kill the plants and cause iron phosphates which have been previously captured to break down and escape into the effluent.

Continuous or frequent flows (such as basement sump pump discharges, cooling water, condensate water, artesian wells, etc.) and flows containing swimming pool and sauna chemicals must be EXCLUDED from routing through bioretention or bioretention filter BMPs since such flows will cause the BMP to MALFUNCTION!

The **Planting Plan, Planting Soil Guidelines, Mulch Layer Guidelines, Plant Material Guidelines, Plant Growth and Soil Fertility** criteria of **MINIMUM STANDARD 3.11: BIORETENTION BASINS**, also apply to bioretention filters.

Basin Liners

Impermeable liners may be either clay, concrete or geomembrane. If geomembrane is used, suitable geotextile fabric shall be placed below and on the top of the membrane for puncture protection. Clay liners shall meet the specifications in **Table 3.11A-2**.

The clay liner shall have a minimum thickness of 12 inches.

If a geomembrane liner is used it shall have a minimum thickness of 30 mils and be ultraviolet resistant.

The geotextile fabric (for protection of geomembrane) shall meet the specifications in **Table 3.11A-3**.

TABLE 3.11A - 2
Clay Liner Specifications (Source: City of Austin)

Property	Test Method	Unit	Specification
Permeability	ASTM D-2434	Cm/Sec	1 x 10^{-6}
Plasticity Index of Clay	ASTM D-423 & D-424	%	Not less than 15
Liquid Limits of Clay	ASTM D-2216	%	Not less than 30
Clay Compaction	ASTM-2216	%	95% of Standard Proctor Density
Clay Particles Passing	ASTM D-422	%	Not less than 30

TABLE 3.11A - 3
Geotextile Specification for Basin Liner "Sandwich"

Property	Test Method	Unit	Specification
Unit Weight		Oz./Sq.Yd.	8 (minimum)
Filtration Rate		In./Sec.	0.08 (minimum)
Puncture Strength	ASTM D-751 (Modified)	Lb.	125 (minimum)
Mullen Burst Strength	ASTM D-751	Psi.	400 (minimum)
Tensile Strength	ASTM D-1682	Lb.	300
Equiv. Opening Size	U.S. Standard Sieve	No.	80 (minimum)

Source: City of Austin

Equivalent methods for protection of the geomembrane liner will be considered on a case by case basis. Equivalency will be judged on the basis of ability to protect the geomembrane from puncture, tearing and abrasion.

When molded chambers are incorporated into the design, a minimum of four inches of gravel or crushed stone should be added beneath the molded chambers or other conveyance system to allow settling of filter fines into the voids. As with bioretention basins, filter strips, grassed channels, and side slopes should be sodded with mature sod, and planting soil should be wrapped up the side slopes under the sod.

All other factors dealing with bioretention filters are identical to those for bioretention basins in general, **M.S.3.11.**

MINIMUM STANDARD 3.11B

GREEN ALLEYS

Definition

Green Alleys consist of a network of bioretention basins/infiltration trenches or bioretention filters that provide both redundant water quality management and stormwater conveyance to stormwater management facilities. They create a carefully landscaped green border along, or a dividing corridor through, a development site. Unless otherwise noted, the information on Green Alleys in this section was provided by Keith Bowers of Biohabitats, Inc.

Green Alleys combine the redundancy of multiple stormwater quality BMPs and stormwater conveyance with urban and suburban site design features. Using bioretention, infiltration, and filtration as a foundation, Green Alleys consist of an above ground and below ground green ribbon of interconnecting BMPs that treat the first flush of stormwater while conveying excess runoff to management facilities. While Green Alleys provide an ecosystem based stormwater management technique, they also connect and facilitate the awareness of natural ecologic and hydrologic cycles.

Above ground, Green Alleys consist of a strip (greenway) consisting of native trees, schrubs, and groundcover that replicates native forest ecosystems and landscape processes to enhance sormwater quality. Green Alleys can also consist of a mixture of hardscape and landscape incorporating such features as walkways, urban plazas, open spaces, and streetscapes. Below ground, Green Alleys consist of sand filters and infiltration trenches that are connected by a series of perforated and solid pipes or molded plastic infiltration galleries that convey excess stormwater to quantity management facilities.

Purpose

Like bioretention basins and bioretention filters, green alleys are used primarily for water quality control. A number of other benefits may also accrue from green alleys. They provide redundancy in the number of treatment techniques and, except where precluded by soil conditions, some opportunity for infiltration even where filters are used; they may reinforce the visual and physical connection between the urban environment and the surrounding natural features; they may provide a greenway corridor (hedgerow) for wildlife habitat and/or pedestrian circulation; they may provide a green buffer between different land uses; and the system continues to function even if individual parts fail.

Water Quality Enhancement

As with other bioretention facilities, the treatment volume is managed and treated through microbial action and soil chemestry (nutrient cycling), evaportransporation, adsorption, and, where applicable, soîl infiltration. The manner in which these processes work is discussed under **MINIMUM STANDARD 3.11, BIOTETENTION BASINS.** **Table 3.11B-1** provides pollutant removal efficiencies for Green Alleys based on the volume of water to be treated.

TABLE 3.11B - 1
Pollutant Removal Efficiencies for Green Alleys

BMP Description	Target Pollutant Removal Efficiency (Phosphorous)
Green Alleys with capture and treatment volume equal to 0.5 inches of runoff from the impervious area.	50%
Green Alleys with capture and treatment volume equal to 1.0 inches of runoff from the impervious area.	65%

Flood Control and Channel Erosion Control

The amount of flood and channel erosion control provided by Green Alleys depends on the local rainfall frequency spectrum, the amount of pre-development (or pre-redevelopment) impervious cover, the amount of post-development impervious cover, and the volume of runoff captured and infiltered by the basin(s). The effect of the BMPs on peak flow rates from the drainage shed must be examined. As with other infiltration practices, bioretention basins tend to reverse the consequences of urban development by reducing peak flow rates and providing groundwater discharge.

Conditions Where Practice Applies

Green Alleys are generally suited for almost all types of development, from single-family residential to fairly high density commercial projects. They are attractive for higher density projects because of their relatively high removal eccifiency. The critical prerequisite is the existence of a deep enough storm sewer to accept drainage from the collector pipe system by gravity flow. All of the applications shown in **Figures 3.11-2** through **3.11-6** under **MS 3.11** may be built as bioretention filters.

Planning Considerations

Stormwater Management Concept Plan

Like all bioretention facilities, Green Alleys must be planned within the context of an overall stormwater management concept plan which addresses potential flooding and streambank erosion protection as well as water quality. This concept plan must be developed very early in the planning process to assure that sufficient space in the proper hydrological and hydraulic locations is reserved for stormwater management facilities. Minimum information necessary to develop a stormwater concept plan includes: existing and proposed drainage areas, size and capacity of downstream drainage conveyances, soils stidies, existing vegetation, and hydrographic features such as streams, floodplains, and wetlands, boundaries of Chesapeake Bay Preservation Resource Protection Areas. The plan must address the proposed location of areas of impervious cover on the site, the methods for collection and conveyance of runoff to an adequate channel or conduit, proposed detention facilities to address streambank erosion and potential flooding, and the proposed methods of providing quality treatment of the runoff.

Site Conditions

The **Site Conditions** considerations for for bioretention basins contained in **MINIMUM STANDARD 3.11: BIORETENTION BASINS** and **MS 3.11A: Bioretention Filters**, apply to Green Alleys which employ these BMPs. The same drainage area range applies, as do the same **Location Considerations.** In addition to site conditions, the following apply specifically to bioretention basins.

All other considerations for **M.S. 3.11, Bioretention Basins**, apply to Green Allies.

Chapter 3.11

Bioretention Filter in ultra-surban setting. Note curb cut, gravel energy dissipater, and clean out/observation wells.

Bioretention Filter located in required parking lot green space.

Bioretention Basin Practices

Chapter 3.11

Bioretention Filter in multi-family residential setting.

Bioretention Basins in office setting parking lot.

Bioretention Basin Practices

MINIMUM STANDARD 3.12

GENERAL INTERMITTENT SAND FILTERS

3.12A	Washington D.C. Underground Vault Sand Filter
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3.12C	Austin Surface Sand Filter

View BMP Images

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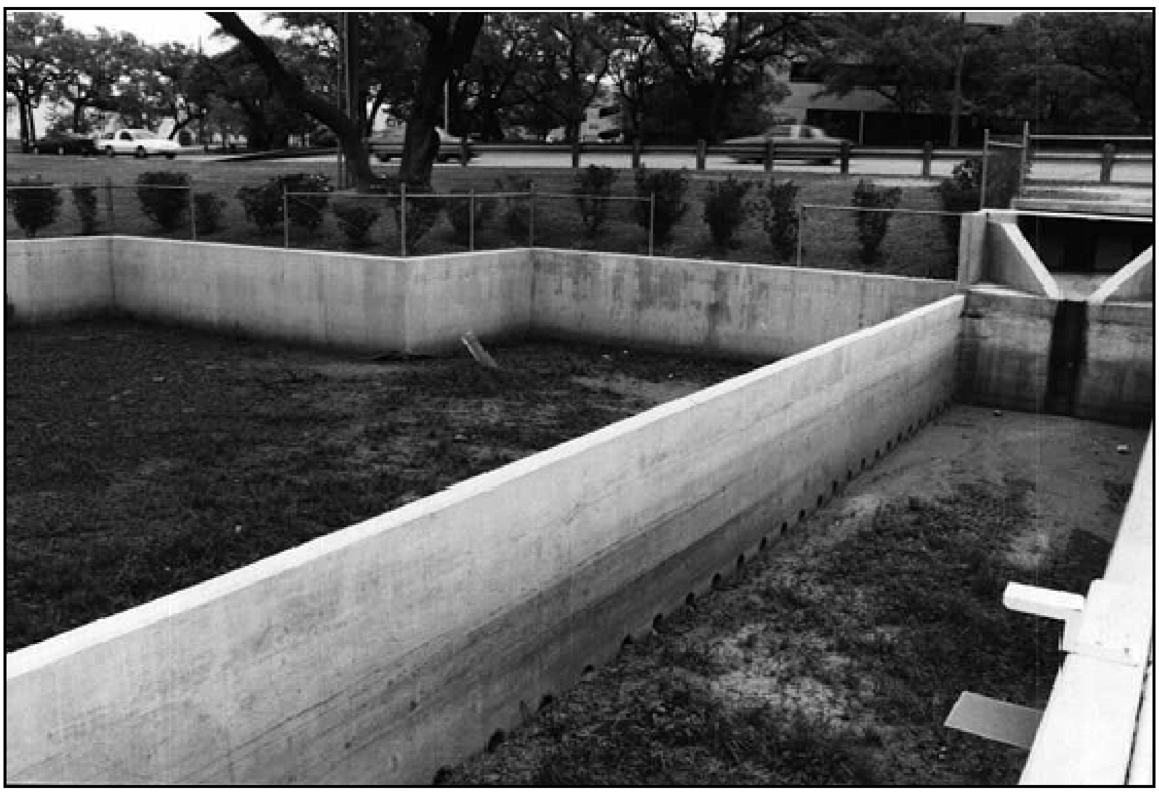
MINIMUM STANDARD 3.12

GENERAL INTERMITTENT SAND FILTER PRACTICES

Definition

Intermittent sand filter facilities capture, pretreat to remove sediments, store while awaiting treatment, and treat to remove pollutants (by percolation through sand media) the most polluted stormwater (the water quality volume) from a site. Intermittent sand filter BMPs may be constructed in underground vaults, in paved trenches within or at the perimeter of impervious surfaces, or in either earthen or concrete open basins. They have been successfully used in Austin Texas, the District of Columbia, The State of Delaware, and in Alexandria, Virginia over the last two decades. **Figure 3.12-1** is a photograph of a sand filter BMP in Austin.

FIGURE 3.12 - 1
Austin Partial Sedimentation Surface Sand Filter



(Photo Courtesy of City of Austin, Texas)

Purpose

Intermittent sand filter facilities are primarily used for water quality control. However, they do provide detention and slow release of the water quality volume from the site being treated. Whether this amount will be sufficient to provide the necessary peak flow rate reductions required for channel erosion control is dependent upon site conditions (hydrology) and required discharge reductions. The 10-year and 100-year flows will usually exceed the detention capacity of a sand media filter. When this occurs, separate quantity facilities must be provided. Table 3.12-1 contains the target removal efficiencies of sand and other soil media filter BMPs. Table 3.12-2 contains the results of an extensive sand filter monitoring study in Alexandria conducted for the Chesapeake Bay Local Assistance Department (Bell, Stokes, Gavan, and Nguyen, 1995).

TABLE 3.12-1
Pollutant Removal Efficiency for Intermittent Sand Filter Facilities

BMP Description	Target Phosphorus Removal Efficiency
Intermittent Sand Filter treating 0.5 inches of runoff from the impervious area.	65%

Pollutant Removal Mechanisms at Work in Intermittent Sand Filter BMPs

Pollutant removal processes at work in intermittent sand filters are complex and involve physical, chemical, and biological transformations (Tchobanoglous and Burton, 1991; Anderson, Siegrist, and Otis, Undated). The most obvious mechanism is physical straining of suspended solids and particulate nutrients.

Suspended Solids

Mechanical straining, straining due to chance contact, and sedimentation are the principal mechanisms by which suspended solids are removed, although the growth of bacterial colonies within the sand grains may also cause autofiltration (Tchobanoglous and Burton, 1991).

Table 3.12-2
Pollutant Removal Efficiencies for a Delaware Sand Filter in Alexandria

Constituent	Mass Balance Removal Efficiency (%)
Cadmium	NA
Copper	NA
Zinc	>90.7
Iron	NA
Ammonia Nitrogen	>39.0
Nitrite Nitrogen	>45.8
Nitrate Nitrogen	-62.7
NO_x	-53.3
Total Kjeldahl Nitrogen	70.6
Total Phosphorous	63.1/72.3[1]
Ortho-Phosphorous	>68.3/74.4[1]
Total Suspended Solids	>78.8/>83.9[2]
Hardness	38.5
Biochemical Oxygen Demand (5 Day)	>77.5
Total Petroleum Hydrocarbons	>84[3]
Total Organic Carbon	65.9

[1] Excluding Anaerobic Incident Data [2] Excluding Storms with Heavy Iron Export
[3] Average Removal from Alaska Marine Lines Filter 3 in Seattle, Washington (Horner,1995)

<u>Phosphorous</u>

Phosphorous removal is performed by physiochemical processes such as mechanical and chance contact straining, precipitation, and adsorption (Piluk and Hao, 1989; Laak, 1986).

There are three general types of adsorption (the condensation and concentration of ions or molecules of one material [the adsorbate] on the surface of another [the adsorbent]): physical, chemical, and exchange. Physical adsorption results from the weak forces of attraction between molecules and is generally quite reversible. Chemical adsorption results from much stronger forces comparable to those leading to the formation of chemical compounds, with the adsorbed material forming a one molecule thick layer over the surface of the absorbent until the capacity of the absorbent is exhausted. Chemical adsorption is seldom reversible. Exchange adsorption, on the other hand, results from electrical attraction between the adsorbate and the surface, such as occurs with ion exchange. Ions of the adsorbate concentrate on the surface of the adsorbent as a result of electrical attraction to opposite charges on the surface. It is sometimes difficult to assign a given adsorption to a specific type (Sawyer, Mcarty, and Parkin, 1994).

Although exchange adsorption may also be involved, most adsorption in intermittent sand filters appears to be chemical adsorption (Piluk and Hao, 1989; Otis, Undated; Anderson, Siegrist, and Otis, Undated).

In addition to the **filter mass available**, the adsorption of phosphorous in sand filters is also affected by the pH of the material being filtered (with higher removal rates occurring with the reduction of pH), temperature, contact time, and the character of the filter media (Laak, 1986). Sands containing iron, aluminum, or calcium have a higher phosphorous removal potential because phosphorous will combine with these elements through chemical precipitation and become relatively insoluble (Laak, 1986, Tchobanoglous and Burton, 1991). If the filter becomes anaerobic, the bonding with iron may break down, releasing orthophosphates (Harper and Herr, 1993). However, aerobic filters enriched with iron may attain almost complete phosphorous removal until the filter capacity is exhausted, and properly sized filters may have a life of up to 20 years (Laak, 1986). Sand particles with sufficient iron content may become positively charged, leading to more favorable medium-particle interactions and increased removal rates (Stenkamp and Benjamin, 1994). Entrapment in the filter of a high percentage of the iron in the runoff being treated may provide a source to replenish used up phosphorous adsorption capacity.

<u>Nitrogen and Biochemical Oxygen Demand</u>

Mineralization of organic nitrogen into ammonium (NH^{+}_{4}) may occur under either aerobic or anaerobic conditions if the required naturally occurring chemoautotrophic bacteria (organisms which obtain energy by oxidizing simple chemical compounds) are present (*Nitrosomonas, Nitrosococcus, Nitrospira, Nitrosolobus, Nitrososovibrio*) ((Laak, 1986; The Cadmus Group, 1991).

Organic N 6 Bacterial enzymes 6 NH_4^+ + other products

Positively charged ammonium ions are then adsorbed to negatively charged sand filter particles through exchange adsorption (The Cadmus Group, 1991).

The transformation of ammonia (NH_3) and ammonium into nitrite and nitrate (NO_2^- and NO_3^-) and the removal of BOD_5 occur under aerobic conditions by microorganisms (such as *Nitrosomonas* and *Nitrobacter*) present in the sand bed (Tchobanoglous and Burton, 1991;, Laak, 1991; The Cadmus Group, 1991).

$NH_4^+ + 1.5O_2$ 6 *Nitrosomonas*, etc 6 $NO_2^- + 2H + H_2O$ + Energy

$NO_2^- + 0.5O_2$ 6 *Nitrobacter* 6 NO_3^- + Energy

Since nitrite and nitrate are soluble anions, they are not affected by the cation exchange complex of the filter, but rather tend to leach readily to the filter effluent (Gold, Lamb, Loomis, and McKiel, Undated). However, anaerobic microenvironments (sometimes called "microsites") routinely coexist in principally aerobic intermittent sand filters (Tchobanoglous and Burton,1991; Gold, Lamb, Loomis, and McKiel, Undated). Naturally occurring anaerobic bacteria (*Pseudomonas, Micrococcus*, *Achromobacter*, *Bacilluss*) in these pockets may convert much of the nitrite into nitrate and the nitrate to nitrogen gas, resulting in total nitrogen removal in intermittent sand filters ranging up to 45-50 percent (Tchobanoglous and Burton, 1991; Laak, 1986; Ronayne, Paeth, and Osborne, Undated).

NO_3^- + Organic Carbon 6 Denitrifying bacteria 6 $N_2 + H_2O + CO_2$ + Cells

Organic carbon must be present for denitrification to occur, but low organic carbon/nitrogen rations will suffice (1:2 or less) (Laak, 1986, p.62). Some studies indicate that optimal denitrification occurs at ratios of 1:1-3:1 (Gold, et al, p.298). The maximum rate of denitrification occurs at temperatures above 10 degrees C and at a pH above 5.5, with the optimum pH range falling between 7.0 and 8.0. (The Cadmus Group, 1991, p.11). However, home wastewater systems have demonstrated excellent denitrification performance when the wastewater temperature was as low as 4 degrees C (Piluk and Hoa, 1989).

Heavy Metals

More than 70 percent of heavy metals in stormwater runoff is in particulate form (Harper and Herr, 1993). Over 70 percent of particulate heavy metals are of greater than 104 microns in size (Shaver and Baldwin, 1990). Particle settling in presettling basins and mechanical straining appear to be the principal mechanism for removing heavy metals in stormwater intermittent sand filter systems. Some iron may be removed by reacting with phosphorous in the runoff being treated.

Hydrocarbons

Mechanical straining and physical adsorption appear to be the mechanisms removing hydrocarbons which reach the sand filter.

Conditions Where Practice Applies

Intermittent sand filters are suitable for use in ultra-urban settings with a high degree of imperviousness where the land cost or loss of economic return on real estate required to construct retention basins may be prohibitive. They are generally suited for high pollutant removal on medium to high density development (65 to 100% impervious cover). Specific conditions such as drainage area size and development conditions are discussed with each type of intermittent sand filter. Because they are subject to failure by clogging, intermittent sand filters are not recommended for use on watersheds where sediment loadings can be significant. Wherever possible, their use should be limited to treating runoff from impervious surfaces. Most of the practices discussed below are designed to treat runoff from watersheds with at least 65% impervious cover. Where other runoff must be treated, sediment protection must be increased to severely curtail the sediment load reaching the filter media.

Planning Considerations

Site Conditions

1. ***Size and Topography of the Site***

Some types of intermittent sand filter BMPs are especially suited to larger drainage sheds, while others have upper size limits on their effective use. **Table 3.12-3** outlines drainage shed size applications of various types of intermittent sand filter facilities. On larger sites with multiple drainage sheds, a variety of BMPs might prove to be most cost effective.

TABLE 3.12 - 3
Appropriate Intermittent Sand Filter Applications to Various Site Areas

Type of Intermittent Sand Filter	Appropriate Drainage Shed to filter
District of Columbia Underground Vault Sand Filters	Medium (0.25-1.25 impervious acres)
Delaware Sand Filters	Small-Medium (≤ 1.25 impervious acres)
Austin Full Sedimentation Sand Filters (Surface or Vault)	Large (≥ 1.25 impervious acres)
Austin Partial Sedimentation Sand Filters (Surface)	Medium-Large
Austin Partial Sedimentation Sand Filters (Underground)	Medium

2. *Stormwater Infrastructure Serving Site*

Both the size and the elevations of stormwater infrastructure serving the site as a whole are important considerations. A critically important design parameter is the potential difference in elevation of the receiving manhole in the stormwater infrastructure and the elevation of the closest manhole in the new storm sewer system draining the site to be served. This will determine the depth of water than can be pooled above the filter media with the system operating on gravity flow. Almost all intermittent sand filter BMPs are designed to flow by gravity. However, in commercial and industrial applications where dedicated maintenance crews with familiarity with mechanical equipment will be available, pumped flow should be considered a viable alternative.

3. *Depth to Seasonally High Groundwater Table*

The liner or concrete shell of intermittent sand filter BMPs is usually placed at least 2 to 4 feet above the seasonally high water table or bedrock in order to assure dry conditions for construction and to minimize infiltration of groundwater into the filter structure. However, in some cases, it may be economical and practical to place filter shells below the seasonally high water table. In such cases, floatation effects must be countered by providing extra weight or hold down components in the filter shell.

4. *Value of the Real Estate and Expected Income from Development*

The value of real estate in highly urbanized areas may drive the overall cost of traditional structural BMPs too high for serious consideration. In Alexandria, for example, the cost of real estate alone to construct retention ponds averages $60,000 per impervious acre treated, while the cost of real estate for extended detention basins averages $40,000 per impervious acre treated. The overall costs of underground vault sand filters, which may be placed under parking lots and private streets or even within building structures and therefore have no real estate cost, can become quite competitive under such circumstances. The income stream from increased development allowed by underground BMPs should also be considered in such analyses.

5. *Aesthetic and Land Use Considerations*

Most traditional stormwater BMPs may be severely lacking in visual attractiveness. This may be especially true with some extended detention basins and retention basins lacking a base flow to prevent eutrophication during hot, dry weather. Questions also often arise about the use of valuable open space on projects for BMPs instead of alternative uses such as recreation. Most sand filter BMPs are visually unobtrusive and may be used in situations where aesthetic considerations or open space use are important.

Sediment Control

Intermittent sand filter BMPs which have been subjected to heavy sediment loadings have historically failed very quickly (LaRock, 1988; Harper and Herr, 1993). In a study in Denver, Colorado, Urbonis, Doerfer, and Tucket found that the hydraulic conductivity of a sand filter serving an equipment parking lot dropped rapidly as sediment accumulated on the surface of the filter (Urbonis, Doerfer, and Tucker, 1996). A layer of sediment approximately 1/16 inch (1.6 millimeters) thick was found to limit hydraulic conductivity to 0.05 feet per hour (1.6 ft/day), considerably less than the design coefficient of permeability used by Northern Virginia jurisdictions in the design of sand filters (*ibid.;* Bell, Stokes, Gavan, and Nguyen, 1995). The filter media of intermittent sand filter BMPs must therefore be protected from excessive sediment loads. This requires isolation during construction of the development, site design to restrict the amount of runoff from pervious areas reaching the filter after construction, and proper sizing of sediment removing features of the BMP to match final site conditions.

1. *Construction Runoff*

Sand filter BMPS must ***never*** *be placed in service until all site work has been completed and stabilization measures have been installed and are functioning properly.*

When this precaution has not been taken in the past, the sand filter BMPs have become clogged with sediment from upland construction operations almost immediately, requiring complete reconstruction of the sand filter and sometimes the collector pipe system. This can prove very expensive. However, since most sand filter BMPs are constructed off-line with a flow splitting device employed to divert only the Water Quality Volume to the filter, the BMP may usually be completely constructed but isolated from runoff by blocking the inflow pipe until the site is fully stabilized.

2. *Urban Runoff*

While experience indicates that intermittent sand filters fail very quickly when directly exposed to runoff from watersheds with low imperviousness and poor vegetated cover (LaRock, 1988; Harper and Herr, 1993), filters which treat runoff from almost exclusively impervious areas, such as highway surfaces, may perform satisfactorily for several years with very little maintenance (Shaver and Baldwin, 1991).

An 18-month, comprehensive study of runoff from street surfaces in 12 cities throughout the U.S. determined that, while most particulate matter is in the fractions equating to sand and gravel, the approximately 6 percent of particles in the silt and clay soil size contain over half the phosphorous and some 25 percent of other pollutants (Sartor, Boyd, and Agardy, 1974). **Table 3.12-4** illustrates this finding.

In planning the layout for a site on which sand filter BMPs are to be employed, care should be taken to direct only runoff from impervious surfaces to the filter insofar as possible. The drainage sheds feeding sand filter BMPs with only partial sediment protection (as delineated in the individual BMP discussions which follow) should ***never*** contain less than 65% impervious cover. Even when full sediment protection is provided in the form of a carefully sized presettlement basin, the amount of runoff from pervious areas directed to the filter must be minimized. The Denver study also indicates that full sediment protection may be required in areas subject to heavy atmospheric deposition of suspended solids even when only runoff from impervious surfaces is being treated.

The presettling basin or sedimentation chamber of an intermittent sand filter BMP is expected to remove all but the very fine particles of sediment, while most of the other pollutant removal is expected to occur in the sand filter, where the very fine particles will be trapped.

TABLE 3.12-4
Percent of Street Pollutants in Various Particle Size Ranges

	Particle Size (Microns)					
Pollutant	**>2000**	**840-2000**	**246-840**	**104-246**	**43-104**	**<43**
Total Solids	24.4	7.6	24.6	27.8	9.7	5.9
Volatile Solids	11.0	17.4	12.0	16.1	17.9	25.6
COD	2.4	4.5	13.0	12.4	45.0	22.7
BOD_5	7.4	20.1	15.7	15.2	17.3	24.3
TKN	9.9	11.6	20.0	20.2	19.6	18.7
Phosphates	0	0.9	6.9	6.4	29.6	56.2
All Toxic Metals	16.3	17.5	14.9	23.5	-	27.8

(Source: Shaver and Baldwin, 1990; adapted from Sartor, Boyd, and Agardy, 1974)

<u>Trash Exclusion</u>

Underground vault BMPs are confined space under Occupational Safety and Health Regulations and are therefore more expensive to enter and maintain than open facilities. Future operations and maintenance costs can substantially reduced by assuring that trash is, insofar as possible, excluded from entering the vault. Grated storm inlets and trash racks in flow splitters are two ready solutions to this problem.

<u>Projected Hydrocarbon Loadings</u>

Sand filters will quickly clog when subjected to direct heavy hydrocarbon loadings. Where such loadings are expected, a design which removes unemulsified hydrocarbons in a separate chamber or structure in the treatment train ahead of the filter should be selected.

Maintenance

The maintenance requirements for intermittent sand filters must be considered during the planning and design of the facility. All chambers of underground sand filters must have personnel access manholes and built-in access ladders . Access roads or streets must be of sufficient width and bearing capacity to support dump trucks loaded with accumulated sediments or heavy vacuum (e.g.”VACTOR”) trucks for removing accumulated sediments and hydrocarbons from sediment chambers and traps on a regular basis. Approximately every 3-5 years, the filter can be expected to clog to the point that replacement of the top few inches of sand or, where employed, the layer of washed gravel and the top layer of filter cloth will be required. **A minimum maintenance headspace of 60 inches above the filter is required in underground vault filters BMPs.** A 36-38-inch diameter maintenance manhole with a small, concentric personnel access lid or a rectangular load bearing access door (minimum 4 ft. x 4 ft.) should be positioned directly over the center of the filter. Large sedimentation basins and open filters must be equipped with access ramps to allow small earthmoving equipment such as “Bobcats” and light trash raking equipment to go into the basins. Finally, before finalizing the BMP design, follow the advice of Joseph J. Skupien, Principal Hydraulic Engineer of Somerset County, New Jersey, and “close your eyes, kick back, and think your BMP through a full year of operations, visualizing how it will perform under the conditions of all four seasons.”

General Design Criteria

The purpose of this section is to provide recommendations and minimum criteria for the design of intermittent sand filter practices intended to comply with the Virginia Stormwater Management program’s runoff quality requirements.

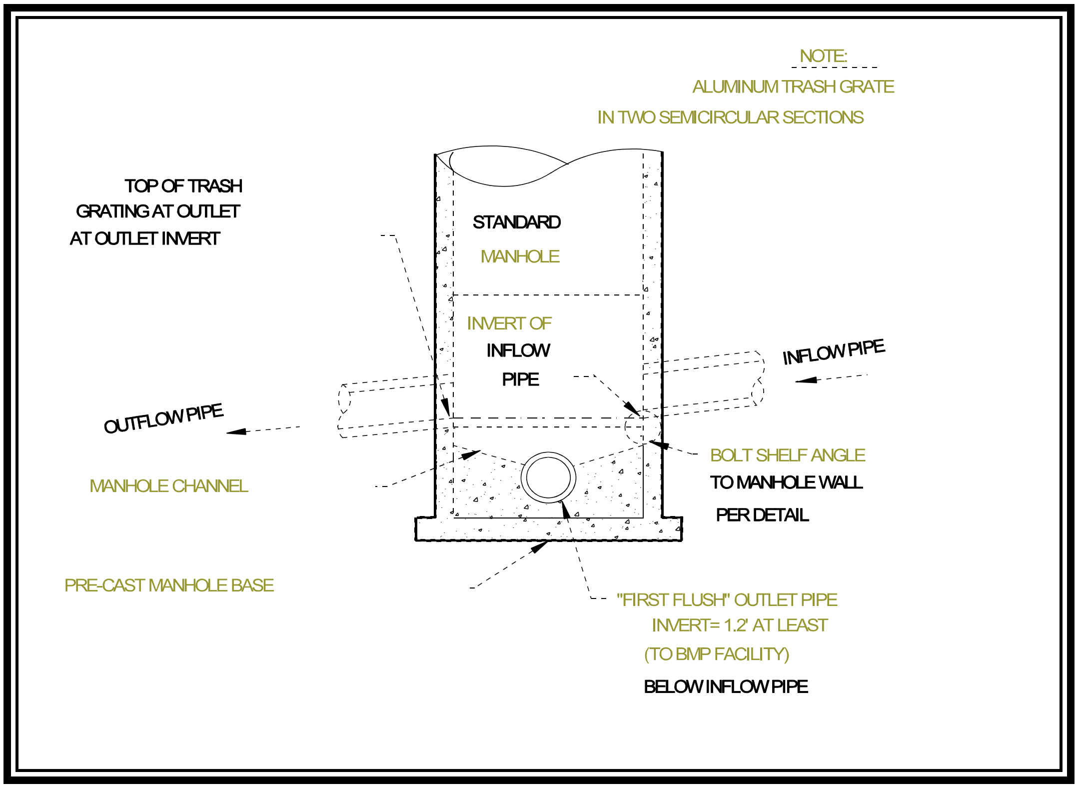
Several types of intermittent sand filter facilities are recognized for stormwater quality management purposes, including ***District of Columbia Underground Vault Filters***, ***Delaware Sand Filters, Austin Full Sedimentation Sand Filters,*** and ***Austin Partial Sedimentation Sand Filters***.

The general design criteria presented below apply to the design of intermittent sand filter facilities for ***water quality control***. This implies that the volume of runoff to be treated is determined by the **water quality volume** (the first 0.5 inches of runoff from the impervious surfaces on the site or drainage shed) and the desired pollutant removal efficiency.

Isolating the Water Quality Volume

The usual method for isolating the WQV is to construct an isolation/diversion weir in the stormwater channel or pipe, with the elevation of the weir set to allow overflow when the BMP is completely full. Additional runoff greater than the WQV spills over the weir to enter a peak flow rate reducer or exit directly to the storm sewer, minimizing mixing with the water in the BMP. Another approach is to provide a lower pipe to feed the filter until it fills, after which water rises in the slitter manhole and continues down a higher pipe. **Figure 3.12 - 2** illustrates this approach (source: Montgomery County, Maryland).

FIGURE 3.12 - 2
Flow Splitting Manhole Structure



Sizing Procedure

The majority of jurisdictions which are employing sand filter BMPs use hydraulic calculations based on Darcy's Law to establish the filter area that will allow flow-through of the treatment volume within the desired time frame, typically 40-48 hours (Austin, 1988, Shaver and Baldwin, 1991, Truong, 1989). Florida uses more complex falling-head computations and allows a drawdown time of up to 72 hours (Livingston, McCarron, Cox, and Sanzone, 1988). However, creating storage for the full WQV in shallow configuration systems may result in a larger filter than the hydraulic calculations would indicate (Alexandria, 1992).

Virginia uses the Austin Sand Filter Formula derived from Darcy's Law by the Austin Environmental and Conservation Services Department to size sand filters (Austin, 1988):

$A_f = I_a H d_f / k(h+d_f)t_f$ where,

A_f = surface area of sand bed (acres or sq. ft.)
I_a = impervious drainage area contributing runoff to the basin (acres or sq. ft.)
H = runoff depth to be treated (ft.)
d_f = sand bed depth (ft.)
k = coefficient of permeability for sand filter (ft/hr)

h = average depth (ft.) of water above surface of sand media between full and empty basin conditions (½ max. depth)
t_f = time required for runoff volume to pass through filter media (hrs.)

1. Coefficient of Permeability

When first installed, the coefficient of permeability of sand filters may be as high as 3.0 ft/hour, but these will typically decrease dramatically after the first few storms. Actual observations of filters in Austin, Texas, established that "ripe" filters stabilized in the range of 0.5-2.7 ft/day for filters with partial sedimentation control (Austin, 1988). This is probably caused by a combination of clogging of some filter pores from sediment loads and initial consolidation of the filter sand. **Figure 3.12 - 3** illustrates the similar rapid decrease in coefficient of permeability as sediment loads accumulated on a sand filter in Denver, Colorado (Urbonas, Doerfer, and Tucker, 1996). Falling head tests on a one year old Delaware Sand Filter in Alexandria, Virginia, resulted in an average coefficient of permeability of 8.5 ft/day (Bell, Stokes, Gavan, and Nguyen, 1995). The Alexandria filter was treating only runoff from pavement surfaces, and the mean input concentration of total suspended solids was only in the range of 75 milligrams/liter (75ppm)(*ibid)*. The Denver runoff, by contrast, had a mean concentration of 400 ppm (Urbonas, Doerfer, and Tucker, 1996), while the filters observed by Austin lacked full sedimentation protection. Use of conservative values for the coefficient of permeability is clearly indicated.

Based on long term observation of existing sand filter basins, Austin uses k values of 3.5 feet per day for systems with full sedimentation pretreatment and 2.0 feet per day for systems with only partial sedimentation pretreatment (full sedimentation pretreatment is defined as complete removal of particles with a diameter equal to or greater than 20 microns). Virginia jurisdictions utilizing intermittent sand filter BMPs have also adopted these values. Full sedimentation may usually be accomplished by capturing the WQV and releasing it to the filter over 24 hours. **Figure 3.12-4** illistrates a full sedimentation basin in Austin. Partial sedmientation basins, such as the one shown on **Figure 3.12-1**, should hold at least 20 percent of the WQV.

2. Drawdown time

Both Austin and the Virginia jurisdictions employ a BMP drawdown time (t_f) of 40 hours. This allows the filter to fully drain down and dry out to maintain an aerobic environment between storms (filters which remain continually wet may develop anaerobic conditions, under which previously captured iron phosphates may break down and wash out).

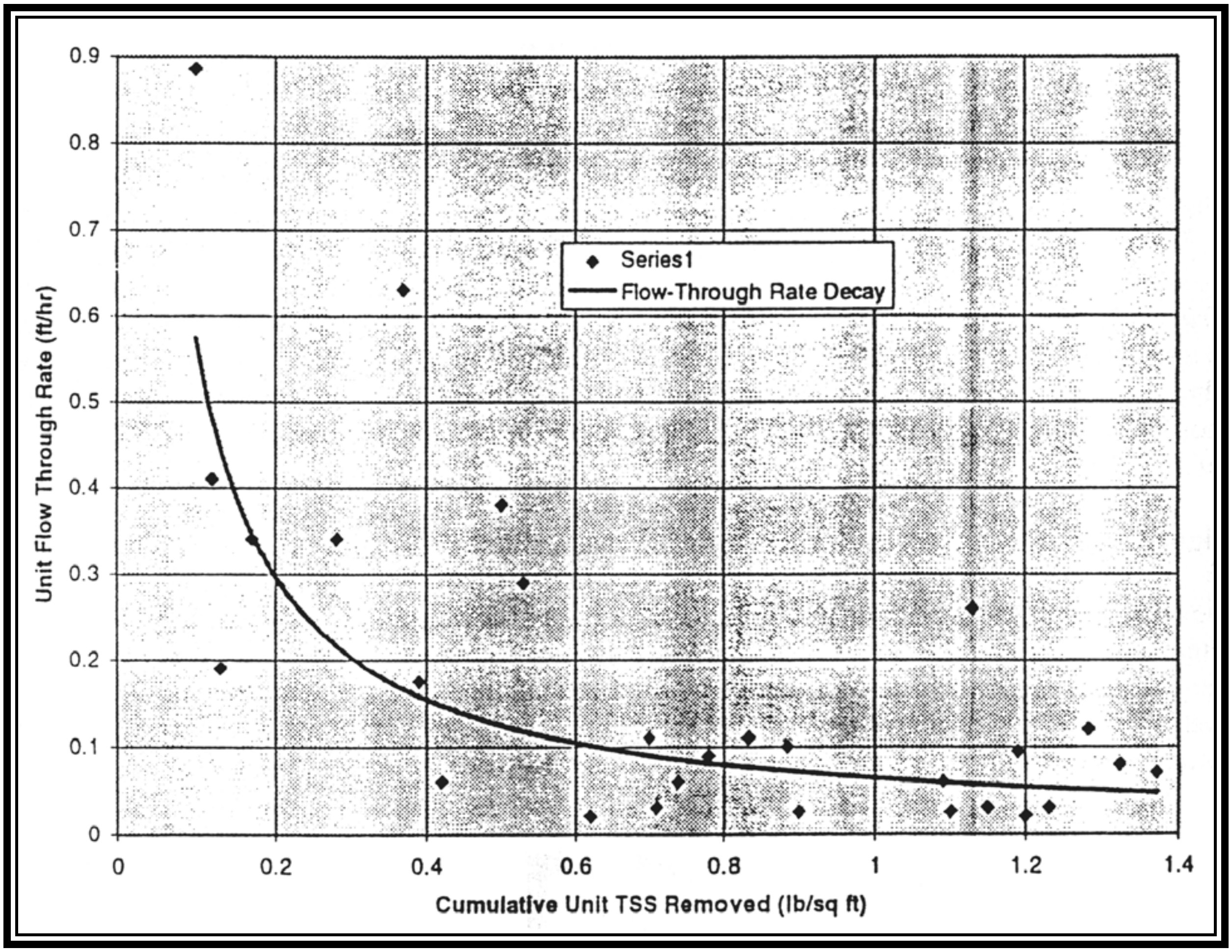
3. Simplified Filter Formula for Filters with Full Sedimentation Protection
(Sedimentation Basin containing full WQV with 24-hour drawdown to filter)

With k = 3.5 ft/day (0.146 ft/hour) and t_f = 40 hours, the sand filter formula reduces to:

$$A_{f(FS)} = 310 I_a d_f / (h + d_f)$$

where A_f is in ft^2 and I_a is in acres.

FIGURE 3.12-3
Degradation of Hydraulic Conductivity of Denver Sand Filter



(Source: Urbonas, Doeffler, and Tucker, 1996)

4. Simplified Filter Formula for Filters with Partial Sedimentation Protection
(Sediment Chamber containing 20% of WQV with free hydraulic flow to filter)

With k = 2.0 ft/day (.0833 ft/hour) and t_f = 40 hours, the formula reduces to:

$$A_{f(PS)} = 545 I_a d_f / (h + d_f)$$

where A_f is in ft^2 and I_a is in acres.

FIGURE 3.12-4

Full Sedimentation Basin on Austin Sand Filter

Exclusion of Continuous Flows and Chloronated Flows

Intermittent sand filter BMPs will **NOT** function properly if subjected to continuous or frequent flows. The basic principles upon which they operate assume that the sand filter will dry out and reaerate between storms. If the sand is kept continually wet by such flows as basement sump pumps, anaerobic conditions will develop, creating a situation under which previously captured iron phosphates degrade, leading to **export** of phosphates rather than the intended high phosphorous removal (Bell, Stokes, Gavan, and Nguyen, 1995). It is also essential to **exclude flows containing chlorine and other swimming pool and sauna chemicals** since these will kill the bacteria upon which the principle nitrogen removal mechanisms depend.

Continuous or frequent flows (such as basement sump pump discharges, cooling water,condensate water, ariesian wells, etc.) and flows containing swimming pool and sauna chemiclals *must be* ***EXCLUDED*** *from routing through intermittent sand filter BMPs since such flows will cause the BMP to* ***MALFUNCTION!***

Checklists

The **Construction Inspection and As-Built Survey Checklist** found in **Appendix 3D** is for use in inspecting intermittent sand filter facilities during construction and, where required by the local jurisdiction, engineering certification of the filter construction. The **Operation and Maintenance Checklist**, also found in **Appendix 3D**, is for use in conducting maintenance inspections of intermittent sand filter facilities.

MINIMUM STANDARD 3.12A

WASHINGTON D.C. UNDERGROUND VAULT SAND FILTER
(WET SEDIMENTATION CHAMBER)

Definition

A Washington D.C. vault sand filter is an underground stormwater sand filter contained in a structural shell with three chambers. The shell may be either precast or cast-in-place concrete, corrugated metal pipe, or fiberglass tanks. This BMP was developed by Mr. Hung V. Truong of the D.C. Environmental Regulation Administration. **Figure 3.12A-1** depicts Mr. Truong's system.

The three feet deep plunge pool in the first chamber and the throat of the second chamber, which are hydraulically connected by an underwater rectangular opening, absorbs energy and provides pretreatment, trapping grit and floating organic material such as oil, grease, and tree leaves.

The second chamber also contains a typical intermittent sand filter. The filter material consists of gravel, sand, and filter fabric. At the bottom is a subsurface drainage system of pierced PVC pipe in a gravel bed. The primary filter media is 18-24 inches of sand. A layer of plastic reinforced geotextile filter cloth secured by gravel ballast is placed on top of the sand. The top filter cloth is a pre-planned failure plane which can readily be replaced when the filter surface becomes clogged. A dewatering drain controlled by a gate valve must be installed to facilitate maintenance.

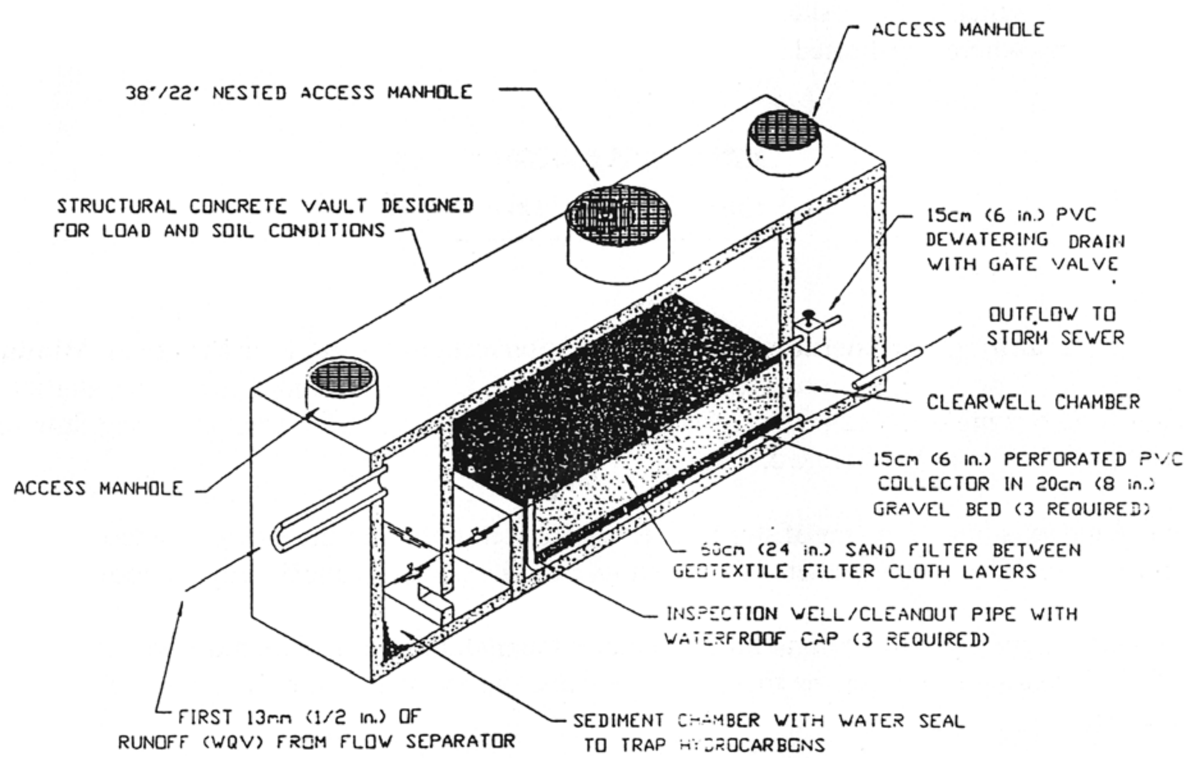
The third chamber, or clearwell, collects the flow from the underdrain pipes and directs it to the storm sewer.

In Virginia, D.C. Sand Filters will normally be placed off-line and be sized to treat the WQV.

Purpose

D.C. Sand Filters are primarily used for water quality control. However, they do provide detention and slow release of the water quality volume from the site being treated. Whether this amount will be sufficient to provide the necessary peak flow rate reductions required for channel erosion control is dependent upon site conditions (hydrology) and required discharge reductions. The 10-year and 100-year flows will usually exceed the detention capacity of a sand media filter. When this occurs, separate quantity must be provided.

FIGURE 3.12A - 1
Washington D.C. Underground Vault Sand Filter



Conditions Where Practice Applies

D.C. Sand Filters are ultra-urban BMPs best suited for use in situations where space is too constrained and/or real estate values are too high to allow the use of conventional retention ponds. Where possible, runoff treated should come only from impervious surfaces.

Drainage Area

Drainage areas served by one vault filter should be limited to 1.25 acres. For larger drainage sheds, either multiple vault filters or Austin Full Sedimentation Filters (surface or vault) should be utilized.

Development Conditions

D.C. Sand Filters are generally suitable BMPs for medium to high density commercial or industrial development. Because of confined space entry restrictions and maintenance requirements, they are not generally suitable for residential applications except for apartment complexes or large condominiums where a dedicated maintenance force will be present.

Planning Considerations

Refer to the **Planning Considerations** for **General Intermittent Sand Filter Practices, Minimum Standard 3.12,** previously discussed in this section. Of special concern are the stormwater infrastructure serving the site and the requirement to isolate the sand filter from receiving flows until the drainage shed is fully stabilized.

Potential and existing elevations of stormwater infrastructure serving the site will determine one of the most critical design parameters: the maximum depth to which runoff may be pooled over the filter and preserve a gravity flow configuration (whatever the pooling depth, there must be a minimum of five feet of clearance between the top of the filter and the top slab of the filter shell to allow filter maintenance).

*Sand filter BMPS must **never** be placed in service until all site work has been completed and stabilization measures have been installed and are functioning properly.*

Design Criteria

The purpose of this section is to provide recommendations and minimum criteria for the design of D.C. Sand Filter BMPs intended to comply with the Virginia Stormwater Management program's runoff quality requirements.

Refer to the **General Design Criteria** previously discussed under **General Intermittent Sand Filter Practices, Minimum Standard 3.12**

Filter Sizing Criteria

The D.C. Sand Filter is a partial sedimentation protection intermittent sand filter BMP. To compute the minimum area of filter required, utilize the Austin Filter Formula for partial sedimentation treatment:

$$A_{fm(PS)} = \frac{545 I_a d_f}{(h + d_f)}$$

where,

A_{fm} = minimum surface area of sand bed (square feet)
I_a = impervious cover on the watershed in acres
d_f = sand bed depth (normally 1.5 to 2ft)
h = average depth of water above surface of sand media between full and empty basin conditions (ft.)

Structural Requirements

The load-carrying capacity of the filter structure must be considered when it is located under parking lots, driveways, roadways, and, certain sidewalks (such as those adjacent to State highways). Traffic intensity may also be a factor. The structure must be designed by a licensed structural engineer and the structural plans require approval by the plan approving jurisdiction.

Design Storm

The inlet design or integral large storm bypass must be adequate for isolating the WQV from the design storm for the receiving storm sewer system (usually the 10 year storm) and for conveying the peak flow of that storm past the filter system. Since D.C. Sand Filters will be used only as off-line facilities in Virginia, the interior hydraulics of the filter are not as critical as when used as an on-line facility. The system should draw down in approximately 40 hours.

Infrastructure Elevations

For cost considerations, it is preferable that D.C. Sand Filters work by gravity flow. This requires sufficient vertical clearance between the invert of the prospective inflow storm piping and the invert of the storm sewer which will receive the outflow. In cases where gravity flow is not possible, a clearwell sump and pump are required to discharge the effluent into storm sewer. Such an application would be appropriate in commercial or industrial situations where a dedicated maintenance force will be available (shopping malls, apartment houses, factories of other industrial complexes, etc.).

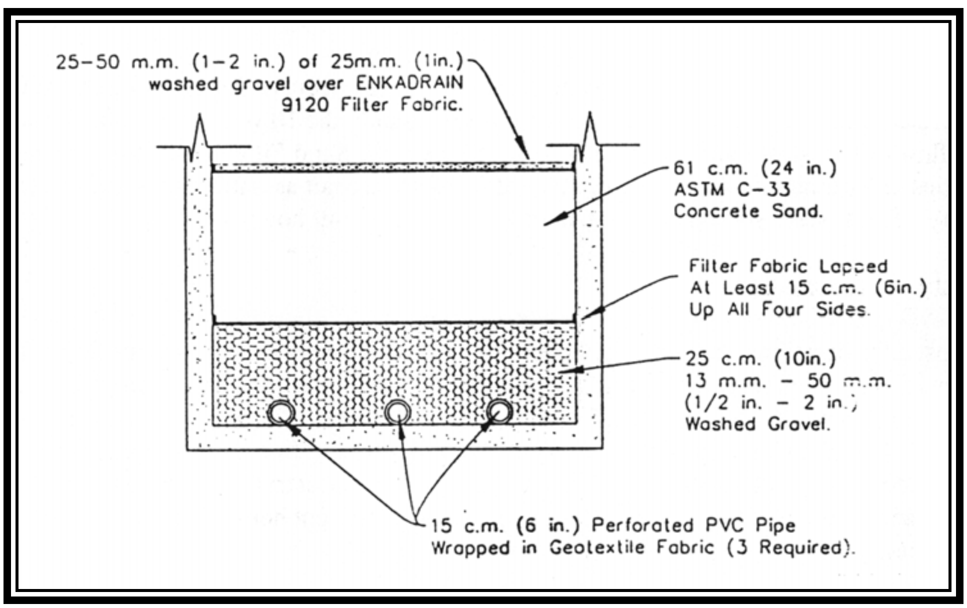
Accessibility and Headroom for Maintenance

Both the sedimentation basin and the filter must be accessible to approriate equipment and vacuum trucks for removing accumulated sediments and trash. The sedimentation basin must be cleaned approximately once per year, and the filter will likely need raking on that frequency to remove trash and restore permeability. When filters are placed in underground vaults, all three chambers must have personnel access manholes and built-in access ladders. **A minimum headspace of 60 inches above the filter is required to allow such maintenance and repair.** A 38-inch diameter maintenance manhole with eccentric nested covers (a 22-inch personnel access lid inside the 38-inch diameter lid) or a rectangular load bearing access door (minimum 4 ft. x 4 ft.) should be positioned directly over the center of the filter.

Construction Specifications

Figure 3.12A-2 is a cross-section of the filter chamber.

FIGURE 3.12A - 2
D.C. Sand Filter Cross-Section



Depth of Sedimantation Pool

The sedimentation "plunge pool" must be at least 36 inches deep to properly remove sediment and absorb energy from the incoming flow.

Depth of the Underwater Opening Between Chambers

To preserve an effective hydrocarbon trap, the top of the underwater opening between chambers must be at least 18 inches below the depth of the weir which divides the filter from the pool. To retain sediment in the first chamber, the bottom of the opening should be at least six inches above the floor. The area of the opening should be at least 1.5 times the cross-sectional area of the inflow pipe(s) to assure that the water level remains equal between the first and second chambers.

Total Depth of Filter Cross-Section

The total depth of the filter cross-section must match the height of the weir dividing the sedimentation pool from the filter. Otherwise, a "waterfall" effect will develop which will gouge out the front of the filter media. If a sand filter less than 24 inches is used, the gravel layer must be increased accordingly to preserve the overall filter depth.

Upper Aggregate Layer

The washed aggregate or gravel layer at the top of the filter shall be at least one inch thick and meet ASTM standard specifications (1-inch maximum diameter).

Geotextile Fabrics

The filter cloth layer beneath the upper aggregate layer shall be reinforced by an HDPE or PVC geomatrix (such as ENKADRAIN 9120) and meet the specifications shown in **Table 3.12C-1**. The filter fabric between the sand layer and the collector gravel shall conform to the specifications in **Table 3.12A-2**. The fabric rolls must be cut with sufficient dimensions to cover the entire wetted perimeter of the filtering area and lap up the filter walls at least six-inches.

Sand Filter Layer

For applications in Virginia, use **ASTM C33 Concrete Sand** or sand meeting the Grade A fine aggregate gradation standards of Section 202 of the VDOT ***Road and Bridge Specifications.*** The top of the sand filter must be completely level.

TABLE 3.12A - 1
Specifications for Nonwoven Geotextile Fabric on Top of D.C. Sand Filter

Property	Test Method	Unit	Specification
Unit Weight	ASTM D-1777	Oz./Sq.yd.	4.3 (minimum)
Flow Rate	Falling Head Test	Gpm/Sq.ft.	120 (minimum)
Puncture Strength	ASTM D-751 (Modified)	Lb.	60 (minimum)
Thickness	--	In.	0.08 (minimum)

Table 3.12A - 2
Specifications for Nonwoven Geotextile Fabric Beneath Sand in D.C. Filter

Property	Test Method	Unit	Specification
Unit Weight	--	Oz./sq.yd.	8.0 (min.)
Filtration Rate	--	In/sec	0.08 (min.)
Puncture Strength	ASTM D-751 (Modified)	Lb.	125 (min.)
Mullen Burst Strength	ASTM D-751	Psi	400 (min.)
Equiv. Opening Size	U.S. Standard Sieve	No.	80 (min.)
Tensile Strength	ASTM D-1682	Lb.	300 (min.)

Gravel Bed Around Collector Pipes

The gravel layer surrounding the collector pipes shall be ½ to two (2) inch diameter gravel and provide at least two (2) inches of cover over the tops of the drainage pipes.

Underdrain Piping

The underdrain piping consists of three 6-inch schedule 40 or better polyvinyl perforated pipes reinforced to withstand the weight of the overburden. Perforations should be 3/8 inch, and each row of perforations shall contain at least six (6) holes. Maximum spacing between rows of perforations shall be six (6) inches.

The minimum grade of piping shall be 1/8 inch per foot (one [1] percent slope). Access for cleaning all underdrain piping is needed. Clean-outs for each pipe shall extend at least six (6) inches above the top of the upper filter surface, e.g. the top layer of gravel.

Each pipe shall be thoroughly wrapped with 8 oz./sq.yd. geotextile fabric meeting the specification in **Table 3.12A-2** above.

Dewatering Drain

When the filter is placed in an underground vault, A 6-inch dewatering drain controlled by a gate valve shall be installed between the filter chamber and the clearwell chamber with its invert at the elevation of the top of the filter. The dewatering drain penetration in the chamber dividing wall shall be sealed with a flexible strip joint sealant which swells in contact with water to form a tight pressure seal.

Access Manholes

When the filter is installed in an underground vault, access to the headbox (sediment chamber) and the clearwell shall be provided through at least 22-inch manholes. Access to the filter chamber shall be provided by a rectangular dood (minimum size: 4 feet by four feet) of sufficient strength to carry prospective imposed loads or by a manhole of at least 3- inch diameter with an offset concentric 22-inch lid (Neenah R-1741-D or equivalent).

Protection from Construction Sediments

The site erosion and sediment control plan must be configured to permit construction of the filter system while maintaining erosion and sediment control.

No runoff is to enter the sand filtration system prior to completion of all construction and site revegitation. Construction runoff shall be treated in separate sedimentation basins and routed to by-pass the filter system. Should construction runoff enter the filter system prior to site revegitation, all contaminated materials must be removed and replaced with new clean materials.

Watertight Integrity Test

After completion of the filter shell but before placement of the filter layers, entrances to the structure shall be plugged and the shell completely filled with water to demonstrate water tightness. Maximum allowable leakage is 5 percent of the filter shell volume in 24 hours. Should the structure fail this test, it shall be made watertight and successfully retested prior to placement of the filter layers.

Hydraulic Compaction of Filter Components

After placement of the collector pipes, gravel, and lower geotextile layer, fill the shell with filter sand to the level of the top of the sediment pool weir. Direct clean water into the sediment chamber until both the sediment chamber and filter chamber are completely full. Allow the water to draw down until flow from the collector pipes ceases, hydraulically compacting the filter sand. After allowing the sand to dry out for a minimum of 48 hours, refill the shell with sand to a level one inch beneath the top of the weir and place the upper geotextile layer and gravel ballast.

Portland Cement Concrete

Concrete liners may be used for sedimentation chambers and for sedimentation and filtration basins. Concrete shall be at least five (5) inch thick Class A3 defined in the Virginia Department of Transportation *Road and Bridge Specifications.*

Maintenance/Inspection Guidelines

The following maintenance and inspection guidelines are not intended to be all inclusive. Specific facilities may require other measures not discussed here.

Inspection Schedule

The water level in the filter chamber shall be monitored by the owner on a quarterly basis and after every large storm for the first year after completion of construction and a log shall be maintained of the results indicating the rate of dewatering after each storm and the water depth for each observation. Once the governing jurisdiction staff indicates that satisfactory performance of the structure has been demonstrated, the monitoring schedule can be reduced to an semiannual basis.

The BMP shall be inspected annually by representatives of the owner and the governing jurisdiction to assure continued proper functioning.

Sediment Chamber Pumpout

The sediment chamber must be pumped out halfway through the inspection cycle (e.g. after six months) and after each joint owner-governing jurisdiction annual inspection. If the chamber contains an oil skim, it should be removed by a firm specializing in oil recovery and recycling. The remaining material may then be removed by vacuum pump and disposed of in an appropriate landfill. **After each cleaning, refill the first chamber to a depth of three feet with clean water to reestablish the water seals**.

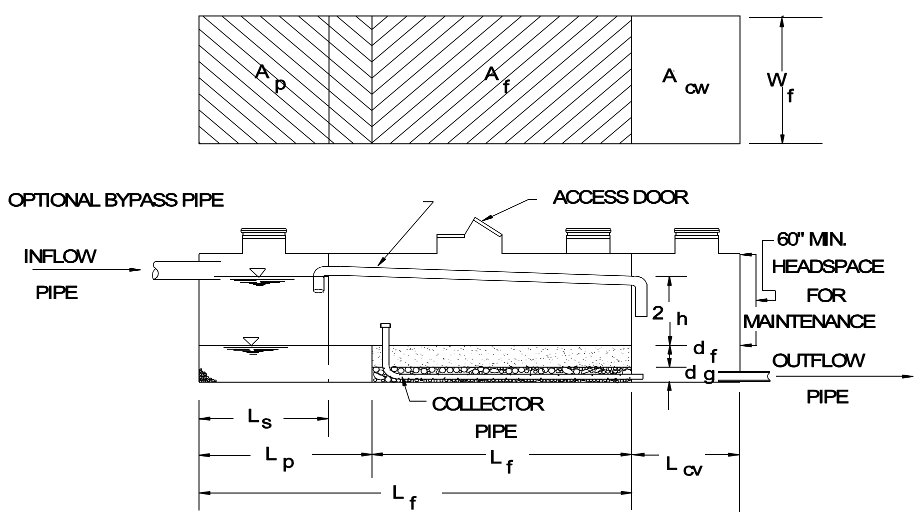
When the filter will no longer draw down within the required 40-hour period, the top layer of filter cloth and ballast gravel must be removed and replaced with new materials conforming to the original specifications. Any discolored or sediment contaminated sand shall also be removed and replaced.

Design Procedures

The following design procedure is structured to assure that the desired water quality volume is captured and treated by the D.C.Sand Filter. The procedure assumes that a filter shell with a rectangular cross-section is to be used.

Figure 3.12A-3 shows the dimensional relationships for a D.C. Sand Filter.

FIGURE 3.12A - 3
Dimensional Relationships for a D.C. Sand Filter



Standard Design Logic

Employ the following design logic to design D.C. Sand Filters for use in Virginia:

1. Determine Governing Site Parameters

Determine the Impervious area on the site (I_a in acres), the water quality volume to be treated (WQV in $ft.^3 = 1816\ I_a$), and the site parameters necessary to establish 2h, the maximum ponding depth over the filter (storm sewer invert at proposed connection point, elevation to inflow invert to BMP, etc).

2. Select Filter Depth and Determine Maximum Ponding Depth

Considering the data from Step 1) above, select the Filter Depth ((d_f) and determine the maximum achievable ponding depth over the filter (2h).

3. Compute the Minimum Area of the Sand Filter (A_{fm})

To compute the area of the filter, use the formula:

$$A_{fmPS} = \frac{545 I_a d_f}{(h + d_f)}$$

A_{fm} = minimum surface area of sand bed (square feet)
I_a = impervious cover on the watershed in acres
d_f = sand bed depth (normally 1.5 to 2ft)
h = average depth of water above surface of sand media between full and empty basin conditions (ft.)

4. Select Filter Width and Compute Filter Length and Adjusted Filter Area

Considering site constraints, select the Filter Width (W_f). Then compute the Filter Length (L_f) and the Adjusted Filter Area (A_f)

$$L_f = A_{fm}/W_f$$

$$A_f = W_f \times L_f$$

Note: From this point forward, computations assume a rectangular filter.

5. Compute the Storage Volume on Top of the Filter (V_{Tf})

$$V_{Tf} = A_f \times 2h$$

6. Compute the Storage in the Filter Voids (V_v)
(Assume 40% voids in filter media)

$$V_v = 0.4 \times A_f \times (d_f + d_g)$$

7. Compute Flow Through Filter During Filling (V_Q)
(Assume 1-hour to fill per D.C. practice)

$$V_Q = \frac{kA_f(d_f + h)}{d_f} \text{ ; use } k = 2 \text{ ft./day} = 0.0833\text{/hr.}$$

8. Compute Net Volume to be Stored Awaiting Filtration (V_{st})

$$V_{st} = WQV - V_{Tf} - V_v - V_Q$$

9. Compute Length of the Permanent Pool (Lpm)

$$Lpm \quad \frac{V_{st}}{(2h \times W_f)}$$

10. Compute Minimum Length of the Sediment Chamber (Lsc)
(to contain 20% of WQV per Austin practice)

$$L_{sm} = \frac{0.2WQV}{(2h \times W_f)}$$

11. Set Final Length of the Permanent Pool (L_p)

If $L_{pm} \geq L_{sm} + 2$ ft., make $L_p = L_{pm}$

If $L_{pm} < L_{sm} + 2$ ft., make $L_p = L_{sm + 2 \text{ ft.}}$

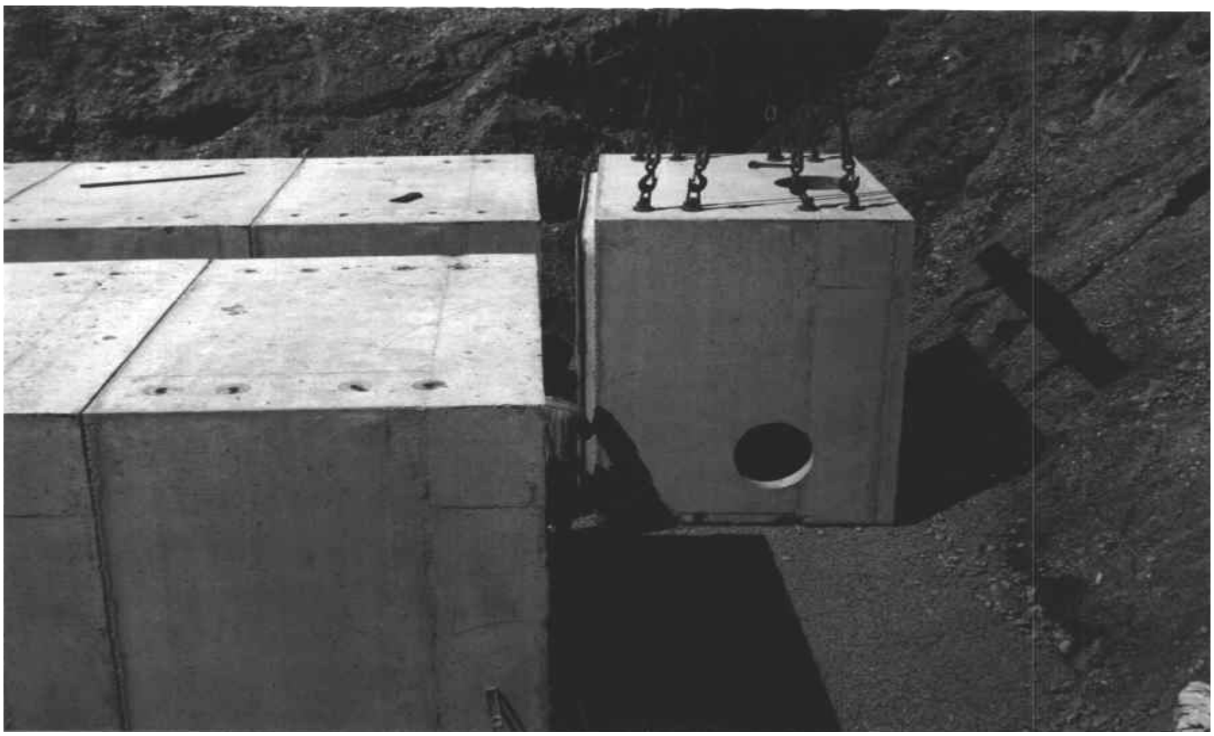
It may be economical to adjust final dimensions to correspond with standard precast structures or to round off to simplify measurements during construction.

Set the length of the clearwell (L_{cw}) for adequate maintenance and/or access for monitoring flow rate and chemical composition of the effluent (minimum = 3 ft.)

Minimizing Filter Shell Costs

Underground vault sand filter costs have been widely varying because many developers have simply had their foundation contractors cast the vault in place. Each installation therefore became a prototype with associated costs and overhead. Precast manufacturers currently offer precasting services for D.C. and other types of sand filter vaults, which should stabilize underground vault costs. **Figure 3.12A-4** is a photograph of a segmented precast filter shell installation in Alexandria.

FIGURE 3.12A - 4
Installing Precast D.C. Sand Filter Shell in Alexandria

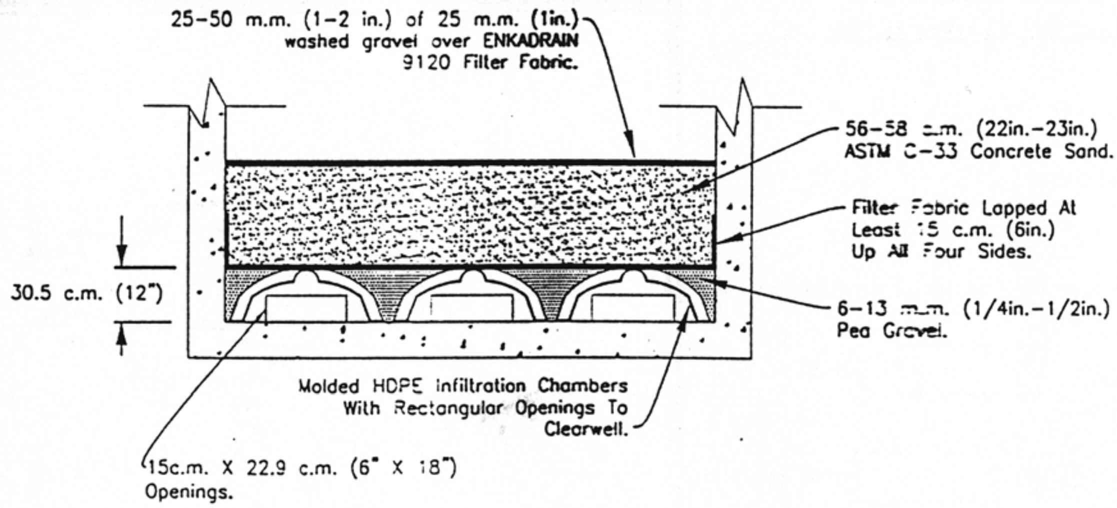


(Photo Courtesy of Rotondo Precast, Fredericksburg, Virginia)

Checklists

Worksheet 3.12A is for use in sizing calculations for D.C. Sand Filters. The **Construction Inspection and As-Built Survey Checklist** found in **Appendix 3D** is for use in inspecting intermittent sand filter facilities during construction and, where required by the local jurisdiction, engineering certification of the filter construction. The **Operation and Maintenance Checklist**, also found in **Appendix 3D**, is for use in conducting maintenance inspections of intermittent sand filter facilities.

FIGURE 3.12A - 5
D.C. Filter Cross-Section with HDPE Infiltration Chamber Collector System

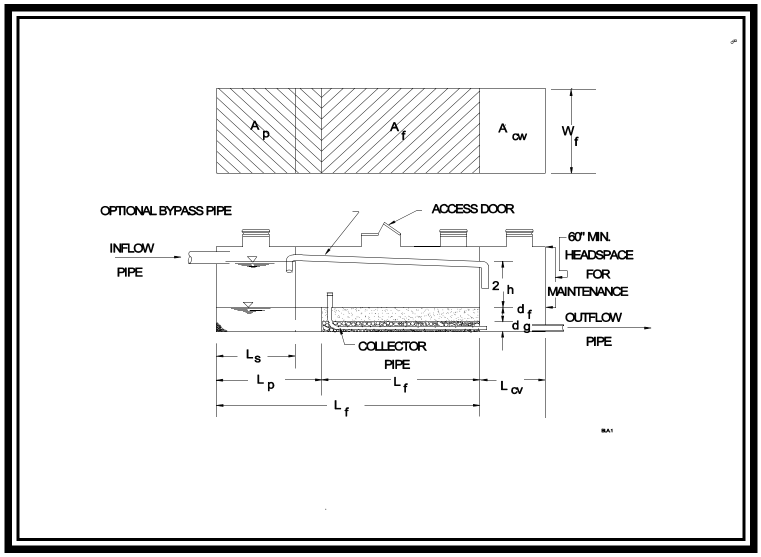


WORKSHEET 3.12A
SIZING COMPUTATIONS FOR D.C. UNDERGROUND VAULT SAND FILTER
Page 1 of 4

Part 1: Select maximum ponding depth over filter:

2h = _______ ft;

h = [ ] ft



From Pollutant Load Sheets:

I_a = [ ] acres

WQV = [ ] ft^3

Outflow by gravity possible __

Effluent pump required __

Part 2: Compute Minimum Area of Filter (A_{fm}):

$$A_{fm} = \frac{545 I_a d_f}{(d_f + h)}$$

= [545 x _______ x _______] / [_______ + _______]

= [ ] ft^2

Part3: Considering Site Constraints, Select Filter Width (W_f) and Compute Filter Length (L_f) and Adjusted Filter Area (A_f):

W_f = [ ] ft;

WORKSHEET 3.12A
SIZING COMPUTATIONS FOR D.C. UNDERGROUND VAULT SAND FILTER
Page 2 of 4

$L_f = A_{fm} / W_f$

= ________/________

= ______, say [ ] ft

$A_f = W_f \times L_f$ = _________ x __________

= [ ] ft^2

Part 4: Compute the Storage Volume on Top of the Filter(V_{Tf})

$V_{Tf} = A_f \times 2h$ = _________x __________

= [ ] ft^3

Part 5: Compute Storage in Filter Voids (V_v):
(Assume 40% voids in filter media)

$V_v = 0.4 \times A_f \times (d_f + d_g)$

= 0.4 x ________ x (________ + _________)

= [ ] ft^3

Part 6: Compute Flow Through Filter During Filling Period (V_Q):
(Assume 1-hour to fill per D.C. practice)

$V_Q = \frac{kA_f(d_f + h)}{d_f}$; use k = 2 ft/day = 0.0833 ft/hr

= [0.0833 x ________ x (_________ + ________)]/__________

= [ ] ft^3

WORKSHEET 3.12A
SIZING COMPUTATIONS FOR D.C. UNDERGROUND VAULT SAND FILTER
Page 3 of 4

Part 7: Compute Net Volume to be Stored Awaiting Filtration (V_{st}):

V_{st} = WQV - V_{Tf} - V_v - V_Q

= _______ - _______ - _______ - _______

= [ ] ft^3

Part 8: Compute Minimum Length of Permanent Pool (L_{pm}):

$L_{pm} = \frac{V_{st}}{(2h \times W_f)}$ = _______ / (_______ x _______)

= [ ] ft

Part 9: Compute Minimum Length of Sediment Chamber (L_{sm})
(to contain at least 20% of WQV per Austin practice)

$L_{sm} = \frac{0.2WQV}{(2h \times W_f)}$ = _______ /_______

= [ ] ft

Part 10: Set Final Length of Permanent Pool (L_p)

L_{sm} + 2ft = ________ + 2 = [ ] ft

If $L_{pm} \geq L_{sm}$ + 2ft, Make $L_p = L_{pm}$ [ ] = ft

If $L_{pm} < L_{sm}$ + 2ft, make $L_p = L_{sm}$ +2ft = [ ]

WORKSHEET 3.12A
SIZING COMPUTATIONS FOR D.C. UNDERGROUND VAULT SAND FILTER
Page 4 of 4

Part 11: Set Length of Clearwell (L_{cw}) for Adequate Maintenance Access (Minimum = 3 ft) and Compute Final Inside Length (L_{ti}):

L_{cw} = [ ] ft;

Sum of interior partition thicknesses (t_{pi}) = _________ ft

$L_{ti} = L_f + L_p + L_{cw} + t_{pi}$

= ________ + ________ + ________ + ________

= [ ] ft

Part 12: Design Effluent Pump if Required

Since pump must be capable of handling flow when filter is new, use k = 12 feet/day = 0.5 ft/hr

$$Q = \frac{kA_f(d_f + h)}{d_f}$$

= [0.5 x ________ x (________ + ________)] /________

= [ ] ft^3/hr ; /3600 = [ ] cfs;

x 448 = [ ] gpm

Part 13: Design Structural Shell to Accommodate Soil and Load conditions at Site:

It may be economical to adjust final dimensions upward to correspond with standard precast structures or to round dimensions upward to simplify layout during construction.

MINIMUM STANDARD 3.12B

DELAWARE SAND FILTER (DSF) SYSTEMS

Definition

Mr. Earl Shaver of the Delaware Department of Natural Resources and Environmental Control has developed a surface sand filter system for use in Delaware (Shaver and Baldwin, 1991)

As originally conceived, the Delaware Sand Filter is an **on-line** facility processing all stormwater exiting the treated site up to the point that its overflow limit is reached (Delaware provides for treating the first one inch of runoff). However, when employed in Virginia, it will usually be provided with an integral flow-splitter to isolate and treat the Water Quality Volume.

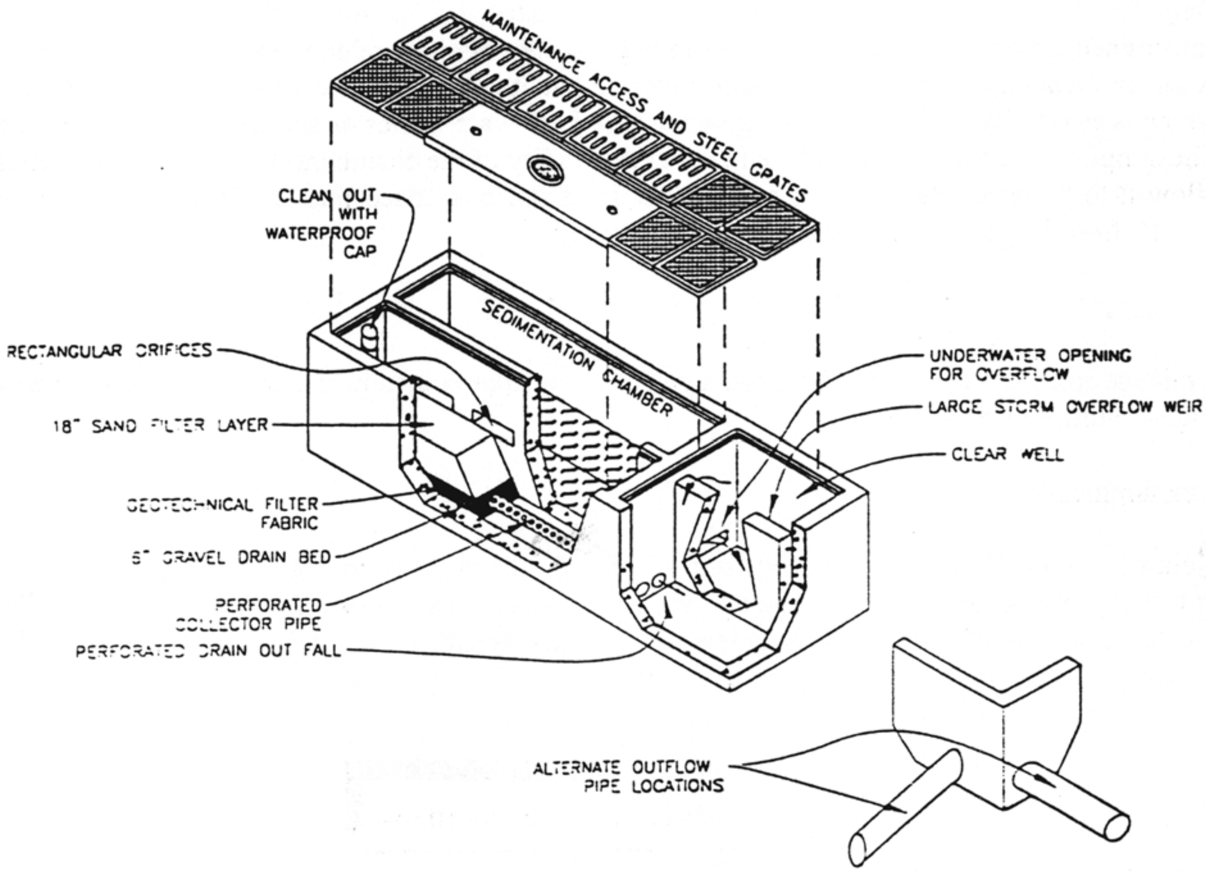
Figure 3.12B-1 shows a schematic drawing of the Delaware Sand Filter as used in Virginia. The system consists of two parallel concrete trenches connected by close-spaced wide notches in the wall dividing the trenches. The trench adjacent to the site being served is the sedimentation chamber. When accepting sheet flow, it is fitted with a grated cover. Concentrated stormwater may also be conveyed to the chamber in enclosed storm drain pipes. The second chamber, which contains the sand filter, is always fitted with a solid cover.

Storm flows enter the sedimentation chamber through the grates, causing the sedimentation pool to rise and overflow into the filter chamber through the weir notches in the dividing wall, assuring that the water to be treated **arrives at the filter as sheet flow**. This is essential to prevent scouring out the sand. The permanent pool in the sedimentation chamber is dead storage, which inhibits resuspension of particles that were deposited in earlier storms and prevents the heavier sediments from being washed into the filter chamber. Floatable materials and hydrocarbon films, however, may reach the filter media through the surface outflow.

The second trench contains at least 18 inches of ASTM C-33 Concrete Sand . When used in Virginia, an underdrain capability must be provided. Runoff percolates through the sand to the underdrain (s) and exits into the flow splitter/clearwell.

A transverse flow-splitter/clearwell at the lower end of the structure collects treated effluent and overflow and conveys the water to the storm sewer. When the filter shell fills with the Water Quality Volume, excess flow is forced through the underwater opening from the sedimentation chamber to the “wet” section of the clearwell to overflow the weir to the outflow pipe chamber. Floating trash and hydrocarbons are retained in the sedimentation chamber by this “trap.”

FIGURE 3.12B - 1
Precast Delaware Sand Filter as Used in Virginia



Purpose

Delaware Sand Filters primarily used for water quality control. However, they do provide detention and slow release of the water quality volume from the site being treated. Whether this amount will be sufficient to provide the necessary peak flow rate reductions required for channel erosion control is dependent upon site conditions (hydrology) and required discharge reductions. The 10-year and 100-year flows will usually exceed the detention capacity of a sand media filter. When this occurs, separate quantity must be provided.

Conditions Where Practice Applies

Delaware Sand Filters are ultra-urban BMPs best suited for use in situations where space is too constrained and/or real estate values are too high to allow the use of conventional retention ponds. A major advantage of the Delaware Sand Filter is that it can be installed in shallow configurations, which is especially critical in flatter regions where high water tables or shallow storm sewers exist. The simplicity of the system and the ready accessibility of the chambers for periodic maintenance allow it to be used where a filter built in confined space is unacceptable. Where possible, only runoff from impervious surfaces should be treated.

Drainage Area

Drainage areas served by one filter should be limited to approximately one acre. For larger drainage sheds, multiple DSFs may be used.

Development Conditions

Delaware Sand Filters are generally suitable BMPs for medium to high density commercial or industrial development. Because of confined space entry restrictions and maintenance requirements, they are not generally suitable for residential applications except for apartment complexes or large condominiums where a dedicated maintenance force will be present.

Planning Considerations

Refer to the **Planning Considerations** for **General Intermittent Sand Filter Practices, Minimum Standard 3.12,** previously discussed in this section. Of special concern are the stormwater infrastructure serving the site and the requirement to isolate the sand filter from receiving flows until the drainage shed is fully stabilized.

Potential and existing elevations of stormwater infrastructure serving the site will determine one of the most critical design parameters: the maximum depth to which runoff may be pooled over the filter and preserve a gravity flow configuration.

Sand filter BMPS must ***never*** *be placed in service until all site work has been completed and stabilization measures have been installed and are functioning properly.*

Design Criteria

The purpose of this section is to provide recommendations and minimum criteria for the design of Delaware Sand Filter BMPs intended to comply with the Virginia Stormwater Management program's runoff quality requirements.

Refer to the **General Design Criteria** previously discussed under **General Intermittent Sand Filter Practices, Minimum Standard 3.12**

Filter Sizing Criteria

Because of the shallow configuration of this BMP, resulting in low levels of hydraulic head above the filter, application of the usual partial sedimentation filter formula may not create enough storage volume to contain the WQV. With the dimensional relationships shown in **Figure 3.12B-2** and k = 2.0 ft/day, the required DSF filter area to contain the WQV may be written as follows:

$$A_f = \frac{1816 I_a}{(4.1h + 0.9)} = \frac{WQV}{(4.1h + 0.9)}$$

where:

A_f = the **area of the filter** in sq.ft.
I_a = the impervious area on the watershed in acres
h = 1/2 the maximum ponding depth over the filter (ft.)

If the maximum ponding depth above the filter (2h) is less than 2.67 feet (2'-8"), the WQV storage requirement governs and the above foumula must be used to size the filter (Alexandria, 1992). If the the maximum ponding depth above the filter (2h) is 2.67 feet or greater, use the partial sedimentation filter formula:

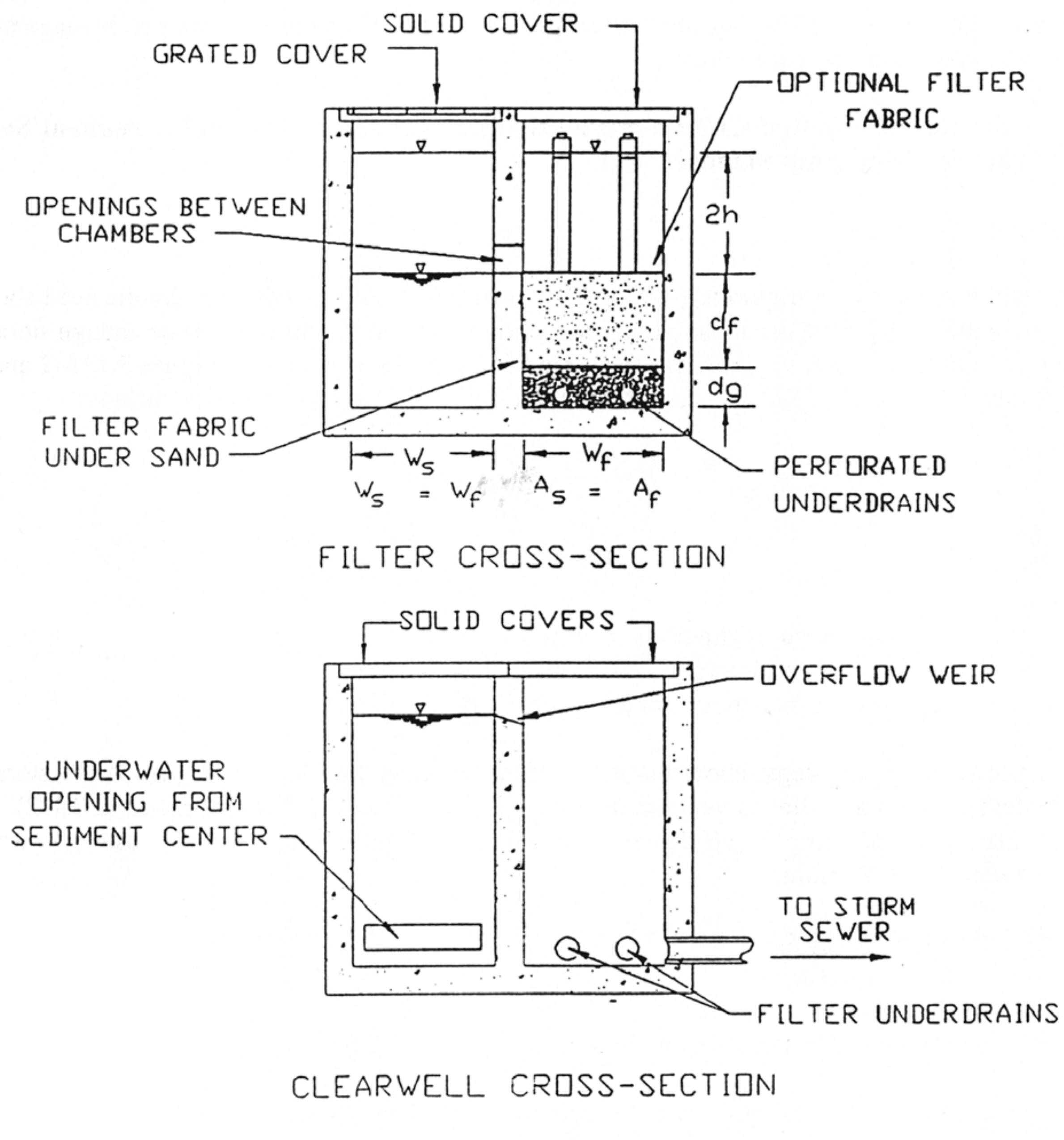
$$A_f = \frac{545 I_a d_f}{(h + d_f)}$$

Where d_f = depth of the filter media in ft. (1.5-2.0)

Delaware and Virginia make the area of the sediment chamber(A_s) equal the area of the filter:

$$A_f = A_s$$

FIGURE 3.12B- 2
Dimensional Relationships for Delaware Sand Filter



Structural Requirements

When the system is placed in a street or parking lot, it must be designed to support traffic wheel loads. When placed completely off the pavement, lower structural loads will be involved. The structure must be designed by a licensed professional engineer, and the design must be approved by the governing jurisdiction.

Design Storm

The inlet integral large storm bypass must be adequate for isolating the WQV from the design storm for the receiving storm sewer system (usually the 10 year storm) and for conveying the peak flow of that storm past the filter system. The system should draw down in approximately 40 hours.

Infrastructure Elevations

For cost considerations, it is preferable that Delaware Sand Filters work by gravity flow. This requires sufficient vertical clearance between the invert of the prospective inflow storm piping and the invert of the storm sewer which will receive the outflow. In cases where gravity flow is not possible, a clearwell sump and pump are required to discharge the effluent into storm sewer. Such an application would be appropriate in commercial or industrial situations where a dedicated maintenance force will be available (shopping malls, apartment houses, factories of other industrial complexes, etc.).

Construction Specifications

Upper Aggregate Layer

Some jurisdictions require a layer of filter cloth and gravel on top of the filter. When used, the washed aggregate or gravel layer at the top of the filter shall be one inch thick and meet ASTM standard specifications (1 inch maximum diameter.)

Geotextile Fabrics

When used, the filter fabric beneath the one-inch layer of gravel on top of the filter shall be Enkadrain 9120 filter fabric or equivalent with the specifications shown in **Table 3.12B - 1**.

Table 3.12B - 1
Specifications for Nonwoven Geotextile Fabric on Top of Delaware Sand Filter

Property	Test Method	Unit	Specification
Unit Weight	ASTM D-1777	Oz./sq.yd.	4.3 (min.)
Flow Rate	Falling Head Test	Gpm/sq.ft.	120 (min.)
Puncture Strength	ASTM D-751 (Modified)	Lb.	60 (min.)
Thickness	--	In.	0.8 (min.)

In instances where heavy hydrocarbon loadings are expected, a layer of activated carbon impregnated filter fabric such as Enkadrain PF-3 may be advantageous. When used, a plan to dispose of the hydrocarbon laden used filter fabric must be approved by the applicable jurisdiction prior to placing the sand filter in service.

The filter cloth layer beneath the sand shall conform to the specifications shown in **Table 3.12B-2**.

Table 3.12B - 2
Specifications for Nonwoven Geotextile Fabric Beneath Sand in Delaware Sand Filter

Property	Test Method	Unit	Specification
Unit Weight	--	Oz./sq.yd.	8.0 (min.)
Filtration Rate	--	In/sec	0.08 (min.)
Puncture Strength	ASTM D-751 (Modified)	Lb.	125 (min.)
Mullen Burst Strength	ASTM D-751	Psi	400 (min.)
Equiv. Opening Size	U.S. Standard Sieve	No.	80 (min.)
Tensile Strength	ASTM D-1682	Lb.	300 (min.)

The fabric rolls must be cut with sufficient dimensions to cover the entire wetted perimeter of the filtering area and lap up the filter walls at least six-inches.

Sand Filter Layer

For applications in Virginia, use **ASTM C33 Concrete Sand.** The top of the sand filter must be completely level. No grade is allowable.

Gravel Bed Around Collector Pipes

The gravel layer surrounding the collector pipes shall be ½ to two (2) inch diameter gravel and provide at least two (2) inches of cover over the tops of the drainage pipes. The gravel and the sand layer above must be separated by a layer of geotextile fabric meeting the specification listed above.

Underdrain Piping

When round perforated pipes are used, the underdrain piping shall consist of a minimum of two (2) schedule 40 or better four (4) inch polyvinyl perforated pipes reinforced to withstand the weight of the overburden. Perforations shall be 3/8 inch, and each row of perforations shall contain at least four (4) holes. Maximum spacing between rows of perforations shall be six (6) inches.

The minimum grade of piping shall be 1/8 inch per foot (one [1] percent slope). Access for cleaning all underdrain piping is needed. Clean-outs for each pipe shall extend at least six (6) inches above the top of the upper filter surface.

Each pipe shall be thoroughly wrapped with 8 oz./sq.yd. geotextile fabric meeting the specification in **Table 3.12B - 2** above.

Alternative Underdrains

Shallow rectangular drain tiles may be fabricated from such materials as fiberglass structural channels, saving several inches of filter depth. Drain tiles shall normally be in two-foot lengths and spaced to provide gaps 1/8-inch less than the smallest gravel sizes on all four sides. Sections of tile may be cast in the dividing wall between the filter and the clearwell to provide shallow outflow oricices. Flat perforated drainage piping such as AdvantEdge® may also be used to reduce the depth of filter. Another approach is to raise a grate on small masonary units above the floor of the shell, lay a layer of PVC or polyethelene geomatrix on the grate to spread the load, and install the filter cloth and sand above this matting; molded HDPE infiltration chambers may also be used as shown in **Figure 3.12A-5.** The entire bottom of the filter shell thus becomes a collector channel. When the shell bottom is so used, it shall have a minimum slope of 1/8 inch per foot (1%).

Weepholes

In addition to the underdrain pipes, weepholes may be installed between the filter chamber and the clearwell to provide relief in case of pipe clogging. The weepholes shall be three (3) inches in diameter. Minimum spacing shall be nine (9) inches center to center. The openings on the filter side of the dividing wall shall be covered to the width of the trench with 12 inch high plastic hardware cloth of 1/4 inch mesh or galvanized steel wire, minimum wire diameter 0.03-inch, number 4 mesh hardware cloth anchored firmly to the dividing wall structure and folded a minimum of 6 inches back under the bottom stone.

Protection from Construction Sediments

The site erosion and sediment control plan must be configured to permit construction of the filter system while maintaining erosion and sediment control.

No runoff is to enter the sand filtration system prior to completion of all construction and site revegitation. Construction runoff shall be treated in separate sedimentation basins and routed to by-pass the filter system. Should construction runoff enter the filter system prior to site revegitation, all contaminated materials must be removed and replaced with new clean materials.

Watertight Integrity Test

After completion of the filter shell but before placement of the filter layers, entrances to the structure shall be plugged and the shell completely filled with water to demonstrate water tightness. Maximum allowable leakage is 5 percent of the filter shell volume in 24 hours. Should the structure fail this test, it shall be made watertight and successfully retested prior to placement of the filter layers.

Hydraulic Compaction of Filter Components

After placement of the collector pipes, gravel, and lower geotextile layer, fill the shell with filter sand to the level of the top of the sediment pool weir. Direct clean water into the sediment chamber until both the sediment chamber and filter chamber are completely full. Allow the water to draw down until flow from the collector pipes ceases, hydraulically compacting the filter sand. After allowing the sand to dry out for a minimum of 48 hours, refill the shell with sand to a level one inch beneath the top of the weir and place the upper geotextile layer and gravel ballast.

Grates and Covers

When placed in traffic lanes, grates and covers must withstand H-20 wheelloadings. Use of standard Virginia Department of Transportation (VDOT) grates (Grate D1-1) will often be most cost-effective. Where allowed by local jurisdictions, galvanized steel bar grates are economical.

Portland Cement Concrete

Portland Cement concrete used for the trench structure shall conform to the A3 specification of the Virginia Department of Transportation ***Road and Bridge Specifications***, latest edition.

Maintenance/Inspection Guidelines

The following maintenance and inspection guidelines are not intended to be all inclusive. Specific facilities may require other measures not discussed here.

Inspection Schedule

During the first year of operation, the cover grates or precast lids on the chambers must be removed quarterly and a joint owner-jurisdiction inspection made to assure that the system is functioning. Once the jurisdiction inspectors are satisfied that the system is functioning properly, this inspection may be made on an annual basis for other than auto-related activities.

Sediment Chamber Pumpout

The sediment chamber must be pumped out when the joint owner-jurisdiction determines that . If the chamber contains an oil skim, it should be removed by a firm specializing in oil recovery and recycling. The remaining material may then be removed by vacuum pump and disposed of in an appropriate landfill. **After each cleaning, refill the first chamber with clean water to reestablish the water seals to the clearwell.**

Sand Filter

When deposition of sediments in the filtration chamber indicate that the filter media is clogging and not performing properly, sediments must be removed (a small shovel may be all that is necessary) along with the top two to three inches of sand. The coloration of the sand will provide a good indication of what depth of removal is required. Clean sand must then be placed in the filter to restore the design depth. Where a layer of geotechnical fabric overlays the filter, the fabric shall be rolled up and removed and a similar layer of clean fabric installed. Any discolored sand shall also be removed and replaced. Disposal of petroleum hydrocarbon contaminated sand or filter cloth should be coordinated with the appropriate environmental official of the local jurisdiction. On filters which employ an upper geotextile layer and ballast, the top layer of filter cloth and ballast gravel must be removed and replaced with new materials conforming to the original specifications when the filter will no longer draw down within the required 40-hour period. Any discolored or sediment contaminated sand shall also be removed and replaced with sand meeting the original specifications (ASTM C-33 Concrete Sand).

Concrete Shell Inspection

Concrete will deteriorate over time, especially if subjected to live loads. The concrete shell, risers, etc., must be examined during each annual inspection to identify areas that are in need of repair, and such repairs must be promptly effected.

Grass Clippings

Grass clippings from landscape areas on the drainage watershed flowing into the DSF must be bagged and removed from the site to prevent them washing into and contaminating the sediment chamber and filter.

Trash Collection

Trash collected on the grates protecting the inlets shall be removed no less frequently than weekly to assure preserving the inflow capacity of the BMP.

Design Procedures

The following design procedure is structured to assure that the desired water quality volume is captured and treated by the Delaware Sand Filter. The procedure assumes that a filter shell with a rectangular cross-section is to be used. **Figure 3.12B-2** shows the dimensional relationships required to compute the design.

Standard Design Logic

Employ the following design logic to design Delaware Sand Filters for use in Virginia:

1. Determine Governing Site Parameters

Determine the Impervious area on the site (I_a in acres), the water quality volume to be treated (WQV in $ft.^3 = 1816\ I_a$), and the site parameters necessary to establish 2h, the maximum ponding depth over the filter (storm sewer invert at proposed connection point, elevation to inflow invert to BMP, etc).

2. Select Filter Depth and Determine Maximum Ponding Depth

Considering the data from Step 1) above, select the Filter Depth ((d_f) and determine the maximum achievable ponding depth over the filter (2h).

3. Calculate the Required Surface Areas of the Chambers

If the maximum ponding depth above the filter (2h) is less than 2.67 feet (2'-8"), the WQV storage requirement governs and the above foumula must be used:

$$A_f = \frac{1816 I_a}{(4.1h + 0.9)} = \frac{WQV}{(4.1h + 0.9)}$$

where:

A_f = the **area of the filter** in sq.ft.

I_a = the impervious area on the watershed in acres

h = 1/2 the maximum ponding depth over the filter (ft.)

If the the maximum ponding depth above the filter (2h) is 2.67 feet or greater, use the partial sedimentation filter formula:

$$A_f = \frac{545 I_a d_f}{(h + d_f)}$$

where:

d_f = depth of the filter media in ft. (1.5-2.0)

Delaware and Virginia make the area of the filter equal the area of the sediment chamber:

$A_f = A_s$

4. Establish Dimensions of the Facility

Site considerations usually dictate the final dimensions of the facility. Sediment trenches and filter trenches normally be 18-30 inches wide. Use of standard VDOT D1-1 grates requires a trench width of 26". Some jurisdictions restrict the maximum allowable trench width to 36 inches.

Minimizing Filter Shell Costs

Underground vault sand filter costs have been widely varying because many developers have simply had their foundation contractors cast the vault in place. Each installation therefore became a prototype with associated costs and overhead. Precast manufacturers currently offer precasting services for D.C. and other types of sand filter vaults, which should stabilize underground vault costs. **Figure 3.12B3** is a photograph of a segmented precast shell installation in Alexandria.

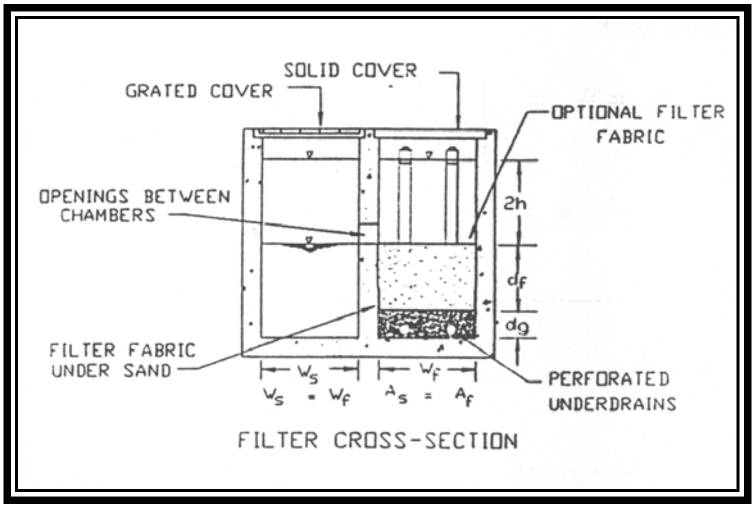
FIGURE 3.12B - 3
Installing Precast Delaware Sand Filter Shell in Alexandria, Virginia

(Photo Courtesy of Rotondo Precast, Fredericksburg, Virginia)

Checklists

Worksheet 3.12B is for use in sizing calculations for Delaware Sand Filters. The **Construction Inspection and As-Built Survey Checklist** found in **Appendix 3D** is for use in inspecting intermittent sand filter facilities during construction and, where required by the local jurisdiction, engineering certification of the filter construction. The **Operation and Maintenance Checklist**, also found in **Appendix 3D**, is for use in conducting maintenance inspections of intermittent sand filter facilities.

WORKSHEET 3.12B
SIZING COMPUTATIONS FOR STANDARD DELAWARE SAND FILTER
Page 1 of 2



Part 1: Select maximum ponding depth over filter:

2h = _______ft;

h = [ ] ft

From Pollutant Load Sheets:

I_a = [ ] acres

WQV = [ ] ft^3

Outflow by gravity possible____; Effluent pump required _____

Part 2: Compute Minimum Area of Filter (A_{fm}) and Sediment Pool (A_{sm}):

a) If 2h ≥ 2.67 feet, use the formula:

$$A_{sm} = A_{fm} = \frac{545 I_a d_f}{(d_f + h)}$$

= [545 x ______ x ______] / [______ + ______]

= [ ] ft^2

b) If 2h < 2.67 feet, use the formula:

$$A_{sm} = A_{fm} = \frac{1816\ I_a}{(4.1h + 0.9)} = \frac{WQV}{(4.1h + 0.9)}$$

= ________ / [(4.1 x ________) + 0.9]

= [ ] ft^2

WORKSHEET 3.12B
SIZING COMPUTATIONS FOR STANDARD DELAWARE SAND FILTER
Page 2 of 2

Part 3: Considering Site Constraints, Select Filter Width (W_f) and Sediment Pool Width (W_s) and Compute Filter Length (L_f) and Adjusted Filter Area (A_f) and Sediment Chamber Area (A_s):

$W_s = W_f =$ [ ] ft;

$L_s = L_f = A_{fm} / W_f$

= _________ /_________

= __________, [ ] say ft

$A_s = A_f = W_f \times L_f =$ __________ x __________

= [ ] ft^2

Part 4: Design Structural Shell to accommodate Soil and Load Conditions at Site:

(Separate computations by a structural engineer).

Part 5: Design Effluent Pump if Required:

Since pump must be capable of handling flow when filter is new, use k = 12 feet/day = 0.5 ft/hr

$$Q = \frac{kA_f(d_f + h)}{d_f}$$

= [0.5 x _________ x (_________ + ________)]/__________

= [ ] ft^3/hr ; /3600 [ ] = cfs;

x 448 = [ ] gpm

MINIMUM STANDARD 3.12C

AUSTIN SURFACE SAND FILTER SYSTEMS

Definition

The City of Austin, Texas, hase been using open basin intermittent sand filtration BMPs for treating stormwater runoff since the early 1980's. The Austin program is managed by the Environmental and Conservation Services Department, which has published design criteria in their *Environmental Criteria Manual* (Austin, 1988). Austin places heavy emphasis on pretreating the stormwater runoff in a sediment trapping presettling basin to protect the filter media from excessive sediment loading. The particles selected by Austin for complete removal in the full sedimentation protection basins are those which are greater than or equal in size to silt with a particle diameter of 0.00007 foot (20 microns) and a specific gravity of 2.65.

Figure 3.12C-1 illustrates an Austin Full Sedimantation Sand Filter application at a shopping center. In this system the sedimentation structure is a concrete basin designed to hold the entire WQV and then release it to the filtration basin over a 24-hour draw-down period. **Figure 3.12C-2** shows an alternative design which allows a smaller sedimentation chamber (20 percent of the WQV) while increasing the filter size to compensate for increased clogging of the filter media. Although the systems shown utilize concrete basins, a sediment pond and a geomembrane-lined filter built directly into he ground may be used where terrain and soil conditions allow.

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Purpose

Austin Sand Filters are used primarily for water quality control. However, they do provide detention and slow release over time of the WQV. Whether this amount will be sufficient to provide the necessary peak flow rate reductions required for channel erosion control is dependent upon the site conditions. However, in cases where quantity detention beyond the volume of the WQV is required, an attractive alternative may well be to utilize a combined detention basin/pre-settling basin configuration, with the controlled release of the entire stored volume to the sand filter facility.

FIGURE 3.12C - 1
Austin Full Sedimentation Sand Filter System at Barton Ridge Plaza

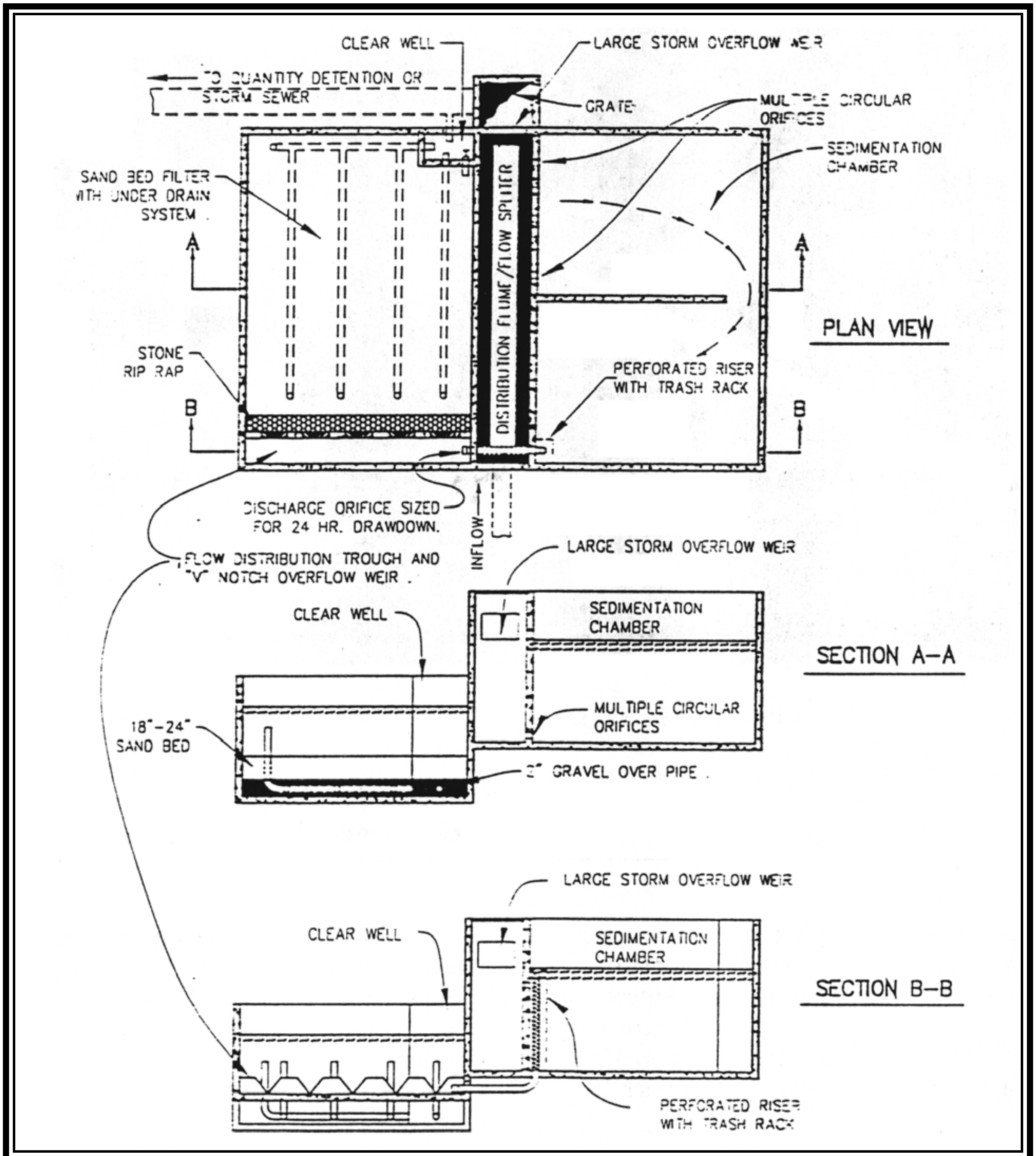


FIGURE 3.12C - 2
Sedimentation Basin of Jolleyville Partial Sedimentation System

(Poto Courtesy of the City of Austin, Texas)

Conditions Where Practice Applies

Austin Sand Filters Filters are ultra-urban BMPs best suited for use in situations where space is too constrained and/or real estate values are too high to allow the use of conventional retention ponds. Unlike D.C. and Delaware Sand Filters, when full sedimentation protection is provided, Austin filters may be used in situations where a higher amount of pervious surfaces are present or where higher sediment loads from deposition of wind-blown sediments are encountered. Because of their design, they may also be used on much larger drainage sheds.

<u>Drainage Area</u>

Austin full sedimentation and partial sedimentation basin sand filters have been used on drainage sheds up to 30 acres, and with great economy of scale. **Table 3.12-1** illustrates the relative costs of varying sized systems in Austin in mid-1990.

TABLE 3.12C - 1
Cost of Austin Sand Filtration Systems *(June 1990)*

Drainage Area (Acres)	**Water Quality Volume (ft^3)**	**Cost/Acre ($/acre)**	**Cost/ft^3 ($/$ft^3$)**	**Total Cost ($)**
1.0	1815	13,613* 19,058#	7.50* 10.50#	13,613* 19,058#
2.0	3,630	8,440* 9,801#	4.65* 5.40#	16,880* 19,602#
5.0	9,075	5,136	2.83	25,682
10.0	18,150	3,812	2.10	38,115
15.0	27,225	3,086	1.70	46,283
20.0	36,300	2,723	1.50	54,450
30.0	54,450	2.360	1.30	70,785

Footnotes:
* Calculated from data provided by Murfee Engineers
# Calculated from data provided by Austin Stormwater Management staff
All other values derived from combined data

While Austin has traditionally built these systems in open basins, there appears no reason why the basic designs cannot be adapted to underground vault construction where real estate values are high enough to justify their use. Austin Partial Sedimentation Sand Filters have been built in underground vaults in Alexandria on sheds of three-four acres of impervious cover. Precast segmented underground vaults are now available in very large configurations. Besides the modified precast box culvert technology illustrated under **MS 3.12A: D.C. Sand Filters**, precast arch technology has also been adapted to the construction of underground vaults. **Figure 3.12C-3** shows such a system. It appears that approximately five acres of impervious cover is the uper limit of the area that should be treated by a single underground vault system.

FIGURE 3.12C - 3
Underground Vault Fabricated From Precast Bridge Arch Components

(Photo Courtesy of BridgeTek Bridge Technologies, LLC., Fredericksburg, Virginia)

Development Conditions

Austin Sand Filters are generally suitable BMPs for medium to high density commercial or industrial development. Because of confined space entry restrictions when constructed in underground vaults and maintenance requirements, they are not generally suitable for residential applications except for apartment complexes or large condominiums where a dedicated maintenance force will be present.

Planning Considerations

Refer to the **Planning Considerations** for **Minimum Standard 3.12: General Intermittent Sand Filter Practices**. Of special concern are the stormwater infrastructure serving the site and the requirement to isolate the sand filter from receiving flows until the drainage shed is fully stabilized.

Potential and existing elevations of stormwater infrastructure serving the site will determine one of the most critical design parameters: the maximum depth to which runoff may be pooled over the filter and preserve a gravity flow configuration (whatever the pooling depth, there must be a minimum of five feet of clearance between the top of the filter and the top slab of the filter shell to allow filter maintenance).

Sand filter BMPS must ***never*** *be placed in service until all site work has been completed and stabilization measures have been installed and are functioning properly.*

Design Criteria

The purpose of this section is to provide recommendations and minimum criteria for the design of Austin Sand Filter BMPs intended to comply with the Virginia Stormwater Management program's runoff quality requirements.

Refer to the **General Design Criteria** previously discussed under **General Intermittent Sand Filter Practices, Minimum Standard 3.12**

Filter Sizing Criteria

1. ***Full Sedimentation with Filtration***

In this configuration, the sedimentation basin receives the WQV and detains it for a minimum draw-down time (time required to empty the basin from a full WQV condition) of 24 hours. The effluent from the sedimentation basin is discharged into the filtration basin..

Austin conducted a literature review of sedimentation basins and slow rate filters to establish design criteria.

For filtration basins, surface area is the primary design parameter. The required surface area is a function of sand permeability, bed depth, hydraulic head and sediment loading. A filtration rate of 0.0545 gallons per minute per square foot has been selected for design criteria (10.5 feet per day or 3.4 million gallons per acre per day). This filtration rate is based on a Darcy's Law coefficient of permeability k =3.5 feet per day, an average hydraulic head (h) of three (3) feet and a sand bed depth (d_f) of 18 inches, and a filter drawdown time, t_f of 40 hours.

Substituting these values in the basic Austin Filter Formula shown in **General Intermittent Sand Filter Practices, Minimum Standard 3.12** yields:

$A_f = I_aH/18$

where “A_f” is the minimum surface area of the filtration media in acres, “I_a” is the contributing impervious runoff area in acres and “H” is the runoff depth in feet (0.5 inch = 0.0417 feet when treating the WQV).

When treating the first 1/2-inch of runoff, this formula reduces to

$A_f = 0.0023I_a = 100\ Ft^2$ of filter per impervious acre.

This formula is obviously based on a number of simplifying assumptions. Determining the actual average depth of ponding over the filter is an extremely complex proposition considering thet the runoff is being released from the sedimentation chamber to the filter at first a rising and then a falling head and then percolating through the sand filter at first a rising and then a falling head. However, this design procedure has worked well for austin for over a decade and may be therefore be considered to be vaild.

When treating a volume greater than the WQV (as when a combined quantity detention/presettling basin is utilized) use the following formula:

$A_f = 0.0023I_a \times (TV / WQV)$

Where TV = the full retention volume of the detention basin/presettling basin.

2. Partial Sedimentation with Filtration

In this configuration, the sedimentation basin or chamber holds a minimum of 20 percent of the WQV and is hydraulically connected to the filter basin with orifices or slots which allow the water level to equalize between the two chambers.

For Austin Sand Filters with partial sedimentation protection, utilize the following formula:

$$A_{fm(PS)} = \frac{545I_ad_f}{(h + d_f)}$$

where,

I_a = impervious cover on the watershed in acres
d_f = sand bed depth (normally 1.5 to 2ft)
h = average depth of water above surface of sand media between full and empty basin conditions (ft.)

Sedimentation Basin Sizing

1. ***Full Sedimentation with Filtration***

The sedimentation basin must hold the entire WQV (or larger treatment volume) and release it to the filter over 24 hours. The volume of the basin is thus set by the amount of area to be treated. For sedimentation basins, the removal of discrete particles by gravity settling is primarily a function of surface loading, "Q_o/A_s ", where "Q_o " is the rate of outflow from the basin and "A_s" is the basin surface area. Basin depth is of secondary importance as settling is inhibited only when basin depths are too shallow (particle resuspension and turbulence effects). For sedimentation, surface area is the primary design parameter for a fixed minimum draw-down time, t_d, of 24 hours. Removal efficiency, E, is also a function of particle size distribution. For design purposes, the particles selected for complete removal in the sedimentation basin are those which are greater than or equal in size to silt with the following characteristics: particle diameter 0.00007 foot (20 microns) and specific gravity of 2.65. These are typical values for urban runoff .

Presettling basins are usually sized using the Camp-Hazen equation (Claytor and Schueler, 1996):

$$A_S = - (Q_O / w) \times \text{Ln } (1 - E)$$

Where,

A_S = Surface area (ft^2) of the sedimentation basin
E = Trap efficiency, which is the target removal efficiency of suspended solids (use 90%)
w = Particle settling velocity; for silt, use 0.0004 ft/sec
Q_O = rate of outflow from the basin = WQV (or treatment volume) divided by the detention time (24 hours)

Substituting the values recommended above yields the simplified formula:

$$A_S = 0.066 \times WQV \quad (ft^2)$$

For 1816 ft^3, this yields an area of 120 ft^2. However, Austin recommends that the sedimentation basin be no more that 10 feet deep, which yields a surface area approximately 115% of the basin Camp-Hazen area. The Austin formula for minimum surface area is:

$$A_S = 0.0042\ I_a$$

Where I_a is the contributing impervious runoff area in acres

2. Partial Sedimentation with Filtration

The minimum area of the sediment chamber may be computed by the formula:

$$A_S = WQV / 2h$$

Where 2h = the maximum depth of ponding over the filter and the sediment chamber.

Additional Full Sedimentation Basin Considerations

1. *Inlet Structure*

The inlet structure design must be adequate for isolating the water quality volume from the design storm and to convey the peak flow for the design storm past the basin. The water quality volume should be discharged uniformly and at low velocity into the sedimentation basin in order to maintain near quiescent conditions which are necessary for effective treatment. It is desirable for the heavier suspended material to drop out near the front of the basin; thus a drop inIet structure is recommended in order to facilitate sediment removal and maintenance. Energy dissipation devices may be necessary in order to reduce inlet velocities which exceed three (3) feet per second.

2. *Outlet Structure*

The outlet structure conveys the water quality volume from the sedimentation basin to the filtration basin. The outlet structure shall be designed to provide for a minimum draw-down time of 24 hours. A perforated pipe or equivalent is the recommended outlet structure. The 24 hour draw-down time should be achieved by installing a throttle plate or other flow control device at the end of the riser pipe (the discharges through the perforations should not be used for draw-down time design purposes)

3. *Basin Geometry*

The shape of the sedimentation basin and the flow regime within this basin will influence how effectively the basin volume is utilized in the sedimentation process. The length to width ratio of the basin should be 2:1 or greater. Inlet and outlet structures should be located at extreme ends of the basin in order to maximize particle settling opportunities.

Short-circuiting (i.e., flow reaching the outlet structure before it passes through the sedimentation basin volume) flow should be avoided. Dead storage areas (areas within the basin which are by-passed by the flow regime and are, therefore, ineffective in the settling process) should be minimized. Baffles may be used to mitigate short circuiting and/or dead storage problems. The sedimentation illustrated in **Figure 3.12C-1** (photo in **Figure 3.12-4**) illustrates the use of baffles to improve sedimentation basin performance.

4. *Sediment Trap (Optional)*

A sediment trap is a storage area which captures sediment and removes it from the basin flow regime. In so doing the sediment trap inhibits resuspension of solids during subsequent runoff events, improving long-term removal efficiency. The trap also maintains adequate volume to hold the water quality volume which would otherwise be partially lost due to sediment storage. Sediment traps may reduce maintenance requirements by reducing the frequency of sediment removal. It is recommended that the sediment trap volume be equal to ten (10) percent of the sedimentation basin volume. Water collected in the sediment trap shall be conveyed to the filtration basin in order to prevent standing water conditions from occurring. All water collected in the sediment trap shall drain out within 60 hours. The invert of the drain pipe should be above the surface of the sand bed filtration basin. The minimum grading of the piping to the filtration basin should be 1/4 inch per foot (two (2) percent slope). Access for cleaning the sediment trap drain system is necessary.

Design Storm

The inlet design or integral large storm bypass must be adequate for isolating the WQV from the design storm for the receiving storm sewer system (usually the 10 year storm) and for conveying the peak flow of that storm past the filter system. Since D.C. Sand Filters will be used only as off-line facilities in Virginia, the interior hydraulics of the filter are not as critical as when used as an on-line facility. The system should draw down in approximately 40 hours.

Infrastructure Elevations

For cost considerations, it is preferable thatAustin Sand Filters work by gravity flow. This requires sufficient vertical clearance between the invert of the prospective inflow storm piping and the invert of the storm sewer which will receive the outflow. In cases where gravity flow is not possible, a clearwell sump and pump are required to discharge the effluent into storm sewer. Such an application would be appropriate in commercial or industrial situations where a dedicated maintenance force will be available (shopping malls, apartment houses, factories of other industrial complexes, etc.).

Special Considerations for Underground Filter Systems

When Austin Sand Filters are placed underground, a number of special considerations pertain. The restrictive orifice or gate valve for controlling the release of water from a separate sedimentation vault should be placed in a manhole located between the sedimentation vault and the filter vault. The sedimentation vault should contain a sediment sump into which accumulated sediments may be flushed with a high pressure hose for removal by vacuum trucks. Water should enter the filter vault in a separate headbox with a permanent pool for energy absorbtion and a hydrocarbon trap like that of a D.C. Sand Filter. The filter vault should also contain a separate clearwell.

Structural Requirements

The load-carrying capacity of the filter structure must be considered when it is located under parking lots, driveways, roadways, and, certain sidewalks (such as those adjacent to State highways). Traffic intensity may also be a factor. The structure must be designed by a licensed structural engineer and the structural plans require approval by the plan approving jurisdiction.

Accessibility and Headroom for Maintenance

Both the sedimentation basin and the filter must be accessible to appropriate equipment and vacuum trucks for removing accumulated sediments and trash. The sedimentation basin must be cleaned approximately once per year, and the filter will likely need raking on that frequency to remove trash and restore permeability. When filters are placed in underground vaults, all chambers must have personnel access manholes and built-in access ladders. **A minimum headspace of 60 inches above the filter is required to allow such maintenance and repair.** A 38-inch diameter maintenance manhole with eccentric nested covers (a 22-inch personnel access lid inside the 38-inch diameter lid) or a rectangular load bearing access door (minimum 4 ft. x 4 ft.) should be positioned directly over the center of the filter. A 30-inch manhole should also be placed directly over the sediment sump in an underground sedimentation vault. Similar manholes must be positioned to provide access for a high-pressure hose to reach all points in the sediment vault.

Construction Specifications

<u>Sedimentation Basin Liners</u>

Impermeable liners may be either clay, concrete or geomembrane. If geomembrane is used, suitable geotextile fabric shall be placed below and on the top of the membrane for puncture protection. Clay liners shall meet the specifications in **Table 3.12C-2**:

The clay liner shall have a minimum thickness of 12 inches.

If a geomembrane liner is used it shall have a minimum thickness of 30 mils and be ultraviolet resistant.

The geotextile fabric (for protection of geomembrane) shall meet the specifications in **Table 3.12C-3**.

TABLE 3.12C - 2
Clay Liner Specifications

Property	Test Method	Unit	Specification
Permeability	ASTM D-2434	Cm/Sec	1×10^{-6}
Plasticity Index of Clay	ASTM D-423 & D-424	%	Not less than 15
Liquid Limits of Clay	ASTM D-2216	%	Not less than 30
Clay Compaction	ASTM-2216	%	95% of Standard Proctor Density
Clay Particles Passing	ASTM D-422	%	Not less than 30

Source: City of Austin

TABLE 3.12C - 3
Geotextile Specification for Basin Liner "Sandwich"

Property	Test Method	Unit	Specification
Unit Weight		Oz./Sq.Yd.	8 (minimum)
Filtration Rate		In./Sec.	0.08 (minimum)
Puncture Strength	ASTM D-751 (Modified)	Lb.	125 (minimum)
Mullen Burst Strength	ASTM D-751	Psi.	400 (minimum)
Tensile Strength	ASTM D-1682	Lb.	300
Equiv. Opening Size	U.S. Standard Sieve	No.	80 (minimum)

Source: City of Austin

Equivalent methods for protection of the geomembrane liner will be considered on a case by case basis. Equivalency will be judged on the basis of ability to protect the geomembrane from puncture, tearing and abrasion.

<u>Portland Cement Concrete</u>

Concrete liners may be used for sedimentation chambers and for sedimentation and filtration basins. Concrete shall be at least five (5) inch thick Class A3 defined in the Virginia Department of Transportation *Road and Bridge Specifications.*

<u>Outlet Structure for Full Sedimentation Basin</u>

A perforated pipe or equivalent is the recommended outlet structure. The 24-hour draw-down should be achieved by installing a throttle plate or other control device at the end of the riser pipe (the discharges through the perforations should not be used for draw-down time design purposes). The perforated riser pipe should be selected from **Table 3.12-4.**

TABLE 3.12C - 4
Perforated Riser Pipes

Riser Pipe Nominal Diameter (inches)	Vertical Spacing Between Rows (Center to Center in Inches)	Number of Perforations Per Row	Diameter of Perforations (inches)
6	2.5	9	1
8	2.5	12	1
10	2.5	16	1

Source: City of Austin

A trash rack shall be provided for the outlet. Openings in the rack should not exceed 1/3 the diameter of the vertical riser pipe. The rack should be made of durable material, resistant to rust and ultraviolet rays. The bottom rows of perforations of the riser pipe should be protected from clogging. To prevent clogging of the bottom perforations it is recommended that geotextile fabric be wrapped over the pipe's bottom rows and that a cone of one (1) to three (3) inch diameter gravel be placed around the pipe. If a geotextile fabric wrap is not used then the gravel cone must not include any gravel small enough to enter the riser pipe perforations. **Figure 3.12C-4** illustrates these considerations.

<u>Outlet Structure for Partial Sedimentation Basin</u>

The outlet structure should be a berm or wall with multiple outlet ports or a gabion so as to discharge the flow evenly to the filtration basin. Rock gabions should be constructed using 6-8 inch diameter rocks. The berm/wall/gabion height should not exceed six (6) feet and high flows should be allowed to overtop the structure (weir flow). Outlet ports should not be located along the vertical center axis of the berm/wall so as to induce flow-spreading. The outflow side should incorporate features to prevent gouging of the sand media (e.g., concrete splash pad or riprap)

<u>Sand Filter Layer</u>

For applications in Virginia, use **ASTM C33 Concrete Sand** or sand meeting the Grade A fine aggregate gradation standards of Section 202 of the VDOT ***Road and Bridge Specifications.*** The top of the sand filter must be completely level.

<u>Geotextile Fabrics</u>

The filter cloth layer beneath the sand shall conform to the specifications shown in **Table 3.12C-5**: The fabric rolls must be cut with sufficient dimensions to cover the entire wetted perimeter of the filtering area and lap up the filter walls at least six-inches.

FIGURE 3.12C - 4
Riser Pipe Detail for Full Sedimentation Basin

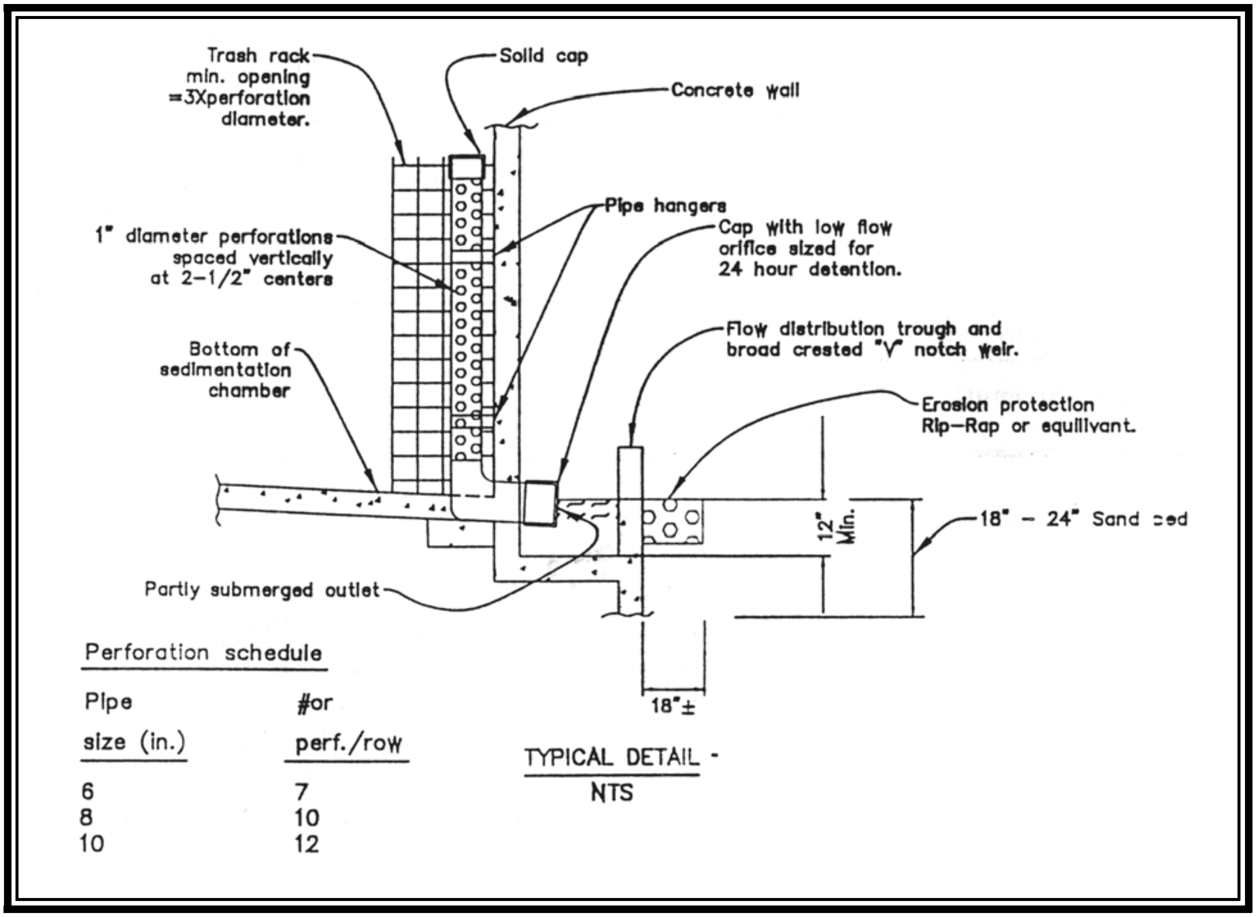


Table 3.12C - 5
Specifications for Nonwoven Geotextile Fabric Beneath Sand in Austin Sand Filter

Property	**Test Method**	**Unit**	**Specification**
Unit Weight	--	Oz./sq.yd.	8.0 (min.)
Filtration Rate	--	In/sec	0.08 (min.)
Puncture Strength	ASTM D-751 (Modified)	Lb.	125 (min.)
Mullen Burst Strength	ASTM D-751	Psi	400 (min.)
Equiv. Opening Size	U.S. Standard Sieve	No.	80 (min.)
Tensile Strength	ASTM D-1682	Lb.	300 (min.)

Gravel Bed Around Collector Pipes

The gravel layer surrounding the collector pipes shall be ½ to two (2) inch diameter gravel and provide at least two (2) inches of cover over the tops of the drainage pipes. The gravel and the sand layer are usually separated by a layer of geotextile fabric meeting the specification listedabove. However, on small underground vault partial sedimentation systems, some jurisdictions allow the substitution for an additional six-inch layer of 1/4-inch washed pea gravel in lieu of the filter fabric. In such cases, hydraulic compaction and refilling of the filter is especially important. **FIGURE 3.12C-5** shows a cross-section of a filter with the usual configuration. **FIGURE 3.12C-6** shows an underground vault filter with a six-inch pea gravel layer.

Underdrain Piping

The underdrain piping consists of 4-inch or 6-inch schedule 40 or better polyvinyl perforated pipes reinforced to withstand the weight of the overburden. Perforations should be 3/8 inch, and each row of perforations shall contain at least four holes for four-inch pipe and six holes for six-inch pipe. Maximum spacing between rows of perforations shall be six (6) inches. Maximum spacing between pipes shall be 10 feet.

The minimum grade of piping shall be 1/8 inch per foot (one [1] percent slope). Access for cleaning all underdrain piping is needed. Clean-outs for each pipe shall extend at least six (6) inches above the top of the upper filter surface, e.g. the top layer of gravel.

Each pipe shall be thoroughly wrapped with 8 oz./sq.yd. geotextile fabric meeting the specification in **Table 3.12C-1** above.

FIGURE 3.12C - 5
Austin Sand Filter Cross-Section With Filter Fabric Layer

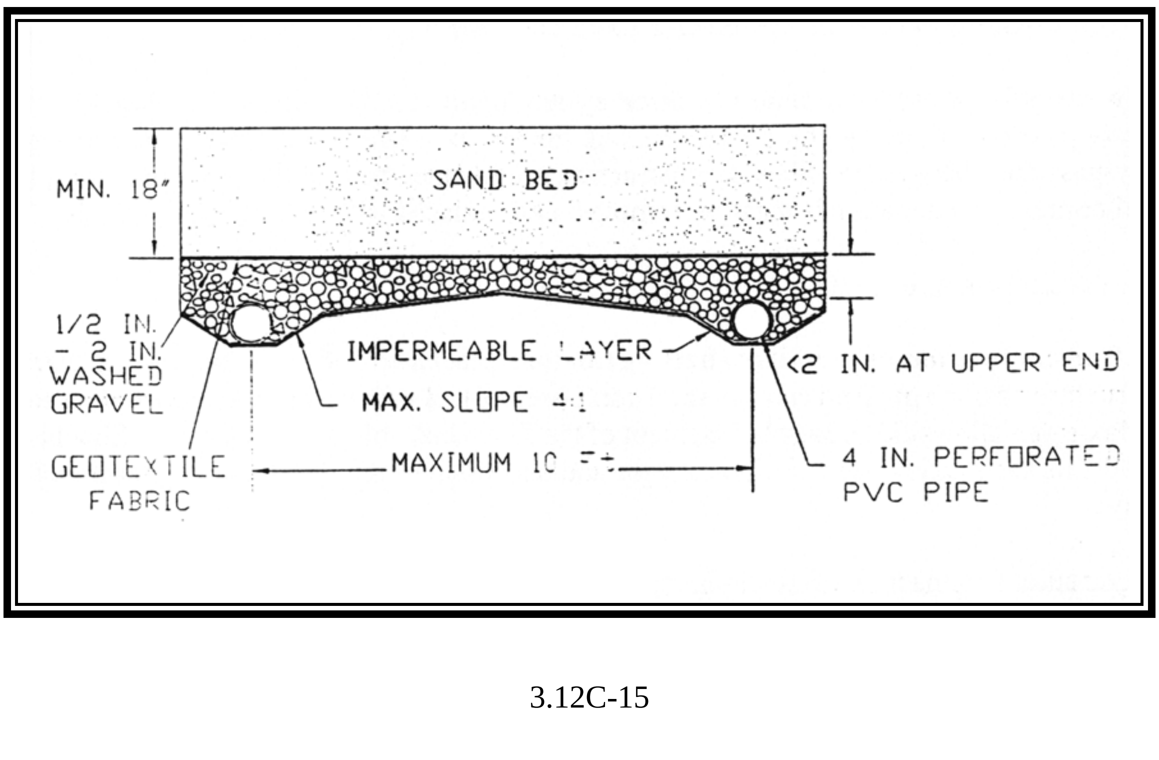
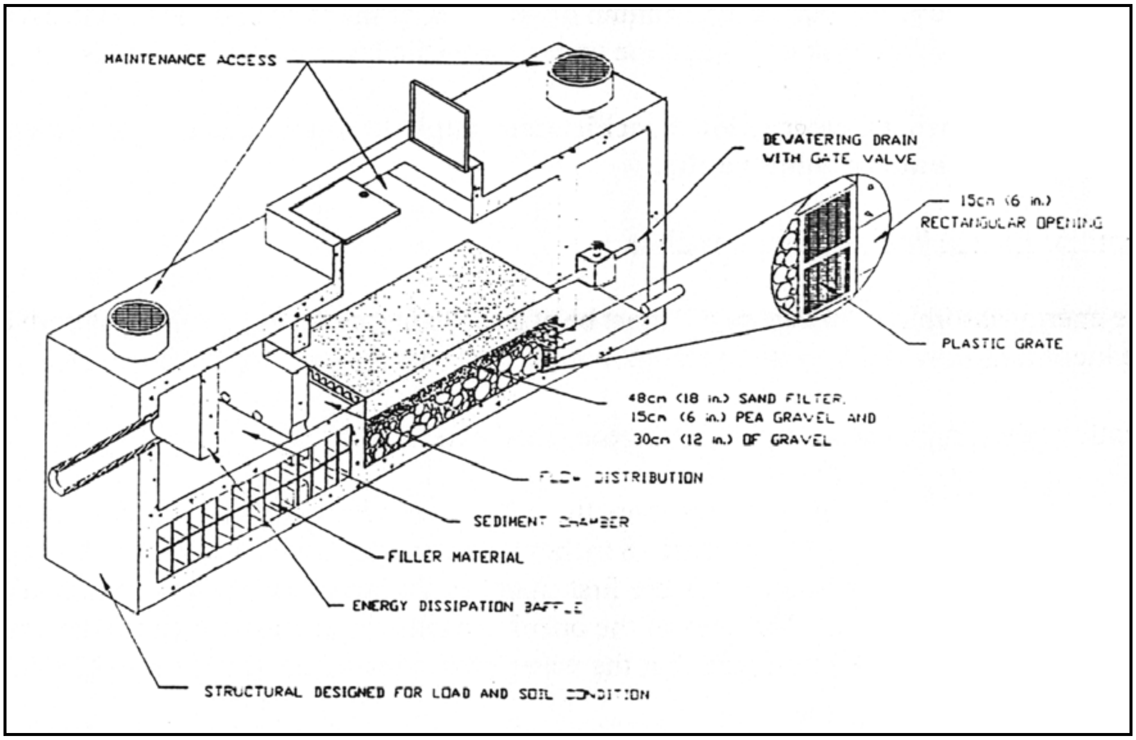


FIGURE 3.12C - 6
Partial Sedimentation Vault Filter With Pea Gravel Layer



<u>Protection from Construction Sediments</u>

The site erosion and sediment control plan must be configured to permit construction of the filter system while maintaining erosion and sediment control.

No runoff is to enter the sand filtration system prior to completion of all construction and site revegetation. Construction runoff shall be treated in separate sedimentation basins and routed to by-pass the filter system. Should construction runoff enter the filter system prior to site revegetation, all contaminated materials must be removed and replaced with new clean materials.

<u>Watertight Integrity Test</u>

After completion of the filter shell but before placement of the filter layers, entrances to the structure shall be plugged and the shell completely filled with water to demonstrate water tightness. Maximum allowable leakage is 5 percent of the filter shell volume in 24 hours. Should the structure fail this test, it shall be made watertight and successfully retested prior to placement of the filter layers.

Hydraulic Compaction of Filter Components

After placement of the collector pipes, gravel, and lower geotextile layer, fill the shell with filter sand to the level of the top of the sediment pool weir. Direct clean water into the sediment chamber until both the sediment chamber and filter chamber are completely full. Allow the water to draw down until flow from the collector pipes ceases, hydraulically compacting the filter sand. After allowing the sand to dry out for a minimum of 48 hours, refill the shell with sand to a level one inch beneath the top of the weir and place the upper geotextile layer and gravel ballast.

Note: The following Construction Specifications apply to Austin Sand Filters which are to be constructed in underground vaults.

Depth of Plunge Pool in Filter Headbox

The energy absorbing "plunge pool" must be at least 36 inches deep to properly absorb energy from the incoming flow and trap any hydrocarbons which pass through the sedimentation vault.

Depth of the Underwater Opening Between Chambers

To preserve an effective hydrocarbon trap, the top of the underwater opening between the headbox and the filter chamber must be at least 18 inches below the depth of the weir which divides the filter from the pool. To retain sediment in the first chamber, the bottom of the opening should be at least six inches above the floor. The area of the opening should be at least 1.5 times the cross-sectional area of the inflow pipe(s) to assure that the water level remains equal between the first and second chambers.

Total Depth of Filter Cross-Section

The total depth of the filter cross-section must match the height of the weir dividing the sedimentation pool from the filter. Otherwise, a "waterfall" effect will develop which will gouge out the front of the filter media. If a sand filter less than 24 inches is used, the gravel layer must be increased accordingly to preserve the overall filter depth.

Dewatering Drain

When the filter is placed in an underground vault, A 6-inch dewatering drain controlled by a gate valve shall be installed between the filter chamber and the clearwell chamber with its invert at the elevation of the top of the filter. The dewatering drain penetration in the chamber dividing wall shall be sealed with a flexible strip joint sealant which swells in contact with water to form a tight pressure seal.

Access Manholes

When the filter is installed in an underground vault, access to the headbox (sediment chamber) and the clearwell shall be provided through at least 22-inch manholes. Access to the filter chamber shall be provided by a rectangular door (minimum size: 4 feet by four feet) of sufficient strength to carry prospective imposed loads or by a manhole of at least 3- inch diameter with an offset concentric 22-inch lid (Neenah R-1741-D or equivalent).

Restrictive Orifice Manhole Between Vaults

The restrictive orifice or gate valve on the outlet pipe from the sedimentation vault should be placed in a manhole between the sedimentation and filter vaults with ready personnel access. **Figure 3.12C-7** illustrates this principle.

Maintenance/Inspection Guidelines

The following maintenance and inspection guidelines are not intended to be all inclusive. Specific facilities may require other measures not discussed here.

Major Maintenance Requirements for Sedimentation Basins

1. Removal of silt when accumulation exceeds six (6) inches in sediment basins without sediment traps. In basins with sediment traps, removal of silt shall occur when the accumulation exceeds four (4) inches in the basins, and sediment traps shall be cleaned when full.

2. Removal of accumulated paper, trash and debris every six (6) months or as necessary.

3. Vegetation growing within the basin is not allowed to exceed 18 inches in height at any time.

4. Corrective maintenance is required any time a sedimentation basin does not drain the equivalent of the Water Quality Volume within 40 hours (i.e., no standing water is allowed).

5. Corrective maintenance is required any time the sediment trap (optional) does not drain down completely within 96 hours (i.e., no standing water allowed).

Major Maintenance Requirements for Filtration Components

1. Removal of silt when accumulation exceeds 1/2 inch. - Removal of accumulated paper, trash and debris every six (6) months or as necessary.

2. Vegetation growing within the basin is not allowed to exceed 18 inches in height.

3. Corrective maintenance is required any time draw-down does not occur within 36 hours after the sedimentation basin has emptied.

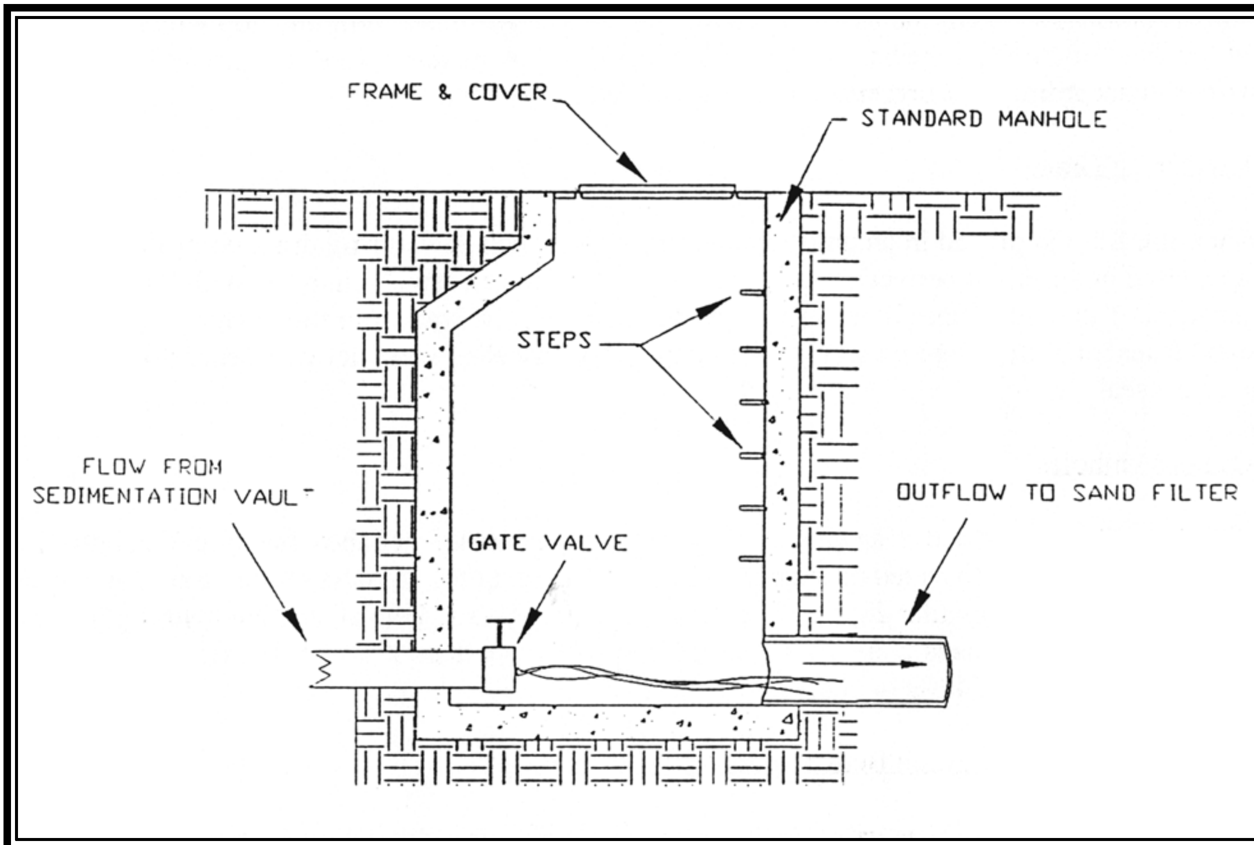
4. When an underground vault filter will no longer draw down within the required 36-hour period because of clogging with silt (approximately every 3-5 years), the upper layer of gravel and

geotechnical cloth must be replaced with new clean materials meeting the original specifications.

5. Monitoring manholes, flumes, and other facilities shall be kept clean and ready for use.

The BMP shall be inspected annually by representatives of the owner and the governing jurisdiction staff to assure continued proper functioning.

FIGURE 3.12C - 7
Restrictive Orifice Access Manhole



Sediment Chamber Pumpout

Full sedimentation chambers or basins require flushing and pumpout with a vacuum truck approximately once per year.

Concrete Shell Inspection

Concrete will deteriorate over time, especially if subjected to live loads. The concrete shell, risers, etc., must be examined during each annual inspection to identify areas that are in need of repair, and such repairs must be promptly effected.

Design Procedures

The following design procedure is structured to assure that the desired water quality volume is captured and treated by theAustin Filter. The procedure assumes that a filter shell with a rectangular cross-section is to be used.

Standard Design Logic

Employ the following design logic to design Austin Sand Filters for use in Virginia:

1. Determine Governing Site Parameters

Determine the Impervious area on the site (I_a in acres), the water quality volume to be treated (WQV in $ft.^3 = 1816\ I_a$), and the site parameters necessary to establish 2h, the maximum ponding depth over the filter (storm sewer invert at proposed connection point, elevation to inflow invert to BMP, etc).

2. Select Filter Depth and Determine Maximum Ponding Depth

Considering the data from Step 1) above, select the Filter Depth ((d_f) and determine the maximum achievable ponding depth over the filter (2h).

3. For Full Sedimantation Systems, size the sedimentation basin (vault) to hold the WQV with a minimum depth of 10 feet.

4. Compute the Minimum Area of the Sand Filter (A_{fm})

For systems with full sediment protection, provide a dediment chamber of sufficient volume to hold the WQV. Make the depth $\leq$ ten feet. To compute the area of the filter, use the formula:

$$A_f = 100I_a$$

Where I_a = the impervious acreage on the drainage shed.

For systems with only partial sediment protection, utilize the formula:

$$A_{fm(PS)} = \frac{545 I_a d_f}{(h + d_f)}$$

A_{fm} = minimum surface area of sand bed (square feet)
I_a = impervious cover on the watershed in acres
d_f = sand bed depth (normally 1.5 to 2ft)
h = average depth of water above surface of sand media between full and empty basin conditions (ft.)

5. Select Filter Width and Compute Filter Length and Adjusted Filter Area

Considering site constraints, select the Filter Width (W_f). Then compute the Filter Length (L_f) and the Adjusted Filter Area (A_f)

$$L_f = A_{fm}/W_f$$

$$A_f = W_f \times L_f$$

Sizing computations are completed at this point for the full sediment protection system. The only remaining task is to assure that the filter chamber is sized to contain a minimum of 20 % of the WQV. The logic continues for the partial sedimentation system.

6. Compute the Storage Volume on Top of the Filter (V_{Tf})

$$V_{Tf} = A_f \times 2h$$

7. Compute the Storage in the Filter Voids (V_v)
(Assume 40% voids in filter media)

$$V_v = 0.4 \times A_f \times (d_f + d_g)$$

8. Compute Flow Through Filter During Filling (V_Q)
(Assume 1-hour to fill per D.C. practice)

$$V_Q = \frac{kA_f(d_f + h)}{d_f} \text{ ; use } k = 2 \text{ ft./day} = 0.0833\text{/hr.}$$

9. Compute Net Volume to be Stored Awaiting Filtration (V_{st})

$$V_{st} = WQV - V_{Tf} - V_v - V_Q$$

10. Compute Length of Sediment chamber (L_{SC})

$$L_{SC} = \frac{V_{st}}{(2h \times W_f)}$$

11. Compute Minimum Length of Sediment Chamber (L_s)
(to contain 20% of WQV per Austin practice)

$$L_{sm} = \frac{0.2WQV}{(2h \times W_f)}$$

12. Set Final Length of the Sediment Chamber (L_{SCF})

If $L_{SC} \geq L_s$, make $L_{SCF} = L_{SC}$

If $L_{SC} < L_{sm}$, make $L_{SCF} = L_{sm}$

It may be economical to adjust final dimensions to correspond with standard precast structures or to round off to simplify measurements during construction.

Checklists

The **Construction Inspection and As-Built Survey Checklist** found in **Appendix 3D** is for use in inspecting intermittent sand filter facilities during construction and, where required by the local jurisdiction, engineering certification of the filter construction. The **Operation and Maintenance Checklist**, also found in **Appendix 3D**, is for use in conducting maintenance inspections of intermittent sand filter facilities.

REFERENCES

Anderson, D.L., Siegrist, R.L. and Otis, R.J. (Undated) Technology assessment of intermittent sand filters. Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Bell, Warren, Stokes, Lucky, Gavan, Lawrence J., and Nguyen, Trong Ngu (1995) Assessment of the pollutant removal efficiencies of Delaware sand filter BMPs. Department of Transportation and Environmental Services, City of Alexandria, Virginia.

Bell, Warren and Nguyen, Trong Ngu (1994) Intermittent sand filter BMPs for stormwater quality. Department of Transportation and Environmental Quality, City of Alexandria, Alexandria, Virginia.

Bitter, Susan D. and Bowers, Keith (1994) Bioretention as a water quality best management practice. In: Watershed Protection Techniques, Volume 1, No. 3, Center for Watershed Protection, Silver Spring, Maryland.

The Cadmus Group, Inc. (1991) Guidance on reducing nitrogen loading from septic systems, Contract No. 68-C0-0020, Work Assignment No. 1, Task 3, U.S. EPA Office of Drinking Water, Underground Injection Control Branch, Washington, D.C.

City of Alexandria, Virginia (1992) Unconventional BMP design criteria. In: Alexandria Supplement to the Northern Virginia BMP Handbook. Department of Transportation and Environmental Services, Alexandria, Virginia.

City of Austin, Texas (1988) Water quality management. In: Environmental Criteria Manual. Environmental and Conservation Services Department, Austin, Texas.

Chang, G.C., Parrish, J.H., Soeur, C., and Librach, A.S. (1990) Removal efficiencies of stormwater control structures. Environmental Resources Management Division, Environmental and Conservation Services Department, Austin, Texas.

Claytor, Richard A. And Schueler, Thomas R. (1996) ***Design of Stormwater Filtering Systems.*** Center for Watershed Protection, Silver Spring, Maryland.

Farnham, R.S. and Noonan, T. (1988) An evaluation of secondary treatment of stormwater inflows to Como Lake, Mn., using a peat-sand filter, EPA Project S-005660-02.

Galli, John (1990) Peat-sand filters: a proposed stormwater management practice for urbanized areas. Department of Environmental Programs, Metropolitan Washington Council of Governments, Washington, D.C.

Galli, John (1992) Analysis of urban BMP performance and longevity in Prince George's County, Maryland. Department of Environmental Programs, Metropolitan Washington Council of Governments, Washington, D.C.

Gold, Arthur J., Lamb, Bonnie E., Loomis, George W., and McKiel, Charles G. (Undated) Nitrogen removal for on-site wastewater treatment, Journal Paper No. 2515, Rhode Island Experiment Station, Kingstown, Rhode Island.

Harper, Harvey H. and Herr, Jeffrey L. (1993) Treatment efficiencies of detention with filtration systems. Final report for Saint Johns River Water Management District Contract No. 90B103, Environmental Research & Design, Inc., Orlando, Florida.

Laak, Rein (1986) Wastewater Engineering Design for Unsewered Areas, Technomic Publishing Company, Inc., Lancaster, Pennsylvania.

LaRock, Paul (1988) Evaluation of the Lake Jackson stormwater treatment facility. Final report, Contract No. LR70(A), Florida Department of Environmental Regulation, Tallahassee, Florida.

Livingston, E.H., McCarron, M.E., Cox, J.H., and Sanzone, P.A. (1988) Underdrains and stormwater filtration systems. In: Florida Development Manual: A Guide to Sound Land and Water Management, Florida Department of Environmental Regulation, Tallahassee, Florida.

Mitchell, Dee (1985) Using upflow anaerobic filters as pretreatment for sand filtration of septic tank effluent. University of Arkansas, Fayetteville, Arkansas.

Northern Virginia Planning District Commission (NVPDC) (1992) Chapter 5, BMP planning considerations. In: Northern Virginia BMP Handbook, Northern Virginia Planning District Commission, Annandale, Virginia.

Otis, Richard J. (Undated) Onsite wastewater treatment intermittent sand filters, Rural Systems Engineering, Madison, Wisconsin In: Introductory Package on Sand Filters, WWPCGN29, Small Flows Clearinghouse, West Virginia University, Morgantown, West Virginia.

Piluk, Richard J. and Hao, Oliver J. (1989) Evaluation of on-site waste disposal system for nitrogen reduction. In: Journal of Environmental Engineering, Vol. 115, No. 4. American Society of Civil Engineers, August.

Prince George's County, Maryland (P.G. County) (1993) Design Manual for Use of Bioretention in Stormwater Management, Department of Environmental Protection, Landover, Maryland.

Rock, C.A. and Pinkham, P. Scott (1986) Development of an artificial drainfield to enhance onsite nitrogen removal. In: Appropriate Wastewater Management Technologies for Rural Areas Under Adverse Conditions, Tech Press in Collaboration with the Centre for Water Resources Studies, Halifax, Nova Scotia, Canada.

Ronayne, M.P., Paeth, R.C., and Osborne, T.J. (Undated) Intermittent sand filter design and performance-an update. In: Oregon State Department of Environmental Quality. Introductory Package on Sand Filters, WWPCGN29, Small Flows Clearinghouse, West Virginia University, Morgantown, West Virginia.

Sartor, J. D., Boyd, G.B., and Agardy, F.J. (1974) Water pollution aspects of street surfaces Contaminants. In: Journal Water Pollution Control Federation, Vol. 46: 458-667, Washington, D.C.

Sawyer, Clair N., McCarty, Perry L., and Parkin, Gene F. (1994) Chemistry for Environmental Engineering, Fourth Edition, McGraw-Hill, Inc., New York, New York.

Schueler, Thomas R., Kumble, Peter A., and Hearaty, Maureen A. (1992) A current assessment of urban best management practices. Department of Environmental Programs, Metropolitan Washington Council of Governments, Washington, D.C.

Shaver, Earl and Baldwin, Robert (1991) Sand filter design for water quality treatment. State of Delaware Department of Natural Resources and Environmental Control, Dover, Delaware.

Stenkamp, V. Susie and Benjamin, Mark M. (1994) Effect of iron oxide coating on sand filtration. In: Journal of the American Water Works Association, Volume 86, No. 8, August 1994, Denver, Colorado.

Tchobanoglous, George and Burton, Franklin L (1991) Wastewater Engineering, Third Edition, Metcalf & Eddy, Inc., McGraw-Hill, Inc., New York, New York.

Truong, H.V. (1989) The sand filter water quality structure. Stormwater Management Branch, District of Columbia Environmental Regulation Administration, Washington, D.C.

Truong, H.V., Burrell, C.R., Phua, M.S., Dallas, R.D. (1993) Application of Washington D.C. sand filter for urban runoff control. Stormwater Management Branch, District of Columbia Environmental Regulation Administration, Washington, D.C.

Urbonas, Ben R., Doerfer, John T., and Tucker, L. Scott (1996) Stormwater sand filtration: a solution or a problem. In: ***APWA Reporter***, Volume 63, No. 6., July 1996, American Public Works Association, Washington, D.C.

Viraraghavan, T. (1986) Anaerobic filters for on-site effluents. In: Appropriate Wastewater Management Technologies for Rural Areas Under Adverse Conditions, Tech Press in Collaboration with the Centre for Water Resources Studies, Halifax, Nova Scotia, Canada.

Sand Filter at entrance to service station.

Sand Filter under construction. Note curb cuts for inflow to wet chamber with weir overflow into sand chamber.

General Intermittent Sand Filters

MINIMUM STANDARD 3.13

GRASSED SWALE

View BMP Images

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MINIMUM STANDARD 3.13

GRASSED SWALE

Definition

A grassed swale is a broad and shallow earthen channel vegetated with erosion resistant and flood-tolerant grasses. Check dams are strategically placed in the swale to encourage ponding behind them.

A water quality swale is a broad and shallow earthen channel vegetated with erosion resistant and flood tolerant grasses, and underlain by an engineered soil mixture.

Purpose

The purpose of grassed swales and water quality swales is to convey stormwater runoff at a non-erosive velocity in order to enhance its water quality through infiltration, sedimentation, and filtration. Check dams are used within the swale to slow the flow rate and create small, temporary ponding areas. A water quality swale is appropriate where greater pollutant removal efficiency is desired.

Water Quality Enhancement

Grassed swalesand water quality swales remove pollution through *sedimentation*, *infiltration*, and *filtration*. Water quality swales are specifically engineered to filter stormwater through an underlying soil mixture while grasses swales are designed to slow the velocity of flow to encourage settling and filtering through the grass lining. Vegetation filters out the sediments and other particulate pollutants from the runoff and increases the opportunity for infiltration and adsorption of soluble pollutants. The flow rate becomes a critical design element, since runoff must pass through the vegetation slowly for pollutant removal to occur. Monitoring of grassed swales has indicated low to moderate removal of soluble pollutants (phosphorous and nitrogen) and moderate to high removal of particulate pollutants.

Flood Control

Grassed swales and water quality swales will usually provide some peak attenuation depending on the storage volume created by the check dams. However, flood control should be considered a secondary function of grassed swales since the required storage volume for flood control is usually more than they can provide.

FIGURE 3.13 - 1
Typical Grassed Swale Configuration

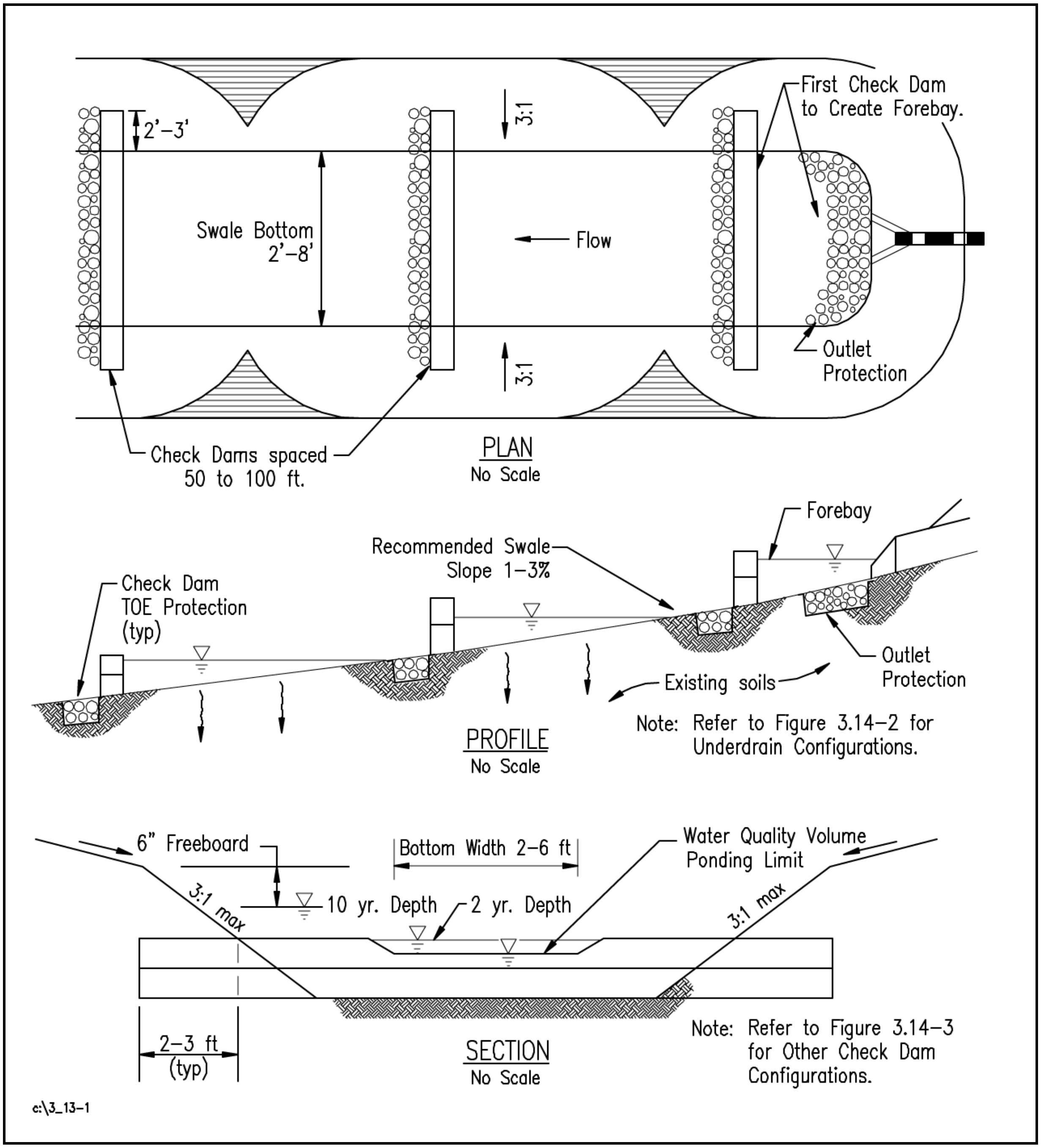


FIGURE 3.13 - 2
Typical Water Quality Swale Configuration

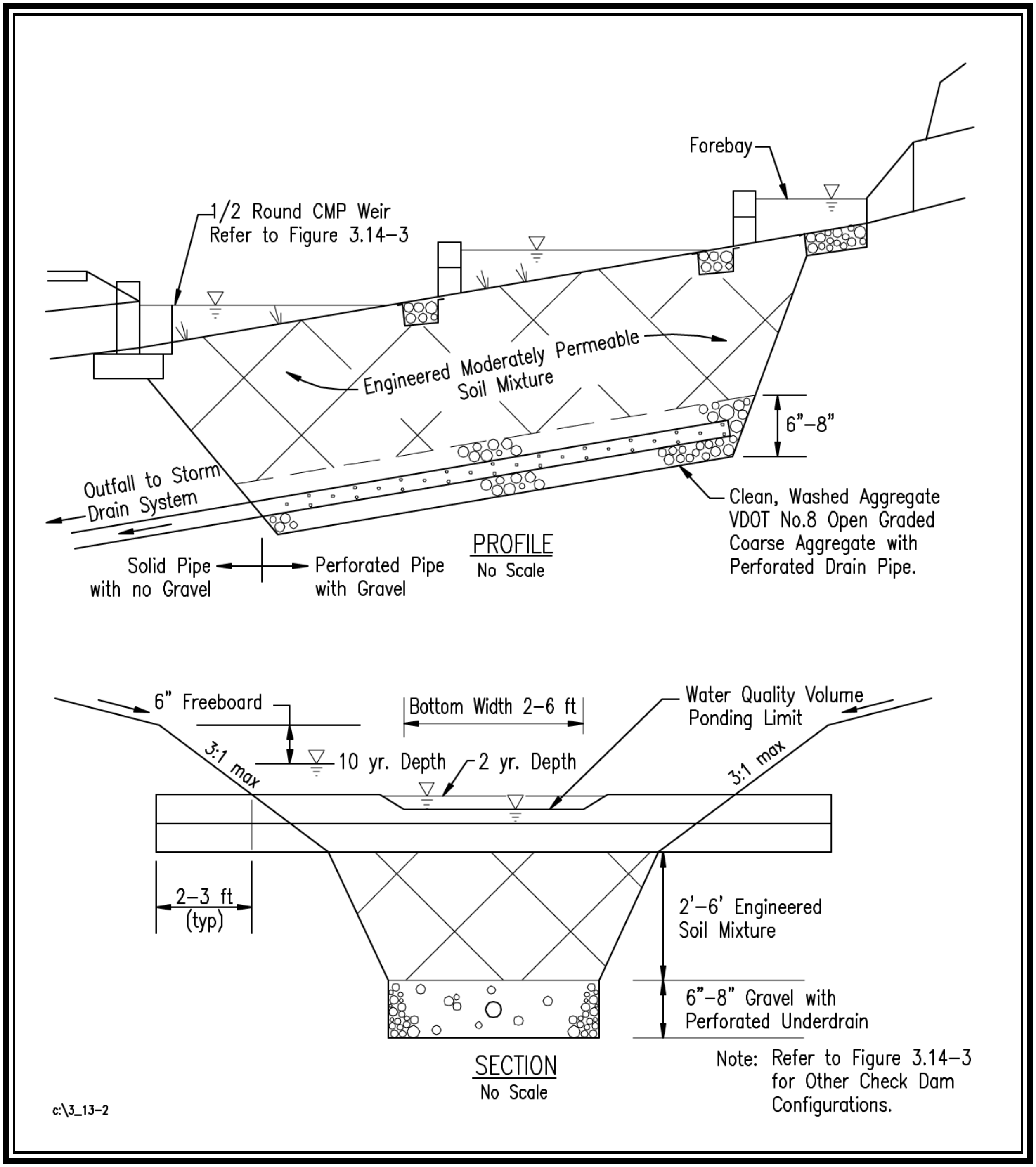


TABLE 3.13 - 1
Pollutant Removal Efficiency for Grassed Swales

Water Quality BMP	Target Phosphorus Removal Efficiency	Impervious Cover
Grassed Swale	15%	16 - 21%
Water Quality Swale	35%	16 - 37%

Channel Erosion Control

Grassed swales and water quality swales may also provide some benefits relative to channel erosion by reducing the peak rate of discharge from a drainage area. However, the holding capacity of a grassed swale designed for water quality purposes is limited.

Condition Where Practice Applies

Drainage Area

Grassed swales and water quality swales engineered for enhancing water quality cannot effectively convey large flows. Therefore, their contributing drainage areas must be kept small. The dimensions (length, width, and overall geometry) and slope of the swale, and its ability to convey the 10-year storm at a non-erosive velocity will set the size of the contributing drainage area.

Development Conditions

Grassed swales are commonly used instead of curb and gutter drainage systems in low- to moderate-density (16 to 21% impervious) single-family residential developments. Since grassed swales do not function well with high volumes or velocities of stormwater, they have limited application in highly urbanized or other highly impervious areas. However, swales may be appropriate for use in these areas if they are constructed in series or as pretreatment facilities for other BMPs.

Grassed swales are usually located within the right-of-way when used to receive runoff from subdivision or rural roadways. They may also be installed within drainage easements along the side or rear of residential lots. Grassed swales can be strategically located within the landscape to intercept runoff from small impervious surfaces (small parking lots, rooftops, etc.) as a component of a subdivision-wide or development-wide BMP strategy.

Water quality swales are appropriate for the same development conditions as those listed for grassed swales with the addition of higher densities of development (16 - 37% impervious) due to the increased pollutant removal capability.

Planning Considerations

Figure 3.13-1 pesents a grassed swale designed to hold small pockets of water behind each check dam. The water slowly drains through small openings in the chack dam and/or infiltrates into the ground. Slow channel velocities allow the vegetation to filter out sediments and other particulate pollutants from the runoff and increases the opportunity for infiltration and adsorption of soluble pollutants.

Figure 3.13-2 presents a water quality swale with an engineered soils media directly under the swale, with an underdrain. This design may be used in areas where the soils are not conducive to infiltration, or in developments where the swale is constructed beside a roadway using fill or compacted soils.

Site Conditions

The following items should be considered when selecting a grassed swale as a water quality BMP:

1. **Soils –** Grassed swales can be used with soils having moderate infiltration rates of 0.27 inches per hour (silt loam) or greater. Besides permeability, soils should support a good stand of vegetative cover with minimal fertilization.

   Water quality swales can be used in areas of unsuitable soil conditions for infiltration since the engineered soil mixture and underdrain system is used in place of the insitu soils.

2. **Topography –** The topography of the site should be relatively flat so that the swale can be constructed with a slope and cross-section that maintains low velocities and creates adequate storage behind the check dams.

3. **Depth to water table –** A shallow or seasonally-high groundwater table will inhibit the opportunity for infiltration. Therefore, the bottom of the swale should be at least 2 feet above the water table.

Sediment Control

Grassed swales may be used for conveyance of stormwater runoff during the construction phase of development. However, the swales should be maintained as required by the Virginia Erosion and Sediment Control Regulations and local program requirements. Before final stabilization, sediment must be removed from the swales and the soil surface prepared for final stabilization. Tilling of the swale bottom may be needed to open the surface pores and re-establish the soil's permeability.

Water quality swales should be constructed after a majority of the drainage area has been stabilized.

(Refer to **Min. Std. 3.11: Bioretention Facilities**).
This section presents minimum criteria and recommendations for the design of grassed swales used to enhance water quality. It is the designer's responsibility to decide which criteria are applicable to the particular swale being designed and to decide if any additional design elements are required. The designer must also provide for the long-term functioning of the facility by choosing appropriate structural materials.

Design Criteria

The design of a water quality grassed swale includes calculations for traditional swale parameters (flow rate, maximum permissible velocities, etc.) along with storage volume calculations for the water quality volume.

Hydrology

The hydrology of a grassed swale's contributing drainage area should be developed per **Chapter 4, Hydrologic Methods**.

Swale Geometry

A grassed swale should have a trapezoidal cross-section to spread flows across its flat bottom. Triangular or parabolic shaped sections will concentrate the runoff and should be avoided. The side slopes of the swale should be no steeper than 3H:1V to simplify maintenance and to help prevent erosion.

Bottom Width

The bottom width of the swale should be 2 feet minimum and 6 feet maximum in order to maintain sheet flow across the bottom and to avoid concentration of low flows. The actual design width of the swale is determined by the maximum desirable flow depth, as discussed below.

Flow Depth

The flow depth for a water quality grassed swale should be approximately the same as the height of the grass. An average grass height for most conditions is 4 inches. Therefore, the maximum flow depth for the water quality volume should be 4 inches (Center for Watershed Protection, 1996).

Flow Velocity

The maximum velocity of the water quality volume through the grassed swale should be no greater than 1.5 feet per second. The maximum design velocity of the larger storms should be kept low enough so as to avoid resuspension of deposited sediments. The 2-year storm recommended maximum design velocity is 4 feet per second and the 10-year storm recommended maximum design velocity is 7 feet per second.

Longitudinal Slope

The slope of the grassed swale should be as flat as possible, while maintaining positive drainage and uniform flow. The minimum constructable slope is between 0.75 and 1.0%. The maximum slope depends upon what is needed to maintain the desired flow velocities and to provide adequate storage for the water quality volume, while avoiding excessively deep water at the downstream end. Generally, a slope of between 1 and 3% is recommended. The slope should never exceed 5%.

Swale length

Swale length is dependent on the swale's geometry and the ability to provide the required storage for the water quality volume.

Swale Capacity

The capacity of the grassed swale is a combined function of the flow volume (the water quality volume) and the physical properties of the swale such as longitudinal slope and bottom width. By using the Manning equation or channel flow nomographs, the depth of flow and velocity for any given set of values can be obtained. The Manning's '*n*' value, or roughness coefficient, varies with the depth of flow and vegetative cover. An '*n*' value of 0.15 is appropriate for flow depths of up to 4 inches (equal to the grass height). The *n* value decreases to a minimum of 0.03 for grass swales at a depth of approximately 12 inches.

A grassed swale should have the capacity to convey the peak flows from the 10-year design storm without exceeding the maximum permissible velocities. (Note that a maximum velocity is specified for the 2-year and 10-year design storms to avoid resuspension of deposited sediments and other pollutants and to prevent scour of the channel bottom and side slopes.) The swale should pass the 10-year flow over the top of the check dams with 6 inches, minimum, of freeboard. As an alternative, a bypass structure may be engineered to divert flows from the larger storm events (runoff greater than the water quality volume) around the grassed swale. However, when the additional area and associated costs for a bypass structure and conveyance system are considered, it may be more economical to simply increase the bottom width of the grassed swale. It should then be designed to carry runoff from the 10-year frequency design storm at the required permissible velocity.

The longitudinal slope and the bottom width may be adjusted to achieve the maximum allowable velocity according to the Manning equation:

$$Q = \left[\frac{1.49}{n} r^{2/3} s^{1/2}\right] A$$

Equation 3.13-1
Manning Equation

Where:
- Q = peak flow rate, cfs
- n = Manning's roughness coefficient
- r = hydraulic radius, ft. = A / wp
- s = longitudinal slope of the channel
- A = cross-sectional area of the channel, ft^2

The portion of the equation within the brackets represents the velocity of flow. **Equation 3.13-1** can be rewritten as:

$$Q = VA$$

Equation 3.13-2
Continuity Equation

Where:
- Q = peak flow rate, cfs
- V = flow velocity, ft/s = $\frac{1.49}{n} r^{2/3} s^{1/2}$
- A = *cross-sectional area of the channel,* ft^2.

Additional guidance on the use of the Manning equation for the design of grassed swales is provided in the Virginia Erosion and Sediment Control Handbook (VESCH), 1992 edition.

Water Quality Volume

If a grassed swale is used as a conveyance channel, its purpose is to transport stormwater to the discharge point. However, the purpose of a water quality grassed swale is to slow the water as much as possible to encourage pollutant removal.

The use of check dams will create segments of the swale which will be inundated for a period of time. The required total storage volume behind the check dams is equal to the water quality volume for the contributing drainage area to that point. However, the maximum ponding depth behind the check dams should not exceed 18 inches. To insure that this practice does not create nuisance conditions, an analysis of the subsoil should be conducted to verify its permeability.

Underlying Soil Bed - Water Quality Swales

An underlying engineered soil bed and underdrain system may be utilized in areas where the soils are not permeable and the swale would remain full of water for extended periods of time (creating nuisance conditions). This soil bed should consist of a moderately permeable soil material with a high level of organic matter: 50% sand, 20% leaf mulch, 30% top soil. The soil bed should be 30 inches deep and should be accompanied by a perforated pipe and gravel underdrain system.

In residential developments with marginal soils, it may be appropriate to provide a soil bed and underdrain system in all grassed swales to avoid possible safety and nuisance concerns.

Check Dams

The use of check dams in a grassed swale should be per the following criteria:

1. **Height –** A maximum height of 18 inches is recommended, and the dam height should not exceed one-half the height of the swale bank.

2. **Spacing –** Spacing should be such that the slope of the swale and the height of the check dams combine to provide the required water quality volume behind the dams.

3. **Abutments –** Check dams should be anchored into the swale wall a minimum of 2 to 3 feet on each side.

4. **Toe Protection –** The check dam toe should be protected with riprap placed over a suitable geotextile fabric. The size (D_{50}) of the riprap should be based on the design flow in the swale. Class A1 Riprap is recommended.

5. **Overflow –** A notch should be placed in the top of the check dam to allow the 2-year peak discharge to pass without coming into contact with the check dam abutments, or the abutments may be protected with a non-erodible material. Six inches of freeboard should be provided between the 10-year overflow and the top of the swale.

6. **Riprap check dams –** Rip rap check dams should consist of a VDOT No. 1 Open-graded Coarse Aggregate core keyed into the ground a minimum of 6 inches, with a Class A1 riprap shell.

7. **Filter fabric –** Filter fabric is required under riprap and gabion check dams.

8. **Driveway culvert weirs –** Where a driveway culvert is encountered, a ½ round corrugated metal pipe weir bolted to the concrete driveway headwall may be utilized as a check dam, or a timber check dam placed at least one foot upstream of the culvert opening.

Outlets

Discharges from grassed swales must be conveyed at non-erosive velocities to either a stream or a stabilized channel to prevent scour at the outlet of the swale. Refer to VESCH, 1992 edition for design procedures and specifications regarding outlet stabilization.

Inflow Points

Swale inflow points should be protected with erosion controls as needed (e.g., riprap, flow spreaders, energy dissipators, sediment forebays, etc.).

Vegetation

A dense cover of water-tolerant, erosion-resistant grass or other vegetation must be established. Grasses used in swales should have the following characteristics:

- a deep root system to resist scouring,
- a high stem density, with well-branched top growth,
- tolerance to flooding,
- resistance to being flattened by runoff, and
- an ability to recover growth following inundation.

Recommended grasses include, but are not limited to, the following: Kentucky-31 tall fescue, reed canary grass, redtop, and rough-stalked blue grass. Note that these grasses can be mixed.

The selection of an appropriate vegetative lining for a grassed swale is based on several factors including climate, soils, and topography. For additional information, refer to STD. & SPEC. 3.32: Permanent Seeding in VESCH, 1992 edition.

Erosion control matting should be used to stabilize the soil before seed germination. This protects the swale from erosion during the germination process. In most cases, the use of sod is warranted to provide immediate stabilization on the swale bottom and/or side slopes. Refer to STD. & SPEC. 3.33: Sodding in VESCH, 1992 edition for additional information.

Construction Specifications

Overall, widely accepted construction standards and specifications, such as those developed by the USDA Soil Conservation Service or the U. S. Army Corps of Engineers, should be followed where applicable. Further guidance can be found in the SCS Engineering Field Manual. Specifications for the work should conform to the methods and procedures specified for earthwork, concrete, reinforcing steel, woodwork and masonry, as they apply to the site and the purpose of the structure. The specifications should also satisfy any requirements of the local government.

Sequence of Construction

The construction of grassed swales should be coordinated with the overall project construction schedule. The swale may be excavated during the rough grading phase of the project to permit use of the excavated material as fill in earthwork areas. Otherwise, grassed swales should not be constructed or placed into service until the entire contributing drainage area has been stabilized. Runoff from untreated, recently constructed areas may load the newly formed swale with a large volume of fine sediment. This could seriously impair the swale's natural infiltration ability.

The specifications for construction of a grassed swale should state the following:

- the earliest point in progress when storm drainage may be directed to the swale, and
- the means by which this delay in use will be accomplished.

Due to the wide variety of conditions encountered among projects, each project should be evaluated separately evaluated to decide how long to delay use of the swale.

Excavation

Initially, the swale should be excavated to within one foot of its final elevation. Excavation to the finished grade should be deferred until all disturbed areas in the watershed have been stabilized or protected. The final phase of excavation should remove all accumulated sediment. When final grading is completed, the swale bottom should be tilled with rotary tillers or disc harrows to provide a well-aerated, highly porous surface texture.

Vegetation

Establishing dense vegetative cover on the swale side slopes and floor is required. This cover will not only prevent erosion and sloughing, but will also provide a natural means to maintain relatively high infiltration rates.

Selection of suitable vegetative materials and application of required fertilizer and mulch should be per VESCH, 1992 edition.

Materials

1. **Check dams –** Check dams shall be constructed of a non-erosive material such as wood, gabions, riprap, or concrete. All check dams shall be underlaid by filter fabric per Std. & Spec 3.19: Rip Rap of VESCH, 1992 edition.

    a. *Wood* - pressure treated logs or timbers, or water-resistant tree species such as cedar, hemlock, swamp oak or locust.

    b. *Gabions* - hexagonal triple twist mesh with PVC coated galvanized steel wire. The maximum linear dimension of the mesh opening shall not exceed 4.5 inches. The area of the mesh opening shall not exceed 10 square inches.

    Stone or riprap for gabions shall be sized according to **Table 3.13-2**. It shall consist of field stone or rough unhewn quarry stone. The stone shall be hard and angular and of a quality that will not disintegrate with exposure to water or weathering. The specific gravity of the individual stones shall be at least 2.5.

    Recycled concrete may be used if it has a density of at least 150 pounds per cubic foot and does not have any exposed steel or reinforcing bars.

    c. *Riprap* - all riprap shall conform with VESCH Std. & Spec 3.19: Riprap, and VDOT Standards for open graded course aggregate.

    d. *Concrete* - All concrete shall conform with VDOT or SCS specifications.

2. **Underlying soil medium –** The underlying soils should consist of the following:

    a. *Soil* - USDA *ML, SM,* or *SC.*

    b. *Sand* - ASTM C-33 fine aggregate concrete sand; VDOT fine aggreagate, grading A or B.

3. **Pea Gravel –** Pea gravel should consist of washed ASTM M-43; VDOT No. 8 Open-graded Course Aggregate.

4. **Underdrain** – An underdrain system below the swale bottom shall consist of the following:

a. *Gravel* - AASHTO #7, ASTM M-43, VDOT No. 3 Open-graded Course Aggregate.

b. *PVC Pipe* - AASHTO M-278, 4-inch rigid schedule 40, perforations of 3/8-inch diameter at 6-inch centers, 4 holes per row.

c. *Filter fabric* - shall be per specifications found in VESCH, 1992 edition.

TABLE 3.13 - 2
Stone or Riprap Sizes for Gabion Baskets

Basket Thickness		**Stone Size** ***(in.)***
(in.)	***(mm.)***	
6	150	3 - 5
9	225	4 - 7
12	300	4 - 7
18	460	4 - 7
36	910	4 - 12

Maintenance and Inspection Guidelines

Maintenance of grassed swales includes upkeep of the vegetative cover and preservation of the swale's hydraulic properties. Individual land owners can usually carry out the suggested maintenance procedures for the swale or the portion of the swale on their property. To ensure continued long term maintenance, all affected landowners should be made aware of their maintenance responsibilities, and maintenance agreements should be included in land titles.

The following maintenance and inspection guidelines are not intended to be all-inclusive. Specific swales may require other measures not discussed here. It is the engineer's responsibility for determining if any additional items are necessary.

Vegetation

A dense and vigorous grass cover should be maintained in a grassed swale. This will be simplified if the proper grass type is selected in the design. Periodic mowing is required to keep the swale operating properly. Grass should never be cut to a height less than 3 inches. Ideally, a grass stand of 6 inches is most effective. Stabilization and reseeding of bare spots should be performed, as needed.

Check Dams

Properly constructed check dams should require very little maintenance since they are made of non-erodible materials. Periodic removal of sediment accumulated behind the check dams should be performed, as needed.

Debris and Litter Removal

The accumulation of debris (including trash, grass clippings, etc.) in the swale can alter the hydraulics of the design and lead to additional maintenance costs. Debris can also alter the flow path along the swale bottom causing low flows to concentrate and result in erosion of the swale bottom. As with any BMP, frequent inspections by the land owner will help prevent small problems from becoming larger.

Sediment Removal

The sediment that accumulates within the swale should be manually removed and the vegetation reestablished. If accumulated sediment has clogged the surface pores of the swale, reducing or eliminating the infiltration capacity, then the surface should be tilled and restabilized. Drilling or punching small holes into the surface layer can be used instead of tilling, if desired.

FIGURE 3.13 - 3
Typical Check Dam Configurations

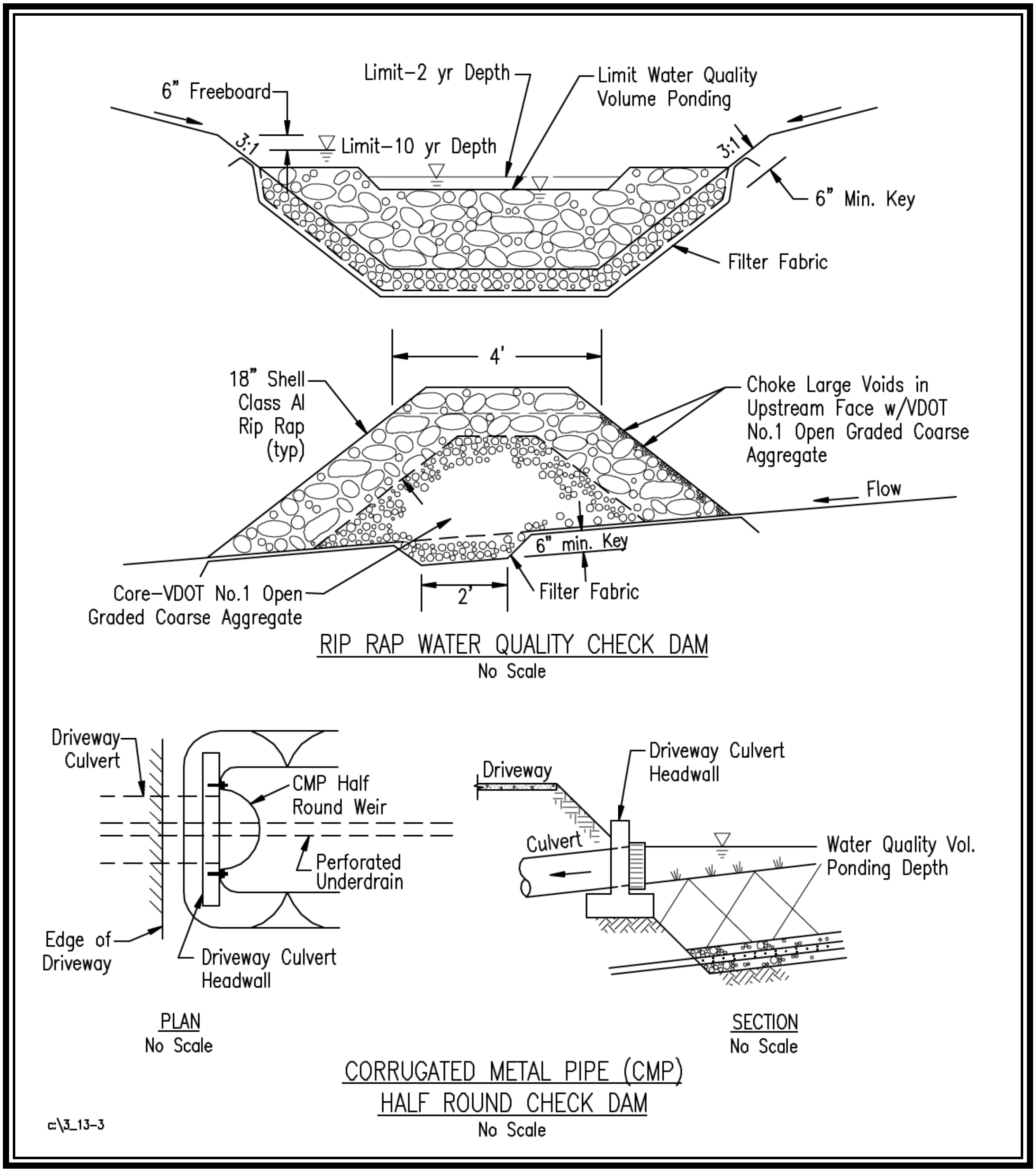
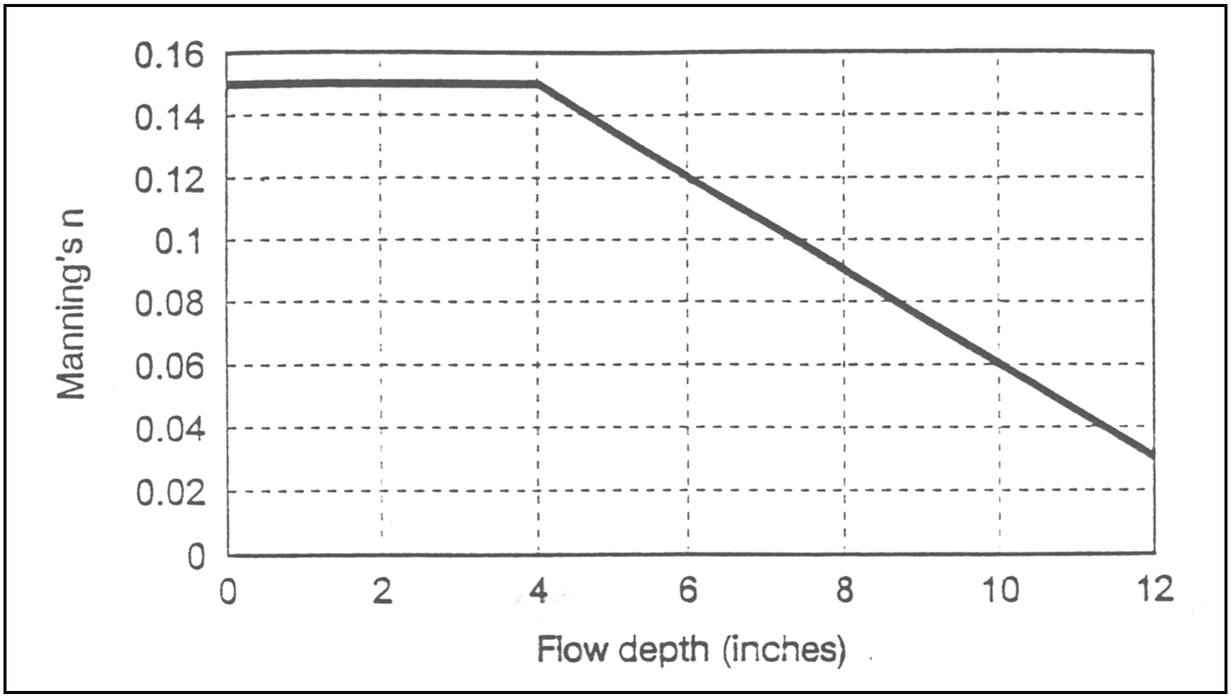


FIGURE 3.13 - 4
Manning's 'n' Values for Varying Depths of Flow



Design Procedures

The following design procedure represents a generic list of the steps typically required for the design of a *water quality grassed swale*.

1. Determine if the anticipated development conditions and drainage area are appropriate for a water quality grassed swale BMP.

2. Determine if the soils (permeability, bedrock, Karst, etc.) and topographic conditions (slopes, existing utilities, environmental restrictions) are appropriate for a grassed swale BMP.

3. Determine any additional stormwater management requirements (channel erosion, flooding) for the project.

4. Locate the grassed swale BMP(s) on the site.

5. Determine the hydrology and calculate the 2-year and 10-year peak discharges (**Chapter 4, Hydrologic Methods**), and the water quality volume for the contributing drainage area.

6. Approximate the geometry of the grassed swale and evaluate water quality parameters: water quality depth of flow (recommended maximum of 4 inches), and storage volume behind check dams (water quality volume). Adjust swale geometry and re-evaluate as needed.

7. Evaluate the grassed swale geometry for the the 2-year design storm peak discharge velocity (4 feet per second), and capacity (check dam overflow), and the 10-year design storm peak discharge velocity (7 feet per second) and capacity (6 inches of freeboard). (**Chapter 5, Engineering Calculations**). Adjust swale geometry and re-evaluate as needed.

8. Establish specifications for appropriate permenant vegetation on the bottom and side slopes of the grassed swale.

9. Establish specifications for sediment control.

10. Establish construction sequence and construction specifications.

11. Establish maintenance and inspection requirements.

REFERENCES

Arnold, J.A., ed., D.E. Line, S.W. Coffey, and J. Spooner. Stormwater Management Guidance Manual. Raleigh, North Carolina: North Carolina Cooperative Extension Service and North Carolina Division of Environmental Management, 1993.

Center for Watershed Protection. Design of Stormwater Filtering Systems. Silver Spring, Maryland: 1996

Chesapeake Bay Local Assistance Department. Chesapeake Bay Local Assistance Manual. Richmond, Virginia: 1989.

Galli, John. Analysis of Urban BMP Performance and Longevity. Washington, District of Columbia: Metropolitan Washington Council of Governments, 1992.

Hampton Roads Planning District Commission. Vegetative Practices Guide for Nonpoint Source Pollution Management. Chesapeake, Virginia: 1992.

Northern Virginia Planning District Commission and Engineers and Surveyors Institute. Northern Virginia BMP Handbook. Annandale, Virginia: 1992.

Schueler, T.R., P.A. Kumble, and M.A. Heraty. A Current Assessment of Urban Best Management Practices. Washington, District of Columbia: Metropolitan Washington Council of Governments 1992.

Virginia Department of Conservation and Recreation. Virginia Erosion and Sediment Control Handbook (VESCH). Richmond, Virginia: 1992.

Grass Swale. Note stone check dam in front of inlet creates shallow ponding area to encourage infiltration and settling.

Grass Swale through residential area. Note flat slope to encourage infiltration – ponding water gone within hours of runoff producing event.

Grassed Swale

Chapter 3.13

Grass Swale with Check Dams. Note significant channel storage capacity created by check dams. Notched center allows safe overflow without scour around sides.

Grassed Swale

MINIMUM STANDARD 3.14

VEGETATED FILTER STRIP

View BMP Images

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MINIMUM STANDARD 3.14

VEGETATED FILTER STRIP

Definition

A vegetated filter strip is a densely vegetated strip of land engineered to accept runoff from upstream development as *overland sheet flow*. It may adopt any naturally vegetated form, from grassy meadow to small forest.

Purpose

The purpose of a vegetated filter strip is to enhance the quality of stormwater runoff through filtration, sediment deposition, infiltration and absorption.

A vegetated filter strip may be used as a pretreatment BMP in conjunction with a primary BMP. This reduces the sediment and particulate pollutant load that could reaching the primary BMP, which, in turn, reduces the BMP's maintenance costs and enhances its pollutant removal capabilities.

TABLE 3.14 - 1
Pollutant Removal Efficiency for Vegetated Filter Strips

BMP	Target Phosphorus Removal Efficiency	Impervious Cover
Vegetated Filter Strip	10%	16 - 21%

Vegetated filter strips rely on their flat cross-slope and dense vegetation to enhance water quality. Their flat cross-slope assures that runoff remains as sheet flow while filtering through the vegetation. There is limited ponding or storage associated with these BMPs, so they are ineffective for reducing peak discharges. Vegetated filter strips may lower runoff velocities and, sometimes, runoff volume. Typically, however, the volume reduction is not adequate for controlling stream channel erosion or flooding.

Conditions Where Practice Applies

Drainage Area

A vegetated filter strip should not receive large volumes of runoff since such flows tend to concentrate and form channels. Channels within a filter strip allow runoff to short-circuit the BMP, rendering it ineffective. Therefore, the contributing drainage area for a vegetated filter strip is based on the linear distance behind it that is maintained as sheet flow. Runoff is assumed to change from sheet flow to shallow concentrated flow after traveling 150 feet over **pervious** surfaces and 75 feet over **impervious** surfaces (Center for Watershed Protection, 1996). A level spreader may be used to convert shallow concentrated flow from larger areas back to sheet flow before it enters the filter strip. In any event, the contributing drainage area should never exceed five acres.

Development Conditions

Vegetated filter strips have historically been used and proven successful on agricultural lands, primarily due to their low runoff volumes. In urban settings, filter strips are most effective in treating runoff from isolated impervious areas such as rooftops, small parking areas, and other small impervious areas. Filter strips should not be used to control large impervious areas.

Since vegetated filter strips should not be used to treat concentrated flows, they are suitable only for low- to medium-density development (16-21% impervious), or as a pretreatment component for structural BMPs in higher density developments.

Planning Considerations

Site Conditions

The following site conditions should be considered when selecting a vegetated filter strip as a water quality BMP:

1. **Soils –** Vegetated filter strips should be used with soils having an infiltration rate of 0.52 inches/hour; (sandy loam, loamy sand). Soils should be capable of sustaining adequate stands of vegetation with minimal fertilization.

2. **Topography –** Topography should be relatively flat to maintain sheet flow conditions. Filter strips function best on 5 percent or less (NVPDC).

3. **Depth of Water Table –** A shallow or seasonally high groundwater table will inhibit the opportunity for infiltration. Therefore, the lowest elevation in the filter strip should be at least 2 feet above the water table.

If the soil's permeability and/or depth to water table are unsuitable for infiltration, the filter strip's primary function becomes the filtering and settling of pollutants. A modified design may be provided to allow ponding of the water quality volume at the filter's downstream end. The ponding area may be created by constructing a small permeable berm using a select soil mixture. (For berm details, see the Pervious Berm section in this standard.) The maximum ponding depth behind the berm should be 1foot.

Water Quality Enhancement

Vegetated filter strips are occasionally installed as a standard feature in residential developments. To be used as a water quality BMP, however, filter strips must comply with certain design criteria. Vegetated filter strip designs should include specific construction, stabilization, and maintenance specifications. The most significant requirement is for runoff to be received as sheet flow. Certain enhancements may be necessary, such as added vegetation and grading specifications, or the use of level spreaders, to ensure that runoff enters the filter strip as sheet flow.

Sediment Control

A natural area that is designed to serve as a vegetated filter strip should not be used for temporary sediment control. Sediment deposition may have significant impacts on the existing vegetation. If a vegetated filter strip is proposed in a natural area marginally acceptable for use, due to topography or existing vegetation, then it may be appropriate to use the filter strip for temporary sediment control. However, when the project is completed, the sediment accumulation should be removed, the area should be regraded to create the proper design conditions (sheet flow), and the strip should be re-stabilized per the landscaping plan.

Design Criteria

This section provides recommendations and minimum design criteria for vegetated filter strips intended to enhance water quality. It is the designer's responsibility to decide which criteria are applicable to the each facility and to decide if any additional design elements are required. The designer must also provide for the long-term functioning of the BMP.

Hydrology

The hydrology of a filter strip's contributing drainage area should be developed per **Chapter 4, Hydrologic Methods**.

Filter Strip Geometry

Compliance with the following parameters will result in optimal filter strip performance (NVPDC):

1. **Length** – The minimum length of a filter strip should be 25 feet, at a maximum slope of 2 percent. The length should increase by 4 feet for any 1 percent increase in slope. **The optimum filter strip length is 80 to 100 feet**.

2. **Width –** The width of the filter strip (perpendicular to the slope) should be equal to the width of the contributing drainage area. When this is not practical, a level spreader should be used to reduce the flow width to that of the filter strip. The level spreader's width will determine the depth of flow and runoff velocity of the stormwater as it passes over the spreader lip and into the filter strip. A wide lip will distribute the flow over a longer level section, which reduces the potential for concentrated flow across the filter.

3. Slope – The slope of the filter strip should be as flat as possible while allowing for drainage. Saturation may occur when extremely flat slopes are used.

Level Spreader

A level spreader should be provided at the upper edge of a vegetated filter strip when the width of the contributing drainage area is greater than that of the filter (see Figure **3.14-2**.) Runoff may be directed to the level spreader as sheet flow or concentrated flow. However, the design must ensure that runoff fills the spreader evenly and flows over the level lip as uniformly as possible. The level spreader should extend across the width of the filter, leaving only 10 feet open on each end.

Pervious Berm

To force ponding in a vegetated filter strip, a pervious berm may be installed. It should be constructed using a moderately permeable soil such as ASTM *ML*, *SM*, or *SC*. Soils meeting USDA sandy loam or loamy sand texture, with a minimum of 10 to 25% clay, may also be used. Additional loam should be used on the berm (± 25%) to help support vegetation. An armored overflow should be provided to allow larger storms to pass without overtopping the berm. **Maximum ponding depth behind a pervious berm is 1 foot**.

Vegetation

A filter strip should be densely vegetated with a mix of erosion resistant plant species that effectively bind the soil. Certain plant types are more suitable than others for urban stormwater control. The selection of plants should be based on their compatibility with climate conditions, soils, and topography and the their ability to tolerate urban stresses from pollutants, variable soil moisture conditions and ponding fluctuations. Virginia has three major physiographic regions that reflect changes in soils and topography: Coastal Plain, Piedmont, and Appalachian and Blue Ridge regions (see **Figure 3.14- 3**).

A filter strip should have at least two of the following vegetation types:

- *deep-rooted grasses, ground covers, or vines*
- *deciduous and evergreen shrubs*
- *under- and over-story trees*

Native plant species should be used if possible. Non-native plants may require more care to adapt to local hydrology, climate, exposure, soil and other conditions. Also, some non-native plants may become invasive, ultimately choking out the native plant population. This is especially true for non-native plants used for stabilization.

Newly constructed stormwater BMPs will be fully exposed for several years before the buffer vegetation becomes adequately established. Therefore, plants which require full shade, are susceptible to winter kill or are prone to wind damage should be avoided.

Plant materials should conform to the American Standard for Nursery Stock, current issue, as published by the American Association of Nurserymen. The botanical (scientific) name of the plant species should be according to the landscape industry standard nomenclature. All plant material specified should be suited for USDA Plant Hardiness Zones 6 or 7 (see **Figure 3.14- 4**).

Construction Specifications

Overall, widely accepted construction standards and specifications, such as those developed by the USDA Soil Conservation Service or the U.S. Army Corps of Engineers, should be followed where applicable to construct a vegetated filter strip. The specifications should also satisfy all requirements of the local government.

Sequence of Construction

Vegetated filter strip construction should be coordinated with the overall project construction schedule. Rough grading of the filter strip should not be initiated until adequate erosion controls are in place.

Soil Preparation

Topsoil should be 8 inches thick, minimum. If grading is necessary, the topsoil should be removed and stockpiled. If the subsoil is either highly acidic or composed of heavy clays, ground dolomite limestone should be applied at an appropriate rate based on soil and slope conditions.

Subsoil should be tilled to a depth of at least 3 inches to adequately mix in soil additives and to permit bonding of the topsoil to the subsoil. If the existing topsoil is inadequate to support a densely vegetated filter strip, then suitable material should be imported. Proper specifications for imported topsoil should include the following:

1. *The USDA textural triangle classification.*

2. *Requirements for organic matter content (not less than 1.5% by weight), pH (6 to 7.5), and soluble salt (not greater than 500 parts per million).*

3. *Placement thickness and compaction. Topsoil should be uniformly distributed and compacted, and should have a minimum compacted depth of 6 to 8 inches.*

All seeding, fertilization, and mulching should be per the Virginia Erosion and Sediment Control Handbook (VESCH), 1992 edition, or as specified by a qualified agronomist.

Maintenance/Inspection Guidelines

Vegetated filter strips require regular maintenance. Field studies indicate that these BMPs usually have short life spans because of lack of maintenance, improper location, and poor vegetative cover.

The following maintenance and inspection guidelines are **NOT** all-inclusive. Specific facilities may require other measures not discussed here. It is the designer's responsibility to decide if additional measures are necessary.

Filter strips should be inspected regularly for gully erosion, density of vegetation, damage from foot or vehicular traffic, and evidence of concentrated flows circumventing the strip. The level spreader should also be inspected to verify that it is functioning as intended.

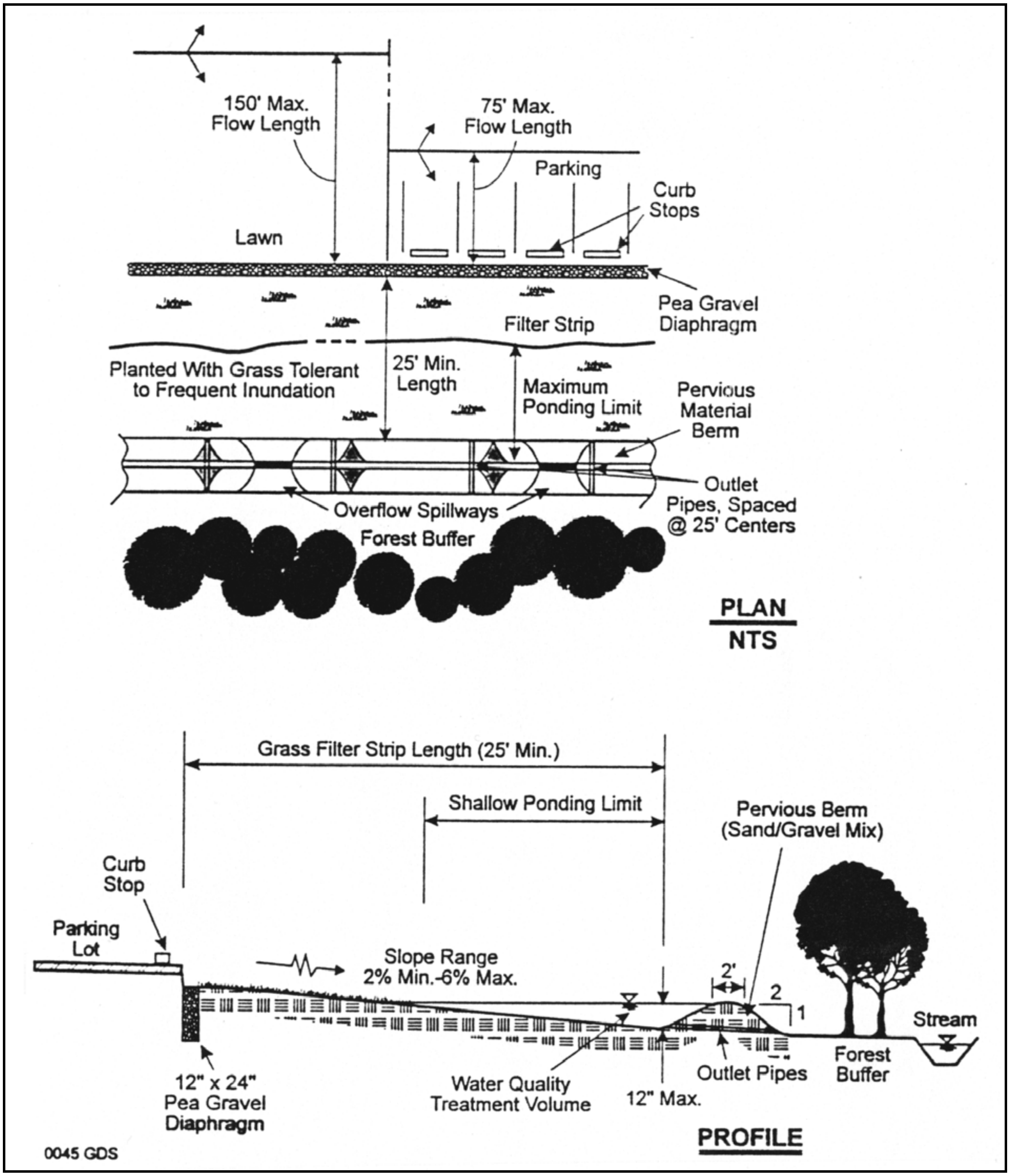
Inspections are critical during the first few years to ensure that the strip becomes adequately established. Maintenance is especially important during this time and should include watering, fertilizing, re-seeding or planting as needed.

Once a filter strip is well established and functioning properly, periodic maintenance, such as watering, fertilizing and spot repair, may still be necessary. However, fertilization efforts should be minimized. Natural selection allows certain species (usually native plants) to thrive while others decline. Excessive fertilization and watering to maintain individual plantings may prove costly, especially in abnormally dry or hot seasons. Overseeding and replanting should be limited to those species which have exhibited the ability to thrive.

To increase the functional longevity of a vegetated filter strip, the following practices are recommended:

- *Regular removal of accumulated sediment,*
- *periodic reestablishment of vegetation in eroded areas or areas covered by accumulated sediment,*
- *periodic weeding of invasive species or weeds, and*
- *periodic pruning of woody vegetation to stimulate growth.*

FIGURE 3.14 - 1
Vegetated Filter Strip



Source: Design of Stormwater Filtering Systems, Center for Watershed Protection,1996

FIGURE 3.14 - 2

Level Spreader

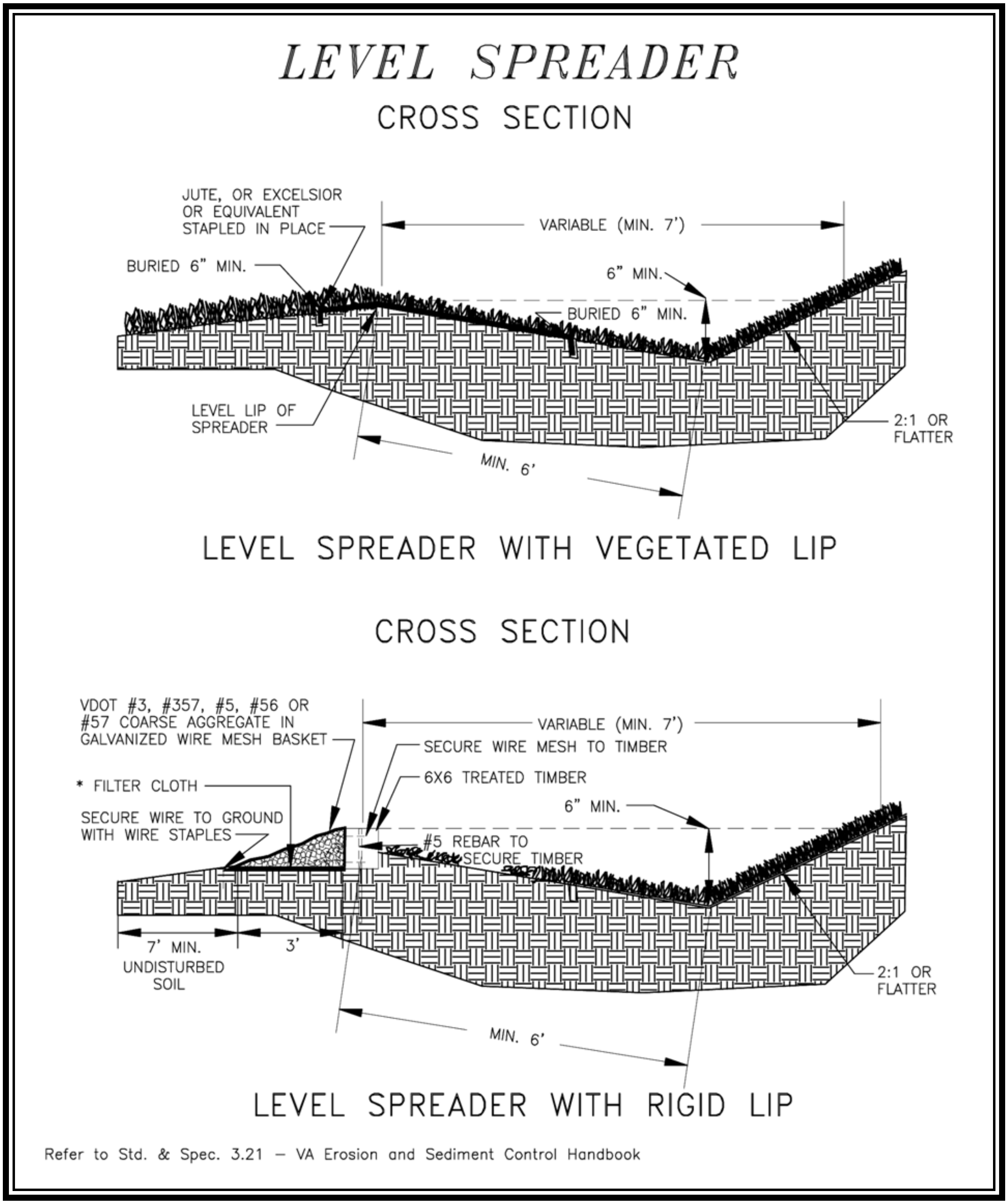


FIGURE 3.14 - 3
Virginia Physiographic Regions

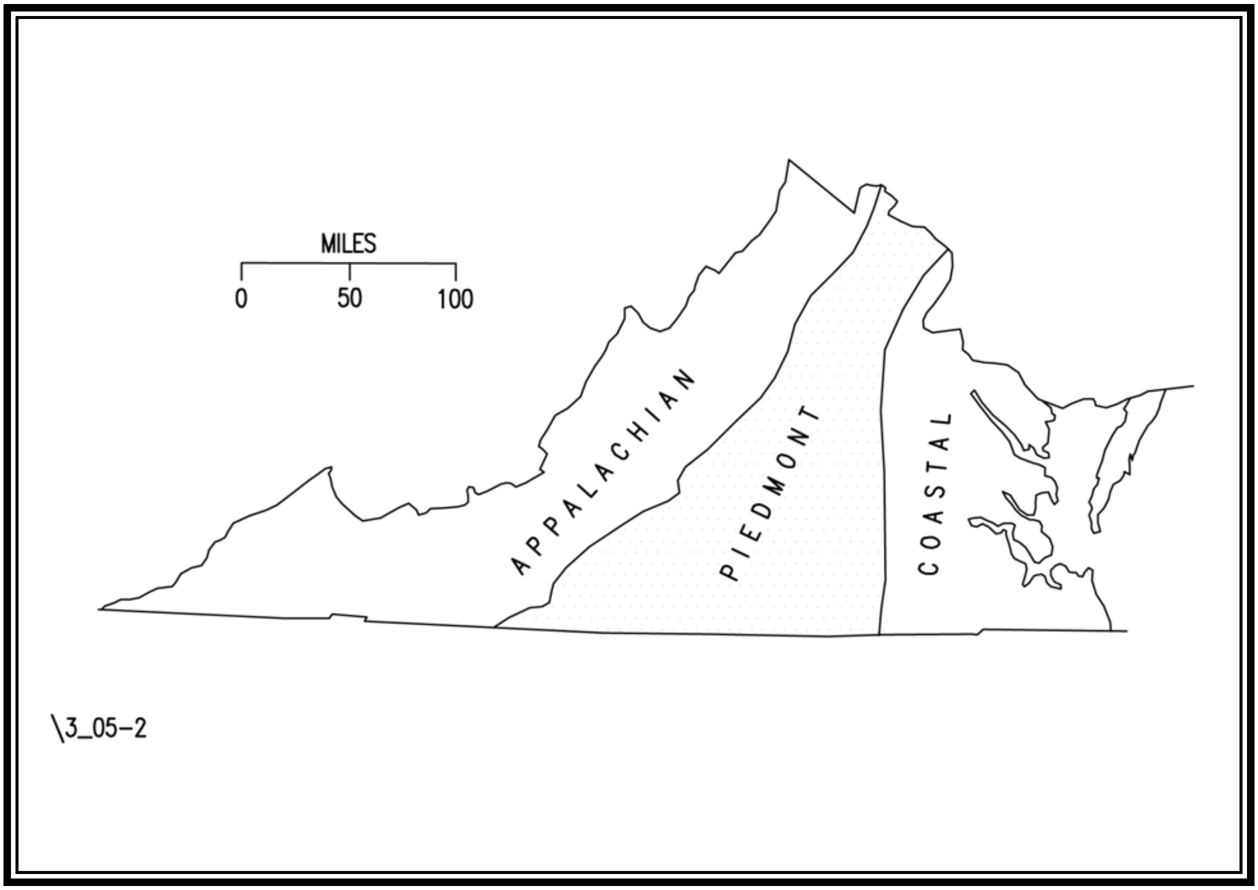
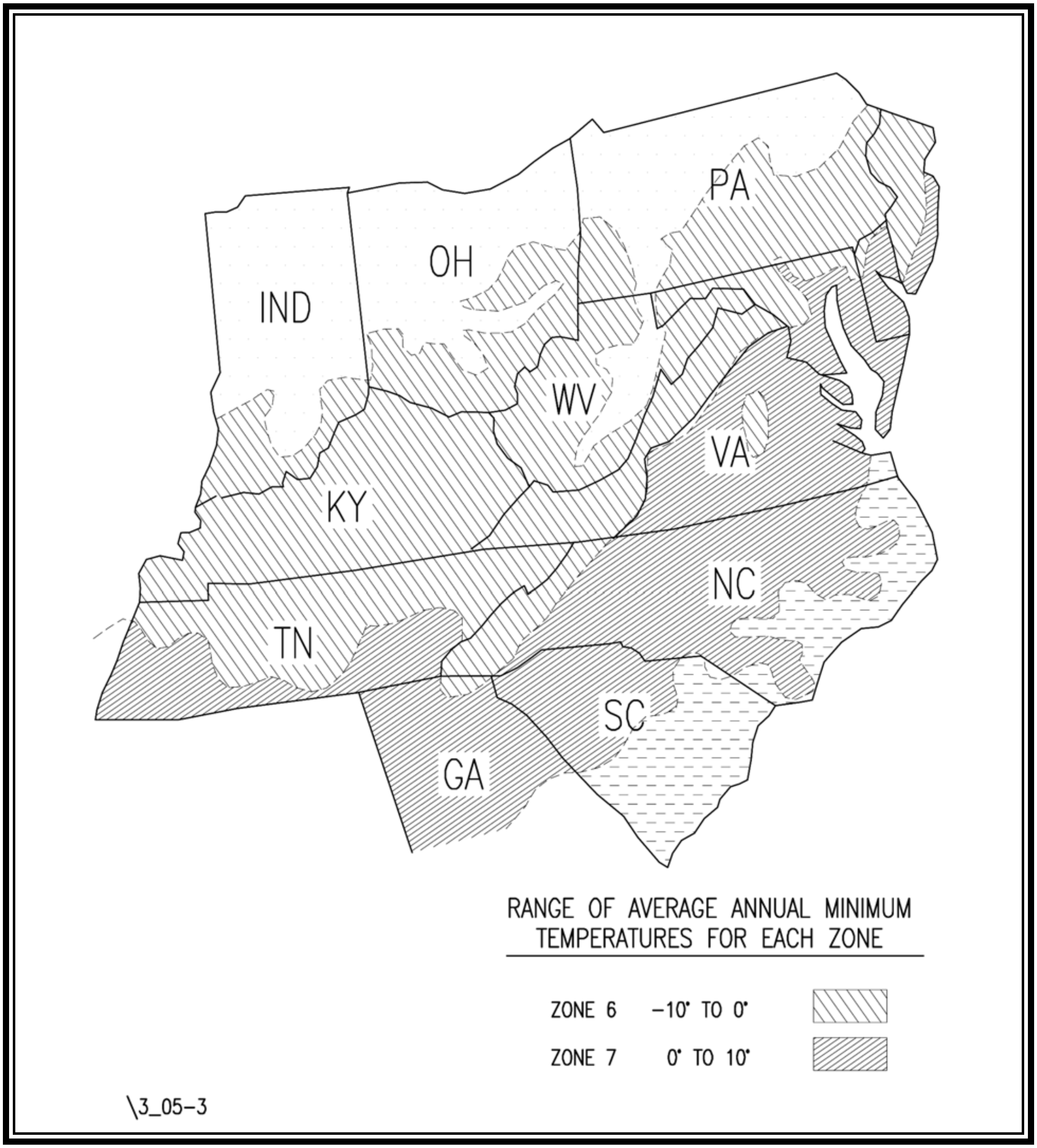


FIGURE 3.14 - 4
USDA Plant Hardiness Zones



REFERENCES

Arnold, J.A., ed., D.E. Line, S. W. Coffey, and J. Spooner. Stormwater Management Guidance Manual. Raleigh, North Carolina: North Carolina Cooperative Extension Service and North Carolina Division of Environmental Management, 1993.

Chesapeake Bay Local Assistance Department. Chesapeake Bay Local Assistance Manual. Richmond, Virginia: 1989.

Chesapeake Bay Program. Water Quality Functions of Riparian Forest Buffer Systems in the Chesapeake Bay Watershed. Technology Transfer Report CBP/TRS 134/95. Annapolis, Maryland: 1995.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. "Vegetative Filter Strips for Agricultural Nonpoint Source Pollution Control." Transactions of the American Society of Agricultural Engineers. Blacksburg, Virginia: 1989.

Galli, John. Analysis of Urban BMP Performance and Longevity. Washington, District of Columbia: Metropolitan Washington Council of Governments, 1992.

Hampton Roads Planning District Commission. Vegetative Practices Guide for Nonpoint Source Pollution Management. Chesapeake, Virginia: 1992.

Metropolitan Washington Council of Governments. Guidance Report 1: Riparian Buffer Programs, A Guide to Developing and Implementing a Riparian Buffer Program as an Urban Stormwater Best Management Practice. Washington, District of Columbia: 1993.

Northern Virginia Planning District Commission and Engineers and Surveyors Institute. Northern Virginia BMP Handbook. Annandale, Virginia: 1992.

Schueler, T. Level Spreader/Filter Strip System Assessed in Virginia. Watershed Protection Techniques, Vol. 1, No. 1. Silver Spring, Maryland: Center for Watershed Protection, 1994.

Schueler, T.R., P.A. Kumble, and M. A. Heraty. A Current Assessment of Urban Best Management Practices. Washington, District of Columbia: Metropolitan Washington Council of Governments, 1992.

Schueler, T. The Architecture of Urban Stream Buffers. Watershed Protection Techniques, Vol 1, No. 4. Silver Spring, Maryland: Center for Watershed Protection, 1995.

The Center for Watershed Protection. Design of Stormwater Filtering Systems. Silver Spring, Maryland: 1996.

Virginia Department of Conservation and Recreation. Virginia Erosion and Sediment Control Handbook. Richmond, Virginia: 1992.

Virginia Department of Forestry. Interim Report to the Chesapeake Bay Executive Council, EC Directive #94-1 Riparian Forest Buffers. Charlottesville, Virginia: 1995.

Wong, S.L. and R.H. McCuen. The Design of Vegetative Buffer Strips for Runoff and Sediment Control. Annapolis, Maryland: Tidewater Administration, Maryland Department of Natural Resources, 1982.

Vegetated Filter Strip. Note landscaped areas parallel to contours to force runoff to spread out. No evidence of channel flow short circuiting filter strip.

Vegetated Filter Strip

MINIMUM STANDARD 3.15

MANUFACTURED BMP SYSTEMS

3.15A *Stormceptor* 3.15-7

3.15B *Vortechs Stormwater Treatment System* 3.15-11

3.15C *Downstream Defender* 3.15-15

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3.15F *BaySaver Separation System* 3.15-27

View BMP Images

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MINIMUM STANDARD 3.15

MANUFACTURED BMP SYSTEMS

The Manufactured BMP Systems presented in this standard have been presented to the Virginia Department of Conservation and Recreation (DCR) by industry manufacturers. DCR acknowledges that there may be additional Manufactured BMP Systems available at this time that are not presented in this handbook. Presentation of the following products does not preclude the use of other available systems, nor does it constitute endorsement of any one system. Additional BMP systems will be presented in Technical Bulletins as they become available.

Definition

A Manufactured BMP system is a structural measure which is specifically designed and sized by the manufacturer to intercept stormwater runoff and prevent the transfer of pollutants downstream.

Purpose

Manufactured BMP systems are used solely for water quality enhancement in urban and ultra-urban areas where surface BMPs are not feasible. These are flow-through structures in that the design rate of flow into the structure is regulated by the inflow pipe or structure hydraulics as opposed to traditional BMPs designed to store the entire water quality volume. When the maximum design inflow is exceeded, the excess flow bypasses the structure or flows through the structure and bypasses the treatment with minimal turbulence and resuspension of previously trapped pollutants. Structures that rely on the inflow pipe to regulate the rate of flow into the treatment chamber typically cause stormwater to back up into the upstream conveyance system or associated storage facility. Depending on the type of structure and the configuration of the conveyance system, this excess flow will either bypass the treatment chamber or be attenuated and allowed to flow through the treatment chamber at the regulated rate.

Pollutant removal efficiencies presented in this standard are based upon currently available studies. Removal efficiencies are very variable, however, and highly dependant on storm size, influent pollutant concentrations, and rainfall intensity. Several monitoring studies are ongoing and many products may be modified to improve pollutant removal performance. Therefore, the removal efficiencies presented may be subject to change. As more of these products are built and additional monitoring studies track their performance over a wide range of rainfall events, the anticipated performance of these systems as water quality BMPs will become better established.

The discussion of each of the manufactured BMP systems presented in this standard includes the target pollutants for which the BMP was designed. Many of these systems were developed to remove a specific range of particulate pollutants, or total suspended solids (TSS), from stormwater runoff. Others, such as the filtering structures discussed below, were developed to capture a broad range of pollutants. The use of phosphorus as the target or "keystone" pollutant is recommended when using the *performance-based* water quality criteria to select a BMP. However, for stormwater "hot-spots", or areas from which a high concentration of urban pollutants can be expected, the primary pollutant of concern may be hydrocarbons (oil and grease), metals, or other compounds besides nutrients. Manufactured BMPs generally provide effective spill containment for material handling and transfer areas such as automobile fuel and service areas, and other urban hot-spots. Careful analysis of the proposed development project and intended uses help in selecting and appropriate BMP.

The manufactured BMP systems which have been evaluated at this time can be categorized as either:

- **Hydrodynamic Structures** - (*Stormceptor, Vortechs Stormwater Treatment System, Downstream defender, BaySaver Separation System*)

- **Filtering Structures** - (*StormFilter, StormTreat System*)

Hydrodynamic Structures

Hydrodynamic structures are those which rely on settling or separation of pollutants from the runoff. The hydrodynamic structures can be generally categorized as Chambered Separation Structures or Swirl Concentration Structures.

<u>Chambered Separation Structures</u> rely on settling of particles and, to a lesser degree, centrifugal forces to remove pollutants from stormwater. These structures contain an upper bypass chamber and a lower storage/separation chamber. Flow enters the structure in the upper bypass chamber and is channeled through a downpipe into the lower storage/separation, or treatment, chamber. The downpipe is configured such that when the rate of inflow into the structure exceeds its operating capacity, the flow simply "jumps" over the downpipe, bypassing the lower treatment chamber.

The outlet configuration of the downpipe forces the water to enter the lower treatment chamber in one direction, which encourages circular flow. This circular flow, as well as gravitational settling, traps the sediments and other particulate pollutants (as well as any pollutants which adsorb to the particulates) at the bottom of the chamber. The water leaves the treatment chamber through a return or riser pipe. The return or riser pipe extends below the water surface within the lower treatment chamber in order to prevent trapped floatables from exiting the structure. The hydraulic gradient of the structure prevents the inflow and the discharge from creating turbulent conditions within the lower treatment chamber. This feature helps prevent the resuspension of previously trapped particulate pollutants during high flow, or "bypass", storm events.

Swirl Separation Structures are characterized by an internal component that creates a swirling motion. This is typically accomplished by a tangential inflow location within a cylindrical chamber. The "swirl" technology is similar, if not identical to, the technology used in treating combined sewer overflows. The solids settle to the bottom and are trapped by the swirling flow path. Additional compartments or chambers act to trap oil and other floatables.

There is no bypass for larger flows prior to the treatment or swirl chamber. The larger flows simply pass through the structure untreated. However, due to the swirling motion within the structure, larger flows do not resuspend previously trapped particulates.

Filtering Structures

Filtering structures are characterized by a sedimentation chamber and a filtering chamber. The manufactured systems presented in this standard, the *StormFilter* and the *StormTreat System*, use very different configurations and filtering media. Both contain a primary settling chamber to remove heavy solids, floatables, oil, etc. The *StormTreat System* then directs the water through a series of screens and geotextile filters and into a containerized wetland system with soil and aquatic plants. The *StormFilter*, on the other hand, uses any one or combination of filter media cartridges. The filter media selected is typically based on the target pollutants to be removed or the desired efficiency. The number of cartridges is dependent on the project size, desired removal efficiency, and peak flow rates.

These categories represent the general groupings of manufactured systems that have been presented to DCR to date. More systems may be added in the future as they become available.

TABLE 3.15-1
Pollutant Removal Efficiencies for Manufactured BMPs

Type	Target Phosphorus Removal Efficiency*
Hydrodynamic Structures (*Stormceptor, Vortechs, Downstream Defender, BaySaver*)	15% - 20%
Filtering Structures (*StormFilter, StormTreat System*)	50%

*Pollutant removal efficiencies are subject to change pending monitoring results.

Conditions Where Practice Applies

Drainage Area

The sizing criteria for each manufactured BMP system should be obtained from the manufacturer to insure that the latest design and sizing criteria is used. In general, the flow-through configuration and treatment limitations will force drainage areas to remain relatively small.

Development Conditions

Manufactured BMP systems are ideal for use in ultra-urban areas since they are space efficient. Most of these systems can be placed under parking lots, or simply installed as a manhole junction box or inlet structure. Since other BMPs, such as sand filters and bioretention structures, are also suited for urban development, the designer must consider the type of pollutant load anticipated from the site, as well as other site factors, such as maintenance, aesthetics, etc., and select an appropriate BMP. In general, hydrodynamic are recommended for the following:

- Pretreatment for other BMPs;
- Retrofit of existing development or Redevelopment; and
- Ultra-urban development areas.

Filtering structures are generally recommended for use in applications similar to General Intermittent Sand Filters (**Minimum Standard 3.12**) and Bioretention Filters (**Minimum Standard 3.11**).

In all cases, Manufactured BMP systems must be designed in accordance with the manufacturers specifications.

Planning Considerations

The most significant feature of manufactured BMP systems is their small size and the ability to use them as retrofits underneath improved areas. (It should be noted that other BMPs, such as sand filters, can also be placed under improved areas.) The fact these BMPs are underground requires the designer to locate an acceptable outfall or improved drainage system for discharging runoff. The vertical elevation of the inflow and outflow pipe connections may be critical to the choice, or design, of the BMP.

Overflow

All of the manufactured BMP systems presented in this standard are flow-through structures that can be located on storm drainage systems that drain improved areas. Most manufactured systems, however, are designed to treat the first flush, or the water quality volume, of runoff. Therefore, an overflow, or bypass, is needed to divert flow that exceeds the design rate, or a storage facility is needed to store the appropriate volume of runoff for treatment. The discussion of each manufactured system will include the overflow or bypass provisions provided, or required.

Design Criteria

The design criteria for manufactured BMP systems should be obtained from the manufacturer. All designs should be reviewed by the manufacturer to insure that the system is appropriately designed and sized.

Maintenance and Inspections

All manufactured BMP systems require regular inspection and maintenance to maximize their effectiveness. The specific maintenance requirements and schedule should be prepared by the manufacturer and signed by the owner/operator. It should be noted that the frequency of maintenance is not only dependent on the type of manufactured system chosen, but also the pollutant load from the contributing drainage area. The frequency of maintenance required may vary from after any major storm, to once a month, to up to twice a year.

A maintenance log should be required to keep track of routine inspections and maintenance. A maintenance log can also help facility owners establish the effectiveness of certain "housekeeping" practices, such as street sweeping. Failure to maintain any stormwater BMP may result in reduced efficiency, resuspension or mixing of previously trapped pollutants, or clogging of the system.

Many suppliers of manufactured BMP systems recommend service contracts to ensure that maintenance occurs on a regular basis. Lack of maintenance is widely acknowledged to be the most prevalent cause of failure of both structural and non-structural BMPs.

Another consideration with manufactured BMP systems is the possible contamination and toxicity of trapped sediments, especially in areas considered to be stormwater hot-spots. Care must be taken in the disposal of sediment that may contain accumulations of heavy metals. Sediment testing is recommended prior to sediment removal to assure proper disposal. Experience in other jurisdictions has indicated a reluctance to on the part of waste water utility operators to accept the pump-out material from these structures. Landowners are encouraged to research the disposal options as part of the planning process prior to selecting the BMP.

MINIMUM STANDARD 3.15A

STORMCEPTOR

Description

Stormceptor is a precast, modular, vertical cylindrical tank, which is divided into an upper bypass chamber and a lower storage/separation chamber. Under normal design flow operating conditions flow enters the structure through the upper chamber and is diverted by a U-shaped weir through a downpipe and into the lower separation/holding, or treatment, chamber. The downward flow is redirected horizontally around the circular walls of the separation chamber by a tee-fitting on the downpipe outlet. This circular flow, as well as gravitational settling, traps sediments and other particulate pollutants (as well as any pollutants which adsorb to the particulates) at the bottom of the chamber.

Water exits the lower chamber through a submerged outlet riser pipe. The bottoms of the inlet downpipe and the outlet riser pipe are submerged and set at the same elevation (the elevation that provides the oil/floatable storage above the pipes, and the solids/sediment storage below the pipes). The submerged outlet riser pipe prevents trapped floatables from exiting the structure. This configuration prevents the inflow and discharge from creating turbulent flow conditions within the lower treatment chamber, thus avoiding resuspension and export of previously trapped pollutants during high flow, or “bypass,” storm events.

There are no moving parts and no external power requirements for the *Stormceptor*.

Overflow – During-high flow periods, stormwater floods over the diversion weir and continues through the upper bypass chamber into the downstream sewer. This rapid activity creates pressure equalization across the bypass chamber, thus decreasing the flow through the lower treatment chamber, and preventing scour and resuspension of previously trapped materials.

Hydraulics – The overflow of the system is controlled by the incoming velocity and the hydraulics of the diversion weir. This system will cause a slight backwater condition in the upstream conveyance system.

Planning Considerations

Stormceptor is precast and comes in various sizes and is designed for all types of land uses. The system is engineered for traffic loading and can be installed as a manhole structure on an existing system (as a retrofit) or on a new system where water quality enhancement is required.

Target Pollutants – *Stormceptor* is designed to capture sediment, total suspended solids (TSS), trash, organic material, and floatable oil and grease. In addition, many other urban pollutants which adsorb to sediments and particulates can also be trapped by the structure.

Design Criteria

The design criteria for the *Stormceptor* should be obtained from the manufacturer. All designs should be reviewed by the manufacturer to insure that the system is appropriately designed and sized.

Maintenance and Construction

It is generally recommended that the system be maintained (full pump-out) once per year. This frequency may have to be adjusted to a shorter interval once loading rates are determined. Regular inspections will help determine the required frequency of cleaning. More frequent inspections are appropriate where oil spills occur regularly. Maintenance is completed using a conventional vacuum truck.

Contact:

Mr. Vince Berg, P.E.
Stormceptor Corporation
600 Jefferson Plaza
Suite 304
Rockville, Maryland 20852
Phone: 1-800-762-4703

FIGURE 3.15-1
Stormceptor - Normal Flow Conditions

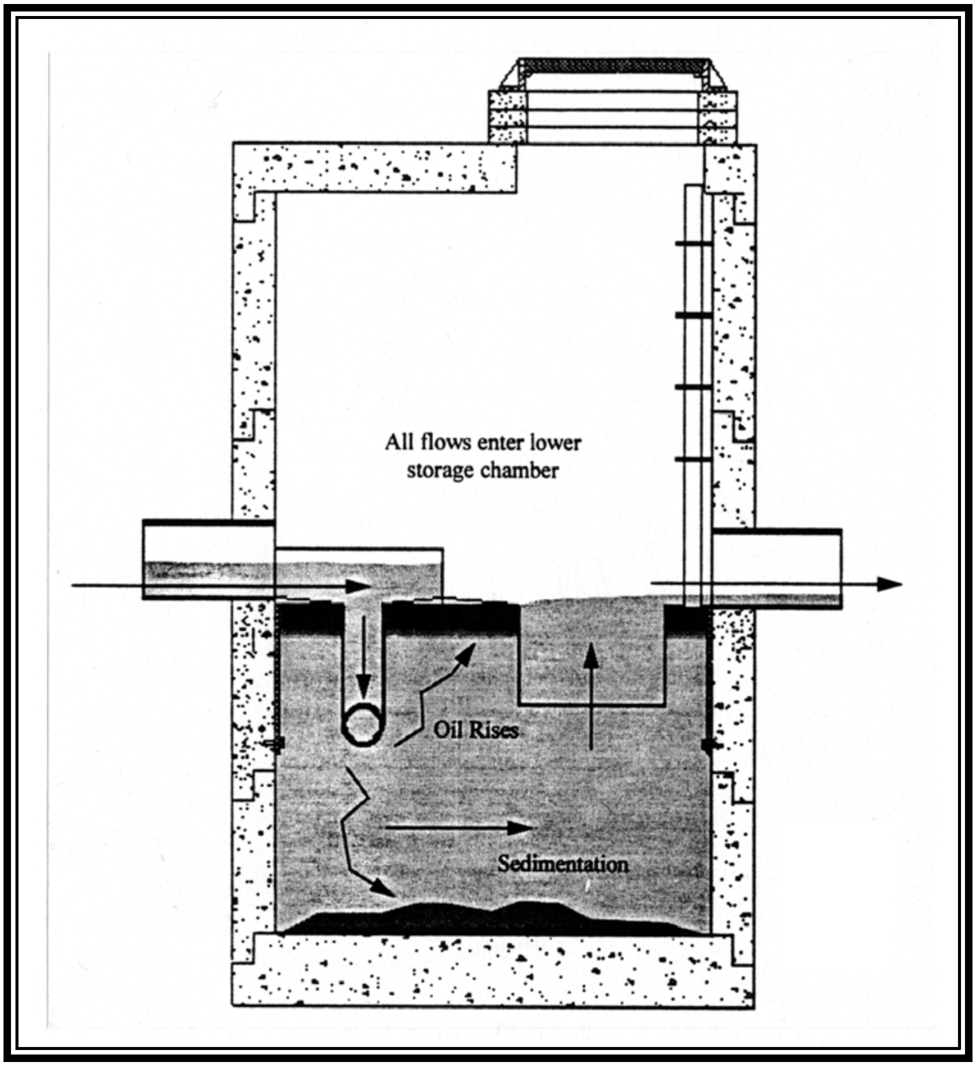
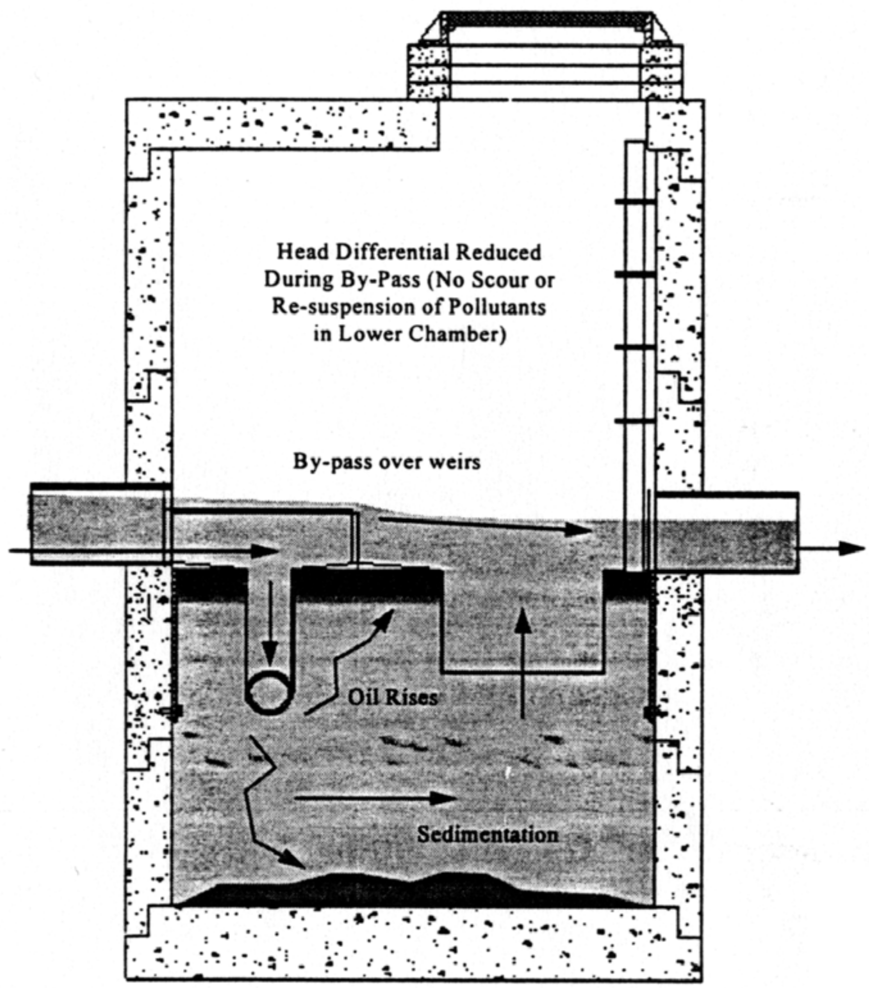


FIGURE 3.15-2
Stormceptor - High Flow Conditions



MINIMUM STANDARD 3.15B

VORTECHS STORMWATER TREATMENT SYSTEM

Description

The *Vortechs Stormwater Treatment System* is a precast rectangular unit with three chambers. The first chamber is referred to as the grit chamber and consists of a 1/4-inch thick aluminum cylinder with openings to release water at a controlled rate. The flow enters this chamber at a tangent to create a swirling motion that directs settlable solids towards the center. The flow is slowly released from the swirl concentrator into the oil chamber. The oil chamber has a barrier which traps oil and grease and other floatables. The final chamber is the flow control chamber, which forces water to back up in the structure, this reducing the inflow velocities and turbulence.

There are no moving parts and no external power requirements for the *Vortechs System.*

Overflow - As the rate of runoff increases, the flow control chamber forces the runoff to fill the *Vortechs* structure. As this occurs, the swirling action in the grit chamber increases, keeping sediments and other material concentrated at the center of the chamber. The flow will back up to a level established by the elevation of the release openings within the overflow chamber. This provides the ability to achieve flow attenuation within the storage capacity of the upstream storm drainage system. If additional flow attenuation or quantity controls are needed, the elevation of the *Vortechs System* can be manipulated to back up water into a detention facility. Because the swirling action increases as the inflow velocity increases, resuspension of previously deposited material during high flows is eliminated.

Hydraulics - The hydraulics of the *Vortechs System* allow for the treatment of runoff from frequent storms as well as the flow from larger, less frequent storms. Larger storms will cause runoff to back up in the drainage system as the storage volume within the structure is above the inflow pipes.

Planning Considerations

The *Vortechs Stormwater Treatment System* is precast and comes in various sizes and is designed for all types of land uses. The system can be engineered for traffic loading, and depending on the invert elevations can be installed on an existing pipe system (as a retrofit) or on a new system where water quality enhancement is required.

Target Pollutants – The *Vortechs System* is designed to capture sediment as fine as clay sized particles, and the nutrients and metals that adhere to sediments. Also targeted are floating materials, including petroleum products.

Design Criteria

The design criteria for the *Vortechs System* should be obtained from the manufacturer. All designs should be reviewed by the manufacturer to insure that the system is correctly designed and sized.

Maintenance and Inspections

The *Vortechs System* has no ongoing maintenance requirements, although routine inspections are necessary to schedule cleaning. To insure proper performance and treatment efficiency, the system must be cleaned out when it is full. The rate at which the system accumulates contaminants is largely dependent upon site activities.

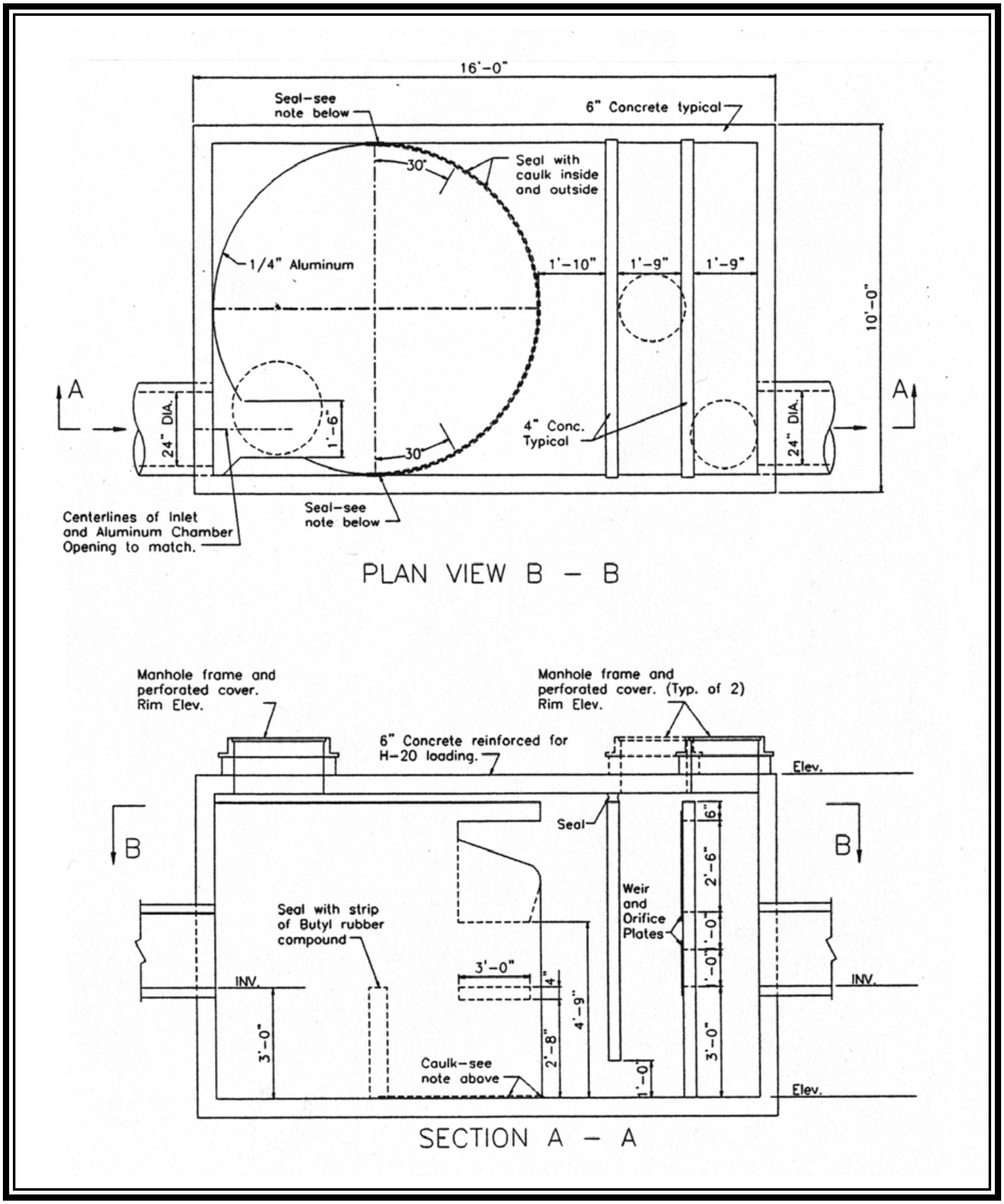
The first year of operation, Vortechnics recommends monthly inspections during periods of heavy contaminant loadings (e.g., winter sanding, soil disturbances, etc.). The inspection schedule can then be modified in subsequent years according to experience.

Clean-out of the *Vortechs System* with a vacuum truck is generally the best and most convenient method. <u>Only the manhole cover above the grit chamber</u> (the one farthest from the system outlet) needs to be opened to remove water and contaminants. As the grit chamber is pumped out, the oil and water drain back into it, so that oil scum, particulates and floatables are removed along with accumulated sediments. A pocket of water between the grit chamber and the flow control chamber seals the bottom of the oil barrier and prevents the loss of floatables to the outlet during cleaning.

<u>Contact</u>:

Tom Adams
Vortechnics
41 Evergreen Drive
Portland, ME 04103-1074
Phone: (207) 878-3662

FIGURE 3.15-3
Vortechs Stormwater Treatment System - Model # 9000



MINIMUM STANDARD 3.15C

DOWNSTREAM DEFENDER

Description

The *Downstream Defender* consists of a concrete cylindrical structure with stainless steel internal components and a internal sloping base. Stormwater runoff enter the structure through a tangential inlet pipe which creates a swirling motion within the structure. The flow spirals down the perimeter of the structure, allowing heavier particles to settle out by gravity and drag forces exerted on the wall and base of the structure.

The base of the *Downstream Defender* is formed at a 30 degree angle. As the flow rotates about the vertical axis, solids are directed towards the base of the structure where they are stored in the collection facility. The steel internal components direct the main flow away from the perimeter and back up the middle of the vessel as a narrower spiraling column rotating at a slower velocity than the outer downward flow.

A dip plate is suspended from the underside of the component support frame. This dip plate serves two purposes: 1) it locates the shear zone, (the interface between the outer downward circulation and the inner upward circulation where a marked difference in velocity encourages solid separation), and 2) it establishes a zone between it and the outer wall where floatables, oil and grease are captured and retained after a storm. When the flow reaches the top of the structure, it is virtually free of solids and is discharged through the outlet pipe.

There are no moving parts and no external power requirements for the *Downstream Defender*.

Overflow - There is no overflow or bypass of larger storms. As the rate of runoff increases, the swirling motion keeps the sediments trapped in the collection facility, thus allowing the full range of storms to pass through the facility with minimum resuspension.

Hydraulics - The outlet flow from the *Downstream Defender* can be regulated with its associated valve, the *Reg-U-Flow Vortex Valve*. The valve can be adjusted to maximize the available storage in the upstream drainage system or upstream detention facility (if additional flow attenuation is required) by reducing the flow and backing the water up in the upstream system.

Planning Considerations

A drop structure upstream of the *Downstream Defender* may be required to ensure that the flow enters into the structure at the appropriate elevation. The *Downstream Defender* comes in various sizes and is designed for all types of land uses. Depending on existing pipe invert elevations it can be installed on an existing pipe system (as a retrofit) or in a new system where water quality enhancement is required.

Target Pollutants – The *Downstream Defender* is designed to capture sediments, and grit (TSS), as well as floatable materials, including petroleum products. In addition, pollutant which adsorb to the particulates can also be trapped.

Design Criteria

The design criteria for the *Downstream Defender* should be obtained from the manufacturer. All designs should be reviewed by the manufacture to insure that the system is correctly designed and sized.

Maintenance and Inspections

A simple sump-vac procedure is periodically required to remove floatables and solids from the *Downstream Defender* collection facility. Regular inspections should be carried out over the first 12 months of operation to determine the rate of sediment and floatables accumulation. A probe may be used after storm events to determine the sediment depth in the collection facility. This information can then be used to establish a maintenance schedule. H.I.L. Technology, Inc. recommends inspection and clean-out at least twice a year.

A standard septic tank hose is not appropriate for the clean-out procedure. A *Vacall* with a 6-inch, or larger, hydraulic hose is required. The *Vacall* is capable of loosening compacted solids by reversing the vacuum pump prior to the sump- vac procedure.

Floatables should be removed prior to emptying the collection facility. The floatables access port is located between the concrete vessel wall and the dip plate. The collection facility access port is located directly over the center shaft.

Contact:

H.I.L. Technologies, Inc.
94 Hutchins Drive
Portland, ME 04102
Phone: 1-800-848-2706

FIGURE 3.15-4
Downstream Defender - Section View

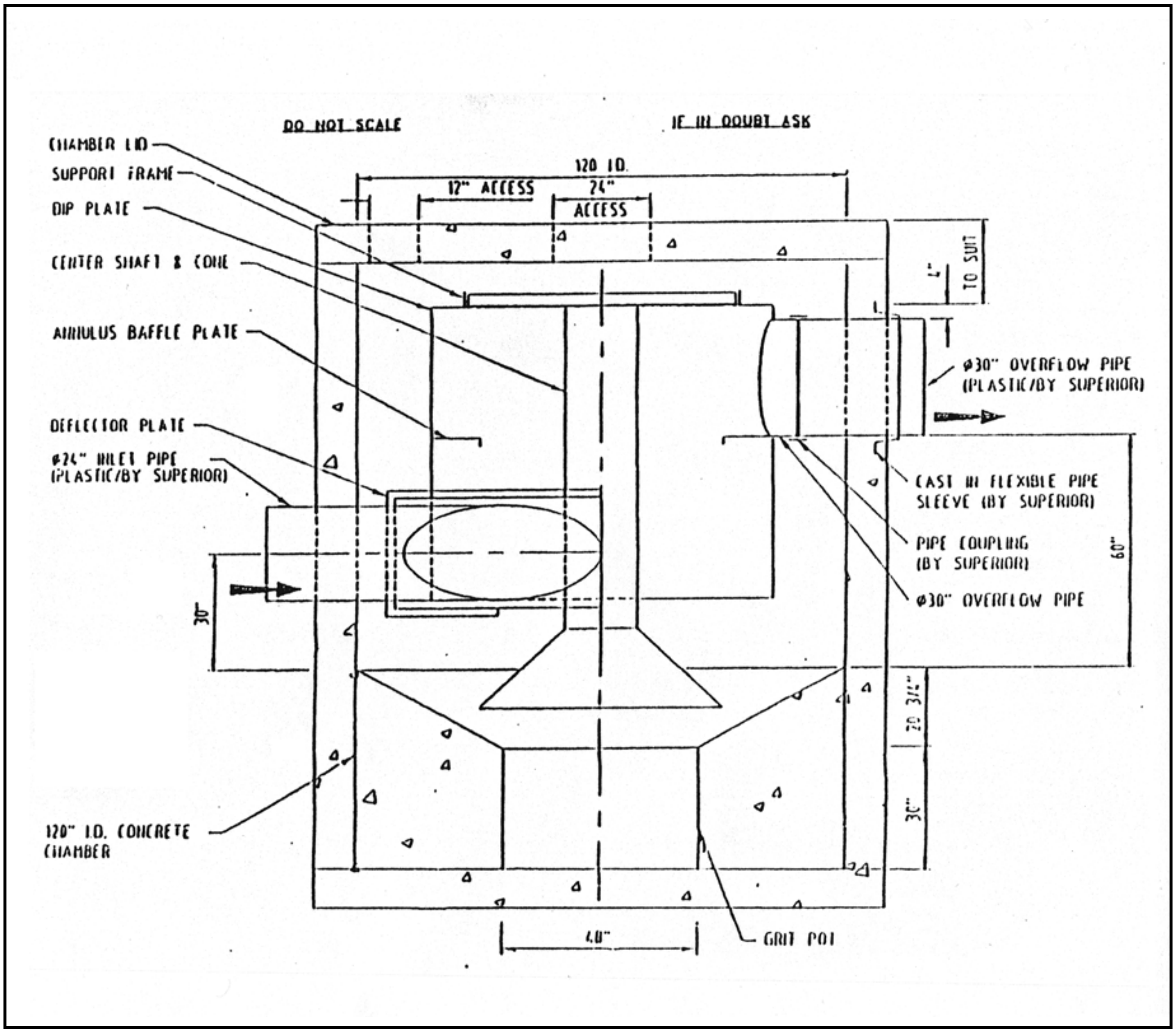
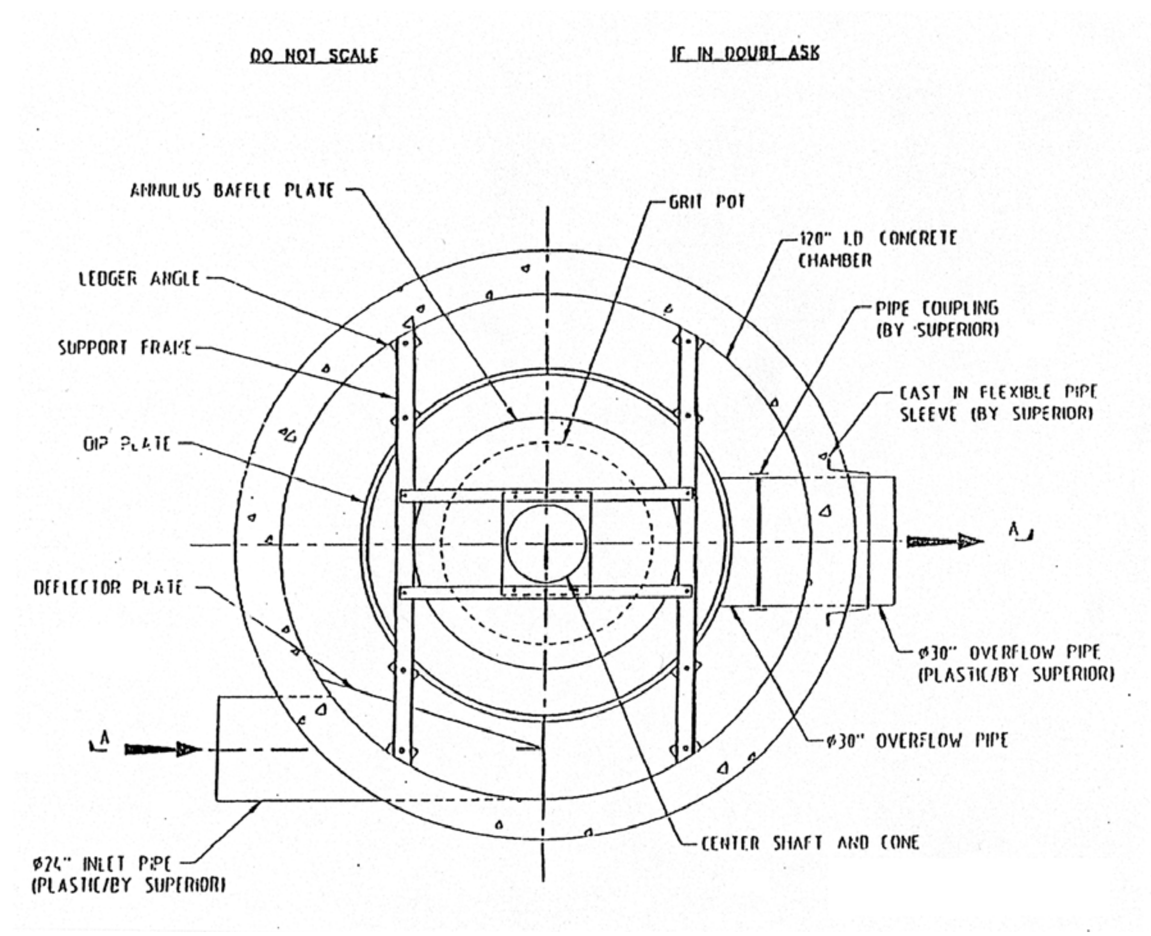


FIGURE 3.15-5
Downstream Defender - Plan View



MINIMUM STANDARD 3.15D

STORMTREAT SYSTEM

Description

The *StormTreat System* captures and treats the first flush of runoff. An optional infiltration feature provides for the treatment of larger quantities of stormwater (beyond the first flush).

The system consists of a series of six sedimentation chambers and a constructed wetland which are contained within a modular 9.5-foot diameter tank. It is constructed of recycled polyethylene, which connects directly to existing drainage structures.

As stormwater enters the system, it is piped into sedimentation chambers where larger-diameter solids are removed. The internal sedimentation chambers contain a series of skimmers which selectively decant the upper portions of the stormwater in the sedimentation basins, leaving behind the more turbid lower waters. The skimmers significantly increase the separation of solids, as compared to conventional settling/detention basins. An inverted elbow trap serves to collect floatables, such as oils, within the inner tank. After moving through the internal chambers, the partially treated stormwater passes into the surrounding constructed wetland through a series of slotted PVC pipes.

The wetland is comprised of a gravel substrate planted with the bulrushes and other wetland plants. Unlike most wetlands constructed for stormwater treatment, the *StormTreat System* conveys stormwater into the subsurface of the wetland and through the root zone, where greater pollutant attenuation occurs through such processes as filtration, absorption, and biochemical reactions.

Precipitation of metals and phosphorus occurs within the wetland substrate, while biochemical reactions, including microbial decomposition, provide treatment of the stormwater prior to discharge through the outlet valve. An outlet control valve provides a variable holding time within the system and can be closed to contain a hazardous waste spill.

There are no moving parts and no external power requirements for the *StormTreat System*.

Overflow - There is no internal, large storm bypass within the *StormTreat System*. An overflow of the treated water is provided and is conveyed to a receiving channel or pipe system, or as option, the overflow can be directed into he surrounding soils for infiltration (if the soils meet the criteria for infiltration facilities - **Minimum Standard 3.10**). This feature can be enhanced by backfilling the excavation around the StormTreat System with 3/4" stone, similar to an infiltration trench with the StormTreat system providing pretreatment.

The flow into the *StormTreat System* is be regulated by the inflow pipe. A storage structure or basin may be used to temporarily hold the runoff until it can drain into the *StormTreat System.*

Hydraulics – The flow through the various filtering mediums is slow and, therefore, the backwater effects are high for this system. Flow through the system is gravity dependent such that a 4-foot difference in elevation is needed from the pavement surface to the discharge point. This may prove difficult on relatively flat sites.

Planning Considerations

The *StormTreat System* can be configured in clusters of tanks to fit within limited areas and is designed for all types of land uses. The manufacturer recommends that a sump catch basin be placed prior to the StormTreat System in order to trap larger diameter sediments.

Target Pollutants – The *StormTreat System* is designed to capture sediment (TSS), fecal coliform bacteria, total petroleum hydrocarbons, total dissolved nitrogen, total phosphorus, lead, chromium, and zinc.

Design Criteria

The design criteria for the *StormTreat System* should be obtained from the manufacturer. All designs should be reviewed by the manufacturer to insure that the system is designed and sized correctly.

Maintenance and Inspections

The *StormTreat System* requires minimal maintenance. Annual inspection is recommended to insure the system is operating effectively. During inspection the manhole should be opened, the burlap grit screening bag covering the influent line should be removed and replaced, and filters should be removed, cleaned, and reinstalled. Sediment should be removed from the system via suction pump once every 3 to 5 years, depending on local soil characteristics and catch basin maintenance practices.

Contact:
Mr. Scott Horsley
StormTreat Systems Inc.
90 Route 6A
Sextant Hill, Unit 1
Sandwich, MA 02563
ph. (508) 833-1033

FIGURE 3.15-6
StormTreat System Tank

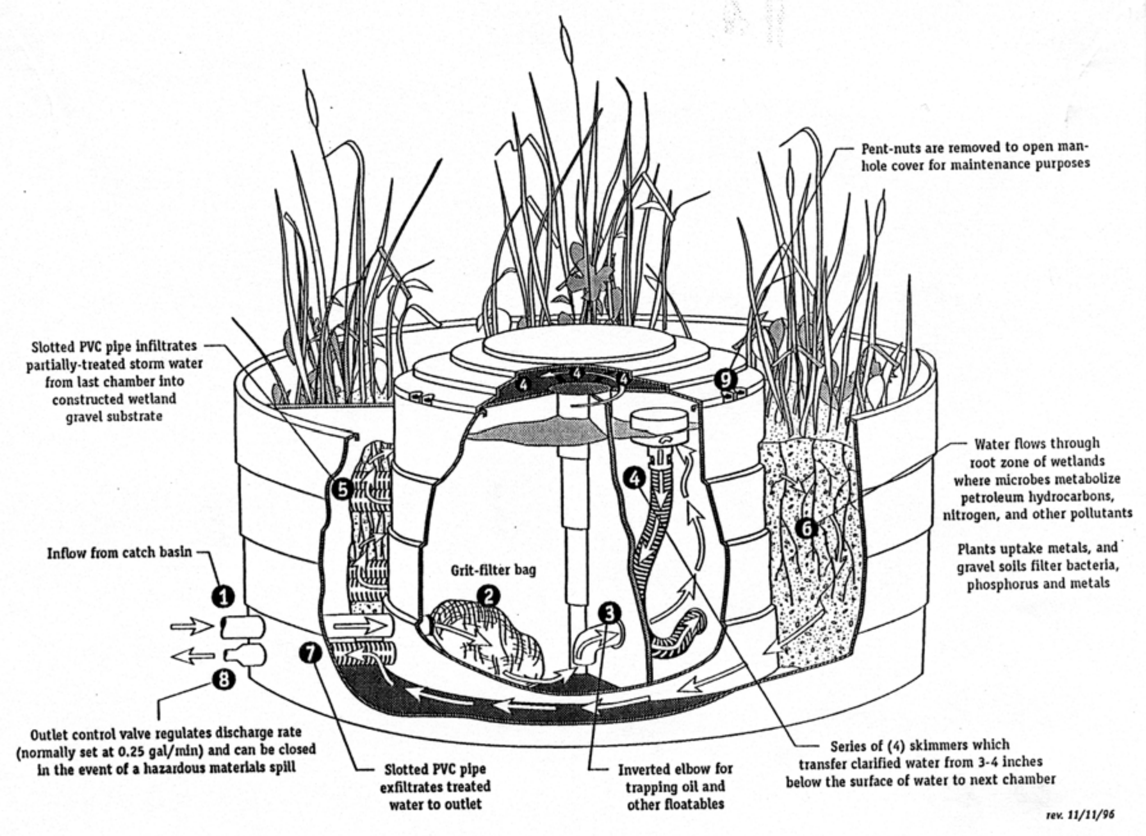
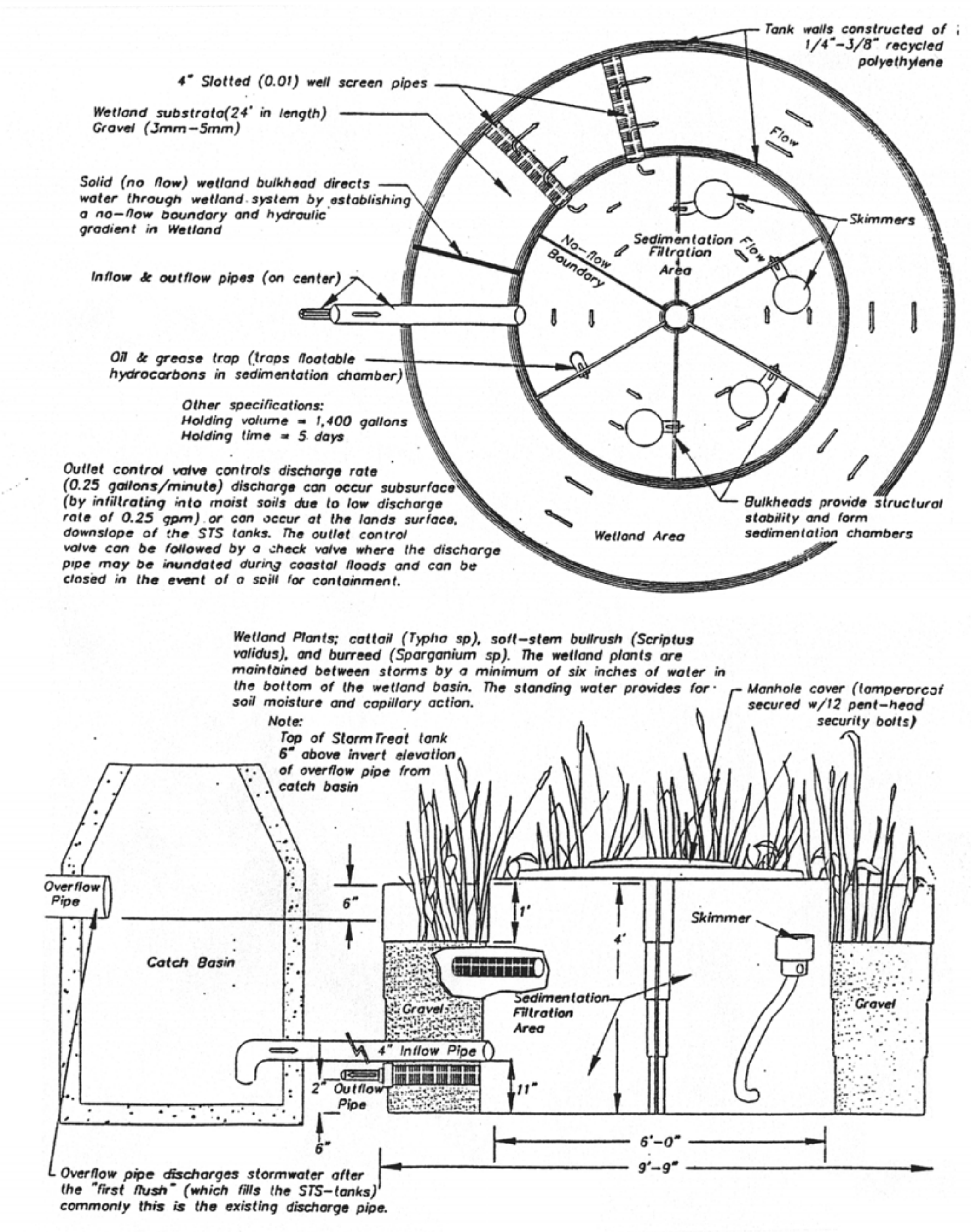


FIGURE 3.15-7
StormTreat System



MINIMUM STANDARD 3.15E

STORMFILTER

Description

The *StormFilter* uses cylindrical rechargeable filter cartridges which hold a variety of filter media and can be customized by using different filter media to remove desired levels of sediments, phosphorus, nitrates, soluble metals, and oil & grease. Housed in standard size pre-cast or cast-in-place concrete vaults, the filter systems can be installed in-line, allowing stormwater to percolate through the cylindrical cartridges before discharging to an open channel drainage way. The *StormFilter* is equipped with scum baffles that trap floating debris and surface films, even during overflow conditions.

There are no external power requirements for the *CSF Stormwater Treatment System*. Moving parts are contained within the filter cartridges as part of the *priming system* discussed in the Hydraulics section.

Overflow – The *CSF system* is designed with an overflow that operates when the inflow rate exceeds the infiltration capacity of the filter media. The overflow consists of a weir wall inside the structure housing. Depending upon individual site characteristics, some filters are equipped with high- and/or low-flow bypasses. High-flow bypasses can be installed when the calculated peak storm event generates a flow which overcomes the overflow capacity of the filter.

Hydraulics – The hydraulics of the *StormFilter* are designed to maintain the design flow rate through the filter without pumps or other motorized devices. Each filter cartridge contains a float-actuated device called a *priming system* within the central drainage tube. This system primes the cartridges, which then develop a siphon inside the drainage tube. The siphon increases as the filter cartridges become progressively clogged to help maintain the design flow.

Planning Considerations

The *StormFilter* is a structural BMP which can be easily installed in a parking lot or in fully developed areas as it does not require additional development space. However, consideration should be given to long term maintenance costs.

Target Pollutants – The *StormFilter* is designed to capture sediment (TSS), soluble metals, and oil and grease, nitrogen, and phosphorus. The various filter media can be selected to target pollutants of primary concern. The following filter media are available:

- Pleated fabric
- CSF leaf media
- Perlite
- Zeolite
- Granular activated carbon

According to the manufacturer, a combination of the pleated fabric and the zeolite media provides the best removal efficiencies for phosphorus and TSS.

Design Criteria

The design criteria for the *CSF Stormwater Treatment System* should be obtained from the manufacturer. All designs should be reviewed by the manufacturer to insure that the system is correctly designed and sized.

Maintenance and Inspections

Maintenance requirements of the *CSF Stormwater Treatment System* are controlled by the amount of plugging of the filters caused by sediment accumulation. The filters are progressively loaded with sediment contained in runoff. At least one scheduled inspection of the filter must be undertaken to perform minor maintenance activities, which includes flow valve adjustment. The major maintenance activity is performed to rejuvenate the media and clean the system. Major maintenance activities may also be required in the event of a chemical spill or excessive sediment loading (due to site erosion or extreme storms). It is also good practice to inspect the system after severe storm events.

When the cartridges become too occluded with sediments, maintenance involves the removal of the exhausted cartridges and replacement with freshly charged cartridges. The time period between when the cartridges are initially installed and when they must be replaced is dependent upon site specific conditions and sediment loading.

As with other filtration systems, sediments will accumulate on the filter surface, eventually slowing the infiltration capacity. To reduce sediment loading to the surface of filters, it is recommended that the filters be used in conjunction with sediment reducing practices such as parking lot sweeping and catch basin sand traps.

Contact:

Mr. James H. Lenhart, P.E.
Stormwater Management
2035 Colombia Boulevard, NE
Portland, Oregon 97211
ph. (800) 548-4667

FIGURE 3.15-8
StormFilter

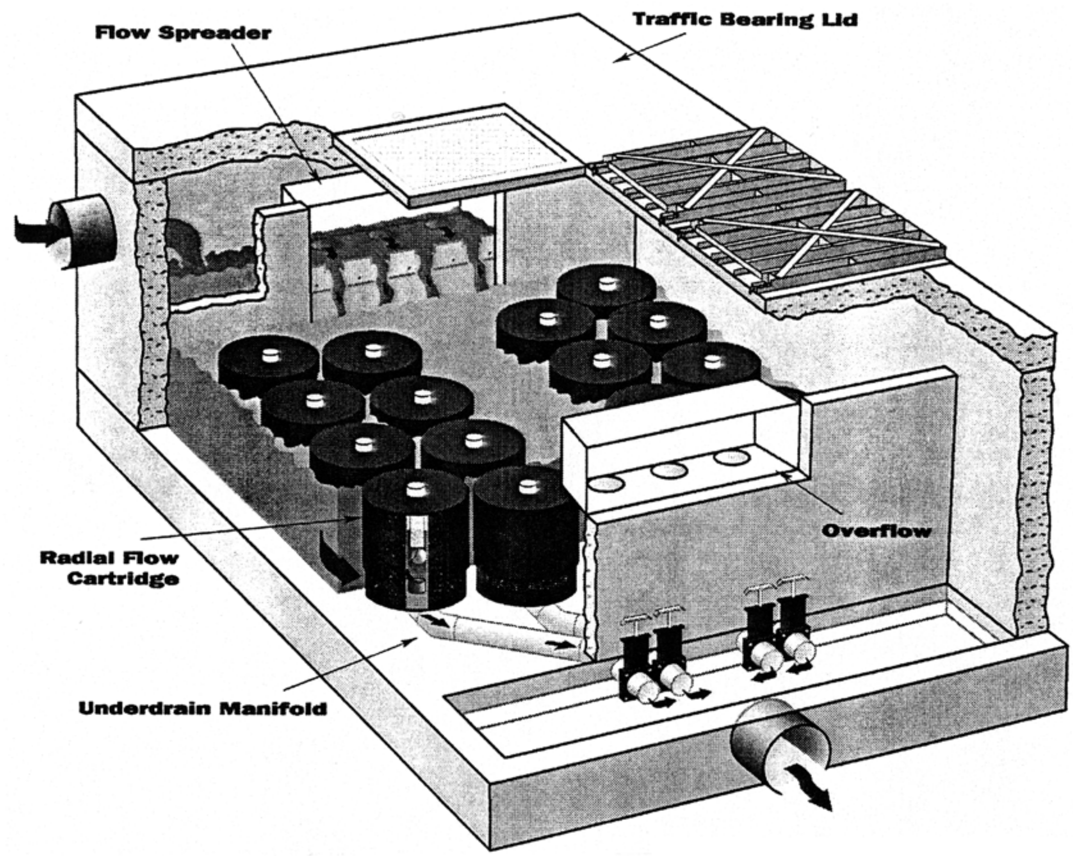
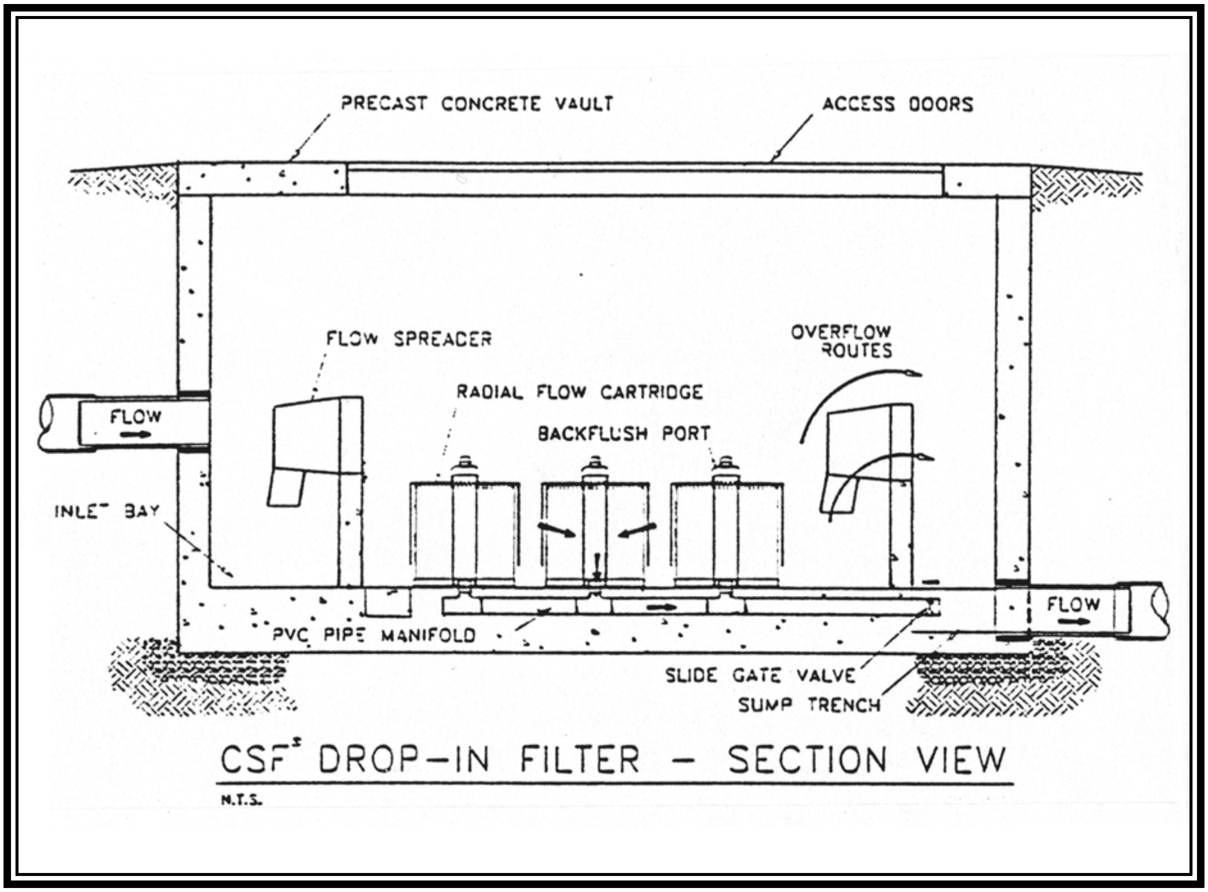


FIGURE 3.15-9
StormFilter Drop-In Filter



MINIMUM STANDARD 3.15F

BAYSAVER

Description

The Bay Saver system is comprised of three main components: the Primary Separation Manhole, the Secondary Storage Manhole, and the BaySaver Separator Unit. The primary and secondary manholes are both standard precast concrete drop structures. The BaySaver Separator Unit is constructed of high-density polyethylene (HDPE).

Stormwater runoff enters the BaySaver system through the primary separation manhole. As the water flows into the manhole, the larger sediments settle to the bottom of the tank. **Figure 3.15-10** shows a profile of the primary manhole. The structure has a minimum water level at the elevation of the BaySaver's surface skimming weir. This weir is a trapezoidal shaped weir with a bottom width ranging from 3" to 6", and a flow depth of 9" to 18", depending on the size unit as required by the contributing drainage area. As water flows into the manhole, the surface water flows over the weir and is diverted to the storage manhole. This water carries with it floating pollutants (oils, for example), debris, and fine sediment particles.

The BaySaver Separator Unit incorporates three flow paths that water can take through the system. The trapezoidal surface-skimming weir diverts first flush and low flows into the second manhole for the most efficient treatment. As the water level rises in the primary separation manhole, more water flows over the weir. The majority of oils and fine sediments are removed by this flow path.

During a more intense storm, the BaySaver unit will also allow water to flow through the inverted 90E elbow pipes. The elbow pipes draw water from the middle of the primary separation manhole, with the intakes approximately four feet below the surface, and discharge directly to the system outfall. The water pulled by the elbows is free of floating contaminants and has had time for suspended sediments to settle out. By discharging this water, the BaySaver can continue full treatment of the surface flow in the second manhole.

If the flow becomes too great for the system to effectively treat, the BaySaver bypasses the treatment stages, conveying water directly from inlet to outlet. Elongated openings in the crown of the elbow pipes serve as pressure equalizers, significantly reducing flow through the submerged inlets of the elbow pipes during bypass. This reduction minimizes the resuspension and discharge of trapped contaminants from the primary manhole. Bypass flows also prevent water from flushing through the storage manhole, providing more protection against the risk of resuspension of fines and oils.

There are no moving parts and no external power requirements for the BaySaver.

Overflow - Large storm bypass is accomplished first by the two 90E inverted elbow pipes, and second by overflowing the top plate over the weir (set approximately at ½ the diameter of the separator unit).

Hydraulics - The separator unit and associated overflow pipes are sized according to the drainage area being served. The system should operate without creating a back water condition in the upstream drainage system.

Planning Considerations

The BaySaver primary and secondary manholes are precast and come in three sizes depending on drainage area size. The system can be installed on an existing system (as a retro fit) or on a new system where water quality enhancement is required.

Target Pollutants - The BaySaver system is designed to capture sediment, total suspended solids (TSS) trash, organic material, and floatable oil and grease. In addition, many other urban pollutants which absorb to sediments and particles can also be trapped by the structure.

Design Criteria

The design criteria for the BaySaver should be obtained from the manufacturer. All designs should be reviewed by the manufacturer to insure that the system is appropriately designed and sized.

Maintenance and Construction

It is generally recommended that the system be maintained (full pump-out) once per year. This frequency may have to be adjusted to a shorter interval once loading rates are determined. Regular inspections will help determine the required frequency of cleaning. More frequent inspections are appropriate where oil spills occur regularly or a large volume of trash and debris are expected.

Contact:

BaySaver, Inc.
1010 Deer Hollow Drive
Mount Airy, Maryland 21771
Phone: (301) 829-6119

FIGURE 3.15-10
BaySaver Primary Separation Manhole

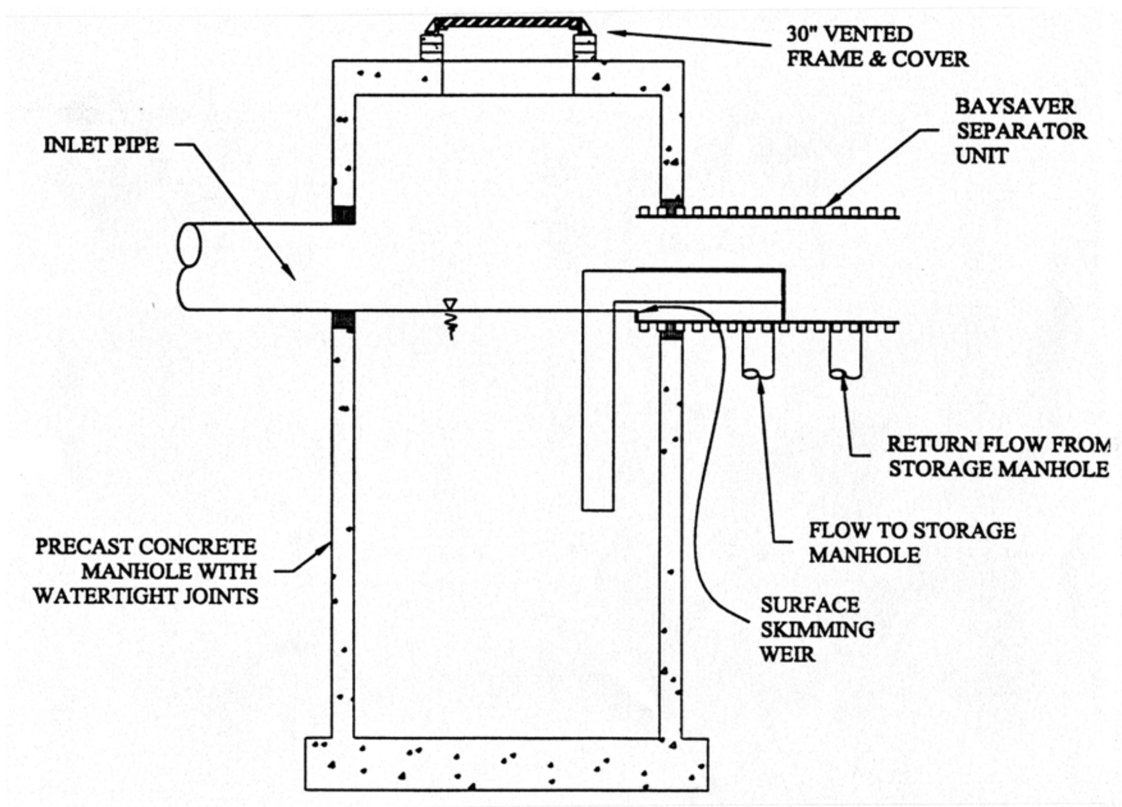
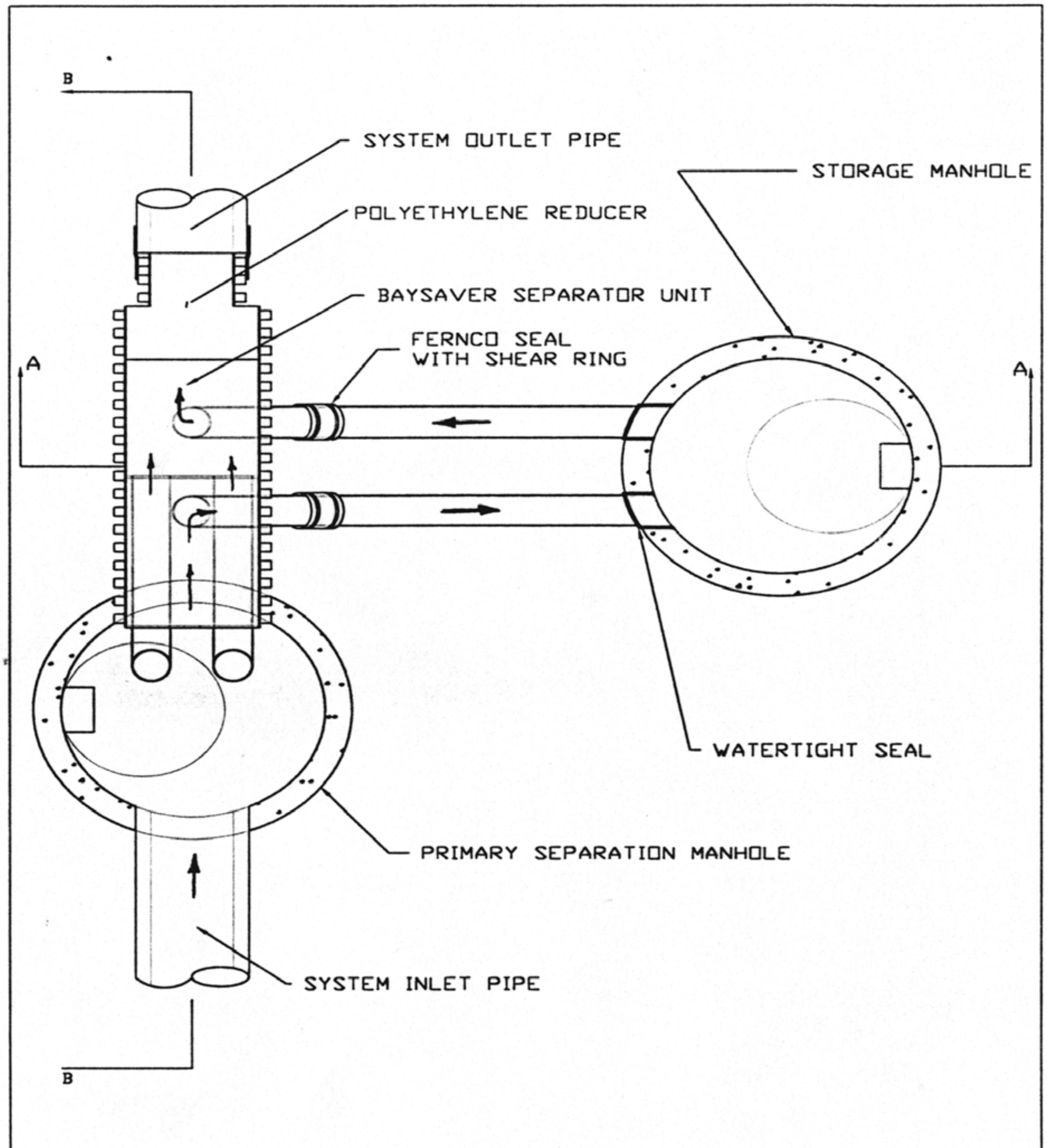


FIGURE 3.15-11
BaySaver Plan View



Plan View

FIGURE 3.15-12
BaySaver Section A-A

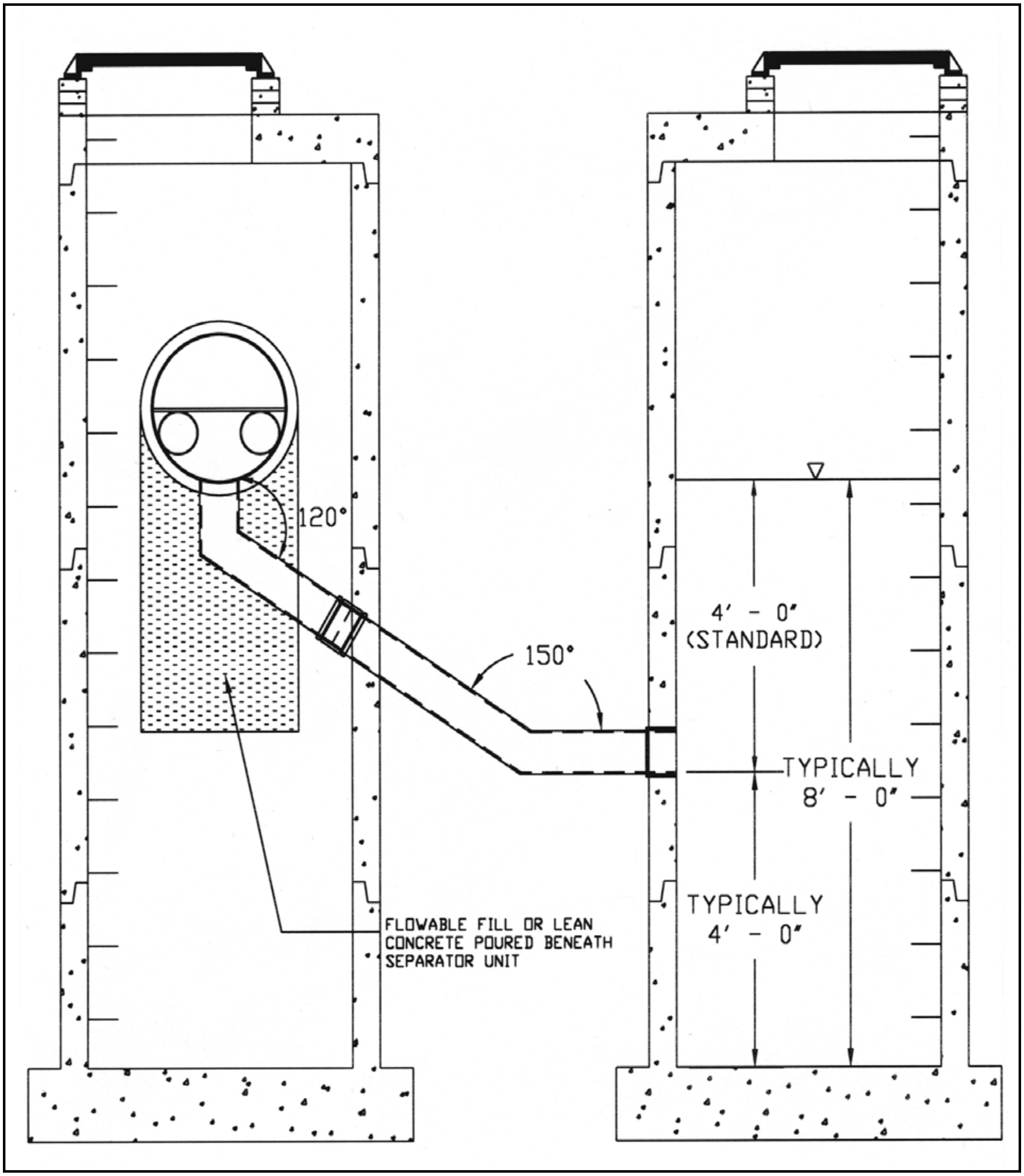
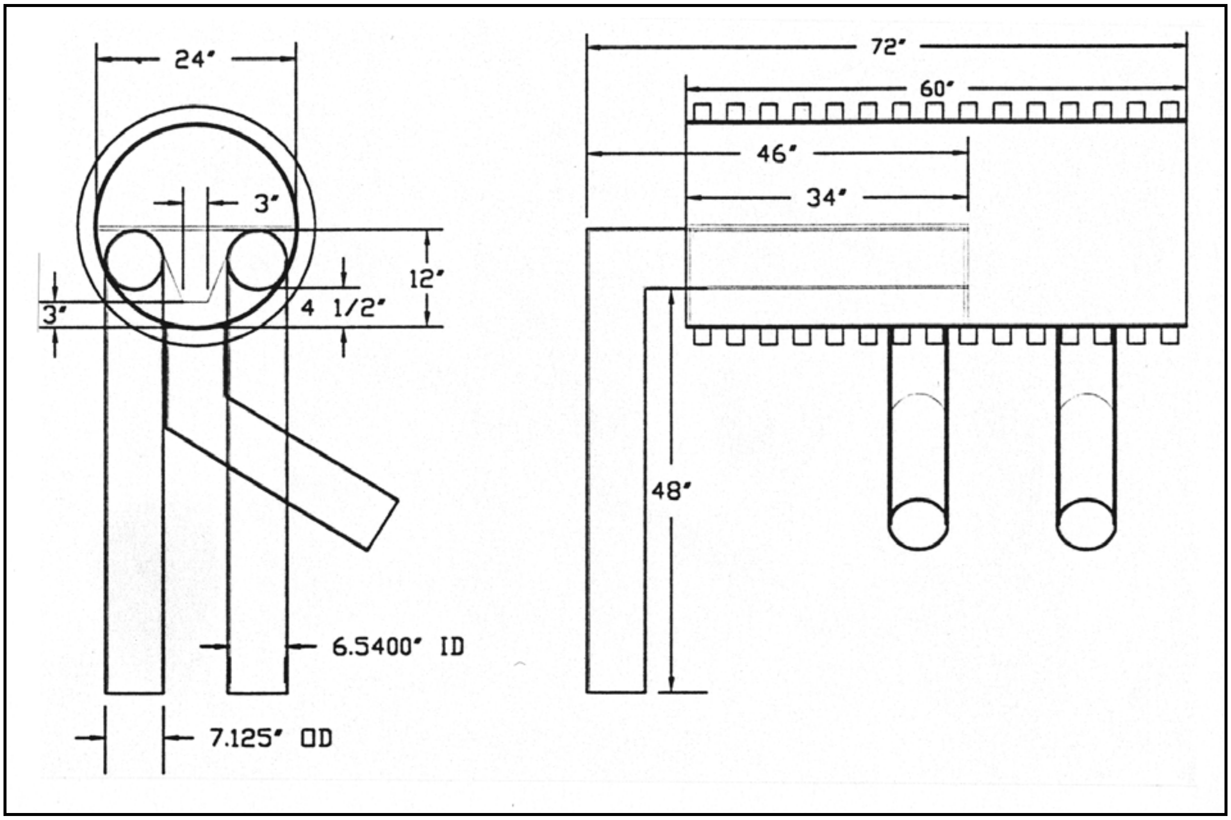


FIGURE 3.15-13
BaySaver 1K Separator Unit



Manufactured BMP Systems. Manufactured systems can be selected to address specific pollutant sources. This trench drain surrounds fuel handling area of a service station to direct any spills or otheridentified petroleum based contaminants to a manufactured system designed specifically for fuel or hydrocarbon containment. Note: fuel area is under cover which serves to limit the design flow entering the system.

CHAPTER 3

APPENDIX

CHAPTER 3

APPENDIX

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- **Operation and Maintenance Inspection Checklist**

APPENDIX 3A

Introduction - Checklists

Design and Plan Review Checklists

Design and plan review checklists provide general guidance for both the designer and plan reviewer. Many items listed on the checklists may not apply to any given design and it is therefore up to the designer to indicate items as "*not applicable*" or "*NA*" as appropriate. Similarly, the reviewer must be able to distinguish which items are required based on the local conditions or requirements and verify the status of those items. These checklists serve as a tool for providing the designer with the necessary information needed to develop an approvable plan, as well as for providing the plan review authority with a consistent review procedure.

Construction Inspections and As-Built Survey Checklists

The purpose of construction inspections and an as-built survey is to verify that constructed SWM facilities and associated conveyance systems have been built in accordance with the approved plan and design specifications. An as-built survey, including construction inspection logs should be provided prior to final site approval and release of the performance guarantee. This is in the best interest of the owner as well as the local program, since long term maintenance costs can increase significantly, if the facility is not built correctly. Also, there could be a problem that the system may not provide the quantitative and/or qualitative control, as prescribed by the approved plan. Liability issues arise if a downstream property owner is adversely affected and can prove that the facility is not per the approved plan.

A. Construction Inspections

Adequate construction inspection of stormwater BMPs will usually require an on-site inspector to verify that the materials, methods, and placement, are in accordance with the approved plans and specifications. Critical components of the design; such as the anti-seep collar or filter and drainage diaphragm on the outlet conduit, the embankment foundation, riser footing, and other sub-surface components, must be examined for compliance to the design prior to being backfilled with the earthen embankment. The use of an on-site inspector will help to avoid delays by allowing the contractor to proceed with the earthwork rather than waiting for a scheduled (or non scheduled) inspection of a critical component.

Localities will usually provide regular inspections of SWM facilities under construction. The frequency of these inspections will vary based on the workload represented by active projects and the number of inspectors on staff. These inspections should verify that the contractor and on-site inspector are documenting the construction inspections in order to adequately substantiate the as-built certification. In the case of a local program requirement of inspections during critical portions of the construction, a signed inspection log by a qualified individual (other than the contractor) should be acceptable. Otherwise, the locality should establish a construction inspection schedule with the contractor prior to construction.

All inspection logs and other related information should be incorporated into a file for each individual project.

B. As-Built Survey

Some as-built documentation must be obtained *during* the construction process, since some vital components are hidden in the final product. Therefore, construction inspections and inspection records are included in the as-built survey. For purposes of discussion, an as-built survey may be broken down into three components. These components are earthwork specifications, material specifications (other than earthwork) and a dimensions and elevations survey. The items noted within these components should be checked, and documentation be retained as needed to substantiate that the SWM BMP has been constructed in accordance with the approved plan and specifications. The following provides a discussion of the components of an as-built survey.

1. Earthwork Specifications

The acceptable completion of earthwork in the construction of a SWM facility is crucial in assuring that a facility is structurally sound. This category covers all aspects pertaining to the completion of earthwork for a facility. It is essential that specific elements of the construction inspection, as well as the pre-construction feasibility analysis of the soils, be documented. This may include compaction tests, inspections of the removal of unsuitable materials under and adjacent to the embankment foundation, construction of the cut off trench and other seepage control measures, compaction around the barrel, riser structure footing, and any other element that is hidden in the final condition. All work should be completed under supervision of a licensed geotechnical engineer. The inspection logs and test results should be included in the final as-built survey.

a. Geotechnical/Geophysical Testing

The examination of existing underlying strata indicates the composition of that strata and if that strata will support a SWM facility. For example, the presence of bedrock at the natural ground surface or in “cut” provides a plane of weakness that water may follow or exfiltrate to. This is especially critical in areas of karst. Also, the presence of organics or other unsuitable materials under the embankment and embankment footing may require additional excavation. This must be documented as having been completed.

Normally, in non-karst terrain (east of the Blue Ridge), simple geotechnical logs taken at the SWM site will provide adequate interpretative results. In karst west of the Blue Ridge, however, it is extremely useful that the testing be expanded to geophysical (seismic) evaluation. These tests provide images of underlying strata and indicate the presence of anomalies. This is critical since limestone geology exhibits extensive caves and cavities where ponding of runoff may exacerbate collapse of underlying cavities, which ultimately results in extremely expensive repairs.

b. Fill Classification

The geotechnical portion of the approved plan should provide a listing of soil classification types that are suitable for use at the project infill. Specialized criteria may also specify the classification of impermeable soil to be used for clay liners in areas of sandy soils or karst. Fill soils containing such materials as excessive or large rock, organic material or "fatty clay" (CH) classification are not acceptable due to the inability to achieve proper compaction or because of their shrink-swell properties. Verification must also be provided that the specifications for materials to be used in the construction of drainage and filter diaphragms have been complied with.

c. Compaction

The application of "lifts" in proper thickness and density is essential in attaining a stable SWM structure. The compaction of dam embankment to a percentage at or above the percent compaction specified in the approved plan and within the optimal range of moisture content assures that there will not be adverse settlement of the embankment. Careful compaction in areas adjacent to the barrel and seepage control measures is critical to eliminate excessive "void space" along the outlet barrel where the potential for embankment failure is high. Sufficient test results should be retained to document uniform compaction of the dam embankment and density/permeability of **existing soil formation and/or soils to be** used for liners (where applicable), in accordance with the approved plan.

2. Material Specifications

Construction materials may be classified as those items other than earthwork. A large number of component items needed for the construction of SWM facilities are grouped into this category. Some of these components must be inspected during installation. Materials would include, but not be limited to, concrete, reinforcing steel, concrete pipe, metal pipe, woodwork, masonry, and any other items that are applicable to the facility and satisfy all the requirements of the local program. The following provides a general discussion of some of the components of a SWM facility:

a. Riprap and Aggregate

The size distribution (diameter of aggregate), the amount of "fines" and integrity of rock may be factors, since aggregate sizing should be in accordance to the plan.

(1) Aggregate sizing plays a role in two distinct areas. In underground reservoir use, the size of aggregate dictates the amount of void space available for infiltration or retention/detention of runoff. In riprap use, the minimum size is critical in maintaining stability during high velocity flow, while a size in great excess of the stone specified may be as equally detrimental in regards to aesthetics and/or proper placement.

(2) The amount of fines contained within aggregate is generally a visual observation, although quarry delivery tags should bear out the specifications per VDOT specs. The percentage of fines generally is important where washed stone is to be utilized for an underground aggregate reservoir, or where the outlet protection of a facility is discharging into a stream or other sensitive area that is susceptible to turbidity.

(3) Rock integrity and shape is generally the visual observation that the aggregate used will meet specifications without long term decay. For example, sandstone does not make good riprap since it may be expected to disintegrate over time. Slate usually exhibits cleavage planes and therefore lays flat. When used for outlet protection, insufficient surface roughness of the slate may not dissipate concentrated flow energy.

b. Control Structure

There are an infinite number of design configurations for a control structure. Whatever the design, there should be project specifications for dimensions, strength and specific materials in accordance with the specifications found in Chapter 3, and any other local requirements. Appropriate documentation from the manufacturer should be retained (as applicable) to document each component. For example, pre-cast concrete risers normally arrive with as-built shop drawings that indicate specifications of the item furnished. Where components are constructed at the site, such as a cast in-place riser footing, test information and/or delivery tags from the concrete plant should be retained, while rebar reinforcement and dimensional information is documented in the construction log. Other items normally applicable to the control structure include:

(1) An outlet barrel, normally affixed to the control structure, is used to convey flow to an accepted discharge point. Items related to proper conduit installation include the procedure used in sealing joints of conduit together, the method of attachment to the control structure and the use of inlet and floor shaping (as applicable) within

the control structure.

There is also a need to inspect and document the existence, location and spacing of anti-seep collars, concrete cradle or other seepage control measures (at the outlet barrel) as specified in the approved plan. Documentation should include verification of critical dimensions, existence of reinforcement and indication of concrete mix strength. In the case of filter diaphragms, both earthwork and materials need to be **considered in installation.**

(2) Trash racks of varying design and construction are normally affixed to a control structure and in some cases inlets which "feed" the SWM facility. Visual observation (with inspection log entry) should indicate bar size, spacing grate configuration, and proper attachment to the control structure, or inlet and the application of rust resistant coating to the same where applicable.

c. Geotextiles

Synthetic fabrics are frequently specified for application beneath various components, under riprap or individually in spillways or for low flow channels. Proper selection of a manufacturer's product along with installation per the plan and/or manufactures directives is necessary to assure the performance intended. Method of installation should be observed and tag be provided from the product that verify compliance to the product specification given in the approved plan.

d. Conveyance System Components

One frequently overlooked portion of a SWM design is the components comprising the drainage system for the site. It is obvious that if the system is not built as intended by the approved plan, then the facility may not function accordingly. Critical items such as conveyance conduit diameter, slope, inlet and grate length/configuration are essential to insure that the required design storm (generated by contributory area) is adequately conveyed to the SWM facility for control and/or that non-contributory area is diverted away from SWM facilities.

3. Dimensions and Elevations Survey

The approved plan provides detailed information for specific elevations such as the inverts of the outlet conduits, control orifice and weir invert elevations, invert of emergency spillway, top of the dam, as well as pond bottom and slope of the same. Additional dimensional information exclusive of the control structure should also be provided. This could include the dimensions of the impoundment area at specific elevations and the top width and side slope of a dam embankment. The purpose of the as-built survey is to substantiate elevations and dimensions per the plan.

G. As-Built Submittal Requirements

As-built information should be documented and submitted in three forms: 1) a copy of the applicant's inspection log book. 2) a red-line revision of the approved SWM plan sheets and 3) a certification statement from a qualified individual regarding the conformance of the as-built to the approved plan.

1. A copy of the inspection log book should be kept at the project site. The log should document all aspects of the construction of the facility (with copies of applicable test results) to insure compliance with the approved plan. Any significant inconsistencies should immediately be reported to the engineer for evaluation and possible modification.

2. Red-line revision plans should be submitted upon completion of the facility. The plans should indicate any changes to the approved plan. Items that differ from the original approved plans and computations should be shown in red on both the plans and computations as follows:

   a. A red check mark must be made beside design values where they agree with actual constructed values.

   b. For changed values "line out" the design value and enter the actual value in red.

   c. Elevations to the nearest 0.1' are sufficient.

   d. A stage-storage summary table comparing the design values and the as-built values should be provided for facilities with storage volume.

3. The project owner should have those persons responsible for the inspection and implementation of the plan submit written certification that the SWM facility(s) and conveyance system have been built in accordance to the approved plan since this will cover underground facilities as well. Survey work during stake out and construction should be documented to verify underground volumes, elevations, pipe sizes, etc.

<u>Operation and Maintenance Inspection Checklists</u>

Once construction is completed, the SWM BMP takes on the role for which it was intended. Periodic site inspections are essential in order to monitor the effectiveness and to anticipate the maintenance needs of the BMP. It should be pointed out that not only the facility or BMP measure installed for stormwater control is important, but also the conveyance system to the BMP and the receiving channel immediately downstream of the BMP. The conveyance channel, curbing and/or storm sewer that convey flow to the facility or intentionally divert flows around it (as a part of the design) are all considered components and must function as intended.

The necessary frequency of inspections will vary with each facility based on the type of facility, size of the contributory drainage area, and development or land use conditions within the contributory drainage area. At a minimum, a full inspection should be performed at least once a year. Periodic inspections for trash and debris accumulation and general aesthetics should be performed after significant storm events.

The following checklists provide a guide for regular inspections of the various types of urban BMPs covered in this manual. The checklists are detailed enough for an inexperienced inspector or homeowner not familiar with the specific components of the facility. Checking the column provided under the *Investigate* heading for any given item indicates a potential problem that requires attention by a qualified individual to interpret the visual indicators for possible maintenance. The checklists should be signed, dated, and maintained at an accessible location such as with an official representative of the homeowners association, the individual or company contracted for maintenance, owner, etc.

APPENDIX 3B

Checklists - Detention, Retention, and Impoundment BMPs

Design and Plan Review Checklist

Page 1 of 7

Applicant:____________________________________ Phone No.:____________________
Designer:_____________________________________ Phone No.:____________________
Project Name: ____
Location:____
Type of Facility and Identification No.:______________________________

Plan status:
____ approved
____ not approved

Legend:
T - Complete
Inc. - Incomplete/Incorrect
N/A - Not Applicable

I. SUPPORTING DATA

_____ Narrative describing stormwater management strategy including all assumptions made in the design.

A. Drainage Area Map

_____ Site and drainage area boundaries
_____ Off-site drainage areas
_____ Pre- and post-developed land uses with corresponding acreage
_____ Pre- and post-developed time of concentration flow paths
_____ Existing and proposed topographic features
_____ Drainage area appropriate for BMP

B. Soils Investigation

_____ Soils map with site and drainage area outlined
_____ Geotechnical report with recommendations and earthwork specifications
_____ Boring locations
  _____ Borrow area
  _____ Basin pool area
  _____ Embankment area: centerline principal spillway, emergency spillway , abutments
_____ Boring logs with Unified Soils Classifications, soil descriptions, depth to seasonal high groundwater table, depth to bedrock, etc.
_____ Compaction requirements specified
_____ Additional geophysical investigation and recommendations in Karst environment

Design and Plan Review Checklist

II. COMPUTATIONS

A. Hydrology

_____ Runoff curve number determinations: pre- and post-developed conditions, with worksheets.

_____ Time of concentration: pre- and post-developed conditions, with worksheets.

_____ Hydrograph generation: pre- and post-developed condition for appropriate design and safety storms (SCS methods or modified rational-critical storm duration method)

B. Hydraulics

_____ Specify assumptions and coefficients used.

_____ Stage-storage table and curve

_____ Riser structure and barrel

- _____ Weir/orifice control analysis for riser structure discharge openings
- _____ Weir/orifice control analysis for riser crest
- _____ Barrel: inlet/outlet control analysis
- _____ Riser/Outlet Structure flotation analysis (factor of safety = 1.25 min.).
- _____ Anti-seep collar or filter diaphragm design.
- _____ Outlet protection per VE&SCH Std.. & Spec. 3.18.
- _____ Provisions for use as a temporary sediment basin riser with clean out schedule & instructions for conversion to a permanent facility.

_____ Emergency spillway adequacy/capacity analysis with required embankment freeboard.

_____ Stage - discharge table and curve (provide equations & cite references).

_____ Storm drainage & hydraulic grade line calculations.

_____ Reservoir routing of post-development hydrographs for appropriate design storms (2-yr., 10-yr., or as required by watershed conditions) & safety storms (100-yr. or as required).

C. Downstream impacts

_____ Danger reach study.

_____ 100 year floodplain impacts.

_____ "Adequate channel" calculations for receiving channel

_____ Provide downstream hydrographs at critical study points.

_____ Storm drainage plans for site areas not draining to BMP

- _____ Safe conveyance - MS-19
- _____ Areas compensated for in water quality performance-based criteria calculations

Design and Plan Review Checklist
Page 3 of 7

D. Water Quality

_____ Impervious cover tabulation
_____ Technology-based criteria: proper selection of BMP based on impervious cover
_____ Performance-based criteria: pre- and post-developed pollutant load and pollutant removal requirement calculations (provide worksheets)
_____ Water quality volume for retention basin I, II, or III permanent pool
_____ Water quality volume for ext. detention and ext. detention enhanced with drawdown calculations
_____ Proper surface area/depth allocations for permanent pool/shallow marsh/constructed wetland
_____ Constructed stormwater wetland / shallow marsh
- _____ Adequate drainage area and/or base flow
- _____ Adequate pool volume
- _____ Adequate surface area
- _____ Allocation of surface area to depth zones
- _____ Maximum ponding depth over pool surface specified

III. PLAN REQUIREMENTS

A. General Items

_____ Plan view drawn at 1"=50' or less (40', 30', etc.)
_____ North arrow
_____ Legend
_____ Location plan and vicinity map
_____ Property lines
_____ Existing & proposed contours (2' contour interval min.)
_____ Existing features & proposed improvements (including utilities and protective measures)
_____ Locations of test borings
_____ Earthwork specifications
_____ Construction sequence for SWM basin and E&S controls
_____ Temporary erosion & sediment control measures
_____ Conveyance of base flow during construction
_____ Temporary and permanent stabilization requirements
- _____ Emergency spillway
- _____ Basin side slopes

Design and Plan Review Checklist

    _____ Basin bottom

_____ Delineation of FEMA 100 year floodplain

_____ Plans sealed by a qualified licensed professional

B. BMP Plan Views

_____ Dimensions of basin features: perm. Pool, sediment forebay, embankment, etc.

_____ Location of all conveyance system outfalls into basin

    _____ Proper orientation to avoid short circuiting

    _____ Outlet protection per VE&SCH

_____ Top of bank & basin bottom elevations

_____ Elevations of permanent pool, water quality volume and max. design water surface elevations for all appropriate design storms and safety storms

_____ Side slope (H:V) of basin storage area and embankment (upstream and downstream slopes)

_____ Proper length-to-width ratio as specified in BMP design criteria

_____ **Pervious** low flow channel

_____ Sediment forebay

_____ Basin bottom slope

_____ Maintenance access to sediment forebay, riser structure, and one side of the basin ponding area

_____ Peripheral ledge for safety

_____ Aquatic Bench

_____ Shoreline protection

_____ Safety fence

_____ Riser and barrel materials and dimensions labeled

_____ Constructed stormwater wetland / shallow marsh

    _____ Basin liner specifications

    _____ Pool depth zones identified on plan

    _____ Pool geometry - wet/dry weather flow path

Design and Plan Review Checklist

Page 5 of 7

C. BMP - Section Views & Related Details

1. Embankment (or dam) and Ponding Areas

_____ Elevations of permanent pool, water quality volume and max. design water surface elevations for all appropriate design storms and safety storms
_____ Top of dam elevations- constructed height and settled height (10% settlement).
_____ Adequate freeboard
_____ Top width labeled
_____ Elevation of crest of emergency spillway
_____ Emergency spillway w/ side slopes labeled.
_____ Emergency spillway inlet, level, and outlet sections labeled
_____ Existing ground and proposed improvements profile along center line of embankment
_____ Existing ground and proposed improvements profile along center line of principal spillway
_____ Typical grading section through pond including typical side slopes with aquatic bench, safety ledge, shoreline protection, etc.
_____ Existing ground and proposed improvements along center line of emergency spillway
_____ Dimensions of zones for zoned embankment

2. Seepage Control

_____ Impervious lining
_____ Phreatic line (4:1 slope measured from the principal spillway design high water).

a. Anti-seep Collar

_____ Anti-seep collar (detail reqd..).
_____ Size (based upon 15% increase in seepage length).
_____ Spacing & location on barrel (at least 2' from pipe joint).

b. Filter Diaphragm

_____ Design certified by a professional geotechnical engineer.

3. Foundation Cut Off Trench or Key Trench

_____ Materials labeled
_____ Bottom width (4' min. or greater per geotech. report).
_____ Side slopes labeled (1:1 max. steepness).
_____ Depth (4' min. or as specified in geotechnical report)

Design and Plan Review Checklist

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4. Multi Stage Riser and Barrel System

_____ Materials labeled
_____ Bedding or cradle details provided
_____ Gauge & corrugation size for metal pipes specified
_____ Barrel diameter, inverts, and slope (%) labeled
_____ Outlet protection per VESCH, Std. & Spec. 3.18, 3.19 w/ filter cloth underlayment
_____ Crest elevation of riser structure shown
_____ Inverts and dimensions of control release orifices/weirs shown
_____ Structure dimensions shown
_____ Control orifice/weir dimensions shown
_____ Extended detention orifice protection (detail required for construction)
_____ Riser trash rack or screen (detail reqd.. for construction).
_____ Riser anti-vortex device (detail reqd.. for construction).
_____ Proper riser structure footing.
_____ Access to riser structure interior for maintenance.
_____ Basin drain pipe

D. Landscape Plan

_____ Planting schedule and specifications (transport / storage / installation / maintenance)
_____ Plant selection for planting zones 1thru 6
_____ Preservation measures for existing vegetation
_____ Top soil / planting soil included in final grading

E. Maintenance Items

_____ Person or organization responsible for maintenance.
_____ Maintenance narrative which describes the long-term maintenance requirements of the facility and all components.
_____ Facility access from public R/W or roadway.
_____ Maintenance easement.

Design and Plan Review Checklist

Page 7 of 7

COMMENTS

BY: ______________________________ DATE: __________

Construction Inspection and As-Built Survey Checklist

Page 1 of 2

Applicant: ______________________________________ **Phone No**.:_______________
Designer:_______________________________________ **Phone No**.:_______________
Project Name:____
Location:____
Contractor:______________________________________ **Phone No**.:_______________
Permit No.: ______________________
Type of Facility and Identification No. ____

A separate checklist is to be completed for separate BMPs, should more than one be used at a given project.

* Key - (T) If acceptable

(Inc.) If not adequate, explanation at the end of a section is required

(NA) If not applicable

I. INSPECTION LOGS and TEST DOCUMENTATION

A. Earthwork

_____ The results and interpretation of geo-physical testing in areas of karst formation (west of the Blue Ridge) or geo-technical analysis (boring log data) of underlying strata elsewhere in the state
_____ Verification of removal of all unsuitable material beneath dam embankment and footing
_____ Verification of fill classification/suitability for use in the embankment
_____ Verification of proper installation of cut-off trench
_____ Verification of soil impermeability for material used in the liner, and proper liner thickness
_____ Multiple compaction test results indicating adequacy throughout the embankment section including areas adjacent to the outlet conduit and any seepage control measures.
_____ Verification that underlying bedrock and/or the water table does not interfere with the impoundment
_____ Verification of dimensions of sub surface features such as the riser structure footing, anti seep collars, filter and drainage diaphragm, etc.

B. Materials

_____ Riprap size distribution and composition
_____ Inlet shaping (within the control structure and system manholes)
_____ Trash rack construction/coatings
_____ Trash rack; method of installation
_____ Shop drawings for control structure detailing dimensions, elevations, and reinforcing information
_____ Verification of structure reinforcement and water tight connections

Construction Inspection and As-Built Survey Checklist

Page 2 of 2

_____ Low-flow channel lining
_____ Outlet barrel size/construction type/length
_____ Outlet protection
_____ Anti-vortex device

(Comments)
____
____
____

II. DIMENSIONS and ELEVATIONS SURVEY (Red Lined Plan Sheets)

_____ Top width, and side slopes (profile) of dam embankment
_____ Inverts and slope (%) of outlet conduit
_____ Elevation and cross section of the emergency spillway
_____ Principal spillway profile including elevations and geometry of riser control orifices and/or weirs
_____ Cast-in-place control structure dimensions/elevations
_____ Riser crest and invert of control structure
_____ Outlet protection
_____ Contours of the ponding area
_____ Slope(s) of storm sewer system conduit with inverts in and out for each pipe
_____ Slope and cross-section of all on-site channels

(Comments)
____
____
____
____

II. CERTIFICATIONS

_____ Certification's from manufacturers for materials used
_____ Seeding tickets and specifications
_____ Certification statement and seal by licensed professional indicating the as-built drawing is accurate, complete and constructed per the approved plan

Operation and Maintenance Checklist

Page 1 of 3

	YES / NO	REPAIR	INVESTIGATE	Inspector Name:____ Inspection Date: ____ Type of BMP:____
Item				**Comments**
I. EMBANKMENT				
A. Crest				
1. Visual settlement				
2. Misalignment				
3. Cracking				
B. Upstream slope				
1. Erosion				
2. Adequate groundcover				
3. Trees, shrubs or other				
4. Cracks, settlements or bulges				
5. Rodent holes				
C. Downstream slope				
1. Erosion				
2. Adequate groundcover				
3. Trees, shrubs or other				
4. Cracks, settlements or bulges				
5. Rodent holes				
D. Abutments				
1. Erosion				
2. Seepage				
3. Cracks				

Operation and Maintenance Checklist

Page 2 of 3

	YES / NO	REPAIR	INVESTIGATE	InspectorName:________________________________ __ Inspection Date:___________________________________ Type of
E. Drainage, seepage control				
1. Internal drains flowing				
2. Seepage at toe				
II.EMERGENCY SPILLWAY				
1. Eroding or backcutting				
2. Obstructed				
3. Leaking				
4. Operational				
IV. PRINCIPAL SPILLWAY BARREL				
1. Seepage into conduit				
2. Debris present				
3. Displaced or offset joints				
V. OUTLET PROTECTION/ STILLING BASIN				
1. Obstructed				
2. Adequate riprap				
3. Undercutting at outlet				
4. Outlet channel scour				
VI. BASIN & UPLAND BUFFER AREA				
A. Low flow channel				
1. Erosion				
2. Adequate vegetation				
3. Obstructed				

Operation and Maintenance Checklist

	YES / NO	REPAIR	INVESTIGATE	Inspector Name:_______________________________________ Inspection Date:_______________________________________ Type of BMP: ____
B. Basin bottom & side slopes				
1. Erosion				
2. Adequate stabilization				
3. Sediment accumulation				
4. Floating debris				
5. High water marks				
6. Shoreline protection				
C. Inflow channels/pipes				
1. Erosion				
2. Adequate stabilization				
3. Undercutting				
D. Sediment forebay				
1. Sediment accumulation				
2. Stable overflow into basin				
E. Upland landscaping				
F. Aquatic landscaping				

APPENDIX 3C

Checklists - Infiltration BMPs

Design and Plan Review Checklist

Page 1 of 5

Applicant:_________________________________ **Phone No.:**__________________
Designer:__________________________________ **Phone No.:**__________________
Project Name: ____
Location:____
Type of Facility and Identification No.:_____________________________

Plan status:
____ approved
____ not approved

Legend:
T - Complete
Inc. - Incomplete/Incorrect
N/A - Not Applicable

I. SUPPORTING DATA

_____ Narrative describing stormwater management strategy including all assumptions made in the design.
(Infiltration basin, infiltration trench, roof downsput system, porous pavement)

A. Drainage Area Map

_____ Site and drainage area boundaries
_____ Off-site drainage areas
_____ Pre- and post-developed land uses with corresponding acreage
_____ Pre- and post-developed time of concentration flow paths
_____ Existing and proposed topographic features
_____ Drainage area appropriate for BMP

B. Soils Investigation

_____ Soils map with site and drainage area outlined
_____ Geotechnical report verifying suitability for infiltration (0.52"/hr $\leq f <$ 8.27"/hr)
_____ Boring locations
_____ Boring logs with Unified Soils Classifications
  _____ Soil descriptions
  _____ Depth to seasonal high groundwater (2' to 4' below design bottom of facility, min.)
  _____ Depth to bedrock (2' to 4' below design bottom of facility, min.)
  _____ Verification of absence of karst topography

Design and Plan Review Checklist

Page 2 of 5

C. Topographic Conditions

_____ Meets minimum slope requirements

- _____ Porous pavement: s < 3% (20H:1V)
- _____ All other infiltration facilities: s < 20% (5H:1V)

II. COMPUTATIONS

A. Hydrology

_____ Runoff curve number determinations: pre- and post-developed conditions, with worksheets.

_____ Time of concentration: pre- and post-developed conditions, with worksheets.

_____ Hydrograph generation: pre- and post-developed condition for appropriate design and safety storms (SCS methods or modified rational-critical storm duration method)

B. Hydraulics

_____ 48 hour drain time provided

_____ Specify assumptions and coefficients used.

_____ Stage-storage table and curve (void ratio of 0.4 for stane storage)

_____ Riser structure and barrel for large storm overflow or bypass

_____ Emergency spillway adequacy/capacity analysis with required embankment freeboard for infiltration basins

_____ Storm drainage & hydraulic grade line calculations.

D. Water Quality

_____ Impervious cover tabulation

_____ Technology-based criteria: proper selection of BMP based on impervious cover

_____ Performance-based criteria: pre- and post-developed pollutant load and pollutant removal requirement calculations (provide worksheets)

_____ Water quality volume for desired target phosphorus removal efficiency.

Design and Plan Review Checklist

Page 3 of 5

III. PLAN REQUIREMENTS

A. General Items

_____ Plan view drawn at 1"=50' or less (40', 30', etc.)
_____ North arrow
_____ Legend
_____ Location plan and vicinity map
_____ Property lines
_____ Existing & proposed contours (2' contour interval min.)
_____ Existing features & proposed improvements (including utilities and protective measures)
_____ Locations of test borings
_____ Construction sequence
    _____ Infiltration BMP to be constructed after site work is completed and stabilization measures have been implemented
    _____ traffic control
_____ Temporary erosion & sediment control measures
_____ Temporary and permanent stabilization requirements
    _____ Infiltration basin emergency spillway
    _____ Infiltration basin side slopes
_____ Construction specifications
    _____ Infiltration basin bottom surface preparation
    _____ Infiltration trench bottom surface preparation
    _____ Infiltration trench filter fabric laydown
    _____ Infiltration trench aggregate placement
_____ Plans sealed by a qualified licensed professional

B. BMP Plan Views

_____ Dimensions of infiltration facility
_____ Location of all conveyance system outfalls into basin with pretreatment and outlet protection per VE&SCH

Design and Plan Review Checklist

_____ Infiltration basin
- _____ Top of bank & basin bottom elevations
- _____ Elevations of water quality volume and max. design water surface elevations for all appropriate design storms and safety storms
- _____ Side slope (H:V) of basin storage area and embankment (upstream and downstream slopes)
- _____ Sediment forebay
- _____ Maintenance access to sediment forebay and riser structure

_____ Safety fence

_____ Observation well

C. <u>BMP - Section Views & Related Details</u>

1. <u>Infiltration Basin</u>

_____ Elevations of water quality volume and max. design water surface elevations for all appropriate design storms and safety storms

_____ Top of dam elevations- constructed height and settled height (10% settlement).

_____ Adequate freeboard

_____ Top width labeled

_____ Elevation of crest of emergency spillway

_____ Principal/emergency spillway w/ side slopes labeled.

_____ Principal/emergency spillway inlet, level, and outlet sections labeled

_____ Existing ground and proposed improvements profile along center line of embankment

_____ Existing ground and proposed improvements profile along center line of principal spillway

_____ Typical grading section through basin

_____ Existing ground and proposed improvements along center line of emergency spillway

_____ Dimensions of zones for zoned embankment

_____ Foundation Cut Off Trench or Key Trench
- _____ Materials labeled
- _____ Bottom width (4' min. or greater per geotech. report).
- _____ Side slopes labeled (1:1 max. steepness).
- _____ Depth (4' min. or as specified in geotechnical report)

Design and Plan Review Checklist

Page 5 of 5

2. Infiltration Trench

_____ Dimensions provided

_____ Backfll material specified

- _____ Stone storage: clean VDOT No. 1 Open Graded Course Aggregate or equal
- _____ Bottom sand layer: VDOT Fine Aggregate, Grading A or B

_____ Filter Fabric

_____ Observation well

3. Porous Pavement

_____ Subgrade preparation

_____ Aggregate

- _____ Filter course: clean VDOT No. 57 Open Graded Course Aggregate or equal
- _____ Reservoir course: clean VDOT No. 3 Open Graded Course Aggregate or equal
- _____ Sand layer: VDOT Fine Aggregate, Grading A or B

_____ Porous asphalt surface course

E. Maintenance Items

_____ Person or organization responsible for maintenance.

_____ Maintenance narrative which describes the long-term maintenance requirements of the facility and all components.

_____ Facility access from public R/W or roadway.

_____ Maintenance easement.

COMMENTS

____

____

____

____

____

____

____

BY: ______________________________ DATE: ________

Construction Inspection and As-Built Survey Checklist

Page 1 of 2

Applicant: ____ **Phone No**.:_______________
Designer:____ **Phone No**.:_______________
Project Name:____
Location:____
Contractor:____ **Phone No**.:_______________
Permit No.: _______________________
Type of Facility and Identification No. ____

A separate checklist is to be completed for each BMP, should more than one be used at a given project.

* Key - (T) If acceptable

(Inc.) If not adequate, explanation at the end of a section is required

(NA) If not applicable

I. INSPECTION LOGS and TEST DOCUMENTATION

A. Flow splitter / Overflow

_____ Overflow invert at correct elevation
_____ Inflow pipe plugged prior to full site stabilization

B. Earthwork

_____ The results and interpretation of geo-physical testing in areas of karst formation (west of the Blue Ridge) or geo-technical analysis (boring log data) of underlying strata elsewhere in the state
    _____ Infiltration rate of soils
    _____ Depth to seasonal watertable
    _____ Depth to bedrock
_____ Verification of removal of all unsuitable material beneath dam embankment and footing
_____ Verification of fill classification/suitability for use in the embankment
_____ Verification of proper installation of cut-off trench
_____ Multiple compaction test results indicating adequacy throughout the embankment section including areas adjacent to the outlet conduit and any seepage control measures.
_____ Verification that underlying bedrock and/or the water table does not interfere with the impoundment
_____ Verification of dimensions of sub surface features such as the riser structure footing, anti seep collars, filter and drainage diaphragm, etc.

B. Materials

_____ Stone aggregate size, composition, and placement
_____ Filter fabric placement

Construction Inspection and As-Built Survey Checklist

Page 2 of 2

C. Sequence of Construction

_____ Site stabilization prior to facility construction
_____ Traffic control

(Comments)

____
____
____

II. DIMENSIONS and ELEVATIONS SURVEY (Red Lined Plan Sheets)

_____ Invert and diameter/geometry of flow splitter, overflow pipes, and channels
_____ Top width, and side slopes (profile) of dam embankment
_____ Dimensions of storage area
_____ Elevation and cross section of the emergency / principal spillway
_____ Outlet protection
_____ Contours of the ponding area
_____ Slope and cross-section of all on-site channels

(Comments)

____
____
____
____

II. **CERTIFICATIONS**

_____ Certification's from manufacturers for materials used
_____ Seeding tickets and specifications
_____ Certification statement and seal by licensed professional indicating the as-built drawing is accurate, complete and constructed per the approved plan

Operation and Maintenance Checklist

Page 1 of 2

Date____________________

Project___________________________________ Site Plan / SUP Number _____________
Location__________________________________ Date Placed in Service _______________
Date of Last Inspection ____________ Inspector ___________________________________
Owner/Owner's Representative ____
"As Built" Plans available: Y / N

	Satisfactory	Unsatisfactory
1. Debris cleanout		
Contributing areas clean of debris	________	________
Filtration facility clean of debris	________	________
Inlets and outlets clear of debris	________	________
2. Vegetation		
Contributing drainage area stabilized	________	________
No evidence of erosion	________	________
Area mowed and clippings removed	________	________
3. Clogging		
No evidence of surface clogging	________	________
Observation well clear of water within 48 hrs of storm event	________	________
4. Structural components		
No evidence of structural deterioration	________	________
Any grates are in good condition	________	________
No evidence of spalling or cracking of structural parts	________	________

Operation and Maintenance Checklist

Site Plan/SUP Number ______________________ Date: __________________________

	Satisfactory	Unsatisfactory
6. Outlets/overflow spillway		
Good condition, no need for repair	________	________
No evidence of erosion (if draining into a natural channel)	________	________
8. Overall function of facility		
No evidence of flow bypassing facility	________	________
No standing water	________	________

Action to be taken:

If any of the answers to the above items are checked unsatisfactory, a time frame shall be established for their correction or repair.

No action necessary. Continue routine inspections_________

Correct noted facility deficiencies by___________________

Facility repairs were indicated and completed. Site reinspection is necessary to verify corrections or repairs.

Site reinspection accomplished on_____________________

Site reinspection was satisfactory. Next routine inspection is scheduled for approximately:_________________

____

Signature of inspector

APPENDIX 3D

Checklists - Intermittent Sand Filters

Construction Inspection and As-Built Survey Checklist

Page 1 of 3

Date______________

Project___________________________________ **Site Plan / SUP Number ___________**

Location__________________________________ **Date BMP Placed in Service _________**

Individual(s) Conducting the Inspection___________________________
"As Built" Plans available Y / N

Warning: If filtration facility has a watertight cover; be careful regarding the possibility of flammable gases within the facility. Care should be taken lighting a match or smoking while inspecting facilities that are not vented. If filtration facility is in a completely enclosed vault, OSHA Confined Space Entry procedures must be followed.

	Satisfactory	Observed and Confirmed by (Initial)
1. Flow Splitter		
Overflow invert at correct elevation	_________	__________
Inflow pipe to filter plugged with watertight seal prior to site stabilization	_________	__________
2. Filter Shell (Note: Separate structural inspections of the filter shell must be conducted and documented during construction)		
Specified number and type of manhole covers and hatches installed	_________	__________
No evidence of structural defects ("honeycombing", etc)	_________	__________
Access ladders installed as specified	_________	__________
Shell completely cleaned of construction debris, dirt, etc.	_________	__________
Dewatering drain meets specs and holds water	_________	__________
Dewatering drain penetration sealed with specified water stop	_________	__________
3. Watertight Integrity Test of Filter Shell		
Watertight plug installed in outflow pipe	_________	__________
Elevation of shell bottom observed at ___________ ft.	_________	__________
Filled with water to bottom of top slab at ___________(Time/date)	_________	__________
Top of water elevation observed at __________ ft.	_________	__________
Observed 24-hour drawdown at _____________ (Time/date)	_________	__________
Top of water elevation after drawdown observed at __________ ft.	_________	__________
Footprint of wetted shell (from drawings) is _____________ $ft.^2$		
Volume of water lost (footprint x elevation drop) = ___________ $ft.^3$		
Volume of initial water (footprint x depth of water) = __________ $ft..^3$		
Percent of initial volume lost = ________ %	_________	__________

Note: If shell had ≤ five % water loss, the shell is satisfactory. If the shell had > five % water loss, find and seal leaks and retest until five % limit is achieved.

Construction Inspection and As-Built Survey Checklist

Page 2 of 3

Site Plan/SUP Number ______________________ Date: __________________________

	Satisfactory	Observed and Confirmed by (Initial)
4. Basin(s) and Basin Liner(s) (Where Applicable)		
Basin(s) graded in conformance with plan	________	________
Basin liner material(s) conforms to specifications (attach 6" x 6" sample)	________	________
Basin liner installation(s) conforms to plans & specifications	________	________
5. Collector System		
Collector pipes meet specs and hole patterns are correct	________	________
Collector pipes wrapped in geotextile meeting specs (attach labeled 6" x 6" sample)	________	________
Specified galvanized hardware cloth installed over weepholes (if used)	________	________
Collector gravel meets specs and is installed to design depth	________	________
Pea gravel (if used) meets spec and is installed to design depth	________	________
Geotextile fabric beneath sand meets spec (attach labeled 6" x 6" sample) and is lapped at least 6" up all 4 sides	________	________
6. Filter Components		
Filter sand meets specifications (attach lab report showing gradation, effective size and uniformity coefficient)	________	________
Filter sand installed to design depth, hydraulically compacted on ________________ (Date) , and refilled to design depth	________	________
Filter top geotextile (if used) meets spec (attach labeled 6" x 6" sample) and is lapped up all four sides	________	________
Filter top ballast(if used) meets specs and is installed to design depth	________	________
7. Clearwell		
Clearwell is free of construction debris and dirt	________	________
Outflow pipe invert is at the design elevation	________	________
Pump (where applicable) meets specs (attach catalog cuts)	________	________
Wiring (where applicable) is in waterproof conduits **(Note:** electrical wiring requires separate building code inspection)	________	________
Panel box (where applicable) is well marked (attach wiring diagram)	________	________
8. Upflow Gravel Prefilter (where used)		
Bottom grate meets spec and installed at design elevation	________	________
Bottom geometries (if used) meets spec and properly installed	________	________
Large bottom stone meets spec and installed to design depth	________	________
Pea gravel meets spec and installed to design depth	________	________

Construction Inspection and As-Built Survey Checklist

Page 3 of 3

Site Plan/SUP Number ________________ Date: ____________________________

	Satisfactory	Observed and Confirmed by (Initial)
9. Monitoring Manholes (where required)		
Manhole shells and covers conform to specs	________	________
Inflow and outflow pipe slopes are as specified	________	________
Straight pipe runs through manholes are as specified (no bends)	________	________
Manholes and pipes are flushed clean	________	________

Note: If any of the answers under items 1 - 9 above are checked unsatisfactory, a time frame shall be established for their correction or and a reinspection shall be scheduled. A new form shall be completely filled out at the time of the reinspection. Only the form documenting completely satisfactory performance shall be submitted to the governing jurisdiction for certification. All persons initialing this form shall complete the table below:

Initial	Full Name	Signature	Title/Position and Organization

CERTIFICATION: Based on the above, I certify that the Best Management Practice covered by this report is constructed in accordance with the approved Final Site Plan and as designed.

____

(Signature)

____

(Typed Name and Title)
(Place professional seal on certification)

Operation and Maintenance Checklist

Page 1 of 2

Date____________________

Project___________________________________ Site Plan / SUP Number _____________
Location__________________________ Date Placed in Service: ___________

Date of Last Inspection _________ Inspector _____________________________________
Owner/Owner's Representative ____
"As Built" Plans available: Y / N Sand Filter Type: _____________________________

Warning: If filtration facility has a watertight cover; be careful regarding the possibility of flammable gases within the facility. Care should be taken lighting a match or smoking while inspecting facilities that are not vented. If filtration facility is in a completely enclosed vault, OSHA Confined Space Entry Procedures must be followed.

	Satisfactory	Unsatisfactory
1. Debris cleanout		
Contributing areas clean of debris	________	________
Filtration facility clean of debris	________	________
Inlets and outlets clear of debris	________	________
2. Vegetation		
Contributing drainage area stabilized	________	________
No evidence of erosion	________	________
Area mowed and clippings removed	________	________
3. Oil and grease		
No evidence of filter surface clogging	________	________
Activities in drainage area minimize oil & grease entry	________	________
4. Water retention where required		
Water holding chambers at normal pool	________	________
No evidence of leakage	________	________
5. Sediment deposition		
Filtration chamber clean of sediments	________	________
Water chambers not more than ½ full of sediments	________	________

Operation and Maintenance Checklist

Page 2 of 2

Site Plan/SUP Number ______________________ Date: __________________________

	Satisfactory	Unsatisfactory
6. Structural components		
No evidence of structural deterioration	________	________
Any grates are in good condition	________	________
No evidence of spalling or cracking of structural parts	________	________
7. Outlets/overflow spillway		
Good condition, no need for repair	________	________
No evidence of erosion (if draining into a natural channel)	________	________
8. Overall function of facility		
No evidence of flow bypassing facility	________	________
No noticeable odors outside of facility	________	________
9. Pump (Where Applicable)		
Catalog cuts and wiring diagram for pump available	________	________
Waterproof conduits for wiring appear to be intact	________	________
Panel box is well marked	________	________
No evidence of pump failure (excess water in pump well, etc.)	________	________

Action to be taken:

If any of the answers to the above items are checked unsatisfactory, a time frame shall be established for their correction or repair.

No action necessary. Continue routine inspections______________

Correct noted facility deficiencies by________________________

Facility repairs were indicated and completed. Site reinspection is necessary to verify corrections or repairs.

Site reinspection accomplished on______________________

Site reinspection was satisfactory. Next routine inspection is scheduled for approximately:__________________

____

Signature of inspector

APPENDIX 3E

Checklists - Bioretention

Plant Selection and Site Consideration Checklist

Page 1 of 2

Date______________

I. General Site Information

Site Plan / SUP Number ____________________

Project Name____

Size of development____

Drainage area size____

II. Plant Material Layout Considerations

A. Site Design Considerations

Importance of aesthetics____
____

Important visual characteristics (foliage, form, etc.)____________________________________
____

Visibility and traffic considerations____
____

Other safety issues____

Conflict with any structural components of site (proposed powerlines, pipes)________________
____

General comments____
____

Plant Selection and Site Consideration Checklist

Page 2 of 2

Site Plan/SUP Number _______________ Date:______________

B. Ecological Factors

Insect and disease infestation on or near site____
____

Wind exposure____

Sun exposure____

Effects upon bioretention area from adjacent plant communities_____________________________
____

Wildlife benefits be included in plant material layout_______________________________________
____

Construction Inspection and As-Built Checklist

Page 1 of 2

Date______________

Project__________________________________ **Site Plan / SUP Number** _______________
Location______________________________ **Date BMP Placed in Service** _____________

Individual(s) Conducting the Inspection__________________________________
"As Built" Plans available: Y / N

Warning: If any bioretention facility component has a watertight cover; be careful regarding the possibility of flammable gases within the facility. Care should be taken lighting a match or smoking while inspecting facilities that are not vented.

	Satisfactory	Observed and Confirmed by (Initial)
1. Flow Splitter or Overflow Drain		
Overflow Invert at correct elevation	________	________
Inflow pipe to filter plugged with watertight seal prior to site stabilization (where applicable)	________	________
2. Basin(s) and Basin Liner(s) (Where Applicable - Bioretention Filters)		
Basin(s) graded in conformance with plan	________	________
Basin liner material(s) conforms to specifications (attach 6" x 6" sample)	________	________
Basin liner installation(s) conforms to plans & specifications	________	________
3. Collector System(Where Applicable--Bioretention-Filters and Green Alleys)		
Collector pipes meet specs and hole patterns are correct	________	________
Collector pipes wrapped in geotextile meeting specs (attach 6" x 6" sample)	________	________
Specified galvanized hardware cloth installed over weepholes	________	________
Collector gravel meets specs and is installed to design depth	________	________
Pea gravel beneath sand meets spec and is installed to design depth	________	________
4. Sand and Planting Soil Components		
Filter sand meets specifications (attach lab report showing gradation, effective size and uniformity coefficient)	________	________
Filter sand installed to design depth	________	________
Planting soil meets design specifications	________	________
Planting soil installed to design depth, hydraulically compacted on ______________ (Date) , and refilled to design depth	________	________

Construction Inspection and As-Built Checklist

Page 2 of 2

	Satisfactory	Observed and Confirmed by (Initial)
5. Bioretention Plant Materials		
Plants meet size and variety specifications	________	________
All plants installed per landscape plan	________	________
Mulch or cover crop installed according to plans and specifications	________	________
6. Clearwell Manhole (Where Applicable--Bioretention Filters and Some Green Alleys)		
Clearwell is free of construction debris and dirt	________	________
Outflow pipe invert is at the design elevation	________	________
Outflow pipe is capped with orifice drilled to design size	________	________
7. Monitoring Manholes (where required)		
Manhole shells and covers conform to specs	________	________
Inflow and outflow pipe slopes are as specified	________	________
Straight pipe runs through manholes are as specified (no bends)	________	________
Manholes and pipes are flushed clean	________	________

Note: If any of the answers under items 1 - 9 above are checked unsatisfactory, a time frame shall be established for their correction or and a reinspection shall be scheduled. A new form shall be completely filled out at the time of the reinspection. Only the form documenting completely satisfactory performance shall be submitted to the governing jurisdiction for certification. All persons initialing this form shall complete the table below:

Initial	Full Name	Signature	Title/Position and Organization

CERTIFICATION: Based on the above, I certify that the Best Management Practice covered by this report is constructed in accordance with the approved Final Site Plan and as designed.

____

(Signature)

____

(Typed Name and Title)
(Place professional seal on certification)

Operation and Maintenance Inspection Checklist

Page 1 of 2

Date______________________________ **Time**__________________________

Project__________________________________ **Site Plan / SUP Number** ______________

Location____

Date Placed in Service: _______________________ **Date of Last Inspection:** ____________

Individual Conducting the Inspection ________________________________

(Owner) ____

"As Built" Plans available: <u>Y / N</u>
Bioretention Facility Type: ____ Infiltration; _____ Filter; _____Green Alley

---

<u>Warning</u>: If filtration facility has a watertight cover; be careful regarding the possibility of flammable gases within the facility. Care should be taken lighting a match or smoking while inspecting facilities that are not vented. If filtration facility is in a completely enclosed vault, OSHA Confined Space Entry Procedures must be followed.

	Satisfactory	Unsatisfactory
1. Debris cleanout		
Contributing areas clean of debris	________	________
Bioretention facility clean of debris	________	________
Inlets and outlets clear of debris	________	________
2. Drainage Area Stabilization		
Contributing drainage area stabilized	________	________
No evidence of erosion	________	________
Area mowed and clippings removed	________	________
3. Oil and grease		
No evidence of filter surface clogging	________	________
Activities in drainage area minimize oil & grease entry	________	________
4. Overflow Structure		
Overflow grate/throat clear of debris	________	________
Any grates are in good condition	________	________
No evidence of erosion (if draining into a natural channel)	________	________

Operation and Maintenance Inspection Checklist

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Site Plan/SUP Number ______________________ **Date:** __________________________

	Satisfactory	Unsatisfactory
5. Bioretention Planting Soil		
No evidence of planting soil erosion	________	________
Bioretention basin clean of sediments	________	________
6. Organic Layer		
Mulch covers entire area (NO voids) and to specified thickness	________	________
Mulch is in good condition	________	________
7. Plants		
Specified number and types of plants still in place	________	________
No dead or diseased plants	________	________
No evidence of plant stress from inadequate watering	________	________
No evidence of deficient stakes or wires	________	________

NOTE: Diseased plants must be treated by a qualified professional. Deficient stakes or wires must be replaced. Dead plants or plants diseased beyond treatment must be replaced by plants meeting original design specifications. New plants must be watered every day for the first 14 days after planting. Reinspections must be scheduled to occur following this period.

Action to be taken:

If any of the answers to the above items are checked unsatisfactory, a time frame shall be established for their correction or repair.

No action necessary. Continue routine inspections______________

Correct noted facility deficiencies by________________________

Facility repairs were indicated and completed. Site reinspection is necessary to verify corrections or repairs.

Site reinspection accomplished on_____________________

Site reinspection was satisfactory. Next routine inspection is scheduled for approximately:__________________

____

Signature of inspector

A HYDROGEOLOGICAL ASSESSMENT OF THE U.S. FOREST SERVICE/BUREAU OF LAND MANAGEMENT MOUNTAIN VALLEY PIPELINE AND EQUITRANS EXPANSION PROJECT SUPPLEMENTAL DRAFT ENVIRONMENTAL IMPACT STATEMENT DECEMBER 2022

Prepared by Pamela C. Dodds, Ph.D., Licensed Professional Geologist
Prepared for The Wilderness Society - January 24, 2023

REFERENCE 12

February 21, 2023

CHAPTER 4

Stormwater Runoff

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STORMWATER RUNOFF

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Criteria Development Reasoning

The problems associated with stormwater runoff in rapidly urbanizing watersheds have become well-known. These problems relate to both the quantity and quality of stormwater runoff. Major problems include increased flooding magnitude and frequency, accelerated stream channel erosion, and water quality degradation.

The basic underlying cause of these problems is not difficult to understand. The hydrologic systems which have reached a natural equilibrium over centuries simply cannot adjust gracefully to the sudden impact of urban development. Flooding occurs because the increased volume and peak rate of runoff exceeds the natural carrying capacity of the streams more often. Stream channel erosion accelerates due to suddenly increased flow velocities and flooding frequency. The water quality itself is degraded by sedimentation and because numerous other pollutants become available to be washed off the land surface and into the streams, rivers and lakes.

Studies have shown that most natural stream channels are formed with a bankfull capacity to pass runoff from a storm with a 1.5- to 2-year recurrence interval. As upstream development occurs, the volume and velocity of flow from these relatively frequent storms increase. Consequently, even smaller storms with less than 1-year recurrence intervals begin to cause streams to flow full or flood.

According to Leopold (76), stream channels are subject to a 3- to 5-fold increase in the frequency of bankfull flows in a typical urbanizing watershed. This increase in the flooding frequency places a stress on the channel to adjust its shape and alignment to accommodate the increased flow. Unfortunately, this adjustment takes place in a very short time period (in geologic terms), and the transition is usually not a smooth one. Meandering stream channels which were once parabolic in shape and covered with vegetation, typically become straight, wide rectangular channels with barren vertical banks. This process of channel erosion often causes significant property damage, and the resulting sediment which is generated is transported downstream, further contributing to channel degradation.

One strategy for dealing with this problem is to increase the carrying capacity and stability of affected streams through channel modifications (e.g., straightening, widening, lining with non-erodible material, etc.). This strategy may be employed most effectively on man-made channels or small, intermittent streams. Significant modifications to natural, continuous flowing steams, however, can be the subject of intense local controversy.

Wherever modification to natural flowing streams are being considered, extreme care must be taken to weigh the benefits of such modifications against the cost and the concerns of the local citizens. Where channel modifications are necessary, an attempt should be made to incorporate conservation practices which will minimize adverse impacts to fish, wildlife, and the aesthetic quality of the stream.

The following stormwater runoff requirements were developed to provide localities with maximum flexibility to deal with their stormwater runoff problems according to local needs and priorities. The only condition which is imposed statewide is that all local stormwater runoff criteria must contain provisions for the control of off-site erosion and sedimentation.

Statewide Stormwater Runoff Standard

The Erosion and Sediment Control Regulations (Minimum Standard #19) require that properties and waterways downstream from new development sites shall be protected from erosion due to increases in the volume, velocity, and peak flow rate of stormwater runoff. (See Chapter 8 for the text of the law and regulations.) In the absence of a local stormwater management program, the following criteria shall apply:

A. Increased volumes of sheet flow that may cause erosion or sedimentation on adjacent property must be diverted to a stable outlet, adequate channel or detention facility.

B. Concentrated stormwater runoff leaving a development site must be discharged directly into an adequate natural or manmade receiving channel, pipe or storm sewer system.

   An adequate channel is defined as "a watercourse that will convey a chosen frequency storm event without overtopping its banks or causing erosive damage to the bed, banks and overbank sections of the watercourse."

   A receiving channel may be considered adequate if the total drainage area to the point of analysis in the channel is 100 times greater than the contributing drainage area of the project site.

   For natural channels, the two-year frequency storm is used to verify that stormwater will not overtop the channel banks nor cause erosion of the channel bed or banks.

   For manmade channels, the ten-year frequency storm is used to verify that stormwater will not overtop the channel banks and the two-year storm is used to demonstrate that stormwater will not cause erosion of the channel bed or banks.

   For pipes and storm sewer systems, the ten-year frequency storm is used to verify that stormwater will be contained within the pipe or storm sewer.

C. If existing natural receiving channels or previously constructed manmade channels or pipes are not adequate, the applicant must choose one of the following options.

   1. Improve the channels to a condition where the ten-year frequency storm will not overtop the channel banks and the two-year frequency storm will not cause erosion to the channel bed or banks. The applicant must provide evidence of permission to make the improvements.

2. Improve the pipe or storm sewer system to a condition where the ten-year frequency storm is contained within the appurtenances. The applicant must provide evidence of permission to make the improvements.

3. Develop a site design that will not cause the pre-development peak runoff rate from a two-year frequency storm to increase when runoff discharges into a natural channel or will not cause the pre-development peak runoff rate from a ten-year storm to increase when runoff discharges into a manmade channel.

4. Provide a combination of channel improvements, stormwater detention or other measures which is satisfactory to the plan-approving authority to prevent downstream erosion.

D. If the applicant chooses an option that includes stormwater detention, the applicant must obtain approval from the locality of a plan for maintenance of the detention facility. The plan must establish the maintenance requirements of the facility and identify the person responsible for performing the maintenance.

E. All hydrologic analyses must be based on the existing watershed characteristics and the ultimate development condition of the project site.

F. In applying these stormwater runoff criteria, individual lots in a residential subdivision development are not considered separate development projects. Instead, the residential subdivision development, as a whole, is considered to be a single development project. Hydrologic parameters that reflect the ultimate subdivision development must be used in all engineering calculations.

G. Proposed commercial or industrial subdivisions must apply these stormwater runoff criteria to the development as a whole. Hydrologic parameters that reflect the ultimate subdivision development must be used in all engineering calculations.

Applying the Criteria

The following commentary is intended to aid the handbook user in understanding and applying the stormwater runoff criteria in the Erosion and Sediment Control Regulations (Minimum Standard #19) for localities which have not adopted comprehensive stormwater management programs.

The basic concept of the state criteria is simple. An applicant must show that the runoff from the development project, (from a 2-year frequency storm) will not damage adjacent properties, or exceed the capacity or cause erosion of receiving streams. This must be proven by engineering calculations in the erosion and sediment control plan. The following items should be considered when determining compliance:

1. The stormwater runoff requirements apply to all land development projects which require an erosion and sediment control plan under state law. With regard to residential subdivision projects, the criteria should be applied to the entire subdivision development, not to the individual lots.

2. The stormwater runoff criteria apply primarily at points of concentrated discharge along the perimeter of the development site. However, the project must also be designed so that increased sheet runoff (e.g., runoff from newly paved areas) will not cause damage to adjacent properties. Such increased sheet flows should be diverted to an outlet where the stormwater runoff criteria can be applied.

3. The applicant must show that, wherever concentrated stormwater will be discharged from the site (e.g., pipe or channel outlets), there is an adequate channel or pipe to receive the flow and carry it into the natural drainage system.

4. Each receiving channel must be tested for adequacy. A channel is considered adequate if any of the following conditions can be met:

   a. The bankfull capacity of the natural receiving channel is sufficient to pass the post development peak flow from the 2-year frequency storm and the channel velocity (2-year frequency storm) does not exceed the permissible (non-erodible) velocity of the channel lining.

   b. The bankfull capacity of the manmade receiving channel is sufficient to pass the post development peak flow from the 10-year frequency storm and the channel velocity (2-year frequency storm) does not exceed the permissible (non-erodible velocity of the channel lining.)

      [Engineering procedures for determining channel adequacy are contained in Chapter 5.]

   c. The 10-year frequency storm is contained within the pipe or storm sewer system.

   d. The contributing drainage area of the development site is less than 1% of the total drainage area to the point of consideration in the channel.

   e. There is no increase in the peak runoff rate for the 2-year frequency storm (for natural receiving channels) or the 10-year frequency storm (for manmade receiving channels) at the point of discharge after development

5. If the receiving channel is found to be inadequate, the applicant must incorporate measures to either improve the receiving channel to an adequate

condition, or detain runoff on his site so that the post-development peak runoff rate for the 2-year storm will not exceed the pre-development peak rate. The plan-approving authority may also approve a combination of channel improvements and detention or other measures deemed satisfactory to protect the channel.

6. If a channel-improvement option is chosen, the applicant must obtain necessary easements and comply with applicable regulations regarding channel modifications. Channel improvements must extend downstream until an adequate channel section is reached or until a point is reached where the total drainage area is at least 100-times greater than the drainage area of the development site.

7. If a stormwater detention option is chosen, the applicant must submit a plan for the continued maintenance requirements of the structure and designate someone who has consented to be responsible to carry out the maintenance. The local government may choose to accept the maintenance responsibility for detention structures. However, where this is not done, the responsibility must be borne by the landowner, a homeowners association, or other legal entity. In this case, a maintenance agreement should be executed between the responsible entity and the local government.

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EROSION AND SEDIMENT CONTROL BEST MANAGEMENT PRACTICE MANUAL

WEST VIRGINIA

DEPARTMENT OF ENVIRONMENTAL PROTECTION

DIVISION OF WATER AND WASTE MANAGEMENT

2006

REVISED

AUGUST 29, 2016

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CHAPTER 1

INTRODUCTION

CHAPTER 1

INTRODUCTION

Erosion is a natural force without which life could not be supported. Erosion forms the landscape and helps produce the soils that grow our crops. However, major problems can occur when large amounts of sediment enter our waterways. Accelerated erosion comes from man's land-altering activities such as mining, agriculture, construction, urban/suburban stream banks, logging, and oil and gas exploration.

The West Virginia Department of Environmental Protection (WVDEP) Erosion and Sediment Control Best Management Practice Manual addresses erosion and sediment control for earth disturbing activities associated with construction. The manual is designed to assist construction site developers, engineers, designers, and contractors to identify and implement the most appropriate best management practices (BMPs) for construction activities.

The purpose of this manual is to provide standardized and comprehensive erosion and sediment control management practices that can be implemented on construction projects throughout West Virginia. This manual should be used as guidance for developing sediment control plans for the General West Virginia/National Pollution Discharge Elimination System Water Pollution Control Permit for Stormwater Associated with Construction Activities. However, the use of other best management practices manuals may also be acceptable. The goal is to reduce the water quality impacts of land-disturbing activities through design and implementation of effective erosion prevention and sediment control.

West Virginia's original manual was created in 1982. While the principles of erosion prevention and sediment control have changed little, a new manual was needed to cover the advancements of the last 24 years. This manual provides updated information on erosion prevention and sediment control measures, engineering methods, and changes in the law and regulations. It should be used by the regulated community, citizens and municipalities developing their own erosion and sediment control rules and regulations.

REGULATORY REQUIREMENTS

Erosion and sediment control requirements exist at the federal, state and local levels of government. Some city and county governments have adopted site development or sediment control ordinances or regulations, usually through subdivision regulations. Developers and contractors should check with local governments to determine whether ordinances may affect their proposed activities. Over the next several years, many municipalities will be developing their own sediment control requirements to meet the provisions of the Municipal Separate Storm Sewer System (MS4) General Permit.

Federal and State Sediment Control Requirements

Congress amended the Clean Water Act (CWA) in 1987, requiring a two-phase program be implemented to regulate stormwater discharges. The U.S. Environmental Protection Agency (EPA) promulgated the Phase I regulations in 1990, which, among other things, required National Pollutant Discharge Elimination System (NPDES) permit coverage for most stormwater discharges from construction activities. EPA authorized WVDEP to administer the NPDES program in West Virginia. WV DEP issued the first NPDES General Permit for stormwater discharges from construction activities in 1992 and has issued follow up General Permits every five years since that time. In 1999, EPA issued the Phase II regulations requiring NPDES permit coverage for sites with one acre or more of land disturbance. West Virginia's current General WV/NPDES Water Pollution Control Permit for stormwater associated with construction activities covers projects with one acre or more of earth disturbance.

Construction Projects that Need a Permit for Stormwater Discharge

Any land-disturbing activity that will disturb an area of one acre or more is required to be covered under an NPDES permit for its stormwater discharge. In addition, sites that disturb less than one acre that are part of a "common plan of development or sale" may also need to be covered by this permit. A common plan of development is a contiguous construction project where multiple separate and distinct construction activities may be taking place at different times and on different schedules, but under one plan. The "plan" is broadly defined as any announcement, piece of documentation or physical demarcation indicating construction activities may occur on a specific plot; most subdivisions are included in this definition.

Construction of single family residences by the homeowner or homeowner's contractor requiring land disturbances less than three acres in size are provided coverage under the General WV/NPDES Water Pollution Control Permit and do not require application for registration. All other terms and conditions of the General Permit, except for the Notice of Termination requirement, still apply.

State Water Quality Standards

West Virginia has several water quality standards that can address runoff from earth disturbing activities. The first are numerical water quality criteria. These are numerical values set forth in the state of West Virginia's Water Quality Standards [47 CSR 2]. They specify the levels of pollutants allowed in receiving waters that are protective of the stream's designated use. Designated uses can be to protect public water supply, for protection of fish, shellfish, and wildlife, and for recreational, agricultural, industrial, and navigational purposes.

Waste assimilation and transport are not designated uses. Therefore sediment traps and basins cannot be installed in waters of the State. Also, streams cannot be used to transport sediment from a construction site to a sediment trap or basin.

The primary numeric water quality standard addressing earth disturbing activities is turbidity. Other criteria that could be violated by runoff from a construction project include pH and iron.

Turbidity is defined as an expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample. It is an indirect measurement of how much suspended material is in a sample of water.

In West Virginia, turbidity in the receiving stream shall not exceed 10 nephlometric turbidity units (NTU) over background turbidity when the background turbidity is 50 NTU or less, or have more than a 10 percent increase plus 10 NTU in turbidity when the background turbidity is more than 50 NTU. The points of measurement are directly above and below the point of discharge [47 CSR 2-8.32].

There are also narrative water quality criteria, listed as "Conditions Not Allowable in State Waters" [47 CSR 2-3]. Several of these are applicable to earth disturbing activities including the prohibition against the following conditions: distinctly visible floating or settleable solids, suspended solids, scum, foam or oily slicks, deposits or sludge banks. Also the discharge must not contain materials that have taste or color or have materials in concentrations that are harmful, hazardous or toxic to man, animal or aquatic life.

Compliance with Standards

Surface water discharges associated with construction activity are subject to applicable state water quality standards. The Construction Stormwater General Permit does not authorize the violation of those standards. WVDEP expects that the selection and implementation of appropriate BMPs will result in compliance with standards for surface water discharges from construction sites. Proper implementation and maintenance of these controls is critical to adequately control any adverse water quality impacts from construction activity.

Total Maximum Daily Loads (TMDLs)

If construction activities will contribute pollutants for which a specific receiving water is listed as impaired, permittees must comply with Total Maximum Daily Loads (TMDLs) set for the receiving stream. Construction sites may be designated as contributors to the impairment if a stream is listed as impaired because of sediment or iron. Section 303(d) of the CWA established the TMDL process to guide the application of state water quality standards to individual water bodies and watersheds. A TMDL defines the amount of a particular pollutant that a water body can absorb daily without violating applicable water quality standards. Once this load is established, the WVDEP allocates a portion to each source of that pollutant within a particular watershed. In the case of construction activities within an impaired watershed, the WVDEP may require the permittee to implement more stringent BMPs, apply for an individual NPDES permit, or take other necessary actions to ensure compliance with TMDL discharge requirements. To find out if there are additional TMDL-related requirements for your project, please contact the WVDEP Stormwater Program.

Local Ordinances

Local regulations, such as zoning and subdivision ordinances, may also regulate construction activities in West Virginia. Numerous cities have subdivision requirements. Some counties and most larger cities have some sort of zoning regulations. Check the phone book under county and city for "Planning Commission". If there is no Planning Commission, contact the city government and county commissions.

Each county and city in the state is required to have a floodplain ordinance in order for residents to qualify for flood insurance. The local governmental authority in charge of the program regulates projects that physically alter land within the 100-year flood zone. When there is a Planning Commission in a county, it is usually their responsibility to manage and enforce the regulations. In other counties the applicant should contact the County Commission.

Endangered Species Act

If a construction project discharges to a receiving water where a federally endangered or threatened species or its habitat is present, potential impacts to that species need to be considered. For information on Endangered Species Act implementation in West Virginia and developing project-specific compliance strategies contact the U. S Fish and Wildlife Service in Elkins at:

U.S. Fish and Wildlife Service
West Virginia Field Office
P.O. Box 1278
Elkins, WV 26241
304-636-6586

Appendix B lists water bodies where Endangered Species may be found.

Permits for In-Stream Construction and Wetland Filling

Developers proposing to conduct construction activities in waterways, including jurisdictional wetlands, may be required to obtain permits from the US Army Corps of Engineers (USACE) and/or the West Virginia Division of Natural Resources (DNR) Office of Land and Streams, as well as WVDEP depending on the project scope and location.

DNR Stream Activity Application

The Office of Land and Streams holds the title to the "waters of the state". Waters of the state "… means any and all water on or beneath the surface of the ground, whether percolating, standing, diffused or flowing, wholly or partially within this state, or bordering this state and within its jurisdiction, and includes without limiting the generality of the foregoing, natural or artificial lakes, rivers, streams, creeks, branches, brooks, ponds (except farm ponds, industrial settling basins and ponds and water treatment facilities), impounding reservoirs, springs, wells, watercourses and wetlands" [22 CSR 12-3].

A DNR Stream Activity Application is required for construction activities that occur within the normal high water mark of a stream in West Virginia. Information on this program and application forms made be obtained at:

Office of Land and Streams
Building 3, Room 643
1900 Kanawha E
Charleston, WV 25305
304-558-3225
http://www.wvdnr.gov/REM/PLC.shtm

Federal Permits

The USACE administers Section 404 of the Clean Water Act (CWA) and Section 10 of the Rivers and Harbors Act of 1899. Under these jurisdictions, the USACE have issued a number of general Nationwide Permits for certain activities or similar types of activities that have a minimal impact on navigable waters (Section 10 permits) or waters of the U.S. (Section 404 permits). For activities not covered under a Nationwide Permit, the developer will need to apply for an Individual Permit.

Section 404 of the CWA establishes a program to regulate the discharge of dredged or fill material into waters of the U.S, including jurisdictional wetlands. Construction activities covered under this program include fill for commercial site development, subdivisions and infrastructure development (such as highways, airports and utility lines).

The USACE conducts and verifies wetland determinations and has the final say on jurisdiction. The USACE also develops policy and guidance on stream and wetland issues and enforces Section 404 permits and provisions.

The ACE District offices are located in Pittsburgh and Huntington.

HUNTINGTON DISTRICT
Regulatory Branch Chief
U.S. Army Corps of Engineers,
Huntington District
502 Eighth Street
Huntington, West Virginia 25701-2070
Phone: 304-399-5710

PITTSBURGH DISTRICT
Regulatory Branch Chief
U.S. Army Corps of Engineers,
Pittsburgh District
William S. Moorhead Federal Building
1000 Liberty Avenue
Pittsburgh, Pennsylvania 15222-4186
Phone: 412-395-7152

401 Water Quality Certification

Section 401 Water Quality Certification is required for each permit or license issued by a federal agency to ensure that proposed projects will not violate the state's water quality standards or stream designated uses. States are authorized to issue Certification under Section 401 of the CWA.

The majority of certification requests are for dredge and fill operations regulated by the US Army Corps of Engineers. The US Coast Guard issues permits for bridge construction on navigable waterways. The Federal Energy Regulatory Commission is responsible for licenses related to hydropower facilities. Applicants must receive State 401 Water Quality Certification before they can receive a permit from the federal agency.

The DWWM may grant, grant with conditions, waive, or deny 401 Water Quality Certification. The decision to issue certification is based on project compliance with West Virginia Water Quality Standards. Field support for the 401 program is provided by the DNR’s Wildlife Resources Section.

Information on this program and application forms made be obtained at:

401 Certification Program
Division of Water and Waste Management
601 57th Street, SE
Charleston, WV 25304
(304) 926-0495

ACKNOWLEDGEMENTS

Development of this manual was begun in the mid-1990s and the current document has survived numerous staffing changes, agency and program reorganizations, and multiple edits and revisions. As such, it has become almost impossible to identify all who may have contributed to the manual and the exact sources of some of the information. We have attempted in the final edit to eliminate any information that could not be properly documented. The State Conservation Agency coordinated a multi-agency committee that established much of the early work on this manual. Several WVDEP staff contributed to the manual. The draft document was completed under a contract with Parsons Brinckerhoff Quade & Douglas, funded by a federal Clean Water Act grant from the US Environmental Protection Agency to the WV DEP DWWM. Final editing was completed by WVDEP Stormwater Program staff.

Technical sources:

Technical sources are noted in the document.

Corrections

Any errors or omissions are the responsibility of the WVDEP. Please report any errors or omissions to the WVDEP DWWM for correction.

Future updates

Modifications to the handbook will be necessary from time to time. The handbook has been designed to be a living document and will be updated as new information or revisions are obtained.

CHAPTER 2

HOW TO PREPARE A SEDIMENT CONTROL PLAN

How to Prepare a Sediment Control Plan

This chapter provides an overview of the important components of, and the process for, developing and implementing the sediment control plan (SCP) component of the construction stormwater pollution prevention plan (SWPPP).

> **Section 1** contains general guidelines with which site planners should become familiar. It describes criteria for plan format and content and ideas for improved plan effectiveness.
>
> **Section 2** outlines and describes a recommended step-by-step procedure for developing a SCP from data collection to finished product. This procedure is written in general terms to be applicable to all types of projects.
>
> **Section 3** includes a checklist for developing a SCP.

Design standards and specifications for best management practices (BMPs) referred to in this chapter are found in Chapter 3.

The SCP and SWPPP are separate stand-alone documents but should be integrated into the overall construction plan set.

Section 1

General Guidelines

What is a construction stormwater pollution prevention plan and how is it different from a sediment control plan?

The **construction stormwater pollution prevention plan** (SWPPP) is the overall document that describes the potential for pollution problems on a construction project and explains and illustrates the measures to be taken to control those problems.

A **sediment control plan** (SCP) is the document that deals exclusively with controlling erosion and sediment during the construction phase.

The SWPPP consists of several components including: the SCP, one or two groundwater protection plans, a stormwater management plan (if necessary) and a plan to control other pollutants. This manual provides practices and procedures necessary to develop a SCP.

The DEP reviews the Construction SWPPPs for compliance and adequacy in controlling erosion and sediment and other pollutants during construction. Single-family home construction projects may use the generic individual house sediment control plan.

The construction SWPPP is a separate and complete document. However, the appropriate sections (SCP in particular) should be incorporated into the contract drawings and documents. The construction SWPPP and site registration application must be located on the construction site for examination by DEP inspection personnel. As site work progresses, the plan must be modified to reflect changing site conditions that affect sediment and erosion control practices. These changes are subject to the permit modification procedures for the state.

What is in a sediment control plan?

The SCP for projects that disturb more than one acre must contain sufficient information to satisfy the state that the pollution problems have been adequately addressed for the proposed project. An adequate SCP includes both a narrative and drawings. The narrative is a written statement to explain the pollution prevention decisions made for a particular project. The narrative contains information about existing site conditions, proposed site conditions, construction schedules and sequence of events, design and calculations and other pertinent items. The drawings and notes describe where and when the various BMPs should be installed and the construction drawings and details of each practice mentioned in the narrative.

On construction sites the primary concern in the preparation of the SCP is impacts to surface water and groundwater. Each of the 12 elements found in the following section should be included in the SCP unless an element is determined not to be applicable to the project.

Best management practice guidelines and specifications

Chapter 3 contains guidelines and specifications for the BMPs referred to in this chapter.

The guidelines and specifications in Chapter 3 of this volume are not intended to limit any innovative or creative effort to effectively control erosion and sedimentation. In those instances where appropriate BMPs are not in this chapter, experimental practices can be considered. Some modifications to guideline practices may also be employed. However, the DEP must approve such practices before they may be used. All experimental practices and modified guideline practices are required to achieve the same or better performance of the BMPs listed in Chapter 3.

General principles

The following general principles should be applied to the development of the SCP:

• The duff layer, native topsoil, and natural vegetation should be retained in an undisturbed state to the maximum extent practicable.

• Prevent pollutant release. Select source control BMPs as a first line of defense. Erosion prevention can be easier than treating turbid runoff.

• Select BMPs depending on site characteristics (topography, drainage, soil type, ground cover, and critical areas) and the construction plan.

• Divert runoff away from exposed areas wherever possible. Keep clean water clean.

• Limit the extent of clearing operations and phase construction operations.

• If topsoil is not available, amend all soils with appropriate lime and fertilizer prior to seeding.

• Maintain and protect natural drainage features whenever possible.

• Minimize slope length and steepness.

• Control water through the use of diversions and slope drains.

• Reduce runoff velocities to prevent channel erosion.

• Prevent the tracking of sediment offsite.

• Control pollutants other than sediment.

• Anticipate rain. View the project controls as if there will be a significant rain event at some point during construction. Determine where runoff will drain to at each stage of the project and make sure there will be an appropriate sediment control device there to intercept it.

• Remember that the ground won't dry out as fast during the winter as it does in the summer.

• Be realistic about the limitations of controls that you specify and the operation and maintenance of those controls. Anticipate what can go wrong, how you can prevent it from happening, and what will need to be done to fix it.

Section 2
Step-By-Step Procedures

There are three basic steps in producing a sediment control plan:

Step 1 - Data collection

Step 2 - Data analysis

Step 3 - SCP development and implementation

Steps 1 and 2 described below are intended for projects that disturb one acre or more. Single-family home construction projects that are part of common plan of development or sale may use the simpler generic individual house sediment control plan.

Step 1 - Data collection

Evaluate existing site conditions and gather information that will help develop the most effective SCP. The information gathered should be explained in the narrative and shown on the drawings.

• Topography - Prepare a topographic drawing of the site to show the existing contour elevations at intervals of at most five feet depending upon the slope of the terrain.

• Drainage - Locate and clearly mark existing drainage swales and patterns on the drawing, including existing storm drainpipe systems.

• Soils - Identify and label soil type(s) and erodibility (low, medium, high, or an index value from the NRCS manual) on the drawing. Soils information can be obtained from a soil survey if one has been published for the county. If a soil survey is not available, a request can be made to a local Natural Resource Conservation Service office.

Soils must be characterized for permeability, percent organic matter, and effective depth by a qualified soil professional or engineer. These qualities should be expressed in averaged or nominal terms for the subject site or project.

• Ground cover - Label existing vegetation on the drawing. Such features as tree clusters, grassy areas, and unique or sensitive vegetation should be shown. Unique vegetation may include existing trees above a given diameter. Local requirements regarding tree preservation should be investigated. In addition, existing denuded or exposed soil areas should be indicated.

• Critical areas - Delineate critical areas adjacent to or within the site on the drawing. Such features as steep slopes, streams, floodplains, lakes, and wetlands should be shown. Delineate setbacks and buffer limits for these features on the drawings. Other related jurisdictional boundaries such as the Federal Emergency Management Agency (FEMA) base floodplain should also be shown on the drawings.

• Adjacent areas - Identify existing buildings, roads, and facilities adjacent to or within the project site on the drawings. Identify existing and proposed utility locations, construction clearing limits, and erosion and sediment control BMPs on the drawings.

• Existing encumbrances - Identify wells, existing and abandoned septic drain fields, utilities, easements, and site constraints.

• Precipitation records - Determine the average monthly rainfall and rainfall intensity for the required design storm events.

Step 2 - Data analysis

Consider the data collected in Step 1 to visualize potential problems and limitations of the site. Determine those areas that have critical erosion hazards. The following are some important factors to consider in data analysis:

• Topography - The primary topographic considerations are slope steepness and slope length. The longer and steeper the slope, the greater the erosion potential.

• Drainage - Natural drainage patterns should be maintained as much as possible in the developed site. Care should also be taken to ensure that increased runoff from the site will not erode or flood the existing natural drainage system. Possible sites for temporary surface water retention and detention should be considered at this point.

Direct construction away from areas of saturated soil - areas where ground water may be encountered - and critical areas where drainage will concentrate. Preserve natural drainage patterns on the site.

• Soils - Evaluate soil properties such as surface and subsurface runoff characteristics, depth to impermeable layer, depth to seasonal ground water table, permeability, shrink-swell potential, texture, settleability, and erodibility. Develop the SCP based on known soil characteristics.

• Ground cover – Preserving ground cover is the most important factor in terms of preventing erosion. Existing vegetation that can be saved will prevent erosion better than constructed BMPs. Trees and other vegetation protect the soil structure. If the existing vegetation cannot be saved, consider such practices as phasing construction, temporary seeding, and mulching. Phasing of construction involves stabilizing one part of the site before disturbing another. In this way, the entire site is not disturbed at once.

• Critical areas - Critical areas may include flood hazard areas, mine hazard areas, slide prone areas, sole source aquifers, wetlands, stream banks, streams, and other water bodies. Any critical areas within or adjacent to the development should exert a strong influence on land development decisions. Critical areas and their buffers shall be delineated on the drawings and clearly flagged in the field. Orange plastic fencing may be more useful than flagging to assure that equipment operators stay out of critical areas. Only unavoidable work should take place within critical areas and their buffers. Such unavoidable work may require special BMPs, permit restrictions, and mitigation plans.

• Adjacent areas - An analysis of adjacent properties should focus on areas upslope and down slope from the construction project. Waterbodies that will receive direct runoff from the site are a major concern. The types, values, and sensitivities of and risks to downstream resources, such as private property, surface water facilities, public infrastructure, or aquatic systems, should be evaluated. Care must be taken where upslope diversions will exit the property.

Erosion and sediment controls should be selected accordingly.

• Timing of the project - An important consideration in selecting BMPs is the timing and duration of the project. Projects that will proceed during the winter or that will last through several seasons must take precautions to remain in compliance with the SWPPP and General Permit. Requirements for some practices, especially seeding and mulching, can change according to the season they are implemented.

Step 3 - SCP development and implementation

After collecting and analyzing the data to determine the site limitations, the planner can then develop a SCP. Each of the 12 elements below must be considered and included in the SCP unless site conditions render the element unnecessary.

12 Basic Sediment Control Plan Elements

Element #1: Mark clearing limits

• Prior to beginning land disturbing activities, clearly mark all clearing limits, sensitive areas and their buffers, and trees that are to be preserved within the construction area. These shall be clearly marked, both in the field and on the plans, to prevent damage and offsite impacts.

• Plastic, metal, or stake wire fence may be used to mark the clearing limits.

• Suggested BMPs:

− Preserving natural vegetation
− Buffer zones
− Safety fence

Element #2: Establish construction access

• Construction vehicle access and exit should be limited to one route if possible.

• Access points shall be stabilized with crushed aggregate to minimize the tracking of sediment onto public and private roads.

• Wheel wash or tire baths should be located on site, if applicable.

• No sediment tracking on the roadway is allowed. In the event that sediment is inadvertently tracked onto the road, the road shall be cleaned thoroughly by the end of each day. Sediment shall be removed from roads by shoveling or pickup sweeping and shall be transported to a controlled sediment disposal area. Street washing of sediments to the storm drain system is not allowed. If street wash wastewater can be controlled from entering the storm drainage system, then it shall be pumped back onto the site, contained, and disposed of properly.

• Construction access restoration shall be equal to or better than the pre-construction condition.

• Suggested BMPs:

− Stabilized construction entrance

− Construction road/parking area stabilization

Element #3: Install sediment controls

• The duff layer, native topsoil, and natural vegetation shall be retained in an undisturbed state to the maximum extent practicable.

• Prior to leaving a construction site, surface water runoff from disturbed areas shall pass through a sediment basin/trap or other appropriate and approved sediment removal BMP.

• BMPs intended to trap sediment on site shall be constructed as one of the first steps in grading. These BMPs shall be functional before other land disturbing activities take place.

• Earthen structures such as dams, dikes, and diversions shall be seeded and mulched according to the timing indicated in Element #5.

• Suggested BMPs:

− Sediment trap
− Temporary sediment basin
− Silt fence
− Super silt fence

− Drop inlet protection
− Vegetated strip
− Wattles

Element #4: Stabilize soils

• Exposed and unworked soils shall be stabilized by application of effective BMPs that protect the soil from the erosive forces of raindrops, flowing water, and wind. The General Permit requires that all graded areas that are at final grade must be seeded and mulched within 7 days and areas that will not be worked again for 21 days or more must be seeded and mulched within 7 days.

• Applicable practices include, but are not limited to, temporary and permanent seeding, sodding, mulching, erosion control fabrics and matting, soil application of polyacrylamide (PAM), the early application of gravel base on areas to be paved, and dust control.

• Selected soil stabilization measures shall be appropriate for the time of year, site conditions, and estimated duration of use.

• Soil stockpiles must be stabilized and protected with sediment trapping measures.

• Linear construction activities such as right-of-way and easement clearing, roadway development, pipelines, and trenching for utilities, shall be conducted to meet the soil stabilization timeframe requirements. Contractors shall install the bedding materials, roadbeds, structures, pipelines, or utilities and re-stabilize the disturbed soils so that the 7-day requirements are met:

• Suggested BMPs:

_Temporary seeding
_Permanent seeding
_Mulching
_Rolled erosion control products
_Sodding
_Topsoiling
_Polyacrylamide for soil erosion protection
_Surface roughening
_Surface water control
_Dust control

Element #5: Protect slopes

• The General Permit prohibits upslope runoff from flowing down fill slopes. Contain fill runoff with temporary berms and in pipes, slope drains, or stabilized channels.

• Design, construct, and phase cut and fill slopes in a manner that will minimize erosion.

• Consider soil type and its potential for erosion.

• Reduce slope runoff velocities by reducing continuous length of slope with benches and diversions, reduce slope steepness, and roughen slope surface.

• Divert upslope drainage and run-on waters with interceptors at top of slope. Surface water from offsite should be handled separately from surface water generated on the site. Diversion of offsite surface water around the site may be a viable option. Diverted flows must be redirected to the natural drainage location at or before the property boundary.

• Provide drainage to remove ground water intersecting the slope surface of exposed soil areas.

• Excavated material shall be placed on the uphill side of trenches, consistent with safety and space considerations.

• Stabilize soils on slopes, as specified in Element #4.

• Suggested BMPs:

_Temporary seeding
_Permanent seeding
_Surface roughening
_Temporary diversions
_Temporary berms
_Pipe slope drains
_Level lip spreader
_Rock check dams
_Commercial check dams

Element #6: Protect drain inlets

• Storm drain inlets operable during construction shall be protected so that surface water runoff does not enter the conveyance system without first being filtered or treated to remove sediment.

• Approach roads shall be kept clean.

• Inlets should be inspected weekly at a minimum and daily during storm events. Inlet protection devices should be cleaned or removed and replaced before six inches of sediment can accumulate.

• Suggested BMPs:

_Drop inlet protection

Element #7: Convey stormwater in a non-erosive manner

• Points of discharge and receiving streams shall be protected from erosion due to increases in the volume, velocity, and peak flow rate of surface water runoff from the project site.

• Design and stabilize any stormwater conveyance for expected flows.

• Consider any local government requirements for stormwater management.

• Suggested BMPs:

− Outlet protection

_Level lip spreader

_Riprap

_Rock check dams

_Surface water controls

_Rolled erosion control products

Element #8: Control other pollutants

• All pollutants, including waste materials and demolition debris, that occur on site during construction shall be handled and disposed of in a manner that does not cause contamination of surface water. Woody debris may be chopped and spread on site.

• Cover, containment, and protection from vandalism shall be provided for all chemicals, liquid products, petroleum products, and non-inert wastes present on the site.

• Maintenance and repair of heavy equipment and vehicles involving oil changes, hydraulic system drain down, solvent and de-greasing cleaning operations, fuel tank drain down and removal, and other activities which may result in discharge or spillage of pollutants to the ground or into surface water runoff must be conducted using spill prevention measures, such as drip pans. Contaminated surfaces shall be cleaned immediately following any discharge or spill incident. Emergency repairs may be performed on-site using temporary plastic placed beneath and, if raining, over the vehicle.

• Wheel wash or tire bath wastewater shall be discharged to a separate on-site treatment system or to the sanitary sewer.

• Application of agricultural chemicals including fertilizers and pesticides shall be conducted in a manner and at application rates that will not result in loss of chemical to surface water runoff. Manufacturers' recommendations for application rates and procedures shall be followed.

• BMPs shall be used to prevent or treat contamination of surface water runoff by pH modifying sources. These sources include bulk cement, cement kiln dust, fly ash, new concrete washing and curing waters, waste streams generated from concrete grinding and sawing, exposed aggregate processes, and concrete pumping and mixer washout waters.

Element #9: Control dewatering

• Foundation, vault, and trench dewatering water shall be discharged into a controlled conveyance system prior to discharge to a sediment pond. Channels must be stabilized, as specified in Element #8.

• Clean, non-turbid dewatering water, such as well-point ground water, can be discharged to systems tributary to state surface waters, as specified in Element #7, provided the dewatering flow does not cause erosion or flooding of receiving waters. These clean waters should not be routed through surface water sediment ponds.

• Highly turbid or contaminated dewatering water from construction equipment operation, work inside a cofferdam shall be handled separately from surface water.

• Other disposal options, depending on site constraints, may include:

1. Infiltration;
2. Transport off-site in vehicle, such as a vacuum flush truck, for legal disposal in a manner that does not pollute state waters;
3. On-site treatment using chemical treatment or other suitable treatment technologies;
4. Sanitary sewer discharge with local sewer utility approval; or
5. Use of a dewatering bag with outfall to a ditch or swale for small volumes of localized dewatering.

Element #10: Maintain BMPs

• Temporary and permanent erosion and sediment control BMPs shall be maintained and repaired as needed to assure continued performance of their intended function. Maintenance and repair shall be conducted in accordance with BMPs.

• Sediment control BMPs shall be inspected weekly or after each storm of 0.5 inches or more.

• Temporary erosion and sediment control BMPs should be removed within 30 days after final site stabilization is achieved or after the temporary BMPs are no longer needed. Trapped sediment shall be removed or stabilized on site. Disturbed soil resulting from removal of BMPs or vegetation shall be permanently stabilized.

• Maintenance should be included as a separate bid item for each BMP, where applicable.

Element #11: Manage the project

• Phasing of Construction - Development projects shall be phased in order to prevent the transport of sediment from the development site during construction, unless the project engineer can demonstrate that construction phasing is infeasible. Revegetation of exposed areas and maintenance of that vegetation shall be an integral part of the clearing activities for any phase.

Clearing and grading activities for developments shall be permitted only if conducted pursuant to an approved site development plan (e.g., subdivision approval) that establishes areas of clearing, grading, cutting, and filling. When establishing clearing and grading areas, consideration should be given to minimizing removal of existing trees and disturbance and compaction of native soils. Any areas required to preserve critical or sensitive areas, and buffers, shall be delineated on both the plans and the site.

• Coordination with Utilities and Other Contractors - The primary project manager shall evaluate, with input from utilities and other contractors, the surface water management requirements for the entire project, including the utilities, when preparing the SCP.

• Inspection and Monitoring - All BMPs shall be inspected, maintained, and repaired as needed to assure continued performance of their intended function.

Whenever inspection and/or monitoring reveals that the BMPs identified in the SCP are inadequate, the SCP shall be modified, as appropriate, in a timely manner.

• Reporting - Report spillage or discharge of pollutants within 24-hours.

• Equipment Maintenance - Maintenance and repair of heavy equipment and vehicles involving oil changes, hydraulic system drain down, solvent and de-greasing cleaning operations, fuel tank drain down and removal, and other activities which may result in discharge or spillage of pollutants to the ground or into surface water runoff must be conducted using spill prevention measures, such as drip pans. Contaminated surfaces shall be cleaned immediately following any discharge or spill incident. Contaminated soil must be disposed of properly. Emergency repairs may be performed on-site using temporary plastic placed beneath and, if raining, over the vehicle.

• Maintenance of the SCP - The SCP shall be retained on-site. The SCP shall be modified whenever there is a significant change in the design, construction, operation, or maintenance of any BMP. The DEP must be notified of any changes to the Construction SWPP. Depending on the significance of the revision, a permit modification may need to be submitted to the DEP.

Element #12: Stabilization

The construction site should be stabilized as soon as possible after completion. Establishment of final cover must be initiated no later than 7 days after reaching final grade. A Notice of Termination must be filed with the DEP when the site reaches final stabilization. Final stabilization means that all soil-disturbing activities are completed, and that either a permanent vegetative cover with a density of 70% or greater has been established or that the surface has been stabilized by hard cover such as pavement or buildings... It should be noted that the 70% requirement refers to the total area vegetated and not just a percent of the site.

Section 3
Checklists for Sediment Control Plans

The SCP typically consists of two parts: a narrative and the drawings. The following two sections describe in general terms the contents of the narrative and the drawings. For more specific information to comply with the General Permit see the instructions to complete a site Registration application form following this section.

Several checklists are included in this manual that can be used as a quick reference to determine if all the major items are included in the SCP.

Narrative

The following topic headings are guideline to be used when preparing the SCP narrative.

• Project description – Describe the nature and purpose of the construction project. Include the size of the project area, any increase in existing impervious area, the area disturbed, and the volumes of grading cut and fill that are proposed.

• Existing site conditions – Describe the existing topography, vegetation, and drainage. Include a description of any structures or development on the parcel including the area of existing impervious surfaces.

• Adjacent areas – Describe adjacent areas, including streams, lakes, wetlands, residential areas, and roads that might be affected by the construction project. Provide a description of the downstream drainage leading from the site to the receiving body of water.

• Critical areas – Describe areas on or adjacent to the site that are classified as critical areas. Describe special requirements for working near or within these areas.

• Soil – Describe the soils on the site, giving such information as soil names, mapping unit, erodibility, settleability, permeability, depth, texture, and soil structure.

• Potential erosion problem areas – Describe areas on the site that have potential erosion problems.

• Twelve (12) elements – Describe how the SCP addresses each of the 12 required elements. Include the type and location of BMPs used to satisfy the each element. If a sediment basin or trap of the required volume cannot be constructed provide a written justification and explain in detail what other sediment and erosion controls will be used in its place.

• Construction phasing – Describe the construction sequence of events and proposed construction phasing.

• Construction schedule – Provide a relative construction schedule. It is not necessary to provide exact dates but rather describe in relative terms when each construction phase will take place and how and where each planned sediment and erosion control device or practice will be installed.

• Engineering calculations – Attach any calculations made for the design of such items as sediment ponds, diversions, and waterways, as well as calculations for runoff and surface water detention design (if applicable). Engineering calculations for permanent structures must bear the signature and stamp of an Engineer licensed in the State of West Virginia. References shall be provided for all variables used.

Drawings

Because contractors seldom will see the SWPPP, the Contract Drawings should include all of the critical provisions of the SWPPP.

Each set of Contract Drawings should have at a minimum the following information.

- Name of the project and owner, address; Parcel Number or other identifying mark; and scale.
- Vicinity Map – Provide a map locating the site in relation to the surrounding area and roads.
- Number of sheets with index.

• **Site map** – Provide a site map(s) showing the following features. The site map requirements may be met using multiple plan sheets for ease of legibility.

1. Standard notes that summarize the critical portions of the SCP. Notes addressing construction sequencing and scheduling must be included on the drawings.
2. Show project limits.
3. The direction of north in relation to the site.
4. Existing structures and roads, if present.
5. The boundaries of and label the different soil types.
6. Areas of potential erosion problems.
7. Any on-site and adjacent critical areas, their buffers, and FEMA base flood boundaries.
8. Existing contours and drainage basins and the direction of flow for the different drainage areas.
9. Final grade contours and developed condition flow paths and drainage basins.
10. Areas that are to be cleared and graded.
11. Existing unique or valuable vegetation and the vegetation that is to be preserved.
12. Cut and fill slopes indicating top and bottom of slope.
13. Stockpile, waste storage, and vehicle storage/maintenance areas.
14. Total cut and fill quantities and the disposal method and location of excess material. All existing and proposed utilities and any associated easements.
15. Proposed permanent structures including roads and parking areas.

• Conveyance systems – Show on the site map(s) the following temporary and permanent onsite and offsite conveyance features:

1. Locations for existing and permanent swales, diversions, or ditches.
2. Drainage pipes, berms, ditches, or diversions associated with erosion and sediment control and surface water management.
3. Temporary and permanent pipe inverts and minimum slopes.
4. Grades, dimensions, and direction of flow in all ditches and swales, culverts, and pipes.
5. Details for bypassing offsite runoff around disturbed areas.
6. Locations and outlets of any dewatering systems.

• **Location of stormwater management structures** – Show on the site map the locations of any stormwater management structures.

• Erosion and sediment control practices – Show on the site map the following erosion and sediment control practices:

1. The location of sediment basins/trap(s), pipes and structures.

2. Dimension basin berm widths and inside and outside pond slopes.
3. The trap/pond storage required and the depth, length, and width dimensions.
4. Typical section views through pond and outlet structure.
5. Typical details of riser and other outlet devices.
6. Stabilization technique details for basin inlets and outlets.
7. Temporary and permanent seeding and mulching specifications. Seeding timeframes.
8. Temporary stabilization methods and timeframe for berms, diversions and slopes.
9. Rock specifications and detail for outlet protection, rock check dam, and any other device used.
10. Construction drawings for each sediment and erosion control device used on the project. Include construction specifications for each device used.
11. The construction entrance location and a stabilization detail.

• Other non-traditional practices--Any structural practices used that are not referenced in this manual should be explained and illustrated with detailed drawings.

• Other pollutant BMPs--Indicate on the site map the location of BMPs to be used for the control of pollutants other than sediment.

Construction Sediment Control Plan Checklist

Project Name:____

Address:____

Section I – SCP Narrative

1. Project Description

___ A. Total Project Area
___ B. Total proposed impervious area.
___ C. Total proposed area to be disturbed.
___ D. Total volumes of proposed cuts/fill.

2. Existing Site Conditions

___ A. Description of the existing topography.
___ B. Description of the existing vegetation.
___ C. Description of the existing drainage.

3. Adjacent Areas

___ A. Description of adjacent areas which may be affected by site disturbance
    ___ 1. Streams
    ___ 2. Lakes
    ___ 3. Wetlands
    ___ 4. Residential areas
    ___ 5. Roads
    ___ 6. Ditches, pipes, culverts
    ___ 7. Other

___ B. Description of the downstream drainage path leading from the site to the receiving body of water. (Minimum distance of 1/4 mile.)

4. Critical Areas

___ A. Description of critical areas that are on or adjacent to the site.
___ B. Description of special requirements for working in or near critical areas.

5. Soils

___ A. Description of on-site soils.
    ___ 1. Soil name(s)
    ___ 2. Soil mapping unit
    ___ 3. Erodibility
    ___ 4. Settleability
    ___ 5. Permeability
    ___ 6. Depth
    ___ 7. Texture

___ 8. Soil structure

6. Erosion Problem Areas

___ A. Description of potential erosion problems on site.

7. Construction Stormwater Pollution Prevention Elements

___ A. Describe how each of the Construction Stormwater Pollution Prevention Elements has been addressed though the SCP.
___ B. Identify the type and location of BMPs used to satisfy the required element.
___ C. Written justification identifying the reason an element is not applicable to the proposal.

12 Required Elements - Construction Stormwater Pollution Prevention Plan:
___ 1. Mark Clearing Limits
___ 2. Establish Construction Access
___ 3. Install Sediment Controls
___ 4. Stabilize Soils
___ 5. Protect Slopes
___ 6. Protect Drain Inlets
___ 7. Convey stormwater in a non-erosive manner
___ 8. Control Other Pollutants
___ 9. Control Dewatering
___ 10. Maintain BMPs
___ 11. Manage the Project
___12. Stabilization

8. Construction Phasing

___ A. Construction sequence
___ B. Construction phasing (if proposed)

9. Construction Schedule

___ A. Provide a proposed construction schedule.

___ B. Wet Season Construction Activities

___ 1. Proposed wet season construction activities.
___ 2. Proposed wet season construction restraints for environmentally sensitive/critical areas.

11. Engineering Calculations

___ A. Provide Design Calculations.

___ 1. Sediment ponds/traps
___ 2. Diversions
___ 3. Waterways
___ 4. Runoff/stormwater calculations

Section II - Erosion and Sediment Control Plans

1. General

___ A. Vicinity Map
___ B. Address, Parcel # and Street names labels
___ C. Erosion and Sediment Control Notes

2. Site Plan

___ A. Legal description of subject property.
___ B. North Arrow
___ C. Indicate boundaries of existing vegetation, e.g. tree lines, pasture areas, etc.
___ D. Identify and label areas of potential erosion problems.
___ E. Identify any on-site or adjacent critical areas and associated buffers.
___ F. Identify FEMA base flood boundaries
___ G. Show existing and proposed contours.
___ H. Indicate drainage basins and direction of flow for individual drainage areas.
___ I. Label final grade contours and identify developed condition drainage basins.
___ J. Delineate areas that are to be cleared and graded.
___ K. Show all cut and fill slopes indicating top and bottom .

3. Conveyance Systems

___ A. Designate locations for swales, interceptor trenches, or ditches.
___ B. Show all temporary and permanent drainage pipes, ditches, or cut-off trenches required for erosion and sediment control.
___ C. Provide minimum slope and cover for all temporary pipes or call out pipe inverts.
___ D. Show grades, dimensions, and direction of flow in all ditches, swales, culverts and pipes.
___ E. Provide details for bypassing offsite runoff around disturbed areas.
___ F. Indicate locations and outlets of any dewatering systems.

4. Location of Stormwater Management Structures

___ A. Identify location of any stormwater management structures.

5. Erosion and Sediment Control Measures

___ A. Show the locations of sediment trap(s), pond(s), pipes and structures.
___ B. Dimension pond berm widths and inside and outside pond slopes.
___ C. Indicate the trap/pond storage required and the depth, length, and width dimensions.
___ D. Provide typical section views through pond and outlet structure.
___ E. Provide typical details of gravel cone and standpipe, and/or other filtering devices.
___ F. Detail stabilization techniques for outlet/inlet.
___ G. Detail control/restrictor device location and details.
___ H. Specify mulch and/or recommended cover of berms and slopes.
___ I. Provide rock specifications and detail for rock check dam(s), if applicable.
___ J. Specify spacing for rock check dams as required.

___ K. Provide front and side sections of typical rock check dams.
___ L. Indicate the locations and provide details and specifications for silt fabric.
___ M. Locate the construction entrance and provide a detail.

6. Detailed Drawings

___ A. Any structural practices used that are not referenced in the Manual should be explained and illustrated with detailed drawings.

7. Other Pollutant BMPs

___ A. Indicate on the site plan the location of BMPs to be used for the control of pollutants other than sediment, e.g. concrete wash water.

8. Monitoring

___ A. Describe inspection reporting responsibility, documentation, and filing.

CHAPTER 3

STANDARD GUIDELINES AND SPECIFICATIONS

3.01 - PRESERVING EXISTING VEGETATION

Introduction

This practice is to preserve the existing natural vegetation thereby reducing erosion wherever practicable. Limiting the amount of disturbance on a construction site is the single most effective method for reducing erosion. For example, trees can hold up to about 50 percent of all rain that falls during a storm. Up to 20-30 percent of this rain may never reach the ground but is taken up by the tree or evaporates. Raindrop erosion is also prevented. Vegetation cools the ground and reduces soil evaporation. Removing natural vegetation and destroying the existing soil profile is one of the greatest causes of increased runoff and subsequent flooding. In urbanizing areas such as the Eastern Panhandle, preserving existing vegetation can be one the most important practice contributing to clean water.

Natural vegetation should be preserved as much as possible but especially on critical areas such as: steep slopes, areas adjacent to perennial and intermittent watercourses or swales or wetlands, and on building sites in wooded areas.

It doesn't make sense to destroy all the trees in a subdivision and then name one of the new streets Shady Oak Lane.

Design and Installation Specifications

Natural vegetation can be preserved in natural clumps or as individual trees, shrubs and vines.

The preservation of individual plants is more difficult because heavy equipment is generally used to remove unwanted vegetation. The points to remember when attempting to save individual plants are:

- Is the plant worth saving? Consider the location, species, size, age, vigor, and the work involved. Check you're your local government. They may have ordinances to save natural vegetation and trees.

- Fence or clearly mark areas around trees that are to be saved. It is preferable to keep all disturbances away from the trees at least as far out as the drip line. (see drawing)

Plants need protection from three kinds of injuries:

Construction Equipment - This injury can be above or below the ground level. Damage results from scarring, cutting of roots, and compaction of the soil. Placing a fenced buffer zone around plants to be saved prior to construction can prevent construction equipment injuries.

Grade Changes - Changing the natural ground level will alter grades, which affects the plant's ability to obtain the necessary air, water, and minerals. Minor fills usually do not cause problems although sensitivity between species does vary and should be checked. Trees can tolerate fill of 6 inches or less. For shrubs and other plants, the fill should be less.

When there are major changes in grade, it may become necessary to supply air to the roots of plants. If fill has to be placed over the root system, place a layer of gravel and a tile system over the roots before the fill is made. The tile system should be laid out on the original grade leading from a dry well around the tree trunk. The system should then be covered with small stones to allow air to circulate over the root area.

Lowering the natural ground level can also seriously damage trees and shrubs. The highest percentage of the plant roots are in the upper 12 inches of the soil and cuts of only 2-3 inches can cause serious injury. To protect the roots it may be necessary to terrace the immediate area around the plants to be saved. If roots are exposed, construction of retaining walls may be needed to keep the soil in place. Plants can also be preserved by leaving them on an undisturbed, gently sloping mound. To increase the chances for survival, it is best to limit grade changes and other soil disturbances to areas outside the drip line of the plant.

Excavations - Protect trees and other plants when excavating for drainfields, power, water, and sewer lines. Where possible, the trenches should be routed around trees and large shrubs. When this is not possible, it is best to tunnel under them. This can be done with hand tools or with power augers. If it is not possible to route the trench around plants to be saved, then the following should be observed:

- Cut as few roots as possible. When you have to cut, cut clean. Paint cut root ends with a wood dressing like asphalt base paint.

- Backfill the trench as soon as possible.

- Tunnel beneath root systems as close to the center of the main trunk to preserve the important feeder roots.

Trees damaged or stressed by construction my die slowly or become more susceptible to attack from disease or insects. Failure to properly protect trees may result in expensive removal costs post construction.

Problem trees: The following trees are more susceptible to damage than others: beech, yellow poplar, Dogwood, hickory, birch, some oaks, most maples, and all conifers. These trees do not readily adjust to changes in the immediate environment and special care should be taken to protect these trees.

Maples and willows have water-seeking roots. These can cause trouble in sewer lines and infiltration fields. On the other hand, they thrive in high moisture conditions that other trees would not.

Minimum Tree Protection Measures

Active tree protection shall consist of, at a minimum, establishing a tree protection zone around each tree or grouping of trees by the installation of fencing at the outer edges of the critical root zone. Protecting the roots of a tree is the most important aspect of tree preservation on a construction project. This root zone can extend two to three times the radius of the drip line.

Despite this the tree protection zone is usually placed along the drip line. Some experts recommend a tree protection root zone calculated as one foot to one and half feet of radius for each inch of tree diameter at breast height. While this is a significant amount of space, if the tree is valuable, the root protection zone should extend to the edge all of the roots. If you want to protect the lower branches, the barrier must be just outside the drip line.

Tree protection fencing and tree protection area signs shall be installed prior to any land disturbance activity or building activity. Tree protection fencing should be at least four feet high and should be installed with either sturdy wooden or metal fence posts around the tree protection zone. Tree protection fencing must remain in good condition throughout the development and construction processes and should only be removed after construction has ceased.

Tree roots need oxygen so it is important to limit compaction around trees. If there is ANY disturbance with the root zone, the tree protection area should be mulched with a minimum of three inches and not more than eight inches of organic mulch such as pine straw, wood chips, tree leaves, or compost.

Allow NO storage, NO heavy equipment, NO machinery, NO trenching, NO digging, NO driving, NO lounging of workers in this area. The area within the protection zone must be off limits to ALL activity.

The Engineer or owner may require the installation of additional tree protection measures to insure survivability of conserved trees.

Materials

1. Protective fencing should be installed anytime existing natural vegetation is to be preserved.
2. Protective fencing is designated as the materials used to protect the root zones of trees. Three basic types of protective fencing materials can be used. Type A and Type B are typical applications and shall be installed where damage potential to a tree root system is high, while Type C shall be installed where damage potential is minimal.

3. The specific type of protective fencing for the work shall be as indicated on the Drawings.
4. Type C fencing shall be replaced by Type A or Type B fencing as directed by the Engineer or designated representative if it fails to perform the necessary function.

   a. Type A Chain Link fence (Typical Application-high potential damage)

      Type A protective fencing shall be installed in accordance with the Division of Highways Standard for Chain Link Fence and shall consist of a minimum five-foot high chain link fencing with tubular steel support poles or "T" posts.

   b. Type B Wood Fence (Typical Application-high potential damage)

      Type B protective fencing shall consist of any vertical planking attached to 2x4-inch horizontal stringers that are supported by 2x4-inch intermediate vertical supports and a 4x4-inch at every fourth vertical support.

   c. Type C Other Materials (Minimal potential damage)

      The following materials may be permitted as alternates for limited or temporary applications and where tree damage potential is minimal:

      (1) High visibility plastic construction fencing. The Standard for SAFETY FENCE in this manual can be used for this specification.
      (2) Other approved equivalent restraining material.

      The fencing materials, identified in (1) and (2) above, shall be supported by steel pipe, tee posts, U posts or 2" x 4" timber posts that are a minimum of 5-1/2 feet in height and spaced no more than 8 feet on centers. The fabric shall be secured to post by bands or wire ties.

Maintenance

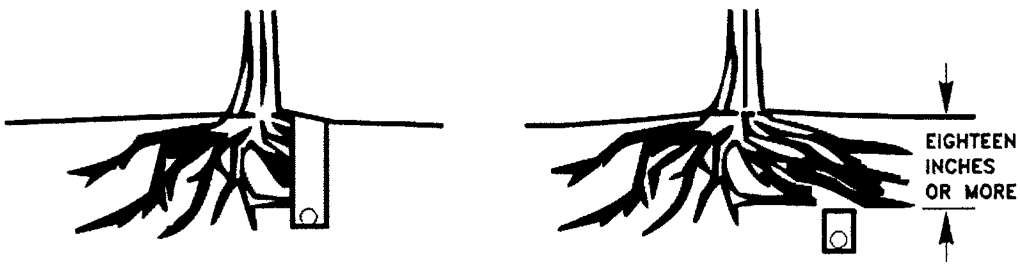
Inspect flagged and/or fenced areas regularly to make sure flagging or fencing has not been removed or damaged. If the flagging or fencing has been damaged or visibility reduced, it shall be repaired or replaced immediately and visibility restored.

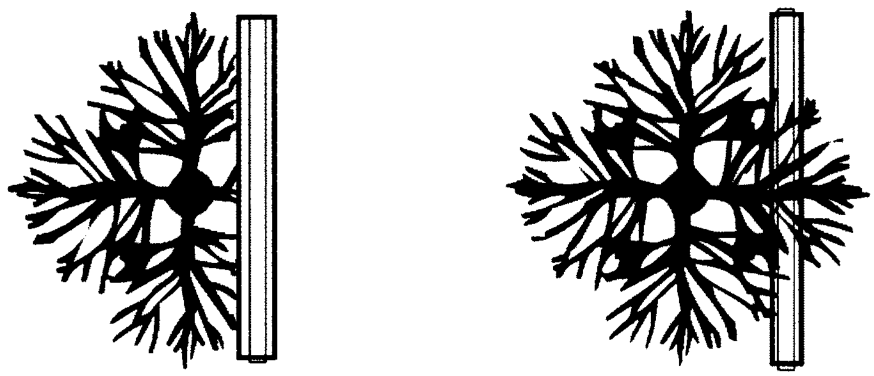
If tree roots have been exposed or injured, “prune” cleanly with an appropriate pruning saw or loppers directly above the damaged roots and recover with native soils. Treatment of sap flowing trees (pine, soft maples) is not advised as sap forms a natural healing barrier.

FIGURE 3.01.1

PRESERVING NATURAL VEGETATION

TRENCHING VS TUNNELING





DESTRUCTION OF FEEDER ROOTS WILL PROBABLY KILL THE TREE

TUNNELING UNDER THE TREE WILL PRESERVE ANY FEEDER ROOTS

SOURCE: US ACOE

FIGURE 3.01.2

TREE PROTECTION ZONES

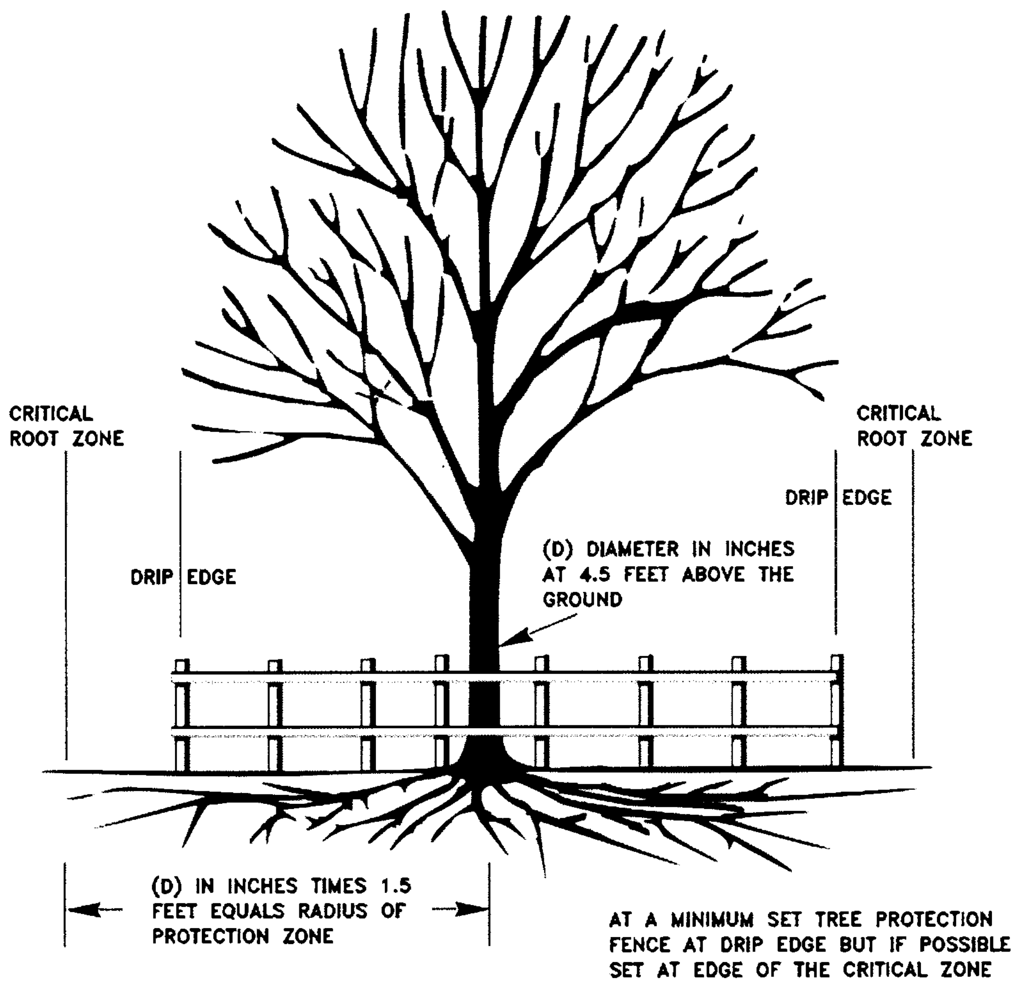
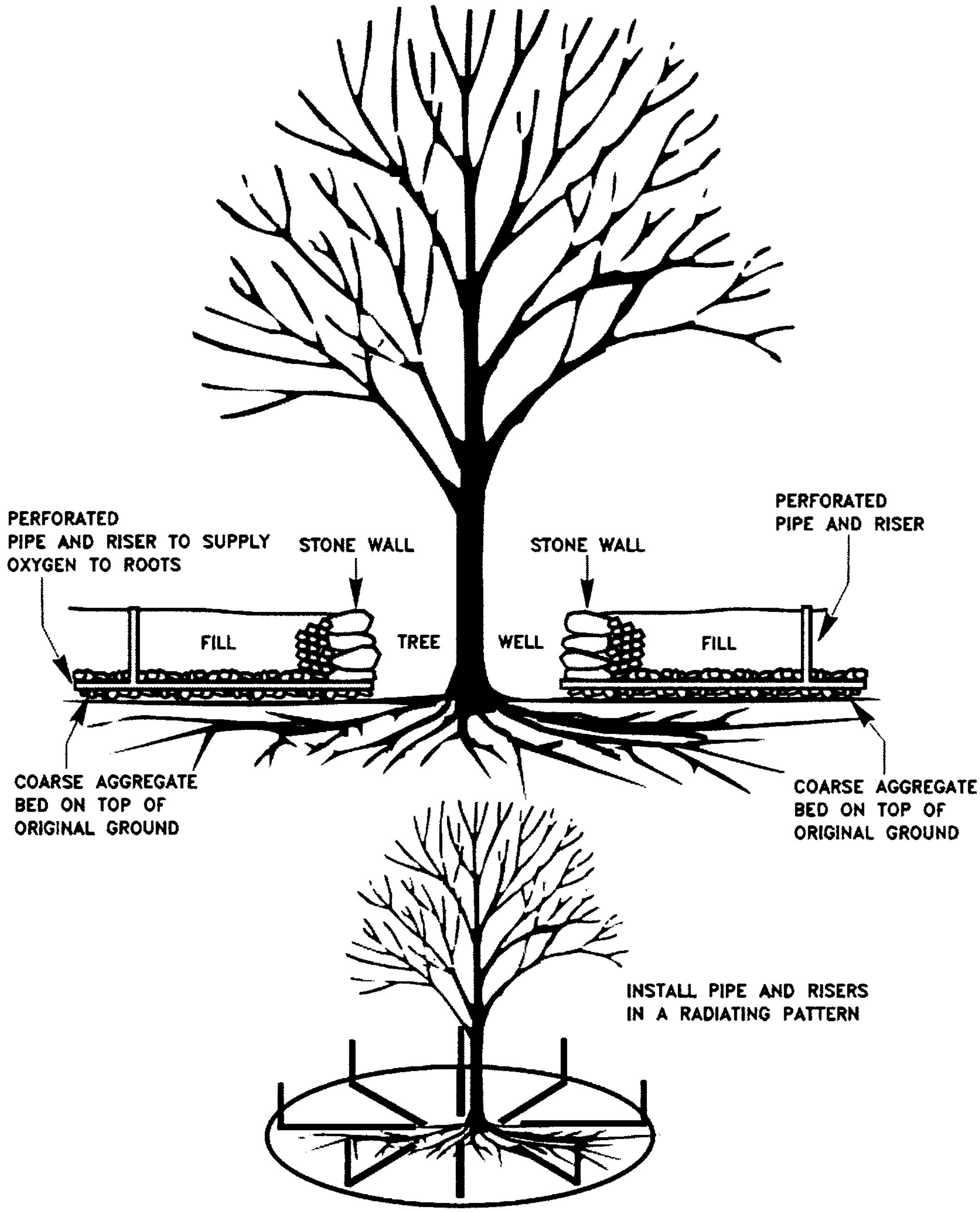


FIGURE 3.01.3

TREE WELL WHEN FILLING OVER TREE ROOTS



3.02 - STABILIZED CONSTRUCTION ENTRANCE

Introduction

Large quantities of mud can be tracked onto public and private roads causing dangerous driving conditions and muddy runoff when it rains. Construction entrances are stabilized to reduce the amount of sediment transported onto paved roads by vehicles or equipment by constructing a stabilized pad of stone at entrances to construction sites.

Conditions Where Practice Applies

Stabilized Construction Entrances shall be installed wherever construction traffic enters and leaves a site.

Design Criteria

1. Use 2-4 inch stone for low volume entrances, larger stone (4-6 inch) for heavy use or material delivery entrances.
2. Length is as required, but not less than 70 feet (except on a single residence lot where a 30 foot minimum length would apply).
3. Thickness should be not less than 6 inches.
4. The width shall be a minimum of 10 feet, but not less than the full width at points where ingress or egress occurs.
5. Geotextile fabric shall be placed over the entire area prior to the placing of stone.
6. All surface water flowing or diverted toward construction entrances shall be piped across the entrance. If a culvert is impractical, a mountable berm with 5:1 slopes shall be used.
7. If necessary, divert any water running down access road to a sediment trap located on either side of the Stabilized Construction Entrance.

Maintenance

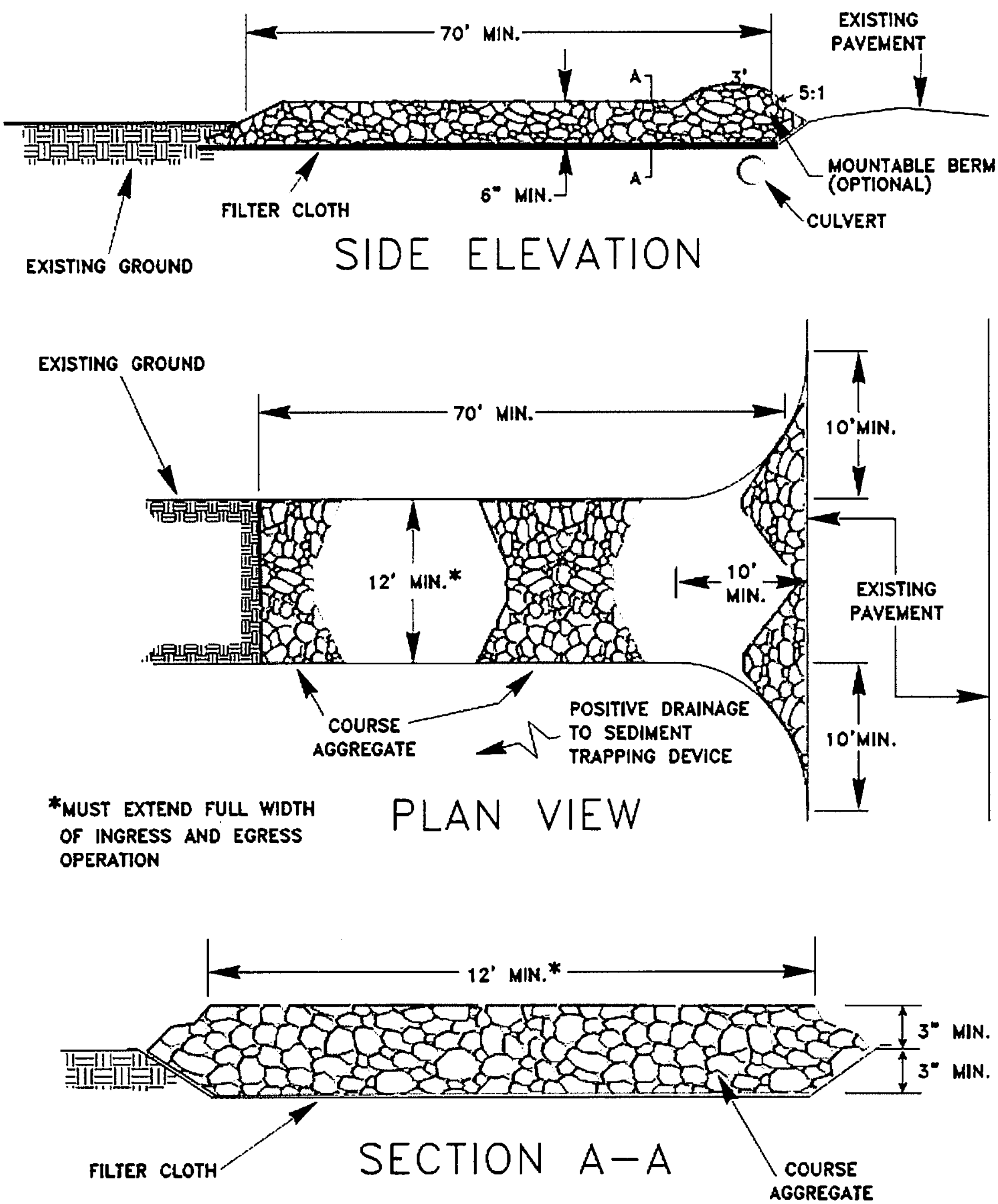
The entrance shall be maintained in a condition that will prevent tracking or flowing of sediment onto public rights-of-way. This may require periodic top dressing with additional stone as conditions demand and repair and/or cleanout of any measures used to trap sediment. All sediment spilled, dropped, washed or tracked onto public rights-of-way must be removed immediately.

Wheels on all vehicles shall be cleaned to remove sediment prior to entrance onto public rights-of-way. If washing is required, it shall be done on an area stabilized with stone and which drains into approved sediment trapping device. If the street is washed precautions must be taken to prevent muddy water from running into waterways or storm sewers.

Inspection and needed maintenance should be provided daily but at a minimum every seven days and after every rain of 0.5 inch or greater.

FIGURE 3.02.1

STONE CONSTRUCTION ENTRANCE



SOURCE: ADAPTED from 1983 Maryland Standards for Soil Erosion and Sediment Control and Va. DSWC

3.03 - TEMPORARY CONSTRUCTION ROAD, WORK AND PARKING AREA STABILIZATION

Introduction

The temporary stabilization of access roads, haul roads, parking areas, laydown, material storage and other onsite vehicle transportation routes with stone immediately after grading. This practice is used to reduce the erosion and subsequent regrading of temporary and permanent roadbeds, work areas and parking areas rutted by construction traffic during wet weather. Provides easier access in all weather and reduces tracking mud onto public roads.

Conditions Where Practice Applies

All temporary work areas on a construction site where vehicular traffic will occur.

Construction Specifications

1. Temporary roads shall follow the contour of the natural terrain to the extent possible. Slopes should not exceed 15 percent.
2. Temporary parking areas should be located on naturally flat areas to minimize grading. Grades should be sufficient to provide drainage but should not exceed 4 percent.
3. Roadbeds should be at least 14 feet wide for one-way traffic and 20 feet wide for two-way traffic. Haul roads should be a least 30 feet wide.
4. All cuts and fills should be 2:1 or flatter.
5. Drainage ditches and culverts shall be provided as needed.
6. The roadbed or parking surface shall be cleared of all vegetation, roots and other objectionable material.
7. A 6-inch course of crushed aggregate shall be applied immediately after grading. Geotextile fabric should be applied to the roadbed for additional stability. In heavy duty traffic situations, stone should be placed at an 8 to10 inch depth to avoid excessive maintenance.
8. Stabilize disturbed areas not covered with stone immediately after installation with appropriate temporary or permanent vegetation according to the applicable standards and specifications contained in this manual.
9. Also see, access road section, for water control practices.

Maintenance

Inspect and perform needed maintenance at a minimum once every seven calendar days and within 24 hours after any storm event greater than 0.5 inches of rain per 24 hour period.

Both temporary and permanent roads, laydown and work areas and parking areas may require periodic top dressing with new gravel.

Seeded areas adjacent to the roads and parking areas should be checked periodically to ensure that a vigorous stand of vegetation is maintained.

Roadside ditches and other drainage structures should be checked regularly to ensure that they do not become clogged with silt or other debris.

3.04 - SAFETY FENCE

Introduction

Protective fencing should be installed to prevent access to potentially hazardous areas of a construction site.

Conditions Where Practice Applies

Applicable to any control measure or series of measures, which can be considered unsafe by virtue of potential for access by the public. The designer, developer, and contractor should always be sure that the most appropriate type of fence is utilized for a particular need.

Construction Specifications

1. Safety fences should be located so as to create a formidable barrier to undesired access, while allowing for the continuation of necessary construction operations.
2. Safety fences are most applicable to the construction of traps and dams. In use with those structures, safety fences should be located far enough beyond the outer toe of the embankment to allow for the passage of maintenance vehicles. Fences should not be installed across the slope of a dam or dike.
3. Signs noting potential hazards such as "DANGER" or "HAZARDOUS AREA --KEEP OUT" should be posted and easily seen by anyone approaching the protected area.
4. Plastic (polyethylene) fence may be used as safety fencing, primarily in situations where the need is for a temporary barrier. The fence should meet the physical requirements noted in Table 3.04.1.

Table 3.04.1 Physical properties of plastic safety fence

Physical property	Test	Requirements
Recommended color	N/A	International Orange
Tensile yield	ASTM D638	Average 2,000 lbs.
Ultimate tensile strength	ASTM D638	Average 2,900 lbs. per 4 ft. width
Elongation at break(%)	ASTM D638	Greater than 1000%
Chemical resistance	N/A	Inert to most chemicals/acids

5. Safety fences should be installed prior to the sediment control measure becoming accessible.
6. Applicable warning signs noting hazardous conditions must be installed immediately upon installation of safety fence.

7. Chain link fence should be used for permanent structures (greater than one year).

Maintenance

Safety fence shall be checked regularly for weather-related or other damage. Any necessary repairs must be made immediately.

Care should be taken to secure all access points (gates) at the end of each working day. All locking devices must be repaired or replaced as necessary.

3.05 - ROCK CHECK DAMS

Introduction

Small temporary stone dams can be constructed across a waterway to reduce the velocity of stormwater flows, thereby reducing erosion of the channel and trapping sediment. This practice is the replacement for the traditionally misused hay/straw bales and silt fence ditch checks. Constructing a small dugout trap upstream of the structure can enhance the sediment trapping efficiency.

Conditions Where Practice Applies

This practice, utilizing a combination of stone sizes, is limited to use in small open channels that drain 5 acres or less. It is never used in live streams. Check dams can be useful in the following instances:

1. Temporary ditches or swales
2. Temporary or permanent ditches and swales which need protection during the establishment of grass linings.
3. This practice is not a substitute for major perimeter trapping measures such as a sediment trap or a sediment basin.

Construction Specifications

No formal design is required for a check dam, however, the following conditions should be adhered to:

1. The drainage area of the ditch or swale being protected shall not exceed 2 acres when 2 to 4 inch aggregate is used alone; and shall not exceed 5 acres when a combination of 4 to 8 inch aggregate (added for stability) and the smaller aggregate is used. Refer to Figure 3.05.1 for orientation of stone and a cross-sectional view of the measure. An effort should be made to extend the stone to the top of channel banks.
2. The maximum height of the dam should be 3 feet.
3. The center of the check dam must be at least 6 inches lower than the outer edges. This is the single most important aspect in the proper installation of the rock check dam. High flows must go over the center of the dam, not around the edges where severe erosion can occur.
4. The maximum spacing between the dams should be such that the toe of the upstream dam is at the same elevation as the top of the downstream dam. The maximum distance between rock check dams is 300 feet.
5. When using a small trap in front of the check dam, ensure the minimum transition from the ditch into the trap is at least 5:1.

Commercial Products

There are several commercially available products on the market now that are viable alternatives to the rock check dam. See commercial silt dike section

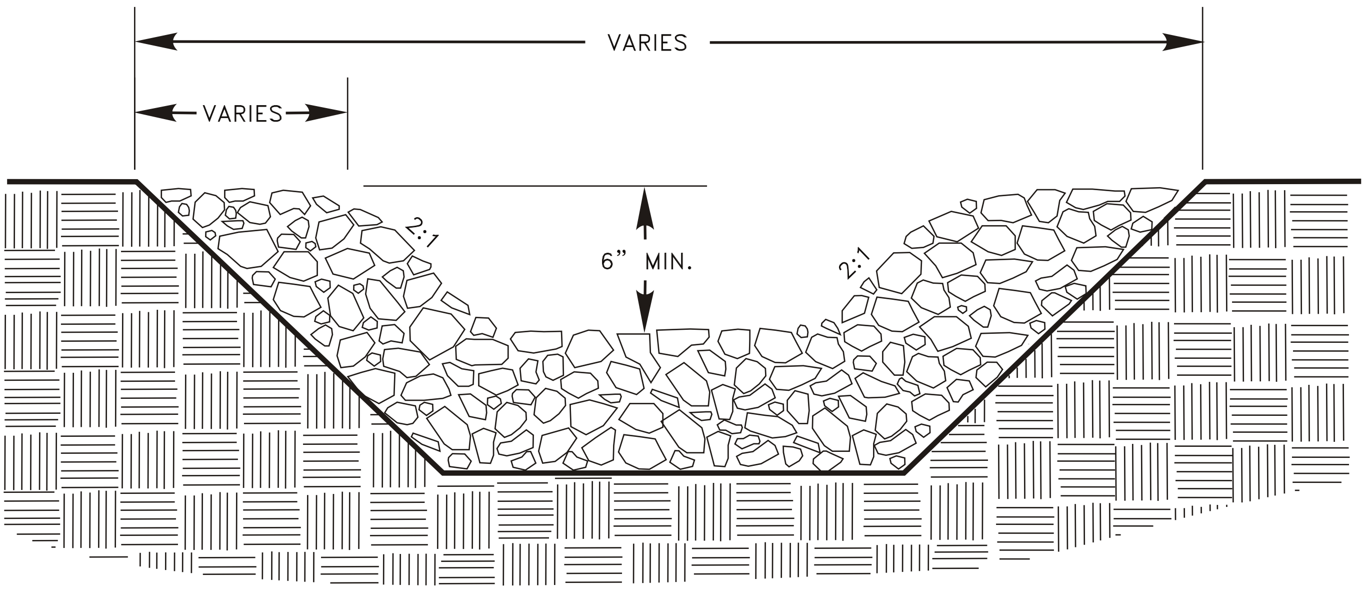
Maintenance

1. Inspect each check dam at a minimum once every seven calendar days and within 24 hours after any storm event greater than 0.5 inches of rain per 24 hour period. Check to see if water has flowed around the edges of the structure.
2. Replace stone and repair dams as necessary to maintain the correct height and configuration.

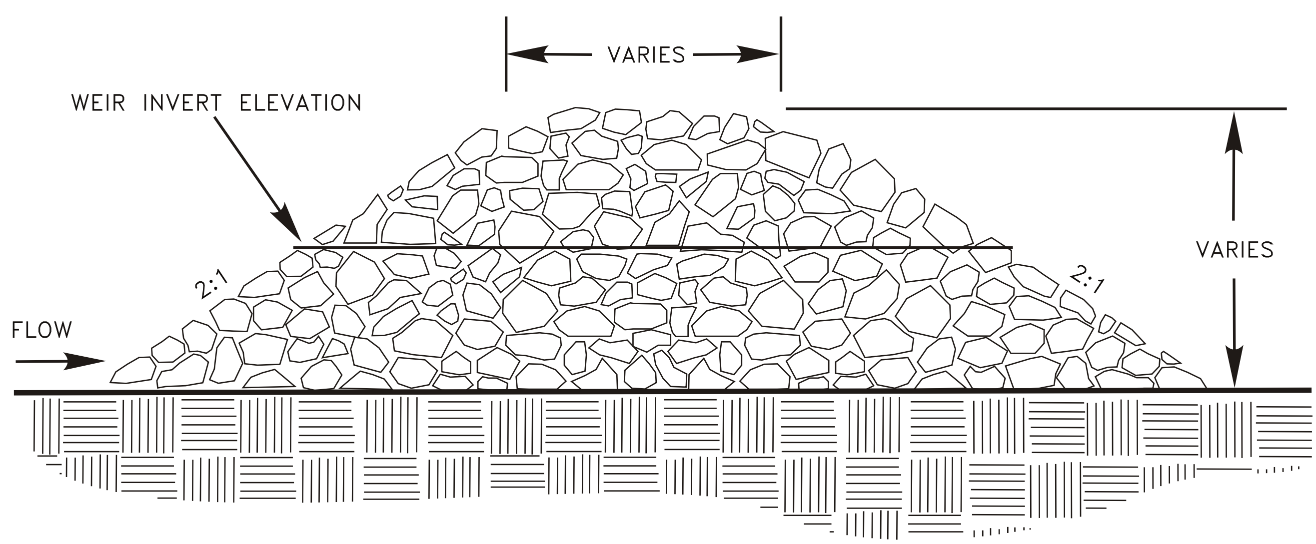
3. Sediment should be removed from behind the check dams when it has accumulated to one half of the original height of the dam. Dispose of the sediment in an appropriate place.

FIGURE 3.05.1

ROCK CHECK DAM



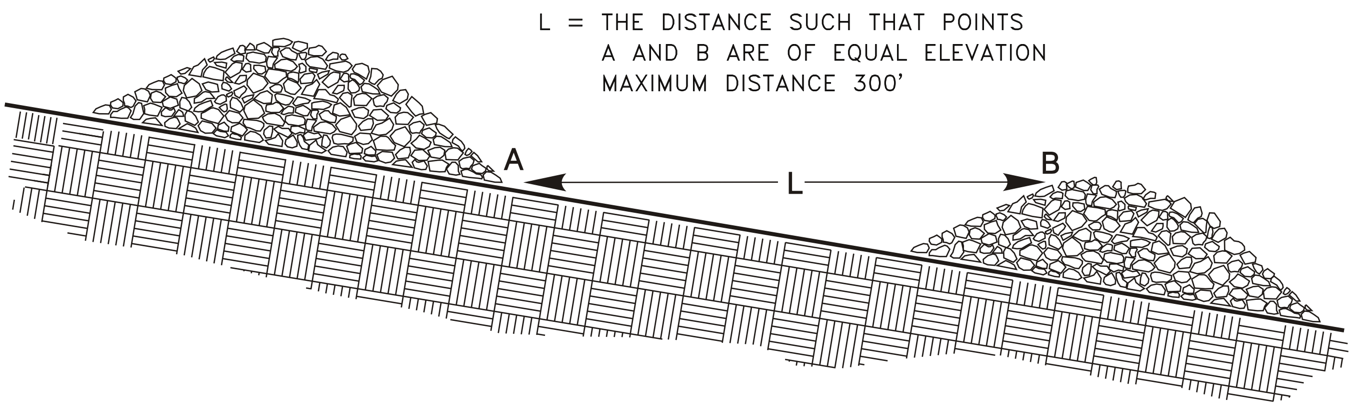
ELEVATION



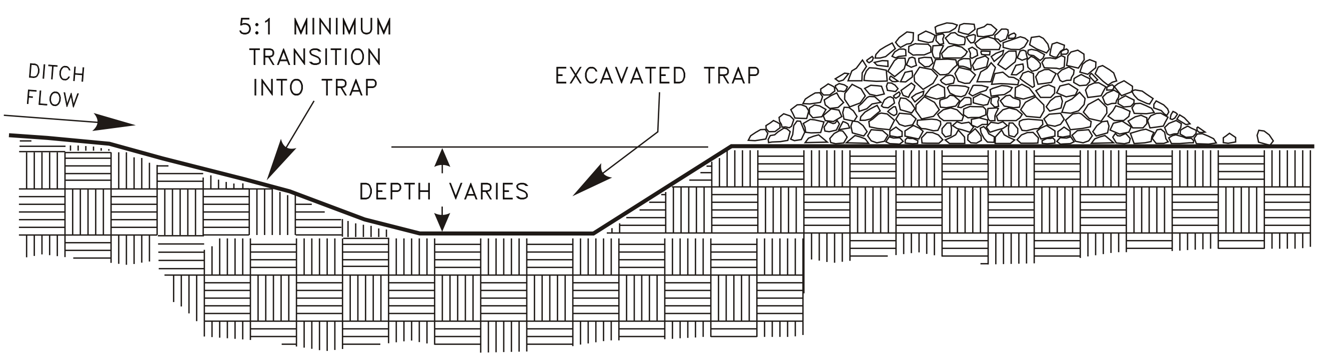
CROSS SECTION

FIGURE 3.05.2

ROCK CHECK DAM



CHECK DAM SPACING



CHECK DAM WITH SUMP

3.06 - WATTLES

Introduction

Wattles are erosion and sediment control barriers consisting of straw or other organic materials wrapped in biodegradable tubular plastic or similar encasing material. Sometimes called Fiber Rolls. Wattles may reduce the velocity and theoretically spread the flow of rill and sheet runoff, and can capture and retain sediment. Wattles are typically 8 to 20 inches in diameter and 10 to 30 feet in length. The wattles are placed in shallow trenches and staked along the contour of disturbed or newly constructed slopes or in low flow ditches where they can function as check dams.

Wattles reduce slope length, and are intended to capture and keep sediment on the slopes. Wattles are useful to temporarily stabilize slopes by reducing soil creep, and sheet and rill erosion until permanent vegetation can be established. Wattles can catch soil that is moved down the slope by the freeze/thaw processes. Organic matter and seeds are trapped behind the rolls, which provide a stable medium for germination. Rolls trap topsoil and retain moisture from rainfall, which aids in growth of seedlings planted upslope of the rolls.

Conditions Where Practice Applies

1. Install on disturbed areas that require immediate erosion protection.
2. Use on slopes requiring stabilization until permanent vegetation can be established.
3. Can be used along the perimeter of a project, as a check dam in unlined ditches and around temporary stockpiles
4. Wattles can be staked to the ground using willow cuttings for added revegetation
5. Erosion can occur beneath and between wattles if not properly entrenched, allowing water to pass below and between wattles. It is therefore very important to install wattles correctly.
6. They can replace sediment fence on steep slopes.
7. Rolls are a short-term solution to help establish native vegetation
8. Rolls store moisture for vegetation planted immediately upslope.
9. Plastic netting will eventually photo-degrade, eliminating the need for retrieval of materials after the fiber or straw has broken down.

Construction Specifications

1. It is critical that wattles are installed perpendicular to the flow direction and parallel to the slope contour.
2. Narrow trenches should be dug across the slope, on contour, to a depth of 3 to 5 inches on clay soils and soils with gradual slopes. On loose soils, steep slopes, and during high rainfall events, the trenches should be dug to a depth of 5 to 7 inches, or ½ to 2/3 of the thickness of the wattle.

3. Start construction of trenches and installing wattles from the base of the slope and work uphill. Excavated material should be spread evenly along the uphill slope and compacted using hand tamping or other method. Construct trenches at contour intervals of 3 to 30 feet apart depending on the steepness of the slope, soil type, and rainfall. The steeper the slope the closer together the trenches should be constructed.
4. Install the wattles snugly into the trenches and abut tightly end to end. Do not overlap the ends.
5. Install stakes at each end of the wattle, and at 4-foot centers along the entire length of the wattle.
6. If required, install pilot holes for the stakes using a straight bar to drive holes through the wattle and into the soil.
7. At a minimum, wooden stakes should be approximately ¾ x ¾ x 24 inches. Willow cuttings or 3/8-inch rebar can also be used for stakes.
8. Stakes should be driven through the middle of the wattle, leaving 2 to 3 inches of the stake protruding above the wattle.

Maintenance

Inspect wattles at least once a week and after each rain event greater than 0.5 inch.

Repair or replace split, torn, raveling, or slumping wattles.

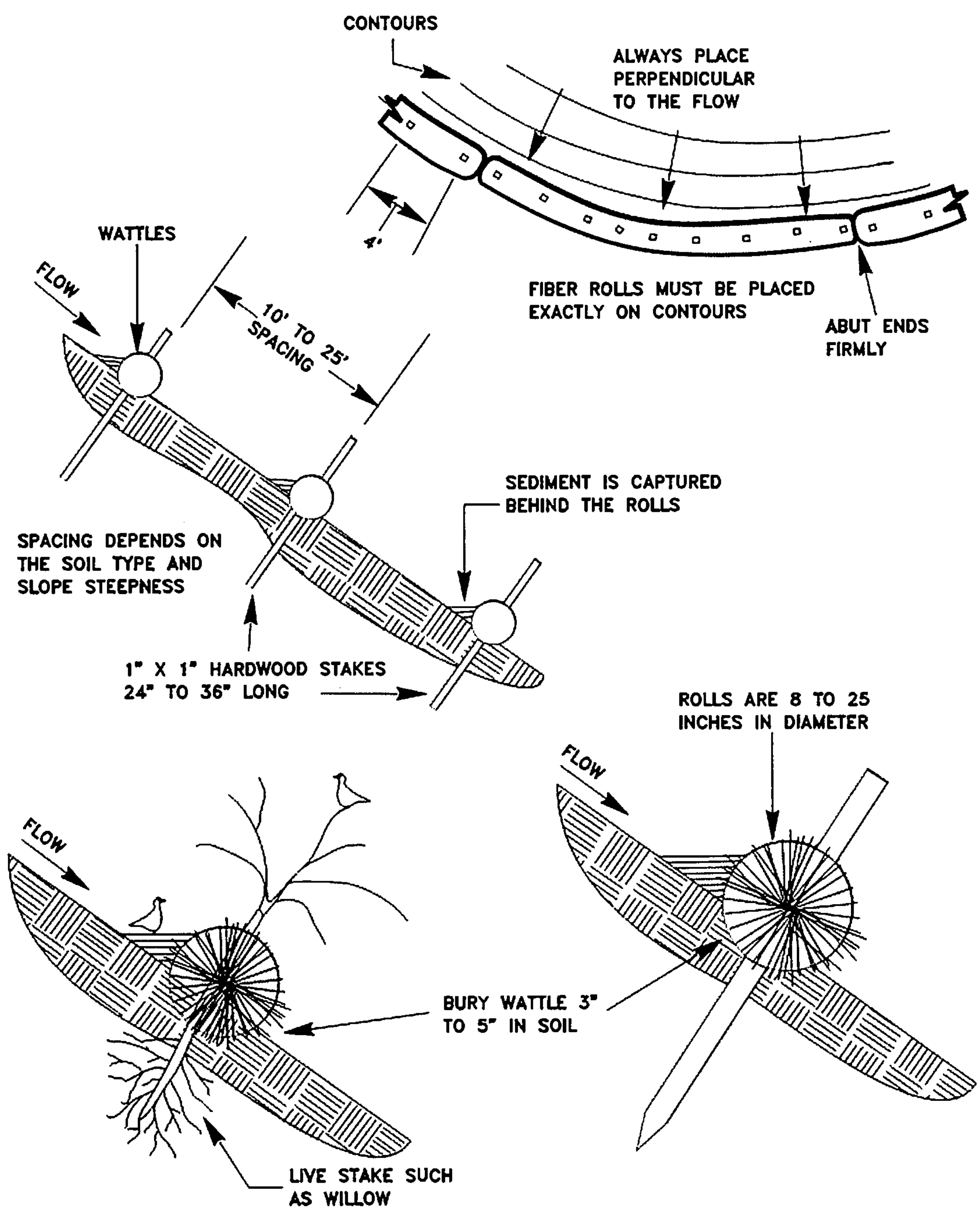
Remove sediment accumulations when exceeding ½ the height between the top of the wattle and the ground surface.

Repair any rills or gullies promptly.

Reseed or replant vegetation if necessary until the slope is stabilized

FIGURE 3.06.1

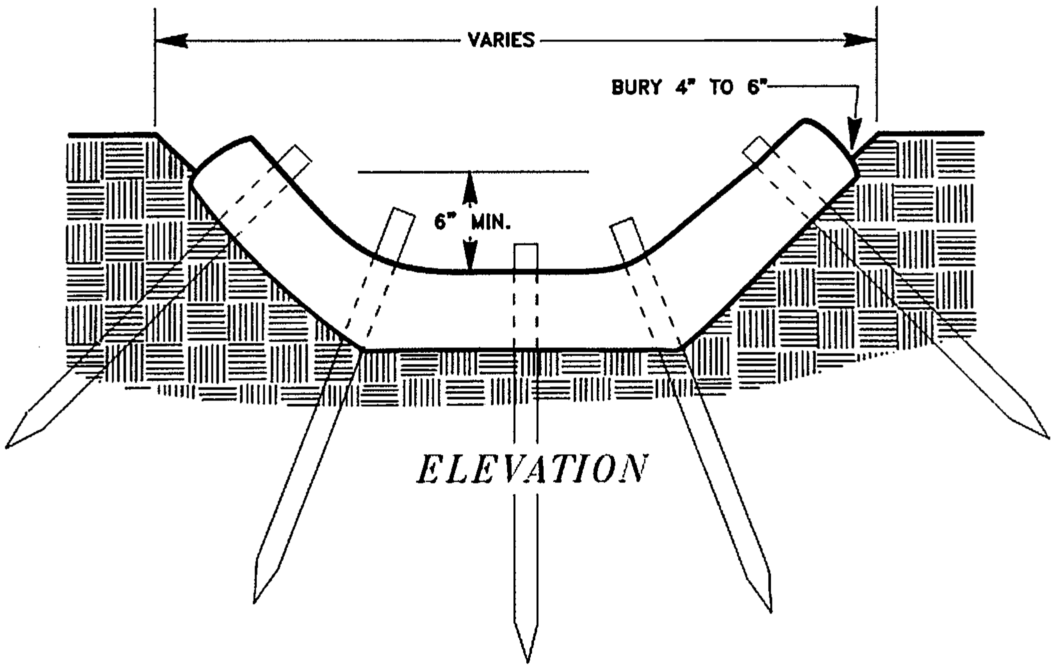
WATTLES



ADAPTED FROM JOHN MCCULLAGH, SALIX AND OREGON DEQ

FIGURE 3.06.2

STRAW WATTLE DITCH CHECK



ELEVATION

3.07 - COMMERCIAL SILT DIKES

Introduction

Rock check dams are the most commonly used practice to protect ditchlines from erosion and to trap small amounts of sediment. There are now several commercially available replacements for rock check dams. These new check dams are made from a variety of lightweight materials. One of these is made from foam rubber surrounded by a geotextile filter fabric. Others are made from plastic or a combination of synthetics and natural materials. They can be used as check dams, perimeter protection, drop inlet protection, or as a temporary interceptor dike.

Commercial silt dikes work on the same principle as rock check dams; they intercept and pond sediment-laden runoff. Ponding the water reduces the velocity of any incoming flow and allows some of the suspended sediment to settle. Water exits some commercial silt dikes by flowing over the top and others by flowing through with higher flows going over the top. The apron on the downstream side of the dike helps prevent scour caused by this flowing water.

Conditions Where Practice Applies

1. In place of rock check dams in ditches, especially in locations where hauling the rock would be difficult or in ditches with shallow soils underlain by rock.
2. May be used on soil with staples or on pavement with adhesive.
3. Commercial silt dikes can be used creatively to build temporary sediment traps, diversion ditches, concrete washout facilities, curbing, water bars, level spreaders, and berms.

Construction Specifications

1. Commercial silt dikes are made of urethane foam sewn into a woven geosynthetic fabric, permeable plastic or wattles.
2. Commercial silt dikes come in various shapes, sizes and materials and must be used as detailed in this practice and as the manufacturer states. The connection between individual pieces must be continuous.
3. Install commercial silt dikes perpendicular to the flow of the water except when used as diversions.
4. The commercial silt dikes should extend far enough so that the bottoms of the end dikes are higher than the top of the lowest center dike. This prevents water from flowing around the commercial silt dikes.
5. Attach the commercial silt dikes and their flaps to the ground with wire staples. Wire staples must be No. 11 gauge wire or stronger and shall be 6 to 12 inches in length. Follow the manufacturer's recommendation for installation.
6. When multiple units are installed, the sleeve of fabric at the end of the unit shall overlap the abutting unit and be stapled.

7. Commercial silt dikes must be located and installed as soon as construction will allow.
8. When used as check dams, the leading edge must be secured with rocks, sandbags, or a small key slot and staples.
9. Space dikes apart as shown for rock check dams.
10. Commercial silt dikes can be removed when the grass channel lining has matured sufficiently to protect the ditch or the ditch is stabilized with some sort of permanent lining such as riprap. The soil beneath the commercial silt dikes check dams shall be seeded and mulched immediately after dam removal.

Maintenance

Inspect at a minimum once every seven calendar days and within 24 hours after any storm event greater than 0.5 inches of rain per 24 hour period. Sediment shall be removed when it reaches one half the height of the silt dike.

Anticipate submergence and deposition above the dike and erosion from high flows around the edges of the dike/dam. Immediately repair any damage or any undercutting of the dike/dam.

3.08 - SURFACE ROUGHENING

Introduction

Surface roughening means providing a rough soil surface with horizontal depressions created by operating a tillage or other suitable implement on the contour, or by leaving slopes in a roughened condition by not fine-grading them. This will aid in establishment of vegetative cover with seed, reduce runoff velocity, and increase infiltration, and reduce erosion and provide for sediment trapping. Surface roughening is also a way to prepare the seedbed.

Conditions Where Practice Applies

1. All slopes steeper than 3:1 require surface roughening, either stair-step grading, grooving, furrowing, or tracking if they are to be stabilized with vegetation.
2. Areas with grades less steep than 3:1 should have the soil surface lightly roughened and loose to a depth of 2 to 4 inches prior to seeding.
3. Slopes with a stable rock face do not require roughening or stabilization.

Planning Considerations

It is difficult to establish vegetation on graded areas with smooth, hard surfaces due to reduced water infiltration and the potential for erosion. Rough slope surfaces with uneven soil and rocks left in place may appear unattractive or unfinished at first, but encourage water infiltration, speed the establishment of vegetation, and decrease runoff velocity.

Rough loose soil surfaces give lime, fertilizer and seed some natural coverage. Niches in the surface provide microclimates that generally provide a cooler and more favorable moisture level than hard flat surfaces; this aids seed germination.

There are different methods for achieving a roughened soil surface on a slope, and the selection of an appropriate method depends upon the type of slope. Roughening methods include stair-step grading, grooving, and tracking. Factors to be considered in choosing a method are slope steepness, mowing requirements, and whether the slope is formed by cutting or filling.

Cut Slope Applications For Areas Which Will Not Be Mowed

Cut slopes with a gradient steeper than 3:1 should be stair-step graded or grooved.

1. Stair-step grading may be carried out on any material soft enough to be ripped with a bulldozer. Slopes consisting of soft rock with some subsoil are particularly suited to stair-step grading.

   The ratio of the vertical cut distance to the horizontal distance shall be less than 1:1 and the horizontal portion of the "step" shall slope toward the vertical wall.

   Individual vertical cuts shall not be more than 30 inches on soft soil materials and not more than 40 inches in rocky materials.

2. Grooving consists of using machinery to create a series of ridges and depressions that run perpendicular to the slope (on the contour). Grooves may be made with any appropriate implement which can be safely operated on the slope and which will not cause undue compaction. Suggested implements include disks, tillers, spring harrows, and the teeth on a front-end loader bucket. These grooves should not be less than 3 inches deep nor further than 15 inches apart.

Fill Slope Applications For Areas Which Will Not Be Mowed

Fill slopes with a gradient steeper than 3:1 shall be grooved or allowed to remain rough as they are constructed. The methods below may be used:

1. Groove according to #2 above.
2. As lifts of the fill are constructed, soil and rock materials may be allowed to fall naturally onto the slope surface.

At no time shall slopes be bladed or scraped to produce a smooth, shiny, hard surface.

Cuts, Fills, and Graded Areas Which Will Be Mowed

Mowed slopes should not be steeper than 3:1. Excessive roughness is undesirable where mowing is planned. These areas may be roughened with shallow grooves such as remain after tilling, disking, harrowing, raking, or use of a cultipacker-seeder. The final pass of any such tillage implement shall be on the contour (perpendicular to the slope).

Grooves formed by such implements shall be not less than 1-inch deep and not further than 12-inches apart. Fill slopes that are left rough as constructed may be smoothed with a dragline or pick chain to facilitate mowing.

Roughening With Tracked Machinery

Roughening with tracked machinery on clayey soils is not recommended unless no alternatives are available. Undue compaction of surface soil results from this practice. Sandy and rocky soils do not compact severely, and may be tracked. In no case is tracking as effective as the other roughening methods described.

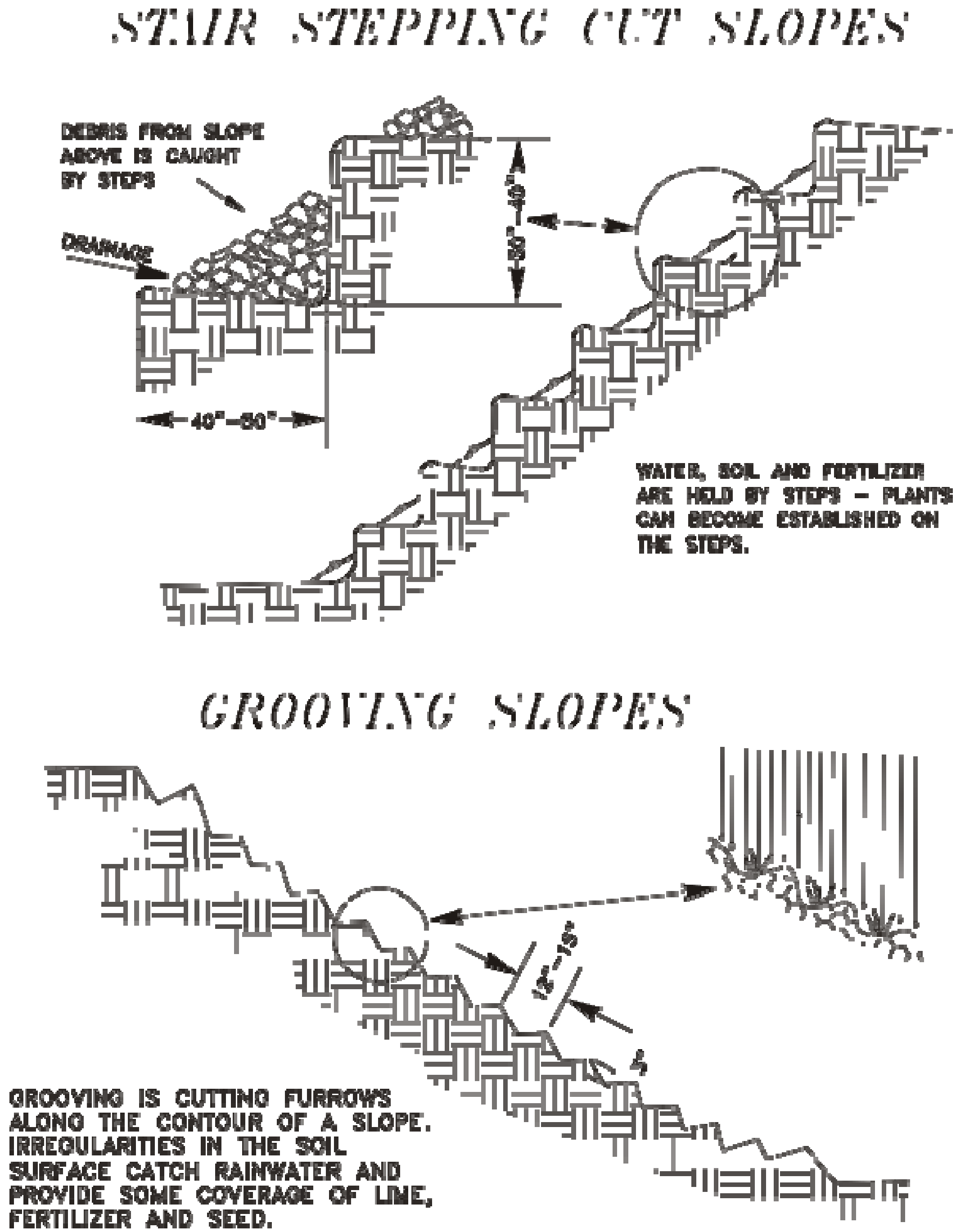
When tracking is the chosen surface roughening technique, it shall be done by operating tracked machinery up and down the slope to leave horizontal depressions in the soil. As few passes of the machinery should be made as possible to minimize compaction.

Seeding

Roughened areas shall be seeded and mulched as soon as possible to obtain optimum seed germination and seedling growth but at a minimum within seven days of reaching final grade or within seven days if no additional activity is anticipated for 21 days or more.

FIGURE 3.08.1

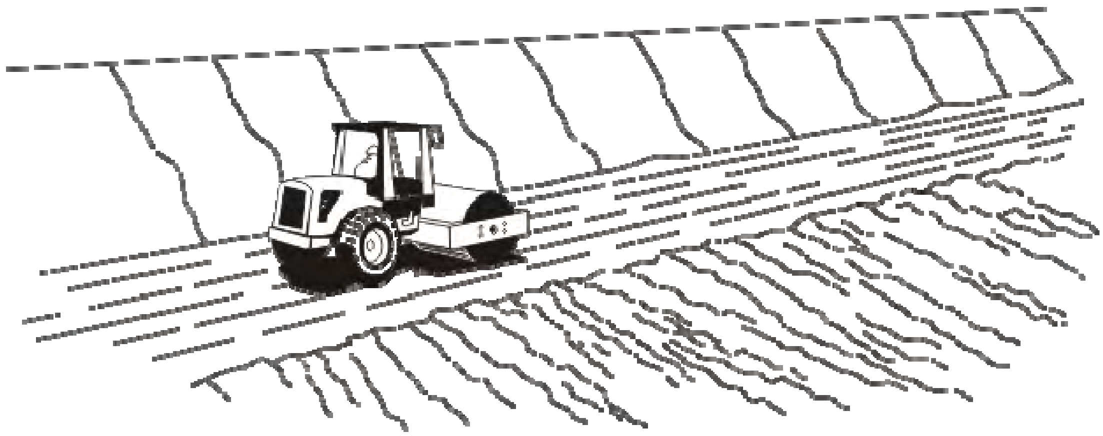
SURFACE ROUGHENING



SOURCE: VA. DSWC

FIGURE 3.08.2

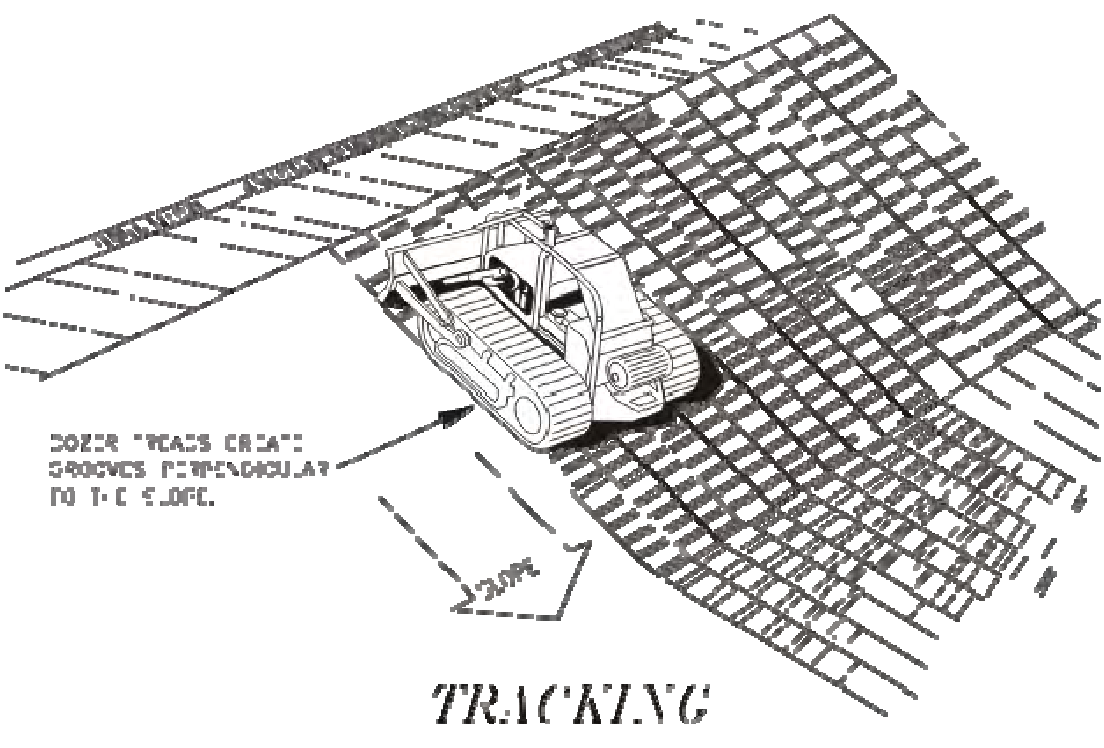
SURFACE ROUGHENING



EACH LIFT OF THE FILL IS COMPACTED, BUT THE OUTER FACE OF THE SLOPE IS ALLOWED TO REMAIN LOOSE SO THAT THE ROCKS, CLODS, ETC. REACH THE NATURAL ANGLE OF REPOSE.

FILL SLOPE TREATMENT

FROM: VA. DSWC



TRACKING

FROM: MICHIGAN SOIL EROSION AND SEDIMENTATION GUIDE

3.09 - TOPSOILING

Introduction

Topsoiling is the spreading of topsoil of a suitable quality over an area to be stabilized by establishing vegetation. Topsoil is the surface layer of the soil profile, generally characterized as darker than the subsoil due to the enrichment with organic matter. It is the major zone of root development and biological activity. Microorganisms that enhance plant growth thrive in this layer. Topsoil can usually be differentiated from subsoil by texture as well as color. Clay content usually increases in the subsoil. Where subsoils are high in clay, the topsoil layer may be significantly coarser in texture. The depth of natural topsoil may be quite variable. On severely eroded sites it may be gone entirely.

Advantages of topsoil include its higher organic matter content, friable consistence (soil aggregates can be easily crushed with only moderate pressure), its available water holding capacity, and its nutrient content. Most often it is superior to subsoil in these characteristics. The texture and friability of topsoil are usually much more conducive to seed germination, emergence, and root growth.

In addition to being a better growth medium, topsoil is often less erodible than subsoil, and the coarser texture of topsoil increases infiltration capacity and reduces runoff.

Vegetative growth is more rapid on sites with at least 4 inches of topsoil, and the health and quality of the vegetation is better than on sites with little or no topsoil.

Conditions Where Practice Applies

Where the preservation or importation of topsoil is determined to be the most effective method of providing a suitable growth medium.

Where the subsoil or existing soil present any or all of the following problems:

1. The texture, bulk density, pH, or nutrient balance of the available soil cannot be modified by a reasonable means to provide an adequate growth medium for the desired vegetation.
2. The soil is too shallow to provide adequate rooting depth or will not supply necessary moisture and nutrients for growth of desired vegetation.
3. The soil contains substances toxic or potentially toxic to the desired vegetation.
4. Where high-quality turf or ornamental plants are desired.

Design Considerations

Determine if sufficient quantities of suitable topsoil is available at the site or nearby. Topsoil shall be spread at a lightly compacted depth of 2 to 4 inches. Depths of 4 inches or greater are recommended where fine-textured (clayey) subsoil or other root limiting factors are present.

If topsoil is to be stockpiled at the site, select a location so that it will not erode, block drainage, or interfere with work on the site.

During construction of the project, soil stockpiles shall be stabilized by temporary seeding and mulching and protected with sediment trapping measures such as silt fence. Perimeter controls shall be placed around the stockpile immediately; seeding and mulching of stockpiles shall be completed within seven days of formation of the stockpile if it is to remain in place for longer than 21 days.

If the topsoil is not properly bonded to the existing soil, water will not infiltrate evenly, and it will be difficult to establish vegetation.

Care must be taken not to apply topsoil to an existing soil surface if the two have contrasting textures. Clayey topsoil over sandy subsoil is a particularly poor combination, as water creeps along the junction between the two soil layers and may cause the topsoil to slough.

Do not apply topsoil to slopes greater than 2:1 to avoid slippage. Topsoiling of steep slopes should be discouraged unless good bonding of the soils can be achieved.

Construction Specifications

The plans and specifications for installing topsoil shall be in keeping with this standard and shall describe the requirements for applying the practice to achieve its intended purpose. At a minimum include the following items:

1. Topsoil source.
2. Stockpile location and method of stabilization prior to its use.
3. Topsoil/subsoil bonding procedures.
4. Site preparation plans and method of application, distribution and compaction.

Site preparation- Before spreading topsoil, assure that all necessary erosion and sediment control practices such as diversions, berms, dikes, waterways, and sediment basins are in place and functioning properly. These practices must be maintained until the site is permanently stabilized.

Grading- Maintain grades on the areas to be topsoiled according to the approved plan and do not alter them by adding topsoil.

Liming of subsoil- Where the pH of the existing subsoil is 6.0 or less, or the soil is composed of heavy clays, incorporate agricultural limestone in amounts recommended by soil tests or specified for the seeding mixture to be used. Incorporate lime to a depth of at least 2 inches by disking.

Roughening- Immediately prior to spreading the topsoil, loosen the subgrade by disking or scarifying to a depth of at least 4 inches, to ensure bonding of the topsoil and subsoil. If no amendments have been incorporated, loosen the soil to a depth of at least 6 inches before spreading the topsoil.

Spreading topsoil- Uniformly distribute topsoil to a minimum compacted depth of 2 inches on 3:1 slopes and 4 inches on flatter slopes.

Topsoil shall not be spread while it is frozen or saturated or when the subsoil is frozen or saturated.

Irregularities in the surface that result from topsoiling or other operations shall be corrected to prevent the formation of depressions or ponding of water.

Compact the topsoil enough to ensure good contact with the underlying soil, but avoid excessive compaction, as it increases runoff and inhibits seed germination and seedling growth. Light packing with a roller is recommended where high-maintenance turf is to be established.

In areas that are not going to be mowed, the surface can be left rough.

Maintenance

After topsoil application, follow procedures for seedbed preparation. Take care to avoid excessive mixing of topsoil into the subsoil. Permanently stabilize the site following appropriate practice standards as quickly as practicable. Periodically inspect the site until permanent stabilization is achieved. Make necessary repairs to eroded areas or areas of light vegetative cover.

3.10 - TEMPORARY SEEDING

Introduction

Temporary erosion control measures consist of seeding and mulching, or matting used to produce a quick ground cover to reduce erosion on exposed soils that may be redisturbed or permanently stabilized at a later date.

Conditions Where Practice Applies

Use this method where exposed soil surfaces are not to be fine-graded for periods longer than 21 days. Such areas include denuded areas, soil stockpiles, dikes, dams, sides of sediment basins, temporary road banks, etc. A permanent vegetative cover shall be applied to areas that will be left unworked for a period of more than six months.

Planning Considerations

Sheet erosion, caused by the impact of rain on bare soil, is the source of most fine particles in sediment. To reduce this sediment load in runoff, the soil surface itself should be protected. The most efficient and economical means of controlling sheet and rill erosion is to establish vegetative cover. Annual plants that sprout rapidly and survive for only one growing season are suitable for establishing temporary vegetative cover. Temporary seeding is encouraged whenever possible to aid in controlling erosion on construction sites.

Temporary seeding also reduces costly maintenance operations on sediment control systems. For example, sediment basin/trap clean-outs can be reduced if its drainage area is vegetated when grading is not taking place. Perimeter dikes are more effective if not choked with sediment. Silt fence does not need to be cleaned as often.

Temporary seeding is essential to preserve the integrity of earthen structures used to control erosion and sediment, such as dikes, diversions, and the banks and dams of sediment basins/traps. If the design life of the basin or trap is more than one year, permanent seeding should be used.

Proper seedbed preparation and the use of quality seed are important in this practice just as in permanent seeding. Failure to carefully follow sound agronomic recommendations will often result in an inadequate stand of vegetation that provides little or no erosion control.

Construction Specifications

Prior to seeding, install necessary erosion control practices such as dikes, waterways, and basins.

Plant Selection

Select plants appropriate to the season and site conditions.

Seedbed Preparation

To control erosion on bare soil surfaces, plants must be able to germinate and grow. Seedbed preparation is essential. If the area has been recently loosened or disturbed, no further roughening is required. When the area is compacted, crusted, or hardened, the soil surface must be loosened by disking, raking, harrowing, or other acceptable means (see surface roughening section).

Seeding

Seed shall be evenly applied with a broadcast seeder, drill, cultipacker seeder or hydroseeder. Small grains shall be planted no more than 1.5 inches deep. Small seeds, such as annual rye, shall be planted no more than quarter inch deep. Other grasses and legumes shall be planted no more than half inch deep.

Mulching

Temporary seeding conducted in fall for winter cover and during hot and dry summer months shall be mulched with straw or hay according to the standard for mulching. Hydromulches (fiber mulch) may not provide adequate temperature and moisture control.

Maintenance

Areas that fail to establish a vegetative cover adequate to prevent rill erosion should be re-seeded as soon as such areas are identified.

Table 3.10.1 Temporary seed chart

PLANT NAMES		PLANTING DATES	APPLICATION RATE LBS/ACRE
COMMON	SCIENTIFIC		
Annual Ryegrass	*Lolium multiflorum*	2/16 – 5/15 8/1 – 11/1	40
Field Bromegrass	*Bromus ciliatus*	3/1 – 6/15 8/1 – 9/15	40
Spring Oats	*Avena sativa*	3/1 –6/15	100
Winter Rye	*Secale cereale*	8/15 –2/28	170
Winter Wheat	*Triticum aestivum*	8/15 – 2/28	180
Japanese Millet	*Echinochloa crusgalli*	5/15 – 8/15	30
Redtop	*Agrostis alba*	3/1 – 6/15	10
Annual Ryegrass and Spring Oats	*Lolium multiflorum* *Avena sativa*	3/1 – 6/15	30 70
German/Foxtail Millet	*Setaria italica*	5/1 – 8/1	40
Hairy Vetch	*Vicia villosa*	8/15 – 4/1	60

*Inoculation is required. If a hydroseeder is utilized,
the application rate is 5 times the recommended rate.

3.11 - PERMANENT SEEDING

Introduction

Permanent seeding is the establishment of perennial vegetative cover on disturbed areas by planting seed.

Purpose

1. To reduce erosion and decrease sediment yield from disturbed areas.
2. To permanently stabilize disturbed areas in a manner that is economical, adaptable to site conditions and allows selection of the most appropriate plant materials.

Conditions Where Practice Applies

1. Disturbed areas where permanent, long-lived vegetative cover is needed to stabilize the soil.
2. Rough-graded areas that will not be brought to final grade for six months or more.

Planning Considerations

Vegetation controls erosion by reducing the velocity and the volume (by increasing infiltration) of overland flows, protecting the bare soil surface from raindrop impact and binding the soil particles together by the roots and rhizomes.

Advantages of seeding over other means of establishing plants include the small initial establishment cost, the wide variety of grasses and legumes available, low labor requirement and ease of establishment in difficult areas.

Disadvantages include the potential for erosion during the establishment stage, a need to reseed areas that fail to establish, limited periods during the year suitable for seeding, the potential need for weed control during the establishment phase, and a need for water and appropriate micro-climatic conditions during germination.

There are so many variables in plant growth that an end product cannot be guaranteed. Much can be done in the planning stages to increase the chances for successful seeding. Selection of the right plants for the site, good seedbed preparation, proper timing and conscientious maintenance are important. By meeting the requirement to seed and mulch your site within seven days, the seedbed preparation and timing components are easily met.

Selecting Plants

The factors affecting plant growth are climate, soils and topography. In West Virginia, there are three major physiographic regions that reflect changes in soil and topography. In selecting appropriate plant materials, one should take into account the characteristics of the physiographic region in which the project is located.

Physiographic Regions

Western Plateau- Characterized by steep slopes and narrow valleys drained by dendritic low gradient streams. Soils are highly variable and on the acidic side. Erosion can be catastrophic and almost impossible to control, especially in the western sections of the state. Clays and silty-clays predominate with rich well-drained soils in the major river valleys. Rainfall averages 40 inches a year and is spread evenly throughout the year. Rain events average every four days. Soil moisture is optimal in the spring and fall. Droughts of short duration can occur every summer. Both cool and warm season grasses will grow.

Ridge and Valley Region- This region is divided into plateaus, mountains, narrow valleys and wide fertile valleys near the major stems of the Potomac River. Streams have medium gradient. Soils tend to be shallow and acid, and may erode rapidly on steep slopes. The significant shalely slopes are often unstable and droughty. This area is significantly drier than the rest of the state; however, storm events are significantly greater. The rugged topography makes plant establishment difficult. Cool season grasses are normally specified in this region.

Mountains-This region consists of high mountains (up to 4,860 feet) and plateaus, deep, steep valleys, short summers and cold snowy winters, and fast flowing, steep gradient streams. Rainfall averages 50 to 60 inches with up to 240 inches of snow each winter in the highest elevations. Soil depths range from bedrock along areas of the Allegheny Front, to thin to moderate. The range of soil fertility is large and many are acidic. Erodibility ranges from low in the shalely soils common to the Ridge and Valley, to very high in the soils formed from the Mauch Chunk sandstones. Erosion can be a problem because of the extreme steepness of the slopes. Because of the shortness of the growing season, the timeliness of seeding is of utmost importance. However, summer drought is unusual.

Soils

Soils in West Virginia usually require some nitrogen fertilization along with phosphorus and potassium to establish plants. Except for shallow limestone soils in Greenbrier, Pocahontas, Jefferson and Berkeley counties, and some small pockets elsewhere, lime is universally needed.

Microclimates, or localized climate conditions, affect plant growth. A south-facing slope is drier and hotter than a north-facing slope, and may require drought-tolerant plants. Shaded areas require shade-tolerant plants; the windward side of a ridge will be drier than the leeward, etc. Shaley soils are droughty.

The addition of lime is equally as important as applying fertilizer. Lime is best known as a pH or acidity modifier, but it also supplies calcium and magnesium, which are plant nutrients. More importantly, the correct pH frees up nutrients to the plant. Soils with a pH that is too low will not allow a plant to utilize nitrogen and phosphorus properly. Raising the pH can also prevent aluminum toxicity by making aluminum less soluble in the soil. Many soils in West Virginia are high in aluminum, which can stunt the growth of plant roots. Also remember that rainfall is acidic, compounding the low pH problem in the soil.

Once the soil temperature is correct, the two key limiting factors of seed germination are pH and moisture. If you control these two factors, your chances of success are greatly enhanced.

Seed Mixtures

As previously noted, the establishment of high quality turf frequently involves planting one single species. However, in seedings for erosion control purposes, the inclusion of more than one species should always be considered. Mixtures need not be excessive in poundage or seed count. The addition of a quick-growing annual provides early protection and facilitates establishment of one or two perennials in a mix. More complex mixtures might include a quick-growing annual, one or two legumes and more than one perennial grass. The addition of a nurse crop (quick-growing annuals added to permanent mixtures) is a sound practice for soil stabilization, particularly on difficult sites - those with steep slopes, poor, rocky, erosive soils, those seeded outside of the optimum seeding periods or in any situation where the permanent cover development is likely to be slow. The nurse crop germinates and grows rapidly, holding the soil until the slower-growing perennial (permanent) seedlings become established.

Maintenance

Even with careful, well-planned seeding operations, failures occur. When it is clear that plants have not germinated on an area or have died, these areas must be prepared and reseeded immediately to prevent erosion damage. It is extremely important to determine why germination did not take place and make any necessary corrective actions. **Healthy vegetation is the most effective erosion control available**. Some highly acidic soils (especially around various coal seams in the coalfields) will resist the best efforts to revegetate them. In these cases, topsoling will be the only way to establish vegetation.

Table 3.11.1 Permanent seeding

SEED MIX	PLANT NAMES		APPLICATION RATE LBS/ACRE
	COMMON	SCIENTIFIC	
A	Kentucky 31 Fescue Red Fescue Birdsfoot Trefoil	*Festuca arundinacea* *Festuca rubra* *Lotus corniculatus*	65 20 5
B	Switchgrass Perennial Ryegrass Redtop Birdsfoot Trefoil	*Panicum virgatum* *Lolium perenne* *Agrostis alba* *Lotus corniculatus*	15 20 5 15
C	Red Fescue Kentucky Bluegrass Merion Bluegrass	*Festuca rubra* *Poa pratensis* *Poa pratensis*	20 40 30
D	Kentucky 31 Fescue Red Fescue Kentucky Bluegrass White Dutch Clover	*Festuca arundinacea* *Festuca rubra* *Poa pratensis* *Trifolium repens*	45 20 25 5
E	Perennial Ryegrass Switchgrass Crownvetch or Perennial Pea	*Lolium perenne* *Panicum virgatum* *Coronilla varia* *Lathyrus latifolius*	30 15 20 30
F	Orchardgrass Ladino Clover Redtop	*Dactylis glomerata* *Trifolium repens* *Agrostis alba*	20 5 5
G	Birdsfoot Trefoil Weeping Lovegrass Perennial Ryegrass	*Lotus corniculatus* *Eragrostis curvula* *Lolium perenne*	15 45 10
H	Crownvetch Orchardgrass	*Coronilla varia* *Dactylis glomerata*	25 40
I	Crownvetch Perennial Ryegrass	*Coronilla varia* *Lolium perenne*	25 30
J	Perennial Pea Orchardgrass	*Lathyrus latifolius* *Dactylis glomerata*	30 30
K	Deertongue Birdsfoot Trefoil Weeping Lovegrass	*Panicum clandestinum* *Lotus corniculatus* *Eragrostis curvula*	30 15 5
L	Orchardgrass Serecia Lespedeza Ladino Clover	*Dactylis glomerata* *Lespedeza cunata* *Trifolium repens*	30 40 5
M	Perennial Ryegrass Ladino Clover Redtop	*Lolium perenne* *Trifolium repens* *Agrostis alba*	50 5 5
N	Crownvetch Orchardgrass Redtop	*Coronilla varia* *Dactylis glomerata* *Agrostis alba*	15 30 5

O	Perennial Ryegrass Birdsfoot Trefoil Redtop	*Lolium perenne* *Lotus corniculatus* *Agrostis alba*	40 15 5
P	Serecia Lespedeza Orchardgrass Redtop	*Lespedeza cunata* *Dactylis glomerata* *Agrostis alba*	40 30 5
Q	Orchardgrass Reed Canarygrass[1] Redtop Ladino Clover	*Dactylis glomerata* *Phalaris arundinacea* *Agrostis alba* *Trifolium repens*	25 30 5 5
R	Kentucky Bluegrass Redtop White Clover or Birdsfoot Trefoil	*Poa pratensis* *Agrostis alba* *Trifolium repens* *Lotus corniculatus*	30 5 5 15
S	Reed Canarygrass[1] Weeping Lovegrass	*Phalaris arundinacea* *Eragrostis curvula*	40 5
T	Perennial Ryegrass Reed Canarygrass[1] Birdsfoot Trefoil	*Lolium perenne* *Phalaris arundinacea* *Lotus corniculatus*	30 15 5
U	Timothy Alfalfa	*Phluem pratense* *Medicago sativa*	10 18
V	Timothy Birdsfoot Trefoil	*Phluem pratense* *Lotus corniculatus*	10 15
W	Redtop Perennial Ryegrass Orchardgrass	*Agrostis alba* *Lolium perenne* *Dactylis glomerata*	5 30 25
X	Reed Canarygrass[1] Birdsfoot Trefoil Redtop	*Phalaris arundinacea* *Lotus corniculatus* *Agrostis alba*	30 20 5
Y	Switchgrass Birdsfoot Trefoil	*Panicum virgatum* *Lotus corniculatus*	30 20
Z	Switchgrass Serecia Lespedeza	*Panicum virgatum* *Lespedeza cunata*	15 30
A-1	Orchardgrass Red Clover	*Dactylis glomerata* *Trifolium pratense*	30 10
A-2	Switchgrass Big Bluestem Indiangrass Little Bluestem Sideoats Grama[2]	*Panicum virgatum* *Andropogon gerardi* *Sorghastrum nutans* *Andropogon scoparius* *Bouteloua curtipendula*	15 5 5 5 5
A-3	Switchgrass Eastern Gamagrass[3]	*Panicum virgatum* *Tripsacum dactyloides*	20 15

NOTE: When utilizing a properly prepared seedbed, the rates of application can be reduced by 30 percent except for seed mixes A-2 & A-3.

[1] Reed Canarygrass shall not be used east of I-79 and/or south of Charleston.
[2] Use north and east of I-64 and I-79.
[3] Use south and west of I-64 and I-79.

Table 3.11.2 Nurse crops

PLANT NAMES		PLANTING DATES	APPLICATION RATE LBS/ACRE
COMMON	SCIENTIFIC		
Annual Ryegrass	*Lolium multiflorum*	2/16 – 5/15 8/1 – 11/1	25
Field Bromegrass	*Bromus ciliatus*	3/1 – 6/15 8/1 – 9/15	20
Spring Oats	*Avena sativa*	3/1 –6/15	50
Winter Rye	*Secale cereale*	8/15 –2/28	85
Winter Wheat	*Triticum aestivum*	8/15 – 2/28	90
Japanese Millet	*Echinochloa crusgalli*	5/15 – 8/15	15
Redtop	*Agrostis alba*	3/1 – 6/15	10
Annual Ryegrass and Spring Oats	*Lolium multiflorum* *Avena sativa*	3/1 – 6/15	15 35
German/Foxtail Millet	*Setaria italica*	5/1 – 8/1	25
Hairy Vetch*	*Vicia villosa*	8/15 – 4/1	30

* Inoculation is required. If a hydroseeder is utilized, the application rate is five times the recommended rate.

Table 3.11.3 Permanent seeding requirements

SEED MIX	FINE LAWN	COARSE LAWN	LOW MAINT.	NO MAINT.	PASTURE	SENSITIVE NATURAL AREAS	pH RANGE	DRAINAGE	SHADE TOLERANCE	PREFERRED PLANTING DATES			
										3/1 -6/15	6/16 -8/14	8/15 - 9/15	9/16 - 2/28
A			✓ 1				6.0 – 7.5	MOD. - WELL	FULL SUN	✓	♦	✓	♦
B				✓			5.0 – 7.5	MOD. – WELL	FULL SUN	✓	♦	✓	♦
C	✓ 1						6.0 – 7.5	MOD. – WELL	FULL SUN	✓		✓	
D		✓ 1					6.0 – 7.5	MOD. – WELL	FULL SUN	✓		✓	
E				✓ 1			6.0 – 7.5	MOD. – WELL	FULL SUN	✓	♦	✓	♦
F			✓	✓	✓		5.5 – 7.5	MOD. – WELL	TOLERANT	✓	♦	✓	♦
G				✓	✓		5.0 – 7.5	MOD. – WELL	FULL SUN	✓	♦	✓	♦
H			✓	✓ 1	✓		5.0 – 7.5	MOD. – WELL	TOLERANT	✓	♦	✓	♦
I			✓	✓ 1	✓		5.0 – 7.5	MOD. – WELL	FULL SUN	✓	♦	✓	♦
J			✓	✓ 1	✓		4.0 – 8.0	MOD. – WELL	TOLERANT	✓	♦	✓	♦
K				✓			4.0 – 7.0	MOD. – WELL	FULL SUN	✓	♦	✓	♦
L				✓	✓		4.5 – 7.5	MOD. – WELL	TOLERANT	✓	♦	✓	♦
M			✓	✓	✓		5.0 – 7.5	MOD. – WELL	TOLERANT	✓	♦	✓	♦
N			✓	✓ 1	✓		5.0 – 7.5	MOD. – WELL	TOLERANT	✓	♦	✓	♦
O			✓	✓	✓		5.0 – 7.5	MOD. – WELL	FULL SUN	✓	♦	✓	♦
P			✓	✓	✓		4.5 – 7.5	MOD. – WELL	TOLERANT	✓	♦	✓	♦
Q			✓	✓	✓		4.5 – 7.5	POOR - WELL	TOLERANT	✓	♦	✓	♦
R			✓	✓	✓		5.5 – 7.5	MOD. – WELL	FULL SUN	✓	♦	✓	♦
S			✓	✓	✓		4.5 – 7.5	POOR – WELL	FULL SUN	✓	♦	✓	♦
T					✓		5.5 – 7.5	POOR – WELL	FULL SUN	✓	♦	✓	♦
U					✓		6.5 – 8.0	MOD. – WELL	FULL SUN	✓	♦	✓	♦
V					✓		5.5 – 7.5	POOR – WELL	FULL SUN	✓	♦	✓	♦
W			✓	✓	✓		5.0 – 7.5	MOD. – WELL	TOLERANT	✓	♦	✓	♦
X					✓		5.5 – 7.5	POOR – WELL	FULL SUN	✓	♦	✓	♦
Y			✓	✓	✓		5.0 – 7.5	MOD. – WELL	FULL SUN	✓	♦	✓	♦
Z			✓	✓	✓		5.0 – 7.5	MOD. – WELL	FULL SUN	✓	♦	✓	♦
A-1					✓		4.5 – 7.5	MOD. – WELL	TOLERANT	✓	♦	✓	♦
A-2				✓	✓	✓	5.0 – 7.5	MOD. – WELL	FULL SUN	✓	♦	✓	♦
A-3				✓		✓	5.0 – 7.5	POOR - WELL	FULL SUN	✓	♦	✓	♦

♦ Nurse crop required – See Table B
1 Urban areas only

Seedbed Requirements

Vegetation should not be established on slopes that are unsuitable due to inappropriate soil texture, poor internal structure or internal drainage, volume of overland flow, or excessive steepness until measures have been taken to correct these problems.

To maintain a good stand of vegetation, the soil must meet certain minimum requirements as a growth medium.

The soil should have these characteristics:

1. Enough fine-grained material to maintain adequate moisture and nutrient supply.
2. Sufficient pore space to permit root penetration. A fine granular or crumb-like structure is favorable.
3. Sufficient depth of soil to provide an adequate root zone. The depth to rock or impermeable layers such as hardpans should be 12 inches or more, except on slopes steeper than 2:1 where the addition of soil is not feasible.
4. A favorable pH range for plant growth.
5. Freedom from toxic amounts of materials harmful to plant growth.
6. Freedom from excessive quantities of roots, branches, large stones, large clods of earth or trash of any kind.

Appropriate structural erosion control practices, such as berms, waterways, diversions, pipe slope drains, water bars or right of way diversions, needed to control overland flow to protect the seedbed should be installed prior to seeding.

Surfaces will be roughened in accordance with surface roughening section contained within this manual.

Soil Conditioners

In order to modify the texture, structure, or drainage characteristics of a soil, the following materials may be added to the soil:

1. Peat is a very costly conditioner, but works well. If added, it shall be sphagnum moss peat, hypnum moss peat, reed-sedge peat or peat humus, from freshwater sources.
2. Sand shall be clean and free of toxic materials. If this practice is considered, consult a professional authority to ensure that it is done properly.
3. Vermiculite shall be horticultural grade and free of toxic substances.
4. Manure, including poultry litter, in its composted form, is a viable soil conditioner. The use of manure should be based on site-specific recommendations offered by a professional in this field such as an agriculture extension agent or USDA employee.
5. Thoroughly rotted sawdust shall have six pounds of nitrogen added to each cubic yard and shall be free of stones, sticks, and toxic substances.
6. When composted, treated sewage sludge offers an alternative soil amendment. This practice should be thoroughly evaluated by a professional and used in accordance with any local, state, and federal regulations.

Lime and Fertilizer

Lime and fertilizer needs should be determined by soil tests. Soil tests may be performed by the WVU Extension Service soil testing laboratory or by a reputable commercial laboratory. Information concerning the WVU soil testing laboratory is available from county extension agents.

Under unusual conditions where it is not possible to obtain a soil test, the following soil amendments will be applied:

Lime

Two tons/acre (90 lbs./1,000 ft.^{2}) pulverized agricultural grade limestone.

Note: An agricultural grade of limestone should always be used except in inaccessible areas; lime may have to be applied separately in pelletized or liquid form.

Fertilizer

Mixed grasses and legumes: 1,000 lbs./acre nutrients (23 lbs./1,000 ft.^{2}) 10-20-10 or equivalent.

Legume stands only: 1,000 lbs./acre (23 lbs./ 1,000 ft.^{2}) 5-20-10 is preferred; however, 1,000 lbs./acre of 10-20-10 or equivalent may be used.

Grass stands only: 1,000 lbs./acre (23 lbs./1,000 ft.^{2})10-20-10 or equivalent nutrients.

Other fertilizer formulations, including slow-release sources of nitrogen (preferred from a water quality standpoint), may be used provided they can supply the same amounts and proportions of plant nutrients.

Lime and fertilizer shall be incorporated into the top 4 to 6 inches of the soil by disking or other means whenever possible. When applying lime and fertilizer with a hydroseeder, apply to a rough, loose surface.

Seeding

1. Appropriately labeled seed will be used for all permanent seeding whenever possible. Labeled seed is inspected by the West Virginia Department of Agriculture. The seed must be appropriately labeled or tagged as defined in the West Virginia Seed Law, Chapter 19 Article 16.
2. Legume seed should be inoculated appropriate to the species. Seed of the lespedezas, the clovers and crownvetch should be scarified to promote uniform germination.
3. Apply seed uniformly with a broadcast seeder, drill, culti-packer seeder or hydroseeder. See Seedbed Requirement above for seedbed preparation. Seeding depth should be a quarter to half inch.
4. To avoid poor germination rates as a result of seed damage during hydroseeding, it is recommended that if a machinery breakdown of 30

minutes to two hours occurs, 50 percent more seed be added to the tank, based on the proportion of the slurry remaining in the tank. Beyond two hours, a full rate of new seed may be necessary.

5. Surface roughening is particularly important when hydroseeding, as a roughened slope will provide some natural coverage for lime, fertilizer and seed.

Legume inoculants should be applied at five times the recommended rate when the inoculant is included in the hydroseeder slurry.

Mulching

All permanent seeding must be mulched immediately upon completion of seed application. Refer to the mulching section contained within this manual.

Irrigation

The newly seeded area should be supplied with adequate moisture. Supply water as needed, especially late in the season, in abnormally hot or dry weather, or on adverse sites. Water application rates should be controlled to prevent excessive runoff. Inadequate amounts of water may be more harmful than no water by causing the seedlings roots to curve towards the surface of the ground looking for moisture.

Reseeding

Inspect seeded areas for failure (less than 70 percent coverage) and make necessary repairs and reseeding within the same growing season, if possible.

a. If vegetative cover is inadequate to prevent rill erosion, overseed and fertilize in accordance with soil test results. If rills are large enough it may be necessary to regrade the rills out and reestablish a seedbed.

b. If a stand has less than 70 percent coverage, reevaluate choice of plant materials and quantities of lime and fertilizer. The soil must be tested to determine if acidity or nutrient imbalances are responsible. Reestablish the stand following seedbed preparation and seeding recommendations.

Fertilization

Cool season grasses should be fertilized 90 days after planting to ensure proper stand and density. Warm season grasses should be fertilized 30 days after planting.

Apply maintenance levels of fertilizer as determined by soil test. In the absence of a soil test, fertilization should be as follows:

Cool Season Grasses

Apply 4 lbs. nitrogen, 1 lb. phosphorus, 2 lbs. potassium per 1,000 $ft.^2$ per year. Seventy-five percent of the total requirements should be applied between September 1 and December 31. The balance should be applied prior to May 1 the following year. More than 1 lb. of soluble nitrogen per 1,000 $ft.^2$ should not be applied at any one time.

Warm Season Grasses

Apply 4 to 5 lbs. nitrogen between May 1 and August 15 per 1,000 $ft.^2$ per year. Phosphorus and Potassium should only be applied according to soil test.

Note: The use of slow-release fertilizer formulations for maintenance of turf is encouraged to reduce the number of applications and the impact on groundwater.

Note: The permanent seeding section is not meant to be an all-inclusive list of possible seeding mixtures. There may be other purposes such as wildlife habitat or natural beauty that would require alternative mixtures. The DEP encourages the submission of enhanced vegetation plans for other purposes with your NPDES permit application.

3.12 – MULCHING INCLUDING FLEXIBLE GROWTH MEDIUM AND BONDED FIBER MATRIX

Introduction

The application of straw, hay or other suitable materials to the soil surface used to:

1. Prevent erosion by protecting the soil surface from raindrop impact and reducing the velocity of overland flow.
2. Foster the growth of vegetation by increasing available moisture and providing insulation against extreme heat and cold. Mulching increases the window of opportunity for seeding by moderating temperature and moisture extremes. This is important because the general permit does not define specific seeding dates and requires only that areas be seeded within seven days of reaching final grade.

Conditions Where Practice Applies

1. Areas that have been temporarily or permanently seeded should be mulched immediately following seeding.
2. Areas that cannot be seeded because of the season should be mulched to provide some protection to the soil surface. An organic mulch should be used, and the area then seeded as soon as weather or seasonal conditions permit. Do not use fiber mulch (cellulose-hydroseed) alone for this practice; at normal application rates it will not give the protection that is achieved by using other types of mulch.
3. Mulch may be used together with plantings of trees, shrubs, or other ground covers that do not provide adequate soil stabilization by themselves.

Planning Considerations

Mulches are applied to the soil surface to conserve desirable soil properties or to promote plant growth. Mulching can be an effective means of controlling runoff and erosion on disturbed land.

Mulches increase the infiltration rate of the soil, reduce soil moisture loss by evaporation, prevent crusting and sealing of the soil surface, modify soil temperatures and provide a suitable microclimate for seed germination.

Organic mulch materials such as straw and hay are the most effective, followed by wood chips, bark and fiber.

At this time chemical soil stabilizers or soil binders should not be used alone for mulch. These materials are useful to bind organic mulches together to prevent displacement.

A variety of manufactured rolled erosion control products have been developed for erosion control in recent years. See standard for erosion control matting for alternatives to mulching. Some of these products can be used as mulches, particularly in critical areas such as waterways, steep slopes and windy ridges. They also may be used to hold other mulches to the soil surface.

The choice of materials for mulching will be based on the type of soil to be protected, site conditions, season and economics. It is especially important to mulch liberally in mid-summer and prior to winter, and on cut slopes and southern slope exposures.

Organic mulches

Straw- The mulch most commonly used in conjunction with seeding. The straw should come from wheat or oats (free of troublesome weed seeds) and may be spread by hand or machine. Straw can be windblown and should be anchored down by an acceptable method. Straw's attributes such as its hollow core (provides insulation), rigidity (does not easily compress) and general lack of weeds makes it the best mulch available

Hay- May be used in lieu of straw where incompatible vegetation will not present a problem, and may be spread by hand or machine. Hay can be windblown and should be anchored or tacked down.

Additionally, when hay or straw mulch decomposes it adds valuable organic material to the soil.

Wood cellulose fiber mulch- Used in hydroseeding operations and applied as part of the slurry. It creates the best seed-soil contact when applied over top of (as a separate operation) newly seeded areas. These mulches do not require tacking, although tacking agents or binders are sometimes used in conjunction with the application of fiber mulch. Fiber mulch does not provide sufficient protection on highly erodible soils or during less favorable growing conditions. **Fiber mulch should not be used alone during the dry summer months or for late fall mulch cover**. Use straw/hay mulch during these periods. Fiber mulch may be used to tack (anchor) straw/hay mulch. Fiber mulch is well suited for steep slopes, critical areas, and areas susceptible to wind.

Chemical mulches, soil binders and tackifiers

A wide range of synthetic spray-on materials is marketed to stabilize and protect the soil surface. These are emulsions or dispersions of petroleum distillates, emulsions of copolymer acrylates, latexes, and polyvinyl acetates, clay colloids, and dry powered vegetable gums derived from guar, psyllium, and sodium alginase, which are mixed with water and sprayed over the mulch and to the soil. They may be used alone in some cases as temporary stabilizers, or in conjunction with fiber mulch, hay or straw. The DEP does not recommend the use of asphalt emulsion as a binder.

Unlike organic mulches, most chemical mulches do not insulate the soil or retain soil moisture when used alone. They may also be easily damaged by traffic. Application of these mulches is usually more expensive than organic mulching, and the mulches decompose quickly.

The industry is continually improving alternative soil binders/mulches and the permittee is encouraged to investigate these new products for use on the site.

Always follow the manufacturer's recommendations when applying any of the above products.

Construction Specifications

Organic mulches

Organic mulches may be used in any area where mulch is required, subject to the restrictions noted in Table 3.12.1.

Select mulch material based on site requirements, availability of materials and availability of labor and equipment. Table 3.12.1 lists the most commonly used organic mulches.

Prior to mulching, complete the required grading and install needed sediment control practices.

Lime and fertilizer should be incorporated and surface roughening accomplished as needed. Seed should be applied prior to mulching except in the following cases:

1. Where seed is to be applied as part of a hydroseeder slurry containing wood cellulose fiber mulch (DEP recommends that the seed be spread prior to the spraying of the fiber mulch if at all possible).
2. Where seed is to be applied following a temporary mulch spread during winter months.

Mulch materials shall be spread uniformly, by hand or machine. When spreading straw mulch by hand, divide the area to be mulched into approximately 1,000 sq. ft. sections and place 70-90 lbs. (1½ to 2 bales) of straw in each section to facilitate uniform distribution.

Straw and hay mulch should be anchored immediately after spreading to prevent displacement. Other organic mulches listed in Table 3.12.1 should not require anchoring. The following methods of anchoring straw and hay may be used:

1. **Mulch anchoring tool (often referred to as a krimper or krimper tool) -** A tractor-drawn implement designed to punch mulch into the soil surface. This method provides good erosion control with straw. It is limited to use on slopes where the equipment can operate safely. Machinery shall be operated on the contour.
2. **Wood cellulose fiber mulch-** Apply fiber mulch by means of a hydroseeder at a rate of 500-750 lbs./acre over top of straw mulch or hay. It has an added benefit of providing additional mulch to the newly seeded area.
3. **Liquid mulch binders-** Application of liquid mulch binders and tackifiers should be heaviest at edges of areas and at crests of ridges and banks, to prevent displacement. The remainder of the area should have binder applied uniformly. Binders may be applied after mulch is spread or may be sprayed into the mulch as it is being blown onto the soil.
4. **Synthetic binders-** Formulated binders or organically formulated products may be used as recommended by the manufacturer to anchor mulch.
5. **Mulch netting-** Lightweight plastic, cotton and coir nets may be stapled over the mulch according to manufacturer's recommendations (See rolled erosion control products section).

Chemical mulches

Chemical mulches* may be used alone only in the following situations:

1. Where no other mulching material is available.
2. From March 15 to May 1 and August 15 to September 30, provided that they are used on areas with slopes no steeper than 4:1, which have been roughened in accordance with surface roughing standards. If rill erosion occurs, another mulch material shall be applied immediately.

* Note: Some chemical mulches may be used to bind other mulches or with fiber mulch in a hydroseeded slurry. Manufacturer's recommendations for application of chemical mulches shall be followed.

Maintenance

All mulches and soil coverings should be inspected periodically (particularly after rainstorms and high winds) to check for erosion and displacement. Where erosion is observed in mulched areas, additional mulch should be applied and erosion repaired if necessary. Nets and mats should be inspected after rainstorms for dislocation or failure. If washouts or breakage occur, reinstall netting or matting as necessary after regrading to repair damage to the slope or ditch. Inspections should take place up until grasses are firmly established or the area is redisturbed.

Table 3.12.1 Organic mulch materials and application rates			
Mulches:	Rates:		Notes:
	Per acre	Per 1,000 ft^2.	
Straw or hay	1½ - 2 tons (minimum 2 tons for winter cover)	70 - 90 lbs.	Free from weeds and coarse matter. Must be anchored. Spread with mulch blower or by hand.
Fiber mulch	Minimum 1,500 lbs.	35 lbs.	Do not use as mulch for winter cover or during hot, dry periods.* Apply as slurry.
Cornstalks	4 - 6 tons	185 - 275 lbs.	Cut or shredded in 4-6" lengths. Air-dried. Do not use in fine turf areas. Apply with mulch blower or by hand.
Wood chips	4 - 6 tons	185 - 275 lbs.	Free of coarse matter. Air-dried. Treat with 12 lbs. nitrogen per ton. Do not use in fine turf areas. Apply with mulch blower, chip handler, or by hand.
Bark chips or Shredded bark	50 - 70 cu. yds.	1-2 cu. yds.	Free of coarse matter. Air-dried. Do not use in fine turf areas. Apply with mulch blower, chip handler, or by hand.

* When fiber mulch is the only available mulch during periods when straw should be used, apply at a minimum rate of 2,000 lbs./ac. or 45 lbs./1,000 sq. ft.

From VA DSWC

3.13 - ROLLED EROSION CONTROL PRODUCTS

Introduction

Rolled Erosion Control Products (RECPs) are temporary or permanent erosion control nets, blankets and three-dimensional matrixes made from a wide variety of natural (such as jute, coir and straw) and manmade materials alone or in combination. There are numerous commercially available products so great care must be used to choose the correct product for the application.

RECPs help prevent erosion in several ways. They can be a direct replacement for straw or hay mulch and provide uniform protection from raindrop erosion, moderating temperature and moisture extremes and preventing detachment of the soil by sheet flow. They can hold seed and mulch in place on slopes and in channels so that vegetation can become established. And they can be used to permanently reinforce turf to protect channels and stream banks in high flows conditions.

Conditions Where Practice Applies

Temporary Rolled Erosion Control Products

Temporary rolled erosion control products (RECPs) consist of prefabricated blankets or netting that are formed from both natural and synthetic materials. Temporary RECPs are used as a temporary surface stabilizing measure and to aid in the establishment of vegetation. They are typically used on steep slopes and to help establish grass in low velocity vegetated channels.

Temporary RECPs consist of netting or blanket materials that are used to stabilize disturbed surfaces and promote the establishment of vegetation. RECPs may also be used to stabilize the surface of channels where the flows are low to moderate until vegetation can be established.

They are manufactured from a wide variety of different materials including coconut fiber (coir), jute, nylon, polypropylene, PVC, straw, hay, or wood excelsior. These materials may be used individually, or in combination to form nets or blankets.

The products function by protecting the ground surface from the impact of raindrops and stabilize the surface until vegetation can be established. RECPs also promote the growth of vegetation by helping to keep seed in place, and by maintaining a consistent temperature and moisture content in the soil.

RECPs are not intended to provide long-term or permanent stabilization of slopes or channels. Their role is to protect the surface until the vegetation can establish itself and become the permanent stabilizing feature. In fact, most RECPs are either biodegradable or photodegradable and will decompose over a period of time.

Jute matting must be used in conjunction with mulch. Excelsior, woven straw blankets and coir (coconut fiber) blankets may be installed without mulch. There are many other types of erosion control nets and blankets on the market that may be appropriate in certain circumstances.

In general, most nets (e.g., jute matting) require mulch in order to prevent erosion because they have a fairly open structure. Blankets typically do not require mulch because they usually provide complete protection of the surface.

The temporary rolled erosion control product shall conform to one of the following specifications and corresponding properties found in Table 3.13.1

Permanent Rolled Erosion Control Products

Permanent RECPs or Turf Reinforcement Mats (TRMs) are similar to the Temporary RECPs but they usually are intended for reinforcing grass-lined channels and stream banks and can be useful when underlying soil boundaries may subside or shift slightly after installation They are composed of ultraviolet (UV) stabilized polymeric fibers, filaments, nettings and/or wire mesh, integrating together to form a three-dimensional matrix. The types of polymer include polypropylene, polyethylene, polyamides, and polyvinyl chloride. Often TRMs are combined with organic material such as coir to aide vegetation establishment and provide the initial temporary erosion control necessary to resist the forces of running water until the vegetation can become established. Typical vegetation includes grasses that can withstand inundation.

TRMs can be installed after applying seed to the prepared soil surface or deployed first, and then seeded following infilling with soil. The former method allows the roots and shoots to grow through and interlock with the geosynthetic matrix.

For applications where natural vegetation alone will not sustain expected flow conditions and/or provide sufficient long-term erosion protection a permanent rolled erosion control product will be required The permanent RECP must have the necessary performance properties to effectively control erosion and reinforce vegetation under the expected long-term site conditions.

The permanent erosion control product shall conform to one of the specifications and corresponding properties found in Table 3.13.2.

Rolled erosion control products are designated as follows:

1. Mulch control netting. (MCN) A planar woven natural fiber or extruded geosynthetic mesh used as a temporary degradable rolled erosion control product to anchor loose fiber mulches.
2. Open weave textile. (OWT) A temporary degradable rolled erosion control product composed of processed natural or polymer yarns woven into a matrix, used to provide erosion control and facilitate vegetation establishment. Can replace straw or hay mulch.
3. Erosion control blanket. (ECP) A temporary degradable rolled erosion control product composed of processed natural or polymer fibers mechanically, structurally or chemically bound together to form a continuous matrix to provide erosion control and facilitate vegetation establishment. Can replace straw or hay mulch.
4. Turf reinforcement mat. (TRM) A rolled erosion control product composed of non-degradable synthetic fibers, filaments, nets, wire mesh and/or other elements, processed into a permanent, three-dimensional matrix of sufficient thickness. TRMs, which may be supplemented with degradable components, are designed to impart immediate erosion protection, enhance vegetation establishment and provide long-term functionality by permanently reinforcing vegetation during and after maturation. Note: TRMs are typically used in hydraulic applications, such as high flow ditches and channels, steep slopes, stream banks, and shorelines, where erosive forces may exceed the limits of natural, un-reinforced vegetation or in areas where limited vegetation establishment is anticipated.

Design Considerations for degradable RECPs

Given the wide variety of RECPs available, it is impossible to cover the design considerations for each type of product herein. Therefore, it is recommended that the designer contact a manufacturer to obtain the appropriate information. Many manufacturers provide design software and/or a RECP product selection guide through their company website. Also, the Erosion Control Technology Council (ECTC) is an organization representing suppliers and manufacturers of rolled erosion control products. (www.ectc.org) The construction specifications that follow are from that organization.

Tables 1 and 2 provide guidance on the selection of appropriate RECPs for various situations.

For channel applications, the final permanent grass lining planned for the channel should be analyzed for the 10-year storm in the permanent vegetated state. The RECP should also be analyzed for shear stress. This analysis should be for the unvegetated state, representing the situation immediately after installation. Since it is considered a temporary measure, stabilizing the channel only until vegetation is established, the RECP does not need to be analyzed for a 10-year event as the vegetation does. Analyses of the RECP's shear strength for a 2-year event is adequate.

Design Considerations for TRMs

There is also a wide variety of TRMs available so it is impossible to cover the specific design considerations of each product. However, most TRM products are designed, tested, and rated for resistance to shear stress. As with all permanent channels use the peak flows from a 10-year/24-hour storm event.

Shear stress in channels lined with TRMs is calculated in the same manner as for grass channels. If the channel is to be vegetated, a variable Manning coefficient will need to be calculated. If the channel is being analyzed for performance with the TRM alone, a constant Manning coefficient, provided by the manufacturer, may be used..

After calculating the shear stress in the channel, an appropriate TRM able to withstand the anticipated shear stress can be selected. Most TRM manufacturers have software available to aid in the calculation of shear stress and the selection of an appropriate TRM. This software may be available through the manufacturer's website or local product representative.

TRMs should always be installed in accordance with the manufacturer's recommendations.

Construction Specifications

This specification is intended to provide general guidelines for the installation of RECPs and does not supersede manufacture's guidelines. The following sections summarize the general, accepted procedures for installation of RECPs and provide basic guidance for slope and channel installations. Detailed design/installation information should be obtained from the manufacturer.

General Procedure. Prepare a stable and firm soil surface free of rocks and other obstructions. Apply soil amendments as necessary to prepare seedbed. Apply seed and fertilizer in accordance with the Permanent Seeding Specification. Typically, RECPs are unrolled parallel to the primary direction of flow. Ensure the product maintains intimate contact with the soil surface over the entirety of the installation. Do not stretch or allow material to bridge over surface inconsistencies. Staple/stake RECPs to soil such that each staple/stake is flush with underlying soil. Install anchor trenches, seams and terminal ends as specified.

Install RECPs after application of seed, fertilizer, mulches (if necessary) and other necessary soil amendments, unless soil in-filling of the TRM is required. For TRMs if soil in-filling, install TRM, apply seed, and other soil amendments lightly brush or rake 0.3 to 0.7 in. of topsoil into TRM matrix to fill the product thickness. If in-filling with a hydraulically-applied matrix or medium is required; install TRM, then install hydraulically-applied matrix or medium at the manufacturer's suggested application rate.

Apply MCNs (Materials Type 1.A., 2.A., 3.A.) immediately after dry mulch application.

Anchor Trenches, Seams and Terminal Ends

(A) **Anchor Trenches** – Utilize one of the methods detailed below for initial anchoring of RECPs:

1. Staples. Install the RECPs 3 ft. beyond the shoulder of the slope onto flat final grade. Secure roll end with a single row of stakes/staples on 1 ft. centers.
2. Anchor trench. Excavate a 6 in. by 6 in. (150 mm by 150 mm) anchor trench. Extend the upslope terminal end of the RECPs 3 ft. past the anchor trench. Use stakes or staples to fasten the product into the bottom of the anchor trench on 1 ft. centers. Backfill the trench and compact the soil into the anchor trench. Apply seed and any necessary soil amendments to the compacted soil and cover with remaining 1 ft. terminal end of the RECPs. Secure terminal end of RECPs with a single row of stakes or staples on 1 ft. centers.
3. Check slot. Construct a stake/staple check slot along the top edge of the RECPs by installing two rows of staggered stakes/staples 4 in. apart on 4 in. centers.

(B) **Seams** – Utilize one of the methods detailed below for seaming of RECPs:

1. Adjacent seams. Overlap edges of adjacent RECPs by 6 in. or by abutting products as defined by manufacturer. Use a sufficient number of stakes or staples to prevent seam or abutted rolls from separating.
2. Consecutive rolls. Shingle and overlap consecutive rolls 6 in. in the direction of flow. IE Cover the downslope roll with the next upslope roll.
3. Check seam. Construct a stake/staple check seam along the top edge of RECPs for slope application and at specified intervals in a channel by installing two staggered rows of stakes/staples 4 in. apart on 4 in. centers.

(C) **Terminal Ends** – Utilize one of the methods detailed below for all terminal ends of RECPs:

1. Staples. Install the RECPs 3 ft. beyond the end of the channel and secure end with a single row of stakes/staples on 1 ft. centers. Stakes/staples for securing

RECPS to the soil are typically 6 in. long. Use longer staples in sandy soils.

2. Anchor trench. Excavate a 6 in. by 6 in. anchor trench. Extend the terminal end of the RECPs 3 ft. past the anchor trench. Use stakes or staples to fasten the product into the bottom of the anchor trench on 1 ft. centers. Backfill the trench and compact the soil into the anchor trench. Apply seed and any necessary soil amendments to the compacted soil and cover with remaining 1 ft. terminal end of the RECPs. Secure terminal end of RECPs with a single row of stakes or staples on 1 ft. centers.

3. Check slot. Construct a stake/staple check slot along the terminal end of the RECPs by installing two rows of staggered stakes/staples 4 in. apart on 4 in. centers.

Slope Installations. At the top of slope, anchor the RECPs according to one of the method detailed in Section (A) above. Securely fasten all RECPs to the soil by installing stakes/staples at a minimum rate of 1.5/yd2. For the most effective RECP installation use stake/staple patterns and densities as recommended by the manufacturer. For adjacent and consecutive rolls of RECPs follow seaming instructions detailed in Section (B) above. The terminal end of the RECPs installation must be anchored using one of the methods detailed in Section (C) above.

Channel Installations. Construct an anchor trench at the beginning of the channel across its entire width according to Section (A) (2) above. Follow the manufacturer's installation guidelines in constructing additional anchor trenches or stake/staple check slots at intervals along the channel reach and at the terminal end of the channel, according to paragraph (A) above respectively. Unroll RECPs down the center of the channel in the primary water flow direction. Securely fasten all RECPs to the soil by installing stakes/staples at a minimum rate of 2/yd2. Significantly higher anchor rates and longer stakes/staples may be necessary in sandy, loose, or wet soils and in severe applications. For adjacent and consecutive rolls of RECPs follow seaming instructions detailed in Section (B) above. All terminal ends of the RECPs must be anchored using one of the methods detailed in Section (C) above.

With any RECP installation, ensure sufficient staples to resist uplift from hydraulics, wind, mowers, and foot traffic. For the most effective installation of RECPs, it is recommended to use stake/staple patterns and densities as recommended by the manufacturer.

Maintenance

During the initial period after installation inspect once at week or after every rain of 0.5" or more. Basic monitoring should consist of visual inspections to determine mat integrity and attachment performance. Rill development beneath the mat or edge lifting is evidence of inadequate attachment.

Until the vegetation is fully established, the ground surface should be inspected for signs of rill or gully erosion below the matting. Any signs of erosion, tearing of the matting, or areas where the matting is no longer anchored firmly to the ground should be repaired. Repair any damaged areas immediately by restoring soil to finished grade, re-applying soil amendments and seed, and replacing the RECPs. Additional staking and trenching can be employed to correct defects. Recently placed mats may be replaced, but once vegetation becomes established, replacement is not a reasonable option unless large failures have occurred. If the RECPs are vegetated, the vegetation should be watered as needed. Getting grass established as quickly as possible is very important.

Table 3.13.1 ECTC STANDARD SPECIFICATION FOR TEMPORARY ROLLED EROSION CONTROL PRODUCTS

For use where natural vegetation alone will provide permanent erosion protection.

ULTRA SHORT-TERM - Typical 3 month functional longevity.

Type	Product Description	*Material Composition*	Slope Applications* Maximum Gradient	Slope Applications* C Factor[2, 5]	Channel Applications* Max. Shear Stress[3, 4, 6]	Minimum Tensile Strength[1]
1.A	Mulch Control Nets	A photodegradable synthetic mesh or woven biodegradable natural fiber netting.	5:1 (H:V)	≤ 0.10 @ 5:1	0.25 lbs/ft² (12 Pa)	5 lbs/ft (0.073 kN/m)
1.B	Netless Rolled Erosion Control Blankets	Natural and/or polymer fibers mechanically interlocked and/or chemically adhered together to form a RECP.	4:1 (H:V)	≤ 0.10 @ 4:1	0.5 lbs/ft² (24 Pa)	5 lbs/ft (0.073 kN/m)
1.C	Single-net Erosion Control Blankets & Open Weave Textiles	Processed degradable natural and/or polymer fibers mechanically bound together by a single rapidly degrading, synthetic or natural fiber netting or an open weave textile of processed rapidly degrading natural or polymer yarns or twines woven into a continuous matrix.	3:1 (H:V)	≤ 0.15 @ 3:1	1.5 lbs/ft² (72 Pa)	50 lbs/ft (0.73 kN/m)
1.D	Double-net Erosion Control Blankets	Processed degradable natural and/or polymer fibers mechanically bound together between two rapidly degrading, synthetic or natural fiber nettings.	2:1 (H:V)	≤ 0.20 @ 2:1	1.75 lbs/ft² (84 Pa)	75 lbs/ft (1.09 kN/m)

SHORT-TERM - Typical 12 month functional longevity.

Type	Product Description	Material Composition	Slope Applications* Maximum Gradient	Slope Applications* C Factor[2, 5]	Channel Applications* Max. Shear Stress[3, 4, 6]	Minimum Tensile Strength[1]
2.A	Mulch Control Nets	A photodegradable synthetic mesh or woven biodegradable natural fiber netting.	5:1 (H:V)	≤ 0.10 @ 5:1	0.25 lbs/ft² (12 Pa)	5 lbs/ft (0.073 kN/m)
2.B	Netless Rolled Erosion Control Blankets	Natural and/or polymer fibers mechanically interlocked and/or chemically adhered together to form a RECP.	4:1 (H:V)	≤ 0.10 @ 4:1	0.5 lbs/ft² (24 Pa)	5 lbs/ft (0.073 kN/m)
2.C	Single-net Erosion Control Blankets & Open Weave Textiles	An erosion control blanket composed of processed degradable natural or polymer fibers mechanically bound together by a single degradable synthetic or natural fiber netting to form a continuous matrix or an open weave textile composed of processed degradable natural or polymer yarns or twines woven into a continuous matrix.	3:1 (H:V)	≤ 0.15 @ 3:1	1.5 lbs/ft² (72 Pa)	50 lbs/ft (0.73 kN/m)
2.D	Double-net Erosion Control Blankets	Processed degradable natural and/or polymer fibers mechanically bound together between two degradable, synthetic or natural fiber nettings.	2:1 (H:V)	≤ 0.20 @ 2:1	1.75 lbs/ft² (84 Pa)	75 lbs/ft (1.09 kN/m)

EXTENDED-TERM - Typical 24 month functional longevity.

Type	Product Description	Material Composition	Slope Applications* Maximum Gradient	Slope Applications* C Factor[2, 5]	Channel Applications* Max. Shear Stress[3, 4, 6]	Minimum Tensile Strength[1]
3.A	Mulch Control Nets	A slow degrading synthetic mesh or woven natural fiber netting.	5:1 (H:V)	≤ 0.10 @ 5:1	0.25 lbs/ft² (12 Pa)	25 lbs/ft (0.36 kN/m)
3.B	Erosion Control Blankets & Open Weave Textiles	An erosion control blanket composed of processed slow degrading natural or polymer fibers mechanically bound together between two slow degrading synthetic or natural fiber nettings to form a continuous matrix or an open weave textile composed of processed slow degrading natural or polymer yarns or twines woven into a continuous matrix.	1.5:1 (H:V)	≤ 0.25 @ 1.5:1	2.00 lbs/ft² (96 Pa)	100 lbs/ft (1.45 kN/m)

LONG-TERM - Typical 36 month functional longevity.

Type	Product Description	Material Composition	Slope Applications* Maximum Gradient	Slope Applications* C Factor[2, 5]	Channel Applications* Max. Shear Stress[3, 4, 6]	Minimum Tensile Strength[1]
4	Erosion Control Blankets & Open Weave Textiles	An erosion control blanket composed of processed slow degrading natural or polymer fibers mechanically bound together between two slow degrading synthetic or natural fiber nettings to form a continuous matrix or an open weave textile composed of processed slow degrading natural or polymer yarns or twines woven into a continuous matrix.	1:1 (H:V)	≤ 0.25 @ 1:1	2.25 lbs/ft² (108 Pa)	125 lbs/ft (1.82 kN/m)

** "C" factor and shear stress for Types 1.A., 2.A. and 3.A mulch control nettings must be obtained with netting used in conjunction with pre-applied mulch material.*

[1] Minimum Average Roll Values, Machine direction using ECTC Mod. ASTM D 5035.

[2] "C" Factor calculated as ratio of soil loss from RECP protected slope (tested at specified or greater gradient, h:v) to ratio of soil loss from unprotected (control) plot in large-scale testing.These performance test values should be supported by periodic bench scale testing under similar test conditions using Erosion Control Technology Council (ECTC) Test Method # 2.

[3] Required minimum shear stress RECP (unvegetated) can sustain without physical damage or excess erosion (> 12.7 mm (0.5 in) soil loss) during a 30-minute flow event in large-scale testing. These performance test values should be supported by periodic bench scale testing under similar test conditions and failure criteria using Erosion Control Technology Council (ECTC) Test Method #3.

[4] The permissible shear stress levels established for each performance category are based on historical experience with products characterized by Manning's roughness coeffecients in the range of 0.01 - 0.05.

[5] Acceptable large-scale test methods may include ASTM D6459, Erosion Control Technology Council (ECTC) Test Method # 2, or other independent testing deemed acceptable by the engineer.

[6] Per the engineers discretion. Recommended acceptable large-scale testing protocol may include ASTM D6460, Erosion Control Technology Council (ECTC) Test Method #3 or other independent testing deemed acceptable by the engineer.

Table 3.13.2 ECTC STANDARD SPECIFICATION FOR PERMANENT ROLLED EROSION CONTROL PRODUCTS

For applications where vegetation alone will not sustain expected flow conditions and/or provide sufficient long-term erosion protection.

Permanent[1] - All categories of TRMs must have a minimum thickness of 0.25 inches (6.35 mm) per ASTM D 6525 and U.V. stability of 80% per ASTM D 4355 (500 hours exposure).

Type	Product Description	Material Composition	Slope Applications Maximum Gradient	Channel Applications Maximum Shear Stress[4, 5]	Minimum Tensile Strength[2,3]
5.A	Turf Reinforcement Mat	Turf Reinforcement Mat (TRM) – A rolled erosion control product composed of non-degradable synthetic fibers, filaments, nets, wire mesh and/or other elements, processed into a permanent, three-dimensional matrix of sufficient thickness. TRMs, which may be supplemented with degradable components, are designed to impart immediate erosion protection, enhance vegetation establishment and provide long-term functionality by permanently reinforcing vegetation during and after maturation. Note: TRMs are typically used in hydraulic applications, such as high flow ditches and channels, steep slopes, stream banks, and shorelines, where erosive forces may exceed the limits of natural, unreinforced vegetation or in areas where limited vegetation establishment is anticipated.	0.5:1 (H:V)	6.0 lbs/ft^2 (288 Pa)	125 lbs/ft (1.82 kN/m)
5.B	Turf Reinforcement Mat		0.5:1 (H:V)	8.0 lbs/ft^2 (384 Pa)	150 lbs/ft (2.19 kN/m)
5.C	Turf Reinforcement Mat		0.5:1 (H:V)	10.0 lbs/ft^2 (480 Pa)	175 lbs/ft (2.55 kN/m)

[1] For TRMs containing degradable components, all property values must be obtained on the non-degradable portion of the matting alone.

[2] Minimum Average Roll Values, machine direction only for tensile strength determination using ASTM D6818 (Supercedes Mod. ASTM D5035 for RECPs)

[3]Field conditions with high loading and/or high survivability requirements may warrant the use of a TRM with a tensile strength of 44 kN/m (3,000 lb/ft) or greater.

[4] Required minimum shear stress TRM (fully vegetated) can sustain without physical damage or excess erosion (> 12.7 mm (0.5 in.) soil loss) during a 30-minute flow event in large scale testing. These performance test values should be supported by periodic bench scale testing under similar test conditions and failure criteria using Erosion Control Technology Council (ECTC) Test Method #3.

[5] Acceptable large-scale testing protocol may include ASTM D6460, Erosion Control Technology Council (ECTC) Test Method #3, or other independent testing deemed acceptable by the engineer

Table 3.13.3 PERMISSIBLE VELOCITIES FOR EARTH LININGS

Soil Types	Permissible Velocities (ft./sec.)
Fine Sand (noncolloidal)	2.5
Sandy Loam (noncolloidal)	2.5
Silt Loam (noncolloidal)	3.0
Ordinary Firm Loam	3.5
Fine Gravel	5.0
Stiff Clay (very colloidal)	5.0
Graded, Loam to Cobbles (noncolloidal)	5.0
Graded, Silt to Cobbles (colloidal)	5.5
Alluvial Silts (noncolloidal)	5.5
Alluvial Silts (colloidal)	5.0
Coarse Gravel (noncolloidal)	6.0
Cobbles and Shingles	5.5
Shales and Hard Plans	6.0

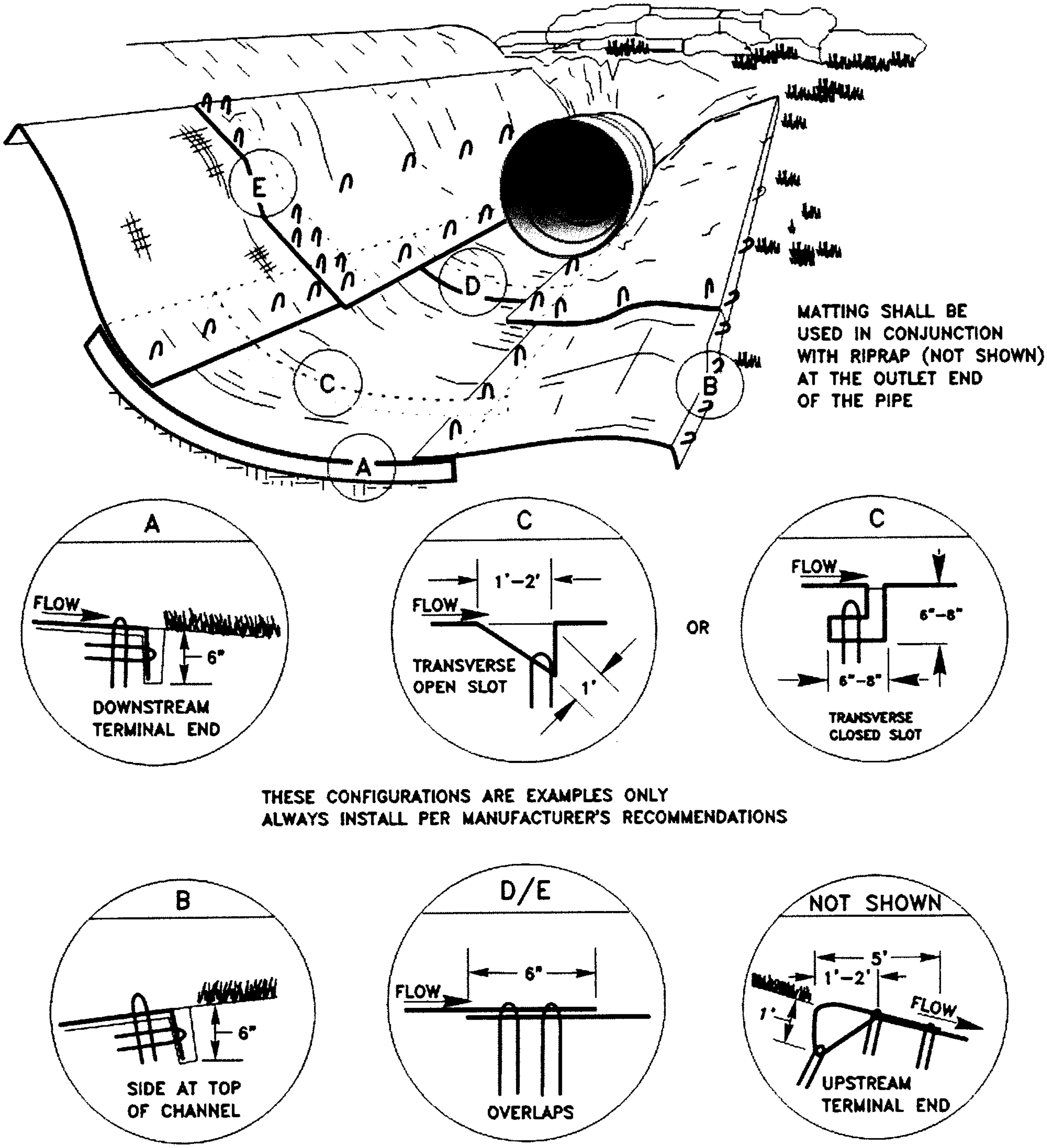
Table 3.13.4 PERMISSIBLE VELOCITIES FOR GRASS-LINED CHANNELS

Channel Slope	Lining	Velocity* (ft./sec.)
0 - 0.5%	Bermudagrass	6
	Reed canarygrass Tall fescue Kentucky bluegrass	5
	Grass-legume mixture	4
	Red fescue Redtop Sericea lespedeza Annual lespedeza Small grains Temporary vegetation	2.5
5 - 10%	Bermudagrass	5
	Reed canarygrass Tall fescue Kentucky bluegrass	4
	Grass-legume mixture	3
Greater than 10%	Bermudagrass	4
	Reed canarygrass Tall fescue Kentucky bluegrass	3

* For highly erodible soils, decrease permissible velocities by 25%.

FIGURE 3.13.1

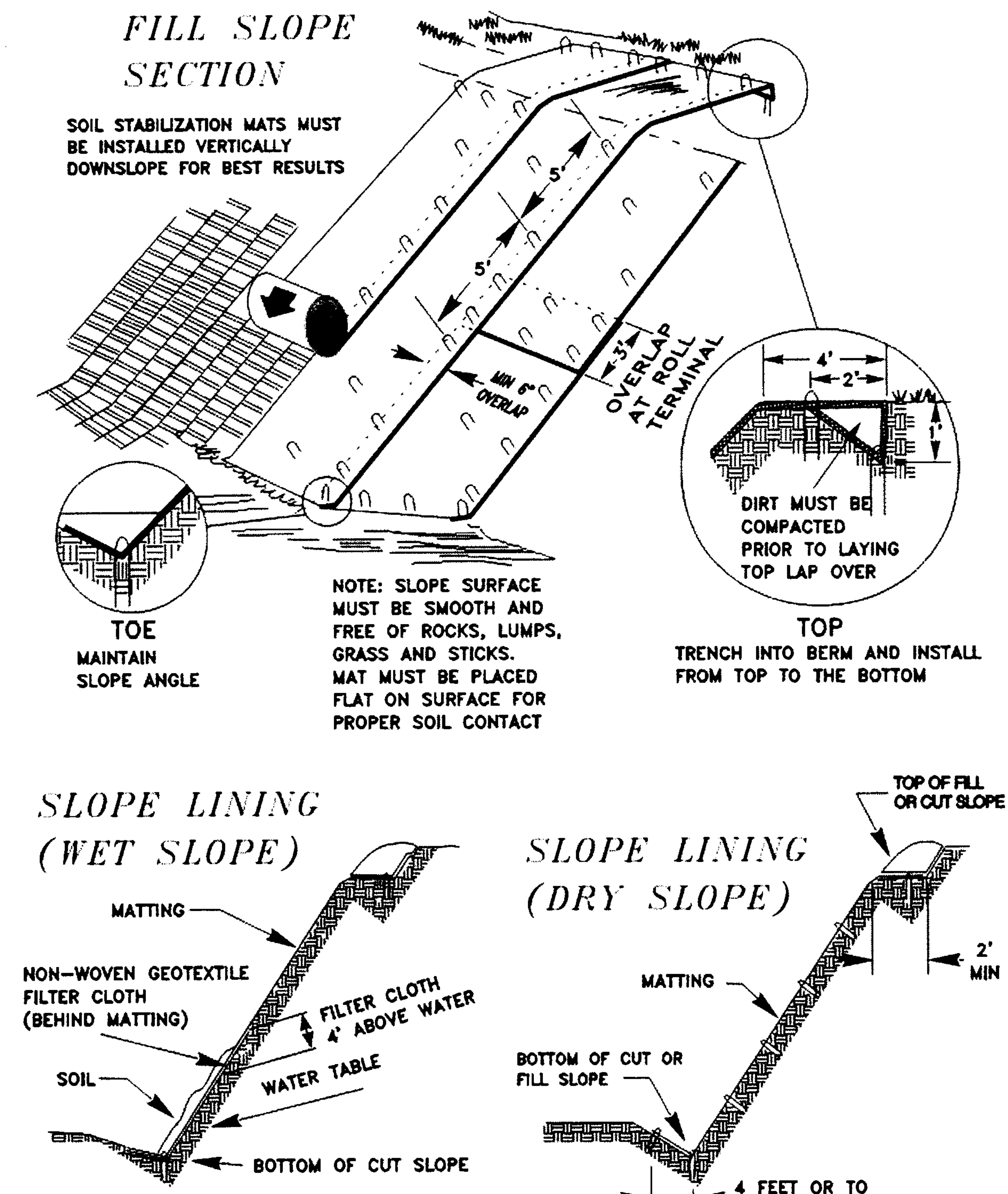
TYPICAL RECP CHANNEL INSTALLATION



SOURCE: VIRGINIA DCR–DSWC AND NORTH AMERICAN GREEN

FIGURE 3.13.2

ROLLED EROSION CONTROL PRODUCTS



SOURCE: VDOT STANDARDS AND VIRGINIA DCR-DSWC

3.14 - SODDING

Introduction

The purpose of sodding is to establish permanent turf for immediate erosion protection and to stabilize drainage ways where concentrated overland flow will occur.

Conditions Where Practice Applies

Sodding may be used in the following areas:

1. Disturbed areas that require short-term or long-term cover
2. Disturbed areas that require immediate vegetative cover
3. All waterways that require vegetative lining. Waterways may also be seeded rather than sodded and protected with a RECP.

Design Consideration

Sod shall be free of weeds, of uniform thickness (approximately 1-inch thick), and shall have a dense root mat for mechanical strength.

Construction Specifications

The following steps are recommended for sod installation:

1. Shape and smooth the surface to final grade in accordance with the approved grading plan.
2. Amend two inches (minimum) of well-rotted compost into the top six inches of the soil if the organic content of the soil is less than 10 percent.
3. Fertilize according to the supplier's recommendations. Disturbed areas within 200 feet of waterbodies and wetlands must use non-phosphorus fertilizer.
4. Work lime and fertilizer one to two inches into the soil, and smooth the surface.
5. Lay strips of sod beginning at the lowest area to be sodded and perpendicular to the direction of water flow. Wedge strips securely into place. Square the ends of each strip to provide for a close, tight fit.
6. Stagger joints at least 12 inches. Staple on slopes steeper than 3:1. Roll the sodded area and irrigate.
7. When sodding is carried out in alternating strips or other patterns, seed the areas between the sod immediately after sodding.

Maintenance

If the grass is unhealthy, the cause shall be determined and appropriate action taken to reestablish a healthy groundcover. If it is impossible to establish a healthy groundcover due to frequent saturation, instability or some other cause, the sod shall be removed, the area seeded with an appropriate mix, and protected with a net or blanket.

3.15 - TEMPORARY DIVERSION

Introduction

A temporary berm or excavated channel or combination berm and channel constructed across sloping land on a predetermined grade. This variable practice is used to protect work areas from upslope runoff and reduce the size of the drainage are going to sediment trapping structures, transport runoff across a project to minimize erosion and to divert sediment-laden water to an appropriate sediment trapping facility.

Conditions Where Practice Applies

This practice applies to construction areas where runoff can be diverted and disposed of properly to control erosion, sedimentation, or flood damage. Specific locations and conditions can include the following:

1. To divert upslope clean water around a construction site to reduce the quantity of water within the sediment control system. Also called a clean water ditch or upslope diversion.
2 To shorten or reduce the length of the slope that runoff will cross. (see also RIGHT OF WAY DIVERSION and the WATER CONTROL sections)
3. To divert upslope water from disturbed areas such as cut or fill slopes to a stabilized outlet or if sediment laden, to a sediment trapping device. Similar in concept to upslope diversion.
5. To divert sediment laden water at or near the perimeter of the construction area to either a sediment basin or a sediment trap. Also called a dirty water ditch or perimeter ditch.
6. To divert internal sediment laden water to a sediment-trapping structure or a stabile internal waterway.
7. Above critical disturbed areas before stabilization to prevent erosion and maintain acceptable working conditions
8. To divert water away from footers, walls, and other structures.

Design Considerations

It is important that diversions are properly designed, constructed and maintained since they concentrate water flow and increase erosion potential. Temporary diversions must be designed and installed so they stable throughout their useful life and to meet the criteria given in this section. Particular care must be taken in planning diversion grades. Too much slope can result in erosion in the diversion channel. This is especially true at the entrance to a sediment trapping structure. Conversely, a reduction in grade will cause sediment to be deposited, plugging the channel. The blockage may cause failure by overtopping and the discharge of sediment-laden runoff off site.

Frequent inspection and timely maintenance are essential to the proper functioning of diversions. Sufficient area should be available to construct and properly maintain diversions.

It is usually less costly to excavate a channel and form a ridge or dike on the downhill side with the spoil than to build diversions by other methods. Where space is limited, it may be necessary to build the ridge by hauling in the berm material. If the diversion is located where construction traffic will cross, stabilize the channel and berm with stone. If there will be extensive traffic it will be necessary to install a temporary culvert.

Whenever possible, install dirty water diversions in conjunction with the construction of the sediment trapping structure prior clearing and grubbing. Install other types diversions as needed.

Because diversions collect overland flow, changing it into concentrated flows, they can create an additional erosion hazard. In areas of highly erodible soils it may be necessary to armor the channel with riprap. This will be necessary especially in the transition into a sediment trap or basin and on slopes over 10 percent.

For longer slopes, several dikes or swales are placed across the slope at intervals. This practice reduces the amount of runoff that accumulates on the face of the slope and carries the runoff safely down the slope.

Diversion may create difficulties in establishing vegetation if water flow is too fast or ponds.

Poorly laid out and constructed diversion require unnecessary additional maintenance, inspections, and repairs.

Interceptor dikes and swales can be permanent controls. However, permanent controls: must be designed to handle runoff after construction is complete, must be permanently stabilized, and should be inspected and maintained on a regular basis.

If the watershed drained by the diversion is unstabilized at any time, the diversion must lead to a sediment-trapping device.

General design criteria:

1. Drainage area should not exceed five acres.
2. The minimum cross section should be adequate for the anticipated flows but at a minimum must handle the peak discharge from a 2-year/24-hour storm.
3. The grade may be variable depending upon the topography and must have a positive grade along its entire length. The maximum channel grade should be limited to 5.0 percent.

5 Diverted runoff must outlet onto a stabilized area, into a properly designed waterway, grade stabilization structure or sediment trapping facility.

6. Diversions that are to serve longer than 14 working days shall be stabilized immediately with seed and mulch with or without a

RECP meeting the requirements found in this manual to preserve dike height, prevent erosion and reduce maintenance.

7. The channel cross section may be parabolic, v-shaped or trapezoidal.

Specific Design Criteria

1. Temporary (less than 6 months) diversions must be designed to handle the peak discharge from a 2-year/24-hour storm with 0.3 ft. of freeboard.
2. A long term (more than 6 months) or permanent diversion must have a minimum capacity to carry the runoff expected from a 10-year/24-hour frequency storm with a freeboard of at least 0.3 foot (see drawing)
3. Diversions designed to protect homes, schools, industrial buildings, roads, parking lots, and comparable high-risk areas, and those designed to function in connection with other structures, shall have sufficient capacity to carry peak runoff expected from a storm frequency consistent with the hazard involved.

Channel The diversion channel may be parabolic, trapezoidal or vee-shaped.

Berm/dike Design The supporting ridge cross section shall meet the following criteria (also see drawings):

1. The side slopes shall be no steeper than 2:1.
2. The width at the design water elevation should be a minimum of 4 feet.
3. The minimum freeboard shall be 0.3 foot.
4. The design of the berm/dike shall include a 10 percent settlement factor.

Outlet: Diversions shall have stabilized outlets that release the concentrated runoff without causing erosion. Acceptable outlets for sediment free runoff include a permanently stabilized stormwater conveyance channel, Level Lip Spreader, drop inlet structure, underground stormwater system, Outlet Protection or natural waterway.

All except the most short-lived diversions, all diversions must be stabilized according to the anticipated velocity and erodibilty of the soil and the ablity of the lining to protect the channel from eroding. Stabilization measures include, grass, grass with a RECP, RECP alone if designed for this purpose, and riprap. The following charts give basic minimum design for the dimensions and the maximum permissible velocities for various linings and soil types. See the section on RECPs for additional information on how to select the appropriate material and the correct installation techniques. If conditions exceed the requirements noted above and in the charts, the channel and lining must be professionally designed.

Table 3.15.1 CHANNEL CROSS SECTION REQUIREMENTS		
	A	**B**
Drainage area	< 5 acres	5 – 10 acres
Bottom width flow channel	4 feet	6 feet
Depth of flow channel	1 foot	1 foot
Side slopes	2:1 or flatter	2:1 or flatter
Grade	0.5% minimum	0.5% minimum

Table 3.15.2 CHANNEL STABILIZATION REQUIREMENTS		
Channel Grade (%)	**A < 5 acres**	**B 5 – 10 acres**
0.5 – 3.0	Seed & straw mulch	Seed & straw mulch
3.1 – 5.0	Seed & straw mulch	Seed & cover /RECP; sod; or line with riprap
5.1 – 8.0	Seed & cover w/ RECP; sod;or line with riprpa	Line with riprap
8.1 – 20.0	Line with riprap	Engineering design

Table 3.15.3
PERMISSIBLE VELOCITIES FOR GRASS-LINED CHANNELS

Channel Slope	Grass Species	Velocity* (ft./sec.)
0 - 0.5%	Bermudagrass	6
	Reed canarygrass Tall fescue Kentucky bluegrass	5
	Grass-legume mixture	4
	Red fescue Redtop Sericea lespedeza Annual lespedeza Small grains Temporary vegetation	2.5
5 - 10%	Bermudagrass	5
	Reed canarygrass Tall fescue Kentucky bluegrass	4
	Grass-legume mixture	3
Greater than 10%	Bermudagrass	4
	Reed canarygrass Tall fescue Kentucky bluegrass	3

* For highly erodible soils, decrease permissible velocities by 25%.

For vegetated earth channels having permanent turf reinforcement matting, the permissible flow velocity shall not exceed 8 ft/sec. Turf reinforcement matting shall meet the requirements in the Section on RECPs.
An erodibility factor (K) greater than 0.35 would indicate a highly erodible soil. Erodibility factors (K-factors) can be obtained from local NRCS offices.

Table 3.15.4 MAXIMUM PERMISSIBLE DESIGN VELOCITIES		
Soil Texture	**Channel Vegetation Retardance and Cover**	**Permissible Velocities (ft./sec.)**
Sand, silt, sandy loam, silt loam, loamy sand	Tall fescue, smooth bromegrass	3.5
	Kentucky bluegrass, redtop, red fescue	3.0
	Annuals 2/, small grain (rye, oats, wheat, ryegrass)	2.5
	Bare channel	1.5
Silty clay loam, sandy clay loam	Tall fescue, smooth bromegrass	4.5
	Kentucky bluegrass, redtop, red fescue	4.0
	Annuals 2/, small grain (rye, oats, wheat, ryegrass)	3.5
	Bare channel	2.0
Clay	Tall fescue, smooth bromegrass	5.5
	Kentucky bluegrass, redtop, red fescue	5.0
	Annuals 2/, small grain (rye, oats, wheat, ryegrass)	4.0
	Bare channel	2.0

1/ To be used only in stabilized protected areas.
2/ Annuals – use only as temporary protection until permanent vegetation is established.

These charts are guidelines only. If conditions on the site do not reflect the parameters in the chart it is recommended to provide a full design using HEC-15 or other similar standard. During plan development label all diversions. Example: Two diversions will direct sediment laden water to a sediment trap. Label the sediment trap as trap I and each ditch respectively Ia and Ib. If the diversions are engineered then use these labels on any charts and design sheets.

Construction Specifications

1. Clear the area of all trees, brush, stumps or other obstructions.
2. Diversions (upslope and perimeter) must be installed as a first step in the land-disturbing activity and must be functional prior to land disturbance. Diversions may be removed when stabilization of the drainage area and outlet are complete.

3. Runoff from undisturbed areas can be channeled to an existing waterway or to a level lip spreader.
4. Stabilization for the dike and flow channel of the swale should be completed immediately after construction.
5. Stabilization materials can include vegetation, RECP or stone/riprap.
6. When the drainage area to the diversion is greater than 10 acres, standard engineering practices shall be used to properly size the channel.
7. Intercepted sediment laden water must always be diverted to a sediment trap or sediment basin, never silt fence
8. Grades over 10% may require engineering design.
9. Construct the diversions to the designed cross-section, line and grade making sure that there are no irregularities or bank projections to impede the flow.
10. The dike shall be compacted using earth-moving equipment to prevent failure of the dike.
11. Attempt to construct the dike where it will not interfere with major areas of construction traffic so that vehicle damage to the dike will be kept to the minimum. Install culvert crossings anywhere regular construction traffic will cross the channel.
12. The swale must have a positive grade for its entire length. There should be no dips or low points in the swale where storm water will collect and pond.
13. If diversions remain in place longer than 14 days, they are to be properly stabilized.
14. Rock check dams can be installed in the diversion if erosion of the channel appears to be a problem and the channel is deep enough.

Maintenance

The measure shall be inspected after every storm of more than 0.5 inch and repairs made as necessary. At least once week, the measure shall be inspected and repairs made immediately. Inspect the dike, flow channel and outlet for deficiencies or signs of erosion. Reseed or otherwise stabilize the dike as needed to maintain its stability. Inspect for sediment deposits, constrictions and blockages. Remove any blockage immediately.

Damages caused by construction activities or traffic must be repaired immediately

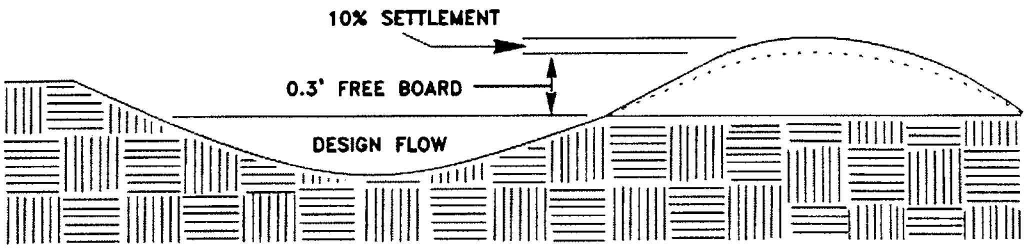
During repairs, properly compacted any material added to the dike.

Vegetated swale channels should be inspected regularly to check for points of scour, bank failure or inadequate vegetative cover; rubbish or channel obstruction; rodent holes or excessive wear from pedestrian or construction traffic. Lined swale channels should be checked regularly for deterioration from freezing, salt or chemicals; scour or undermining at the inlet and outlet; or points of sediment deposition.

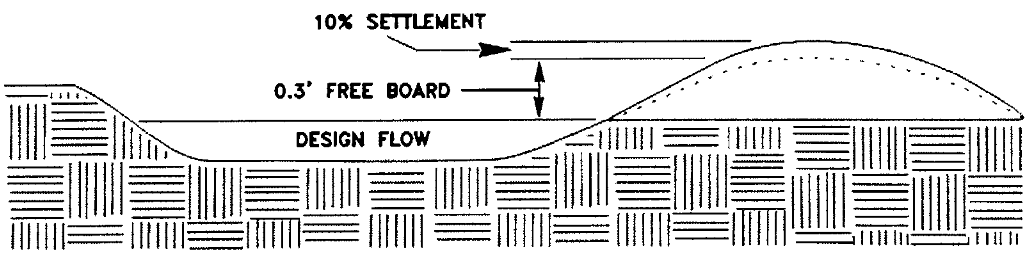
Any needed repairs shall be made promptly.

FIGURE 3.15.1

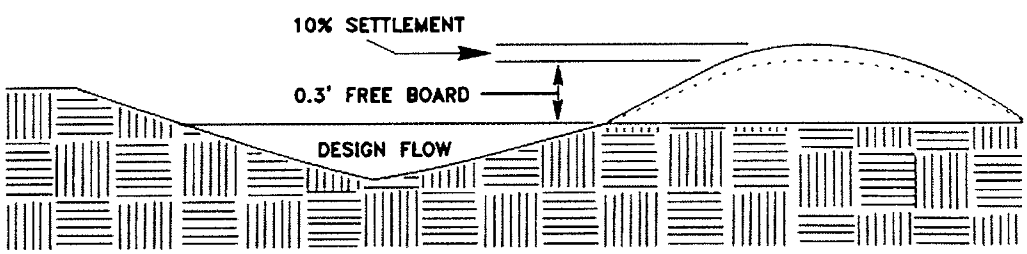
TYPICAL DIVERSIONS



PARABOLIC DIVERSION



TRAPEZOIDAL DIVERSION

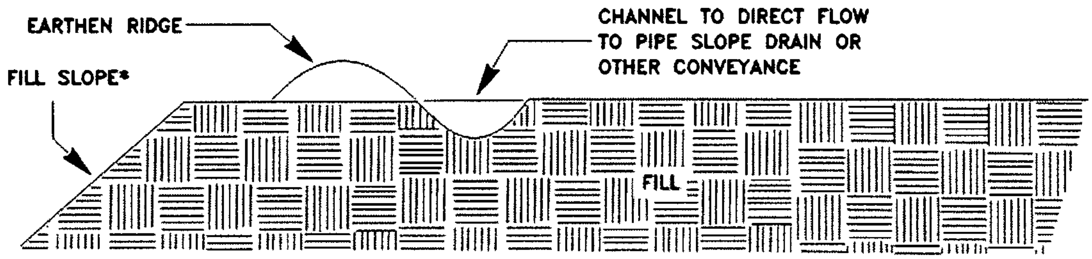


VEE-SHAPED DIVERSION

Source: VIRGINIA DCR-DSWC

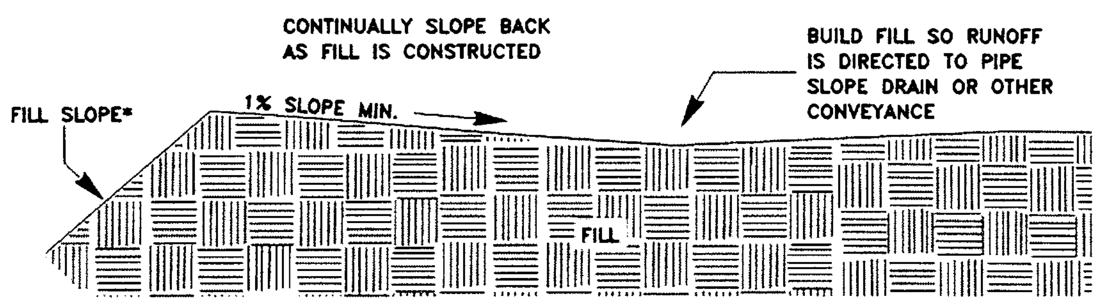
FIGURE 3.15.2

TEMPORARY FILL DIVERSIONS



TEMPORARY BERM

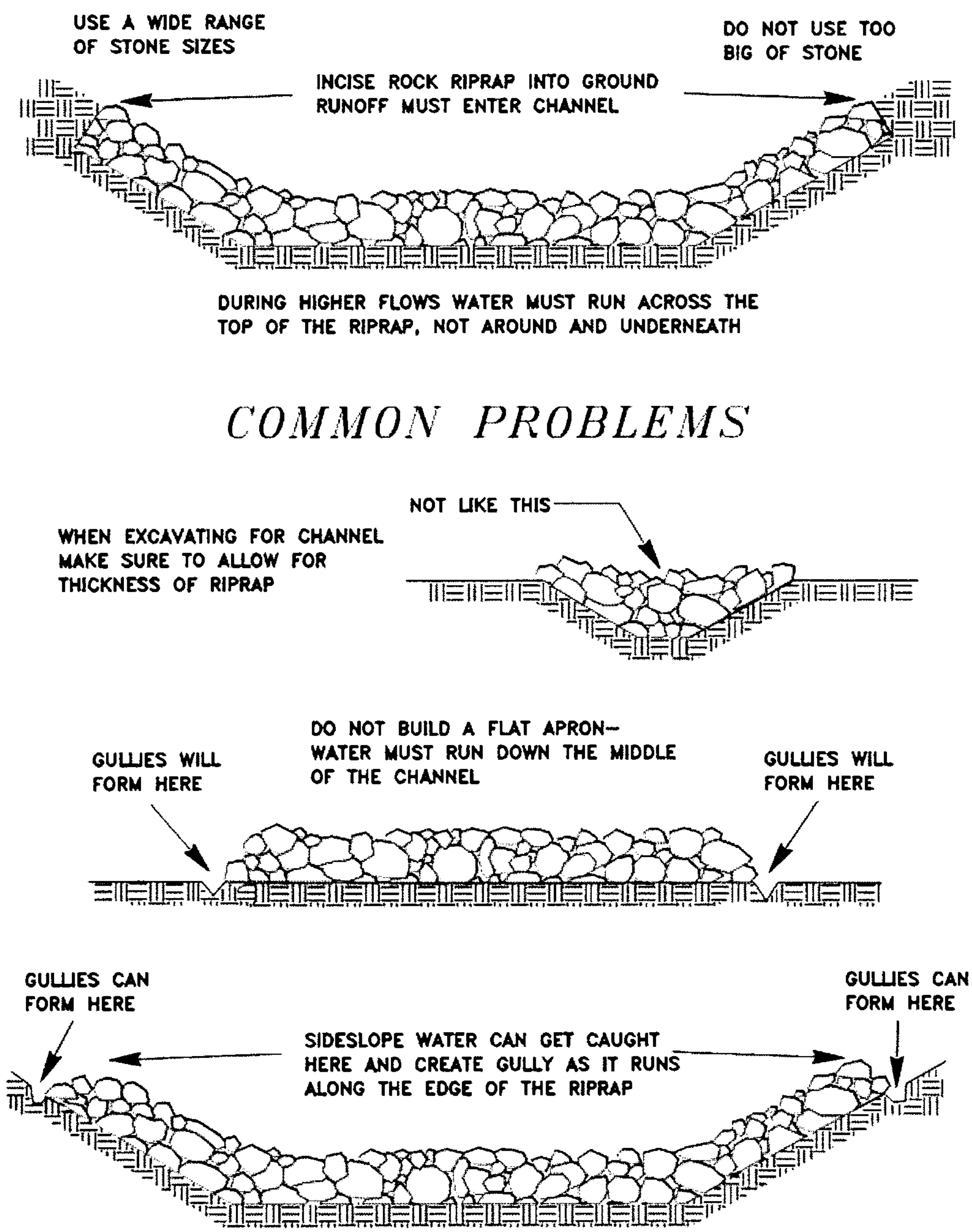
*SEED AND MULCH FILL SLOPE
EVERY 10 FEET OF FILL OR
EVERY 7 DAYS, WHICHEVER
COMES FIRST



GRADING

FIGURE 3.15.3

RIPRAP DIVERSION



3.16 - PIPE SLOPE DRAIN

Introduction

A flexible tubing or conduit extending from the top to the bottom of a cut or fill slope to temporarily conduct concentrated stormwater runoff down the face of the cut or fill in a non-erosive manner.

Conditions Where Practice Applies

There is often a significant lag between the time a cut or fill slope is completed and the time a permanent drainage system can be installed. During this period, the slope is usually not stabilized and is particularly vulnerable to erosion. This situation also occurs on slope construction that is temporarily delayed before final grade is reached. Temporary slope drains can provide valuable protection of exposed slopes until permanent drainage structures can be installed or vegetation can be established.

Table 3.16.1 PIPE SIZES FOR PIPE SLOPE DRAIN

Size Diameter (D)	12	18	21	24
Maximum Drainage in Area (Acres)	0.5	1.5	2.5	5.0

Pipe slope drains are used in conjunction with diversions and berms. The diversion/berm direct surface runoff to the slope drain, which conveys concentrated flow down the face of a slope or across a disturbed area. The drainage to a pipe slope drain should be limited to 5 acres.

Because of the height limitation of the berms or diversions, the maximum pipe diameter will be 24".

Construction Specifications

1. The Pipe Slope Drain shall have a slope of 3 percent or steeper.
2. The top of the dike over the inlet pipe shall be at least 8" above the top of the Pipe.
3. Flexible corrugated plastic tubing is preferred. However, corrugated metal pipe or equivalent PVC pipe can be used. All connections shall be watertight.
4. A flared end section can be attached to the inlet end of pipe with a watertight connection. Filter cloth can be placed under the inlet of the pipe slope drain and shall extend out 5 feet from the inlet. The filter cloth shall be entrenched on all sides.
5. The entrance section shall pitch toward the slope at the minimum rate of 1/2 inch per foot.
6. The Pipe Slope Drain shall be securely anchored to the slope by staking at the grommets provided or with straps made specifically for this

purpose. Spacing for anchors shall be as provided by the manufacturer's specification, but no less than 10 feet. In no case shall less than two (2) anchors be provided equally spaced along the length of pipe.

7. The soil around and under the pipe and end section shall be hand tamped in 4-inch lifts to the top of the earth dike.
8. All pipe connections shall be watertight.
9. Where a Pipe Slope Drain drains an unstabilized area, it shall outlet into a SEDIMENT TRAP OR BASIN. If this is not possible then the pipe slope drain will discharge into a stable conveyance that leads to a sediment trap or basin. When discharging into a trap or basin the Pipe Slope Drain shall discharge at the same elevation as the wet pool elevation. The discharge area must be protected from erosion. The discharge from the Pipe Slope Drain must be located at the most distant point from the sediment control device's outlet as possible.
10. When the drainage area is stabilized or undisturbed, the Pipe Slope Drain shall discharge onto a stabilized area at a non-erosive velocity.
11. The Pipe Slope Drain should be placed on undisturbed soil or well-compacted fill.
12. Do not space more than 250 feet apart.
13. A small sediment trap can be installed at the entrance to the pipe if saturation of the fill will not be a problem.

Maintenance

Inspect and perform any required maintenance once a week and after each 0.5-inch rain event.

The inlet must be kept open at all times. It is very important that these temporary structures be installed properly, since their failure will often result in severe gully erosion on the site and sedimentation below the slope.

The contractor should avoid the placement of any material on and prevent construction traffic across the pipe slope drain.

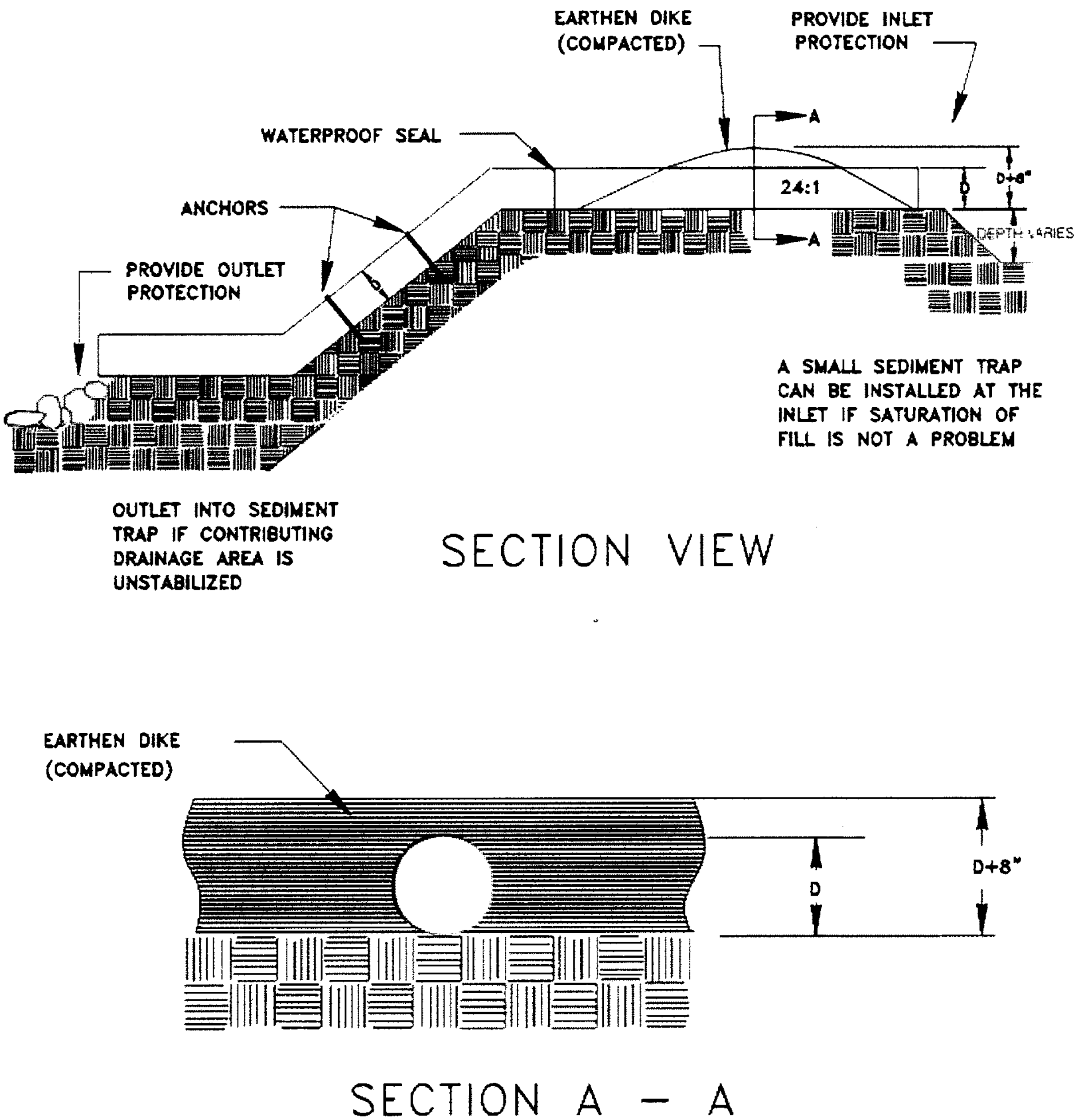
The diversion and berm must be kept clear to keep water flowing to the inlet. Correct any erosion of the berm and remove sediment deposits along the berm.

It cannot be overstated that maintenance is extremely important with this device. Occasionally this device will be left in place over the winter. A written maintenance schedule, using the above requirements, should be established and rigorously followed.

While this structure prevents erosion of the fill slope, failure to properly maintain this structure can cause **catastrophic** erosion over the dike and on the face of the fill slope.

FIGURE 3.16.1

PIPE SLOPE DRAIN



FROM: VA. DSWC

3.17 - OUTLET PROTECTION

Introduction

A section of rock protection placed at the outlet end of the culverts and channels.

Pipe outlets are points of critical erosion potential. Stormwater exiting from a closed conveyance system generally reaches a velocity that exceeds the permissible or erosion resistant velocity of the receiving channel or overland area. To prevent scour at stormwater system outlets, a flow transition structure is needed which will absorb the initial impact of the flow and reduce the flow velocity to a level which will not erode the receiving channel or overland area.

Outlet protection consists of the construction of an erosion resistant section between a conduit outlet and a stable downstream channel. Erosion at an outlet is chiefly a function of soil type and the velocity of the conduit discharge. Therefore, in order to mitigate erosion, an adequate design must stabilize the area at the conduit outlet and reduce the outlet velocity to a velocity consistent with a stable condition in the downstream channel.

The design of riprap outlet protection applies to the immediate area or reach downstream of the pipe outlet and does not apply to continuous rock linings of channels or streams. For pipe outlets at the top of exit slopes or on slopes greater than 10%, the designer should assure that suitable safeguards are provided beyond the limits of the localized outlet protection to counter the highly erosive velocities caused by the re-concentration of flow beyond the initial riprap apron. Every effort should be made to protect the receiving channel from erosion down to a location in a natural waterway that can resist the forces of the water.

This standard applies to the planning, design, and construction of rock riprap and gabions for protection of downstream areas. It does not apply to rock lining of channels or streams. However, the riprap apron can be extended downstream for reasonable distances until stable conditions are reached even though this may exceed the length calculated for design velocity control.

Conditions Where Practice Applies

This practice applies where discharge velocities and energies at the outlets of culverts, conduits, or channels are sufficient to erode the next downstream reach. This applies to:

1. Culvert outlets of all types.
2. Pipe conduits from all sediment basins, dry storm water ponds, and permanent type ponds.
3. New channels constructed as outlets for culverts and conduits.

4. Velocity at outlet should be below 15 fps. If velocities exceed 15 fps a specifically designed outfall structure such as plunge pool or stilling basin should be used.

Design Criteria

The most commonly used device for outlet protection is a riprap-lined apron. Where practical, they are constructed at a zero grade or a minimum slope to slow the outlet velocity. The type and length of the riprap-lined apron is related to the outlet flow rate, the tailwater level and whether there is a defined channel downstream.

If the tailwater depth is less than half the outlet pipe rise, it shall be classified as a Minimum Tailwater Condition. If the tailwater depth is greater than or equal to half the outlet pipe rise, it shall be classified as a Maximum Tailwater Condition.

The design of rock outlet protection depends entirely on the location. Pipe outlets at the top of cuts or on slopes steeper than 10 percent, cannot be protected by rock aprons or riprap sections due to re-concentration of flows and high velocities encountered after the flow leaves the apron. Several counties in West Virginia have regulations and design procedures that may establish the dimensions, type and size of materials, and locations where outlet protection is required. Where these requirements exist, they shall be followed.

Tailwater Depth--The depth of tailwater immediately below the pipe outlet must be determined for the design capacity of the pipe. If the tailwater depth is less than half the diameter of the outlet pipe, and the receiving stream is wide enough to accept divergence of the flow, it shall be classified as a Minimum Tailwater Condition; see Figure 3.17.2 on page 3.17-11 as an example. If the tailwater depth is greater than half the pipe diameter and the receiving stream will continue to confine the flow, it shall be classified as a Maximum Tailwater Condition; see Figure 3.17.1 on page 3.17-10 as an example. Pipes which outlet onto flat areas with no defined channel may be assumed to have a Minimum Tailwater Condition; see Figure 3.17.2 on page 3.17-11 as an example.

Apron Length--The apron length shall be determined from the curves solely according to the tailwater conditions.

Minimum Tailwater – Use Figure 3.17.2 on page 3.17-11
Maximum Tailwater – Use Figure 3.17.1 on page 3.17-10

Apron Width--Where there is no defined channel immediately downstream of the apron, the width of the apron at the pipe outlet should be three times the maximum inside pipe span and the width at the end of the apron should be as follows:

For Minimum Tailwater Conditions:

Width at end of apron should equal the pipe diameter plus the calculated length of apron.

For Maximum Tailwater Conditions:

Width at end of apron should equal the diameter of the pipe plus 0.4 times the length of the outlet.

If the pipe discharges directly into a well defined channel, the apron shall extend across the channel bottom and up the channel banks to an elevation one foot above the maximum tailwater depth or to the top of the bank, whichever is less. The upstream end of the apron, adjacent to the pipe, shall have a width three (3) times the diameter of the outlet pipe, or conform to pipe end section if used. The bottom width of the apron should be at least equal to the bottom width of the existing channel.

Bottom Grade--The outlet protection apron shall be constructed with no slope along its length. There shall be no overfall at the end of the apron. The elevation of the downstream end of the apron shall be equal to the elevation of the receiving channel or adjacent ground.

Alignment--The outlet protection apron shall be located so that there are no bends in the horizontal alignment.

Materials--The outlet protection may be done using rock riprap, grouted riprap, or gabions. Riprap shall be composed of a well-graded mixture of stone size so that 50 percent of the pieces, by weight, shall be larger than the d_{50} size determined by using the charts. A well-graded mixture, as used herein, is defined as a mixture composed primarily of larger stone sizes, but with a sufficient mixture of other sizes to fill the smaller voids between the stones. The diameter of the largest stone size in such a mixture shall be 1.5 times the d_{50} size.

Thickness--The minimum thickness of the riprap layer shall be 1.5 times the maximum stone diameter. The following chart lists some examples:

D_{50} (inches)	d_{max} (inches)	blanket thickness (inches)
4	6	9
6	9	14
9	14	21
12	18	27
15	22	33
18	27	41
21	32	48
24	36	54

Stone Quality--Stone for riprap shall consist of fieldstone or rough unhewn quarry stone. The stone shall be hard, angular and of a quality that will not disintegrate on exposure to water or weathering. The specific gravity of the individual stones shall be at least 2.5. Recycled concrete equivalent may be used provided it has a density of at least 150 pounds per cubic foot, and does not have any exposed steel or reinforcing bars.

Separation Fabric--In all cases, filter fabric shall be placed between the riprap and the underlying soil to protect soil movement into, through, and underneath the riprap. The material must meet or exceed these requirements: The plastic filter cloth can be woven or non-woven monofilament yarns, and shall meet these base requirements: thickness 20-60 mils, grab strength 90-120 lbs; and shall conform to ASTM D-1777 and ASTM D- 1682.

Gabions--Gabions shall be made of hexagonal triple twist mesh with heavily galvanized steel wire. The maximum linear dimension of the mesh opening shall not exceed 4 ½ inches and the area of the mesh opening shall not exceed 10 square inches.

Gabions shall be fabricated in such a manner that the sides, ends, and lid can be assembled at the construction site into a rectangular basket of the specified sizes. Gabions shall be of single unit construction and shall be installed according to manufacturer's recommendations.

The area on which the gabion is to be installed shall be graded as shown on the drawings. Foundation conditions shall be the same as for placing rock riprap, and filter cloth shall be placed under all gabions. Where necessary, key, or tie, the structure into the bank to prevent undermining of the main gabion structure.

For submittal to DEP, include the following in the SWPPP:

- Location where the practice will be installed.
- Dimensions of the practice.
- Plan view, profile and cross section of each channel reach between the storm drain outlet under consideration and the existing publicly maintained system or the natural stream channel receiving the discharge flow.
- Rock size.
- Rock thickness.
- Fabric specifications.

Table 3.17.1
PERMISSIBLE VELOCITIES FOR GRASS-LINED CHANNELS

Channel Slope	Lining	Velocity* (ft./sec.)
0 - 0.5%	Bermudagrass	6
	Reed canarygrass Tall fescue Kentucky bluegrass	5
	Grass-legume mixture	4
	Red fescue Redtop Sericea lespedeza Annual lespedeza Small grains Temporary vegetation	2.5
5 - 10%	Bermudagrass	5
	Reed canarygrass Tall fescue Kentucky bluegrass	4
	Grass-legume mixture	3
Greater than 10%	Bermudagrass	4
	Reed canarygrass Tall fescue Kentucky bluegrass	3
* For highly erodible soils, decrease permissible velocities by 25%.		

Source: Soil and Water Conservation Engineering, Schwab, et. al. and American Society of Civil Engineers

Table 3.17.2
PERMISSIBLE VELOCITIES FOR EARTH LININGS

Soil Types	Permissible Velocities (ft./sec.)
Fine Sand (noncolloidal)	2.5
Sandy Loam (noncolloidal)	2.5
Silt Loam (noncolloidal)	3.0
Ordinary Firm Loam	3.5
Fine Gravel	5.0
Stiff Clay (very colloidal)	5.0
Graded, Loam to Cobbles (noncolloidal)	5.0
Graded, Silt to Cobbles (colloidal)	5.5
Alluvial Silts (noncolloidal)	5.5
Alluvial Silts (colloidal)	5.0
Coarse Gravel (noncolloidal)	6.0
Cobbles and Shingles	5.5
Shales and Hard Plans	6.0

Source: Soil and Water Conservation Engineering, Schwab, et. al. and American Society of Civil Engineers

Construction Specifications

1. The subgrade for the filter, riprap, or gabion shall be prepared to the required lines and grades. Any fill required in the subgrade shall be compacted to a density of approximately that of the surrounding undisturbed material.

2. The rock or gravel shall conform to the specified grading limits when installed respectively in the riprap or filter.

3. Filter cloth shall be protected from punching, cutting, or tearing. Any damage other than an occasional small hole shall be repaired by placing another piece of cloth over the damaged part or by completely replacing the cloth. All overlaps, whether for repairs or for joining two pieces of cloth shall be a minimum of one foot.

4. Stone for the riprap or gabion outlets may be placed by equipment. Both shall be constructed to the full course thickness in one operation and in such a manner as to avoid displacement of underlying materials. The stone for riprap or gabion outlets shall be delivered and placed in a manner that will ensure that it is reasonably homogenous with the smaller stones and spalls filling the voids between the larger stones. Riprap shall be placed in a manner to prevent damage to the filter blanket or filter cloth. Hand placement will be required to the extent necessary to prevent damage to the permanent works.

Maintenance

Once a riprap outlet has been installed, the maintenance needs are very low. It should be inspected after high flows for evidence of scour beneath the riprap or for dislodged stones. If a significant number of stones have been dislodged it will be necessary to recalculate stone size and replace the existing stone with properly sized stone. Any repairs must be made immediately.

Design Procedure

1. Investigate the downstream channel to assure that non-erosive velocities can be maintained.

2. Determine the tailwater condition at the outlet to establish which curve to use.

3. Enter the appropriate chart with the design discharge to determine the riprap size and apron length required. It is noted that references to pipe diameters in the charts are based on full flow. For other than full pipe flow, the parameters of depth of flow and velocity must be used to adjust the design discharges.

4. Calculate apron width at the downstream end if a flare section is to be employed.

Examples

Example 1: Pipe Flow (full) with discharge to unconfined section.

Given: A circular conduit flowing full.

> Q = 280 cfs, diameter = 66 in., tailwater (surface) is 2 ft. above pipe invert (Minimum Tailwater Condition).

Find: Read d_{50} = 1.2 ft and apron length (L_a) = 38 ft.

Apron width = diam. + L_a = 5.5’ + 38’ = 43.5 ft.

Use: d_{50} = 15”, d_{max} = 22”, blanket thickness = 32”

Example 2: Box Flow (partial) with high tailwater

Given: A box conduit discharging under partial flow conditions. A concrete box 5.5 ft. x 10 ft. flowing 5.0 ft. deep,

Q = 600 cfs and tailwater surface is 5 ft. above invert (max. tailwater condition).

Since this is not full pipe and does not directly fit the nomograph assumptions substitute depth as the diameter, to find a discharge equal to full pipe flow for that diameter, in this case 60 inches.

$$\text{Since, } Q = AV \text{ and } A = \frac{\pi D^2}{4}$$

First, compute velocity:

V = (Q/A) = (600/(5) (10)) = 12 fps

Then substituting:

$$Q = \frac{\pi D^2}{4} \text{ x } V = \frac{3.14\,(5\text{ ft})^2}{4} \text{ x } 12 \text{ fps} = 236 \text{ cfs}$$

At the intersection of the curve, d = 60 in. and Q = 236 cfs, read d_{50} = 0.4 ft.

Then reading the d = 60 in. curve, read apron length (L_a) = 40 ft.

Apron width, W = conduit width + (6.4)(L_a) = 10 + (0.4) (40) = 26 ft.

Example 3: Open Channel Flow with Discharge to Unconfined Section

Given: A trapezoidal concrete channel 5 ft. wide with 2:1 side slopes is flowing 2 ft. deep, Q = 180 cfs (velocity = 10 fps) and the tailwater surface downstream is 0.8 ft. (minimum tailwater condition).

Find: Using similar principles as Example 2, compute equivalent discharge for a 2 foot, using depth as a diameter, circular pipe flowing full at 10 feet per second.

Velocity:

$$Q = \frac{\pi\,(2\text{ft})^2}{4} \text{ x } 10 \text{ fps} = 31.4 \text{ cfs}$$

At intersection of the curve, d = 24 in. and Q = 32 cfs, read d_{50} = 0.6 ft.

Then reading the d = 24 in. curve, read apron length (L_a) = 20 ft.

Apron width, W = bottom width of channel + L_a = 5 + 20 = 25 ft.

Example 4: Pipe flow (partial) with discharge to a confined section

Given: A 48 in. pipe is discharging with a depth of 3 ft. Q = 100 cfs, and discharge velocity of 10 fps (established from partial flow analysis) to a confined trapezoidal channel with a 2 ft. bottom, 2:1 side slopes, n = .04, and grade of 0.6%.

Calculation of the downstream channel (by Manning's Equation) indicates a normal depth of 3.1 ft. and normal velocity of 3.9 fps.

Since the receiving channel is confined, the Maximum Tailwater Condition controls.

Find: discharge using previous principles:

$$Q = \frac{\pi\,(3ft)^2}{4} \times 10 \text{ fps} = 71 \text{ cfs}$$

At the intersection of d = 36 in. and Q = 71 cfs, read d_{50} = 0.3 ft.

Reading the d = 36" curve, read apron length (L_a) = 30 ft.

Since the maximum flow depth in this reach is 3.1 ft. that is the minimum depth of riprap to be maintained for the entire length of the apron.

FIGURE 3.17.1

DESIGN OF OUTLET PROTECTION FROM A ROUND PIPE FLOWING FULL
MAXIMUM TAILWATER CONDITION ($T_w \geq 0.5$ DIAMETER) (USDA-NRCS)

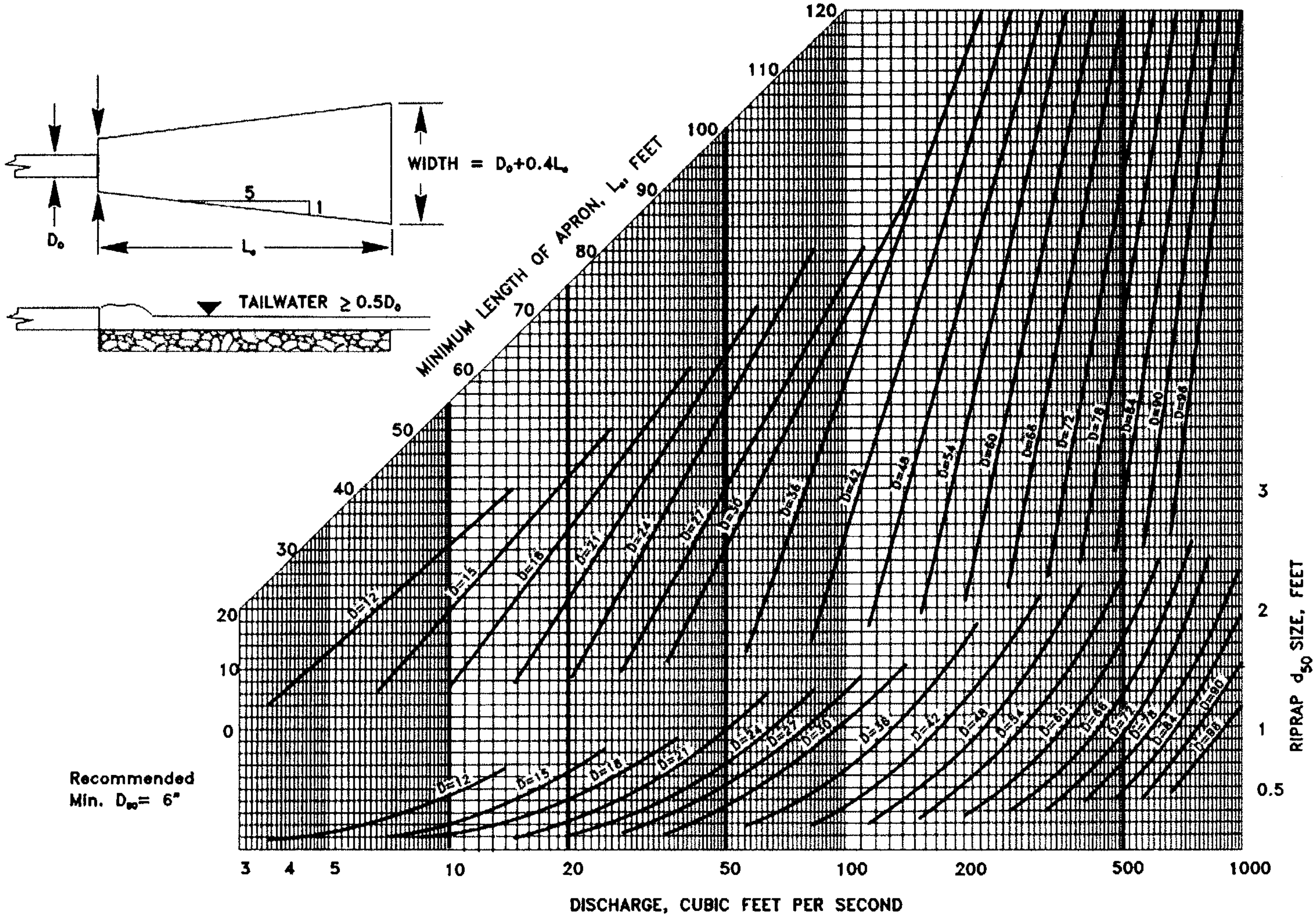


FIGURE 3.17.2

DESIGN OF OUTLET PROTECTION FROM A ROUND PIPE FLOWING FULL
MINIMUM TAILWATER CONDITION (T_w <0.5 DIAMETER) (USDA–NRCS)

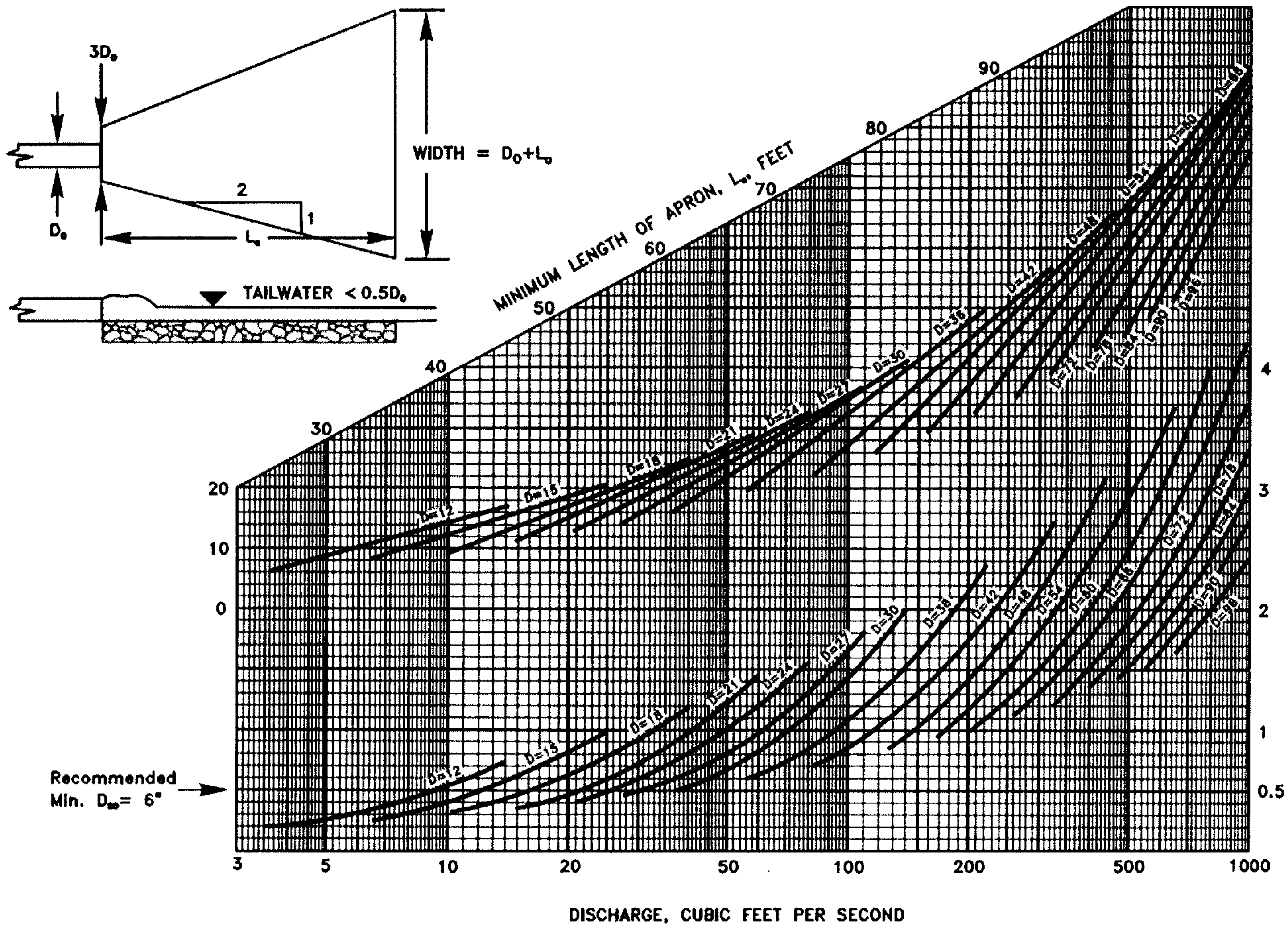
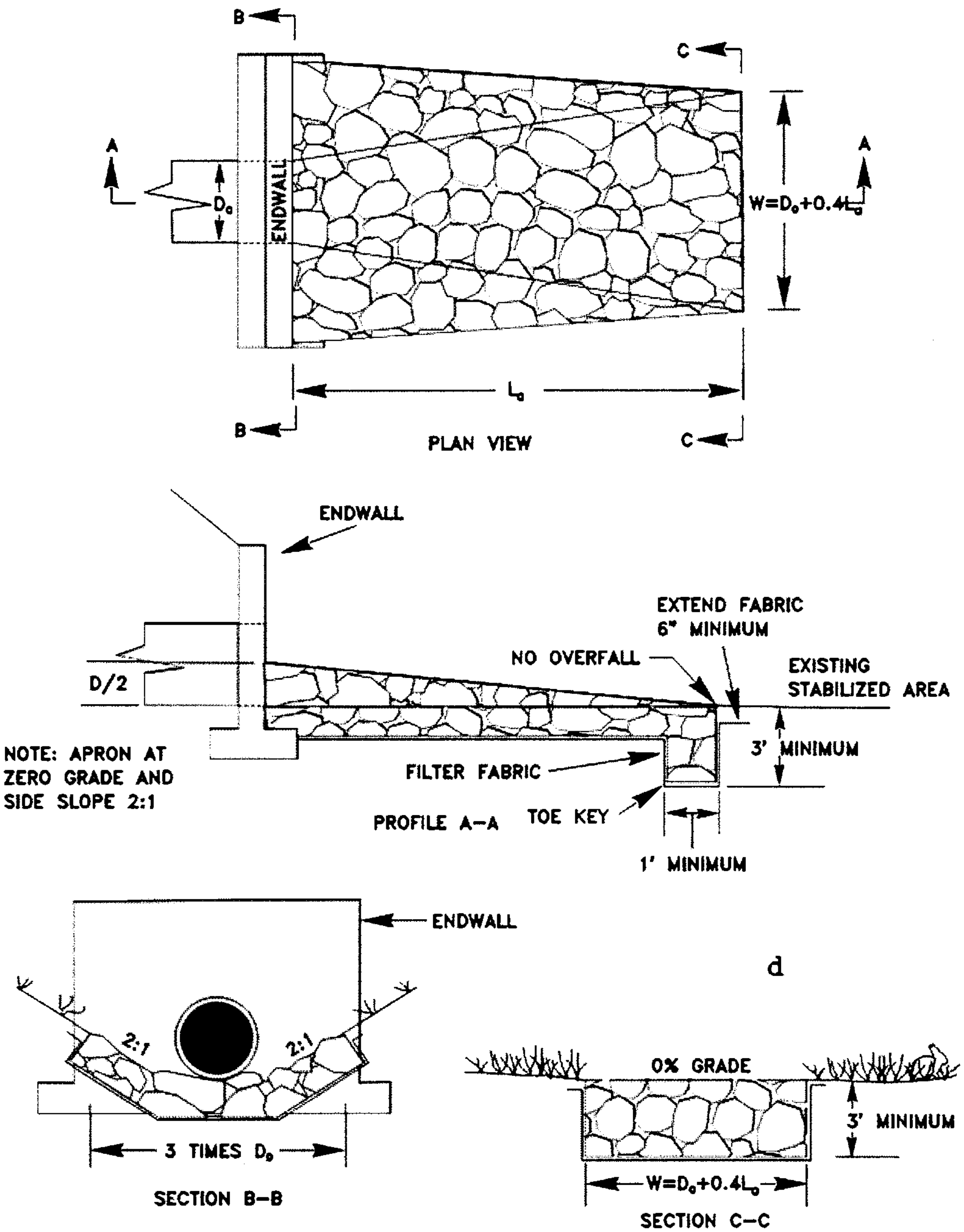


FIGURE 3.17.3

OUTLET PROTECTION

DISCHARGE TO UNCONFINED SECTION
(MINIMUM TAILWATER)

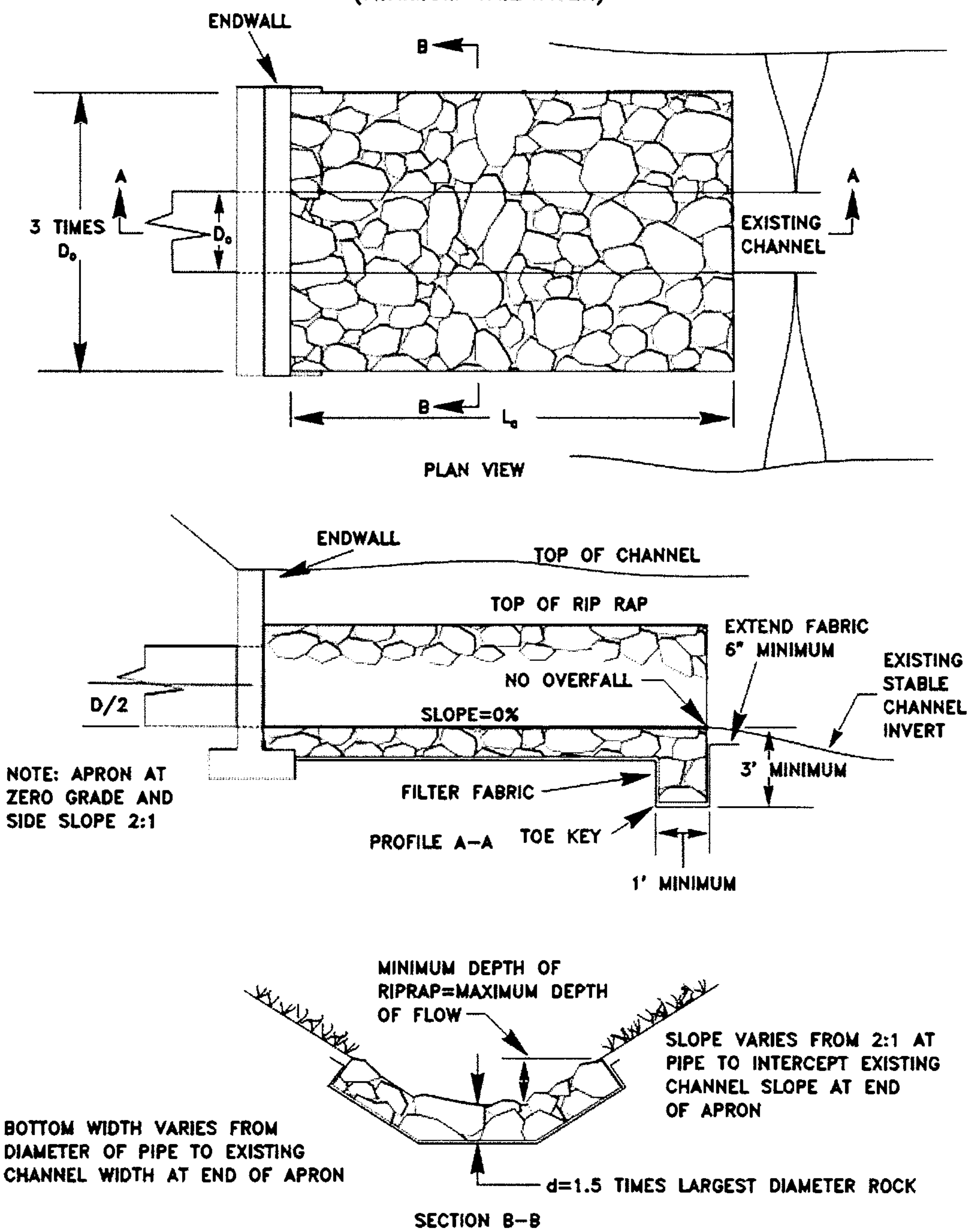


FROM NEW YORK STANDARDS AND SPECIFICATIONS
FOR EROSION AND SEDIMENT CONTROL

FIGURE 3.17.4

OUTLET PROTECTION

DISCHARGE TO CONFINED CHANNEL
(MINIMUM TAILWATER)

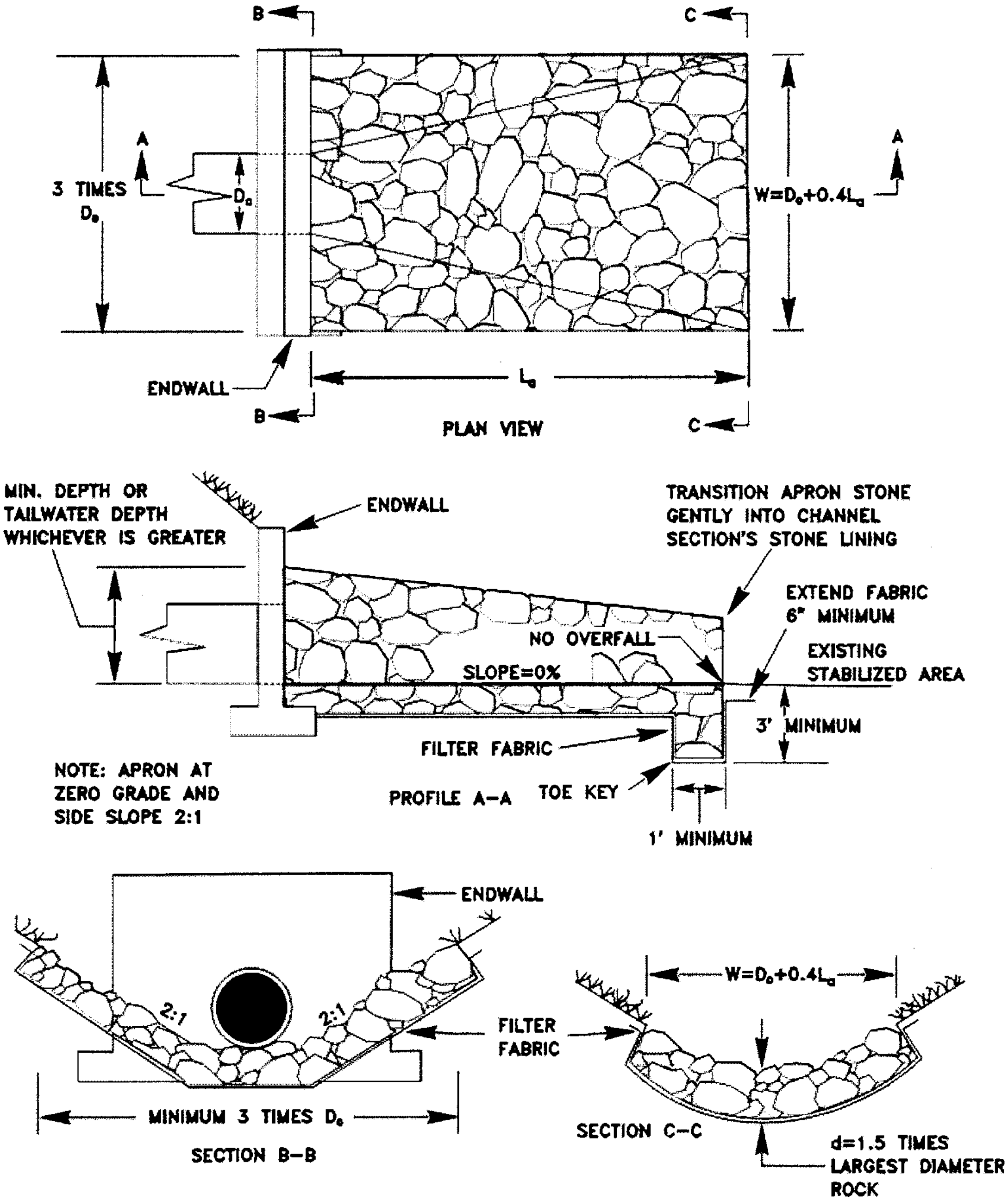


FROM NEW YORK STANDARDS AND SPECIFICATIONS FOR EROSION AND SEDIMENT CONTROL

FIGURE 3.17.5

OUTLET PROTECTION

DISCHARGE TO SEMI-CONFINED SECTION
(MAXIMUM TAILWATER)



FROM NEW YORK STANDARDS AND SPECIFICATIONS
FOR EROSION AND SEDIMENT CONTROL

3.18 - RIGHT OF WAY DIVERSION

Introduction

Right-of-way Interceptor Diversion is a ridge of dirt or a ridge and a channel combination constructed on an angle across a utility right-of-way used to shorten flow paths and flatten slopes to reduce the erosive force of water or to direct water away from critical resources. It can be both a temporary and permanent structure.

Conditions Where Practice Applies

This practice is applicable on all utility construction that occurs on sloping ground. In fact, it is probably the most common sediment control practice used in pipeline construction.

Design Criteria

No formal design is required. The spacing between diversions shall not exceed the requirements below.

Construction Specifications

1. Drainage Area: The maximum allowable drainage area is 1 acre.
2. Spacing: Use the following table when choosing the placement of the diversion. Use this chart for both permanent and temporary diversions.

Table 3.18.1 Right-of-way Diversion Spacing

Percent Slope	Spacing in Feet
[5	300
10	175
15	125
20	100
〈25	75

* It is difficult to install diversions on slopes steeper than 35%, the Division of Water and Waste Management will allow greater distances between diversions on extreme slopes.

3. Height: The minimum allowable height measured from the upslope side of the dike is 12 inches.
4. Grade: The channel behind the dike shall have a positive grade to a stabilized outlet. The diversion must be angled at least 3 or 4 degrees relative to the fall line of the slope and should not exceed 8 degrees.
5. Outlet: Each diversion should exit onto stabilized ground. It should never exit onto the right-of-way where it can run down to the next diversion.

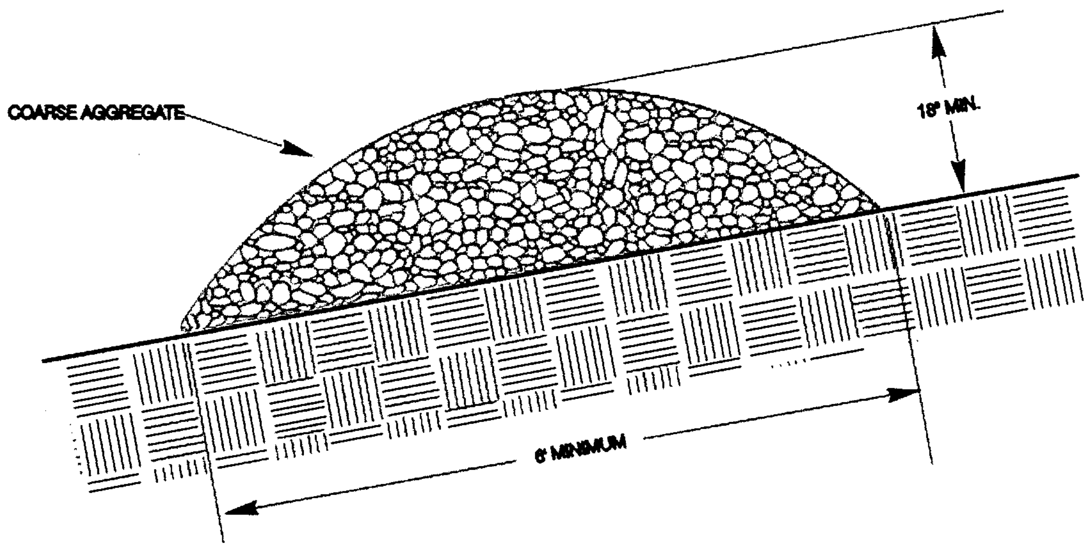
6. Temporary diversion dikes must be installed as a first step after clearing and grubbing, or grading on a replacement project.
7. The diversions must be in place and functional at the end of each workday, especially when work will be discontinued for several days as on a weekend. Keep an eye on the weather forecast.
8. The berm shall be compacted by running a tracked piece of equipment across the length of the berm at least once.
9. Where the required spacing cannot be met due to excessive slope, a diversion will be installed at the nearest convenient point above and below the step section.

Maintenance

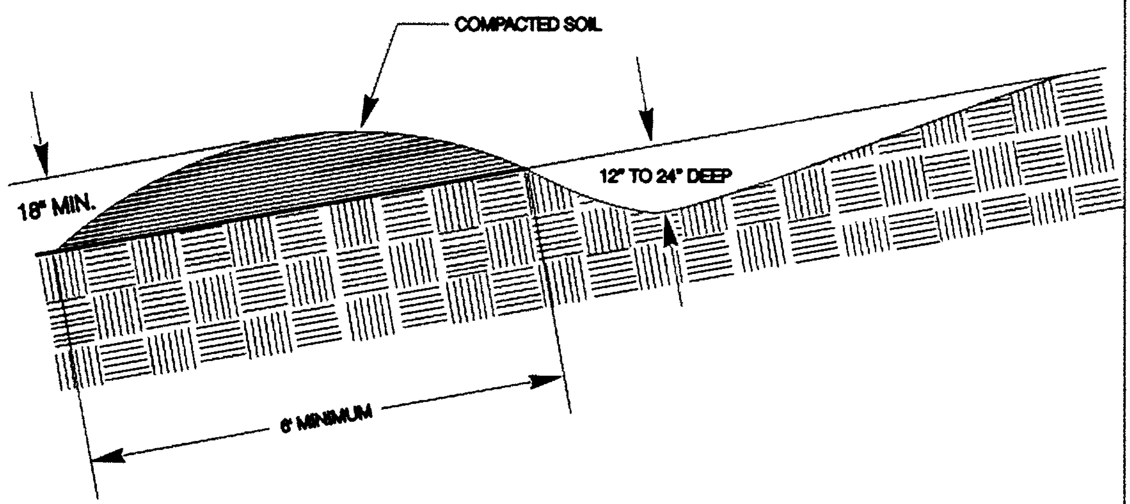
The measure shall be inspected after every rain event of .5 inch or more and repairs made as necessary. Once every week, whether a storm event has occurred or not, the measure shall be inspected and repairs made if needed. In areas where construction is actively occurring, diversions should be inspected daily, and damage caused by construction traffic or other activity repaired before the end of each working day.

FIGURE 3.18.1

RIGHT-OF-WAY DIVERSIONS



TYPICAL GRAVEL STRUCTURE

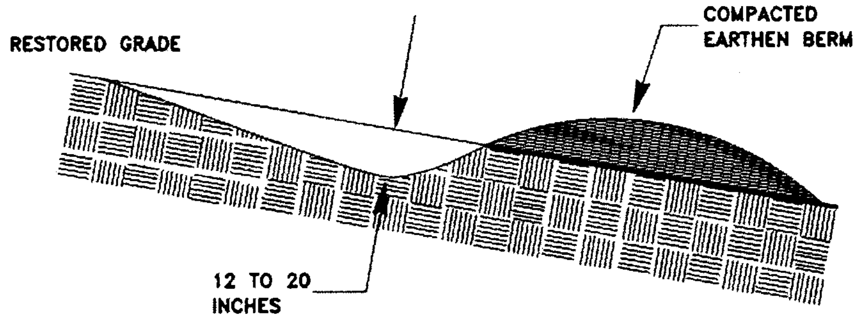


TYPICAL EARTHEN STRUCTURE

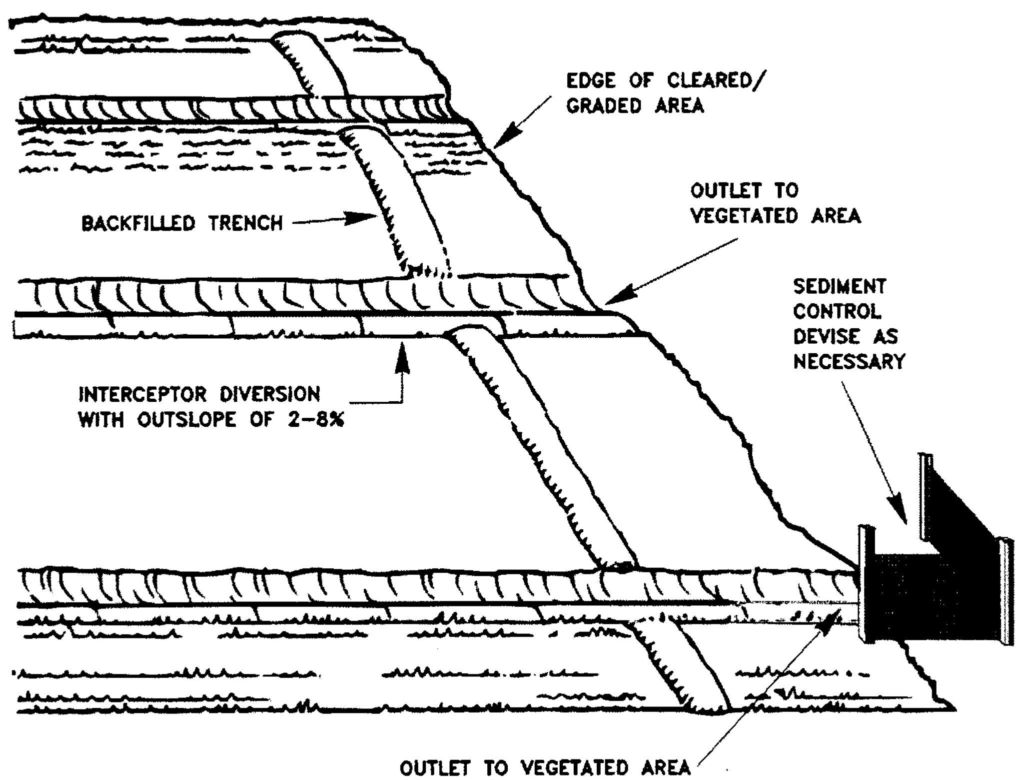
Source: Va. SWCC

FIGURE 3.18.2

RIGHT-OF-WAY DIVERSION



FINAL DIVERSION CROSS-SECTION



3.19 - LEVEL LIP SPREADER

Introduction

An outlet for dikes and diversions consisting of an excavated depression constructed at zero grade across a slope used to convert concentrated runoff to sheet flow and release it uniformly onto areas stabilized by existing vegetation.

Conditions Where Practice Applies

Where there is a need to divert **small** amounts of clean stormwater away from disturbed areas to avoid overwhelming erosion control measures; where sediment-free storm runoff can be released in sheet flow down a well-vegetated, stabilized slope without causing erosion.

This practice applies only in those situations where the spreader can be constructed on undisturbed soil and the area below the level lip is uniform with a slope of 10% or less and is stabilized by natural vegetation or other non-erosive materials. The runoff water should not be allowed to re-concentrate after release unless it occurs during interception by another measure (such as a permanent pond or detention basin) located below the level spreader.

Caution should be used in using this device. Sheet flow easily changes to concentrated flow and consequently can cause downslope erosion if the specifications in this section are not followed closely.

Planning Considerations

The Temporary Diversion Dike, permanent stormwater conveyances and other waterways call for a stable outlet for concentrated stormwater flows. The level spreader is a relatively low-cost structure to release small volumes of concentrated flow but only when site conditions are suitable.

The outlet area must be uniform and well vegetated with slopes 10% or less. Particular care must be taken to construct the outlet lip completely level in a stable, undisturbed soil. Any depressions in the lip will concentrate the flow, resulting in erosion. Under higher design flow conditions, a rigid outlet lip design should be used to create the desired sheet flow conditions. Runoff water containing high sediment loads must be treated in a sediment-trapping device before being released to a level spreader.

This practice is difficult to install correctly. It is critical to install the lip perfectly level; failure to do so will cause a concentration of flows and erosion.

Design Criteria

No formal design is required except in the case of a permanent application the spreader should be designed to handle the peak discharge expected from a 10-year/24-hour storm.

Construction Specifications

1. Level spreaders must be constructed on undisturbed soil (not fill material).
2. The entrance to the spreader must be shaped in such a manner as to insure that runoff enters directly onto the 0% channel.
3. Construct a 20-ft. transition section from the diversion channel to blend smoothly to the width and depth of the spreader.
4. The level lip shall be constructed at 0% grade to insure uniform spreading of stormwater runoff.
5. Protective covering (blankets) for vegetated lip should be a minimum of 4 feet wide extending 6 inches over the lip and buried 6 inches deep in a vertical trench on the lower edge. The upper edge should butt against smoothly cut sod and be securely held in place with closely spaced heavy-duty wire staples.
6. Rigid level lip should be entrenched at least 2 inches below existing ground and securely anchored to prevent displacement. An apron of AASHTO #1, #2 or #3 Coarse Aggregate should be placed to top of level lip and extended downslope at least 3 feet. Place filter fabric under stone and use galvanized wire mesh to hold stone securely in place.
7. The released runoff must outlet onto undisturbed stabilized areas with slope not exceeding 10%. Slope must be sufficiently smooth to preserve sheet flow and prevent flow from concentrating.
8. The level spreader should be sized to transfer 0.25 cfs per linear foot of spreader for the peak discharge from a ten-year/24-hour storm.
9. Immediately after its construction, appropriately seed and mulch the entire disturbed area of the spreader.

Maintenance

The measure shall be inspected after every rainfall of .5" or more and repairs made, if required. After construction and until fully revegetated, the level spreaders need to be carefully inspected for any signs of channelization and immediately repaired.

Level spreader lip must remain at 0% slope to allow proper function of measure.

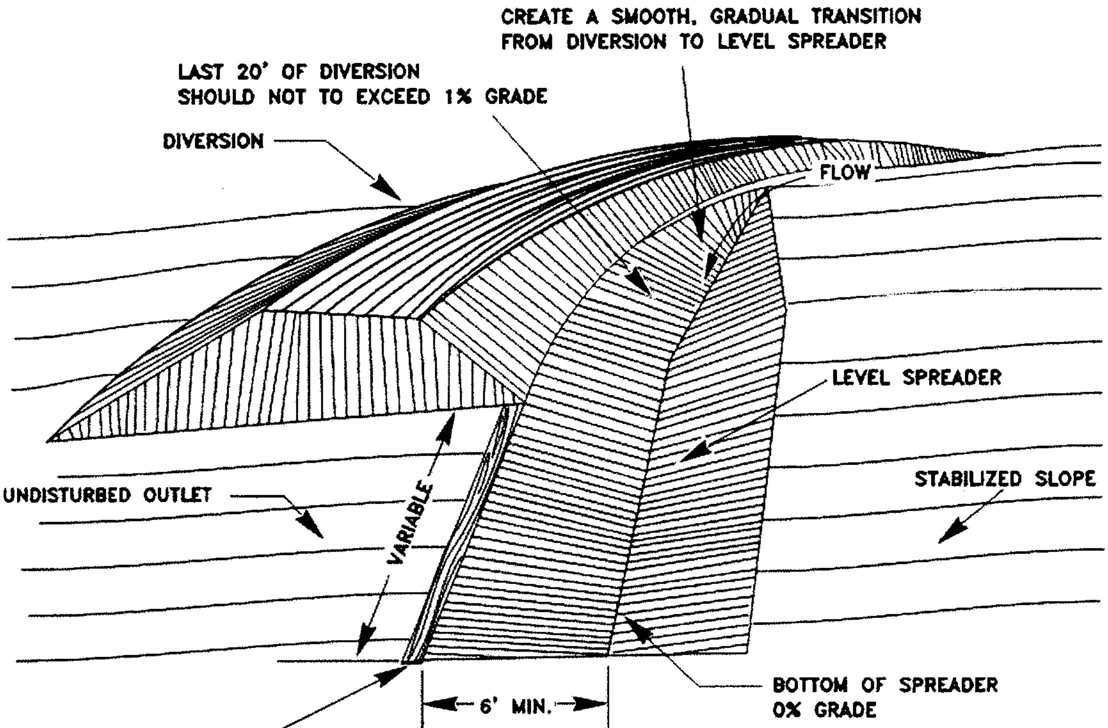
The contractor should avoid the placement of any material on and prevent construction traffic across the structure.

If the measure is damaged by construction traffic, it shall be repaired immediately.

Repeated failure of the structure will require the developer to replace the Level Lip Spreader with a properly designed stormwater conveyance channel from the diversion to the nearest natural waterway or stormwater basin.

FIGURE 3.19.1

LEVEL SPREADER



PERSPECTIVE VIEW

NOTE: ALL TEMPORARY BERMS, SWALES AND LEVEL SPREADER DITCH MUST RECEIVE TEMPORARY SEEDING AND MULCHING AFTER INSTALLATION

SOURCE: ADAPTED FROM N.C. E&S Control Planning and Design Manua and VA DESCI

3.20 - SURFACE WATER CONTROL

Introduction

One of the most important (but often overlooked) techniques of sediment and erosion control is the proactive management of surface water runoff. By anticipating where runoff will occur and directing water to go where it will do the least damage, erosion can be, in some cases, almost eliminated. By directing runoff to stabilized conveyances such as pipe slope drains, riprap channels and rock underdrains, slopes, fills and haul roads can be protected from excessive erosion. Work areas dry quicker after rainfall events, and the contractor saves time and money by not having to regrade areas damaged by erosion. The use of some of these techniques can reduce the size requirements of sediment basins and traps, but only if approved by DWWM during the SWPPP review.

Except for areas that can be treated by silt fence or super silt fence, all runoff from disturbed areas must be intercepted and conveyed to a sediment pond or trap.

At a minimum, temporary storm water conveyances should have the capacity to pass the peak flow from 2-year/24-hour storm. Significant sources of clean upslope surface water that drain onto disturbed areas shall be intercepted and conveyed to a stabilized discharge point where the water will not drain back onto the disturbed area. Upslope diversions must discharge where there can be no damage to adjacent land. Surface water controls shall be installed concurrently with rough grading.

Conditions Where Practice Applies:

The purpose of surface water control is to collect and convey surface water so that erosion is minimized and contaminated runoff from disturbed areas is treated by a sediment pond or trap. Upslope diversions reduce the volume of runoff to the disturbed area on a construction project and allows for the design of a smaller sediment trapping structure.

Surface water control consists of several practices alone or in combination:

1. Interception of runoff above cut slopes to a stable outlet.
2. Conveyance of the contaminated runoff to a sediment pond or trap.
3. Internal control of runoff across roadways and fills.
4. Control runoff from fill areas via pipe slope drains, rip-rap channels, or rock wick underdrains.
5. Control of water on the cut slope.
6. Conveyance of the treated runoff from the trap or basin to a stable waterway.

However, “controlling runoff” is not easily defined and there will be numerous conditions during the construction phase that this specification will not cover. Contractors are encouraged to incorporate these techniques and guidelines into their typical construction methods. However, the most important concept is to plan construction as if it will rain, not that it won't rain.

Timing of Installation

Surface water controls such as upslope clean water diversions and dirty water diversions to sediment basins and traps are to be constructed during the initial clearing and grubbing of an area and must be functional prior to the start of major grading operations.

The rock underdrain must be started prior to initial fill placement.

The rest of the water runoff control practices are installed as needed as grading operations proceed. Diversion berms at the top of slopes and either pipe slope drains or rip rap channels are installed as the fill progresses.

When using the riprap channel conveyance the installation of the channel must coincide with filling operations. There should be little or no delay in installing the channel and connecting it to the top of the fill.

Positive drainage and/or diversions must be maintained at all times to direct runoff towards the pipe slope drain, rock underdrain or rip rap channel.

Individual BMPs used in this practice:

1. Interceptor dikes/swales,
2. Rock wick or underdrain.
3. Rip rap ditches
4. Pipe slope drains,
5. Outlet protection

See the following drawings for schematic representation on the use of these measures.

Materials

The Surface Water Control Best Management Practice utilizes a number of other individual Best Management Practices from this Manual. Except for the rock underdrain, the material requirements can be found under each individual practice.

The Rock Underdrain is constructed like a huge French Drain. Rock for the underdrain or wick shall consist of durable Shot Rock, Select Embankment or large Riprap with little or no fine material. The rock core must be wrapped in a suitable filter fabric geotextile to prevent soil fines from clogging the voids.

Maintenance

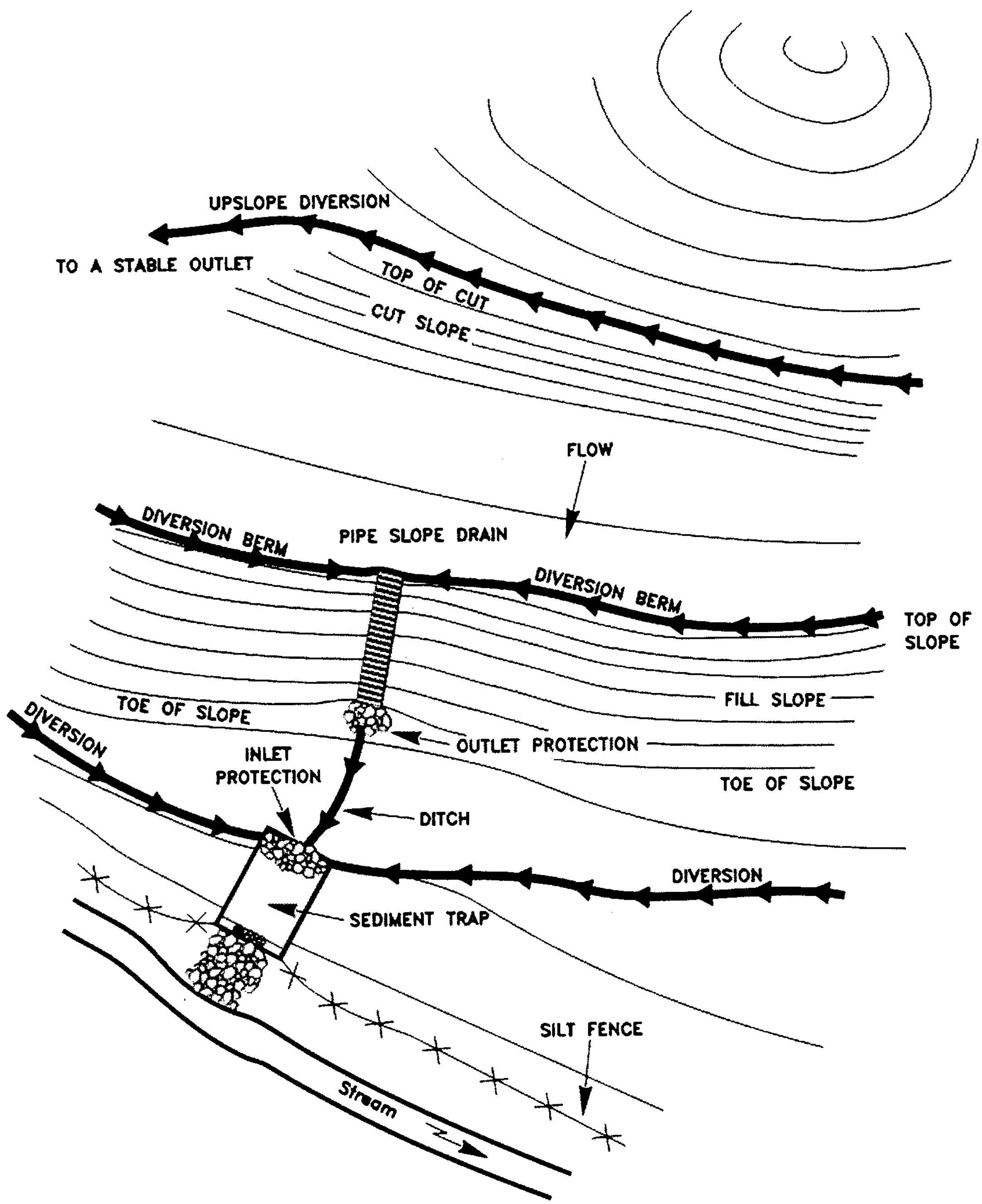
Maintenance requirements are listed in each separate practice. But in general, this practice is to be inspected once a week or immediately after each 0.5-inch or greater rain event.

Positive drainage towards the conveyance(s) must be maintained at all times.

NOTE **The use of the Fill with Rock Underdrain may not be appropriate in all cases and should be reviewed by a geotechnical engineer.**

FIGURE 3.20.1

SURFACE WATER CONTROL



From: King County, Washington ESC Manual

FIGURE 3.20.2

SURFACE WATER CONTROL

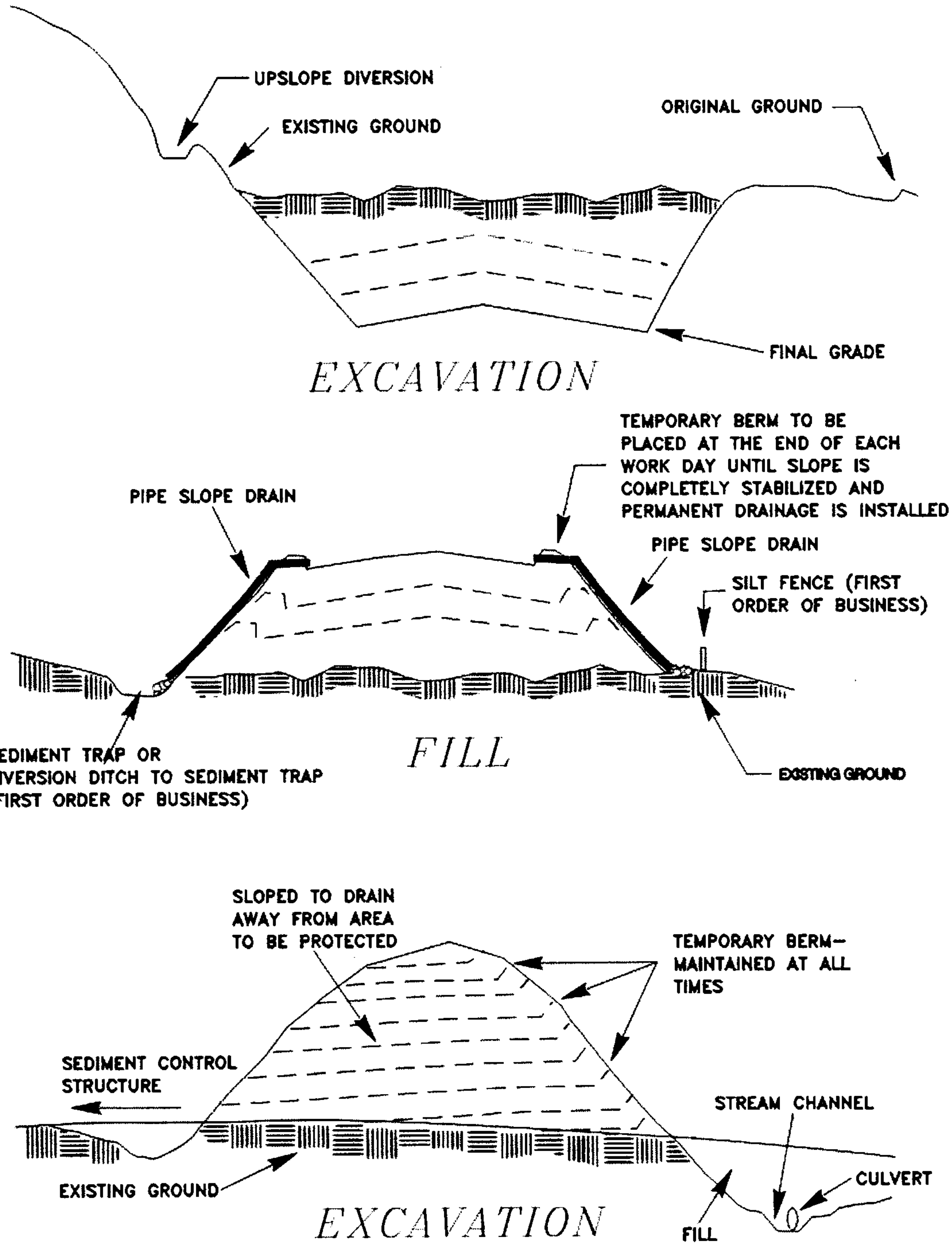


FIGURE 3.20.3

SIDE HILL CUT AND FILL

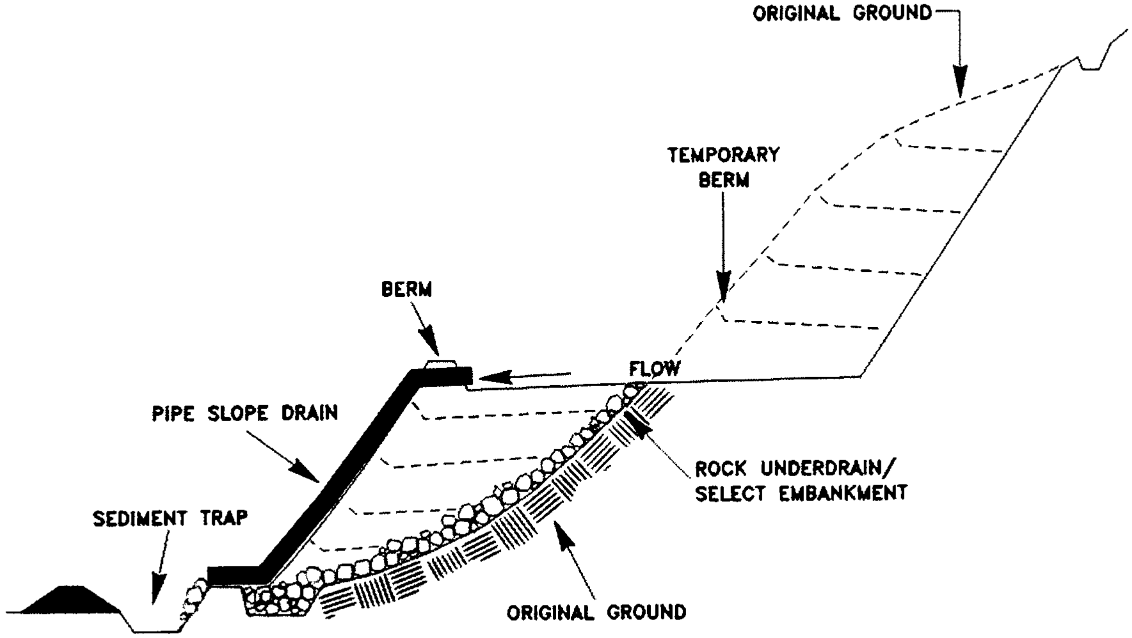
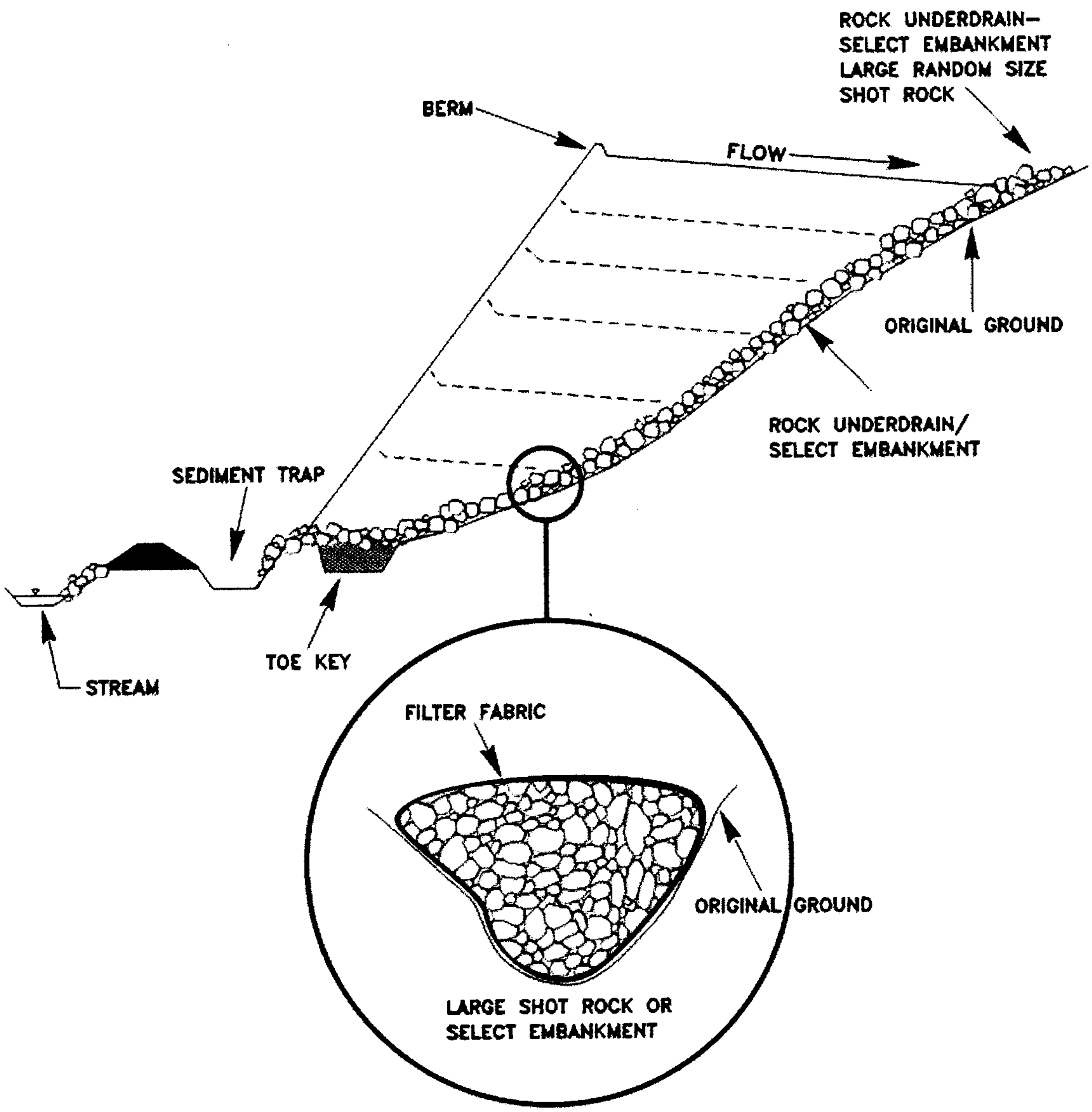


FIGURE 3.20.4

FILL WITH ROCK UNDER DRAIN

SECTION A–A



SECTION OF
ROCK UNDERDRAIN

FIGURE 3.20.5

FILL WITH ROCK UNDER DRAIN

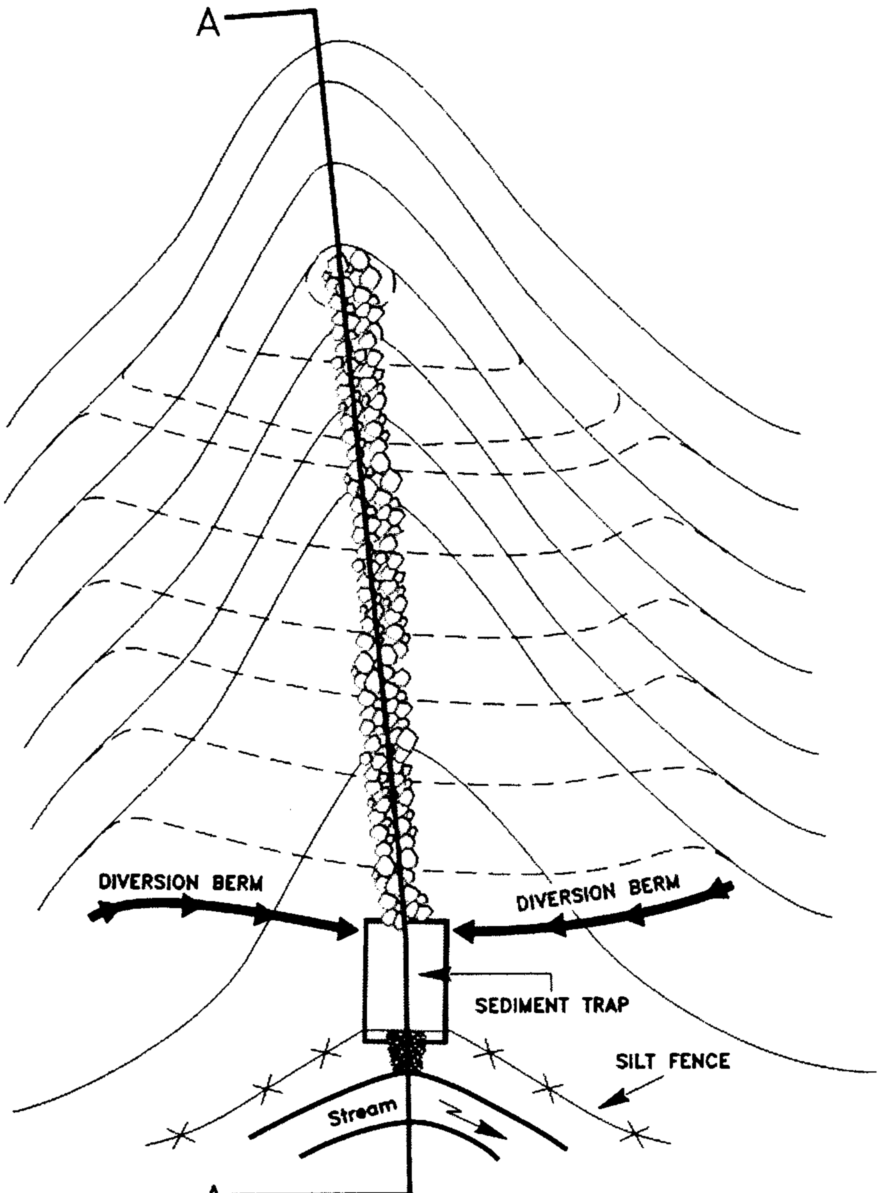
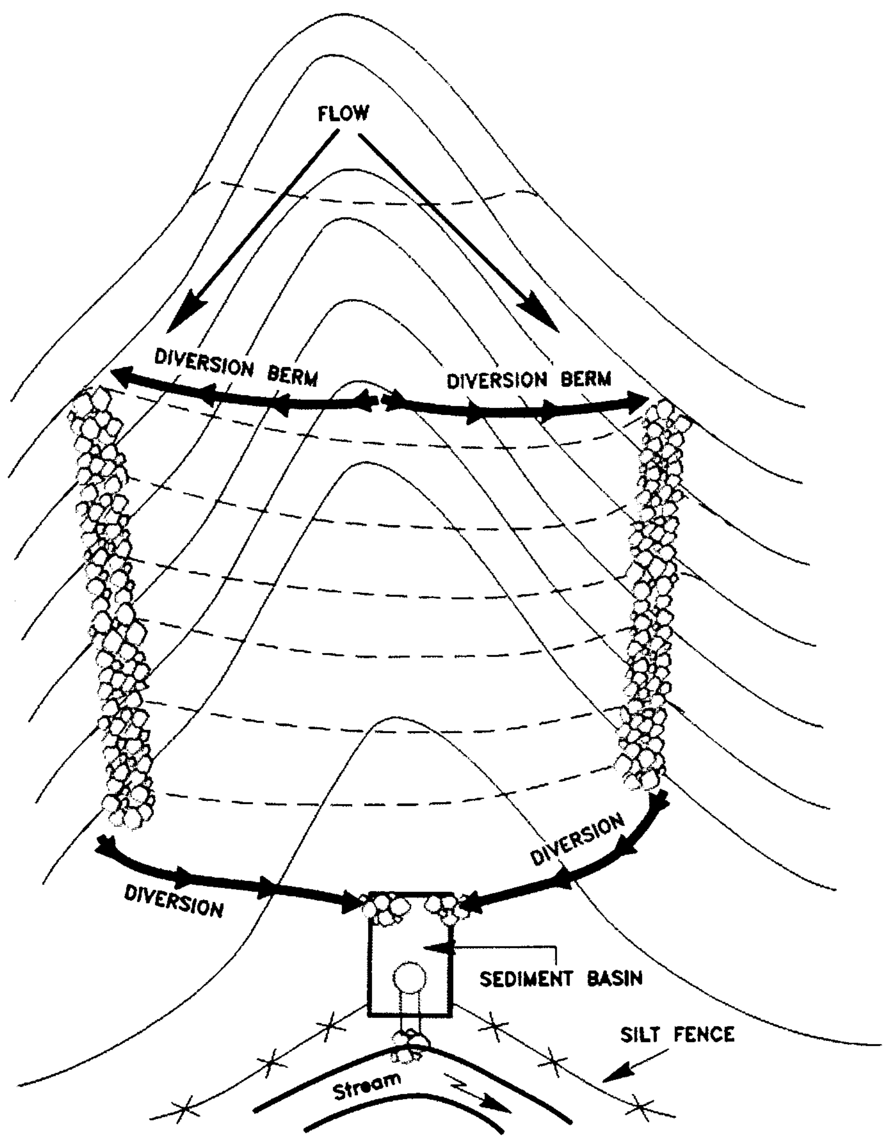


FIGURE 3.20.6

FILL WITH ROCK CHANNELS



3.21 - INSTREAM BMPs

Introduction

Many times construction activities have to take place within the streambed. Utility construction in particular, by virtue of its linear nature, frequently crosses and negatively impacts streams. Large amounts of sediment can be generated when equipment is working in a stream. The only way that sediment be reduced during instream construction is by isolating the work or "working in the dry". By isolating the work area from the stream flow much of this sediment can be eliminated. There are several techniques that can be used to dewater and isolate the work area.

While this practice emphasizes utility construction each of these techniques can be used for any type of instream construction activity.

When the project will last more than 72 hours and the work area has to be completely dewatered such as when culverts are being installed, the temporary stream diversion can be used.

Runoff from the shore and approaches can also produce sediment, as can improperly stabilized streambanks.

Conditions Where Practice Applies

These practices are applicable to all instream construction activities such as utility lines, bridge piers and abutments, retaining walls and/or bank stabilization, culverts, water intakes and pipe outfalls. Temporary isolation techniques are used when construction within a full flowing stream will create severe environmental impacts due the resulting sedimentation.

Under most circumstances the pump around technique will be sufficient to dewater the work site. However, a full stream diversion is required when the construction of an instream structure will take place across the entire channel width and the pump around or flume would not be sufficient to handle the anticipated stream flows. It is also applicable when the construction timeframe is longer than 72 hours and there is sufficient lead-time to construct the new channel and stabilize it.

The stream diversion technique only works if there is sufficient room to install the diversion and construct the structure.

These practices are not permanent. A full engineering design is required if a stream channel has to be relocated into new permanent channel. There are numerous requirements, including natural stream design, in the Army Corps of Engineers' Section 404 Permit, WV DEP Section 401 Certification and the Public Lands Corporation Right-to-Enter.

Planning Considerations

The production of significant amounts of sediment is inevitable when conducting construction activities in a stream. There is also a potential for excessive sediment loss into a stream by runoff from the adjoining streamside and approach areas.

It is often a difficult task to decide what type of control to use when working in a stream. The ONLY way to limit sediment is to work “in the dry”. Any attempt to trap sediment in the stream below the construction site is pointless. There are several very effective methods that can be used to work in the dry and prevent the creation of sediment One, “boring and jacking” or horizontal directional drilling of pipe under the streambed, which prevents any disturbance within the watercourse, is the least destructive and preferred method. However, boring is expensive and sometimes impractical. But when working in very high quality steams such as Tier 2.5 or 3 it may be the only method allowed. In others it may be convenient as a continuation of an ongoing project, such as extending a Division of Highways’ road bore underneath an adjacent stream.

However, when instream work is unavoidable, consideration must be given to providing adequate mitigation of sediment loss while minimizing the amount of encroachment and time spent working in the channel. There are several methods available that completely isolate the work area from the stream flow. These “dry ditch” measures include pumping around, flume pipes, cofferdams and stream diversions. Each of these techniques work in smaller streams and during periods of low flows.

In larger streams where isolation techniques become difficult or impossible to install, there can be some “give and take”. Sometimes there can be less damage to the environment if minimal instream sediment control takes place. When using these “wet ditch” methods it is necessary to minimize the amount of time spent working in the stream, quickly stabilize the work area and provide substantial controls on the approach areas. However, when the construction within streambed and banks will take an extended period of time, consideration should be given to substantial in-stream controls or to construct a stream diversion.

As a result of the difficulty in choosing the right method for a utility stream crossing, designers should always make a site visit of proposed crossing to ensure that the most appropriate method is chosen. The designer should also be aware that most instream construction projects are subject to federal section 404 Army Corps of Engineers, NPDES Construction Permit and Public Lands Corporation’s Right of Entry.

Included in this BMP are several methods (with varying construction time and stream size scenarios) which allow for “work in the dry” to prevent excessive sedimentation damage. By no means are these methods all-inclusive. As with other control measures, site-specific design and innovative variations are encouraged.

All planning should begin with an onsite evaluation. The following items should be considered when designing a stream crossing..

- Site Conditions
  - Channel Cross Section
  - Channel Bed (Solid Rock, Cobbles, Soil)
  - Bank Slopes
  - Bank Stability
  - Flow Characteristics of Stream
- Season
- Suitable Location
  - Avoid bends of the steams
  - Avoid Wetlands or other environmental sensitive areas
- Other Considerations
  - Applicability of other permitting regulations (See Permitting section of this manual)
  - Endangered Species
- Floodplain encroachment
- Determine the appropriate construction method

General Design Criteria

1. The drainage area should be no greater than one square mile (640 acres).
2. All filter cloth used in the construction of the utility crossing must conform to physical requirements noted in GEOTEXTILE.
3. Water diverting structures should be used at all trenching and/or construction road approaches (50 feet on either side of the crossing).
4. Design criteria more specific to each particular crossing can be found in the following drawings.
5. All construction activities must meet the applicable Minimum Standard for Instream Construction.
6. Bank stabilization should be based on soil erodibility and bank-full velocity. Restabilization shall consist of the installation of ungrouted riprap on all disturbed streambank areas (or on the area 6 feet on both sides of the centerline of its utility trench, whichever is greater) with slopes of 3:1 or greater. Refer to RIPRAP and the drawings in this section for installation requirements. For slopes of 3:1 or less, vegetative stabilization may be used, pending approval by the Division of Water and Waste Management. Stabilization of its streambed and banks and the approach areas should occur immediately following the attainment of final grade.
7. Provide sediment control such as SILT FENCE, SUPER SILT FENCE or DIVERSIONS and SEDIMENT TRAP on either side of the stream

Construction Criteria

The following specifications are for stream crossings such as would be needed for a utility line crossing. Each can be used for other instream activities with little or no modification. The stream diversion will typically be used for larger projects.

The least damaging and preferred method is “boring and jacking” or horizontal directional drilling..

Open cut dry ditch methods - In these methods the work area is isolated by diverting the stream around the pipeline crossing. The trench is then excavated, the pipe installed and backfilled and the stream and streambank stabilized, all “in the dry”.

The three main methods of dry ditch crossings are the pump around, cofferdam and the flume pipe methods. In the pump around, the stream is dammed and water is moved around the construction site with a pump. In the cofferdam method, impervious barriers are used to isolate part of the work area. Typically half the stream is dammed and the pipe is laid before moving to the other half. In the flume method, the stream is dammed and the stream is bypassed in a culvert that spans across the work area.

One negative to using these methods is the installation and removal of the dam can create a good bit of sediment. Other problems include: leakage around/underneath dam, dam and flume failures, insufficient pump capacity, flooding, and inadequate maintenance.

Pump-Around

The pump around method is the preferred technique to dewater a work site. It is the simplest method if the necessary equipment is available. This method requires damming the stream with a non-erodible material covered with an impervious membrane to create a pool upstream of the work area where a pump intake can be placed. Depending on the gradient of the stream another dam below the work area may be needed. In between the dams a dry work area is created. A pump moves the water around the construction area where the installation of the pipe can be done in the dry. It can be labor intensive when placing the sand or gravel bags. Obtaining sand bags in West Virginia can also be problematic.

Key issues:

1. Provide adequate sediment and erosion control on the approaches.
2. Construction should be preformed in low flow periods.
3. Use a pump or pumps sufficiently large to pump the entire stream flow around the site
4. Construct a dam impervious to water.
5. The inlet of the pump is to be suspended above the streambed in order to prevent sucking mud and sediment.
6. The discharge point must be stabilized with rock to disperse the energy and prevent erosion.

Cofferdam

Cofferdams have long been used to provide dry work areas. Their use is declining as other methods gain ground. However in the right circumstance they can still provide adequate performance. Cofferdams are labor intensive and costly and can be difficult to seal to prevent infiltration of water. To be used when stream diversion is not practical and stream is wide enough (10 feet or wider) to make cofferdam installation practical.

If the stream needs to be diverted more than 75% of its width, then Diversion Channel criteria should be followed.

a) Construction should be performed in low flow periods
b) Crossing shall be accomplished in a manner that will not inhibit the flow of the stream.
c) Dewatering to be accomplished in accordance with section for DEWATERING.
d) Cofferdams should not extend beyond 2/3 the width of the streambed to allow for stream flows.
e) As with all utility line crossings, approach areas should be controlled with perimeter measures (silt fence, diversions, etc.)
f) Remove large rocks, woody vegetation, or other material from the streambed and banks that may get in the way of placing the stone, sandbags, sheet metal, or wood planks or installing the utility pipe or line.
g) Form a cofferdam by placing stone or sandbags, jersey barriers (or other non-erodible materials), covered by an impervious material in a semicircle along the side of the stream in which the utility installation will begin. It must be surrounded and underlain with filter cloth as shown in the drawing. The height of and area within the dam will depend upon the size of the work area and the amount of stream flow. Stack materials as high as will be necessary to keep water from overtopping the dam and flooding the work area.
h) Cofferdams should be no more than one half the height of the stream bank plus one-foot.
i) When the stream flow is successfully diverted by the cofferdam, dewater the work area into a dewatering structure.
j) Stabilization of the crossing, streambanks, and approaches should occur immediately following completion of the crossing.

There are commercially available cofferdams now on the market. These water filled bladders or standing steel supports can be installed quickly and can provide cost savings over traditional hardened cofferdams. Their installation and removal can lessen the creation of sediment. Some of the products available are Portadam, Dam-it Dams, and Aqua-Barrier

Flume Pipe

A flume pipe crossing consists of two impervious dams across a stream with one or more culverts installed to pass the stream flow across the work area. A flume pipe crossing can be used when in-stream construction will last less than 72 hours and stream is narrow (less than 15 feet wide) or wider in low water conditions. Ideal for gas pipeline, sewerline and waterline construction especially when used in conjunction with and as an extension of a Vehicular Stream Crossing.

a) The flume pipe crossing must be made operational prior to the start of the instream construction.

b) A large flume pipe(s) or culvert(s) of an adequate size to support normal water channel flow (see Table 3.21.1) shall be installed in the streambed across the proposed pipeline trench centerline. Riprap, jersey barrier or sandbags shall be placed close to each end of the flume pipe so as to dam off the creek forcing the water to flow through the flume pipe (see drawing). Sandbags are the preferred method for diverting water into the flumes. The commercial cofferdams can be used if a tight seal can be created.

c) The entrapped water in the work area can then be pumped into an approved Dewatering Device. The trench can then be dug under the flume pipe. The pipe sections will then be installed to the proper depth under the flume pipe. After the pipe is installed, the ditch will be backfilled and restabilization shall be carried out.

d) Reclamation of the stream banks will occur the same day as the installation of he pipe is completed. Restabilization shall consist of the installation of ungrouted riprap on all disturbed streambank areas (or on the area 6 feet on both sides of the centerline of the utility trench, whichever is greater) with slopes of 3:1 or greater. Refer to the specification for Riprap, for installation requirements. For slopes of 3:1 or less, vegetative stabilization with or without Rolled Erosion Control Product may be used, pending approval by the Division of Water and Waste Management. Stabilization of its streambed and banks and the approach areas should occur immediately following the attainment of final grade.

e) After completion of backfilling operation and restoration of stream banks and leveling of streambed, the flume pipe can then be removed. The stone can be removed or spread as stabilization of the streambed depending on permit requirements. Sediment control in approach areas shall not be removed until all construction is completed in the stream crossing area and the contributing drainage area to the device is stabilized. All ground contours shall be returned to their original condition.

Drainage Area (Acres)	Table 3.21.1 Average Slope of Watershed			
	1%	4%	8%	16%
	Culvert Size			
1 – 25	24	24	30	30
26 - 50	24	30	36	36
51 – 100	30	36	42	48
101- 150	30	42	48	48
151 - 200	36	42	48	54
200 - 250	42	48	60	60
251 - 300	42	48	60	60
301 - 350	42	48	60	60
351 - 400	42	54	60	60
401 - 450	42	54	60	72
451 - 500	42	54	60	72
501 - 550	48	60	60	72
551 - 600	48	60	60	72
601 - 640	48	60	72	72

Note: Table is based on USDA-SCS Graphical Peak Discharge Method for 2-year frequency storm event, CN = 65; Rainfall depth = 3.5 inches (average for Virginia). Source: Va. DSWC

Open cut wet ditch

This technique does not use any method to divert the stream around the work area. The utility line is installed and backfilled while the river/stream continues to run through the site. The benefits are low cost and a quick completion time. However, this type of crossing produces some very negative impacts. These include severe pollution from greatly increased total suspended sediment (TSS) concentrations, changes in channel morphology, and localized destruction of aquatic ecosystems. These impacts can be somewhat mitigated by a quick completion time.

DEP does not recommend this type of crossing unless a creating a dry ditch is impossible. There shouldn't be any significant rain forecast during the entire construction timeframe. This method may be used with prior approval when other preferred methods are proven to be unfeasible.

Stabilization of the crossing, streambanks, and approaches should occur immediately following completion of the crossing.

The wet ditch method may be used when the following conditions are met:

a.) When the distance across the flume pipes become too wide for a backhoe to dig from both sides and connect the trench underneath the pipes. This measurement would vary according to the number of flume pipes, the height of the stream banks, the size and digging angle of the backhoe, the depth to bed rock and ease of digging.

b.) When the crossing can be accomplished within 72 hours. However, the contractor should make every effort to complete the crossing in one working day. All disturbed streambanks must be stabilized the same day the construction is finished

c.) When the crossing is at right angles (± 5°) to the stream channel.

d.) If water is pumped during the installation of the pipe it must be treated as per the DEWATERING specification.

This method is also applicable to small intermittent and ephemeral streams that are completely dry and no rain is forecast for the entire installation timeframe.

Stream Diversion Bypass

Temporary stream diversions are used when construction within a full flowing stream will create severe environmental impacts due the resulting sedimentation. This technique also provides a safe and dry work area. Typically a stream diversion is required when the construction of an instream structure will take place in the entire channel and the pump around or flume dewatering techniques would not be sufficient to handle the anticipated stream flows. It is also applicable when there is a significant construction timeframe. A stream diversion is most commonly used when a large fill is placed across a valley and a culvert is installed to carry the stream such as when building a road or dam.

Once started, any work to relocate the stream and install the permanent structure shall not be discontinued until it is completed. The connection to the natural channel should be performed under dry conditions

Diversion channels only work if there is sufficient room to both install the diversion and construct the structure.

Construction Specifications

a) The diversion channel crossing must be operational before the construction activity starts so that construction can occur “in the dry").
b) Minimum width of bottom shall be four feet or equal to average width of existing streambed, whichever is greater.
c) Maximum steepness of side slopes shall be 2:1. Depth and grade may be variable, dependent on site conditions, but shall be sufficient to ensure continuous flow of water in the diversion.
d) There are three types of diversion channel linings that can be used, based upon expected velocity of bankfull flow. Refer to the drawing and the accompanying table.

e) The seed mix for the grass liner is to be in accordance with the Temporary Seeding" section. An average growth of two inches in height shall be achieved throughout the diversion with 70% cover before water is turned into it.

f) Stream diversion liners shall be entrenched at the upstream end as shown in the stream channel drawing for ROLLED EROSION CONTROL PRODUCTS. Fabric liners must be stapled every three feet. Polyethylene liners shall be weighted with rock along the base of the side slope.

Table 3.21.2
STREAM DIVERSION LININGS

Acceptable Lining Material	Classification	Maximum Velocity
Grass and Matting	TYPE A	5.0 f.p.s.
Geotextile Filter Cloth	TYPE B	8.0 f.p.s.
Class I Riprap and Filter Cloth	TYPE C	13.0 f.p.s.

g) Start installing stream diversion liners at the downstream end. Stream diversion liners should be overlapped 18 inches (upstream over downstream) when a continuous liner is not available or is impractical. Overlaps along the sides should be made such that a liner is placed in the steam diversion bottom first and additional pieces of liner on the slopes overlap the bottom piece by a minimum of 18 inches. See ROLLED EROSION CONTROL PRODUCTS for drawings.

h) Stream diversion liners shall be entrenched at the top of the diversion slopes (slopes breaks) along with a line of silt fence. Silt fence may be excluded if the diversion liner is extended to such a point that siltation of the stream will not occur. If silt fence is excluded, the diversion liner must be secured. Liners shall extend from slope break to slope break as shown in the drawing.

i) Non-erodible materials such as riprap, jersey barriers, sandbags, or sheet piling, shall be used as flow barriers to divert the stream away from its original channel and to prevent or reduce backup into the lower end of the construction area.

j) The downstream and upstream connection to the natural channel should be performed under dry conditions and may be so accomplished by use of sandbag cofferdams. The downstream flow barrier is to be removed prior to the upstream barrier when preparing a stream diversion for the transport of water.

k) The diversion should be sealed off at the down stream end and then backfilled once water is put back in its original channel.

l) Stream should be re-diverted only after restabilization of original streambed and banks is completed or the inlet and outlet of the culvert pipe is finished. Stabilization of the streambed and banks and the approach areas should occur immediately following the attainment of final grade.

m) Temporary bypass channels should be backfilled and properly stabilized by riprap or RECPs to prevent the stream from reestablishing the path.

n) Any water pumped from this operation shall be directed into an approved Dewatering Structure.

Alternative Technique

Designers need to know that another way of installing culverts is possible. Traditionally a new culvert was installed as close to the original alignment of the existing stream as possible. This entails the construction of a significant stream diversion. If the conditions are right there is another way.

An alternative to building a stream diversion is to design and install the new culvert outside the existing stream channel and use the existing natural channel as the bypass. With this method there is much less likelihood of erosion and sedimentation of a temporary channel. Time can also be saved by not having to construct a whole new channel. The only "instream" work will be the tying in the old channel into the inlet and outlet channels of the new culvert or spillway.

It is sometimes likely that a combination of existing and new channel will be needed.

Other Considerations

Stream crossings must be approached as a separate project. All materials necessary to construct the crossing must be on site and ready to use. If possible, pipe should be coupled on shore and then pulled across and placed in the trench in one operation.

During reclamation it is not necessary to create a perfectly smooth stream bottom. Elevated spots should be removed but in most cases the bed load and scour from next high water event will eliminate all signs of the crossing. On smaller crossings the bed load from one flood event can fill the entire trench. In these cases, anchoring the pipe with river weights or critically placed buckets of gravel may be all that is required to reclaim the creek bottom.

It is important to use machinery that is in good mechanical shape. Use newer pieces of equipment that are less likely to have fluid leaks. Maintain spill containment kits inside each piece of equipment working in moving water. Maintain hydraulic hoses on equipment that is used for work in or around streams.

Refuel and maintain vehicles a minimum of 100 feet from of the stream. A comprehensive spill containment and cleanup kit should be readily available on site.

Maintenance

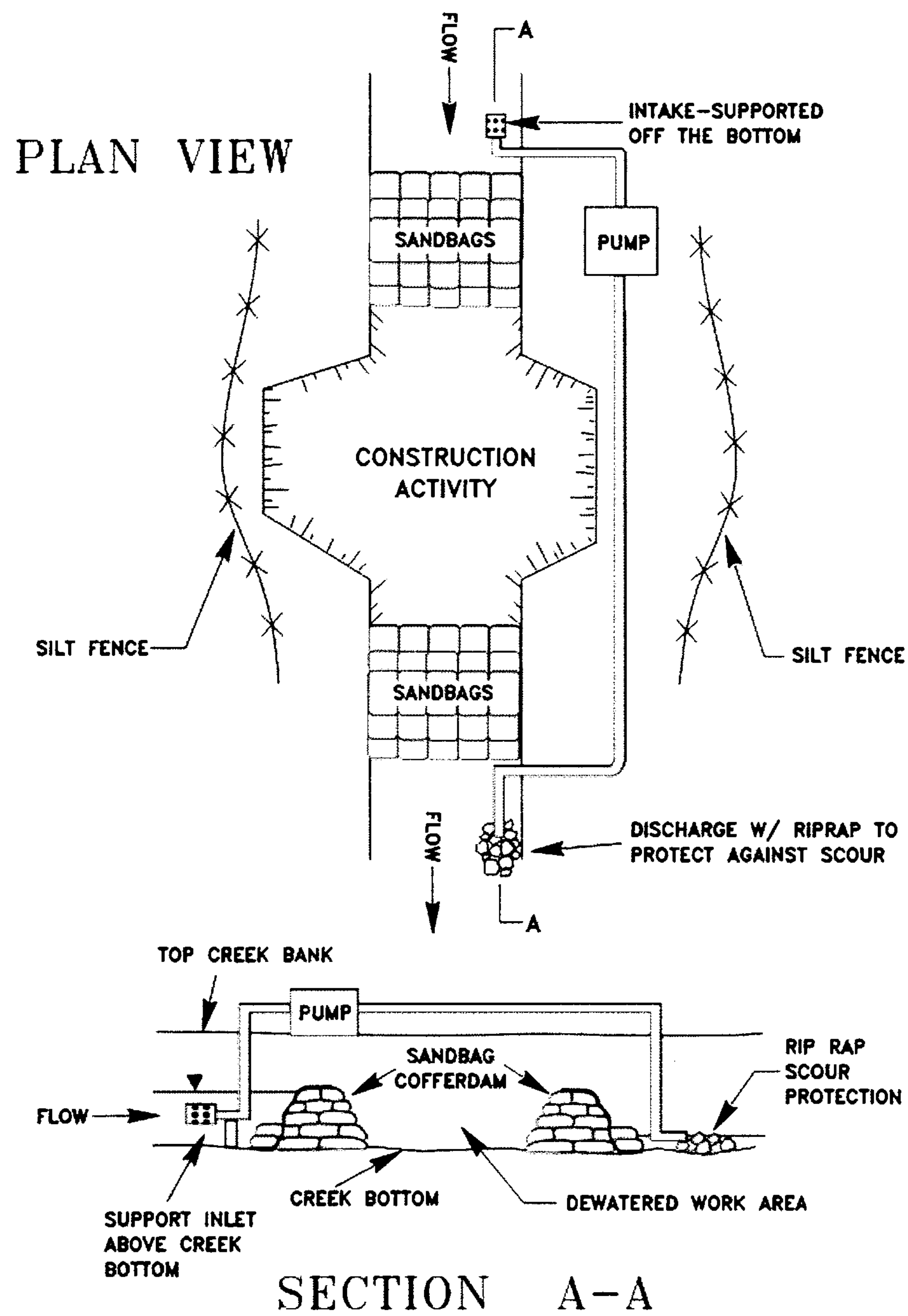
Structures and erosion and sediment controls should be inspected after every rainfall of 0.5 inches or more and at least once a week and repair all damages immediately. Check for debris especially flotsam clogging the inlet to the culverts. All deposited materials and obstructions must be removed immediately.

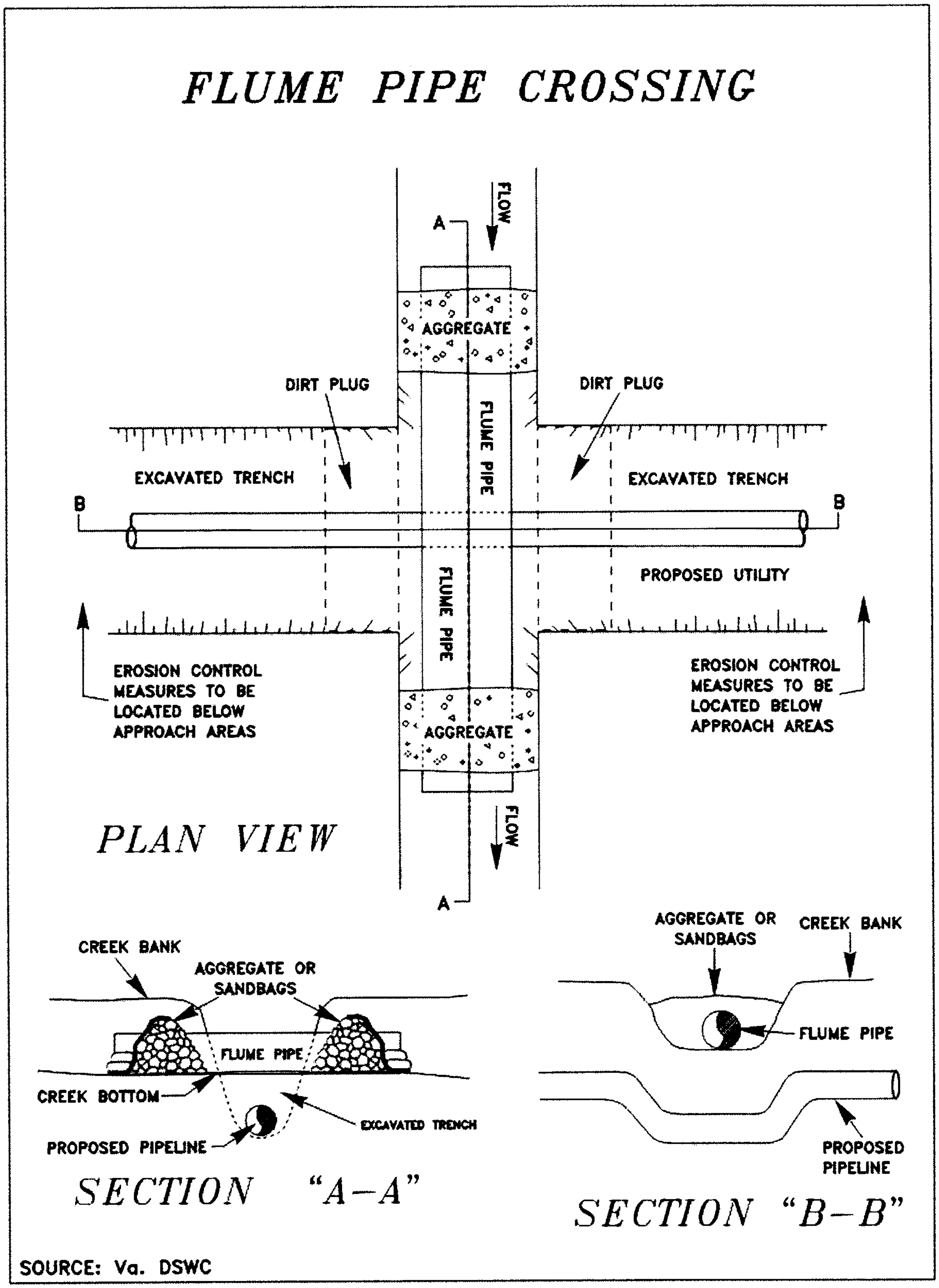
In general inspect all active steam crossings at the end of each day to make sure that the construction materials are positioned securely. This will ensure that the work area stays dry and that no construction materials float downstream. The contractor should carefully watch the weather forecast and coordinate the installation based on the proper conditions.

Cleanup and stabilize the entire stream crossing site immediately upon completion of the installation of the pipe. One exception would be on a natural gas transmission lines where the attached vehicle crossing will be used for an extended time. Stabilize all other areas immediately.

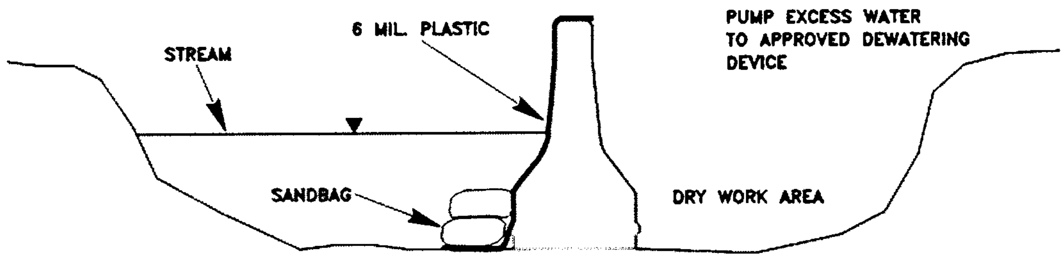
FIGURE

PUMP AROUND

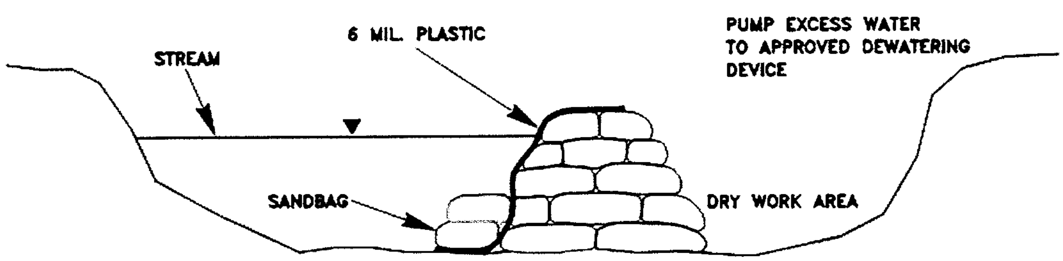



FLUME PIPE CROSSING
FLOW
A
AGGREGATE
DIRT PLUG
DIRT PLUG
FLUME PIPE
EXCAVATED TRENCH
EXCAVATED TRENCH
B
B
PROPOSED UTILITY
FLUME PIPE
EROSION CONTROL MEASURES TO BE LOCATED BELOW APPROACH AREAS
EROSION CONTROL MEASURES TO BE LOCATED BELOW APPROACH AREAS
AGGREGATE
PLAN VIEW
FLOW
A
CREEK BANK
AGGREGATE OR SANDBAGS
FLUME PIPE
CREEK BOTTOM
EXCAVATED TRENCH
PROPOSED PIPELINE
SECTION "A–A"
AGGREGATE OR SANDBAGS
CREEK BANK
FLUME PIPE
PROPOSED PIPELINE
SECTION "B–B"
SOURCE: Va. DSWC

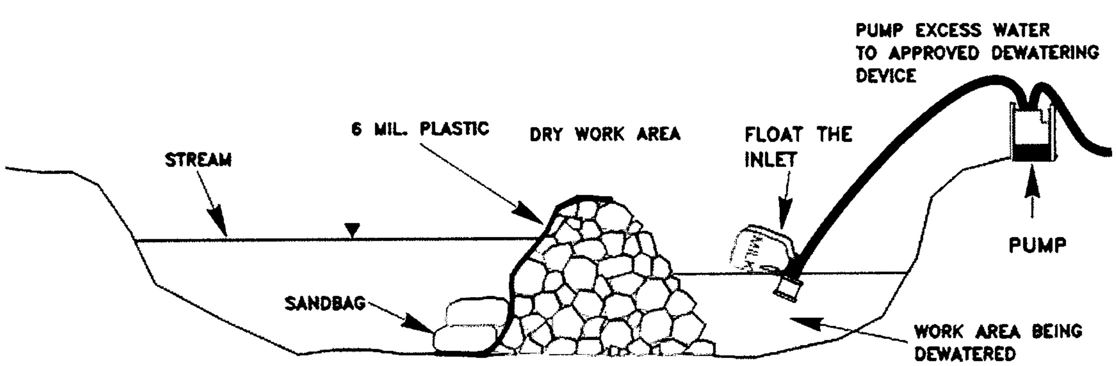
COFFERDAMS



JERSEY BARRIER COFFERDAM

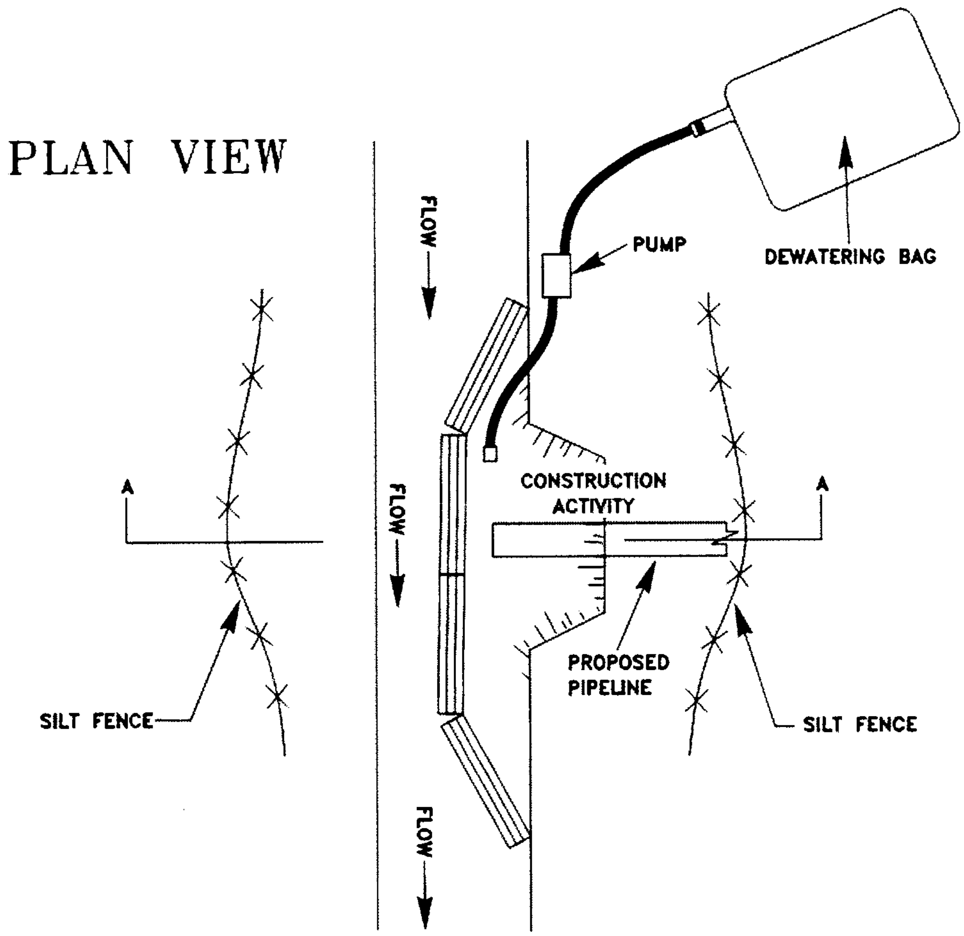


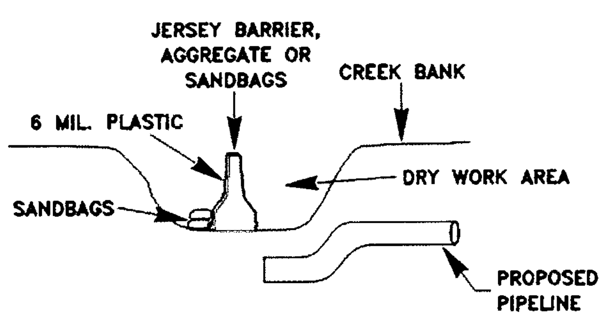
SAND or GRAVEL BAG COFFERDAM



ROCK COFFERDAM

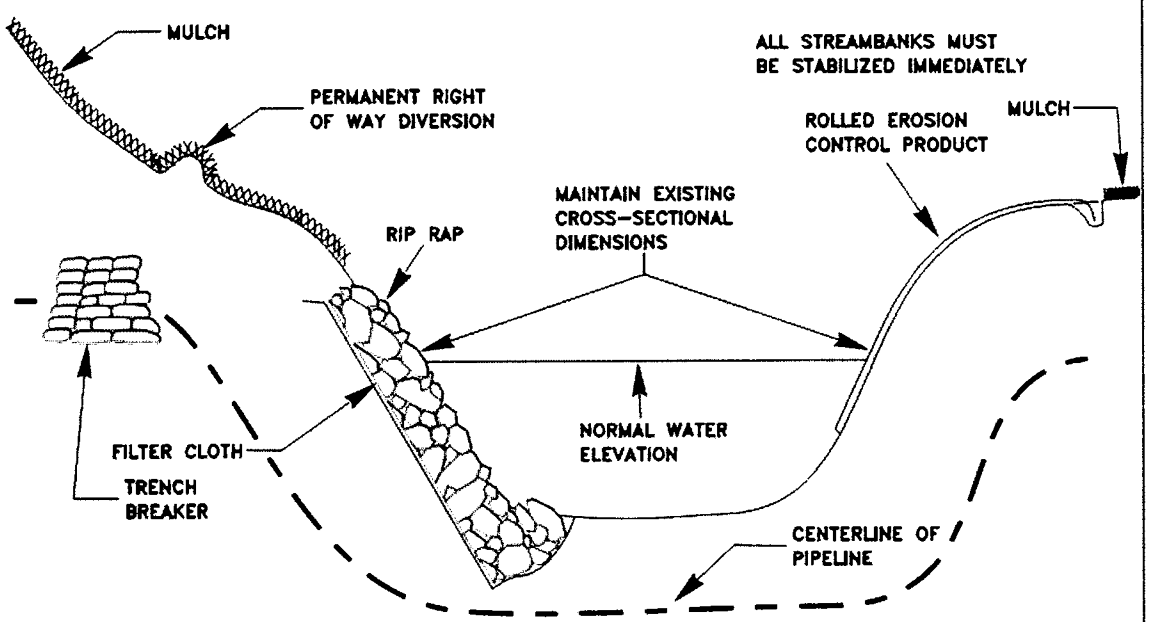
COFFERDAM CROSSING



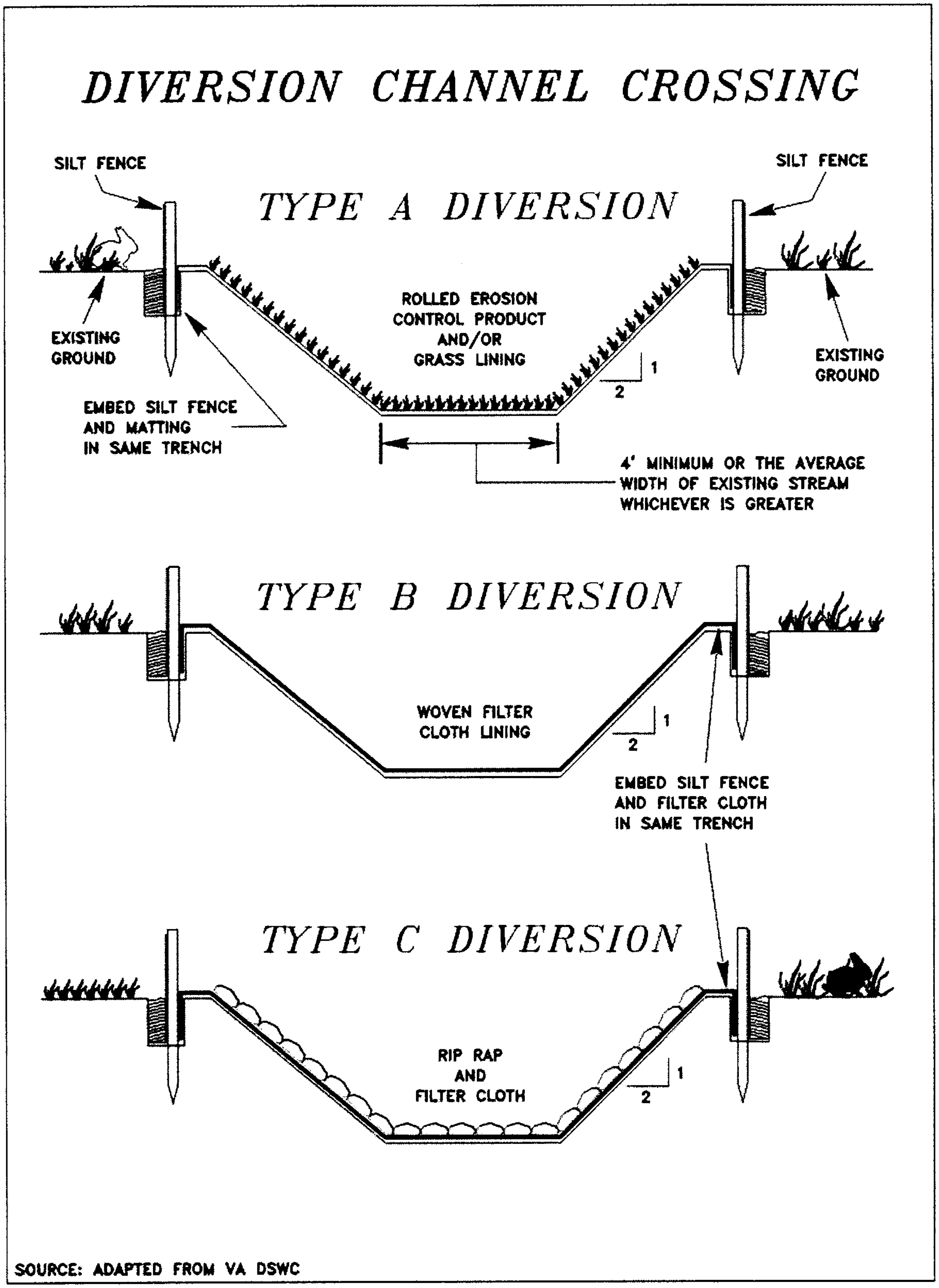


SECTION "A – A"

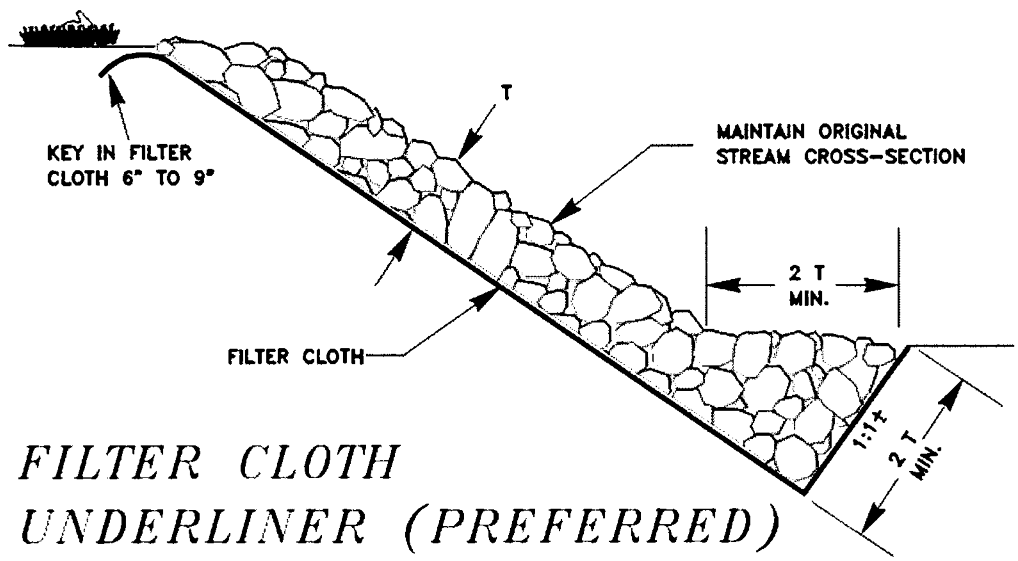
STREAM BANK STABILIZATION SHOWING VARIETY OF E/S CONTROLS



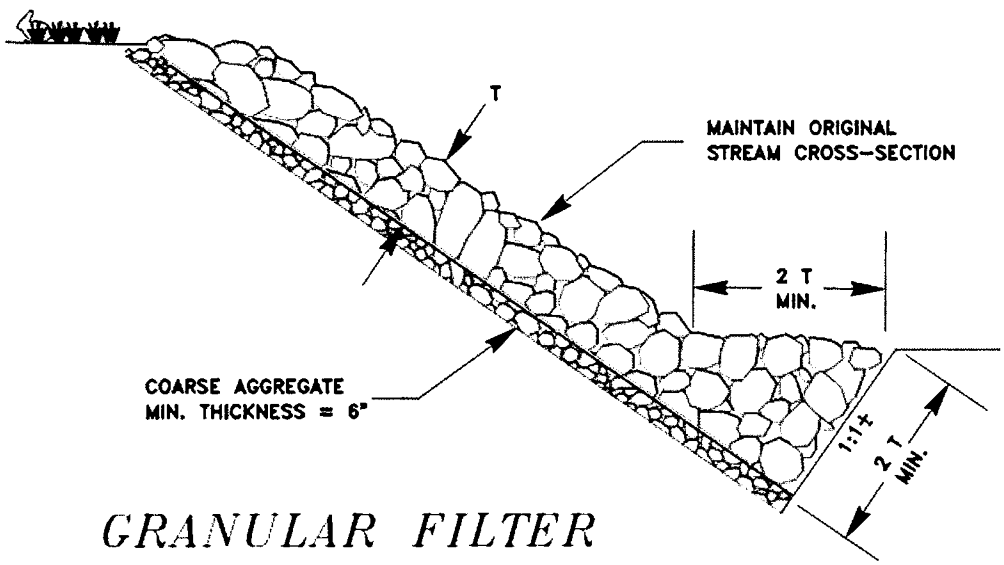
ADAPTED FROM DOMINION RESOURCES


DIVERSION CHANNEL CROSSING
SILT FENCE
SILT FENCE
TYPE A DIVERSION
ROLLED EROSION CONTROL PRODUCT AND/OR GRASS LINING
EXISTING GROUND
EXISTING GROUND
1
2
EMBED SILT FENCE AND MATTING IN SAME TRENCH
4' MINIMUM OR THE AVERAGE WIDTH OF EXISTING STREAM WHICHEVER IS GREATER
TYPE B DIVERSION
WOVEN FILTER CLOTH LINING
1
2
EMBED SILT FENCE AND FILTER CLOTH IN SAME TRENCH
TYPE C DIVERSION
RIP RAP AND FILTER CLOTH
1
2
SOURCE: ADAPTED FROM VA DSWC

TOE AND UNDERLAYMENT REQUIREMENTS FOR BANK STABILIZATION



FILTER CLOTH UNDERLINER (PREFERRED)



GRANULAR FILTER

SOURCE: Adapted from VDOT Drainage Manual

Temporary Vehicular Stream Crossing

A temporary structural span (includes bridges, round pipes, pipe arches, or oval pipes) installed across a watercourse for use by construction traffic. These structures are used to provide a means for construction traffic to cross a stream without damaging the channel or banks and to keep sediment generated by construction traffic out of the stream.

A rule of thumb is that if there are more than two crossings a stabilized stream crossing must be installed. As an example, if during the clearing and grubbing a bulldozer has to cross a stream going out and coming back just once a culverted stream crossing is not necessary. However if the route the bulldozer takes becomes the access to the site and more than one other vehicle has to cross the stream then a crossing a specified here needs to be installed.

Generally applicable to streams with drainage areas less than 1 square mile (660 acres).

For streams larger than 1 square mile the structure should be designed by a registered professional engineer, using professionally recognized methods that will more accurately define the actual hydrologic and hydraulic parameters that will affect the functioning of the structure.

Design Criteria

Temporary Bridge Crossing

a. Bridges may be designed in various configurations. However, the materials used to construct the bridge must be able to withstand the anticipated loading of the construction traffic.

b. Crossing Alignment - The temporary waterway crossing shall be at right angles to the stream. Where the approach conditions dictate, the crossing may vary 15E from a line drawn perpendicular to the centerline of the stream at the intended crossing location.

c. The centerline of both roadway approaches shall coincide with the crossing alignment centerline for a minimum distance of 50 feet from each bank of the waterway being crossed. If physical or right-of-way restraints preclude the 50 feet minimum, a shorter distance may be provided. All fill materials associated with the roadway approach shall be limited to a maximum height of 2 feet above the existing flood plain elevation.

d. A water diverting structure such as a dike or swale shall be constructed (across the roadway on both roadway approaches) 50 feet (maximum) on either side of the waterway crossing. This will prevent roadway surface runoff from directly entering the waterway. The 50 feet is measured from the top of the waterway bank. If the roadway approach is constructed with a reverse grade away from the waterway, a separate diverting structure is not required.

e. Appropriate perimeter controls such as SILT FENCE, SUPER SILT FENCE and/or DIVERSION and SEDIMENT TRAP must be employed when necessary along banks of stream parallel to the same.

f. Clearing and excavation of the streambed and banks shall be kept to a minimum.

g. The temporary bridge structure shall be constructed at or above bank elevation to prevent the entrapment of floating materials and debris.

h. Any abutments shall be placed parallel to and on stable banks.

i. Bridges shall be constructed to span the entire channel. Instream piers should be kept to a minimum. Any work within the normal high water mark will require a Public Lands Corporation Right-of-Entry, a Army Corps of Engineers 404 Permit and WV DEP 401 Certification..

j. Stringers shall either be logs, sawn timber, pre-stressed concrete beams, metal beams, or other engineer-approved materials.

k. Curbs or fenders may be installed along the outer sides of the deck. Curbs or fenders are an option that will provide additional safety and keep mud from flowing over the edge into the stream.

l. Bridges should be securely anchored at only one end using steel cable or chain. Anchoring at only one end will prevent channel obstruction in the event that floodwaters float the bridge. Acceptable anchors are large trees, large boulders, or driven steel anchors. Anchoring shall be sufficient to prevent the bridge from floating downstream and possibly causing an obstruction to the flow.

m. All areas disturbed during installation shall be stabilized immediately.

n. When the temporary bridge is no longer needed, all structures including abutments and other bridging materials should be removed immediately.

o. Final clean up shall consist of removal of the temporary bridge from the waterway, protection of banks from erosion, and removal of all construction materials. All removed materials shall be stored outside flood plain of the stream. Removal of the bridge and clean up of the area shall be accomplished without construction equipment working in the waterway channel.

Temporary Culvert Crossing

a. 2” to 4” Coarse Aggregate or larger will be used to form the crossing. DO NOT USE ERODIBLE MATERIAL FOR CONSTRUCTION OF THE CROSSING. The depth of stone cover over the culvert shall be equal to one-half the diameter of the culvert or 12 inches, whichever is greater. If multiple culverts are used, they shall be separated by at least 12 inches of compacted aggregate fill. To protect the sides of the stone from erosion, riprap shall be used.

b. If the structure will remain in place for up to 6 months, the culvert shall be large enough to convey the bankfull flow without appreciably altering the stream flow characteristics. To insure the proper capacity the culvert(s) should have cross sectional area equal to the cross sectional area of the stream at bankfull.

Should the structure will remain in place 6 months or longer, the culvert shall be large enough to convey the flow from a 10-year frequency storm. In this case, the hydrologic calculations and subsequent culvert size must be done for the specific watershed characteristics. If the structure must remain in place over 1 year, a qualified registered Professional Engineer must design it as a permanent measure.

c. Multiple culverts may be used in place of one large culvert if they have the equivalent capacity of the larger one. The minimum sized culvert that may be used is 18 inches. Two 18-inch culverts do not replace a 36-inch culvert.

d. All culverts shall be strong enough to support their cross-sectioned area under maximum expected loads.

e. The culvert(s) shall extend a minimum of five foot beyond the upstream and downstream toe of the aggregate placed around the culvert.

f. The slope of the culvert shall be at least 0.25 inch per foot.

g. Crossing Alignment - The temporary waterway crossing shall be at right angles to the stream. Where approach conditions dictate, the crossing may vary 15 from a line drawn perpendicular to the centerline of the stream at the intended crossing location.

h. The centerline of both roadway approaches shall coincide with the crossing alignment centerline for a minimum distance of 50 feet from each bank of the waterway being crossed. If physical or right-of-way restraints preclude the 50 feet minimum, a shorter distance may be provided. All fill materials associated with the roadway approach shall be limited to a maximum height of 2 feet above the existing flood plain elevation.

i. The roadway approaches to the structure shall consist of stone pads meeting the following specifications:

1) Stone: 2”- 4”
2) Minimum thickness: 6 inches
3) Minimum width: equal to the width of the structure
4) Minimum length: 50 feet on either side of the crossing.

j. A water diverting structure such as a swale shall be constructed (across the roadway on both roadway approaches) 50 feet (maximum) on either side of the waterway crossing. This will prevent roadway surface runoff from directly entering the waterway. The 50 feet is measured from the top of the waterway bank. If the roadway approach is constructed with a reverse grade away from the waterway, a separate diverting structure is not required.

k. Appropriate perimeter controls such as SILT FENCE, SUPER SILT FENCE and/or DIVERSION and SEDIMENT TRAP must be employed when necessary along banks of stream parallel to the same.

l. Clearing and excavation of the streambed and banks shall be kept to a minimum.

m. The invert elevation of the culvert shall be installed on the natural streambed grade to minimize interference with fish migration.

n. Filter cloth shall be placed on the streambed and streambanks prior to placement of the pipe culvert(s) and aggregate. The filter cloth shall cover the streambed and extend a minimum of six inches and a maximum of one foot beyond the end of the culvert and bedding material. Filter cloth reduces settlement and improves crossing stability. The required physical qualities of the filter cloth should be sufficient for the anticipated loads.

o. When the crossing has served its purpose, all structures including culverts, bedding and filter cloth materials shall be removed. Removal of the structure and clean up of the area should be accomplished without construction equipment working in the waterway channel.

p. Upon removal of the structure, the stream bank shall immediately stabilized.

q. During routine road maintenance do not grade mud and debris over the sides of the crossing into the stream.

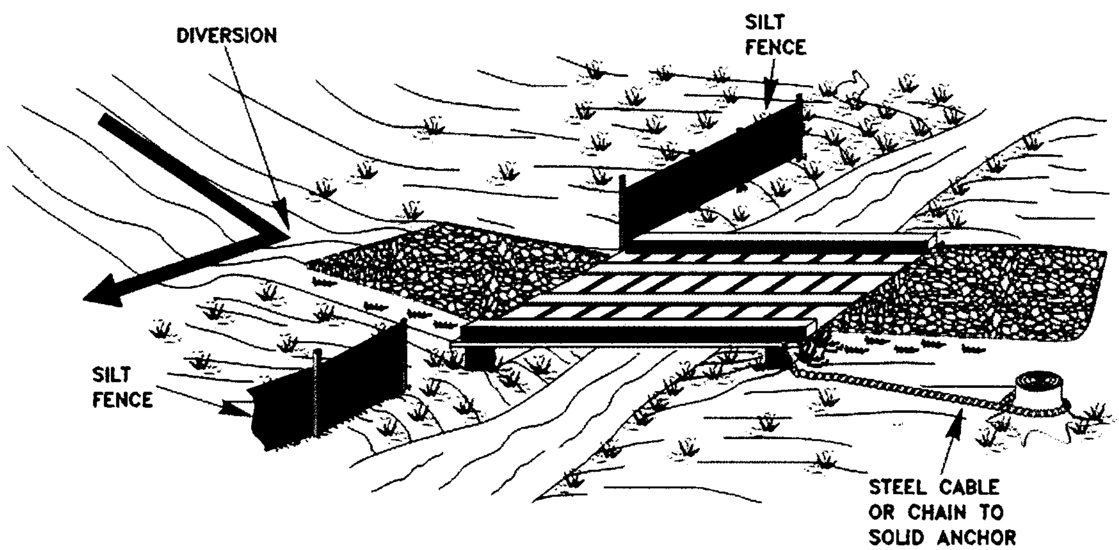
When the temporary structure has served its purpose, including bridge abutments or culverts and other bridging materials shall be removed and the disturbed area stabilized within 7 days. Care should be taken so that any aggregate left does not create an impediment to the flow or restrict fish passage.

All construction materials shall be stored outside the waterway flood plain. Clean up shall be accomplished without construction equipment working in the stream channel.

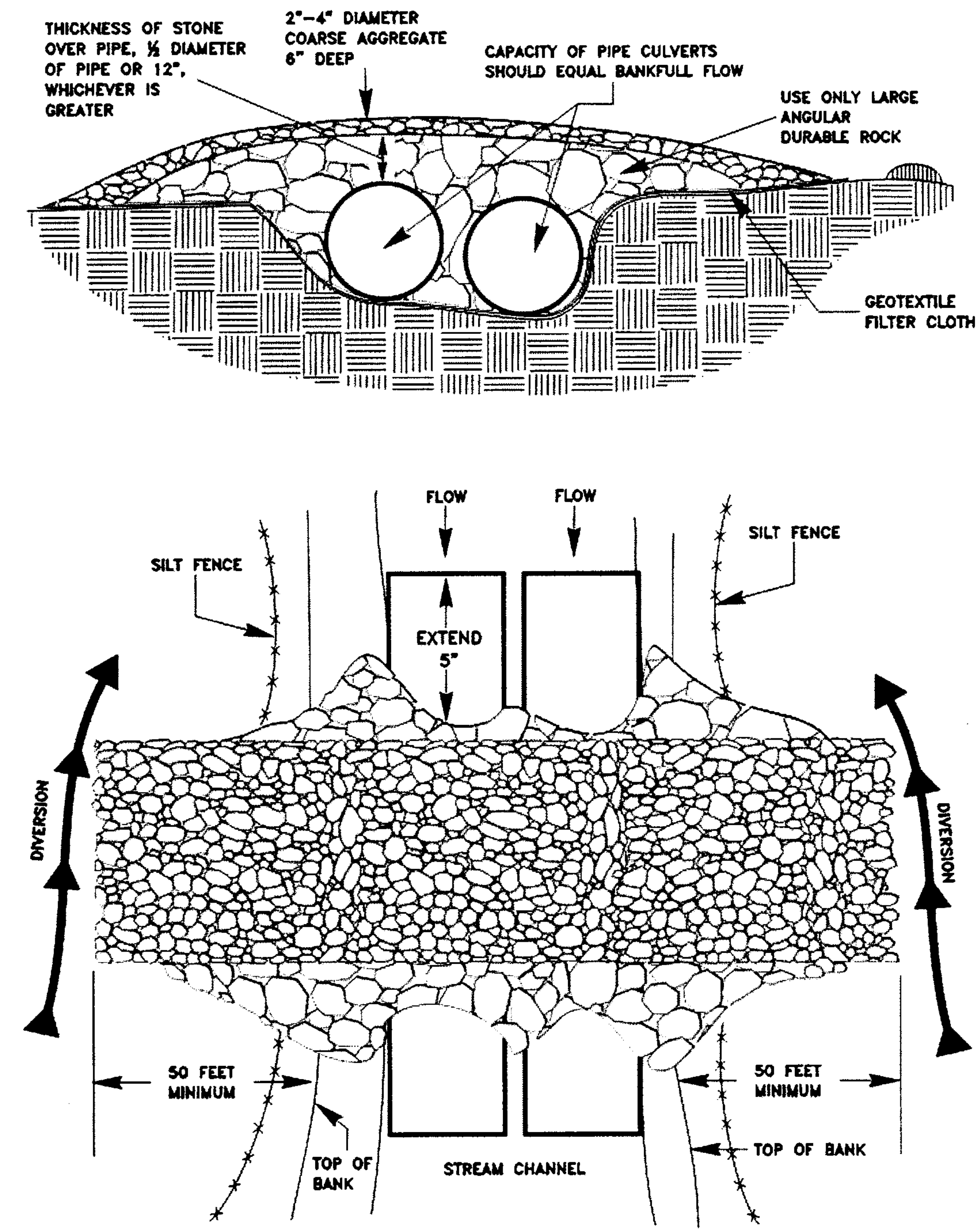
Maintenance Periodic inspection must be performed to ensure that the bridge, culverts, streambed and stream banks are maintained and not damaged, that sediment is not entering the stream. At a minimum each crossing must be inspected after every rain event of 0.5 inches or more and once a week. Never allow the culverts to become clogged with debris Remove any obstructions immediately.

Sediment and debris removed shall be disposed of outside of the flood plain and stabilized.

TEMPORARY BRIDGE CROSSING



CULVERT STREAM CROSSING



FROM: VA DSWC

MINIMUM STANDARDS FOR INSTREAM CONSTRUCTION ACTIVITIES

General Requirements for all instream activities

1. All appropriate permits should be obtained prior to beginning instream construction activities such as construction activities such as creating a restriction or impediment of flow. See the Regulatory Requirements section of this manual.
6. Isolating the work area and "working in the dry" is the only effective way of controlling sediment.
7. All instream construction should be scheduled to occur during low flow periods, typically during the summer and fall months. If construction must be accomplished during higher flows, the work area must be isolated from the stream by a structural measure such as a non-erodible cofferdam or sheet piling. Emergency repairs of public utilities or public roads are exempted.
8. All streambanks are to be stabilized with an appropriate protective material such as riprap, revegetation, geotextiles, revetments, etc. immediately upon completion of the final grading.
9. The choice of stabilization materials (vegetative or structural) should be based on sound engineering practices and will include investigations of the soil's erodibilty and the anticipated velocities of the stream.
10. Inlet and outlet protection is required for all culverts (both temporary and permanent). Outlet protection can consist of riprap, gabion baskets, or other approved materials. See Outlet Protection section of this manual.
11. Every effort, in both planning and construction, should be made to limit the amount of instream work. Utility lines should not be installed within the stream, with the exception of stream crossing, without irrefutable proof that alternate avenues of alignment are not available. Convenience is not a justifiable reason to install a utility line down a stream.
12. Utility lines and roadways should cross the stream at right angles (± 15°) to the flow of the water.
13. Each stream crossing should be treated as a separate project and work should progress until the approaches and stream banks are completely stabilized. In no case should stabilization of the stream bank exceed 24 hours from completion of the backfill.
14. Streamside vegetation should be left intact to the greatest extent possible. Riparian buffer zones are to be enhanced whenever possible.
15. The sequence of construction events for the each instream activity should be included in the sediment control plan.

16. When a stream crossing is being constructed for vehicles, the crossing should be constructed as detailed in vehicle stream crossing section of this manual.
17. When work is performed in a flowing stream, precautions should be taken to minimize encroachment, control sediment transport and stabilize the work area to the greatest extent possible during construction. Use only non-erodible material for the construction of causeways, stream diversions and berms and cofferdams. Earthen fill may be used for cofferdams if armored by non-erodible cover materials such as filter fabric and appropriately sized stone.
18. All water pumped from a work area along, in or near a stream must be treated in an approved settling structure located outside the waterway before being discharged into a waterway. See DEWATERING section of this manual.
19. Green concrete is toxic to aquatic life and must not be placed in contact with flowing water.
20. Streambed excavation should be undertaken from the top of stream banks whenever possible.
21. When instream work is required, the use of rubber-tired vehicles and excavators is recommended.
22. Excavated material to be reused for trench backfill should be stockpiled outside the stream channel. Surround the storage area by silt fence or similar barrier to prevent sediment and mud from running back into the stream. Material not used for backfill should be removed to an appropriate soil disposal area located outside the floodplain and properly stabilized.
23. Temporary access roads in close proximity to a stream should be stabilized using the same requirements for a Stabilized Construction Entrance.
24. Do not use the stream as a vehicular right-of-way. Do not use the stream to deliver materials or to move construction equipment from one section to another.
25. Spill containment kits should be readily available onsite.

3.22 - DEWATERING

Definition

Dewatering refers to the act of removing and discharging water from excavated areas on construction sites, utility line construction or from sediment traps or basins on construction sites.

Given the unique conditions at any particular construction site, any or all of the practices may apply. In all cases, every effort shall be made to eliminate sediment pollution associated with dewatering.

Practices for Dewatering Excavated Areas

1. Pumping of water to an existing sediment basin or trap in which the entire volume of water from the area to be dewatered can be contained without discharge to receiving waters.
2. Pumping of water to an existing sediment basin or trap such that the entire volume of water from the area to be dewatered can be managed without exceeding the design outflow from the sediment control structure.
3. Use of a straw bale/silt fence pit or trap as shown in the drawings.
4. Pumping water through a geotextile bag made specifically for this purpose.
5. A well-vegetative Filter Strip, capable of withstanding the velocity of discharged water without eroding. Install some sort of energy dissipation (haybales, riprap or sheet of plywood) at the pump discharge.
6. Use a sump pit as shown on drawings to reduce the pumping mud.

Dewatering of Sediment Traps and Basins

Designers shall specify on plans, in the sequences of events and in the the practices for dewatering of traps and basins. In all cases, water removed from traps and basins shall be discharged so that it passes through a sediment control device prior to entering receiving waters.

Practices for Dewatering of Traps and Basins

1. Use of a straw bale/silt fence pit or trap as shown in the drawings.
2. Pumping water through a geotextile bag made specifically for this purpose.
3. A well-vegetative Filter Strip, capable of withstanding the velocity of discharged water without eroding. Install some sort of energy dissipation (haybales, riprap or sheet of plywood) at the pump discharge.
4. Regardless of the type of treatment always use a floating suction hose to pump the cleaner water from the top of the pond. As the cleaner water is pumped, the suction hose will lower and

eventually encounter sediment-laden water. At this point cease pumping operations and remove the remainder of the trapped sediment with machinery. Even when pumping from the top of the water column, provisions must still be made to filter water as required in this section prior to discharging to a stream. During the dewatering, personnel should be assigned to monitor pumping operations at all times to ensure that sediment pollution is abated. Pumping sediment-laden water into the waters of the State without filtration is prohibited.

Design Criteria

1. The dewatering device must be sized (and operated) to allow pumped water to flow through the filtering apparatus without exceeding the capacity of the structure. The following formula can be used to determine the storage volume for dewatering structures:

   Pump discharge (g.p.m.) x 16 = cubic feet of storage required

2. Material from any required excavation shall be stored in an area and protected in a manner that will prevent sediments from eroding and moving off-site.
3. An excavated basin (applicable to "Straw Bale/Silt Fence Pit") may be lined with filter fabric to help reduce scour and to prevent erosion of soil from within the structure. It may also be helpful to direct the discharge onto a hay or straw bale or riprap.
4. Design criteria more specific to each particular dewatering device can be found in the drawings.

Construction Methods

Straw Bale/Silt Fence Pit

a. Measure shall consist of straw bales, silt fence, a stone outlet consisting of a combination of 4-8 inch riprap and ½ to 2 inch aggregate and a wet storage pit oriented as shown in drawing.
b. The excavated area should be a minimum of 3 feet below the base of the perimeter measures (straw bales or silt fence).
c. Once the water level nears the crest of the stone weir (emergency overflow), the pump must be shut off while the structure drains down to the elevation of the wet storage.
d. The wet storage pit may be dewatered only after a minimum of 6 hours of sediment settling time. This effluent should be pumped across a well-vegetated area or through a silt fence prior to entering a watercourse.
e. Once the device has been removed, ground contours will be returned to original condition.

Geotextile Filter Bag

a. The bag shall be installed on a very slight slope so incoming water flows downhill through the bag without creating more erosion.
b. The neck of the Filter Bag shall be tightly strapped (minimum two straps) to the discharge hose.
c. The bag should be placed on an aggregate or hay bale bed to maximize water flow through the entire surface area of the bag.
d. The Filter Bag is full when it no longer can efficiently filter sediment or pass water at a reasonable rate.
e. Flow rates vary depending on the size of the Dewatering Device, amount of sediment discharged into the Dewatering Device, the type of ground, rock, or other substance under the bag and the degree of the slope on which the bag lies. The Filter Bag should be sized to accommodate the anticipated flow rates from the type of pump used. Typically Filter Bags can handle flow rates of up to 1000 gallons per minute, but in all cases follow the manufacturers recommendations for flow rates.
f. Use of excessive flow rates or overfilling the Dewatering Device with sediment will cause ruptures of the bag or failure of the hose attachment straps.
g. The Filter Bag can be left in place after cutting the top off and seeding and mulching the accumulated sediment or removed and disposed of offsite in an approved landfill.
h. Each standard Dewatering Device shall have a fill spout large enough to accommodate the discharge hose. Use two stainless steel straps to secure the hose and prevent pumped water from escaping without being filtered.
i. The Dewatering Device shall be a nonwoven bag, which is sewn with a double needle stitching using a high strength thread.
j. The Dewatering Device seams shall have an average wide width strength per ASTM D 4884 of 100 LB/IN (1.15 kg/meter).
k. The geotextile fabric shall be a nonwoven fabric with the following properties:

Table 3.22.1 GEOTEXTILE FABRIC PROPERTIES

Properties	Test Method	English	Metric
Grab Tensile	ASTM D-4632	250 Lbs.	113 kg
Puncture	ASTM D-4833	165 Lbs.	75 kg
Flow Rate	ASTM D-4491	70 Gal/Min/ Square Foot	25 liters/Min/ Square Meter
Permitivity	ASTM D-4491	1.3 Sec.-1	1.3 Sec.-1
Mullen Burst	ASTM D-3786	550 Lbs./ Square inch	3.79 MPa
UV Resistant	ASTM D-4355	70%	70%
AOS % Retained	ASTM D-4751	100%	100%

*All properties are minimum average roll value.

Maintenance

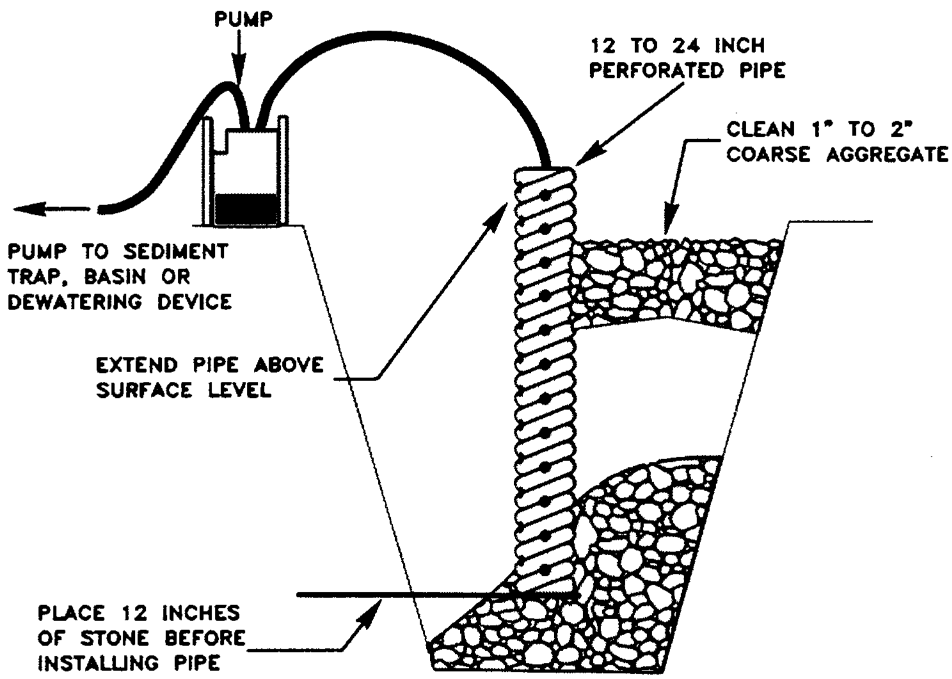
The filtering devices must be inspected frequently during pumping operations and repaired or replaced once the sediment build-up prevents the structure from functioning as designed.

Once the wet storage area becomes filled with sediment to one-half of the excavated depth, accumulated sediment shall be removed and disposed of properly.

The accumulated sediment that is removed from a dewatering device must be spread on-site and stabilized or disposed of at an approved disposal site as per approved plan.

FIGURE 3.22–1

SUMP PIT

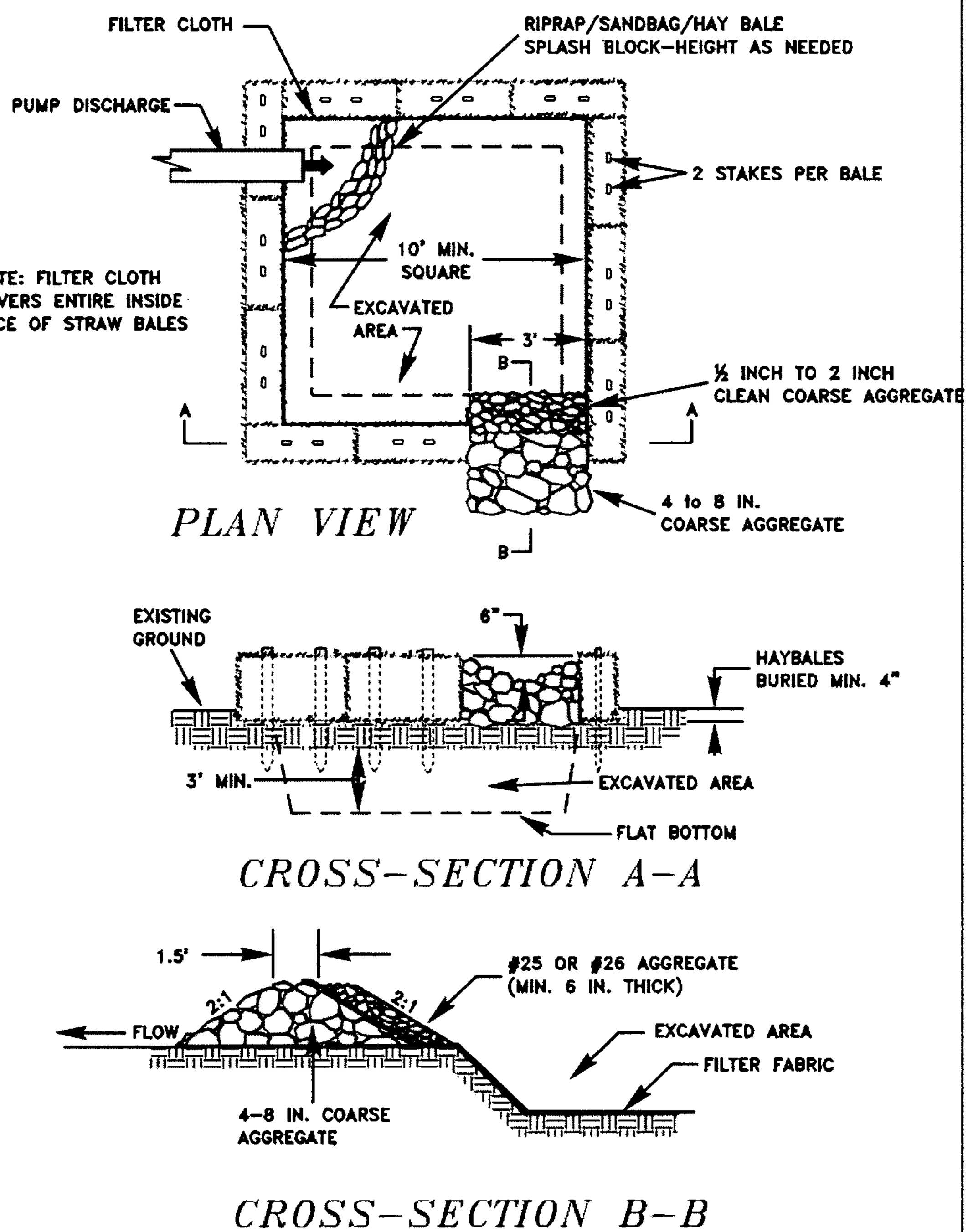


FROM NEW YORK DEC

3.22-5

FIGURE 3.22-2

STRAW BALE/SILT FENCE PIT

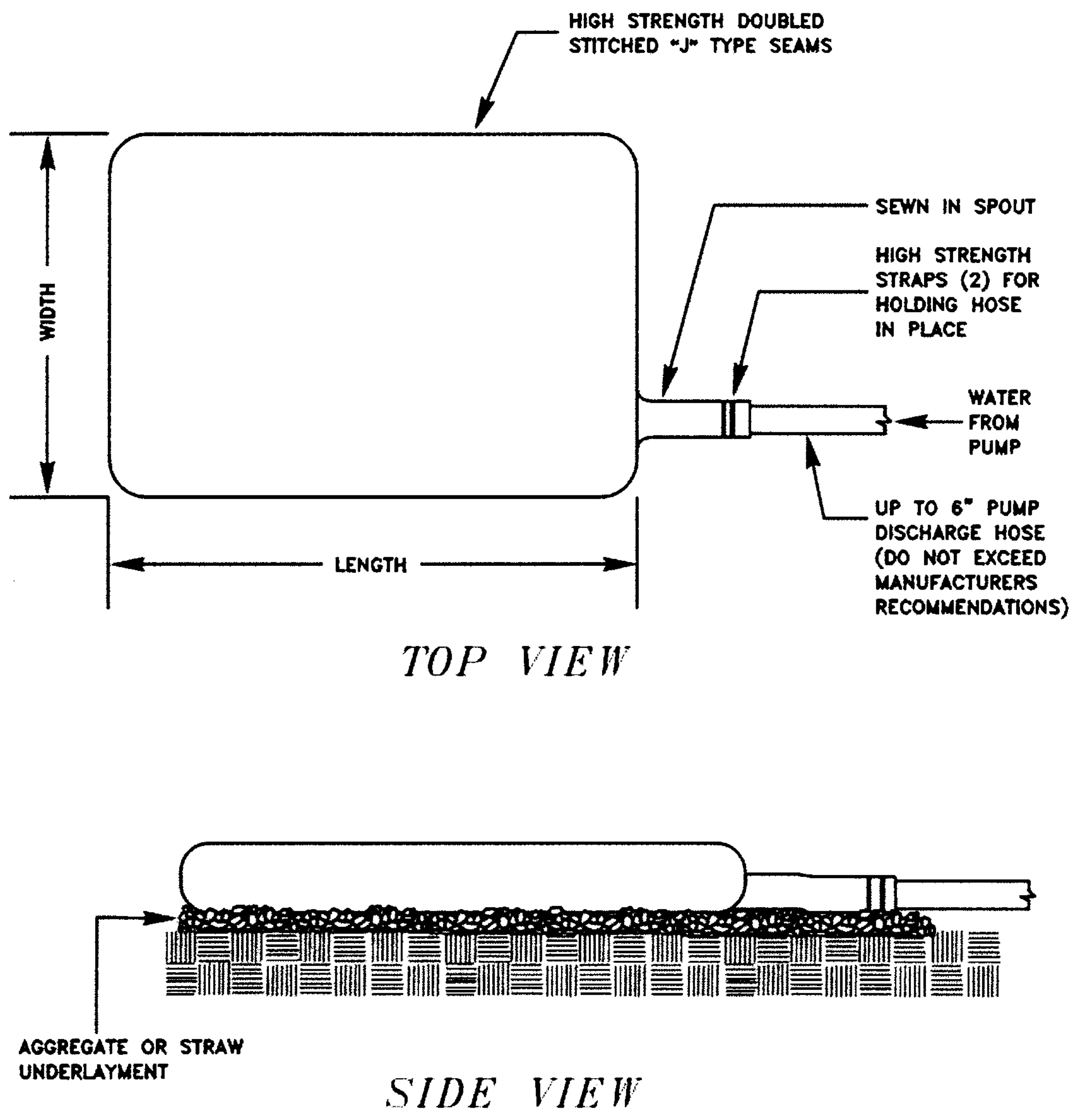


SOURCE: Va. DSWC

3.22-6

FIGURE 3.22-3

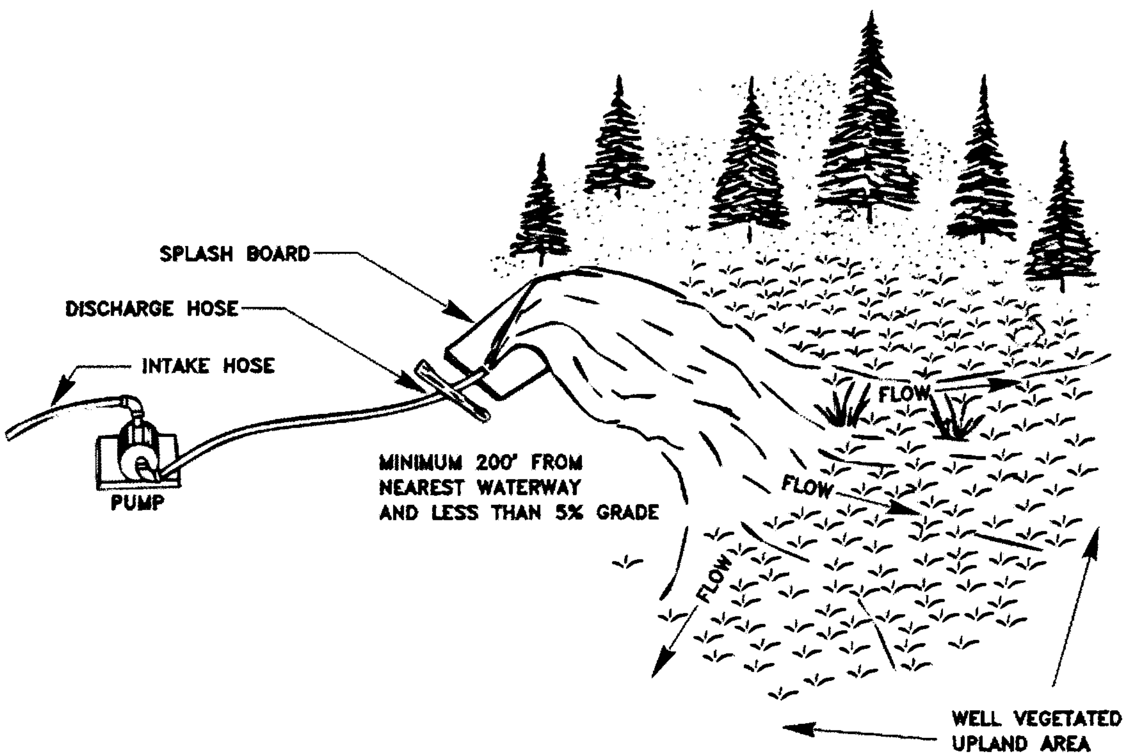
DEWATERING BAG



3.22-7

FIGURE 3.22–4

DEWATERING DISCHARGE IN UPLAND AREA WITH ADEQUATE VEGETATION



FROM: CNG TRANSMISSION CORP.

3.22-8

3.23 - RIPRAP

Introduction

A permanent, erosion-resistant ground cover of large, loose, angular stone with filter fabric or granular underlining used to protect the soil from:

1. The erosive forces of concentrated runoff.

2. To slow the velocity of concentrated runoff while enhancing the potential for infiltration.

3, To stabilize slopes with seepage problems and/or non-cohesive soils.

Conditions Where Practice Applies

Wherever soil and water interface and the soil conditions, water turbulence and velocity, expected vegetative cover, etc., are such that the soil may erode under the design flow conditions. Riprap may be used, as appropriate, at storm drain outlets, on channel banks and/or bottoms, roadside ditches, drop structures, at the toe of slopes, as transition from concrete channels to vegetated channels, etc.

Planning.

Riprap is classified as either graded or uniform. A sample of graded riprap would contain a mixture of stones that vary in size from small to large. A sample of uniform riprap would contain stones which are all fairly close in size. For most applications, graded riprap is preferred to uniform riprap. Graded riprap forms a flexible self-healing cover, while uniform riprap is more rigid and cannot withstand movement of the stones. Graded riprap is cheaper to install, requiring only that the stones be dumped so that they remain in a well-graded mass. Hand or mechanical placement of individual stones is limited to that necessary to achieve the proper thickness, line and grade. Uniform riprap requires placement in a more or less uniform pattern, requiring more hand or mechanical labor.

Riprap sizes can be designed by either the diameter or the weight of the stones. The weight of the stone is the more significant design parameter but it is simpler to specify the diameter of the stone. The correlation between stone size and weight is typically based upon an assumed specific weight of 165 lbs./ft3.

Since graded riprap consists of a variety of stone sizes, a method is needed to specify the size range of the mixture of stone. This is done by specifying a diameter of stone in the mixture for which some percentage, will be smaller. For example, d85 refers to a mixture of stones in which 85% of the stone would be smaller than the diameter specified. Most designs are based on d50. In other words, the design is based on the median size of stone in the mixture, where 50% will be larger than the d50 and 50% will be smaller. It is also necessary to give the upper and lower limits for the stone size too.

To ensure that stone of substantial weight is used when constructing riprap structures, specified weight and diameter ranges for individual stones and composition requirements should be followed. Such guidelines will help to prevent inadequate stone from being used in construction of the measures and will promote more consistent stone classification statewide. Table 3.23.1 notes these requirements.

Table 3.23.1 AASHTO RIPRAP GRADATION CLASSES

Riprap Class	Rock Size[1] feet (mm)		Rock Size[2] pounds (kg)		Percent of Riprap Smaller Than
A	1.30	(400)	200	(90)	100
	0.95	(290)	75	(35)	50
	0.40	(120)	5	(2)	10
B	1.80	(550)	500	(225)	100
	1.30	(400)	200	(90)	50
	0.40	(120)	5	(2)	10
C	2.25	(690)	1000	(455)	100
	1.80	(550)	500	(225)	50
	0.95	(290)	75	(35)	10
D	2.85	(870)	2000	(910)	100
	2.25	(690)	1000	(455)	50
	1.80	(550)	500	(225)	5
E	3.60	(1100)	4000	(1815)	100
	2.85	(870)	2000	(910)	50
	2.25	(690)	1000	(455)	5
F	4.50	(1370)	8000	(3630)	100
	3.60	(1100)	4000	(1815)	50
	2.85	(870)	2000	(910)	5

1 Assuming a specific gravity of 2.65.
2 Based on AASHTO gradations.

In practice though it is hard to acquire stones of the desired size. Quarries normally sell a narrower range of riprap sizes and in ranges incompatible with the above chart. The typical range of riprap available in West Virginia will be 4"-8" (gabion stone per DOH specifications), 6"-12", 10"-24", and 12"-36". Many times the contractor will crush their own stone on site.

If stone is crushed on site great care must be taken to produce stone sizes that mirror the requirements created by the designer and this specification. The most common problem is generating stone that is much too large and in a range of sizes that does not meet the gradation requirements.

Oversize stones, even in isolated spots, may cause riprap failure by precluding mutual support between individual stones, providing large voids that expose filter and bedding materials, and creating excessive local turbulence that removes smaller stones. Small amounts of oversize stone should be removed individually and replaced with proper size stones.

> When excessively large stone is used for channel lining there is an increased chance of erosion underneath the rock, which can cause a total failure of the channel. During higher flows the runoff must travel across the top of the riprap, not underneath. This point cannot be stressed enough. Bigger is not better when it comes to rock for channel lining.

Sequence of Construction

Since riprap is used where erosion potential is high, construction must be sequenced so that the riprap is put in place as quickly as possible.

Disturbance of areas where riprap is to be placed should be undertaken only when final preparation and placement of the riprap can follow immediately behind the initial disturbance. Where riprap is used for outlet protection, the riprap should be installed before the construction of the pipe or channel is competed

Design Criteria

Gradation-The riprap shall be composed of a well-graded mixture down to the l-inch size particle such that 50% of the mixture by weight shall be larger than the d50 size as determined from the design procedure. A well-graded mixture as used herein is defined as a mixture composed primarily of the larger stone sizes but with a sufficient mixture of other sizes to fill the progressively smaller voids between the stones. The diameter of the largest stone size in such a mixture shall be 1.5 times the d50 size.

The designer, after determining the riprap size that will be stable under the flow conditions, should consider that size to be a minimum size and then, based on riprap gradations actually available in the area, select the size or sizes that equal or exceed the minimum size. The possibility of damage by children shall be considered in selecting a riprap size, especially if there is nearby water or a gully in which to toss the stones.

Thickness-The minimum thickness of the riprap layer shall be 2 times the maximum stone diameter, but not less than 6 inches.

Quality of Stone-Stone for riprap shall consist of fieldstone or rough unhewn quarry stone of approximately rectangular shape. The stone shall be hard and angular and of such quality that it will not disintegrate on exposure to water or weathering and it shall be suitable in all respects for the purpose intended. The specific gravity of the individual stones shall be at least 2.5.

Rubble concrete may be used provided it has a density of at least 165 pounds per cubic foot, and other wise meets the requirements of this BMP. All rebar shall be removed flush with the surface of the concrete.

Filter Fabric Underlining--A lining of engineering filter fabric (geotextile) shall be placed between the riprap and the underlying soil surface to prevent soil movement into or through the riprap. GEOTEXTILE has the minimum physical properties of the filter fabric.

Filter fabric shall not be used on slopes greater than 1.5:1 as slippage may occur and should be used in conjunction with a layer of course aggregate (granular filter blanket is described below) when the riprap to be placed is Class C or larger.

Granular Filter--Although the filter cloth underlining or bedding is the preferred method of installation, a granular (stone) bedding is a viable option when the following relationship exists:

$$\frac{d_{15}\, filter}{d_{85} base} \langle\ 5 \ \langle\ \frac{d_{15}\, filter}{d_{15} base} \langle\ 40$$

and

$$\frac{d_{50}\, filter}{d_{50} base} \langle\ 40$$

In these relationships, filter refers to the overlying material and base refers to the underlying material. The relationships must hold between the filter material and the base material and between the riprap and the filter material. In some cases, more than one layer of filter material may be needed. Each layer of filter material should be approximately 6-inches thick.

Riprap at Outlets-

Design criteria for sizing the stone and determining the dimensions of riprap pads used at the outlet of drainage structure are contained in OUTLET PROTECTION. A filter fabric underlining is required for riprap used as outlet protection.

Riprap for Channel Stabilization

Riprap for channel stabilization shall be designed to be stable for the condition of bankfull flow in the reach of channel being stabilized. This method establishes the stability of the rock material relative to the forces exerted upon it. (see Figure 3.21.7)

Riprap shall extend up the banks of the channel to a height equal to the maximum depth of flow or to a point where vegetation can be established to adequately protect the channel.

The riprap size to be used in a channel bend shall extend upstream from the point of curvature and downstream from the bottom of the channel to a minimum depth equal to the thickness of the blanket and shall extend across the bottom of the channel the same distance.

Freeboard and Height of Bank

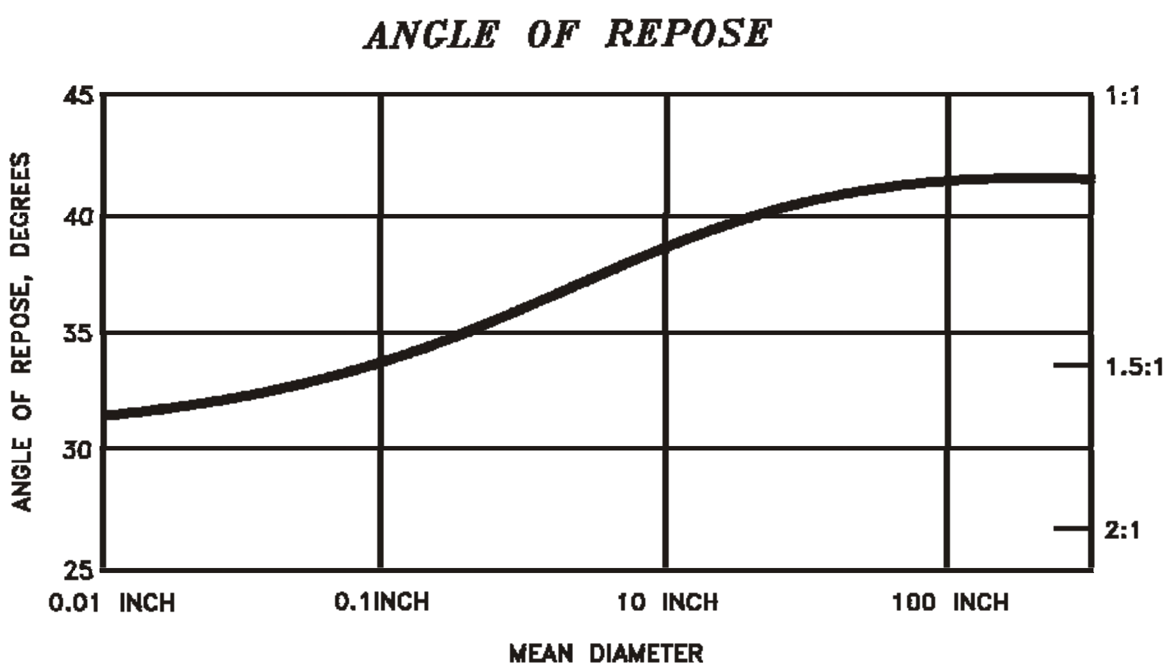
For riprapped and other lined channels, the height of channel lining above the water surface should be based on the size of the channel, the flow velocity, the curvature, inflows, wind action, flow regulation, etc. This manual does not provide the design for riprap revetment. The Federal Highway Administration in HEC-11 provides the necessary information to design riprap streambank protection.

The height of the bank above the water surface varies in a similar manner, depending on the above factors plus the type of soil.

Riprap for Slope Stabilization

Riprap for slope stabilization shall be designed so that the natural angle of repose of the stone mixture is greater than the gradient of the slope being stabilized (see Figure 3.23.1).

Figure 3.23.1 ANGLE OF REPOSE



Construction Specifications

Subgrade Preparation: The subgrade for the riprap or filter shall be prepared to the required lines and grades. Any fill required in the subgrade shall be compacted to a density approximately that of the surrounding undisturbed material. Brush, trees, stumps and other objectionable material shall be removed.

Filter Fabric or Granular Filter: Placement of the filter fabric should be done immediately after slope preparation. For granular filters, the stone should be spread in a uniform layer to the specified depth, normally 6 inches. Where more than one- layer of filter material is used, the layer should be spread so that there is minimal mixing of the layers.

When installing geotextile filter cloths, the cloth should be placed directly on the prepared slope. The edges of the sheets should overlap by at least 12 inches. Anchor pins, 15 inches long, should be spaced every 3 feet along the overlap. The upper and lower ends of the cloth should be buried at least 12 inches. Care should be taken not to damage the cloth when placing the riprap. If damage occurs, that sheet should be removed and replaced. For large stone (Class C or greater), a 6-inch layer of granular filter will be necessary to prevent damage to the cloth.

Stone Placement: Placement of riprap should follow immediately after placement of the filter. The riprap should be placed so that it produces a dense well-graded mass of stone with a minimum of voids. The desired distribution of stones throughout the mass may be obtained by selective loading at the quarry, controlled dumping of successive loads during final placing, or by a combination of these methods.

The riprap should be placed to its full thickness in one operation. The riprap should not be placed in layers. The riprap should not be placed by dumping into chutes or similar methods that are likely to cause segregation of the various stone sizes.

Blend the stone surface smoothly with the surrounding area, allowing no protrusions, overfall or in the case of channels so the stone does not form a dam to incoming runoff.

Care should also be taken not to dislodge the underlying material when placing the stones.

The finished slope must be free of pockets of small stone or clusters of large stones.

Hand placing may be necessary to achieve the required grades and a good distribution of stone sizes. Final thickness of the riprap blanket should be within plus or minus 1/4 of the specified thickness.

Common Installation Problems

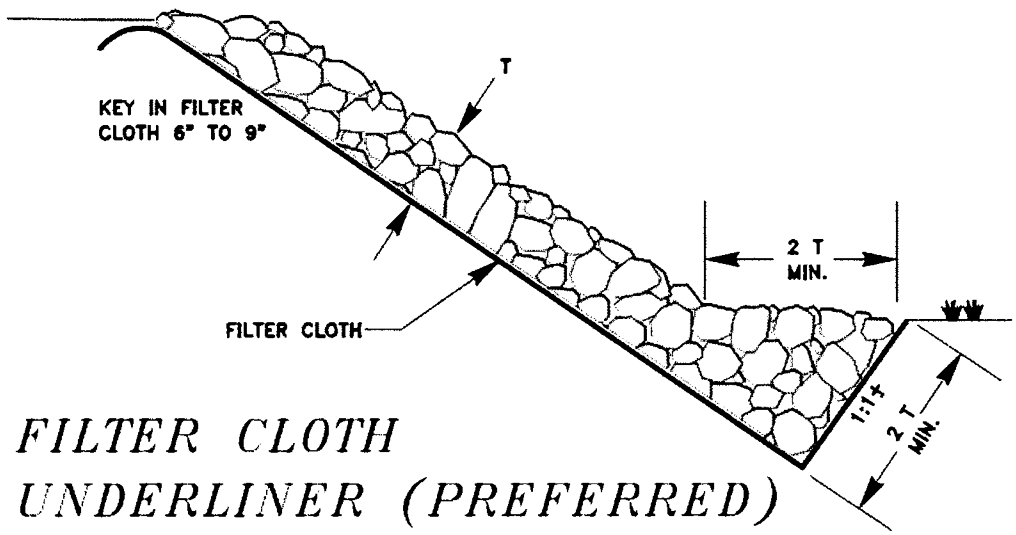
- Channel not excavated deep enough to accept the design thickness of the stone. Riprap blocks channel, resulting in erosion along edges.
- Stone too large resulting in water eroding underneath and undermining the stone.
- Slope too steep: Results in stone displacement. Do not use riprap as a retaining wall.
- Foundation not properly smoothed for filter placement: Results in damage to filter.
- Filter omitted or damaged: Results in piping or slumping.
- Riprap not properly graded: Results in stone movement and undermining and erosion of foundation.
- Foundation toe not properly reinforced: Results in undercut riprap slope or slumping.
- Fill slopes not properly compacted before placing riprap: Results in stone displacement.

Maintenance

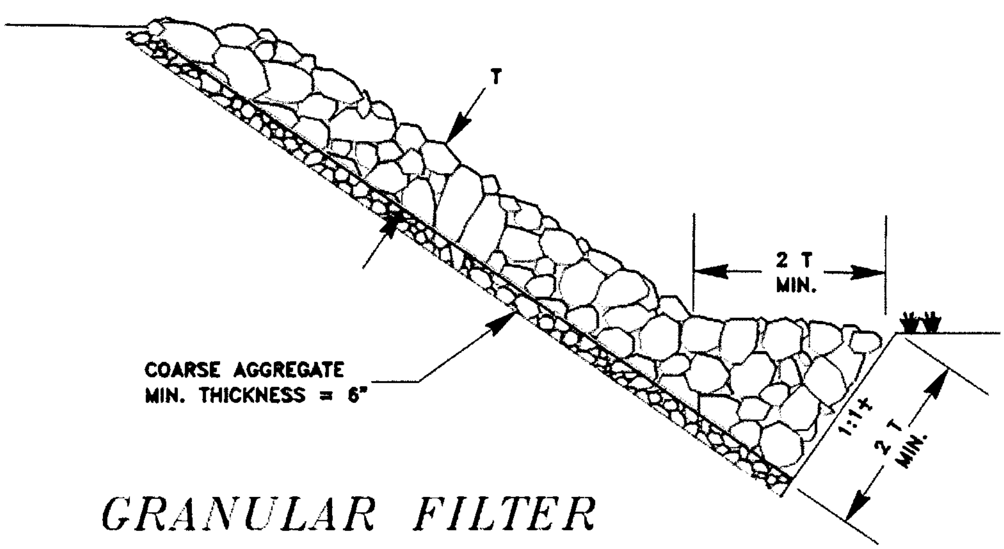
Once a riprap installation has been completed, it should require very little maintenance. It should, however, be inspected periodically to determine if high flows have caused scour beneath the riprap or filter fabric or dislodged any of the stone. Care must be taken to properly control sediment-laden construction runoff that may drain to the point of the new installation. If repairs are needed, they should be accomplished immediately.

FIGURE 3.23.2

TOE REQUIREMENTS FOR BANK STABILIZATION



FILTER CLOTH UNDERLINER (PREFERRED)



GRANULAR FILTER

SOURCE: Adapted from VDOT Drainage Manual

3.24 - GEOTEXTILES

Introduction

Geotextiles are any permeable textile fabric used to increase soil stability, provide erosion control or aid in drainage. Geotextiles are usually made from a synthetic polymer such as polypropylene, polyester, polyethylenes and polyamides. Geotextiles can be woven, knitted or non-woven.

Conditions Where Practice Applies

Geotextiles come in a tremendous variety and are used in many situations on a construction site. Geotextiles usage falls into four broad categories, three of which are important to sediment and erosion control. These three categories are separation, reinforcement and filtration. The fourth type is as an impervious barrier. Each subcategory of geotextile is designed to perform a specific function. To select the right product, it is important to understand the product's functions and the physical characteristics needed to meet those functions.

Separation- It is sometimes necessary to maintain a physical separation between two dissimilar materials to maximize the physical attributes of each of those materials. For example, in drainage systems, it is necessary to prevent fine soils from filling the voids in a rock base; otherwise, the drainage system becomes clogged and ineffective over time. Yet, it is important to allow water to pass between the soil and the drainage system.

In other applications, it is desirable to prevent any water from coming into contact with the soil, so an impervious separation surface is required. The selection of an appropriate product to achieve a physical separation is determined, therefore, by the desired outcome.

Reinforcement- The physical characteristics of soils, especially on slopes resulting from cuts and fill activities, can create unstable conditions. Geotextiles can help strengthen the soil face and increase the soil's ability to remain in place. Slopes can be stabilized either temporarily or permanently, slowing or preventing creep or slips. Also, geotextiles can be used either to prevent water from permeating a slope or to control the amount of infiltration that occurs during rainfall.

Geotextiles are especially useful in reinforcing inadequate subsoil when building roads, parking areas and paths. When soil conditions are weak, adding an appropriate geotextile can create a three-dimensional surface that will withstand heavier vehicles.

Filtration- The filtration aspect of geotextiles was understood early on by the originator of silt fence as a sediment control device. Where the flows are minimal, a geotextile can be placed across the contour to create a dam and settle out the suspended solids contained in the runoff. While not technically a filter, the geotextile's openings serve as the outlet necessary to pass water through the dam and filter out soil particles that are in suspension. Finer particles can pass through the fabric, so the size of the particles, the flow rate of the water and the physical location of the filter will determine the type of fabric that is appropriate.

For most geotextile applications relating to the construction industry, the American Association of State Highway and Transportation Officials (AASHTO) has developed guidelines. These guidelines provide classifications that are primarily based on the mechanical stresses the geotextile would be subjected to during installation. Typically, the stresses borne by geotextiles are highest during the installation of the fabric and placement of the cover material. The charts in this section are based on these AASHTO guidelines but come from the city of Seattle.

Geotextiles are either woven or non-woven.

Woven- Typically, woven fabric provides higher strengths. Weaving two or more strands of synthetic yarn at right angles produces woven fabrics. The yarn typically comes in two shapes: round and flat. Flat, also called slit film, is used where high strength is required but filtration is not. Round, or monofilament fabric, provides both high strength and filtration.

Woven stabilization fabrics provide the strength and separation needed for paved or unpaved road applications. High tensile strength and low elongation reduces rutting in both paved and unpaved surfaces. The fabrics separate the base course while reinforcing the adjacent soft soil.

Woven fabric is also used for silt fence and super silt fence. Geotextiles used for these practices must have the porosity and strength to withstand and pass through water as well as ultraviolet light inhibitors to protect it from the sun.

Non-woven- Non-woven fabric resembles felt and can provide planar water flow when used in subsurface drains, asphalt pavement overlays and erosion control. Higher weight non-woven fabric can be also used for separation under aggregate.

Non-woven fabric, slit films and combination fabrics have little open area, and often trap soil particles with the thickness of the fabric, clogging the geotextile.

Care must be taken to choose the appropriate fabric for the existing conditions, and, as with all commercial products, follow the manufacturer's recommendations.

Other design considerations are the porosity of the fabric, permitivity, tensile strength, elongation, Mullen burst, puncture strength, AOS (average opening size), seam strength and resistance to ultraviolet radiation. Each use will have a unique set of requirements that need to be taken into consideration.

ASSHTO M288 Classifications

M288-96 is based on geotextile survivability from installation stresses. Selection of the geotextile is based on knowledge of the anticipated exposure to installation stresses. M288-96 covers six geotextile applications: subsurface drainage, separation, stabilization, permanent erosion control, temporary silt fences and paving fabrics.

In M288-92, geotextile survivability was divided into classes A and B. Class A was used where installation stresses determined by aggregate shape, trench depth, and the size and height of an armor stone drop were more severe than in Class B installations. There are no definitive measurements set for differentiating between severe and less severe installation stresses.

In M288-96, the general strength requirements for the subsurface drainage, separation, stabilization and permanent erosion control applications are broken into three classes of geotextiles. Class 1 represents the most robust and Class 3 the least. Within each survivability class, the strength requirements are established based on elongation at break in the grab strength test. The highest strength requirement is for materials that break at less than 50 percent elongation (typically woven) and the least for those that break at greater than 50 percent elongation (typically unwoven). The requirements for the silt-fence applications are based on supported or unsupported fences. Paving fabrics are limited to fabrics with elongation at break of greater than 50 percent.

AASHTO Specification M288-96 for geotextiles is published in the two volume Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 18th Ed.

Design Considerations

In order to choose the appropriate geotextile, a proper evaluation of the proposed use, material specification and installation procedure is required. Since using geotextiles for stabilization of soils involves four basic functions, reinforcement, separation, filtration and drainage, it is important to be familiar with both the site conditions where the fabric will be installed and the various properties of geotextiles. The local soil characteristics and groundwater are two of the more important considerations to be considered. And since fabric strength calculations are based primarily on installation stresses, the type and size of the aggregate to be used is also important. Therefore there are a number of factors that will need to be considered when specifying fabrics.

Geotextile and thread for sewing

The material shall be a geotextile consisting only of long chain polymeric fibers or yarns formed into a stable network such that the fibers or yarns retain their position relative to each other during handling, placement and design service life. At least 95 percent by weight of the material shall be polyolefins or polyesters. The material shall be free from defects or tears. The geotextile shall also be free of any treatment or coating which might adversely alter its hydraulic or physical properties after installation. The geotextile shall conform to the properties as indicated in Tables 3.24.2 through 3.24.7 for each use specified.

Thread used for sewing shall consist of high strength polypropylene, polyester or polyamide. Nylon threads will not be allowed. The thread used to sew permanent erosion control geotextiles shall be resistant to ultraviolet radiation. The thread shall be of contrasting color to that of the geotextile itself.

The geotextile uses included in this section and their associated tables of properties are as follows:

Table 3.24.1 List of geotextile tables

Geotextile application	Applicable property tables
Underground drainage, low survivability, Classes A, B, and C	Tables 3.24.2 and 3.24.3
Underground drainage, moderate survivability, Classes A, B, and C	Tables 3.24.2 and 3.24.3
Separation	Table 3.24.4
Soil stabilization	Table 3.24.4
Permanent erosion control, moderate survivability, Classes A, B, and C	Tables 3.24.5 and 3.24.6
Permanent erosion control, high survivability, Classes A, B, and C	Tables 3.24.5 and 3.24.6
Ditch lining	Table 3.24.5
Temporary silt fence	Table 3.24.7

Table 3.24.2 Geotextile for underground drainage strength properties for survivability

		Geotextile property requirements[1]	
Geotextile property	**Test method[2]**	**Low survivability woven/non-woven**	**Moderate survivability woven / non-woven**
Grab tensile strength, min. in machine and x-machine direction	ASTM D 4632	180 lbs. / 115 lbs. min.,	250 lbs. / 160 lbs. min.
Grab failure strain, in machine and x-machine direction	ASTM D 4632	<50% / / 50%	<50% / /50%
Seam breaking strength	ASTM D 46323[3]	160 lbs. / 100 lbs. min.	220 lbs. / 140 lbs. min.
Puncture resistance	ASTM D 4833	67 lbs. / 40 lbs. min.	80 lbs. / 50 lbs. min.
Tear strength, min. in machine and x-machine direction	ASTM D 4533	67 lbs. / 40 lbs. min.	80 lbs. / 50 lbs. min.
Ultraviolet (UV) radiation stability	ASTM D 4355	50% strength retained min., after 500 hrs. in weatherometer	50% strength retained min., after 500 hrs. in weatherometer

See notes after Table 3.24.7, this specification.

Table 3.24.3 Geotextile for underground drainage filtration properties

		Geotextile property requirements[1]		
Geotextile property	**Test method[2]**	**Class A**	**Class B**	**Class C**
AOS	ASTM D 4751	.43 mm max. (No. 40 sieve)	.25 mm max. (No. 60 sieve)	.18 mm max. (No. 80 sieve)
Water permittivity	ASTM D 4491	.5 sec^{-1} min.	.4 sec^{-1} min.	.3 sec^{-1} min.

See notes after Table 3.24.7, this specification.

Table 3.24.4 Geotextile for separation or soil stabilization

		Geotextile property requirements[1]	
Geotextile property	**Test method[2]**	**Separation woven/non-woven**	**Soil stabilization woven/non-woven**
AOS	ASTM D 4751	.60 mm max. (No. 30 sieve)	.43 mm max. (No. 40 sieve)
Water permittivity	ASTM D 4491	.02 sec-1 min.	.10 sec-1 min.
Grab tensile strength, min. in machine and x-machine direction	ASTM D 4632	250 lbs. / 160 lbs. min.	315 lbs./200 lbs. min.
Grab failure strain, in machine and x-machine direction	ASTM D 4632	<50% / /50%	<50% / /50%
Seam breaking strength	ASTM D 46322[3]	220 lbs. / 140 lbs. min.	270 lbs./180 lbs. min.
Puncture resistance	ASTM D 4833	80 lbs. / 50 lbs. min.	112 lbs./79 lbs. min.
Tear strength, min. in machine and x-machine direction	ASTM D 4533	80 lbs. / 50 lbs. min.	112 lbs./79 lbs. min.
Ultraviolet (UV) radiation stability	ASTM D 4355	50% strength retained min., after 500 hrs. in weatherometer	50% strength retained min., after 500 hrs. in weatherometer

See notes after Table 3.24.7, this specification.

Table 3.24.5 Geotextile for permanent erosion and ditch lining

		Geotextile property requirements[1]		
		Permanent erosion control		Ditch lining
Geotextile property	**Test method[2]**	**Moderate survivability woven / non-woven**	**High survivability woven / non-woven**	**Woven / non-woven**
AOS	ASTM D 4751	See Table 3.24.6	See Table 3.24.6	.60 mm max(No. 30 sieve)
Water permittivity	ASTM D 4491	See Table 3.24.6	See Table 3.24.6	.02 sec^{-1} min.
Grab tensile strength, min. in machine and x-machine direction	ASTM D 4632	250 lbs. / 160 lbs. min.	315 lbs. / 200 lbs. min.	250 lbs. / 160 lbs. min.
Grab failure strain, in machine and x-machine direction	ASTM D 4632	15%- 50% / > 50%	15%- 50% / > 50%	<50% / ³ 50%
Seam breaking strength	ASTM D 4632[3]	220 lbs./ 140 lbs. min.	270 lbs. / 180 lbs. min.	220 lbs. / 140 lbs. min.
Burst strength	ASTM D 3786	400 psi/ 190 psi min.	500 psi / 320 psi min.	----------------
Puncture resistance	ASTM D 4833	80 lbs./ 50 lbs. min.	112 lbs. / 79 lbs. min.	80 lbs. / 50 lbs. min.
Tear strength, min. in machine and x-machine direction	ASTM D4533	80 lbs./ 50 lbs. min.	112 lbs. / 79 lbs. min.	80 lbs. / 50 lbs. min.
Ultraviolet (UV) radiation stability	ASTM D 4355	70% strength retained min., after 500 hrs. in weatherometer	70% strength retained min., after 500 hrs. in weatherometer	70% strength retained min., after 500 hrs. in weatherometer

See notes after Table 3.24.7, this specification.

Table 3.24.6 Filtration properties for geotextile for permanent erosion control

		Geotextile property requirements[1]		
Geotextile property	**Test method[2]**	**Class A**	**Class B**	**Class C**
AOS	ASTM D4751	0.43 mm max. (No.40 sieve)	0.25 mm max. (No.60 sieve)	0.22 mm max. (No. 70 sieve)
Water permittivity	ASTM D4491	0.7 sec^{-1} min.	0.4 sec^{-1} min.	0.2 sec^{-1}min.

See notes after Table 3.24.7, this specification.

Table 3.24.7 Geotextile for temporary silt fence

		Geotextile property requirements[1]	
Geotextile property	**Test method[2]**	**Unsupported between posts**	**Supported between posts with wire or polymeric mesh**
AOS	ASTM D 4751	.60 mm max. for slit film wovens (No. 30 sieve) .30 mm max. for all other geotextile types (No. 50 sieve).15 mm min.(No. 100 sieve)	.60 mm max. for slit film wovens (No. 30 sieve).30 mm max. for all other geotextile types (No. 50 sieve).15 mm min. (No. 100 sieve)
Water permittivity	ASTM D 4491	.02 sec^{-1} min.	.02 sec^{-1} min.
Grab tensile strength, min. in machine and x-machine direction	ASTM D 4632	180 lbs. min. in machine direction, 100 lbs. min. in x-machine direction	100 lbs. min.
Grab failure strain, min. in machine direction only	ASTM D 4632	30% max. at 180 lbs. or more	--------------------
Ultraviolet (UV) radiation stability	ASTM D 4355	70% strength retained min., after 500 hrs. in weatherometer	70% strength retained min., after 500 hrs. in weatherometer

Notes

[1]All geotextile properties in Tables 1 through 6 are minimum average roll values (i.e., the test result for any sampled roll in a lot shall meet or exceed the values shown in the table).
[2]The test procedures used are essentially in conformance with the most recently approved ASTM geotextile test procedures, except for geotextile sampling and specimen conditioning, which are in accordance with WSDOT Test Methods 914 and 915, respectively.
[3]With seam located in the center of 8-inch long specimen oriented parallel to grip faces.

Source for tables: http://www2.ci.seattle.wa.us/util/engineering/ArticleView.asp?ArticleID=9-05.22#9-05.22

Construction Specifications

Since the greatest stresses occur during installation of the geotextile and overlying material, the following conditions should be met:

1. Ensure the ground surface is clear of stones, roots, and debris.
2. Provide a surface to lay the fabric on that is as smooth as possible and free of humps or holes.
3. Ensure that the geotextile is in intimate contact with the soil.
4. Carefully place the stone on top of the fabric to prevent damage to the geotextile.

When the geotextile is used between two layers of aggregate, there is a greater chance of stress and damage, so it is recommended to use a higher strength fabric.

Maintenance

Once the installation of the filter fabric system has been completed, it should require very little maintenance. It should, however, be inspected periodically to determine if high flows have caused scour beneath the fabric or dislodged any of the stone. If repairs are needed, they should be completed immediately.

References

City of Seattle

L. David Suits and Gregory N. Richardson on www.geosynthetics.com, FNW Geosynthetics Division

“Basic Geosynthetics: A Guide to Best Practices” Jonathan Fannin Ph.D., P. Eng., Forest Resources Management and Civil Engineering, University of British Columbia, Canada.

3.25 - VEGETATIVE BUFFER STRIP

Introduction

A vegetative buffer strip is the maintenance of existing or planted vegetation adjacent to streams, wetlands, or other areas of significant natural resource value for the purpose of stormwater pollutant removal. The term vegetative buffer is typically used to describe the preservation of existing vegetation without specific regard to pollutant removal efficiency, whereas the term filter strip is generally used when vegetation (usually grass) is specifically designed to achieve pollutant removal goals.

However, since the terms are often used interchangeably and provide essentially the same sediment removal function, both will be considered as one practice. However, developers should not destroy native vegetation to plant a grass strip for this practice. The protection of vegetation along streams also stabilizes stream banks, moderates water temperatures, and provides food sources and habitat for fish and wildlife.

Conditions Where Practice Applies

This practice may be utilized on construction sites with good existing vegetative cover or where good vegetative cover can be established prior to site disturbance. Vegetative buffers are most useful adjacent to streams, wetlands or other water bodies, although they may also be used as a non-structural practice on upland sites. To function effectively, runoff to and flow across the buffer area must not be concentrated or channelized. The use of level spreaders or other energy-dissipating devices may be utilized in some circumstances to promote overland (sheet) flow across the buffer. Buffers are probably more effective as filters during the growing season, when the density of vegetation is generally higher.

Approved Practices

1. Retaining existing native vegetation adjacent to the area to be protected. The width needed is dependent on site conditions (see design criteria).
2. Establishing vegetation by planting or natural regeneration adjacent to the area to be protected. The width and vegetation type is dependent on site conditions (see design criteria). Planting and/or natural regeneration can be used in conjunction with preserving existing vegetation if needed to achieve desired buffer width. All vegetation must be established prior to site disturbance.
3. Stormwater runoff to the buffer area must be in the form of overland (sheet) flow. If treatment occurs outside of the buffer, stabilized outlets may be located within the buffer area. The use of energy-dissipating devices may be used in some circumstances to promote overland flow within the buffer.
4. No disturbance is permitted within a vegetative buffer, except for necessary infrastructure improvements (utility lines, road crossings, etc.), or unless planting is required.

Design Criteria

It is recommended that designers use site-specific criteria to determine the appropriate buffer width, if possible. Factors to consider include soil type, slope, size distribution of the sediment, contributing drainage area, vegetation present and other natural resource considerations, such as fish and wildlife habitat value. Because vegetative buffers along streams provide many environmental benefits, designers are encouraged to provide as large a buffer area as practicable for the project. If there is insufficient buffer width, the buffer available may be used in conjunction with other BMPs such as silt fence or super silt fence.

1. The minimum vegetative buffer width shall be 100 feet, unless specific design information can be provided to justify a smaller buffer width. For slopes greater than 10 percent, the minimum distance is 250 feet. Smaller buffers may be used in conjunction with other BMPs.
2. The width of the contributing area to the vegetative buffer should not exceed 300 feet, unless energy-dissipating devices are provided. Buffers may be used as a supplement to other BMPs for larger drainage areas.
3. Good (minimum of 80 percent) vegetative cover must be present in the proposed buffer area.

Construction Specifications

1. The buffer boundary shall be clearly marked onsite prior to site clearing or grading.
2. No soil disturbances, equipment storage or construction traffic shall occur within the buffer area.

Maintenance

Inspect at a minimum once every seven calendar days and within 24 hours after any storm event greater than 0.5 inches per 24 hour period. Heavy deposits of sediment should be removed (with minimal disturbance to the buffer vegetation). If erosion gullies form, the use of an energy- dissipating device or an alternative BMP is needed.

3.27 - SILT FENCE

Introduction

A temporary sediment barrier consisting of a synthetic filter fabric stretched across and attached to supporting posts and entrenched. Used to intercept and detain small amounts of sediment from disturbed areas during construction operations in order to prevent sediment from leaving the site.

No sediment control device is misused more than silt fence (with the possible exception of hay bales). Much of the silt fence used in West Virginia is not installed properly. The device does not work if:

1. not entrenched a minimum of 4 inches.
2. not placed on the contour-perpendicular to the flow of the water.
3. installed in areas of concentrated flows.
4. installed to contain sediment from too large of an area.
5. little or no maintenance is performed on it.

Silt fence does not actually filter sediment from muddy water. In field conditions silt fence acts as a barrier to the flow of water, like a dam, reducing the energy of the water, which causes the suspended material to settle out. It is because of the low permeability of the fabric that silt fence is limited to small drainage areas

Installing silt fence is very labor intensive. It is usually installed by hand and accumulated sediment must be removed and disposed of by hand. In many scenarios, installing a diversion and sediment trap would be more effective and less expensive than using silt fence. In addition, the NPDES permit requires that a sediment trap or basin be installed whenever possible.

Conditions Where Practice Applies

1. Below disturbed areas where erosion would occur in the form of sheet and small rill erosion.
2. Where the size of the drainage area is no more than one-quarter acre per 100 feet of silt fence length; the maximum gradient above the barrier should be less than 2:1.
3. Silt fence will not be used in areas where rock or some other hard surface prevents the full and uniform anchoring of the barrier.
4. Silt fence should NEVER be installed in streams or swales or in any area where there is a reasonable chance of concentrated flow. In areas where concentrated flows can be expected, use diversions and sediment traps and /or sediment basins. In ditches or swales rock check dams should be used in place of silt fence.

Design Criteria

1. No formal design is required. An effort should be made to locate silt fence at least 5 feet to 10 feet beyond the toe of slope.

2. Silt fence should be limited to situations in which only sheet is expected.
3. Silt fence should be installed prior to major soil disturbance.
4. Silt fence should be placed across the bottom of a slope along a line of uniform elevation (ALWAYS perpendicular to the direction of flow).
5. Any time a section of silt fence is knocked down by concentrated flows the silt fence will be replaced with a diversion and sediment trap or super silt fence.

Construction Specifications

Materials

1. Synthetic filter fabric shall be a pervious sheet of propylene, nylon, polyester or ethylene yarn and shall be certified by the manufacturer or supplier as conforming to the requirements noted in WV DOT DOH Specifications or the GEOTEXTILE section.
2. Synthetic filter fabric shall contain ultraviolet ray inhibitors and stabilizers to provide a minimum of 6 months expected usable construction life at a temperature range of 0 to 120 degrees Fahrenheit.
3. If wooden stakes are utilized for silt fence construction, they must be a minimum of 2" x 2" when oak is used and 2" x 4" when pine is used. Wooden stakes should have a minimum length of 5 feet.
4. If steel posts (standard "U" or "T" section) are utilized for silt fence construction, they must have a minimum weight of 1.33 pounds per linear foot and should have a minimum length of 5 feet.

Installation

1. The height of a silt fence shall be a minimum of 16 inches above the original ground surface and shall not exceed 34 inches above ground elevation.
2. The filter fabric shall be purchased in a continuous roll cut to the length of the barrier to avoid the use of joints. When joints are unavoidable, the silt fence shall be spliced together only at a support post, by twisting the last post of each run around the other, and securely sealed. (see drawing)
3. A trench shall be excavated approximately 4 inches wide and 4 inches deep on the upslope side of the proposed location of the measure.
4. The filter fabric shall be fastened securely to the upslope side of the posts using one inch long (minimum) heavy-duty wire staples or tie wires and eight inches of the fabric shall be extended into the trench. The fabric shall not be stapled to existing trees. The most common type of silt fence has the stakes attached to the fabric at the factory.
5. The 4-inch by 4-inch trench shall be backfilled and the soil compacted over the filter fabric.

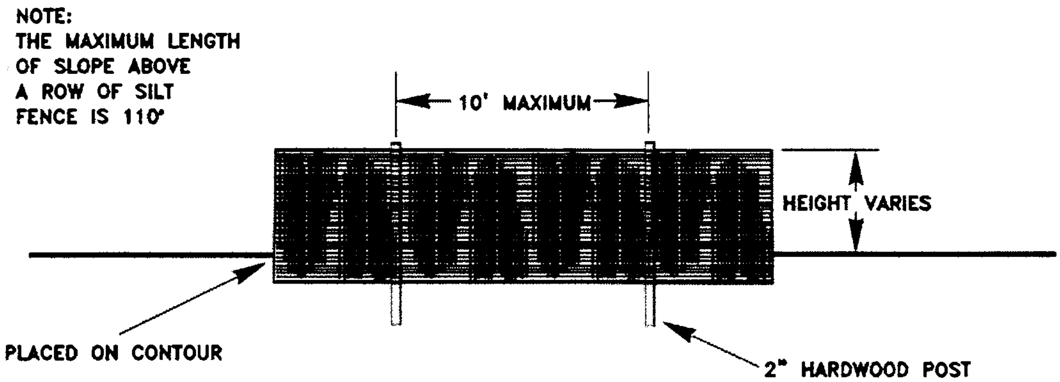
6. Silt fence shall be removed when it has served its useful purpose, but not before the upslope area has been permanently stabilized.
7. Turn the end of a run of Silt Fence slightly uphill to prevent runoff from going around the end.

Maintenance

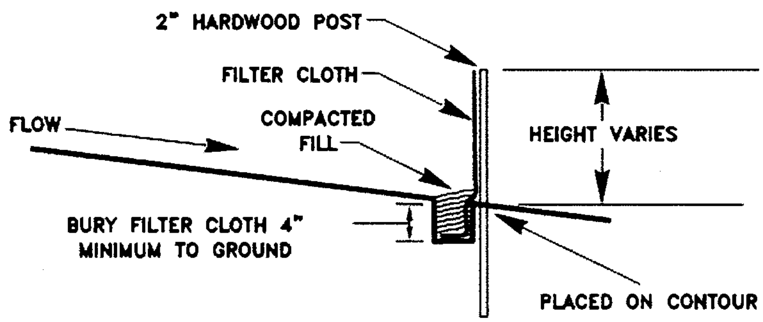
1. Silt fences shall be inspected immediately after each rainfall of 0.5 inch or greater and at least daily during prolonged rainfall or once a week. Any required repairs or maintenance shall be made immediately.
2. Close attention shall be paid to the repair of damaged silt fence resulting from end runs and undercutting. If the fence is not installed on the contour (perpendicular to the flow of the water) both of these conditions can occur.
3. Should the fabric on a silt fence decompose or become ineffective prior to the end of the expected usable life and the barrier still is necessary, the fabric shall be replaced promptly.
4. Sediment deposits should be removed after each storm event. They must be removed when deposits reach approximately one-half the height of the barrier.
5. If any section of silt fence is knocked down during a rain event (because it was installed in an area of concentrated flow) then other measures such as a sediment trap and diversion or super silt fence must be installed.

FIGURE 3.27.2

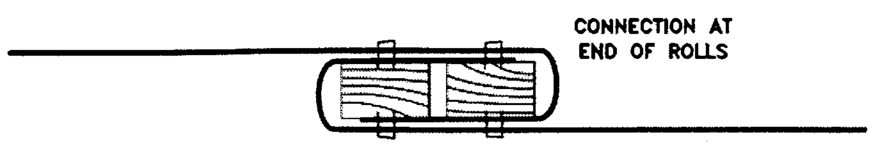
SILT FENCE



FRONT ELEVATION



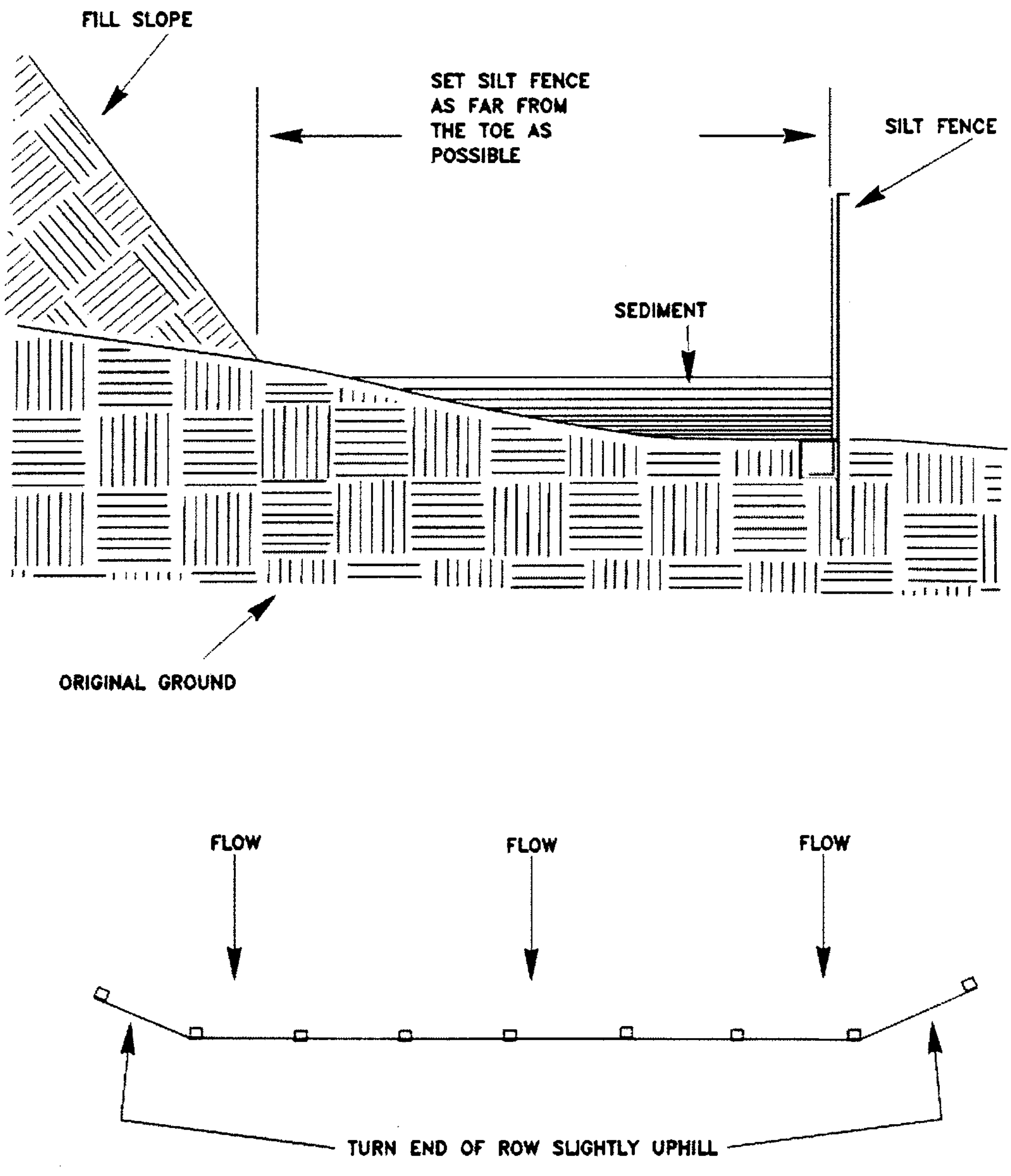
SIDE ELEVATION



TOP VIEW

FIGURE 3.27.1

PLACEMENT OF SILT FENCE



3.28 - SUPER SILT FENCE

Definition

A super silt fence is a temporary barrier of geotextile fabric over chain link fence. It is used to intercept sediment-laden runoff from areas that are too large for regular silt fence. Super silt fence can be a replacement for sediment traps in certain instances.

Conditions Where Practice Applies

To reduce runoff velocity and allow sediment to become trapped behind or up slope of the super silt fence. Limits imposed by ultraviolet light stability of the fabric will dictate the maximum period that the silt fence may be used.

Super silt fence provides a barrier that can collect and hold debris and soil, preventing the material from entering critical areas, streams, streets, etc.

Super silt fence can be used where the installation of a DIVERSION and/or SEDIMENT TRAP would destroy sensitive areas, woods, wetlands, riparian zones, etc. This practice is very useful below bridge piers and abutments along streams and rivers.

Design Criteria

Design computations are not needed.

- Slope length above the fence should not exceed 400 ft in steep terrain. In flatter terrain the slope length can be extended with consultation with DWWM.
- Where ends of the geotextile fabric come together, the ends shall be overlapped, folded, and stapled to prevent sediment bypass.
- The backfilled trench shall be compacted.
- Only woven geotextile fabric will be used.
- Super silt fence should be placed as close to the contour as possible. No section of silt fence should exceed a grade of 5% for more than a distance of 20 feet.

Construction Specifications

Fencing shall be 48 inches in height and constructed in accordance with the WV DOT, Division of Highways specification for Chain Link Fencing. The DOT specification for a 6-foot fence shall be used, substituting 48-inch fabric and 6 foot length posts. The filter fabric shall meet the requirements of 715.11.5/AASHTO M 288, Section 7, Class 1.

1. The poles do not need to set in concrete.
2. Chain link fence shall be fastened securely to the fence posts with wire ties or staples.
3. Geotextile fabric shall be fastened securely to the chain link fence with ties spaced every 24” at the top and mid section.

4. Geotextile fabric shall be embedded a minimum of 12” into the ground.
5. When two sections of geotextile fabric adjoin each other, they shall be overlapped by 6” and folded.
6. Metal posts as specified by DOH can be replaced by pressure-treated 4” x 4” posts.

Maintenance

Silt fences shall be inspected immediately after each rainfall, daily during prolonged rainfall and once a week during dry periods. Any required repairs shall be made immediately.

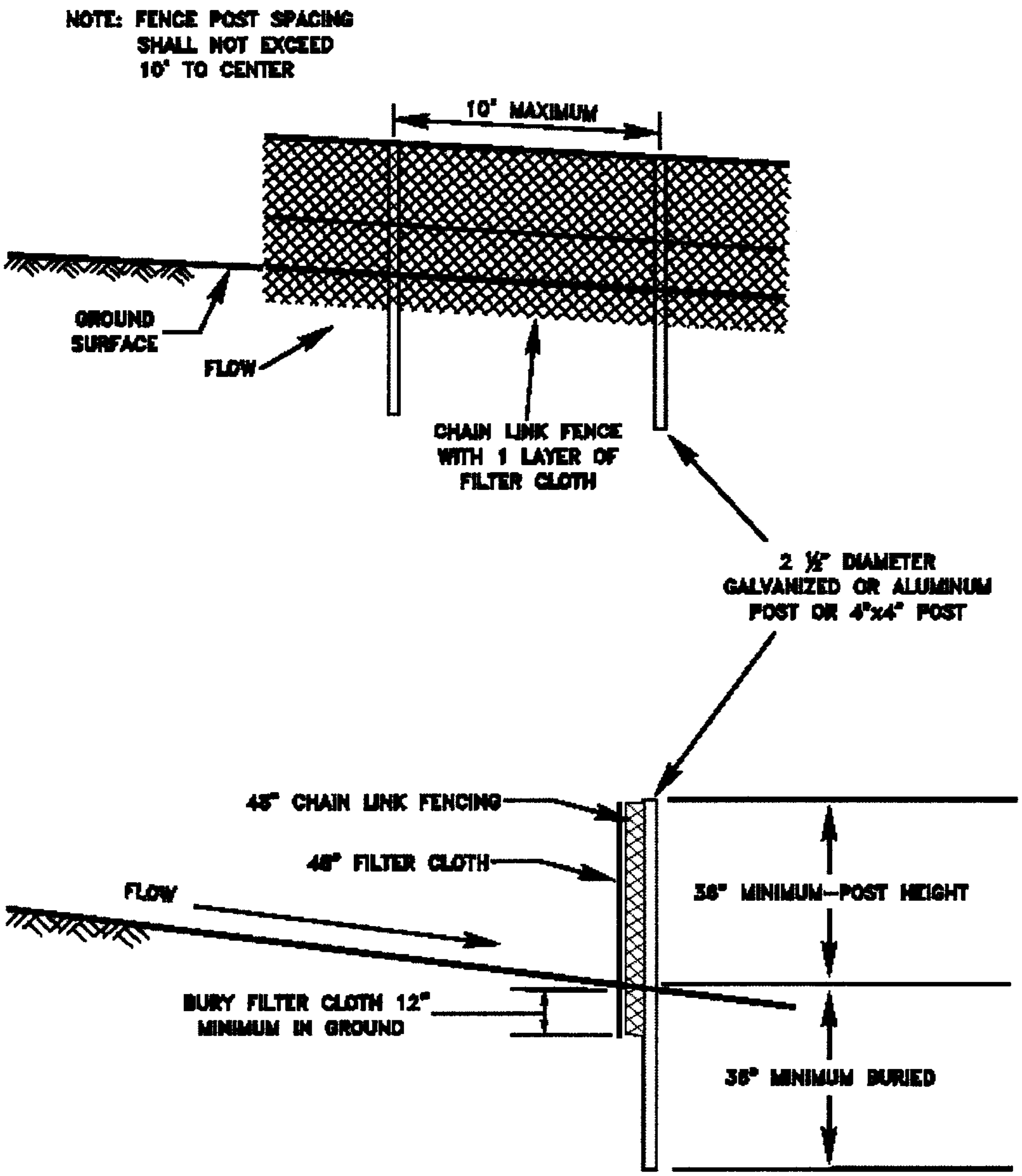
Close attention shall be paid to the repair of damaged silt fence resulting from end runs and undercutting. If the fence is not installed perpendicular to the flow of the water, these conditions will occur.

Should the fabric on a silt fence decompose or become ineffective, the fabric shall be promptly replaced.

Sediment deposits shall be removed when deposits reach approximately one-half the height of the barrier.

FIGURE 3.28.1

SUPER SILT FENCE



3.29 - SEDIMENT TRAP

Introduction

A temporary ponding area formed by constructing an embankment or excavation and embankment that will trap the flow of sediment-laden runoff. Sediment traps have a properly stabilized outlet/weir or riser and pipe to detain sediment-laden runoff from small disturbed areas of five acres or less. Outlets must be designed to extend the detention time and allow the majority of the sediment to settle out.

This practice is one of the most efficient and cost effective methods of sediment control. When possible, sediment traps should be constructed as a first step in any land-disturbing activity. As with any sediment control device the sediment trap should not be removed until the contributing drainage area is stabilized.

Sediment traps can be highly variable in design and configuration. Almost every site has someplace to install one or more sediment traps. However it may not be evident during the design stages exactly where a trap would fit best. Once clearing, grubbing and site excavation begins, logical locations usually appear. It may be necessary to state in the plan that a particular trap will be field located to fit the site conditions.

Conditions Where Practice Applies

1. Sediment traps are appropriate for drainage areas of 5 acre or less. For drainage areas greater than 5 acres use a Sediment Basin (See SEDIMENT BASIN)
2. At the outlet of ditches and other perimeter controls installed during the first stage of construction.
3. At the outlet of any structure which concentrates sediment-laden runoff i.e. at the discharge point of diversions, channels, slope drains, or other runoff conveyances.
4. At the inlet to culverts underneath roads
5. Above a storm water inlet that may receive sediment-laden runoff.

Design Considerations

The following items should be addressed where applicable when planning and designing a sediment trap.

1. The sediment trap should have a storage volume of 3600 cubic feet per acre of drainage area. Half of the volume must be in the form of a permanent pool or wet storage to provide a stable-settling medium. The remaining half must be in the form of a drawdown or dry storage, which provides extended settling time. The volume of the wet storage should be measured from the low point of the excavated area to the base of the outlet structure or the invert of the first perforation in the riser. The volume of the dry storage should be measured from the base of the outlet to the crest of the outlet (overflow mechanism) or from the lowest perforation in the riser to the top of riser.

2. The embankment should not exceed 5 feet in height. The recommended minimum width at the top of the embankment should be equal to the height of the embankment.
3. The recommended inside embankment should be a 2:1 slope or flatter. The recommended outside embankment should be a 3:1 slope or flatter.
4. The width of the outlet channel weir must not be less than 4 ft. wide or, 2 feet plus 2 feet for each acre of drainage i.e. 12 ft wide for 5 acres. The top of the outlet channel must be at least 1 ft. below the top of embankment to provide a minimum of 1 ft. of free board.
5. The trap should be accessible for ease of maintenance.
6. Sediment must be removed from the trap when the trap's wet storage volume is reduced by one-half. Designers should designate a clean-out elevation.
7. The trap should provide a storage area which is at least twice as long as it is wide; with the outlet position at the furthest possible point from the inlet (measured from point of maximum runoff introduction to the outlet). Baffling can be used if this 2 to 1 ratio cannot be met.
8. All earthen side slopes should be a minimum of 2:1.
9. Seed and mulch all disturbed areas associated with the installation of the sediment trap immediately.
10. The sediment trap must have a stabilized outlet, either a weir or pipe and riser. Outlet protection must be provided.
11. Fill material around the pipe spillway where it goes through the embankment shall be hand compacted in 4" to 6" layers. A minimum of 2' of hand compacted backfill should be placed over the barrel before construction traffic is allowed to cross.
12. The riser shall be anchored with either a concrete base or steel plate bases sufficient to prevent flotation. For concrete bases, the depth shall be 12" with the riser buried 9". A 1/4" minimum thickness steel plate shall be attached to the riser by a continuous weld around the bottom to form a watertight connection and then place 2" of stone, gravel or tamped earth on the plate.
13. Anti-seep collars are required. Install based on manufacturers' instructions.
14. It is recommended that a concentric trash rack and anti-vortex device be installed on all risers.
15. If a stone outlet is used for the sediment trap, it should consist of a stone section of the embankment located at the low point in the basin. The stone outlet should be a combination of coarse aggregate and rock riprap. The stone section of the embankment should be separated from the earthen embankment by a geotextile. Riprap should consist of well-graded stone 2 inches to 8 inches in diameter. Coarse aggregate is washed gravel ½ to 1½ inches in diameter. The course aggregate is placed 1 ft thick on the upstream face of he stone outlet. The crest of the stone outlet must be at least 1.0 foot below the top of the embankment to ensure that the flow will travel over the stone and not the embankment. The outlet should be configured as noted in the drawing.
16. The outlet pipe and riser should be sized as noted in the table below. The riser pipe should be weighted to prevent flotation. An anti-seep collar is

recommended around the outlet pipe as well as a concentric trash rack and anti-vortex device.

17. If there is any chance that a failure of the structure could damage any downstream property, the designer should look into creating a spillway or combination of spillways commensurate with the level risk should the structure fail.
18. The inlet to the sediment trap should be excavated to provide for a gentle transition from the diversion ditch to the bottom of the trap to protect from head cutting and scour.
19. The maximum depth of excavation within the wet storage area should be 4 feet to facilitate clean-out and for site safety considerations

Table 3.29.1 PIPE OUTLET DIAMETER SELECTION

Maximum Drainage Area (Acres)	Minimum Size Outlet Diameter (inches)	Minimum Size Riser Diameter (inches)
1	12	15
2	15	18
3	18	21
4	21	24
5	21	27

Volume calculation

For an embankment sediment trap, the **wet storage volume** may be approximated as follows:

$$V_1 = 0.85 \times A_1 \times D_1$$

where,

V_1 = the wet storage volume in cubic feet

A_1 = the surface area of the flooded area at the base of the stone outlet, in square feet

D_1 = the maximum depth in feet, measured from the low point in the trap to the base of the stone outlet

The **dry storage volume** may be approximated as follows:

$$V_2 = \frac{A_1 \times D_2}{2} \times D_2$$

where,

V_2 = the dry storage area of the flooded area at the base of the stone outlet in square feet

A_1 = the surface area of the flooded area at the base of the stone outlet, in square feet

A_2 = the surface area of the flooded area at the crest of the stone outlet (overflow mechanism), in square feet

D_2 = the depth in feet, measured from the base of the stone outlet to the crest of the stone outlet

Plan Preparation

During the preparation of the sediment control plan for the Construction Storm Water General Permit prepare a table detailing the key design aspects of each sediment trap planned and designed.

Table 3.29.2 SEDIMENT TRAP KEY DESIGN ASPECTS

TRAP NUMBER	1	2	3	4	5	6
TYPE (stone weir/pipe)						
DRAINAGE AREA						
WET STORAGE REQ						
WET STORAGE PROV						
DRY STORAGE REQ						
DRY STORAGE PROV						
WEIR WIDTH						
PIPE DIAMETER						
WEIR/PIPE ELEVATIONS						
STORAGE DEPTH						
CLEANOUT ELE						
EMBANKMENT ELE						
TRAP BOTTOM ELE						

Construction Specifications

1. The area under the embankment should be cleared, grubbed, and stripped of any vegetation and root mat.
2. Fill material for the embankment should be free of roots or other woody vegetation, organic material, large stones, and other objectionable material. The embankment should be compacted in 6-inch layers by traversing with construction equipment.
3. The earthen embankment should be seeded and mulched to provide temporary or permanent vegetation immediately after installation.
4. Construction operations should be carried out in such a manner that erosion and water pollution are minimized.
5. Sediment Traps should not be removed until the contributing disturbed area has been stabilized.
6. Material removed from the excavated section of the sediment trap should be placed in an area and stored in a manner that will not create an erosion problem.

7. The outlet pipe and riser connections should be watertight.
8. Above the wet storage elevation, the riser should be perforated with 1-inch diameter holes spaced 8 inches vertically and 10 inches to 12 inches horizontally.

Maintenance

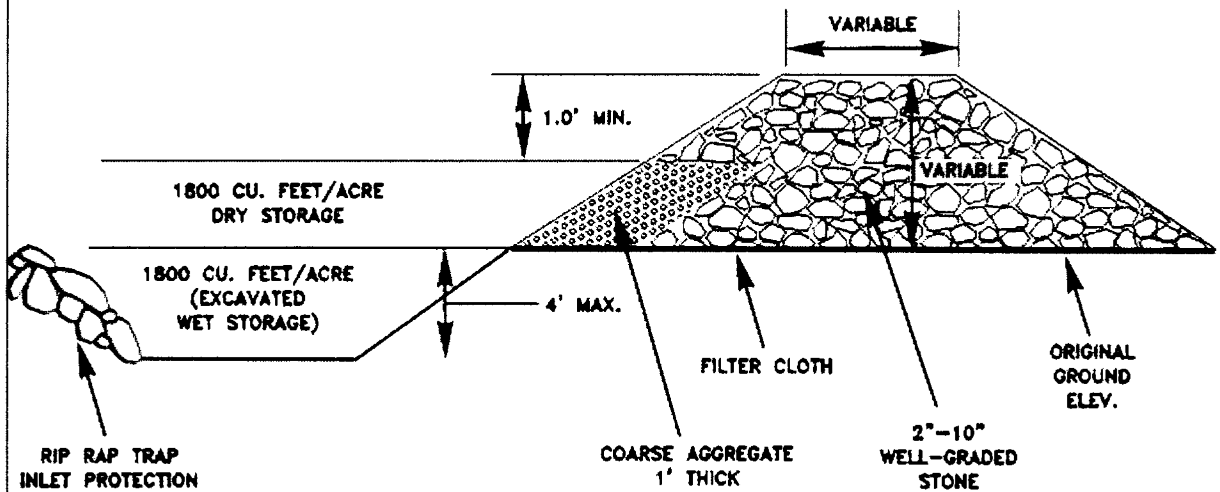
Sediment should be removed from the trap before the traps wet storage volume is reduced by one-half. Sediment removed from the trap should be stored or disposed in a manner in which will not create an erosion or sediment problem.

Filter stone should be regularly checked to ensure that filtration performance is maintained. Stone choked with sediment should be removed and cleaned or replaced

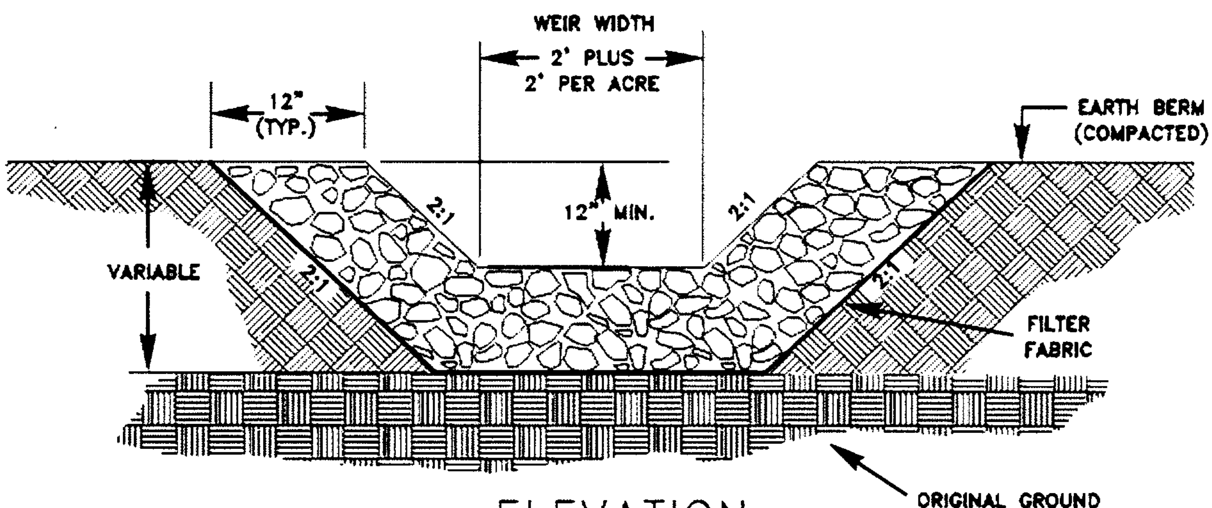
The structure shall be checked every 7 days and /or after 0.5 inch of rain to ensure that it is structurally sound and has not been damaged.

FIGURE 3.29.1

ROCK OUTLET SEDIMENT TRAP



CROSS SECTION



ELEVATION

FIGURE 3.29.2

PIPE RISER SEDIMENT TRAP

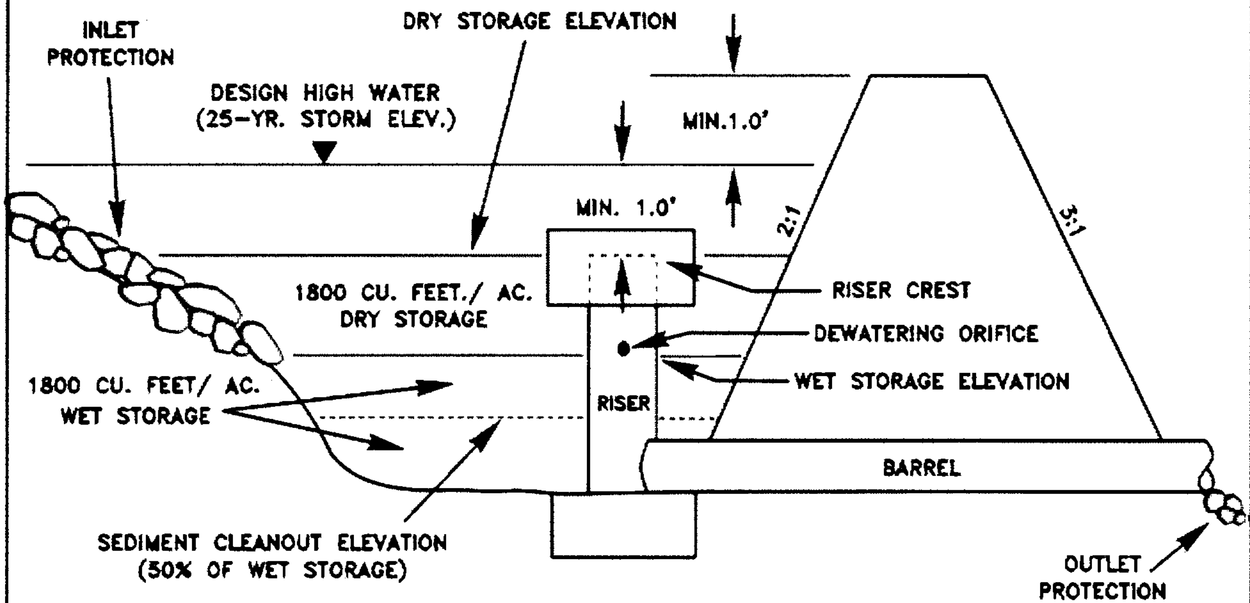


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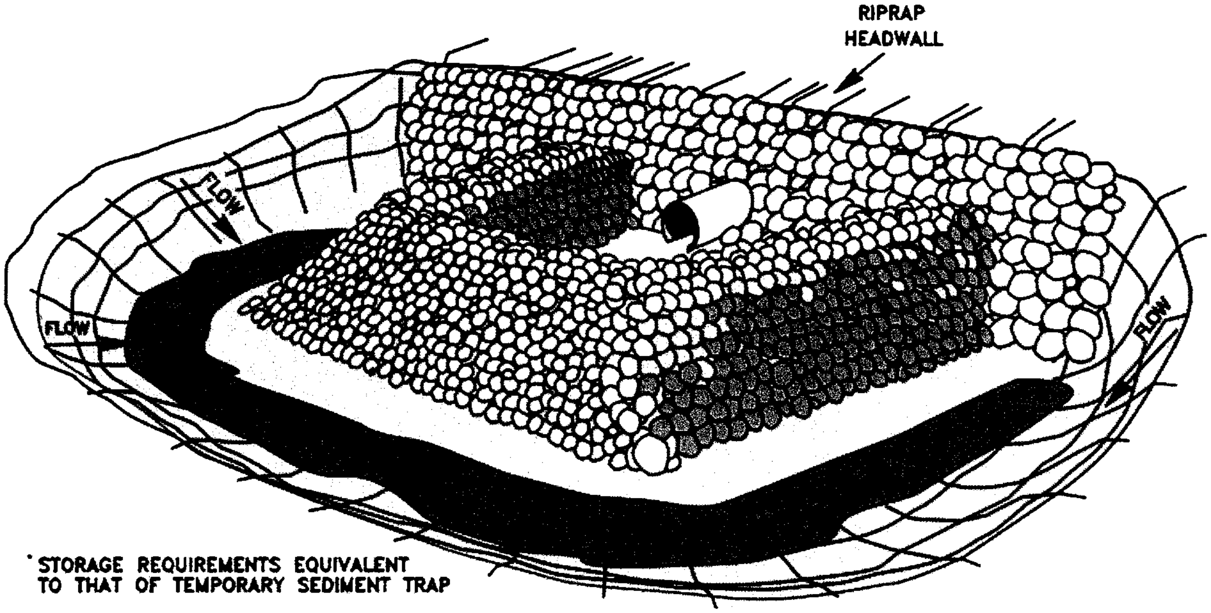
FIGURE 3.29.3

CULVERT INLET SEDIMENT TRAP

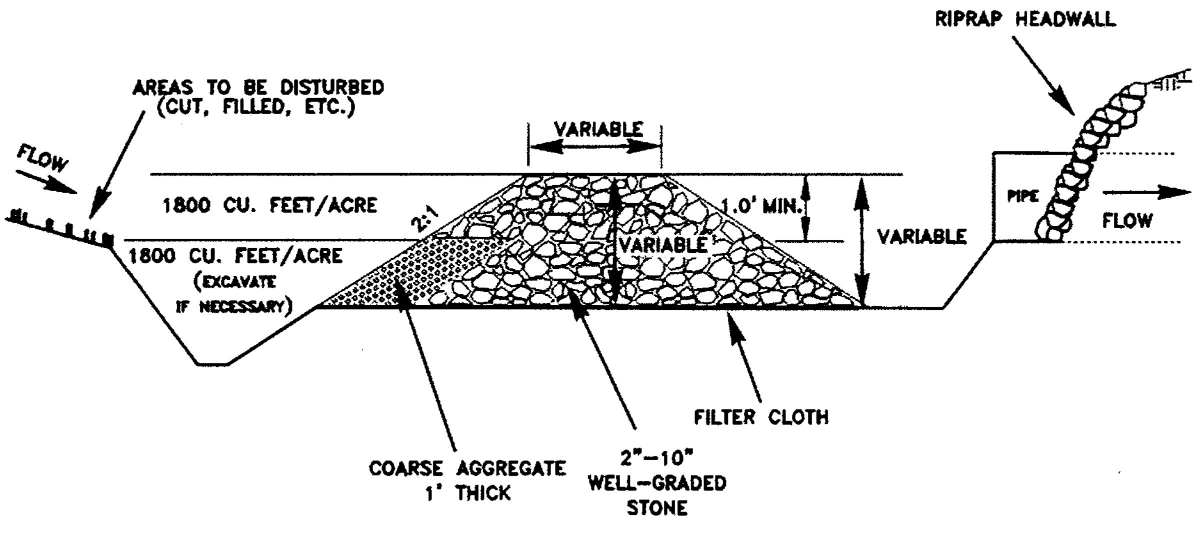


*STORAGE REQUIREMENTS EQUIVALENT TO THAT OF TEMPORARY SEDIMENT TRAP

1800 CU FEET/ACRE WET STORAGE (BELOW INVERT OF PIPE)

1800 CU FEET/ACRE DRY STORAGE (INVERT OF PIPE TO TOP OF STONE BERM)

PERSPECTIVE VIEW



CROSS SECTION

From VA DSWC

3.30 - SEDIMENT BASIN

Introduction

A temporary structure consisting of an earthen embankment, or embankment and excavated area, located in a suitable area to capture sediment laden runoff from a construction site. A sediment basin reduces the energy of the water through extended detention (48 to 72 hours) to settle out the majority of the suspended solids and sediment and prevent sedimentation in waterways, culverts, streams and rivers. Sediment basins have both wet and dry storage space to enhance the trapping efficiency and are appropriate in drainage areas of 5 acres and greater. For drainage areas of less than 5 acres see the standard for SEDIMENT TRAP.

Basins are dewatered through a riser and drainage hole(s) or a skimmer system. Because sediment basins are located in larger drainage areas and the failure of a structure could cause significant damage or death they need to be designed to safely pass the peak discharge from a 25-year/24-hour storm with one foot of freeboard.

They are temporary structures but are often modified to function as a permanent structure after construction is completed.

Properly designed and maintained sediment basins can be very effective in preventing sedimentation of downstream areas. Coarse and medium size particles and associated pollutants will settle out in the basin. Suspended solids and attached nutrients may break down before proceeding downstream.

The effectiveness of sediment trapping structures is greatly improved by use of aggressive erosion control (especially in diversions leading to the basin) in the contributing drainage.

Conditions Where Practice Applies

Sediment basins are needed where drainage areas exceed the design criteria of other measures. Sediment traps are allowed in watersheds of 5 acres and less. General criteria for installation of a sediment basin are as follows:

1. Keep the drainage area less than 100 acres;
2. Ensure that basin location provides a convenient concentration point for sediment-laden flows from the area served;
3. Ensure that basin location allows access for sediment removal and proper disposal under all weather conditions;
4. Keep the basin life limited to 1 year, unless it is designed as a permanent structure;
5. Should not locate sediment basins in intermittent or perennial streams;
6. Sediment basins must dewater in 2 to 3 days;

7. Skimmers can be used to enhance trapping efficiency, however perforated risers are also acceptable;
8. Install basins where they will not interfere with construction activities.

Planning Considerations

Select key locations for sediment basins during initial site evaluation. Install basins before any site grading takes place within the drainage area. Select basin sites to capture sediment from all areas that are not treated adequately by other sediment trapping devices. Always consider access for cleanout and disposal of the trapped sediment. Locations where a pond can be formed by constructing a low dam across a natural swale are generally preferred to sites that require excavation. If practical, divert sediment-free runoff away from the basin. This will help reduce the size of the structure and decrease the amount of erosion on the construction site.

Sediment trapping efficiency is primarily a function of sediment particle size, the ratio of basin surface area to inflow rate and the ability of the basin to reduce the energy of the water. Therefore, design the basin to have a large surface area for its volume and the maximum amount of detention time.

The performance of sediment trapping structure depends on several factors:

1. The size and shape of the basin
2. The soil properties
3. Runoff volume and flow rates
4. Water chemistry
5. Outlet type
6. Temperature

Structures larger than 25 feet in height from the downstream toe to highest point along the crest of the dam and have a maximum storage capacity of 15 acre-feet of water or more are subject to the West Virginia Dam Safety Act.

By virtue of their potential to impound and release large volumes of water, the design of sediment basins is required to be completed by professionals trained in the design of impounding structures, and in accordance with good engineering practices. Sediment basins with an expected life greater than 1 year should be designed as permanent structures. Permanent ponds must be designed and certified by a Professional Engineer. Permanent pond design is beyond the scope of this manual. For further information the USDA Soil Conservation Service Practice Standard Ponds Code No. 378 is an excellent source of information and provides criteria for design of permanent ponds.

In larger drainages or when the discharge is to a Tier 2.5 or 3 Stream, an alternative design procedure that more accurately defines the specific hydrology, sediment loading, hydraulics of the site, and the control measures in use be utilized to perform design calculations. The design criterion in this manual does not generate hydrographs, estimate erosion and delivery rates, provide hydraulic routing or predict sediment capture efficiency. More rigorous and accurate design considerations that are more site specific than those in this manual, are acceptable and encouraged with any size basin.

The design and construction of sediment basins shall comply with all state and local laws, ordinances, permit requirements, rules and regulations. Basins shall be constructed according to the approved Storm Water Pollution Prevention Plan (SWPPP) unless modified a engineering design professional.

Sediment basins must dewater in 2 to 3 days. Skimmers are the preferred dewatering device, however perforated risers are also acceptable.

Sediment basins should be provided with an emergency spillway constructed in original ground with a minimum bottom width of 8'. Energy dissipaters must be included at all inlet and outfalls to prevent scouring.

Sediment basins are attractive to children and can be very dangerous. Local ordinances regarding health and safety must be adhered to. If fencing of the basin is required, the type of fence and its location should be shown in the SWPPP and in the construction specifications.

Limit the contributing area to the sediment basin to only the runoff from the disturbed soil areas. Use temporary water controls to divert runoff from undisturbed areas away from the sediment basin.

The basin should be located: (1) by excavating a suitable area or where a low embankment can be constructed across a swale, (2) where post-construction (permanent) detention basins will be constructed, and (3) where the basins can be maintained during construction to provide access for maintenance, including sediment removal and sediment stockpiling in a protected area, and to maintain the basin to provide the required capacity.

As with all sediment control device it must be maintained until the drainage area is permanently stabilized.

Provide construction details for each proposed sediment basin on the erosion and sediment control plans. Show all significant features and elevations on those plans.

Design Criteria

Drainage areas—Limit drainage areas to 100 acres.

Design basin life—Ensure a design life of 1 year or more.

Dam height—Limit dam height to 15 feet if possible. Height of a dam is measured from the highest point of the dam to the lowest point at the downstream toe. According to the Dam Control Act the volume is measured to the highest point on the top of the dam.

Basin locations—Select areas that:

Provide capacity for storage from as much of the planned disturbed area as practical;

Exclude runoff from undisturbed areas, where practical;

Provide access for sediment removal throughout the life of the project and;

Interfere minimally with construction activities.

Basin shape—It is important that the designer of the sediment basin incorporate features to maximize detention time and reduce the energy of the inflow before water is discharged. Some of the methods to improve basin geometry:

1. Length to width ratio of at least 2:1, with 4:1 optimal. Try not to exceed 6:1 as basin velocities can increase and the basin starts to behave as a channel. Length is measured at the elevation of the principal spillway.
2. Wedge shape with the inlet at the narrow end. Line up the inlet, riser and center or the dam.
3. Installation of baffles
4. Maximize surface area to provide efficient settling.

Storage volume—Ensure that the sediment storage volume of the basin, measured at the elevation of the crest of the principal spillway, is at least 3,600 cubic feet per acre of the total area draining into the basin.

Unless using a skimming device, half of the volume shall be in wet storage and half of the storage shall be in dry storage. Use the maximum drainage area found at any point during construction. Since watersheds often change during grading operations, the largest drainage area is not necessarily the pre- or post-construction drainage area. The maximum watershed area used to size the basin should be delineated on the drawings.

Remove sediment from the basin when approximately one-half of the wet storage volume has been filled. Show this elevation in the plans and provide a method of determining it in the field.

When the construction of a single basin with storage volume of 3600 cubic feet per acre is not feasible due to site constraints it can be advantageous to install several smaller structures in series with a combined storage volume of 3600 cubic feet. Creating a fore bay can also improve the trapping efficiency.

The volume requirements of the General Permit and this standard should be regarded as the minimum necessary to protect water quality. The design professional is encouraged to increase these storage requirements to protect a critical aquatic resource such as Tier 2.5 or 3 streams or the safety/health of the public. The following conditions could require additional storage or increased spillways capacity:

1. Highly erodible soils
2. Steep upslope topography
3. Space limiting basin geometry (depth or shape)
4. Degree to which off-and/or on-site runoff is diverted from the contributing undisturbed areas
5. Sediment cleanout schedule
6. Ease of access to clean out basin
7. Flocculant use
8. Extent of upslope erosion and sediment control
9. Critical downstream conditions

Minimum depth The sediment basin should be at least two feet deep.

Spillway capacity—The combined spillway system must carry the peak runoff from the 25-year/24 hour storm with a minimum 1-foot of freeboard.

Base peak flow runoff computations on the largest disturbed area expected and the worst soil cover conditions during the effective life of the structure.

Sediment basin spillways must be able to discharge 2 cfs/acre from the entire contributing watershed. However, if this rule of thumb is used, a minimum of 24 inches of freeboard will be required above the elevation of the 2 cfs/acre. If the emergency spillway is being used to provide part of the 2 cfs/acre discharge, the freeboard must be provided above the design flow elevation in the emergency spillway.

Principal spillway—Construct the principal spillway with a vertical riser connected to a horizontal barrel that extends through the embankment and outlets beyond the downstream toe of the dam, or an equivalent design.

• Capacity—The primary spillway system should carry the peak runoff from the 2-year storm, with the water surface at the emergency spillway crest elevation.

Basin dewatering

A sediment basin must be able to dewater the dry storage volume in 48 to 72 hours. There are two traditional ways to accomplish this

The basin should be provided either with a perforated riser with a hole or series of holes at the wet storage elevation or to enhance the trapping efficiency a surface skimmer.

Dewatering orifice---In order to dewater the sediment basin in 48 to 72 a hole or several holes that add up to A_o should be cut into the riser.

$$A_o = A_s \times (2h)^{0.5} / (T \times C_d \times 20{,}428)$$

where

A_o = total area of dewatering holes, ft^2;
A_s = surface area of the basin, ft^2;
h = head of water above the hole, ft;
C_d = coefficient of contraction for an orifice, approximately 0.6;
T = detention time or time needed to dewater the basin, hours

• **Skimmer**—A floating skimmer may be attached to the base of the riser. The orifice in the skimmer will control the rate of dewatering. The skimmer should be sized to dewater the basin in 48-72 hours.

Use the manufacturers Installation Manual to size the skimmer orifice. See SKIMMER BASIN for details on the installation of skimmers.

Sediment cleanout elevation—The clean out elevation is 50 percent of the wet storage elevation. Indicate on the drawings this elevation and mark in the field with a permanent stake.

Crest elevation—Keep the crest elevation of the riser a minimum of 1 foot below the crest elevation of the emergency spillway.

Riser and Barrel—Keep the minimum barrel size at 15 inches for corrugated metal pipe or 12 inches for smooth wall pipe to facilitate installation and reduce potential for failure from blockage. Ensure that the pipe is capable of withstanding the maximum external loading without yielding, buckling or cracking. To improve the efficiency of the principal spillway system, make the cross-sectional area of the riser at least 1.5 times that of the barrel. The riser should be sized to minimize the range of stages when orifice flow will occur.

Pipe Connections—Ensure that all conduit connections are watertight.

Rod and lug type connector bands with gaskets are preferred for corrugated metal pipe to assure water tightness under maximum loading and internal pressure. Do not use dimple (universal) connectors under any circumstances.

It is important that a suitable trash guard be installed to prevent the dewatering holes from becoming clogged.

Trash rack—Install a trash rack on the top of the riser to prevent trash and other debris from clogging the conduit. A combination anti-vortex device and trash rack improves the efficiency of the principal spillway and protects against trash intake.

Protection against piping—Install at least one watertight anti-seep collar with a minimum projection of 1.5 feet around the barrel of principal spillway conduits, 8 inches or larger in diameter. Locate the anti-seep collar slightly downstream from the dam centerline. A properly designed drainage diaphragm installed around the barrel may be used instead of an anti-seep collar when it is appropriate.

Protection against flotation—Secure the riser by an anchor with buoyant weight at least 1.25 times greater than the water displaced by the riser.

Outlet—Protect the outlet for the barrel against erosion. Discharge velocities must be within allowable limits for the receiving stream. (See OUTLET PROTECTION)

Emergency spillway—Construct the entire flow area of the emergency spillway in undisturbed soil (not fill). Make the cross section trapezoidal at least 8 feet wide and with side slopes of 3:1 or flatter. Make the control section of the spillway straight and at least 20 feet long. The inlet portion of the spillway may be curved to improve alignment, but ensure that the outlet section is straight due to supercritical flow in this portion. The channel should be located so as to avoid sharp bends. The outlet of the spillway channel should be to a defined natural channel downstream of the toe of the embankment.

Capacity—The minimum design capacity of the emergency spillway must be the peak rate of runoff from the 25-year/24 hour storm, less any reduction due to flow in the principal spillway. In no case should freeboard of the emergency spillway be less than 1 foot above the design depth of flow.

Outlet Velocity—Ensure that the velocity of flow discharged from the basin is non-erosive for the existing conditions. When velocities exceed that allowable for the receiving areas, provide outlet protection (See OUTLET PROTECTION).

Embankment Design Standards

Cut-off trench Excavate a minimum of 2 feet wide trench with 1:1 side slopes at the centerline of the embankment. Ensure that the trench is in undisturbed soil and extends through the length of the embankment to the elevation of the riser crest at each end. A minimum of 2 feet depth is recommended.

Top width The minimum top width of the dam is as follows.

Acceptable Dimensions for Basin Embankment

Fill Height	minimum top Width
less than 10 ft	8.0 ft
10 ft to 15 ft	10.0 ft
16 ft to 25 ft	15.0 ft

Freeboard Ensure that the minimum difference between the design water elevation in the emergency spillway and the top of the settled embankment is 1 foot.

Side slopes Make the side slopes of the impoundment structure so that the total slope of both sides equals 5:1 or flatter. IE. If the upstream slope is 2:1 the downstream must be 3:1 but at no time shall an embankment slope exceed 2:1.

Allowance for settlement Increase the constructed height of the fill at least 10 percent above the design height to allow for settlement.

Erosion protection Stabilize all areas disturbed by construction (except the lower 1/2 of the wet storage pool) by suitable means immediately after completing the basin.

Trap efficiency Sediment basin trapping efficiency can be improved by using the following considerations in the basin design:

Surface area In the design of the settling pond, allow the largest surface area possible. Studies indicate that surface area (in acres) should be larger than 0.01 times the peak inflow rate in cfs.

$$A = 0.01q$$

where A is the basin surface area in acres and q is the peak inflow rate in cubic feet per second

Length The length to width ratio should be between 2:1 to 6:1.

Baffles Provides a minimum of two baffles to evenly distribute flow across the basin and reduces turbulence. See specification on BAFFLES.

Inlets Locate the sediment inlets to the basin the greatest distance from the principal spillway. Protect the inlet from scour and erosion with appropriate riprap protection. If there is room, provide a forebay to help slow the speed of the water down.

Inflow rate Reduce the inflow velocity and divert all sediment-free runoff away from the basin's watershed.

A summary table showing all critical dimensions and elevations for each basin should be prepared for the construction drawings and the NPDES application.

Construction Specifications

Site preparation—Install appropriate sediment and provide erosion controls as required. Clear, grub, and strip topsoil from areas under the embankment to remove trees, vegetation, roots, and other objectionable material. Delay clearing the pool area until the dam is complete and then remove brush, trees, and other objectionable materials to facilitate sediment cleanout and prevent floatables that can clog the outlets. Stockpile all topsoil or soil containing organic matter for use on the outer shell of the embankment to facilitate vegetative establishment.

Cut-off trench—Excavate a cut-off trench along the centerline of the earth fill embankment. Cut the trench to stable soil material, but in no case make it less than 2 feet deep. The cut-off trench must extend into both abutments to at least the elevation of the riser crest. Make the minimum bottom width wide enough to permit operation of excavation and compaction equipment, but in no case less than 2 feet. Make side slopes of the trench no steeper than 1:1. Compaction requirements are the same as those for the embankment. Keep the trench dry during backfilling and compaction operations.

Embankment Core - The core shall be parallel to the centerline of the embankment as shown on the plans. The top width of the core shall be a minimum of four feet. The height shall extend up to at least to the top of the riser or as shown on the plans. The side slopes shall be 1 to 1 or flatter. The core shall be compacted with construction equipment, rollers, or hand tampers to assure maximum density and minimum permeability. In addition, the core shall be placed concurrently with the outer shell of the embankment.

Embankment—Take fill material from the approved areas shown on the plans. It should be clean mineral soil, free of roots, woody vegetation, rocks, organic topsoil and other objectionable material. Scarify areas on which fill is to be placed before placing fill. Fill material for the center of the embankment, and cut off trench shall conform to Unified Soil Classification GC, SC, CH, or CL and must have at least 30% passing the #200 sieve. The fill material must contain sufficient moisture so it can be formed by hand into a ball without crumbling. If water can be squeezed out of the ball, it is too wet for proper compaction.

Place fill material in 8 inch continuous layers over the entire length of the fill area and compact it. Hand compact areas around the anti-seep collars. Compaction may be obtained by routing the construction hauling equipment over the fill so that the entire surface of each layer is traversed by at least one wheel or tread track of heavy equipment, or a compactor may be used. Construct the embankment to an elevation 10 percent higher than the design height to allow for settling.

As an alternate, the following can be used to specify embankment placement. The minimum required density shall not be less than 95% of maximum dry density with a moisture content within 2% of the optimum. Each layer of fill shall be compacted as necessary to obtain that density, and is to be certified by the Engineer at the time of construction. All compaction is to be determined by AASHTO Method T-99 (Standard Proctor).

Conduit spillways—Securely attach the riser to the barrel or barrel stub to make a watertight structural connection. Secure all connections between barrel sections by approved watertight assemblies. The backfill adjacent to pipes or structures shall be of the type and quality conforming to that specified for the adjoining fill material. Place the barrel and riser on a firm, smooth foundation of impervious soil. Do not use pervious material such as sand, gravel, or crushed stone as backfill around the pipe or antiseep collars. Place the fill material around the pipe spillway in 4-inch layers, and compact by hand tampers or other manually directed compaction equipment under and around the pipe to at least the same density as the adjacent embankment. The material needs to fill completely all spaces under and adjacent to the pipe. The pipe shall be firmly and uniformly bedded throughout its entire length. Where rock or soft, spongy or other unstable soil is encountered, all such material shall be removed and replaced with suitable earth compacted to provide adequate support. Care must be taken not to raise the pipe from firm contact with its foundation when compacting under the pipe haunches. At no time during the backfilling operation shall driven equipment be allowed to operate closer than four feet, measured horizontally, to any part of a structure. Place a minimum depth of 2 feet of compacted backfill over the pipe spillway before crossing it with construction equipment.

Anchor the riser in place by concrete or other satisfactory means to prevent flotation.

In no case should the pipe conduit be installed by cutting a trench through the dam after the embankment is complete.

Emergency spillway—Install the emergency spillway in undisturbed original ground. The achievement of planned elevations, grade, design width, and entrance and exit channel slopes are critical to the successful operation of the emergency spillway.

Inlets—Discharge water into the basin in a manner to prevent erosion. Use diversions with outlet protection to divert sediment-laden water to the upper end of the pool area to improve basin trap efficiency (See DIVERSIONS and OUTLET PROTECTION).

Erosion control— The installation of a sediment basin can in some instances be a significant construction project in its own right. The designer must create a comprehensive sediment control plan for each sediment basin installation.

Install appropriate sediment control prior to starting constructing. Minimize the disturbed area. Divert surface water away from bare areas and around the embankment footprint. Complete the embankment before the remaining construction site is cleared. Stabilize the emergency spillway embankment and all other disturbed areas above the wet storage elevation immediately after construction. Install Riprap channel protection in the emergency spillway if needed and at the outlet of the pipe.

Care of Water during Construction --All work on permanent structures shall be carried out in areas free from water. The contractor shall construct and maintain all temporary dikes, levees, cofferdams, drainage channels, and stream diversions necessary to protect the areas to be occupied by the permanent works. The contractor shall also furnish, install, operate, and maintain all necessary pumping and other equipment required for removal of water from various parts of the work and for maintaining the excavations, foundation, and other parts of the work free from water as required or directed by the engineer for constructing each part of the work.

After having served their purpose, all temporary protective works shall be removed or leveled and graded to the extent required to prevent obstruction in any degree whatsoever of the flow of water to the spillway or outlet works and so as not to interfere in any way with the operation or maintenance of the structure. Stream diversions shall be maintained until the full flow can be passed through the permanent works.

The removal of water from the required excavation and the foundation shall be accomplished in a manner and to the extent that will maintain stability of the excavated slopes and bottom required excavations and will allow satisfactory performance of all construction operations. During the placing and compacting of material in required excavations, the water level at the locations being refilled shall be maintained below the bottom of the excavation at such locations which may require draining the water sumps from which the water shall be pumped.

Baffles Install baffles as specified in Baffles section.

Safety—Sediment basins may attract children and can be dangerous. Avoid steep side slopes, and fence and mark basins with warning signs if trespassing is likely. Follow all state and local requirements.

Sediment Basin Removal and Cleanup

Final cleanup and disposition : The designer shall prepare a Sediment Control Plan for the removal of all sediment-trapping structures. Include in the Plan the method for dewatering the wet storage and removal of the trapped sediments.

Once the site is stabilized and the basin is no longer needed the structure shall be removed and the original contours reestablished. Sediment shall be removed so it cannot reenter a waterway.

Dewatering must not cause water quality violations. See the Basin or Sediment Trap Sediment Storage Dewatering Facility drawing for approved procedures to dewater a basin or trap.

All disturbed areas will be seeded and mulched immediately according to the specifications in this manual.

Maintenance

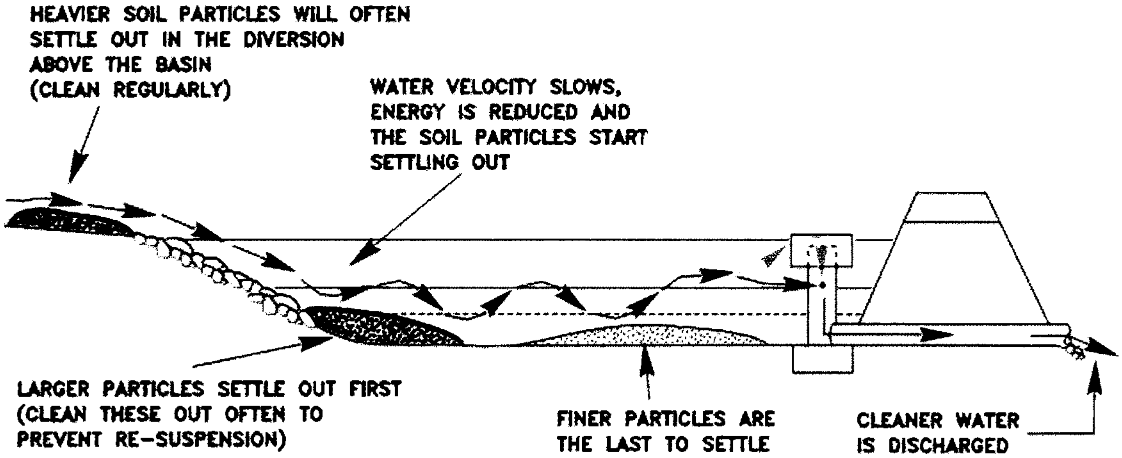
Inspect temporary sediment basins weekly and after each rainfall event 0.5 inch or greater and repair immediately.

Provide access for sediment removal and other required maintenance activities. Remove sediment and restore the basin to its original dimensions when it accumulates to one-half the wet storage depth. Place removed sediment where there is no possibility of its reentry into a waterway.

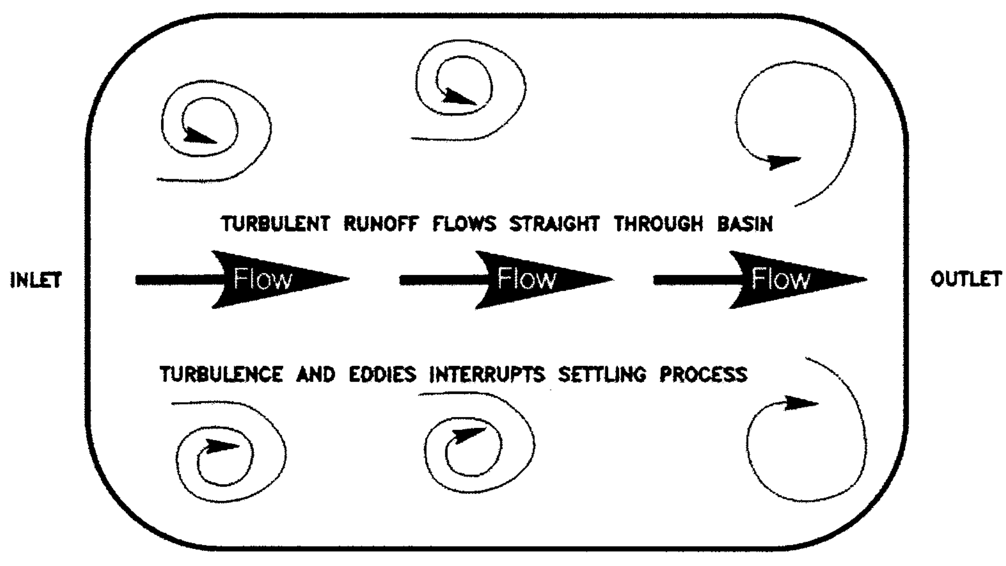
Check the embankment, spillways, and outlet for erosion damage, and inspect the embankment for piping and settlement. Make all necessary repairs immediately. Remove all trash and other debris from the riser and pool area.

FIGURE 3.30.1

HOW A SEDIMENT BASIN WORKS



HOW A SEDIMENT BASIN DOES NOT WORK

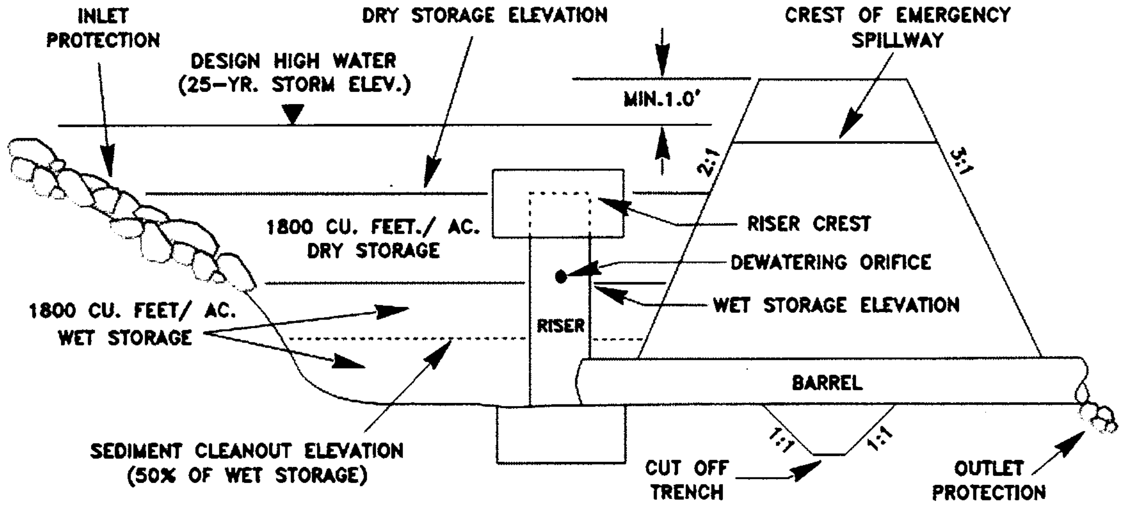


DURING PEAK STORM DISCHARGES THE VELOCITY AND ENERGY OF THE INFLOW ACROSS THE TRAP OR BASIN REMAINS TOO HIGH FOR MUCH SETTLING TO OCCUR.

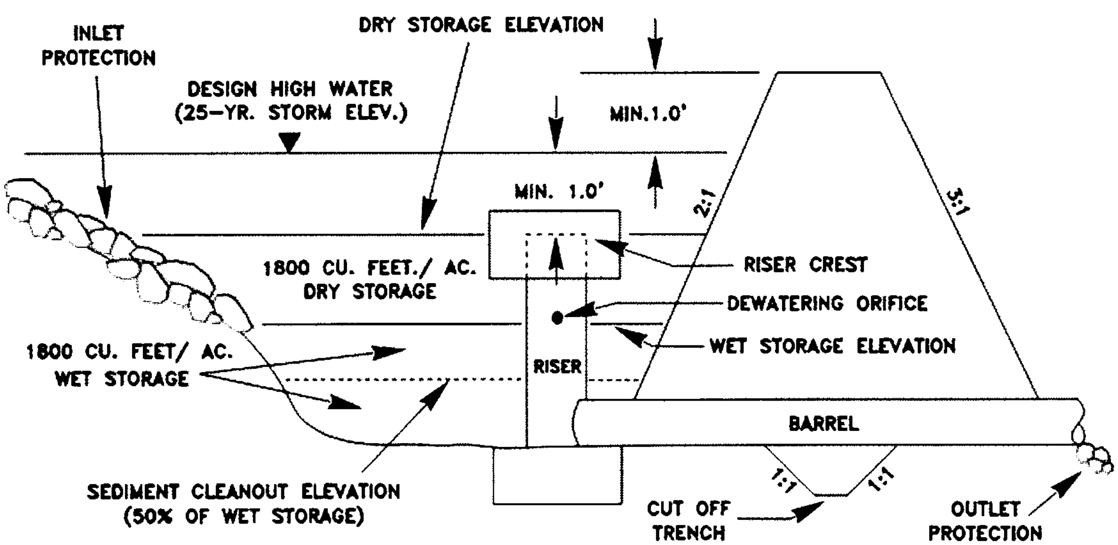
FROM: SOIL FACTS NORTH CAROLINA COOPERATIVE EXTENSION

FIGURE 3.30.2

SEDIMENT BASIN



DESIGN ELEVATIONS WITH EMERGENCY SPILLWAY



DESIGN ELEVATIONS NO EMERGENCY SPILLWAY

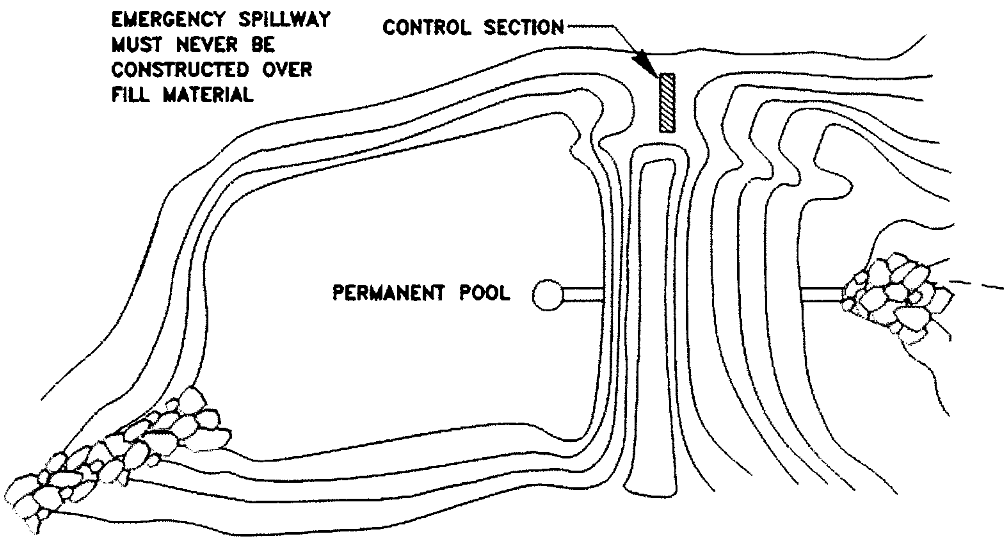
(NTS)

ADAPTED FROM: VA. DSWC

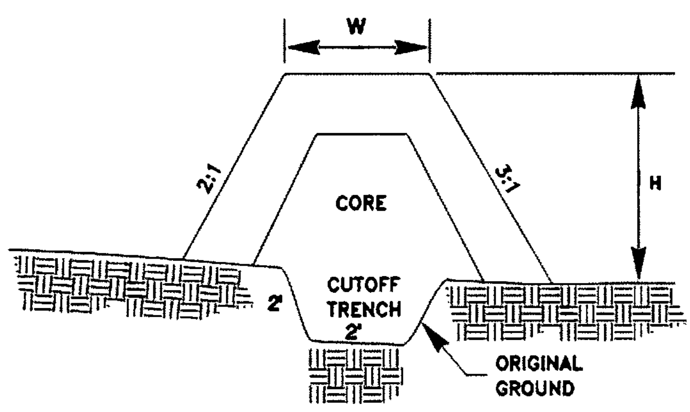
FIGURE 3.30.3

BASIN SCHEMATIC

EMERGENCY SPILLWAY



MINIMUM DIMENSIONS FOR SEDIMENT BASIN EMBANKMENTS

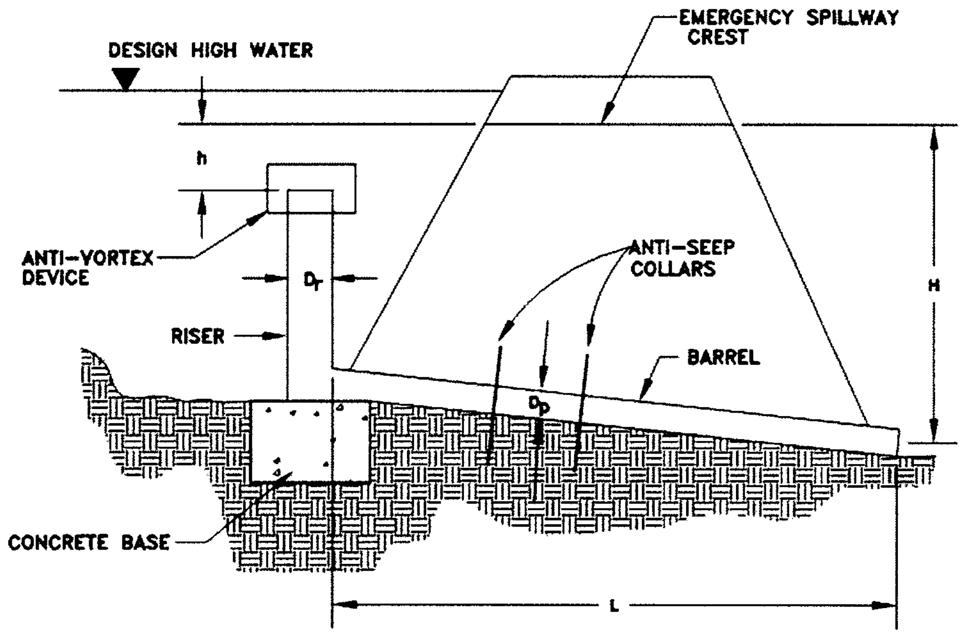


H	W
LESS THAN 10 ft.	8.0 FT.
10 FT TO 15 FT	10.0 FT.
15 AND HIGHERT	15.0 FT.

SOURCE: VA. DSWC

FIGURE 3.30.4

PRINCIPAL SPILLWAY DESIGN



H = HEAD ON PIPE THROUGH EMBANKMENT

h = HEAD OVER RISER CREST

L = LENGTH OF PIPE THROUGH EMBANKMENT

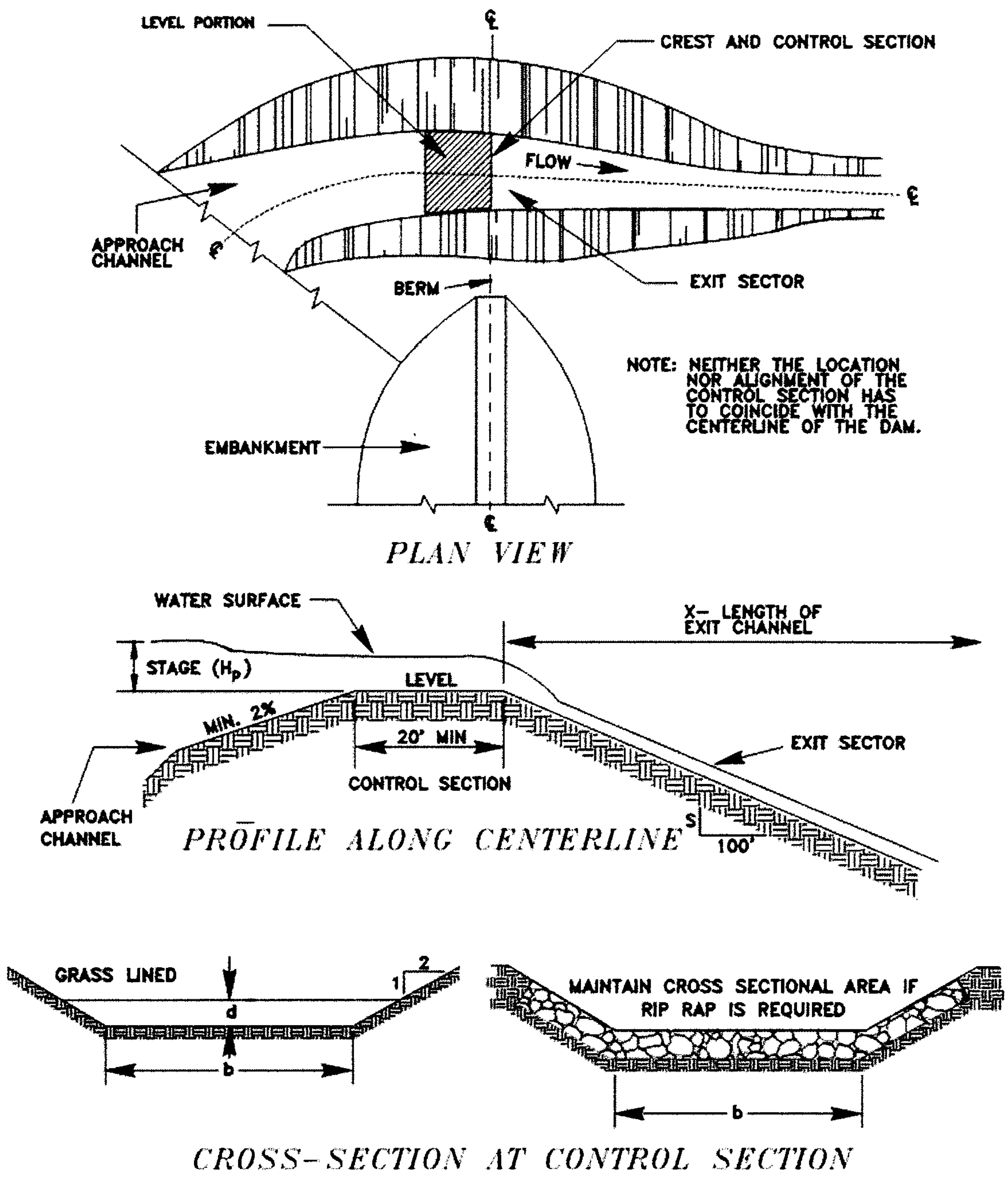
D_p = DIAMETER OF PIPE THROUGH EMBANKMENT

D_r = DIAMETER OF RISER

SOURCE: VA. DSWC

FIGURE 3.30.5

EXCAVATED EARTH SPILLWAY



SOURCES: USDA-NRCS AND VA DNRC

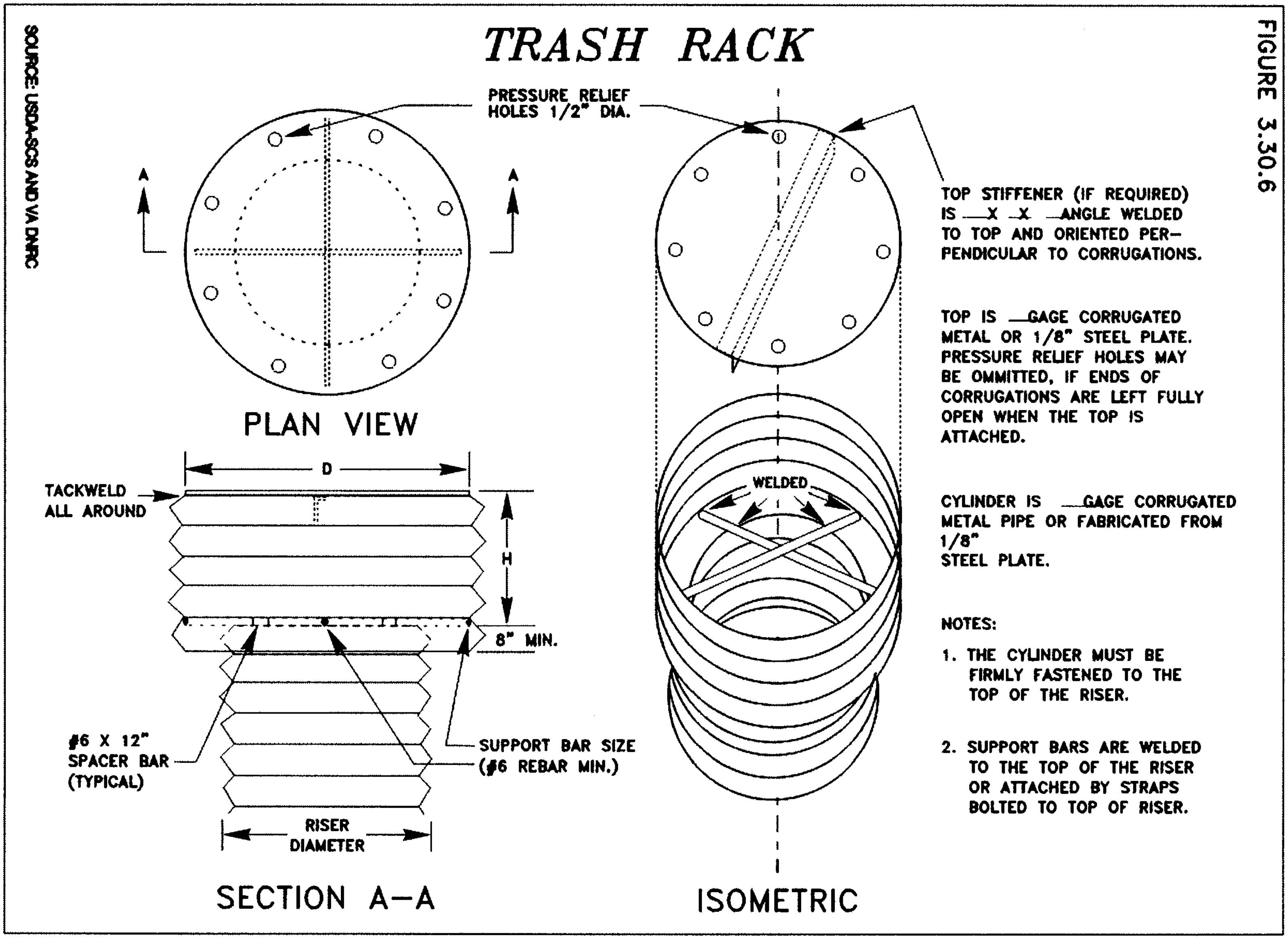
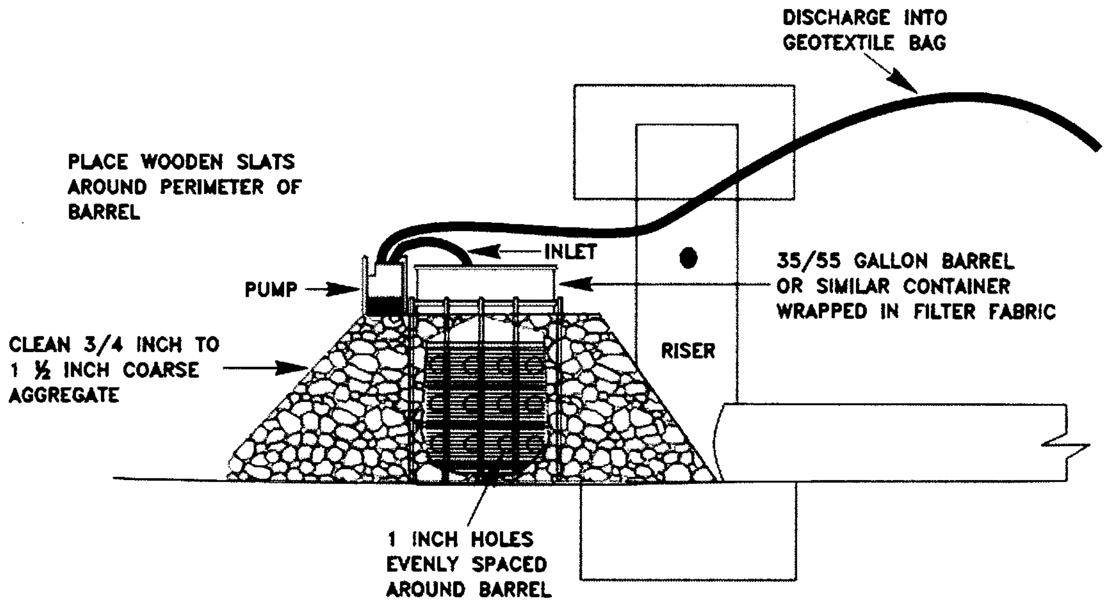


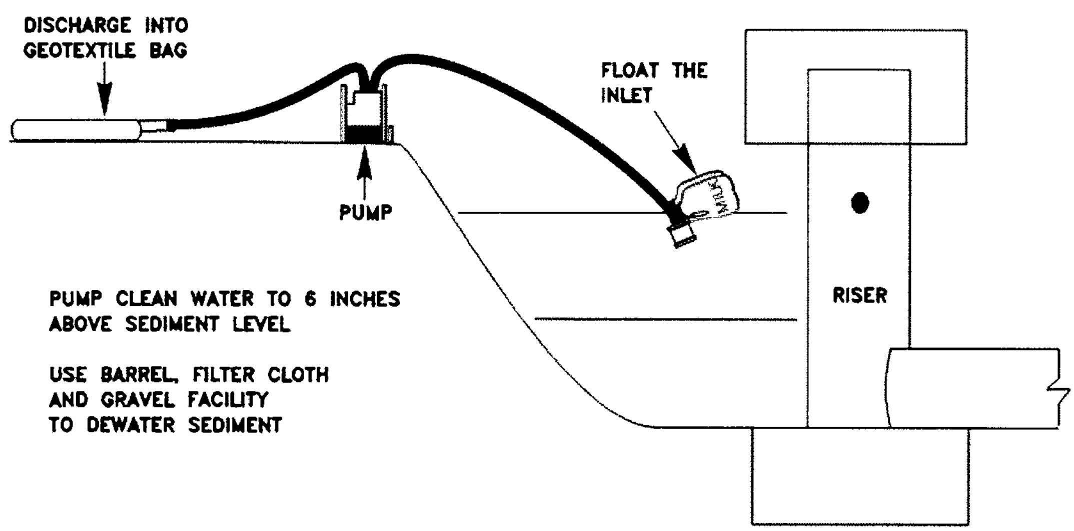
FIGURE 3.30.6
TRASH RACK
PRESSURE RELIEF HOLES 1/2" DIA.
TOP STIFFENER (IF REQUIRED) IS __X __X __ANGLE WELDED TO TOP AND ORIENTED PER- PENDICULAR TO CORRUGATIONS.
TOP IS __GAGE CORRUGATED METAL OR 1/8" STEEL PLATE. PRESSURE RELIEF HOLES MAY BE OMMITTED, IF ENDS OF CORRUGATIONS ARE LEFT FULLY OPEN WHEN THE TOP IS ATTACHED.
CYLINDER IS __GAGE CORRUGATED METAL PIPE OR FABRICATED FROM 1/8" STEEL PLATE.
NOTES:
1. THE CYLINDER MUST BE FIRMLY FASTENED TO THE TOP OF THE RISER.
2. SUPPORT BARS ARE WELDED TO THE TOP OF THE RISER OR ATTACHED BY STRAPS BOLTED TO TOP OF RISER.
A
A
PLAN VIEW
D
H
TACKWELD ALL AROUND
8" MIN.
#6 X 12" SPACER BAR (TYPICAL)
SUPPORT BAR SIZE (#6 REBAR MIN.)
RISER DIAMETER
SECTION A–A
WELDED
ISOMETRIC
SOURCE: USDA-SCS AND VA DNRC

FIGURE 3.30.7

SEDIMENT BASIN OR TRAP DEWATERING DEVICE



FROM PENNSYLVANIA EROSION AND SEDIMENT POLLUTION CONTROL PROGRAM MANUAL



3.33 - DROP INLET PROTECTION

Introduction

A sediment barrier and/or an excavated impounding area around a storm drain drop inlet or curb inlet used to trap sediment before contaminated runoff enters a storm drainage system.

Conditions Where Practice Applies

Where storm drain inlets are to be made operational before permanent stabilization of the corresponding disturbed drainage area.

Storm sewers that are made operational prior to stabilization of the associated drainage areas can convey large amounts of sediment to natural drainageways. In case of severe sediment loading, the storm sewer itself may clog and lose a major portion of its capacity. To avoid these problems, it is necessary to prevent sediment from entering the system at the inlets.

>>Storm sewers are installed to handle the runoff from their contributing drainage area and are sized to handle the flows from a particular size storm event. Installing any of these drop inlet protection practices reduces opening size of the inlet or severely restricts the hydraulic conditions entering the inlet, thereby reducing the capacity of the inlet to handle the excess flows from storm events. Design and install each of these practices with great care. It is highly recommended to use the 6" freeboard requirement whenever possible. Care must be taken not to create conditions where flooding will occur either when the inlet becomes clogged with sediment or debris and/or the top of the drop inlet protection is higher than the nearest low spot and storm flows bypass the inlet. This could lead to a cascading series of failures of other inlet protection, ending up with severe flooding to adjacent properties or severe erosion of fill slopes.

This practice contains several types of inlet barriers and traps that have different applications dependent upon site conditions and type of inlet. Plan developers are encouraged to investigate some of the commercially available products now on the market.

General Design Criteria

1. The drainage area should be no greater than 1 acre per inlet. The drainage area should be fairly flat with slopes of 5% or less and the area immediately around the inlet should not exceed a slope of 1%.
2. The inlet protection device shall be constructed in a manner that will facilitate clean out and disposal of trapped sediment and minimize interference with construction activities.
3. The inlet protection devices shall be constructed in such a manner that any resultant ponding of stormwater will not cause excessive inconvenience or damage to adjacent areas or structures.
4. For the inlet protection devices that utilize stone as the chief ponding/filtering medium, a range of stone sizes is offered The designer should attempt to get the greatest amount of "filtering" action possible

(by using smaller-sized stone), while not creating significant ponding problems.

5. In all designs that utilize stone with a wire-mesh support as a filtering mechanism, the stone can be completely wrapped with the wire mesh to improve stability and provide easier cleaning.
6. Filter Fabric may be added to any of the devices that utilize stone to significantly enhance sediment removal, but with a reduced flow capacity. The fabric, which must meet the physical requirements noted for "extra strength", should be secured between the stone and the inlet (on wire-mesh if it is present). As a result of the significant increase in filter efficiency provided by the fabric, a larger range of stone sizes (up to gabion size) may be utilized with such a configuration.
   Note: Significant ponding will occur at the inlet if filter cloth is utilized in this manner.
7. If there is a possibility that ponding will occur, the top of the inlet protection must be at least six inches below the nearest low spot to insure sufficient freeboard. See Figure 3.33.2.
8. Remove any obstructions to excavating and grading. Excavate any sump area, grade slopes and properly dispose of soil.
9. The inlet grate should be secured to prevent seepage of sediment-laden water.
10. Ensure that weep holes in the inlet structure are protected by filter fabric and gravel.
11. Hardware cloth or wire mesh with ½-inch inch openings.
12. Filter fabric
13. Washed gravel 3/4 inches to 4 inches in diameter. All cut slopes shall be 2:1 or flatter.

Construction Specifications

Silt Fence Drop Inlet Protection

a. Silt Fence shall conform to the specifications for "extra strength" and shall be cut from a continuous roll to avoid joints.
b. For stakes, use 2 x 4-inch wood (preferred) or equivalent metal with a minimum length of 3 feet.
c. Space stakes evenly around the perimeter of the inlet a maximum of 3-feet apart, and securely drive them into the ground, approximately 18 inches deep.
d. To provide needed stability to the installation, frame with 2 x 4-inch wood strips around the crest of the overflow area at a maximum of 1 foot above the drop inlet crest.
e. Place the bottom 12 inches of the fabric in a trench and backfill the trench with 12 inches of compacted soil. This limits this practice to unpaved areas.
f. Fasten fabric securely by staples or wire to the stakes and frame. Joints must be overlapped to the next stake.
g. It may be necessary to build a temporary dike on the downslope side of he structure to prevent bypass flow.
h. It is recommended that a sediment trapping sump of 1 to 2 feet in depth with side slopes of 2:1 by provided.
i. If the filter fabric becomes clogged it should be replaced immediately.

j. Make sure that the stakes are firmly in the ground and that the filter fabric continues to be securely anchored.

Gravel and Wire Mesh Drop Inlet Protection

a. Wire mesh shall be laid over the drop inlet so that the wire extends a minimum of 1 foot beyond each side of the inlet structure. Wire mesh with ½-inch openings shall be used. If more that one strip of mesh is necessary, the strips shall be overlapped.

b. Coarse aggregate shall be placed over the wire mesh as indicated in the drawing. The depth of stone shall be at least 12 inches over the entire inlet opening. The stone shall extend beyond the inlet opening at least 18 inches on all sides.

c. If the stone filter becomes clogged with sediment so that it no longer adequately performs its function, the stones must be pulled away from the inlet, cleaned and/or replaced.

Note: This filtering device has no overflow mechanism; therefore, ponding is likely especially if sediment is not removed regularly. This type of device must never be used where overflow may endanger an exposed fill slope or flooding of adjacent properties. Consideration should also be given to the possible effects of ponding on traffic movement, nearby structures, working areas, adjacent property, etc.

Block and Gravel Drop Inlet Protection

a. Place concrete blocks lengthwise on their sides in a single row around the perimeter of the inlet, with the ends of adjacent blocks abutting. The height of the barrier can be varied, depending on design needs, by stacking combinations of 4-inch, 8-inch and 12-inch wide blocks. The barrier of blocks shall be at least 7½-inches high but no greater than 24-inches high.

b. Wire mesh shall be placed over the outside vertical face (webbing) of the concrete blocks to prevent stone from being washed through the holes in the blocks. Wire mesh with ½-inch openings shall be used.

c. Stone shall be piled against the wire to the top of the block barrier, as shown in the drawing.

d. If the stone filter becomes clogged with sediment so that it not longer adequately performs its function, the stone must be pulled away from the blocks, cleaned and replaced.

Pipe Riser Drop Inlet Protection

a. Each pipe riser must be constructed from steel plate that is cut to the dimensions of the drop inlet grate with an inch over lap on each side and a length of 12 inch corrugated metal pipe. Use a minimum of 10 gauge steel plate with a 12 inch hole cut in the center. The corrugated pipe is welded to the plate.

b. Cut a series of one-inch holes in the corrugated pipe as shown on the drawings. Wire mesh with ½ inch openings can be wrapped around the outside of the pipe to prevent stone from being washed through the holes.

c. Place a square piece of geotextile filter fabric at least one foot larger than the inlet dimensions around the riser and over the metal plate.

d. Stone shall be piled to the top of the pipe, as shown in the drawing.

e. If the stone filter becomes clogged with sediment so that it not longer adequately performs its function, the stone must be pulled away from the blocks, cleaned and replaced.

f. This practice can be combined with the Excavated Drop Inlet Sediment Trap to increase the available storage.

Excavated Drop Inlet Sediment Trap

a. The excavated trap shall be sized to provide a minimum storage capacity calculated at the rate of 3600 cubic feet per acre of drainage area. (if attainable). The trap should be not less than 1-foot nor more than 2-feet deep measured from the top of the inlet structure. Side slopes shall not be steeper than 2:1.

b. The slope of the basin may vary to fit the drainage area and terrain. Observations must be made to check trap efficiency and modifications shall be made as necessary to ensure satisfactory trapping of sediment. Where an inlet is located so as to receive concentrated flows, such as in a highway median, it is recommended that the basin have a rectangular shape in a 2:1 (length/width) ratio, with the length oriented in the direction of the flow.

c. Sediment shall be removed and the trap restored to its original dimensions when the sediment has accumulated to one-half the design depth of the trap. Removed sediment shall be deposited in a suitable area and in a manner such that it will not erode.

d. If there is sufficient freeboard available this practice can be combined with other drop inlet protection devices such as Silt Fence or Pipe Riser.

Gravel Curb Inlet Protection

a. Wire mesh with ½-inch openings shall be placed over the curb inlet opening so that at least 12 inches of wire extends across the inlet cover and at least 12 inches of wire extends across the concrete gutter from the inlet opening, as depicted in drawing.

b. Stone shall be piled against the wire so as to anchor it against the gutter and inlet cover and to cover the inlet opening completely.

c. If the stone filter becomes clogged with sediment so that it no longer adequately performs its function, the stone must be pulled away from the block, cleaned and replaced.

Curb Inlet Protection with 2-inch x 4-inch Wooden Weir

a. Attach a continuous piece of wire mesh (30-inch minimum width x inlet throat length plus 4 feet) to the 2-inch x 4-inch wooden weir (with a total length of throat length plus 2 feet) as shown in the drawing. Wood should be "construction grade" lumber.

b. Place a piece of approved "extra-strength" filter cloth of the same dimensions as the wire mesh over the wire mesh and securely attach to the 2-inch x 4-inch weir.

c. Securely nail the 2-inch x 4-inch weir to the 9-inch long vertical spacers which are to be located between the weir and inlet face at a maximum 6-foot spacing.

d. Place the assembly against the inlet throat and nail 2-foot (minimum) lengths of 2-inch x 4-inch board to the top of the weir at spacer locations. These 2-inch x 4-inch anchors shall extend across the inlet tops and be held in place by sandbags or alternate weight.

e. The assembly shall be placed so that the end spacers are a minimum 1 foot beyond both ends of the throat opening.

f. Form the wire mesh and filter cloth to the concrete gutter and against the face of curb on both sides of the inlet. Place coarse aggregate over the wire mesh and filter fabric in such a manner as to prevent water from entering the inlet under or around the filter cloth.

g. This type of protection must be inspected frequently and the filter cloth and stone replaced when clogged with sediment.

h. Assure that storm flow does not bypass inlet by installing temporary earth or asphalt dikes directing flow into inlet.

Block and Gravel Curb Inlet Protection

a. Two concrete blocks shall be placed on their sides abutting the curb at either side of the inlet opening.

b. A 2-inch x 4-inch stud shall be cut and placed through the outer holes of each spacer block to help keep the front blocks in place.

c. Concrete blocks shall be placed on their sides across the front of the inlet and abutting the spacer blocks as depicted in the drawing.

d. Wire mesh with ½-inch opening shall be placed over the outside vertical face (webbing) of the concrete blocks to prevent stone from being washed through the holes in the blocks.

e. Coarse aggregate shall be piled against the wire to the top of the barrier as shown in the drawing.

f. If the stone filter becomes clogged with sediment so that it not longer adequately performs its function, the stone must be pulled away from the blocks, cleaned and/or replaced.

Gravel Bag Curb Inlet Protection

a. In general, gravel bags are used to create a small sediment trap upstream of inlets and are appropriate for gently sloping streets where ponded water will not endanger the public or cause property damage

b. Flow from a severe storm should not overtop the curb.

c. In areas of high clay and silts, use filter fabric and gravel as additional filter media.

d. Use sandbags made of geotextile fabric (not burlap) and fill with uniform coarse aggregate material such as ½” rock or ¼” pea gravel. Do not use sand, as the bag must be porous.

e. Place one or two layers of overlapping gravel bags, and pack them tightly together. A gap of one sandbag on the top row on either side of the inlet can serve as an overflow spillway for larger storms.

f. Leave room upstream of barrier for water to pond and sediment to settle.

g. Drape geotextile filter fabric over the barrier and place the aggregate to "filter" sediment from storm water. Small pipes (2" diameter or smaller) for additional safety can be placed through the gravel bag barrier if also covered by filter fabric.

h. If the stone filter becomes clogged with sediment so that it not longer adequately performs its function, the stone must be pulled away from the blocks, cleaned and/or replaced

Manufactured Drop Inlet Protection

There are a number of new commercially available products on the market now. Some show great promise in providing excellent sediment control. However, great care must be taken when choosing a product as some have significant problems with their design.

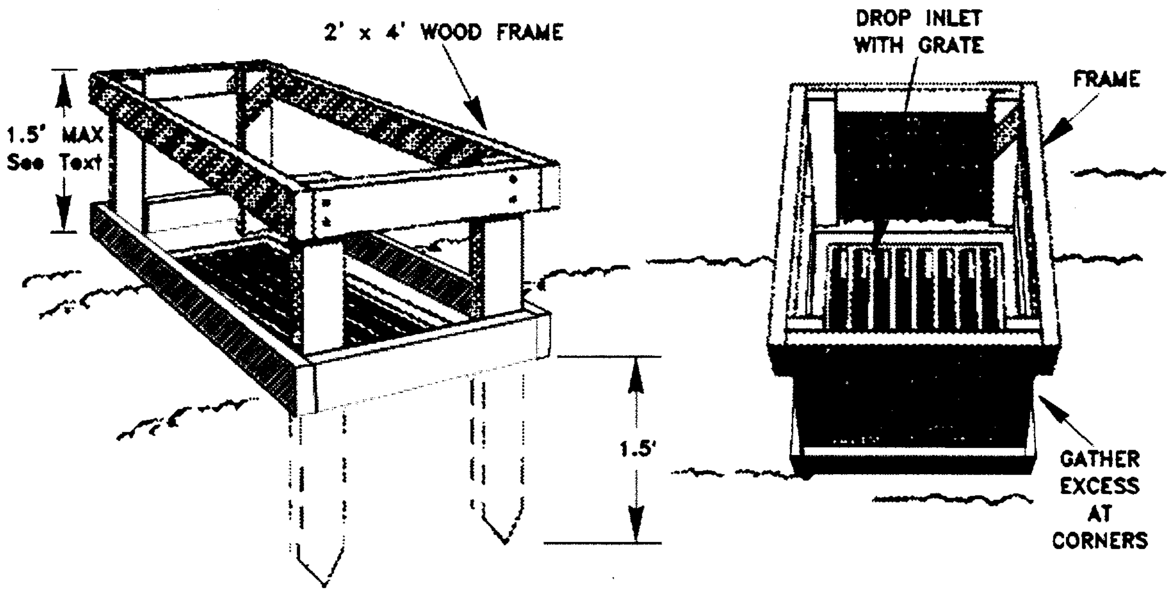
Do not install any practice that completely blocks the entrance of a drop inlet without some type of excess freeboard or adequate overflow. There are several curb inlet protections that block the inlet while providing several small holes for overflow. These holes are not large enough to pass larger storm events and can cause localized flooding. Some drop inlet protections cover the entire top of the inlet or are installed under the grate. These too have little overflow capacity and must be used judiciously. Practices that are placed inside inlets and out of sight are particularly easy to forget and become clogged and fail. In all cases the freeboard requirement must be met. While some of the products can work, great care must be taken to install correctly and to inure the design capacity of the inlet is not compromised.

Maintenance

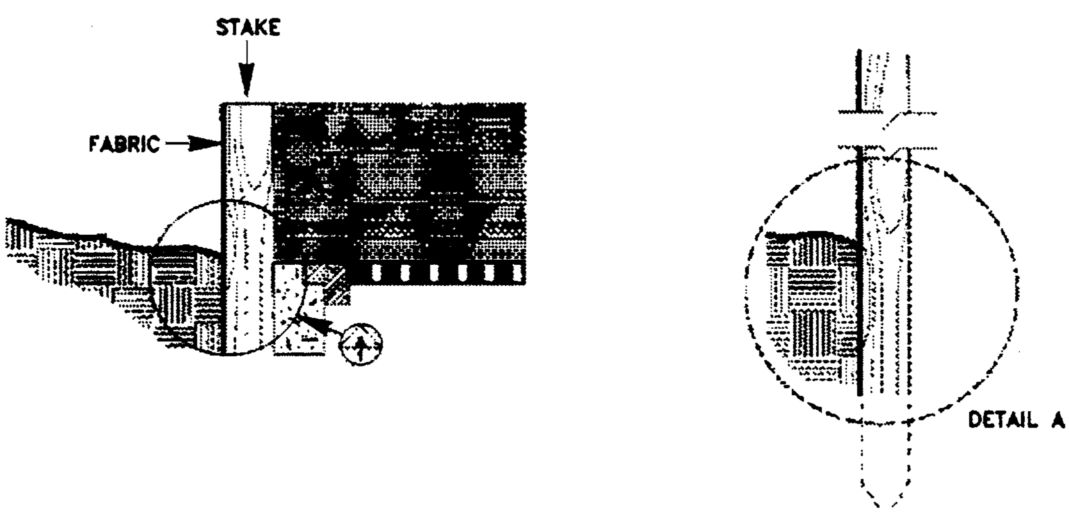
1. The structure shall be inspected after each .5" of rain and at least once a week and repairs made as needed. Construction traffic has a tendency to destroy these practices so frequent inspections are necessary.
2. Sediment shall be removed and the trap restored to its original dimensions when the sediment has accumulated to one half the design depth of the trap. Removed sediment shall be deposited in a suitable area and in such a manner that it will not erode.
3. Inlet protection should remain in place and operational until the drainage area is completely stabilized. Immediately stabilize the area disturbed by the installation and removal of the practice.
4. It is essential that maintenance be done to insure that structures do not fail, especially to prevent clogging. Failure of one practice can create a domino effect of failures, with the potential of severe flooding of adjacent properties.

FIGURE 3.33.1

SILT FENCE DROP INLET PROTECTION



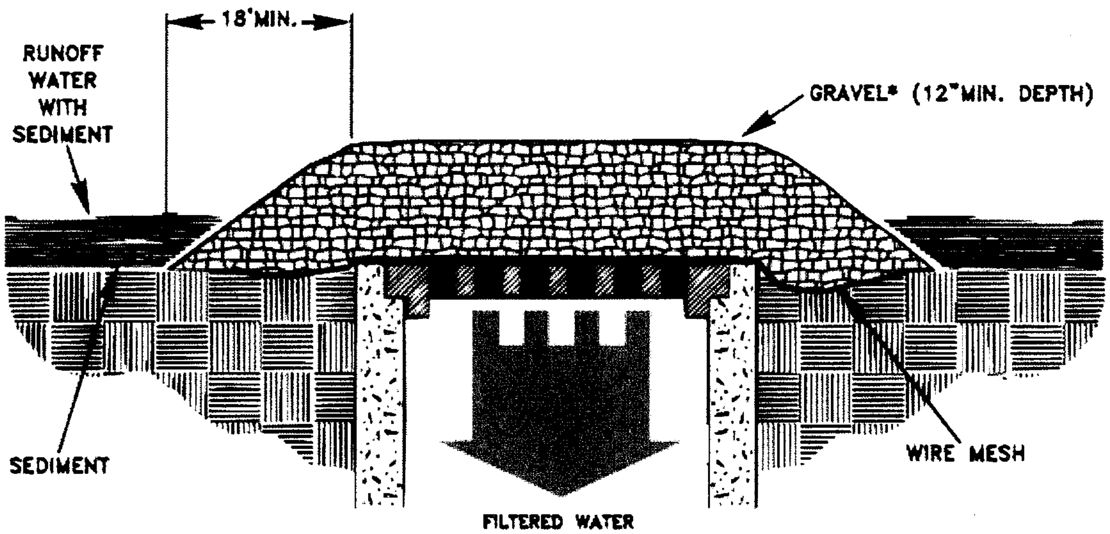
PERSPECTIVE VIEWS



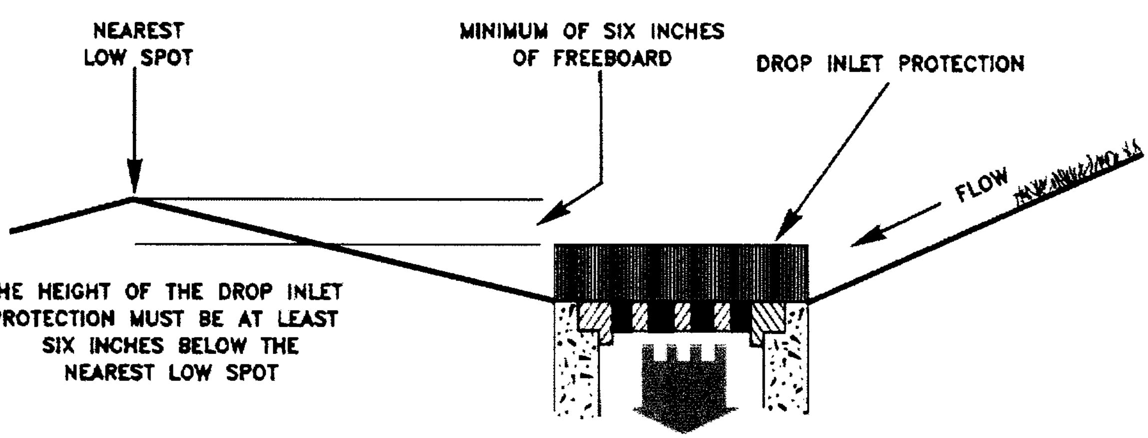
SPECIFIC APPLICATION

FIGURE 3.33.2

GRAVEL AND WIRE DROP INLET PROTECTION



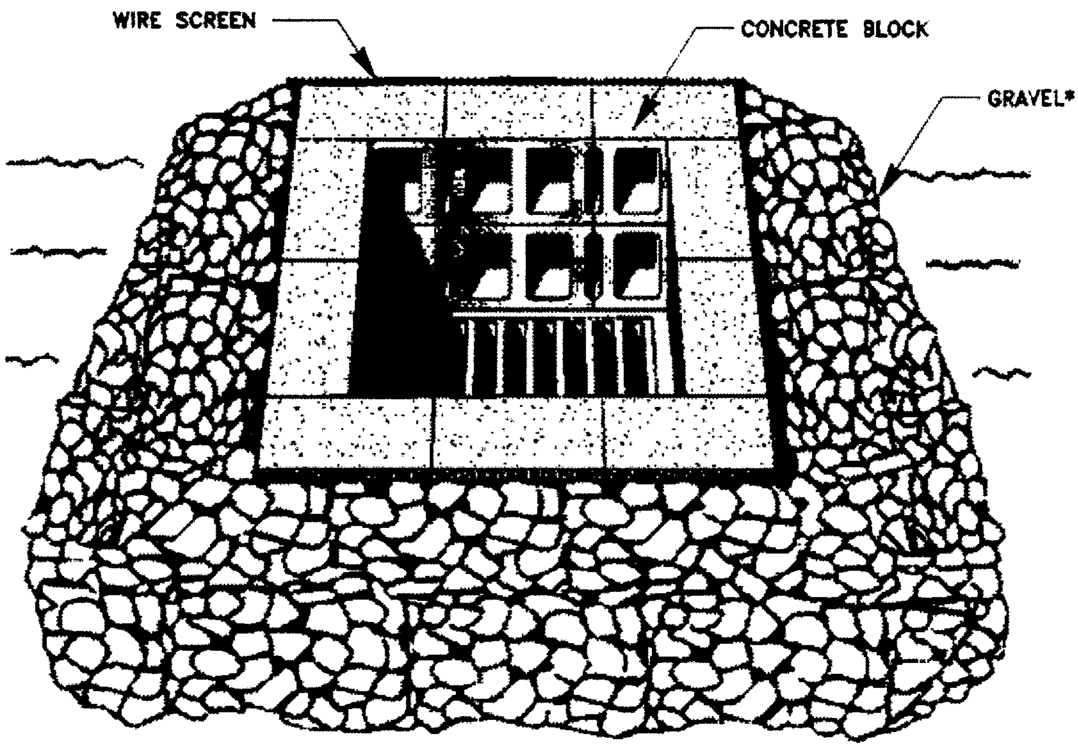
FREEBOARD REQUIREMENTS FOR ALL DROP INLET PROTECTION

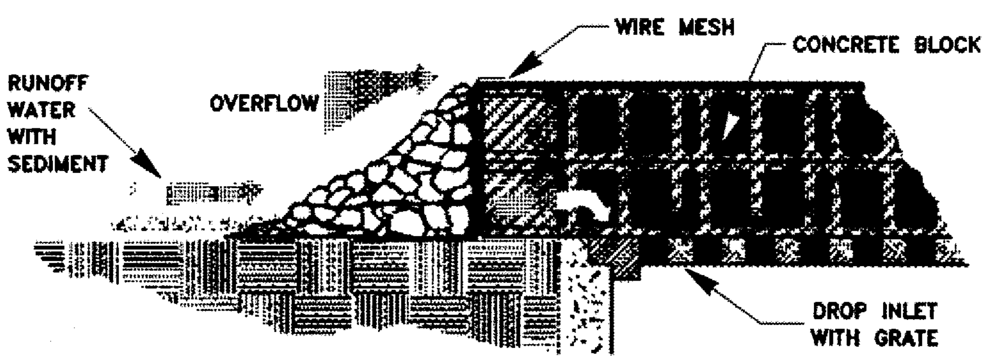


* GRAVEL SHALL BE CLEAN 3/4" TO 2" COARSE AGGREGATE

FIGURE 3.33.3

BLOCK AND GRAVEL DROP INLET SEDIMENT FILTER



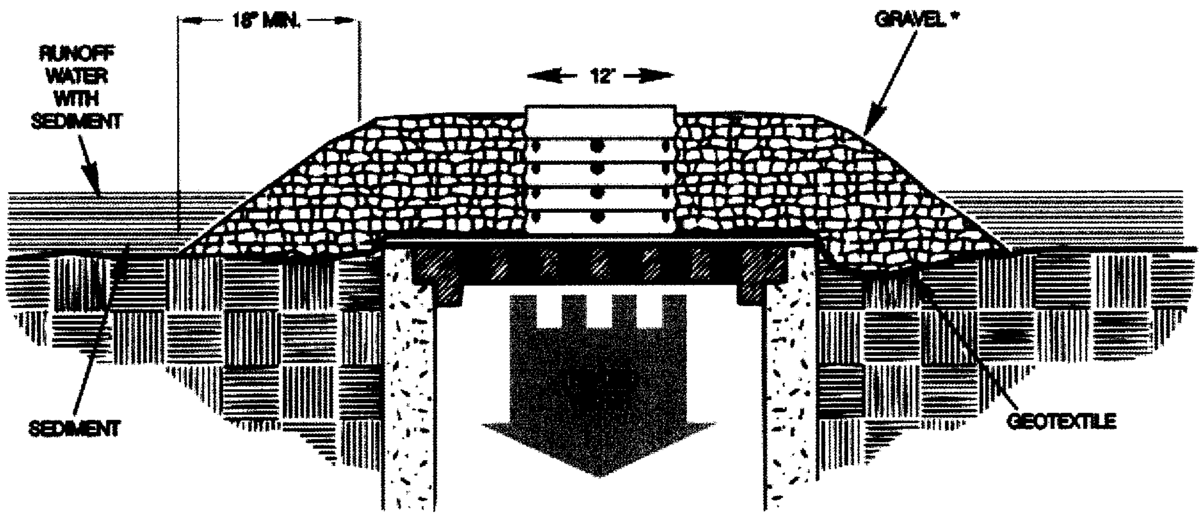


SIDE ELEVATION

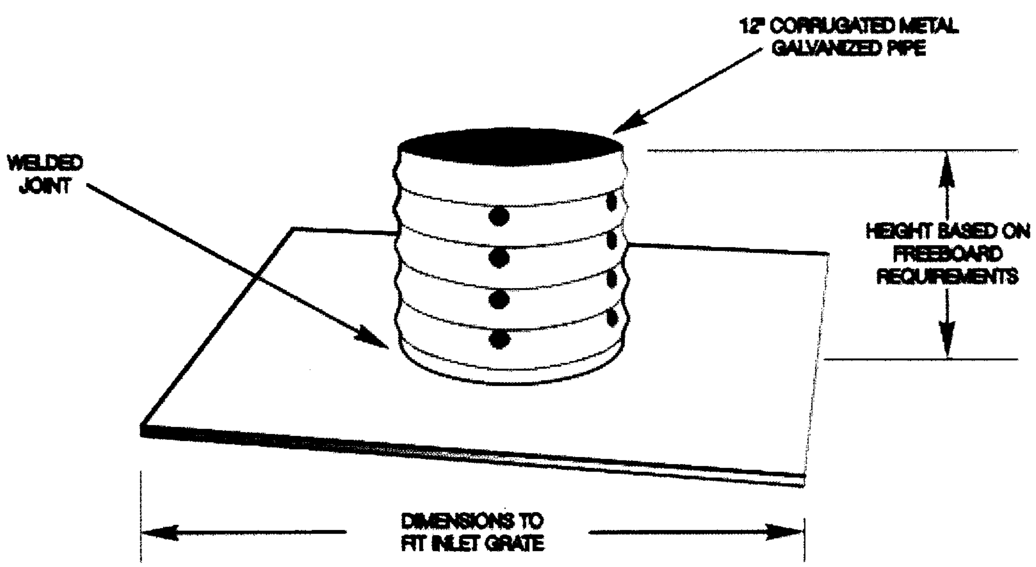
* GRAVEL SHALL BE CLEAN 3/4" TO 2" COARSE AGGREGATE

FIGURE 3.33.4

PIPE RISER AND GRAVEL DROP INLET PROTECTION



SIDE ELEVATION



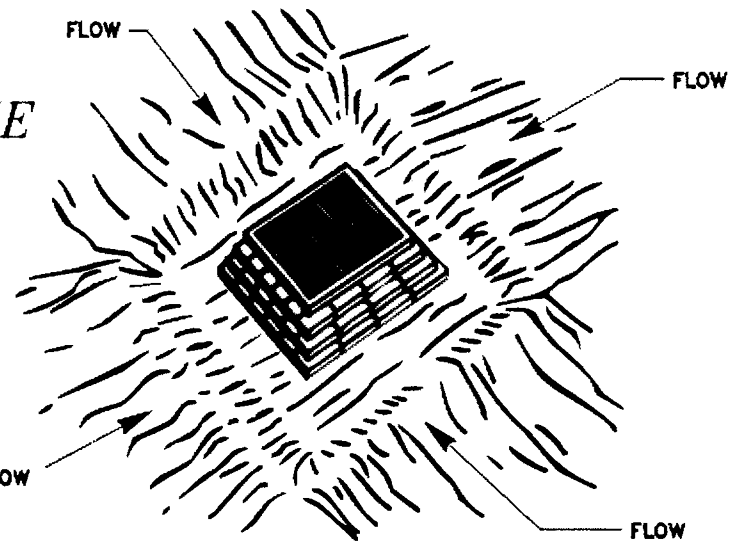
PERSPECTIVE VIEW

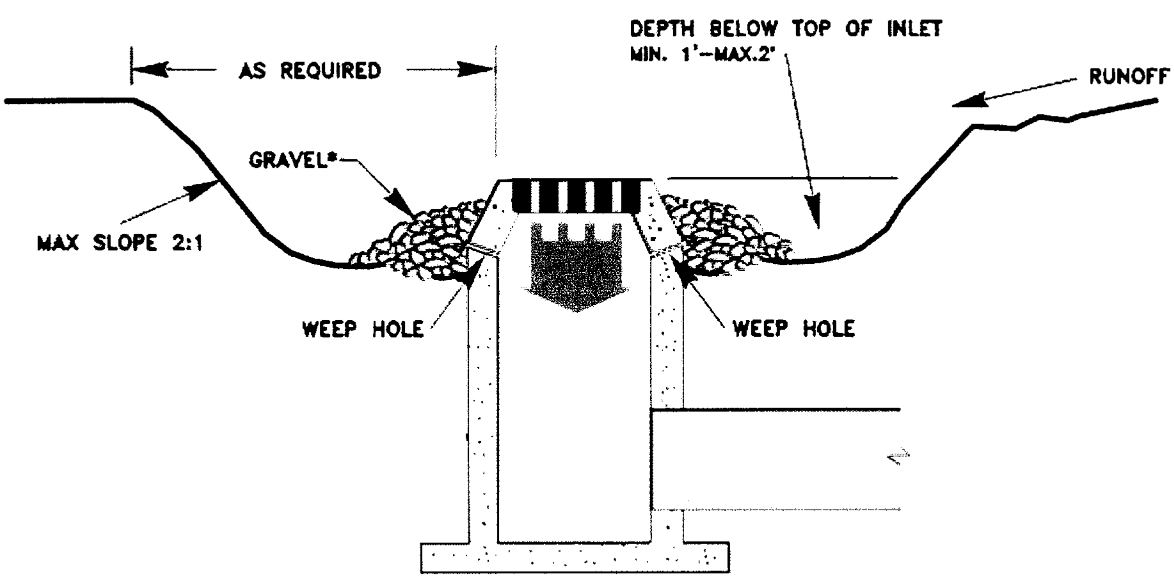
* GRAVEL SHALL BE CLEAN 3/4" TO 2" COARSE AGGREGATE

FIGURE 3.33.5

EXCAVATED DROP INLET PROTECTION

PERSPECTIVE VIEW



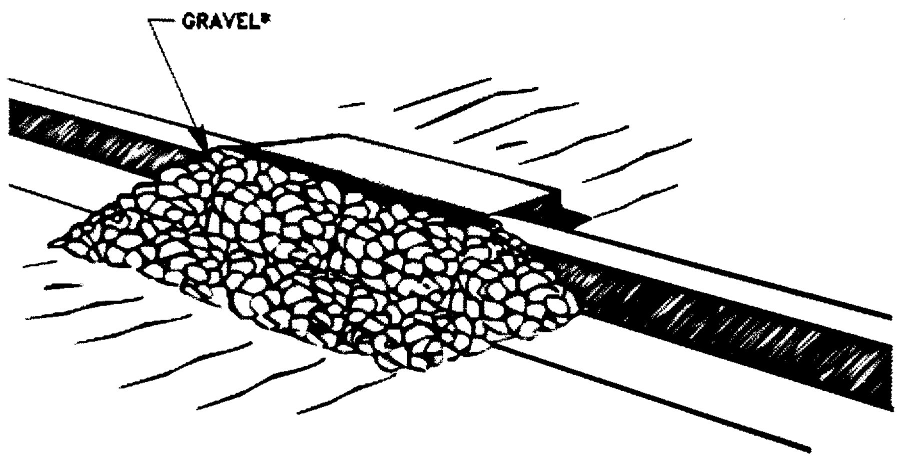


SIDE ELEVATION

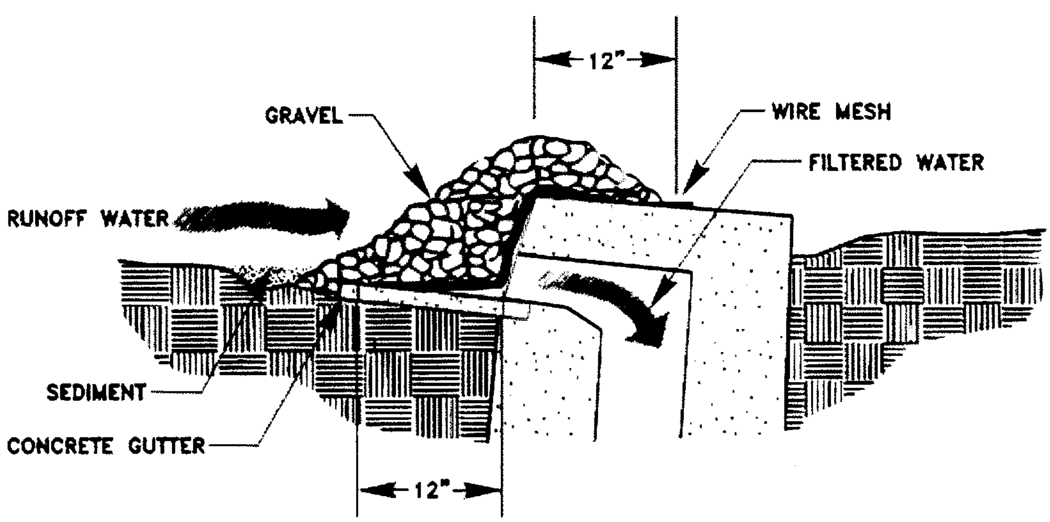
* GRAVEL SHALL BE CLEAN
3/4" TO 2" COARSE AGGREGATE

FIGURE 3.33.6

GRAVEL AND WIRE CURB INLET PROTECTION



PERSPECTIVE VIEW

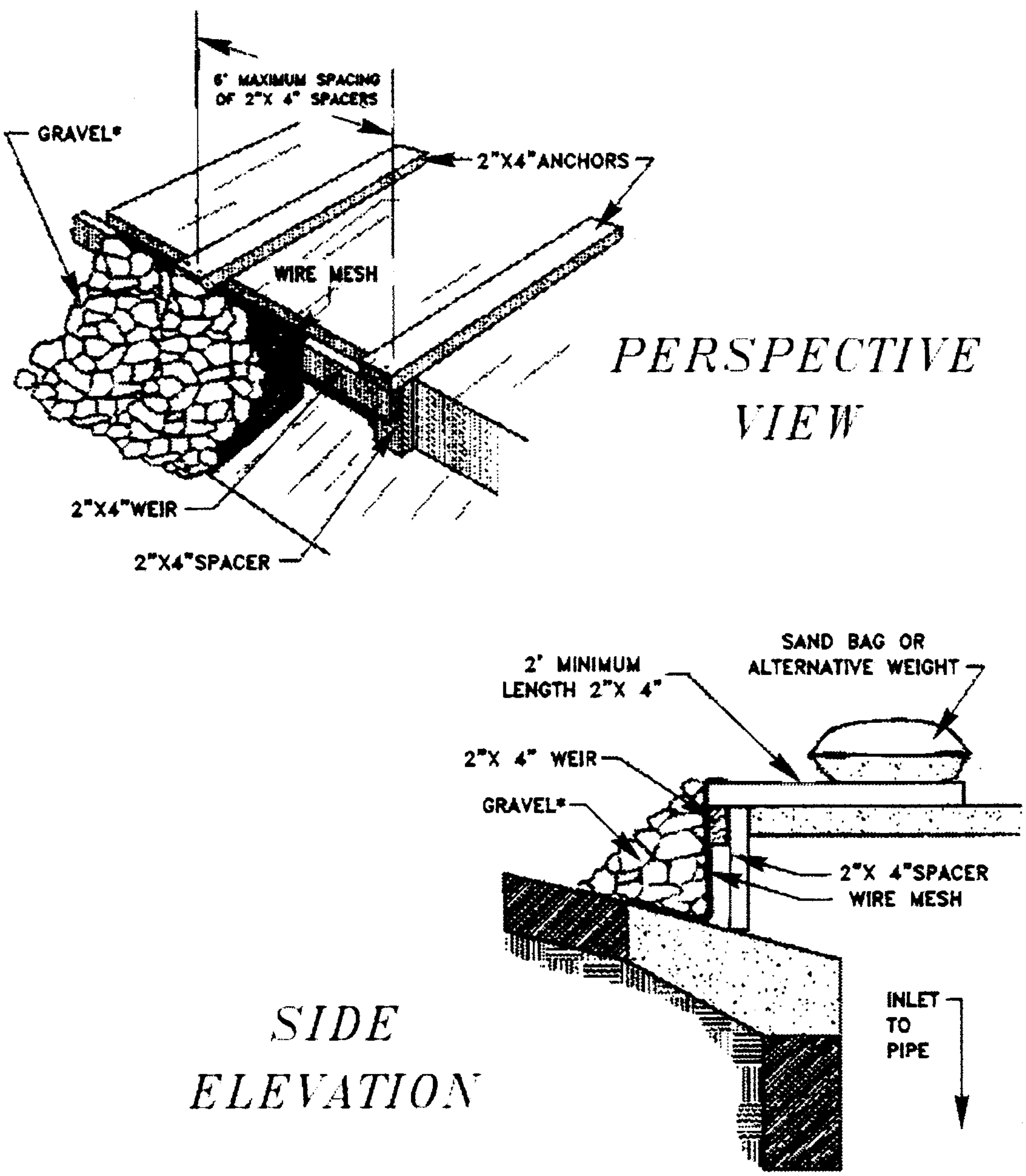


SIDE ELEVATION

* GRAVEL SHALL BE CLEAN 3/4" TO 2" COARSE AGGREGATE

FIGURE 3.33.7

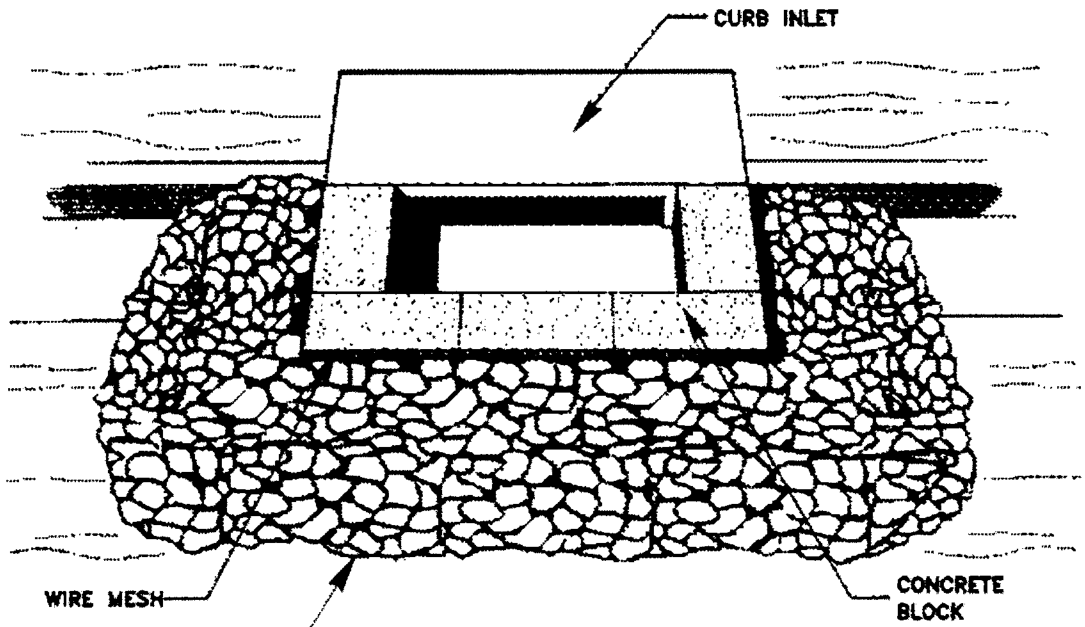
CURB INLET PROTECTION WITH 2" x 4" WOODEN WEIR



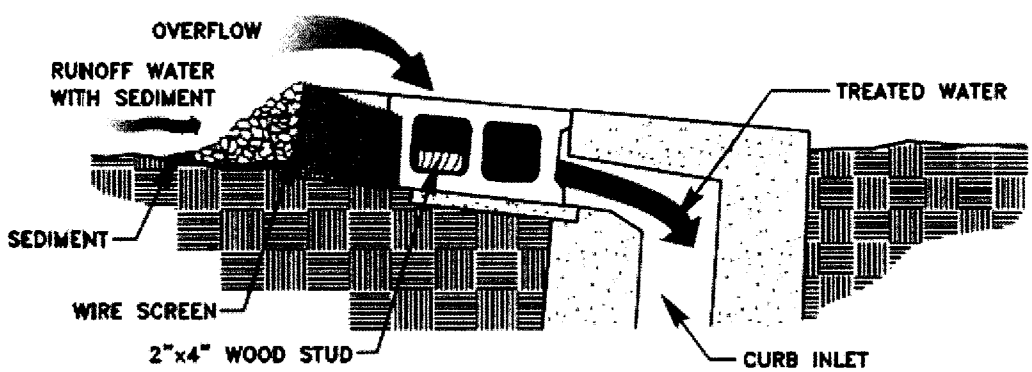
* GRAVEL SHALL BE CLEAN 3/4" TO 2" COARSE AGGREGATE

FIGURE 3.33.8

BLOCK & GRAVEL CURB INLET PROTECTION



PERSPECTIVE VIEW



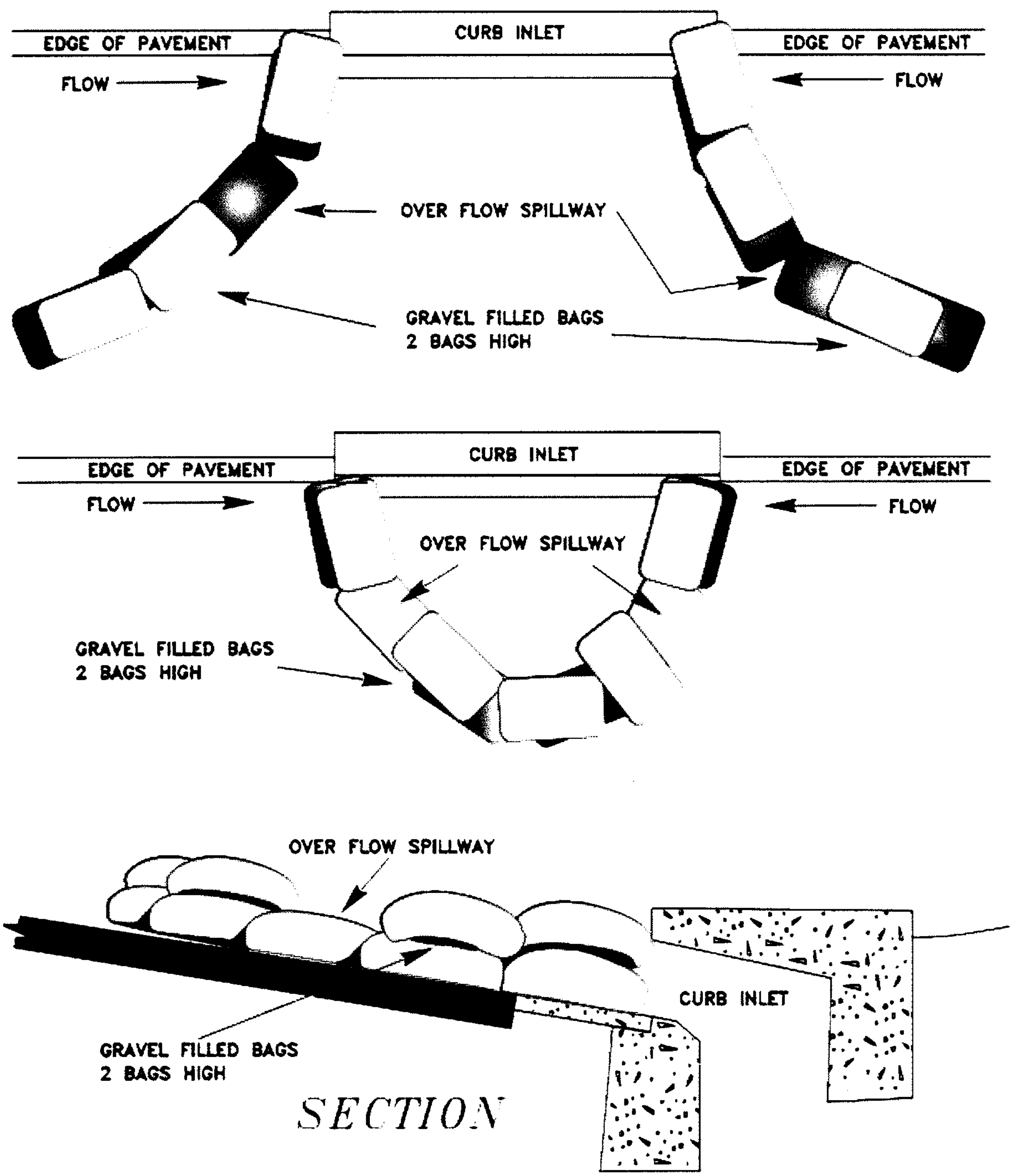
SIDE ELEVATION

SPECIFIC APPLICATION
THIS METHOD OF INLET PROTECTION IS APPLICABLE AT CURB INLETS WHERE AN OVERFLOW CAPABILITY IS NECESSARY TO PREVENT EXCESSIVE PONDING OR FLOODING.

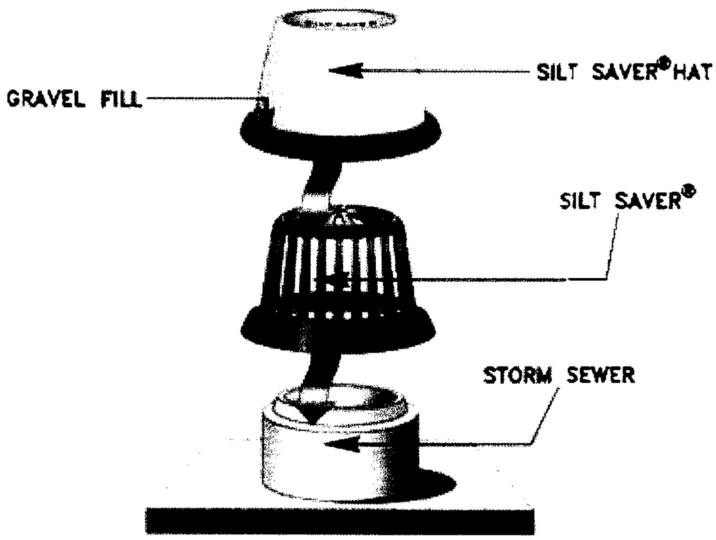
* GRAVEL SHALL BE CLEAN 3/4" TO 2" COARSE AGGREGATE

FIGURE 3.33.9

GRAVEL BAG CURB INLET PROTECTION

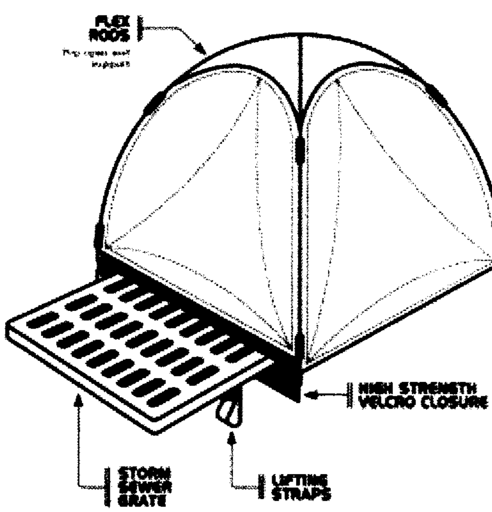


COMMERCIAL INLET PROTECTION

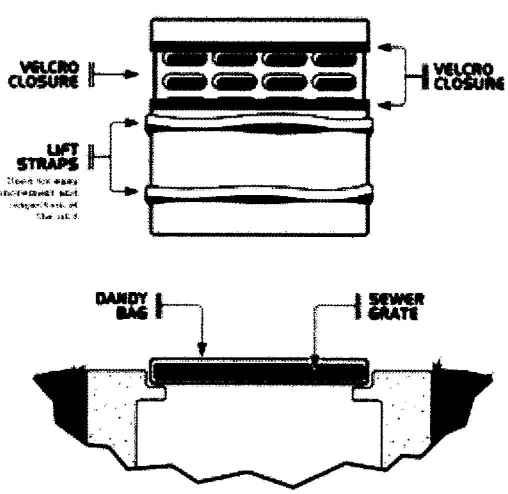


SILT SAVER®
FRAME AND FILTER ASSEMBLY

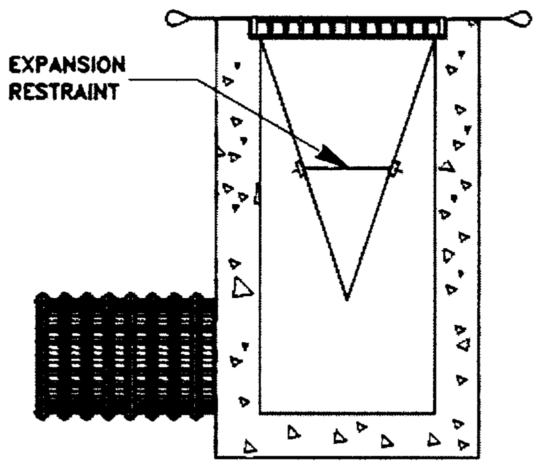
DANDY POP



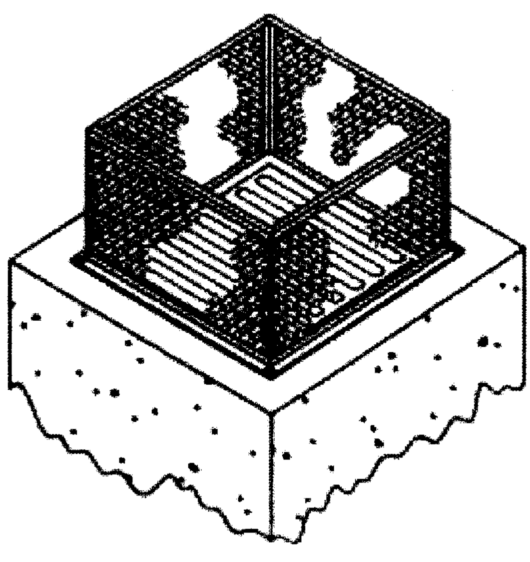
DANDY BAG



COMMERCIAL INLET PROTECTION



SILT SACK™



VERTI-PRO™

3.35 - ACCESS ROAD/ LOW VOLUME ROAD/DRIVEWAY

Introduction

Access roads and driveways are a major source of sediment in the State of West Virginia. Roads can dramatically change the hydrologic conditions of the immediate watershed. Roads that are improperly designed, constructed and stabilized can cause significant erosion and produce vast quantities of sediment. Common problems with roads are:

1. Inadequate number and size of culverts.
2. Road grade too steep.
3. Road surface not stabilized.
4. Poor soil conditions.
5. Poor drainage.
6. Poor stream crossings.
7. Cuts and fills too steep causing slips.

Since roads are typically long-term features, cutting costs during the construction phase almost always costs more in the long run as maintenance costs will be significantly higher on improperly designed and constructed roads.

To control sediment from roads it is necessary to practice aggressive erosion control. The single most important thing to do when designing and building a road is to control the water. Running water more than a few hundred feet down a road will cause long-term erosion and increase maintenance costs.

It is important that concentrated upslope water from streams or drainageways is directed immediately across the road with a culvert. Adequately sized and stabilized ditches to catch minor hillside runoff must also be constructed. The goal is to maintain the existing hydrologic conditions as much as possible by installing adequate numbers of cross culverts.

Conditions Where Practice Applies

Wherever low volume access roads are built. This practice can apply to any type of dirt or gravel road outside the Department of Transportation's road system.

Planning.

Planning and location are two of the more important aspects of road development and takes considerable time and effort. Good planning upfront can forestall problems later on.

1. You will need topographic maps, soil surveys and soil maps, and a device to determine grade. Roads should not be built on some soils. Check with the Natural Resources Conservation Service for information on soils. Review available information and

consult with professionals as necessary to help identify erodible soils and unstable areas, and to locate appropriate road surface materials.

2. Fit the road to the topography by locating roads on natural benches and following natural contours. Avoid long, steep road grades and narrow valleys.
3. If possible use switchbacks where it is impossible to construct a road below the maximum grade.
4. If it is necessary to construct in steep terrain break the road grade as much as possible by alternating steep section with flatter sections. Sometimes the road grade can be reversed which will shorten slope length and reduce the number of culverts, water bars and broad-based dips.
5. Locate roads on stable geology, including well-drained soils and rock formations that tend to dip into the slope. Avoid slumps and slide prone areas characterized by steep slopes, highly weathered bedrock, clay beds, concave slopes, hummocky topography, and rock layers that dip parallel to the slope.
6. Avoid wet areas, including moisture laden or unstable toe slopes, seeps, wetlands, and natural drainage channels. Ridge tops can be good places for a road as long as proper drainage can be constructed. Be aware that conditions may change when constructing in the dryer times of the year. Be prepared to add culverts after construction when hidden springs and streams start back up in the winter and spring.
7. Avoid crossing streams, if practical. If unavoidable, look for the best places to cross, considering the following.

    - Always cross at right angles.
    - Cross at points where the stream is narrow and the stream banks are stable.
    - Minimize the number of crossings.
    - Leave a buffer zone of undisturbed ground between the road and streambed, where the road runs parallel to the stream.
    - Divert water from road with a diversion or water bar to prevent water running directly into the stream.

8. If possible build roads on the drier south or west facing slopes. Clear trees to allow the sun to hit the road as much as possible.
9. Stabilization of all disturbed soil must take place as quickly as possible. Seed and mulch all cut and fill slopes and shoulders within seven days of reaching final grade. Stabilize the ditches as the line and grade is finalized.
10. Stabilization should occur as the road is constructed. Build the road in sections. Initiate stabilization on a finished section prior to moving to the next section. Finish road crossings and section nearest the creek immediately. Do not rough grade the entire road and then come back to the beginning to start restoration and stabilization. Quick stabilization of the disturbed area will greatly enhance any sediment control.

Mapping

Using the above information, locate control points (areas where you can and can't build a road) such as rock outcrops, extreme slopes, slip prone areas, poor soils, streams, ridges, saddles, hillside benches, property lines, access points and end point on a topo map. Lay the road out on a contour map with a pencil hitting or missing these control points. Calculated the grade of the road, attempting to keep it below 10 percent. This will show where sections are too steep and the road needs to be moved. Grades over 12 percent for more than a few hundred feet should be avoided if possible. Change the location of the road or break the grade to maintain the optimum grade. After all the changes are made it is time to go to the field to verify the site conditions.

Next mark on the map the tentative locations of the culverts using this formula:

400/% grade + 75' = culvert spacing

Do not space culverts more than 300' apart.

In field walk the centerline. Locate the control points and flag the centerline by tying plastic ribbon at eye level. Using an Abney Level or Clinometer, check the actual grades from ribbon to ribbon, back checking each run. Adjust the grade where the road exceeds 12 percent

Look for wet spots, springs and water features missed because of the topo map's scale. Move the centerline to miss any unmapped features or add culverts where needed. It may be necessary to move most of the culverts to make it easier to install them and to correctly locate where concentrated flows cross the road. If bedrock is found, the culvert can be moved down hill even if it exceeds the spacing requirement. Sometimes it is advantageous to add a culvert immediately above a steep section to keep upslope drainage from entering a high velocity section.

Approaches to public roads need an Entrance Permit from the Division of Highways. Do not allow water to run onto public roads, divert with berm or water bar. The BMP for STABILIZED CONSTRUCTION ENTRANCE can be used for permanent access roads.

Design and Construction Criteria

The are several critical design criteria that must be met if the long-term stability of an access road is to be maintained.

The key criteria are:

1. Cross-section
2. Road Grade
3. Ditch line protection
4. Water Control

5. Stream Crossing
6. Stabilization
7. Sediment Control

One of the most important design parameters is to keep the road grade as flat as possible. Any road grade over 10 percent can cause difficulties with surface stability, washing off of the gravel surface, and gully formation. If steeper sections (such as to get over a rocky section) are necessary install more culverts or break the grade, or add water bars.

Road Cross-Sections Five road cross-sections typically are used in road construction: crowned fill, crowned turnpike, outslope, inslope with ditch, and crowned and ditched (Figure 3.35.1).

The choice of which cross-section to use depends on the drainage needed, soil stability, slope, and the expected volume of traffic on the road. You can use these cross-sections in combination as the terrain changes or as drainage problems are encountered.

- Crowned fill section is for use on flat ground where water standing on a road surface may be a problem.
- Outslope section is for use on moderate slopes for low volume roads and stable soils. Outsloping can be more dangerous in wet and snowy weather. Broad-based dips and water bars can be used on this cross-section rather than culverts.
- Inslope with ditch section is for use on steep hills, areas with fine textured soils, winter logging, and areas where drainage is necessary.
- Crowned and ditched section is for high volume roads on steep side hills.

Road Grade: Road grade is the single most important factor in planning a low volume road. Road grades must be kept to a minimum. If possible do not exceed 10 percent. The maximum for short distances can be 12 percent but it will be harder to keep gravel in place, ditch lines are harder to stabilize and culverts, water bars and broad-based dips are harder to install. Ruts form easier and the higher runoff velocities will erode them faster.

Grade is expressed as a percent and can be determined as follows.

percent slope = rise in vertical feet divided by the horizontal run in feet.

Ditch line Protection: Recommended ditch line protection can be based on the grade as follows:

1. Less than 3 percent - grassed
2. 3 – 8 percent - grass with rolled erosion control products

3. Greater than 9 percent - riprap or equivalent geotextile (must submit manufacturers specifications and calculated velocities).

If the flows are significant the protection should based on an engineering study of the particular characteristics of the waterway and soils.

For more information see DIVERSIONS.

Water Control Structures: The construction of roads can radically alter the hydrologic regime of the local watershed. By installing structures, devices and measures to reestablish or approximate the original flow paths, erosion and road maintenance can be almost eliminated. Conversely, failure to provide adequate flow management can create very serious erosion. In most situations, providing appropriate measures is straightforward and simple. Proper planning and the flexibility to address onsite problems are necessary to control storm flows and will make it easier to protect the investment of building the road and improve water quality.

The single most common problem on low volume roads is the lack of culverts. Culverts allow the upslope water to cross the road at right angles and without coming into contact with the road surface. Maintaining the natural flow path is critical to reducing erosion on roads. Streams of any size should NEVER be allowed to run down a road. The road surface can wash away and ditch lines can be destroyed.

Culverts: There are two types of culverts on roads. One is used to pass upslope perennial and intermittent streams across the road. The other is sometimes called a cross-drainage culvert and is used to move lesser amounts of water from springs, seeps and upslope runoff across the road.

Culverts must be installed at each stream/waterway crossing and periodically along the roadway. Cross-drainage culverts are spaced apart at least 125’ and no more than 300’.

400/percent grade + 75’ = culvert spacing

Install OUTLET PROTECTION at each culvert. Install a headwall or similar device at each culvert.

The minimum size should be 12 inches. The culvert chart (Table 3.35.1) can be used to size culverts with a drainage area up to 600 acres.

The minimum grade should be 1 percent and culverts should be installed from 25 to 45 degrees to the centerline of the ditch to minimize turbulence at the inlet.

Culverts must extend at least one foot beyond the toe of the fill. Do not discharge onto the side of a road fill. If not possible, design OUTLET PROTECTION using grouted riprap .

Firmly backfill the trench and around culvert with fine-grained material, taking care to create good contact underneath the pipe. Cover the top of the culvert with at least 12 inches of fill, more if heavy loads are anticipated on the road.

Drainage Area (Acres)	**Table 3.35.1 Average Slope of Watershed**			
	1%	4%	8%	16%
	Culvert Size			
1 – 25	24	24	30	30
26 - 50	24	30	36	36
51 – 100	30	36	42	48
101- 150	30	42	48	48
151 - 200	36	42	48	54
200 - 250	42	48	60	60
251 - 300	42	48	60	60
301 - 350	42	48	60	60
351 - 400	42	54	60	60
401 - 450	42	54	60	72
451 - 500	42	54	60	72
501 - 550	48	60	60	72
551 - 600	48	60	60	72
601 - 640	48	60	72	72

Broad-based Dips: Broad-based dips (Figure 3.35.3) were developed at the Fernow Experimental Forest in West Virginia to control surface water on Forest Service roads. Under the right conditions and correctly constructed they are an excellent method of controlling runoff.

Regular traffic can easily traverse them and once installed require little maintenance. However, they are almost impossible to install on steep roads and difficult to maintain in poor soil conditions. They are easily installed on roads with less than 10 percent grade and where the subgrade material is suitable:

Broad-based dips cannot be used to pass continuous flowing water across the road or under extended damp conditions such as where springs are located. Culverts are required in these situations.

Spacing for Broad-based Dips is the same as culverts.

400/percent grade + 75 feet = dip spacing

Do not space broad-based dips more than 300 feet apart.

Water Bars: Water bars (Figure 3.35.4) are a small berm and swale construction across a road to direct surface water off the road and into a stabilized vegetated area. Water bars are useful on infrequently used or abandoned roads.

Water bars are installed similarly to TEMPORARY RIGHT-OF-WAY DIVERSIONS. They should be installed at an angle (30 to 45 degrees) across the road. The water bar must extend across the entire width of the road. They should never dam the water but should intercept and divert the water off the road. The discharge point should be fully open and protected from erosion and discharge to a stable vegetated area or undisturbed forest flow.

As with the broad-based dip it should not be used where there is a continuous flow of water such as a stream or spring or seep. It is very important the water bar not create erosion over the road fill. To prevent erosion use RIP RAP or a RECP.

The spacing for water bars is the same as for broad based dip.

Turnouts: Turnouts are extensions of the ditch line into a vegetated area or natural waterway. Sometimes the ground drops off either side of the road and a culvert can't be installed. A turnout can be constructed to transfer water away from the roadway into a natural water way or onto a flat well-vegetated area. Turnouts are similar to LEVEL LIP SPREADERs but for smaller quantities of flow. It is important that a dam isn't formed at the end that can erode and the turnout is PERMANENT SEEDED immediately upon completion.

It is possible to install a SEDIMENT TRAP at the end of many turnouts.

Stream Crossings: See the specification under INSTREAM CONSTRUCTION BMPS for more information. Bridges are always preferable to culverts when crossing a perennial stream.

Culverts installed for permanent applications must be designed at a minimum to pass the peak discharge from a ten-year/24-hour storm with out causing upstream backup and downstream scour.

Sediment Control: During construction sediment control will consist of installing appropriate sediment control devices such as BRUSH BARRIERS, SILT FENCE, SUPER SILT FENCE and SEDIMENT TRAPS. (Figure 3.35.2)

On extreme slopes it may be impossible to install anything other than a BRUSH BARRIER or SILT FENCE. Sediment control can be accomplished by following the recommendations in this BMP and by rapid restoration and stabilization according to the PERMANENT SEEDING specification. Recognizing these difficulties, DEP will allow lesser sediment control if offset by an aggressive stabilization schedule shown in the SWPPP.

Critical areas such as stream crossings will still require appropriate sediment control while in other areas smaller traps/sumps may be used. Alternative sediment controls can be pursued or modifying existing one may be necessary. One place is at the head of most of the side ditch culverts. A small sediment trap/sump can be installed here.

This BMP does not cover specifications for earth moving nor sets out standards other than the basics covered above.

For more information on construction see the following drawings.

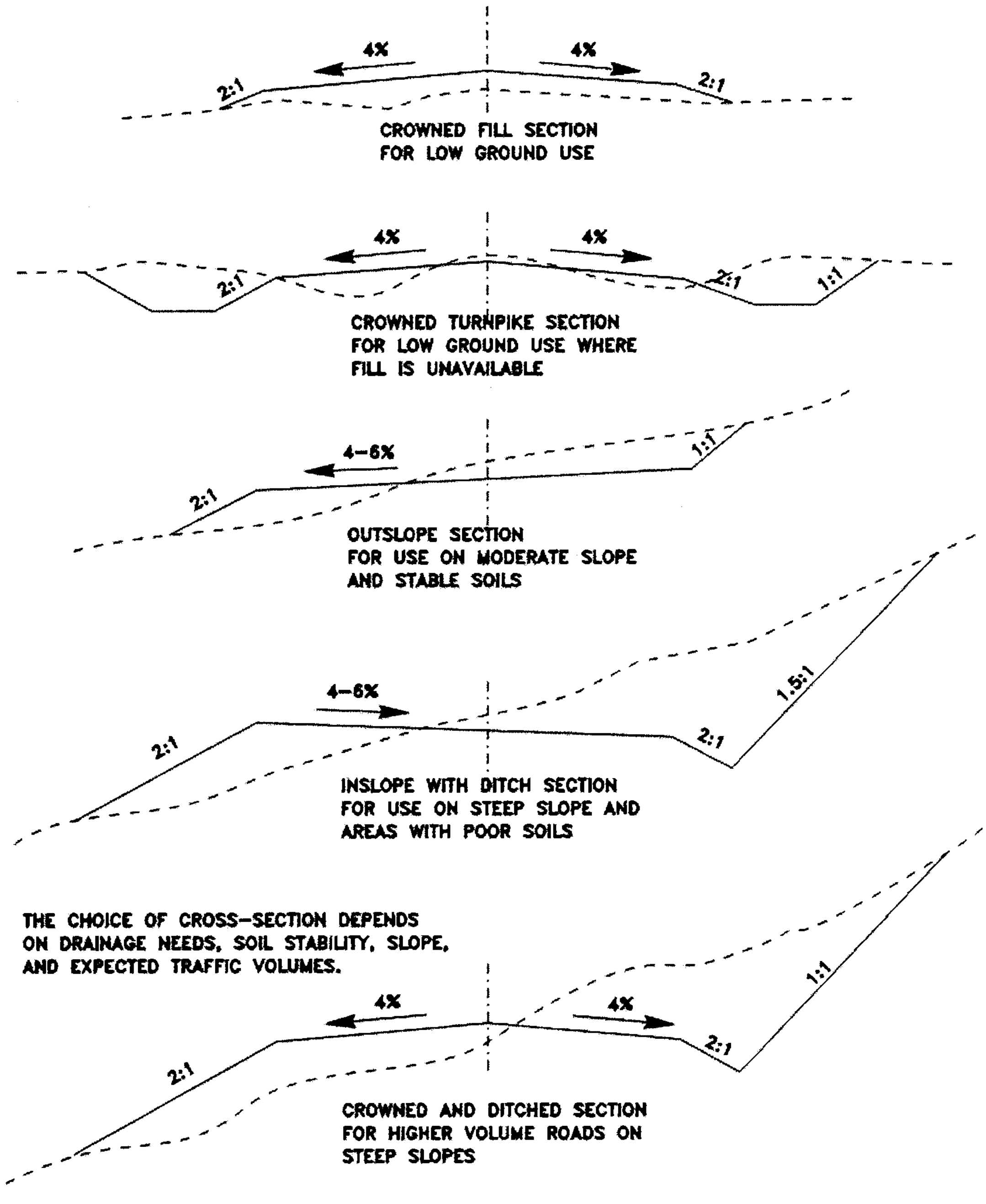
Maintenance

Initially inspect the road after each rainfall of 0.5 inch or more. Initially it would be better to inspect during the first few rainstorms. Look for water running down the road and for scour in the ditch lines. Look for water coming out of cut slopes and for upslope concentrated flows not going to culverts. If water bars or broad based dips are used see if they are deep enough to capture road surface runoff. If runoff goes past either practice, repair immediately.

If ruts are found immediately regrade and direct runoff into ditch line or to outslope as necessary.

FIGURE 3.35.1

TYPES OF ROAD CROSS-SECTIONS



FROM: US FOREST SERVICE AND MICHIGAN DNR

FIGURE 3.35.2

SEDIMENT AND EROSION CONTROL FOR ACCESS ROADS AND DRIVEWAYS

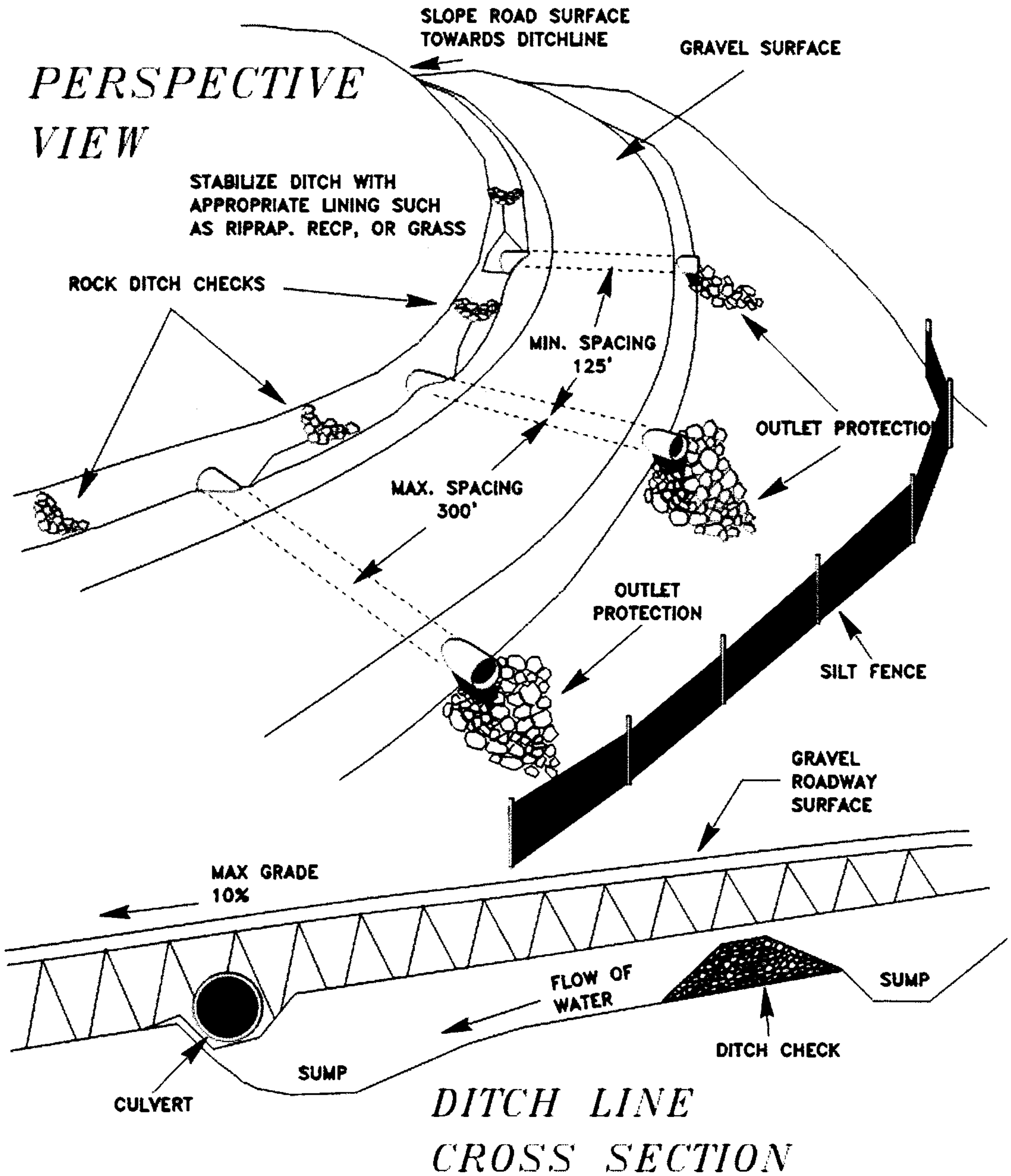
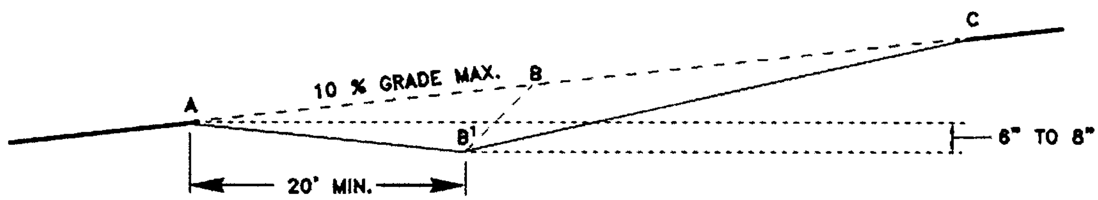
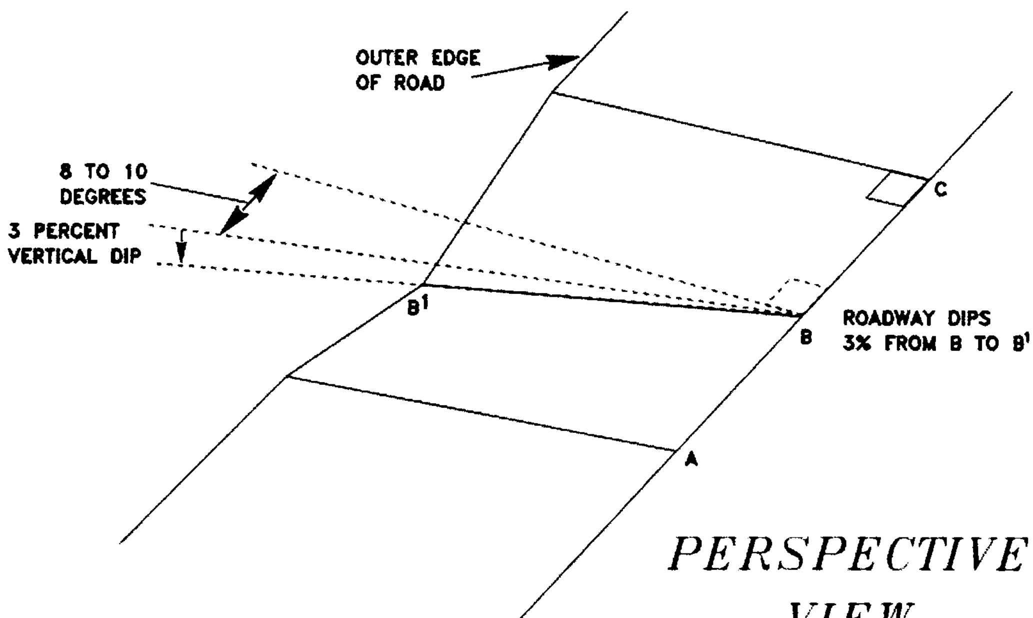


FIGURE 3.35.3

BROAD-BASE DIP



CROSS-SECTION

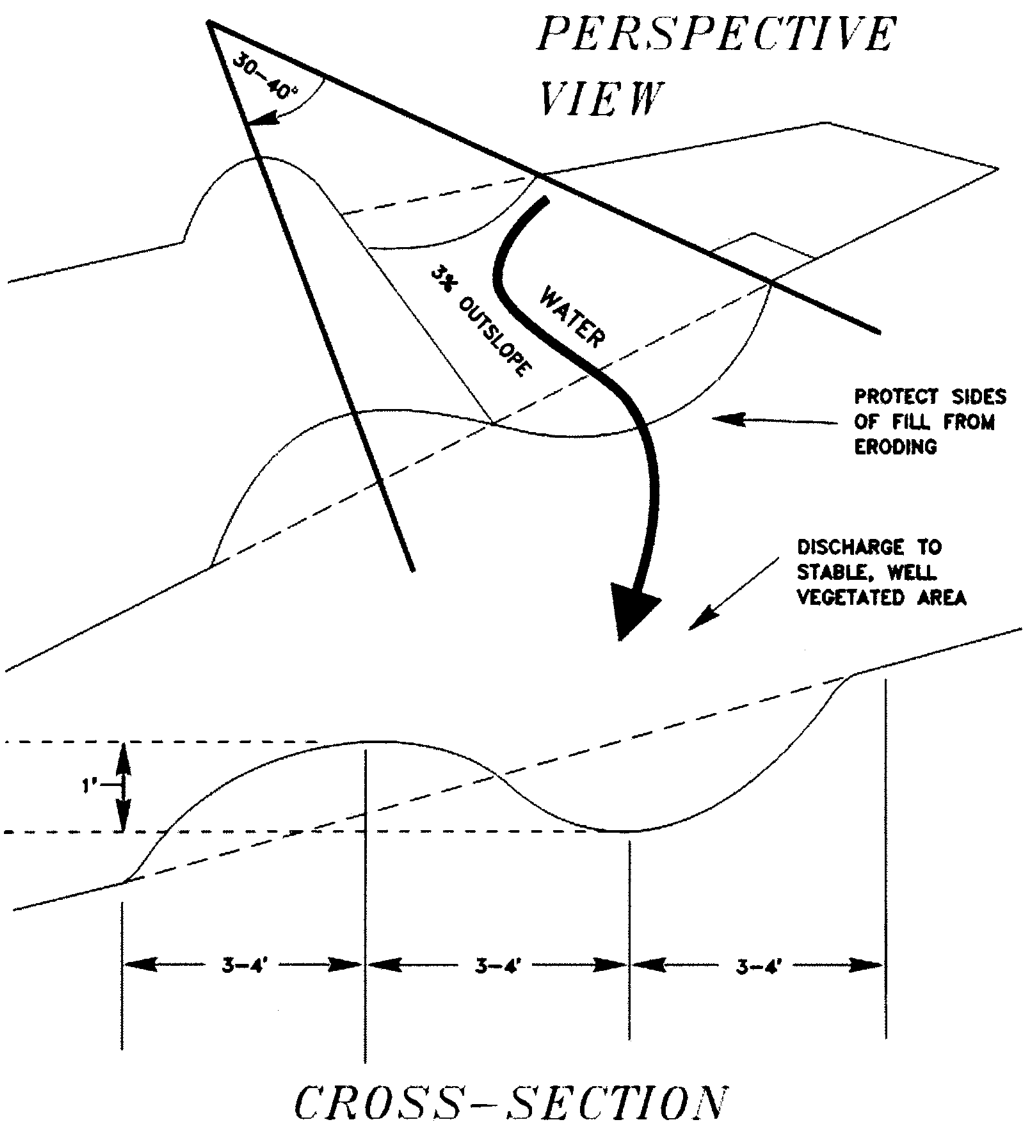


PERSPECTIVE VIEW

SPACING = 400/% GRADE + 75'

FIGURE 3.3.4

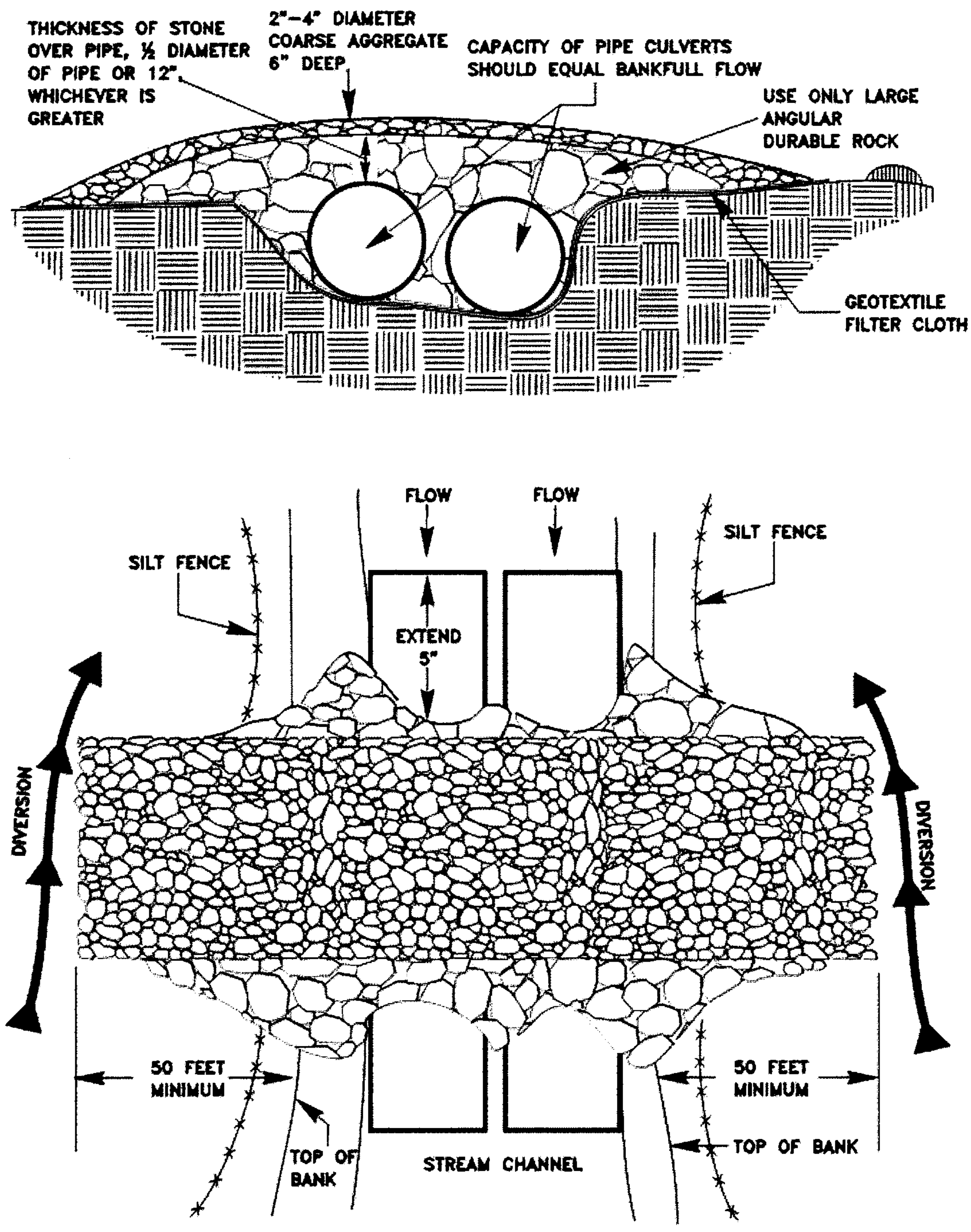
WATER BAR



INCREASE THE DISTANCE BETWEEN THE BOTTOM OF THE DIP AND TOP OF THE BERM FOR IMPROVE DRIVEABILITY

FIGURE 3.35.5

CULVERT STREAM CROSSING



FROM: VA DSWC

CHAPTER 4

HYDROLOGY

URBAN HYDROLOGY FOR SMALL WATERSHEDS (TR-55)

URBAN HYDROLOGY FOR SMALL WATERSHEDS – TR-55

The following information was developed by the United States Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division in Urban Hydrology for Small Watersheds TR-55, Technical Release 55 June 1986.

Preface

Technical Release 55 (TR-55) presents simplified procedures to calculate storm runoff volume, peak rate of discharge, hydrographs, and storage volumes required for floodwater reservoirs. These procedures are applicable in small watersheds, especially urbanizing watersheds, in the United States. First issued by the Soil Conservation Service (SCS) in January 1975, TR-55 incorporates current SCS procedures. This revision includes results of recent research and other changes based on experience with use of the original edition.

The major revisions and additions are:

- A flow chart for selecting the appropriate procedure;
- Three additional rain distributions;
- Expansion of the chapter on runoff curve numbers;
- A procedure for calculating travel times of sheet flow;
- Deletion of a chapter on peak discharges;
- Modifications to the Graphical Peak Discharge method and Tabular Hydrograph method;
- A new storage routing procedure;
- Features of the TR-55 computer program; and
- Worksheets.

This revision was prepared by Roger Cronshey, hydraulic engineer, Hydrology Unit, SCS, Washington, DC; Dr. Richard H. McCuen, professor of Civil Engineering, University of Maryland, College Park, MD; Norman Miller, head, Hydrology Unit, SCS, Washington, DC; Dr.Walter Rawls, hydrologist, Agricultural Research Service, Beltsville, MD; Sam Robbins (deceased), formerly hydraulic engineer, SCS, South National Technical Center (NTC), Fort Worth, TX; and Don Woodward, hydraulic engineer, SCS, Northeast NTC, Chester, PA. Valuable contributions were made by John Chenoweth, Stan Hamilton, William Merkel, Robert Rallison (ret.), Harvey Richardson, Wendell Styner, other SCS hydraulic engineers, and Teresa Seeman.

Revised June 1986
Update of Appendix A January 1999

A copy of the TR-55 Manual can be obtained at:

www.wcc.nrcs.usda.gov/hydro/hydro-tools-models-tr55.html

CHAPTER 5

DESIGN EXAMPLES

Sediment Basin Design Example

Problem statement: Design a sediment basin that captures a drainage area of 25 acres during construction. The disturbed project area equals the drainage area to the basin.

When locating your basin, try to capture as much of the disturbed area from the construction site as necessary, while diverting as much undisturbed runoff coming to the site as possible.

Calculate the resultant total area draining to basin = 25 acres.
Calculate the total disturbed area draining to basin = 25 acres.
Required wet storage = 25 ac. x 1800 cf/ac = 45,000 cf
Required dry storage = 25 ac. x 1800 cf/ac = 45,000 cf
The clean-out volume corresponds to the volume equal to half the wet storage volume.
Clean-out volume = 25 x 900 cf/ac = 22,500 cf.

Stage-Storage Chart (determined from the basin/pond geometry, which is not given for this example). Assumes the following:

Elevation (ft.)	**Sum Volume** (ac-ft.)
151	0.00
152	0.15
153	0.33
154	0.55
155	0.81
156	1.10
157	1.44
158	1.82
159	2.25
160	2.73
161	3.26
162	3.84
163	4.48
164	5.18
165	5.93
166	6.75

With a pond bottom of elevation 151, the corresponding elevation for the wet storage volume = 45,000 cf (1.033 ac-ft) is approximately 155.8 feet.

The clean-out elevation is the elevation corresponding to the clean-out volume = 22,500 cf (0.52 ac-ft), which is equal to approximately 153.9 feet. Show this elevation on the plans and provide a means of determining it in the field.

With the wet storage volume elevation set at 155.8, the corresponding elevation for the dry storage volume (cumulative 90,000 cf or 2.066 ac-ft) is approximately 158.6 feet.

Set the top of the temporary riser above this elevation so top of riser = 159.0.

A perforated riser with a hole or series of holes should be provided at the wet storage elevation. In order to dewater the sediment basin in 48 to 72 hours, perforations should be sized in the riser according to the following equation:

Ao = As x (2h)^0.5/(T x Cd x 20,428)

Where

Ao = total area of dewatering holes, ft^2
As – surface are of the basin, sq.ft.
H = head of water above the hole, ft
Cd = coefficient of contraction for an orifice, ~ 0.6
T = detention time needed to dewater the basin, hours

Using the basin geometry gives:

Ao = 21,000 sq.ft. x (2 x 3.2 ft.)^0.5/(72 x 0.6 x 20428)
Ao = 0.06 sq.ft. which equals an orifice area with a diameter of 3.3 inches.
Use 3 – 1-inch holes

Compute the peak discharge from a 2-year and 25-year, 24-hour storm event.

Condition	Area	CN	Tc
	Acre		Hrs
Pre-developed	25	73	0.499
Post-developed	25	78	0.267

From TR-55 Worksheets 2 and 3

Perform Preliminary Hydrologic Calculations

The site is located in a county in West Virginia that has the following 24-hour rainfalls:

2-year, 24-hour rainfall = 2.75 inches
25-year, 24-hour rainfall = 4.78 inches

Condition	Q 2-yr	Q2-yr	Q 25-yr	Q 25-yr
Runoff	inches	cfs	inches	cfs
Post-developed	0.962	24.4	2.530	69.2

From TR-55 Worksheet 4 or 5b

Determine the maximum principal spillway capacity for a Q2 of 24.4 cfs

- Try a riser with a diameter of 36-inches and a barrel with a diameter of 24 inches, trying to keep the diameter of the riser = 1.5 x the diameter of the barrel to improve the efficiency of the principle spillway system.
- Solving the weir equation for the riser with a perimeter, L = 9.4248 feet and an area, A = 7.06858, gives an H = 0.88 feet feet. So the 2-year storm will pass through the temporary riser with an H of 0.88 feet.
- Check the pipe barrel performance for the 2-year event with an assumed size of 24-inches, a pipe length of 100 feet, a pipe slope of 10%, and a roughness coefficient of n=0.024.
- Solving the pipe equation for inlet control gives Q = 45.4 cfs (refer to Sediment Basin Outlet results).
- Solving the pipe equation for outlet control gives Q = 44.0 cfs (refer to Sediment Basin Outlet results).
-

For the 25-year design storm:

Condition	Q 25-yr	Q 25-yr
Runoff	inches	cfs
Post-developed	2.530	69.2

From TR-55 Worksheet 4 or 5b

- Knowing the Runoff Q (inches) from TR-55 Worksheet 2 and the Area (in square miles), compute the Runoff Volume Vr = Q (A) 53.33
  = 2.53 x 0.0.03906 x 53.33 = 5.27 ac. ft.

Stage-Storage Chart Using the stage-storage chart for a runoff volume of 5.27 ac-ft.-

Elevation	**Sum Volume**
(ft.)	(ac-ft.)
151	0.00
152	0.15
153	0.33
154	0.55
155	0.81
156	1.10
157	1.44
158	1.82
159	2.25
160	2.73
161	3.26
162	3.84
163	4.48
164	5.18
165	5.93
166	6.75

With a pond bottom of elevation 151, the corresponding elevation for the 25-year runoff volume = 5.27 ac-ft is approximately 164.1 feet. Set the emergency spillway at an elevation at least 1 foot minimum above the top of the temporary riser elevation of 159.0 feet, , while ensuring a minimum freeboard of 1' above the top of the basin elevation which is 164 feet. Try setting the emergency spillway at 161.00.

Use the Design Data for Earth Spillways (USDA-SCS) to determine the spillway width for the associated head. A width of 28 feet using the earth spillway design data allows for the passage of 56 cfs with 1 foot of head, and 179 cfs with 2 foot of head, assuming a z of 2 and an n value of 0.040. (See the Sediment Basin Outlet results).

Follow the recommendations for providing a core trench if necessary, anti-seep collars as needed, provide an allowance for settlement of the embankment, and provide baffles as needed.

Sediment Basin Outlet Results

Elevation	Orifice Outlet						36" Riser Outlet								24" Barrel Pipe				Emergency Spillway		Overtopping the Dam		Total Discharge	Storage
							Orifice		Weir		Orifice		Weir		Inlet		Outlet							
(ft)	H1 (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H2 (ft)	Q (cfs)	H3 (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H4 (ft)	Q (cfs)	H5 (ft)	Q (cfs)	H6 (ft)	Q (cfs)	H (ft)	Q (cfs)	Q (cfs)	Ac-ft.
151	0	0	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.0	0.00
152	1	0	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.0	0.15
153	2	0	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.0	0.33
154	3	0	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.0	0.55
155	4	0	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.0	0.81
156	5	0	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.0	1.10
157	6	0	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.0	1.44
158	7	0	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.0	1.82
159	8	0	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.0	2.25
160	9	0	0	0	0	0	1	34.0	1	29.2	0	0	0	0	9	45.4	19	44.0	0	0	0	0	29.2	2.73
161	10	0	0	0	0	0	2	48.1	2	82.6	0	0	0	0	10	47.8	20	45.2	0	0	0	0	45.2	3.26
162	11	0	0	0	0	0	3	59.0	3	151.8	0	0	0	0	11	50.2	21	46.3	1	56	0	0	102.3	3.84
163	12	0	0	0	0	0	4	68.1	4	233.7	0	0	0	0	12	52.4	22	47.4	2	179	0	0	226.4	4.48
164	13	0	0	0	0	0	5	76.1	5	326.7	0	0	0	0	13	54.5	23	48.4	3	361	0	0	409.4	5.18

Orifice Equation
Inv. =
centerline =
C=
A=
Q=CA((2gH)^1/2)

Riser Orifice Equation
Inv. = 159
C= 0.6
A= 7.0686
Q=CA((2gH)^1/2)

Riser Weir Equation
Inv.= 159
C= 3.1
L= 9.4248
Q=CL(H^3/2)

Barrel Inlet Control
Inv. = 150
centerline = 151
C= 0.6
A= 3.1416
Q=CA((2gH)^1/2)

Barrel Outlet Control
Inv. Out= 140
Centerline= 141
L= 100
km= 0.024
kp= 0.0246
A= 3.1416
Q=A[((2gH)/(1+km+kpL))^1/2]

Emergency Spillway taken from USDA-SCS
Earth Spillway Data
Width = 28', z=2, n=0.040

Stormwater Management Pond Design Example

Problem statement: Design a stormwater management extended detention pond that will provide control of the channel protection volume (1-yr) event with a 24-hour extended detention time, the overbank protection volume (10-year) event, and also safely pass the 100-year event.

Step 1 – Compute runoff control volumes from the SCS approach.

Be sure to check to see if there is a Water Quality Volume (WQv) requirement, and compute as required (for example, there is a WQv requirement in Berkeley County). The following example assumes there is no water quality volume requirement.

Develop Site Hydrologic and Hydrologic Input Parameters. Any hydrologic models using SCS procedures, such as TR-20, HEC-HMS, or HEC-1, can be used to perform preliminary hydrologic calculations. Chapter 4 of the manual contains TR-55 Urban Hydrology for Small Watersheds that gives instructions and examples in determining the Runoff Coefficient, and Time of Concentration. TR-55 methodology is used in this design example.

Condition	Area	CN	Tc
	Acre		Hrs
Pre-developed	38	73	0.499
Post-developed	38	78	0.267

From TR-55 Worksheets 2 and 3

Perform Preliminary Hydrologic Calculations

The site is located in a county in West Virginia that has the following 24-hour rainfalls:

1-year, 24-hour rainfall = 2.35 inches
10-year, 24-hour rainfall = 4.20 inches
100-year, 24-hour rainfall = 5.75 inches

Condition	Q 1-yr	Q1-yr	Q 10-yr	Q 100-yr
Runoff	inches	cfs	cfs	cfs
Pre-developed	0.49	29.2	115.3	210.7
Post-developed	0.69	62.8	197.2	335.3

From TR-55 Worksheet 4 or 5b

Compute Channel Protection Volume, (Cpv)

For stream channel protection, provide 24 hours of extended detention for the 1-year event.

Utilize SCS approach to compute channel protection storage volume

- Initial abstraction (Ia) for CN of 78 is 0.564 [Ia = (200/CN)-2]
- Ia/P – (0.564)/2.35 inches = 0.24
- Tc = 0.267 hours
- qu = 645 csm/in (Type II storm)

Knowing qo, qi, qu and T (extended detention time), find qo/qi for the 1-year design event. For a Type II rainfall distribution, and using TR-55 Worksheet 6a:

- Peak outflow discharge/peak inflow discharge (qo/qi) = 29.2/62.8 = 0.465
- Using qo/qi and TR-55 Figure 6-1, find Vs/Vr, where Vs equals channel protection storage (Cpv) and Vr equals the volume of runoff in inches.
- Vs/Vr = 0.295
- Knowing the Runoff Q (inches) from TR-55 Worksheet 2 and the Area (in square miles), compute the Runoff Volume Vr = Q (A) 53.33
  = 0.692 x 0.1406 x 53.33 = 5.19 ac. ft.
- Storage Volume Vs = Vr (Vs/Vr) = 5.19 x 0.295 = 1.53 ac.ft or 66,647 cf.

Compute Overbank Flood Protection Volume, (Q10-yr)

Knowing qo, qi, qu and T (extended detention time), find qo/qi for the 10-year design event. For a Type II rainfall distribution, and using TR-55 Worksheet 6a:

- Peak outflow discharge/peak inflow discharge (qo/qi) = 115.3/197.2 = 0.585
- Using qo/qi and TR-55 Figure 6-1, find Vs/Vr, where Vs equals overbank flood protection volume storage and Vr equals the volume of runoff in inches.
- Vs/Vr = 0.250
- Knowing the Runoff Q (inches) from TR-55 Worksheet 2 and the Area (in square miles), compute the Runoff Volume Vr = Q (A) 53.33
  = 2.048 x 0.1406 x 53.33 = 15.36 ac. ft.
- Storage Volume Vs = Vr (Vs/Vr) = 15.36 x 0.250 = 3.84 ac.ft or 167,270 cf.

Analyze Safe Passage of the 100-Year Design Storm (Q100)

Check to see if there are any local requirements or field observations that would advocate controlling the 100-year storm. If so, storage estimates would have been made similar to the volumes in the previous steps.

Step 2 – Determine pond location and preliminary geometry. Keep in mind the recommendations of keeping the length to width ratio greater than 2:1, making the distance between the inflows and outflow of the pond as maximum as possible, and providing sediment forebays, safety ledges and other features recommended in the local jurisdiction.

Step 3 – Set water surface elevation for Channel Protection Event.

Use TR-55 Worksheet 6A to develop a stage/storage chart for the pond based on the preliminary geometry.

Stage-Storage Chart (determined from the basin/pond geometry, which is not given for this example) Assumes the following:

Elevation (ft.)	**Sum Volume** (ac-ft.)
151	0.00
152	0.15
153	0.33
154	0.55
155	0.81
156	1.10
157	1.44
158	1.82
159	2.25
160	2.73
161	3.26
162	3.84
163	4.48
164	5.18
165	5.93
166	6.75

Determine the maximum storage elevation corresponding to the storage volume computed in Step 1 for the 1-year channel protection event. From the stage-storage chart, the corresponding water surface elevation for the 1-year channel protection design event = 157.3.

Next, determine the size of a low-flow orifice by defining the average release rate to empty 1.53 ac-ft in 24 hours.
Q = (1.53ac-ft x 43,560 ft^2/ac)/(24 hrs x 3600 sec/hr) = 0.771 cfs

With the pond bottom set at elevation 151.0 feet, that gives an average head of 3.15 ft, as the pond empties from 157.3 feet to 151.00 feet. Solve the orifice flow equation:
Q = C A ((2 g h) ^ (½))
where
Q = discharge, cfs
C = discharge coefficient, 0.62
A = cross sectional area of the orifice, ft^2
h = total head, using an average head of 3.15 ft to empty the volume.

Solving for the area, A, gives an orifice diameter of approximately 4 inches.

Step 4 – Set water surface elevation for Overbank Protection Volume.

From the stage/storage chart, determine the maximum storage elevation corresponding to the 10-year design event storage volume.
From the stage-storage chart, the corresponding water surface elevation for the 10-year design event = 162.0 feet.

Set the elevation of the riser above the 1-year water surface elevation but below the 10-year water surface elevation and then calculate the size of the riser by solving the weir and orifice equations.

- Set the crest elevation at 160.0 feet, which gives a head of 2.0 feet. At this elevation, the low flow orifice head is 10.833', measured to the centerline of the orifice. Solving the orifice equation, the low flow orifice Q = 1.4cfs.
- The maximum outflow Q = 115.3 – 1.4 cfs – 113.9 cfs (Pre-developed 10-year flow minus the orifice flow)
- Solving the weir equation for the riser gives an L=13.01 feet. In order to make sure that the barrel pipe controls the flow before the riser is submerged, choose a riser with a slightly larger L. Therefore, select a 60-inch riser with a perimeter, L = 15.7 ft and an area, A = 19.63 square feet.
- Design the pipe barrel based on the 10-year storm event.
- Corresponding 10-year water surface elevation from above = 162.0 feet.
- Invert elevation = 150.0 feet.
- Head = 12.0 feet
- Determine the slope of the outlet pipe; Slope = 10%.
- Maximum Q = 115.3 cfs
- Assuming CMP, with a Manning's roughness n = 0.024, determine the diameter barrel to pass 115.3 cfs.
- Try a diameter D = 36-inches.
- Solving the pipe equation for inlet control gives Q = 110.3 cfs (refer to Detention Basin Outlet results).
- Solving the pipe equation for outlet control gives Q = 121.6 cfs (refer to Detention Basin Outlet results).

Next, develop and complete the stage-discharge storage summary (see the Detention Basin Outlet result) up to the preliminary 10-year water surface elevation = 162.0 feet and route the 10-year post-developed condition inflow by hand or using computer software.

Step 5 - Design the emergency spillway based on safely passing the 100-year storm event with a minimum of 1 foot of freeboard.

Set the emergency spillway elevation above the 10-year water surface elevation, but at least a minimum of 2' below the top of the embankment. Setting the crest elevation at elevation 16 feet gives a head of 1.0 feet.
The maximum Q100 inflow = 210.7 cfs – 125 cfs (barrel outflow) = 85.7 cfs.

Use the Design Data for Earth Spillways (USDA-SCS) to determine the spillway width for the associated head. A width of 28 feet using the earth spillway design data allows for the passage of 56 cfs with 1 foot of head, and 179 cfs with 2 foot of head, assuming a z of 2 and an n value of 0.040. (See the Detention Basin Outlet results).

There are several excellent examples in various stormwater management manuals available on the internet for designing a stormwater management pond as well as other best management practices. This example only illustrates the preliminary, basic design for a stormwater management pond.

Detention Basin Outlet Results

Elevation	4" Orifice Outlet						60" Riser Outlet								36" Barrel Pipe				Emergency Spillway		Overtopping the Dam		Total Discharge	Storage
							Orifice		Weir		Orifice		Weir		Inlet		Outlet							
(ft)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	Q (cfs)	Ac-ft.
151	0	0	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.00	0.00
152	0.8333	0.38	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.38	0.15
153	1.8333	0.57	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.57	0.33
154	2.8333	0.71	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.71	0.55
155	3.8333	0.82	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.82	0.81
156	4.8333	0.92	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0.92	1.10
157	5.8333	1.01	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	1.01	1.44
158	6.8333	1.10	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	1.10	1.82
159	7.8333	1.18	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	1.18	2.25
160	8.8333	1.25	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0	1.25	2.73
161	9.8333	1.32	0	0	0	0	1	94.52	1	48.7	0	0	0	0	9.5	104.9	19.5	118.5	0	0	0	0	50.0	3.26
162	10.833	1.38	0	0	0	0	2	133.67	2	137.7	0	0	0	0	10.5	110.3	20.5	121.5	0	0	0	0	110.3	3.84
163	11.833	1.45	0	0	0	0	3	163.71	3	252.9	0	0	0	0	11.5	115.4	21.5	124.5	0	0	0	0	115.4	4.48
164	12.833	1.51	0	0	0	0	4	189.04	4	389.4	0	0	0	0	12.5	120.3	22.5	127.3	1	56	0	0	176.3	5.18
165	13.833	1.56	0	0	0	0	5	211.35	5	544.1	0	0	0	0	13.5	125.1	23.5	130.1	2	179	0	0	304.1	5.93
166	14.833	1.62	0	0	0	0	6	231.52	6	715.3	0	0	0	0	14.5	129.6	24.5	132.9	3	361	0	0	490.6	6.75

Orifice Equation
Inv. = 151
centerline = 151.17
C= 0.6
A= 0.087 sf
Q=CA((2gH)^1/2)

Riser Orifice Equation
Inv. = 160
C= 0.6
A= 19.635
Q=CA((2gH)^1/2)

Riser Weir Equation
Inv.= 160
C= 3.1
L= 6.283
Q=CL(H^3/2)

Barrel Inlet Control
Inv. = 150
centerline = 151.5
C= 0.6
A= 7.0686
Q=CA((2gH)^1/2)

Barrel Outlet Control
Inv. Out= 140
Centerline= 141.5
L= 100
km= 0.024
kp= 0.0246
A= 7.0686
Q=A[((2gH)/(1+km+kpL))^1/2]

Emergency Spillway taken from USDA-SCS
Earth Spillway Data
Width = 28', z=2, n=0.040

CHAPTER 6

SAMPLE PLAN –
INDIVIDUAL HOUSE SITE

SAMPLE PLAN –
SMALL COMMERCIAL DEVELOPMENT SITE

SAMPLE PLAN –
UTILITY LINE CROSSING

6.0 – Individual House
Sample Sediment and Erosion Control Plan

Primary Concerns Related to Erosion and Sedimentation

Water Quality

Sediment is the number one pollutant, by volume, of surface waters in the state of West Virginia. It impacts water quality by degrading the habitat of aquatic organisms and fish, by decreasing recreational value, and by promoting the growth of nuisance weeds and algae.

Flooding

Sediment accumulation in streams, lakes, and rivers reduces their capacity to contain stormwater, which can result in increased flooding.

Local Taxes

Sediment that finds its way into streets, storm sewers, and ditches results in additional maintenance costs for local, state, and federal governments.

Property Values

Sediment deposits not only impair water quality but also damage property, thus reducing its use and value.

Sample Erosion and Sediment Control Plan

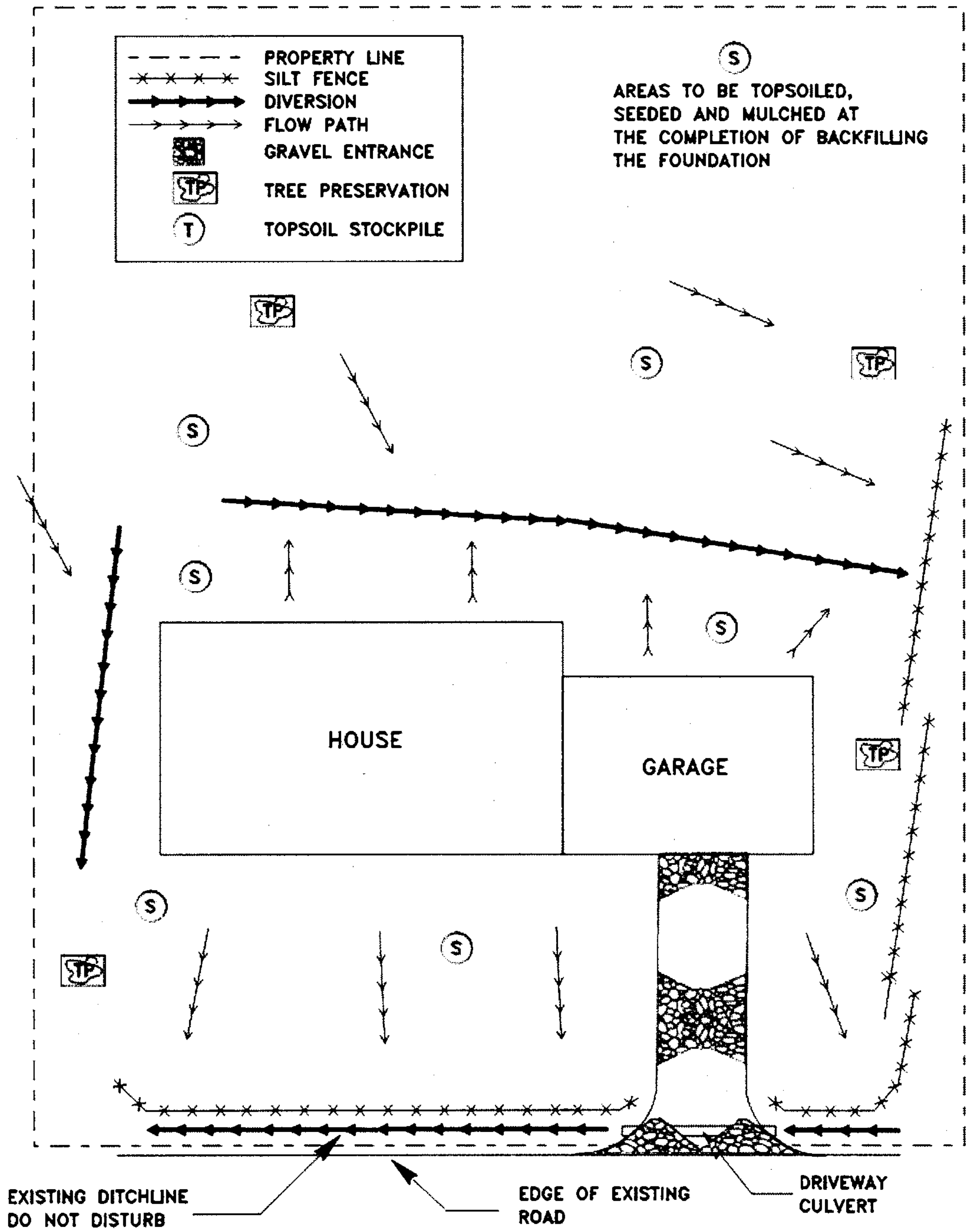
Every building site is unique and poses its own potential erosion hazards. In many instances, additional or alternative control methods are necessary if the lot is adjacent to a creek, lake, or wetland; slopes are greater than six percent; receives runoff from adjacent areas; and/or more than one acre of ground is disturbed.

NOTES:

1. It is the responsibility of the property owner and contractor to comply with State laws and local and county ordinances regarding construction site erosion and sediment control.
2. This plan is only a sample plan and is not intended to be all-inclusive or address every situation; additional or modified practices may be required on some sites.
3. Erosion or sediment control measures must be functional and maintained throughout construction.
4. Maintain positive drainage away from the structure(s).

FIGURE 6.1

INDIVIDUAL HOUSE LOT SEDIMENT CONTROL PLAN



Controlling Building Site Erosion & Sedimentation

Erosion control is important on any building site regardless of its size. Usually, principles and methods for controlling erosion and reducing offsite sedimentation are relatively simple and inexpensive. Here are four basic steps to follow when developing a building site.

Evaluate the Site

Inventory and evaluate the resources on the lot before building. Location of structures should be based on the lot's natural features. Identify trees that you want to save and vegetation that will remain during construction. Also identify areas where you want to limit construction traffic. Wherever possible, preserve existing vegetation to help control erosion and off-site sedimentation.

Select & Install Initial Erosion/ Sediment Control Practices

Determine the specific practices needed, and install them before clearing the site. Among the more commonly used practices are vegetative filter strips, silt fences, gravel drives, and inlet protection.

Develop a Maintenance Program

Maintenance of all practices is essential for them to function properly. Practices should be inspected twice a week and after each rainfall event. When a problem is identified, repair or replace the practice immediately. If frequent repairs are required (such as Silt Fence being knocked down), another more substantial practice may need to be selected. In addition, any sediment that is tracked onto the street should be scraped and deposited in a protected area. Do not flush sediment from the street with water.

Revegetate the Site

Providing a vegetative cover is the most important practice in preventing erosion and sediment. Therefore, establish vegetation as soon as possible. A well-maintained lot has a higher sale potential.

Building Lot Drainage

The best time to provide for adequate lot drainage is before construction begins. With proper planning, most drainage problems can be avoided. That's important because correcting a problem after it occurs is usually much more difficult and costly. Here's what it takes to ensure good lot surface and subsurface drainage.

Surface Drainage

- Position the structure a minimum of 18 inches above street level.

- Divert stormwater runoff away from the foundation by grading the lawn to provide at least six inches of vertical fall in the first ten feet of horizontal distance.

- Construct side and rear yard swales to take surface water away from the structure.

- Do not fill in existing drainage channels and roadside ditches, since that could result in wetness problems on someone else's property and/or damage to adjacent road surfaces.

Subsurface Drainage

- Provide an outlet for foundation or footer drains and for general lot drainage by using storm sewers (where allowed), or obtain drainage easements if you must cross adjoining properties.

Construction Sequence for Erosion & Sediment Control Practices

1. Evaluate the Site

Before construction, evaluate the site; mark vegetative areas and trees to be protected, unique areas to preserve, on-site septic system absorption fields, and vegetation suitable for filter strips, especially in perimeter areas.

Identify Vegetation to be Saved

Select and identify the trees, shrubs and other vegetation to be saved (see Step 2: "Vegetative Filter Strips").

Protect Trees & Sensitive Areas

- To prevent root damage, do not grade, burn, stock pile topsoil, or park vehicles near trees or in areas marked for preservation.
- Place plastic mesh or snow fence barriers around the trees' driplines to protect the area below their branches.
- Place a physical barrier, such as plastic fencing, around the area designated for a septic system absorption field (if applicable).

2. Install Perimeter Erosion and Sediment Controls

Identify the areas where sediment-laden runoff could leave the construction site, and install perimeter controls to minimize the potential for off-site sedimentation. It's important that perimeter controls are in place before any earthmoving activities begin.

Protect Down-Slope Areas with Vegetative Filter Strip

- On slopes of less than six percent, preserve a 20-to 30-foot wide (minimum) vegetative buffer strip around the perimeter of the property, and use it as a filter strip for trapping sediment.
- Do not mow filter strip vegetation shorter than four inches.

Protect Down-Slope Areas with Silt Fence and Other Appropriate Practices

- Use silt fencing along the perimeter of the lot's downslope side(s) to trap sediment. Refer to silt fence practices.

Install Stabilized Construction Entrance

- Restrict all lot access to this drive to prevent vehicles from tracking mud onto roadways or destroying perimeter controls. Refer to Stabilized Construction Entrances.

3. Prepare the site for construction

Prepare the site for construction and for installation of utilities. Make sure all contractors (especially the excavating contractor) are aware of areas to be protected.

Salvage and Stockpile Topsoil or Subsoil

- Remove topsoil (typically the upper four to six inches of the soil material) and stockpile.
- Remove subsoil, including any excavated material associated with basement construction, and stockpile separately from the topsoil.
- On small building sites, it may not be feasible to stockpile soil material on each individual lot due to space limitations. In these situations, soil material should be transported to protected areas designated on the overall construction plan or those areas designated by the developer.
- Locate the stockpiles away from any downslope street, driveway, stream, lake, wetland, ditch or drainageway.
- Immediately after stockpiling, temporary seed the stockpiles with annual rye or winter wheat and/or install sediment barriers around the perimeter of the piles.

4. Build Structure(s) and Install Utilities

Construct the home and install the utilities; also install the sewage disposal system and drill water well (if applicable); then consider the following:

Install Downspout Extenders

- Although not required, downspout extenders are highly recommended as a means of preventing lot erosion from roof runoff.
- Add the extenders as soon as the gutters and downspouts are installed.
- Be sure the extenders have a stable outlet, such as a paved area, or a well vegetated area. Do not route runoff directly to a street in winter due to the formation of ice.

Refer to temporary downspout extenders diagram.

5. Maintain Control Practices

Maintain all erosion and sediment control practices until construction is completed and the lot is stabilized.

- Inspect the control practices daily and after each storm event, making any needed repairs immediately.
- Toward the end of the each workday, sweep or scrape up any soil tracked onto roadway(s). Do not flush mud down the street with water.

6. Revegetate Building Site

Immediately after all outside construction activities are completed, stabilize the lot with sod, seed, and/ or mulch.

Redistribute the Stockpiled Subsoil and Topsoil

- Spread the stockpiled subsoil to rough grade.
- Spread the stockpiled topsoil to a depth of four to six inches over rough-graded areas.
- Fertilize and lime according to soil test results or recommendations of a seed supplier or a professional landscaping contractor. Fertilize and lime if needed according to soil test (or apply 10 lb./1000 sq. ft. of 10-10-10 fertilizer).

Seed or Sod Bare Areas

- Contact local seed suppliers or professional landscaping contractors for recommended seeding mixtures and rates.
- Follow recommendations of a professional landscaping contractor for installation of sod.
- Rake lightly to cover seed with ¼” of soil. Roll lightly.
- Water newly seeded or sodded areas every day or two to keep the soil moist. Less watering is needed once grass is two inches tall.

Mulch Newly Seeded Areas

- Spread straw mulch on newly seeded areas, using one and one half to two bales of straw per 1,000 square feet. The mulch should cover to where the ground is just visible.
- On flat or gently sloping land, anchor the mulch by crimping it two to four inches into the soil. On steep slopes, anchor the mulch with netting or tackifiers. An alternative to anchored mulch would be the use of erosion control blankets.

Temporary Seeding

If the site will not be permanently seeded anytime soon, sow 40 lbs of Annual Rye (year round) or 170 lbs. of Winter Wheat (fall and winter) per acre on all disturbed soils immediately upon backfilling the foundation.

7. Remove Remaining Temporary Control Measures

Once the sod and/or vegetation is well established, remove any remaining temporary erosion and sediment control practices, such as:

- Remove downspout extenders. Or, shorten to outlet on an established vegetated area, allowing for maximum filtration.
- Remove storm sewer inlet protection measures.

Individual Erosion & Sediment Control Practices for Homebuilders

Silt Fence

1. Install silt fence parallel to the contour of the land.
2. Extend ends upslope to allow water to pond behind fence.
3. Excavate a trench 4-inches wide, 8-inches deep.
4. Install fence with posts on the down slope side.
5. Place 12-inches of fabric in the trench, extending the bottom four inches toward the upslope side.
6. Join silt fence sections by using a wrap joint.
7. Backfill trench with soil materials and compact.
8. Inspect at least weekly and after each storm event, repairing as needed and removing sediment deposits when they reach one-half the fence height.

Note: Silt fence has a life expectancy of six months to one year, whereas straw bale barriers have a limited life of three months or less.

Stabilized Construction Entrance

1. Place six inches of 2” to 4”coarse aggregate over a stable subgrade.
2. Construct the drive at least 12-feet wide and 50-feet long or the distance to the foundation.
3. Add stone as needed to maintain six inches of clean depth.
4. To improve stability or if wet conditions are anticipated, place geotextile fabric on the graded foundation.

Temporary Downspout Extenders

1. Install extenders as soon as gutters and downspouts are installed to prevent erosion from roof runoff.
2. Use non-perforated (un-slotted) drainage tile.

3. Route water to a stable grassed or paved area or to the storm sewer. Do not route water directly to a street or sidewalk in the winter due to the formation of ice.
4. Remove downspout extenders after vegetation is established.

For more detailed information of these and other practices, the West Virginia Erosion and Sediment Control Manual is available to assist you in making informed decisions.

FIGURE 6.2

SILT FENCE

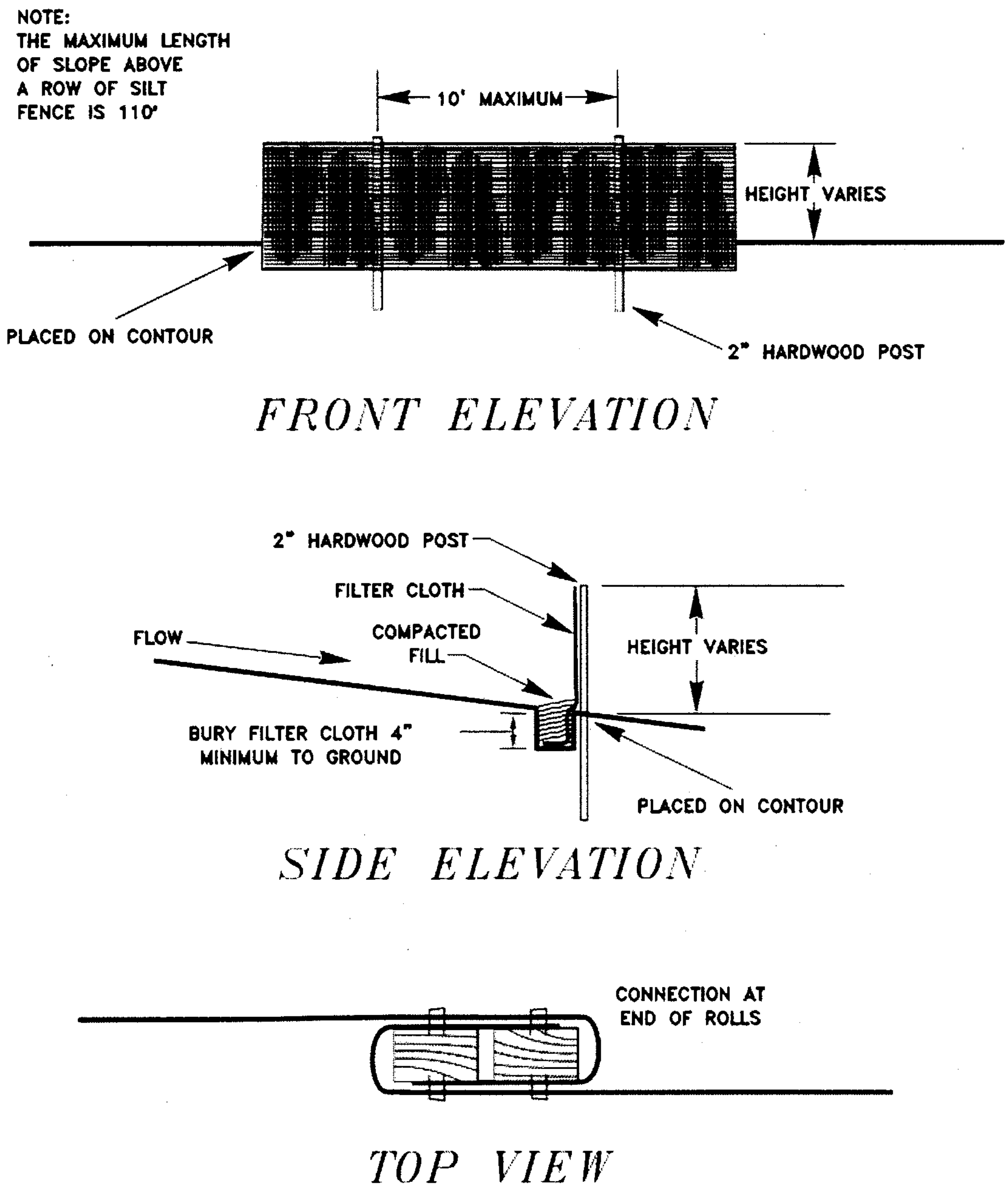
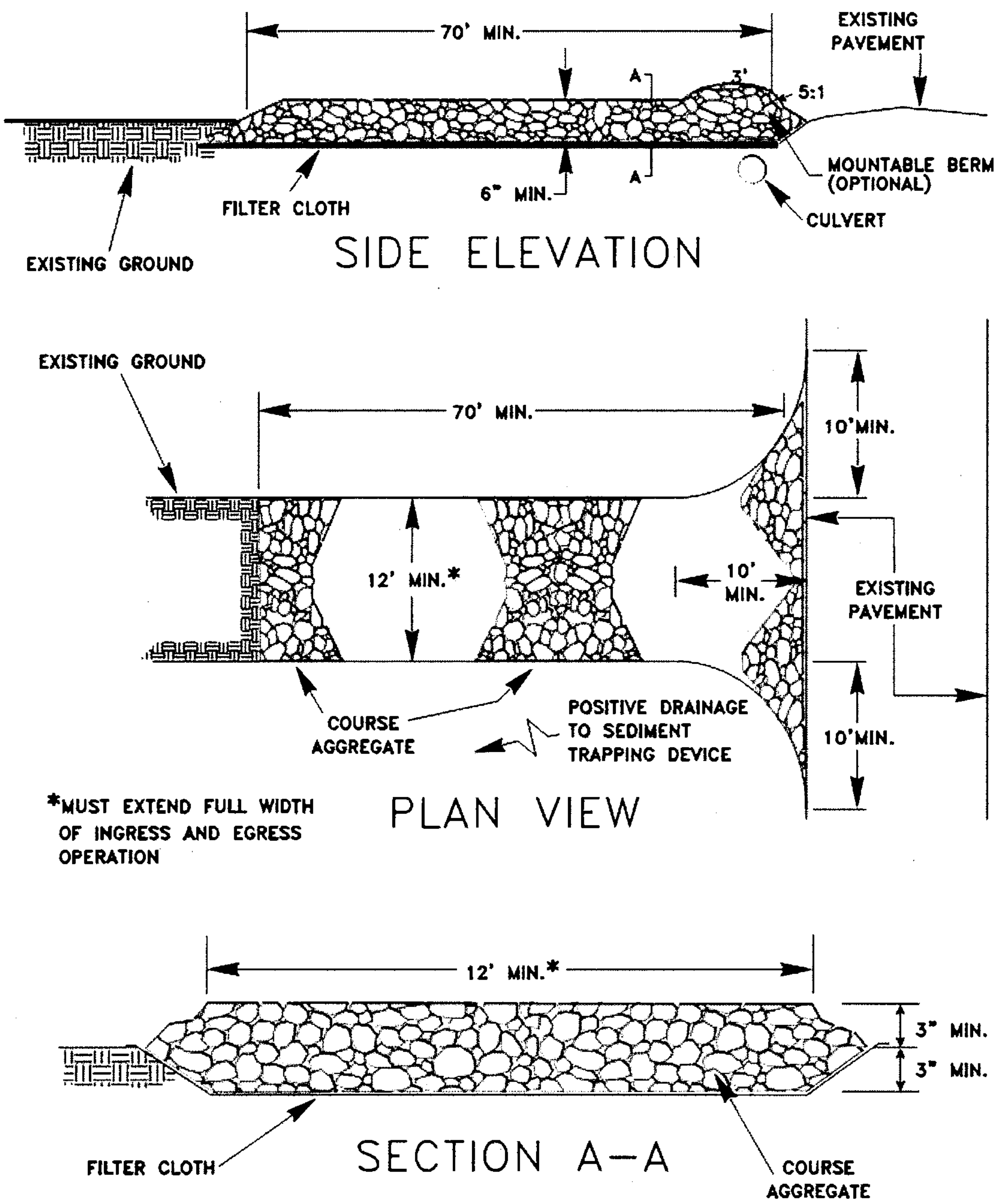


FIGURE 6.3

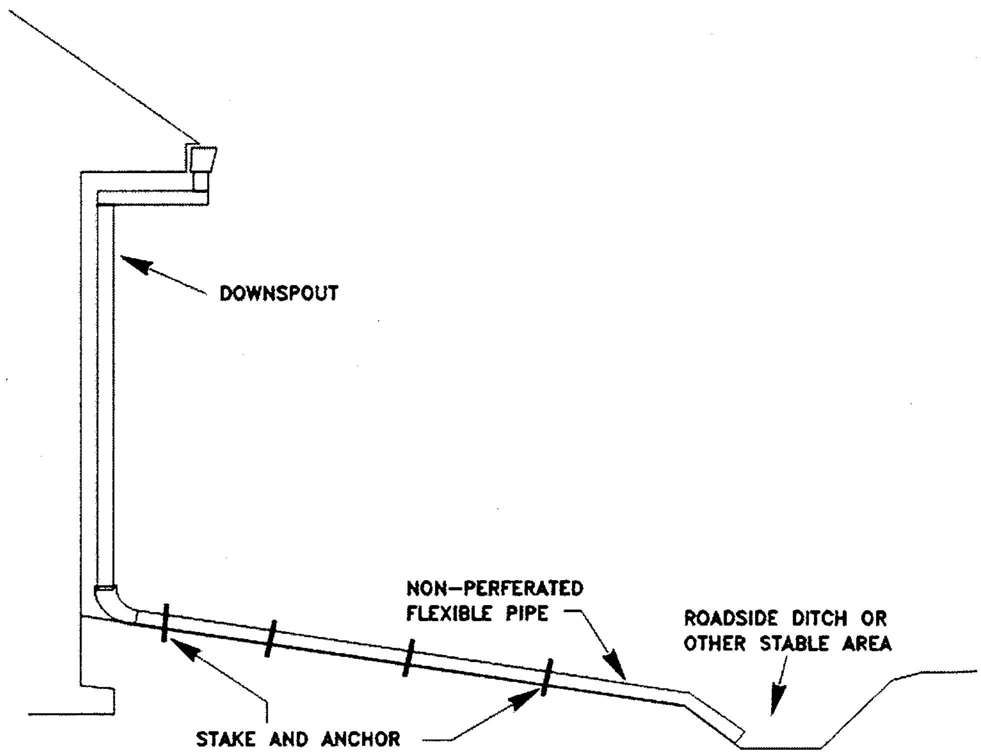
STONE CONSTRUCTION ENTRANCE



SOURCE: ADAPTED from 1983 Maryland Standards for Soil Erosion and Sediment Control and Va. DSWC

6-09

FIGURE 6.4



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CHAPTER 7

STREAM RESTORATION STANDARD GUIDELINES AND SPECIFICATIONS

Chapter 7 – Stream Restoration BMPs

Introduction

The Natural Stream Design (NSD) approach to stream restoration uses the characteristics of a stable stream to design the restoration of an unstable one. Some of the stream characteristics that should be identified are the bed and bank materials (clay, sand, gravel, cobble and bedrock), stream pattern, channel gradient, dimension and size of the floodplain.

NSD projects require federal and state permits for in-stream construction. Therefore, NSD projects are thoroughly reviewed by the resource agencies to assure that the project will have a net positive benefit on the aquatic resource. The NPDES program was designed to eliminate and/or dramatically reduce stormwater and associated sediment from upland residential, commercial or industrial construction projects from entering the watercourse. NSD projects aim to enhance/restore stable dimensions, patterns, and profiles to stream channels as well as to enhance/restore floodplains and riparian zones. Methods commonly employed involve the construction of new channel reaches, installation of in-stream structures (rock vanes, log vanes, cross vanes, J-hooks) and construction of floodplain benches. These activities take place in or immediately adjacent to the active stream channel. Best Management Practices (BMPs) for upland construction or other in-stream construction projects are not always practical or appropriate for NSD projects. Therefore, a set of BMPs specifically for NSD projects that reduce turbidity to reasonable, practical and acceptable levels during construction of the stream restoration project have been developed. In addition to the BMPs developed for NSD projects, other appropriate BMPs as defined in Chapter Three may be utilized in developing the Storm Water Pollution Prevention Plan (SWPPP).

Conditions where Practice Applies

NSD is a broad term that encompasses a variety of projects that have the common goal of improving the quality of the stream ecosystem. Channelization and dredging to increase the flow capacity of the stream is not considered a NSD-type project. Impacts associated with channel construction such as increased turbidity, disturbance of channel substrates and floodplain alteration can be visually dramatic. However, these temporary impacts are mitigated by long-term restoration of the impaired channel to a more natural stable condition.

Planning Considerations

NSD projects may be relatively simple habitat improvement projects using structures such as cross vanes designed to improve pool habitat, or simple bank stabilization projects using rock/log vanes. Other NSD projects will be more complex and may physically alter the dimension, pattern, and/or profile of the stream.

Enhancement Projects – This category generally includes riparian buffer establishment; non-point source removal activities (livestock exclusion, removal of adjacent agriculture fields from further production, elimination of future timber harvest); bank revegetation; and/or removal or reduction of impervious surfaces in the watershed. The category also incorporates activities that augment channel stability, water quality and stream ecology in accordance with a reference condition where appropriate. These activities may include in-stream and/or streambank activities, but fall short of restoring one or more of the geomorphic variables, which include dimension, pattern and profile. Examples may include stabilization of streambanks using bioengineering techniques; creation of bankfull benches; and introduction of in-stream habitat.

Restoration Projects – These projects involve the conversion of an unstable, altered or degraded stream corridor, including adjacent riparian zones (buffers) and flood-prone areas, to a natural stable condition based on historical, recent and future watershed conditions. This process is typically based on a reference condition/reach for the stream valley type and includes restoration of the appropriate geomorphic dimension (cross-section), pattern (sinuosity), and profile (channel slope). This process supports reestablishing physical, biological and chemical integrity, including transport of the water and sediment produced by the stream's watershed in order to achieve dynamic equilibrium.

Construction Criteria

The following general practices are accepted methods to be used to reduce temporary impacts associated with construction of NSD type projects. These practices are general in nature and some may be included as special conditions in the 404/401 permit. Some general BMP's may have more detailed specifications listed in following sub-sections. Other practices may be approved on a case by case basis.

1. On-site pre-application and/or pre-construction meetings are strongly encouraged to review each project, permit application and the selected BMP(s). These meetings should include the project designer, project sponsor(s), construction contractor(s), USACE, DNR, and DEP permitting and/or enforcement personnel and other appropriate personnel.

2. Clean and inspect equipment prior to arriving on the construction site and before leaving the site to minimize transferring invasive species and contaminating the aquatic system with fluids.

3. If it's necessary for maneuvering equipment prune overhanging vegetation prior to construction. All pruned vegetation should be cut clean.

4. Minimize construction time, and maximize efficiency by:

   a. Utilizing the proper size, type and quantity of equipment
   b. Ensuring that the sufficient type, quality and quantity of materials are on-site during construction
   c. Ensuring sufficient personnel are on-site during construction
   d. Preparing and following an effective sequence of construction
   e. Minimizing down time. Once the project is under construction, it should be completed without undue delay.

5. Preserving riparian vegetation (including sod) is critical for minimizing site disturbance, reduction of upland sediment inputs, and post-construction project stability (see appropriate BMPs in Chapter Three).

6. Use upland transportation corridors to minimize impacts to the riparian zone.

7. Work in-the-dry or from the top of bank whenever feasible and practical. Minimize the amount of time and extent of disturbance in the channel as much as possible.

8. Pump-around may be used when feasible and practical.

9. Update field map with minor field modifications daily.

10. While the permit is in effect, project sites must be stabilized according to the approved Erosion and Sediment Control Plan for the 1-year, 24-hour rainfall event, ***or bankfull event for NSD projects***. If a storm event exceeds the 1-year, 24-hour rainfall limit ***or bankfull***, follow "upset procedures" in General Permit conditions.

11. Practice contemporaneous site reclamation to the extent feasible and practical during construction. Stabilize all

disturbed areas concurrently with restoration activities (see appropriate BMPs in Chapter Three).

12. Follow manufacturer specifications on equipment and materials, or provide the justification to vary from them in NPDES permit application.

7.01- IN-STREAM STRUCTURES, RIFFLES AND POOLS

Introduction

In-stream structures, and profile alterations such as riffles and pools, are constructed to provide bank stabilization, habitat enhancement, improved sediment transport and stream restoration. Types of structures may include cross vanes, rock vanes, j-hooks, and possibly log structures. In-stream structures and profile alterations are constructed to provide long -term stability to the stream reach.

Conditions Where Practice Applies

These techniques should be practiced, all or in part, during all phases of stream restoration projects. The practices that are determined most effective and feasible to sediment and erosion control for the specific site should be exercised.

Construction Specifications:

1. Where practical and feasible, in-stream work should be done on the side of the stream where the structure is being built.

2. Tracks of stationary equipment working in the stream should be parallel to stream flow when practical and feasible, to do so.

3. Minimize drop height when placing material in the channel.

4. Minimize use of temporary stream diversion/deflection structures (see drawings, attached) to reduce additional stream impacts. When used, deflection structures should:

   a. Deflect flow away from the side of stream where structures are being placed and/or profile is being altered.
   b. Be composed of native channel material if available adjacent to structure, and if channel material is to be removed anyway. This saves the impact of hauling in clean fill, while also hauling out channel material. If native channel material is not to be removed from an adjacent location, clean non-erodible rock with 15% or less of fines of like material should be imported to build deflection structures.
   c. Serve as a platform upon which equipment can be stationed to build in-stream structure.

6. Use appropriately-sized equipment to build structures, with hydraulic thumbs to place rock. Equipment that is smaller than necessary will take more time; equipment that is larger than necessary will have more impact on the site.

7. Construction should be sequenced and specified effectively and efficiently to complete the project.

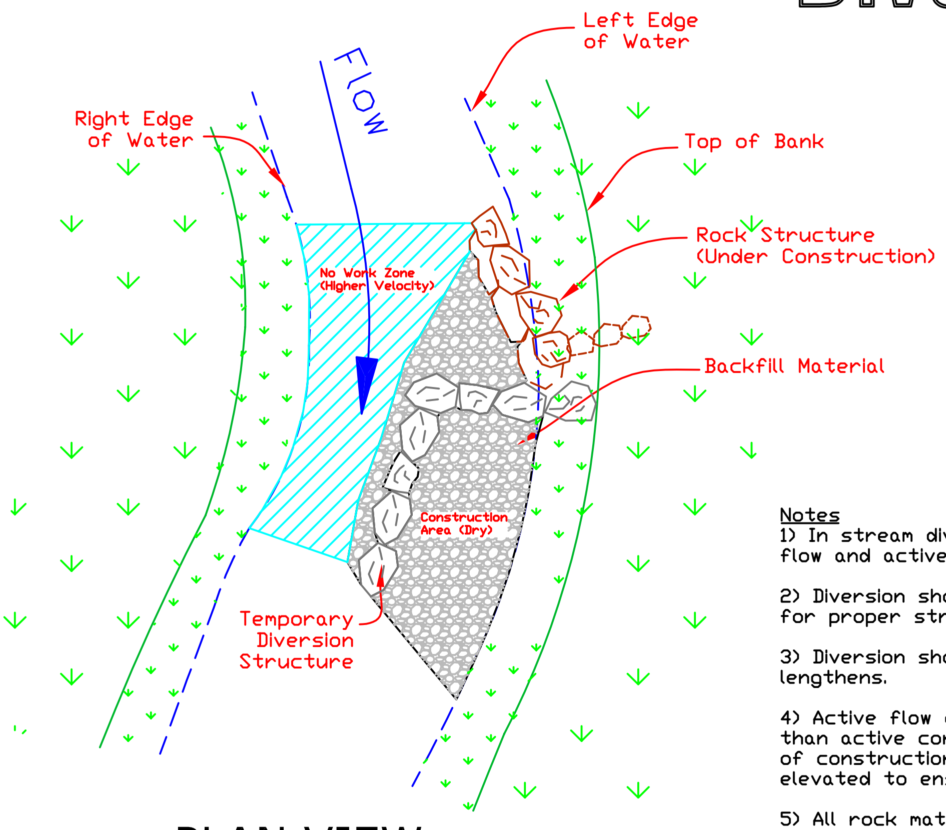
8. Where site conditions permit, turbidity curtains may be utilized per manufacturer's recommendations around structures under construction.

9. Geotextile (woven or non-woven) fabric should be placed behind structures and backfilled in channels with gravel beds (or finer particles).

10. Work in-the-dry or from the top of bank whenever feasible and practical. Minimize the amount and extent of disturbance in the channel as much as possible.

11. Pump-around may be used when feasible and practical.

In Stream Diversion (Dry)



PLAN VIEW

Notes

1) In stream diversion to act as barrier to the active flow and active construction area.

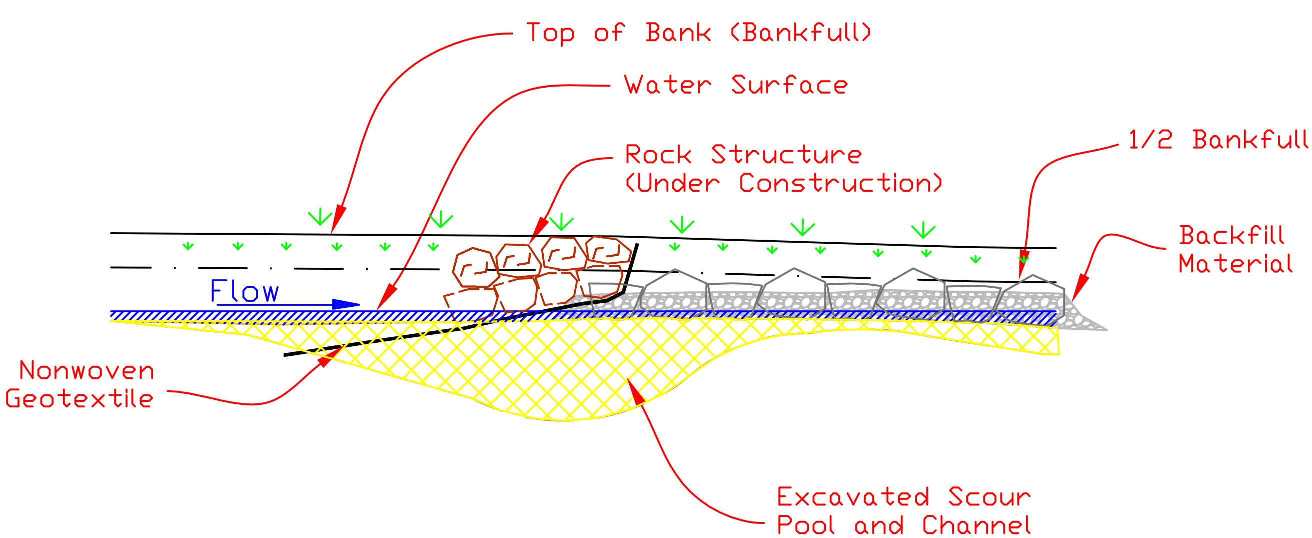
2) Diversion should be placed below structure and allow for proper structure placement.

3) Diversion shall expand up stream as structure lengthens.

4) Active flow area shall have a thalweg depth greater than active construction area to allow for dewatering of construction area. Active construction area will be elevated to ensure for a dry working area.

5) All rock materials shall be of proper size and quality, as stated in construction specifications.

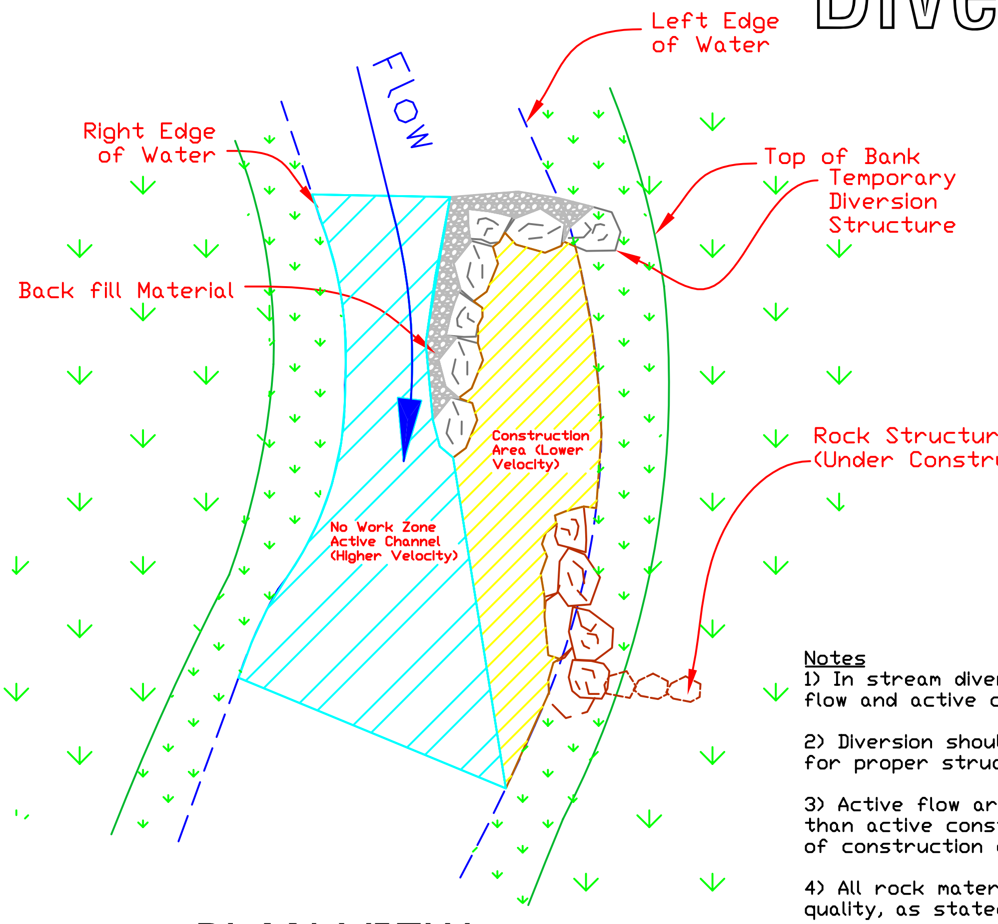
6) All rock and fabric material used in construction of diversion shall be removed immediately after completion of project.



PROFILE VIEW

Figure 7.01.2

In Stream Diversion (wet)



PLAN VIEW

<u>Notes</u>

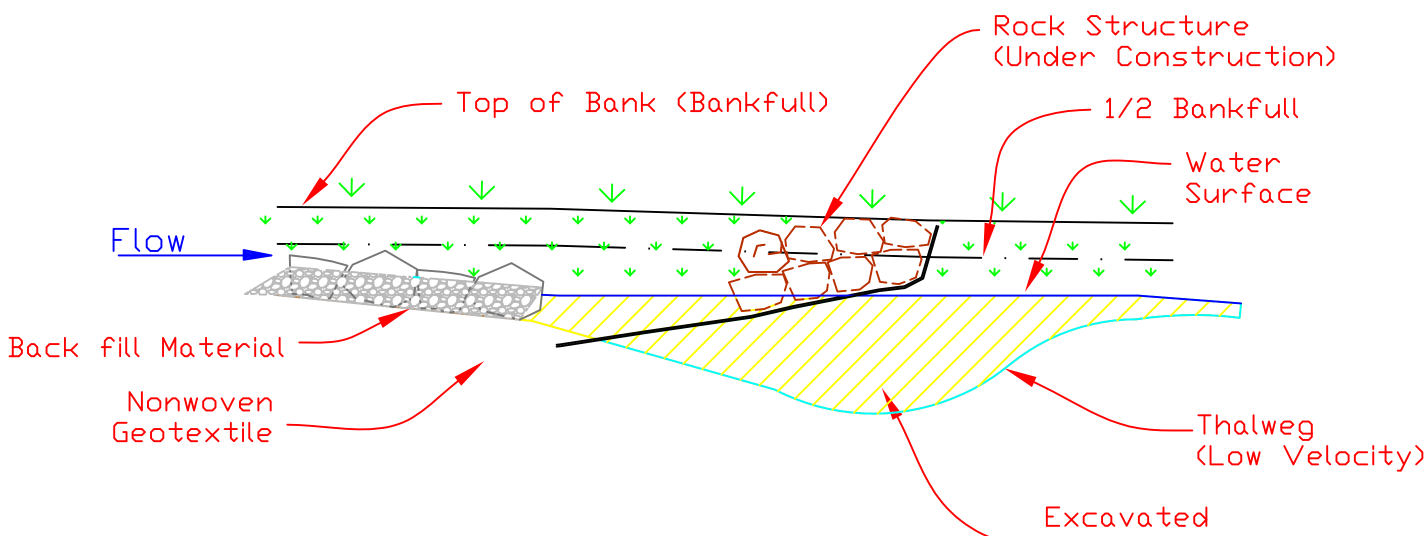
1) In stream diversion to act as barrier to the active flow and active construction area.

2) Diversion should be placed above structure and allow for proper structure placement.

3) Active flow area shall have a thalweg depth greater than active construction area to allow for dewatering of construction area.

4) All rock materials shall be of proper size and quality, as stated in construction specifications.

5) All rock and fabric material used in construction of diversion shall be removed immediately after completion of project.



PROFILE VIEW

7.02 - CONSTRUCTED BENCHES AND FLOODPLAINS

Introduction

Construction of new benches and floodplains improves both the lateral and vertical stability of the reach by allowing the stream to access the floodplain, and reduces the bank height ratio. Stabilizing banks also reduces turbidity from on-going bank erosion. BMPs exercised during construction should be site specific.

Conditions Where Practice Applies

Minimizing project area disturbance is critical to sediment and erosion control during stream restoration projects. Site specific factors influencing BMPs include quality of riparian buffer, bank material, bed material, bankfull width, bankfull depth, floodprone width, stream gradient, discharge and bank height.

Construction Specifications

1. New bankfull benches and floodplains should be seeded and mulched. Choose seed appropriate to season, region and site conditions (see appropriate BMPs in Chapter Three).

2. Install berms or silt fences along transportation routes on new benches or floodplains.

3. When constructed benches are composed of fine soils, they should be back-sloped away from the channel (using a slope of 20:1) until final grading and seeding. The back-sloped areas should be drained into ditches or sumps. Any dewatering must be through appropriate devices (see appropriate BMPs in Chapter Three).

4. Stabilize bench and floodplain slopes, and justify stabilization method according to slope material.

7.03 – NEW CHANNEL CONSTRUCTION

Introduction

Restoring natural pattern, dimension and profile may sometimes require the construction of an entirely new stream channel, or sections of new channel tied into the existing channel. Building new channel is often combined with creating suitable floodplain and establishing a riparian zone. The new stream channel will be constructed with a stable pattern and profile and appropriate dimensions based on reference conditions and design parameters. The new floodplain and riparian zone will also be established based on site and reference conditions, and will support the physical, biologic, and chemical restoration goals of the project. The construction of the new channel and floodplain must incorporate BMPs to control stormwater and associated sediment inputs.

Conditions Where Practice Applies

This restoration alternative should be applied to any new channel construction or relocation.

Construction Specifications

1. Construction should occur "in the dry", out of the existing flow, whenever possible.

2. Construction should be sequenced to effectively and efficiently complete the project.

3. When constructed benches are composed of fine soils, they should be back-sloped away from the channel (using a slope of 20:1) until final grading and seeding. The back-sloped areas should be drained into ditches or sumps to pump out, as necessary. Follow existing NPDES permit requirements about filtering all pumped discharge into streams.

4. Install sediment and erosion control at downstream end of active construction zone.

5. Stabilize new channel and bank slopes before releasing flow into the new channel, and justify stabilization method according to slope material.

6. Where feasible, release of the flow into the new channel should be a staged process. This can be accomplished by gradually removing the barrier between the old and the new channel, which allows more control of the stream flow.

7. If the abandoned channel will be backfilled, the process should proceed from upstream to downstream, and existing BMPs for seeding and mulching should be followed (Chapter Three). If the abandoned channel will not be backfilled, it must be stabilized.

8. Material excavated from the new channel should be placed in stockpile area(s) with appropriate sediment and erosion control, and utilized or disposed of in accordance with permittee's NPDES registration.

9. Disturbance to riparian vegetation adjacent to the new stream channel should be minimized when possible.

7.04 –TRANSPORTING MATERIALS ON THE STREAM BED

Introduction

Preserving riparian vegetation (including sod) is critical in minimizing site disturbance, upland sediment and turbidity inputs. Depending on local site conditions, constructing the access road along the riparian corridor may result in greater impacts than using sections of the stream bed to transport material. Examples of local site conditions where transporting material on the stream bed may be justified include but are not limited to infrastructure or other physical constraints that restrict transportation activities beyond the stream channel, critical and/or fragile riparian environments, and impact-resistant stream beds composed of bedrock or cobble. Any use of the stream bed as a route to transport materials must be clearly justified and explained in the NPDES permit application. If transporting materials on the stream bed would create considerable turbidity issues, the use of multiple stream access points may be a suitable alternative (see appropriate BMPs in Chapter Three).

Conditions Where Practice Applies

The use of the stream bed as a route for transportation of materials is limited to stream beds composed of bedrock, cobble, or large gravel, and where a transportation route on the stream bed will cause less impact than a transportation route in adjacent uplands.

Construction Specifications

When using the stream bed as a route to transport materials:

1. Use equipment of the appropriate type and size to transport material efficiently and effectively. Equipment must be no wider than the bottom width of the channel.

2. Equipment with low ground pressure is recommended to minimize stream impacts.

3. Inspect equipment daily. Low toxicity oil and coolant is recommended.

4. Limit transportation to low-flow periods (considering both daily and seasonal conditions).

5. Keep equipment out of the water where possible.

6. Limit transportation activities to one route in any single stream reach.

7. Minimize the number of turns and trips in the channel.

8. Minimize transportation activities in the rain.

9. Limit the number of stream access points and crossings to the fewest possible.

10. Locate, design and construct stream access points to minimize erosion and sedimentation into the stream. Provide adequate sediment and erosion control at stream access points.

11. Plan material storage areas and transportation routes to allow work to be done in an efficient and effective manner.

12. Stabilize all stream access and turn-around points immediately following the completion of the in-stream work.

CHAPTER 8

STEEP SLOPE CONSTRUCTION GUIDELINES IN AREAS OF HIGH SLIP POTENTIAL SOILS

Chapter 8 – Steep Slope Construction Guidelines in areas of High Slip Potential Soils

Introduction

Landslide issues at many construction sites in West Virginia illustrate the importance making some changes to the storm water permitting process in order to identify potential problems and incorporate additional requirements to reduce the number of future slips.

Conditions Where Practice Applies

High slip potential soils are a key factor with the majority of slips at construction projects in West Virginia (see **Appendix D** for table showing West Virginia High Slip Potential Soils by County).

Planning Considerations

Dewatering a critical slope is usually simple, cost efficient and will potentially provide an effective means to stabilize a slope and prevent slips.

The following provides a description of BMP's employed to protect slopes in high slip potential areas at or greater than 3:1 and to minimize soil erosion and/or slips due to seeps, springs and surface runoff that can percolate into soil strata during and after earth disturbance and trenching excavation. This moisture infiltration has the potential to cause slips by saturating the soils resulting in lower resistance to movement while decreasing the angle of repose. The methods proposed for water management is to direct flows away from potentially unstable areas by installing horizontal drains to passively drain water from the slope area and prevent saturation of slope materials. The following construction criteria is technical guidance on the design of bleeder drains however on a case by case basis, other techniques may be satisfactory.

Construction Criteria

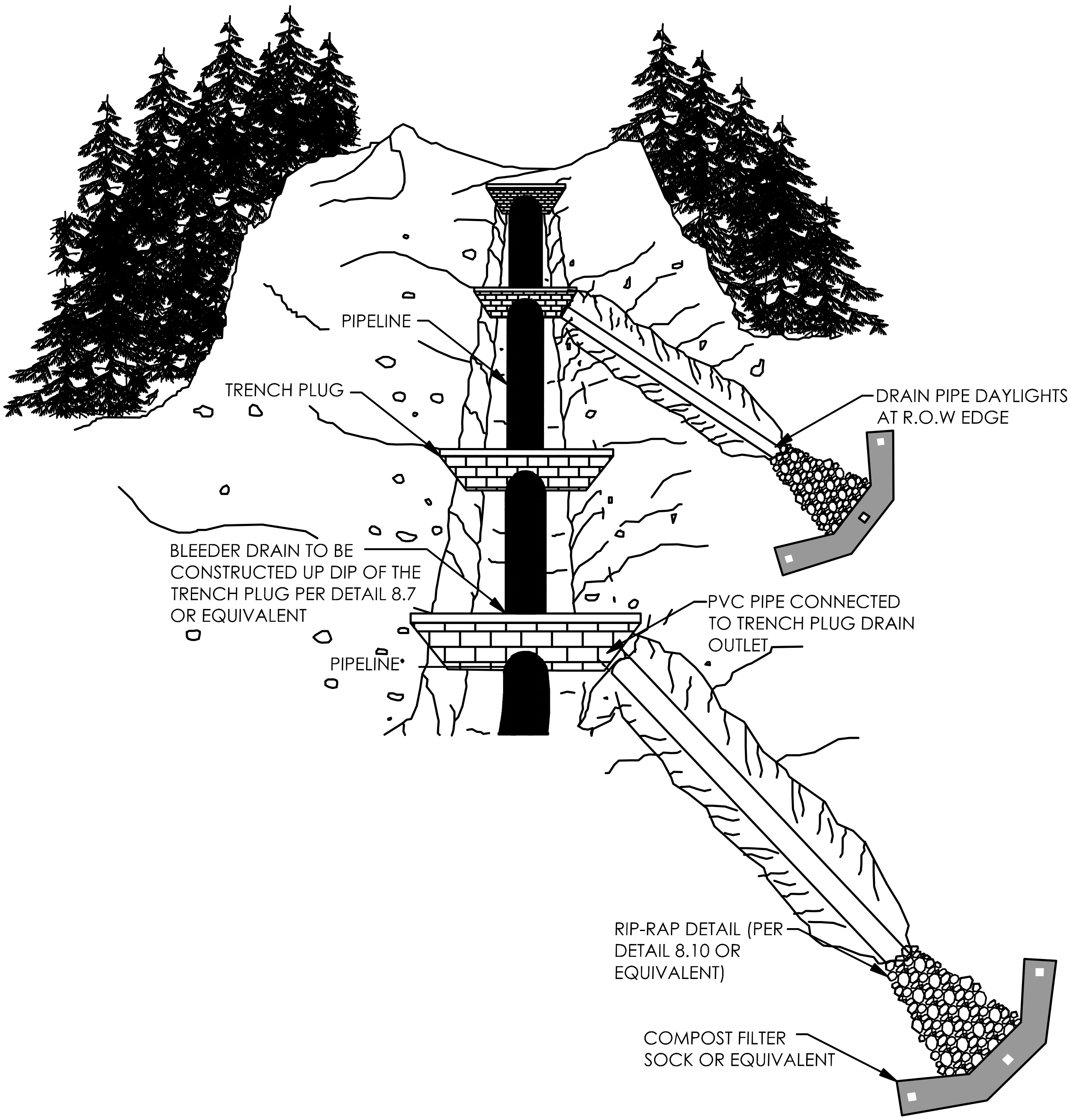
There are three (3) areas where these drains will be required:

1. In order to avoid the consequences of a “dam” behind trench plugs caused by ground water or surface water infiltrating the backfilled trench, water management is required to prevent soil saturation of the trench area by installing passive bleeder drains. (See Exhibits 8.4 thru 8.7 for bleeder drain illustrations).

2. A drain shall be installed at low topographical areas where the existing ground slopes perpendicular to the ROW are greater than 3:1 and with significant contributing drainage area Two (2) acres or more. (See Exhibits 8.8 and 8.9).

3. A drain shall be installed at seepage areas encountered during construction and positioned upslope from backfilled trench to intercept water before it seeps into the backfilled trench. (See Exhibits 8.11 and 8.12).

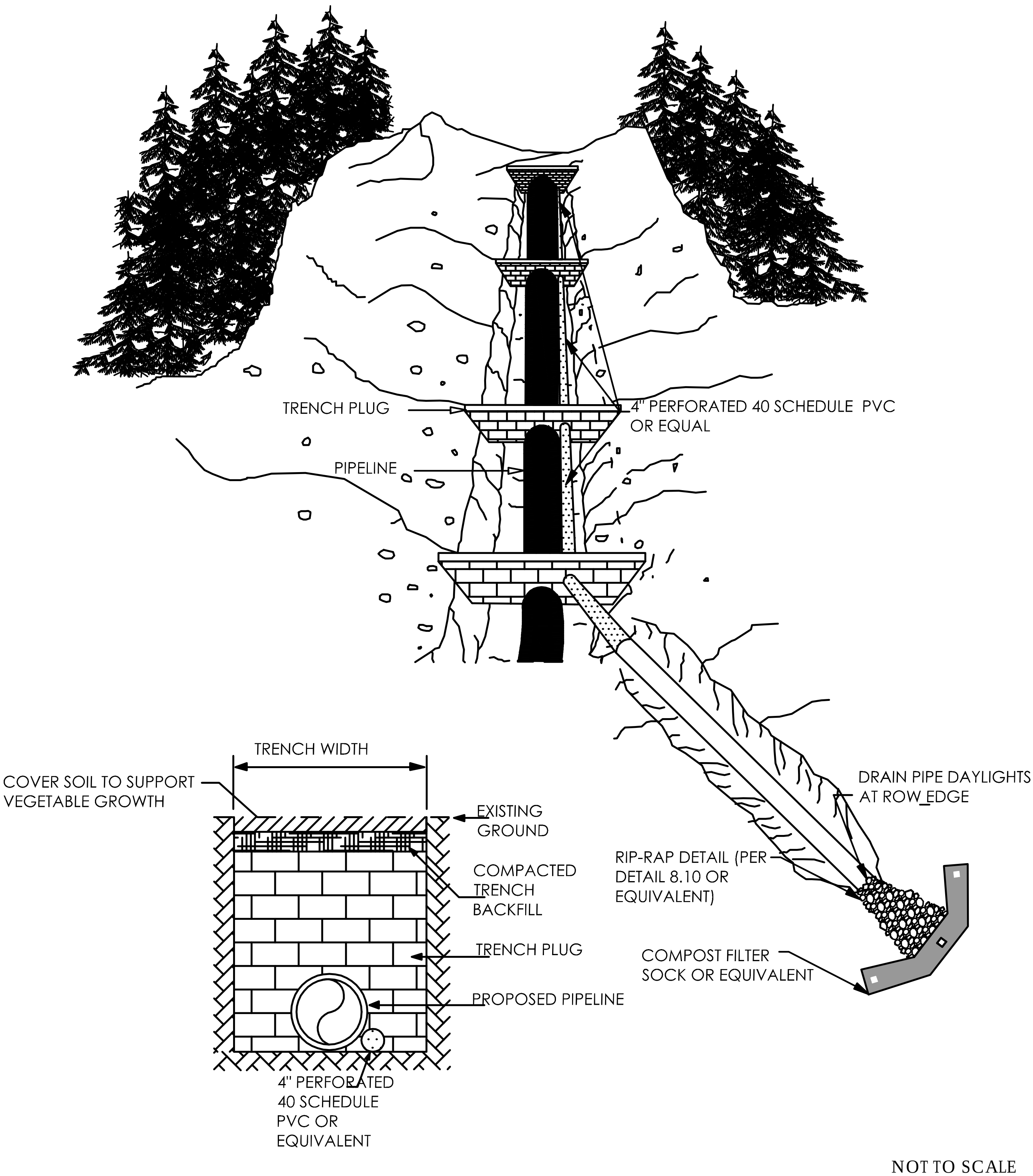
Where trenching activities are proposed in high slip potential soils and in areas where existing ground slopes are greater than 3:1, bleeder drains shall be installed to passively drain water from the trench area. The following illustration shows a drain placed at every second trench plug.



NOT TO SCALE

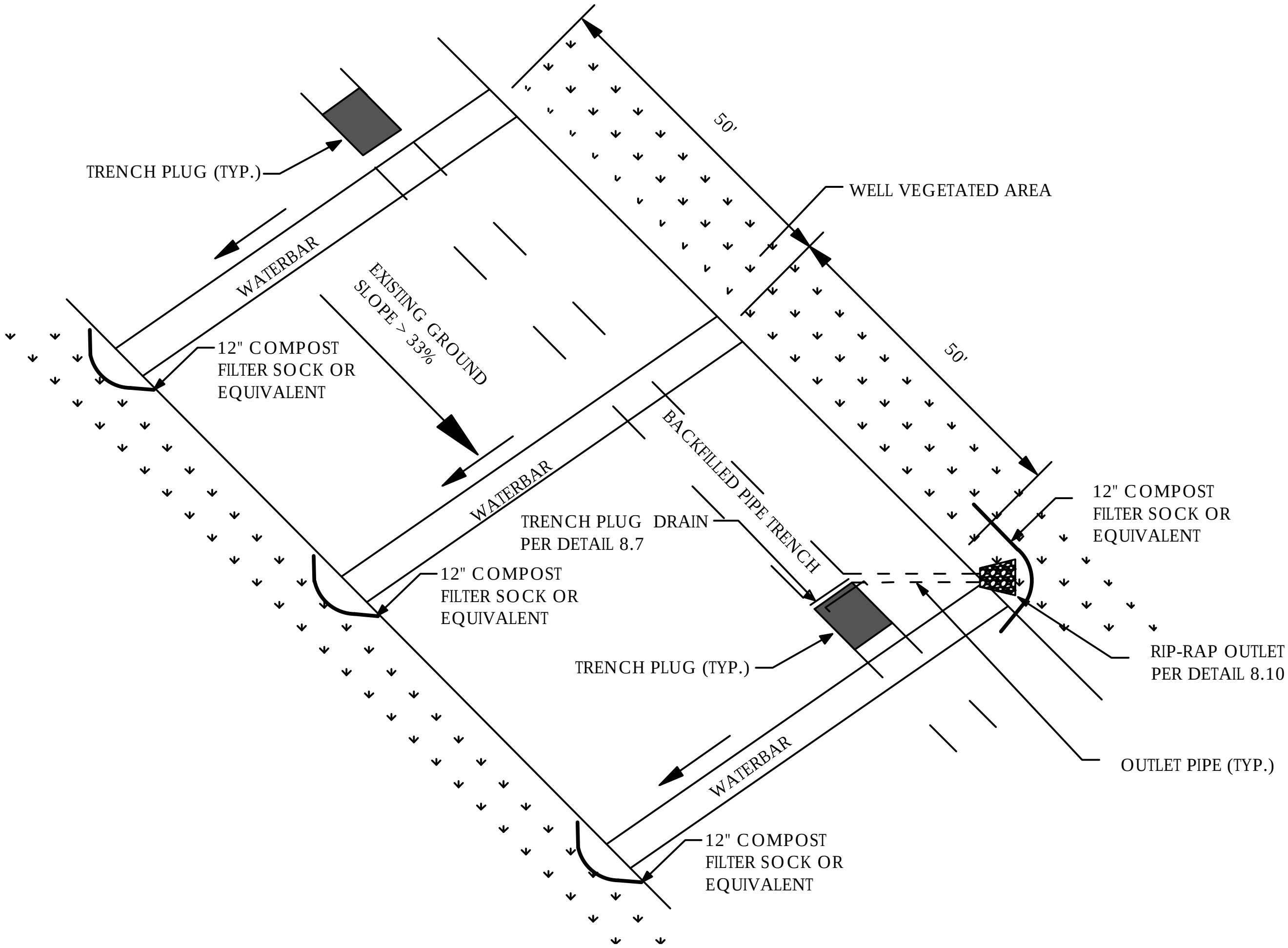
SLIP PREVENTION: BLEEDER DRAIN AND OUTLET DETAIL

A bleeder drain placed parallel along the pipeline is an effective way to passively drain water from the backfilled trench area. This technique will reduce the number of outlets and control the placement of outlets. The following illustration shows this method.



SLIP PREVENTION: BLEEDER DRAIN PARALLEL TO PIPELINE

The outlets associated with pipeline trench drains are typically used in conjunction with right-of-way diversions. Used in this manner, additional outlets and sediment filter controls will not be needed. Spacing for trench plugs in high slip potential soils is related to the severity of the ROW slopes. Trench plug drains shall be installed at every other trench plug on slopes that are 30% or greater.



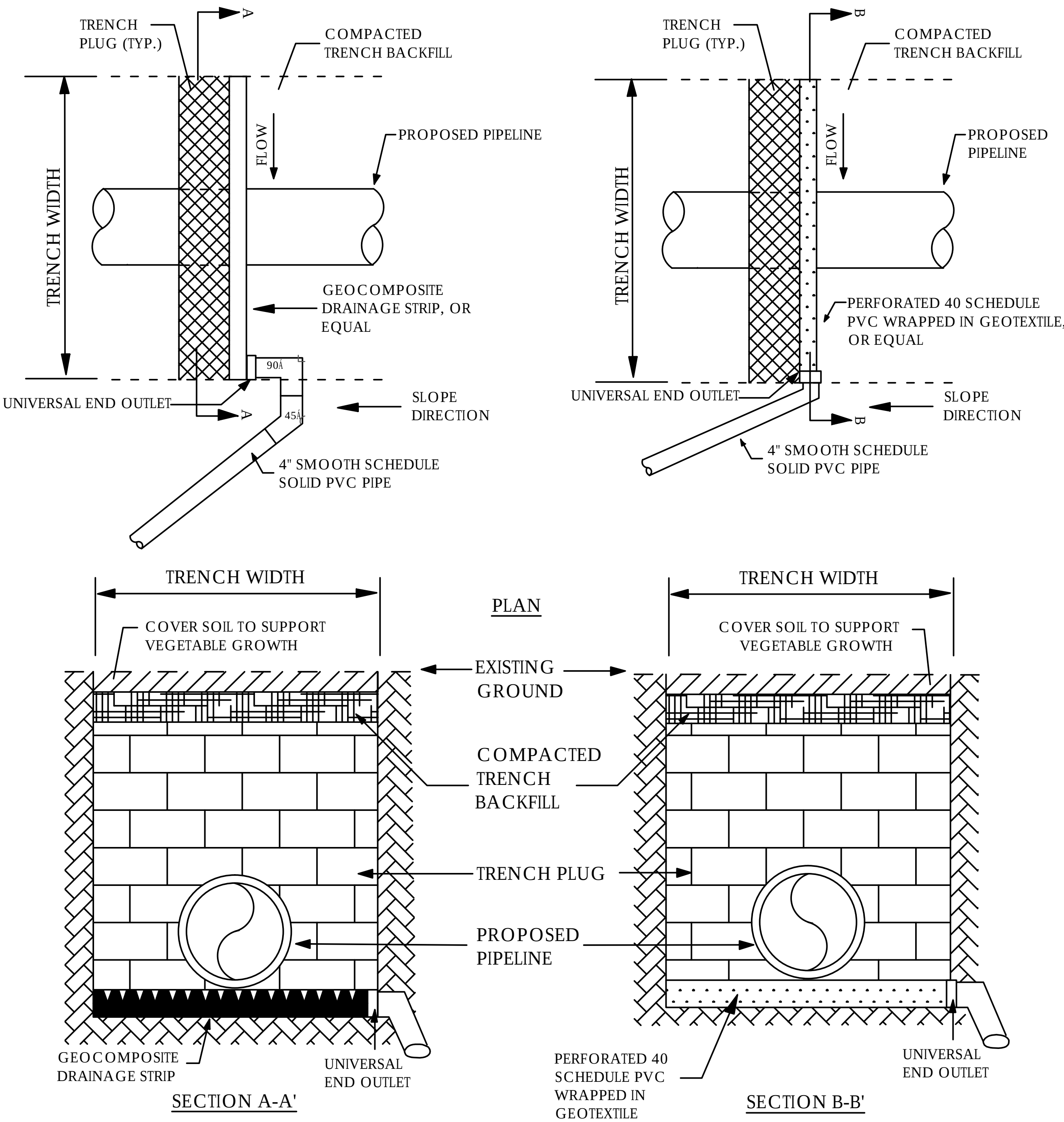
<u>Spacing of Trench Plugs (Drains to be installed at every other Plug)</u>

Percent Slope	Spacing in Feet
<5	*
5 - 15	500
15 - 25	300
25 - 35	200
➢ 35	100

NOT TO SCALE

SLIP PREVENTION: TRENCH PLUG DRAIN OVERVIEW

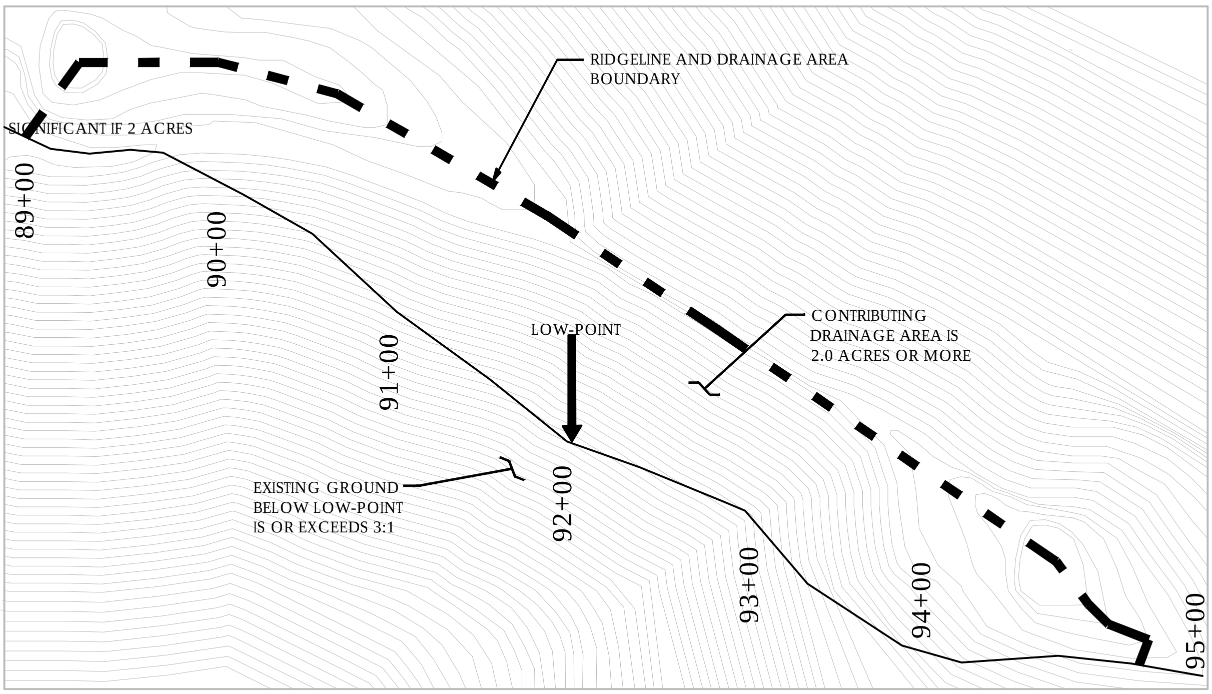
Two (2) types of trench plug drains are illustrated below. Geocomposite Drainage Strips or Perforated Schedule 40 PVC placed behind the trench plug and below the pipeline are effective ways to passively drain water. Both methods show Schedule 40 PVC discharge pipe at a minimum of a 2% grade.



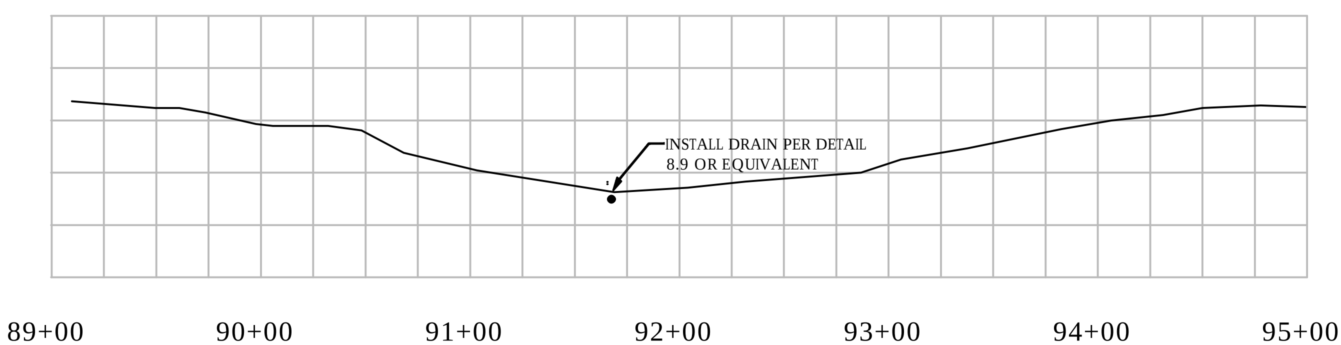
NOT TO SCALE

SLIP PREVENTION: TRENCH PLUG DRAIN DETAILS

Bleeder drains will sometimes be required at low points associated with side hill construction activities in high slip potential soils. Drainage from the undisturbed profile can infiltrate the backfilled soil within the trench and drain to a low point with the potential of saturating the soil. A drain shall be installed at low topographical areas where the existing ground slopes perpendicular to the ROW are greater than 3:1 and with significant contributing drainage area two (2) acres or more. Unusual conditions will be reviewed on a case by case basis.



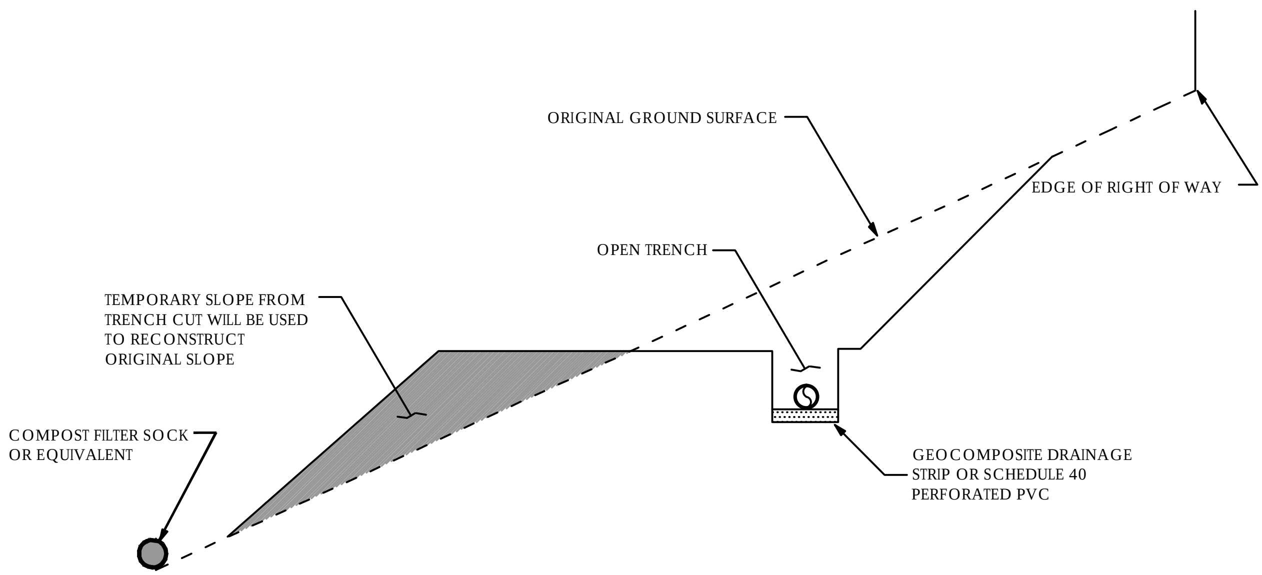
PROPOSED PIPELINE PLANVIEW

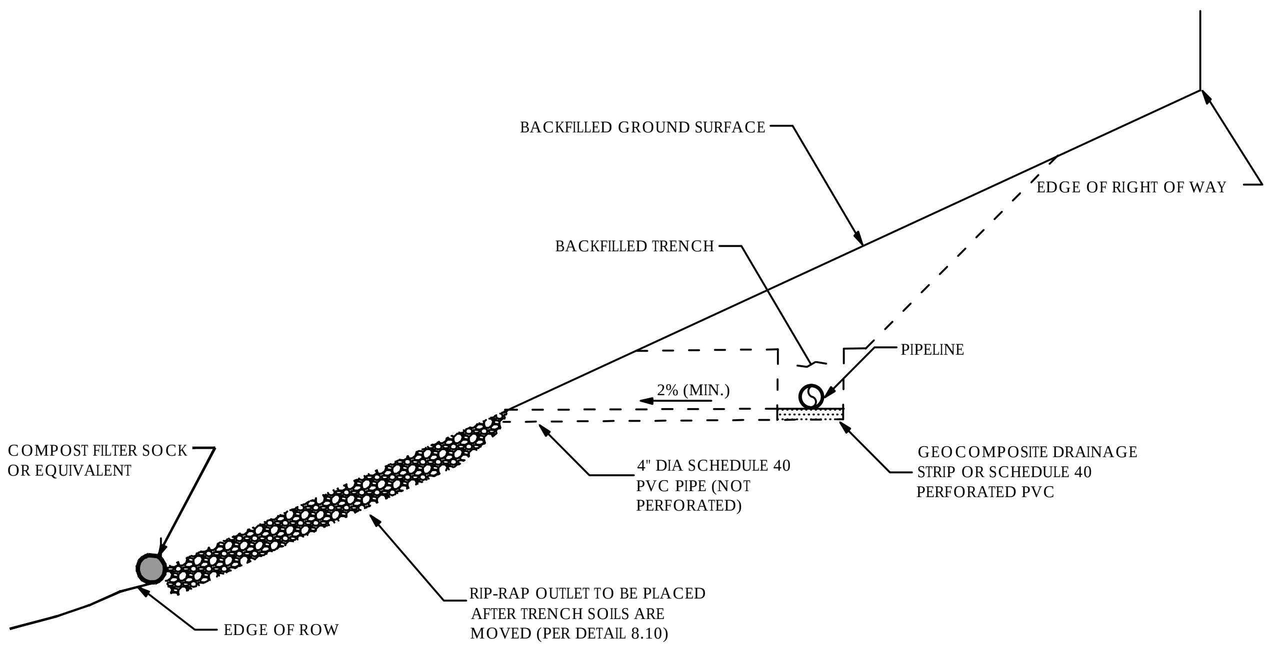


PROPOSED PIPELINE PROFILE

SLIP PREVENTION: SIDE HILL CONSTRUCTION

Two (2) types of low point drains are illustrated below. Geocomposite Drainage Strips or Perforated Schedule 40 PVC placed below the pipeline are effective ways to passively drain water. Both methods show Schedule 40 PVC discharge pipe at a minimum of a 2% grade.

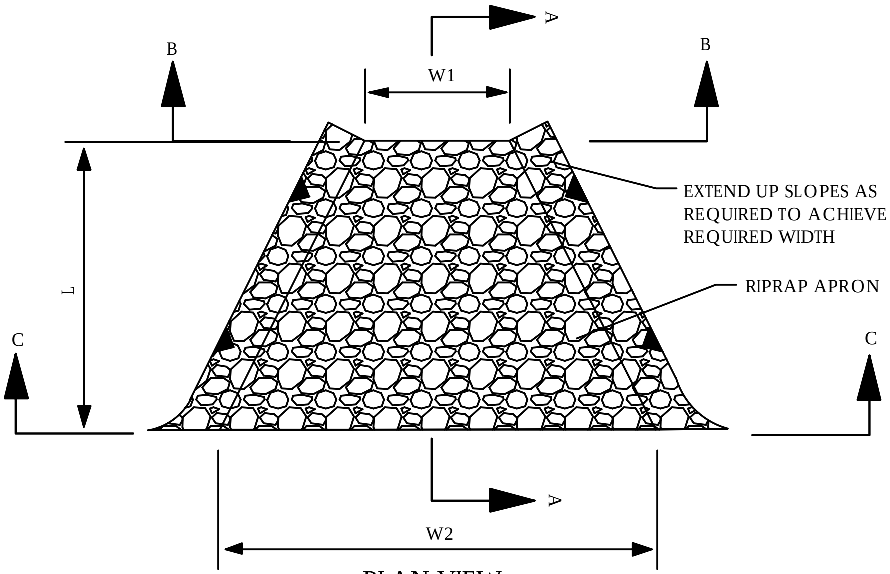




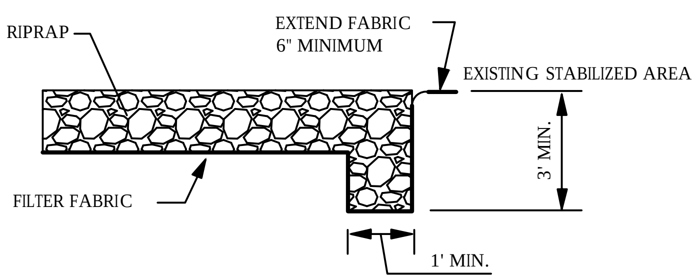
NOT TO SCALE

SLIP PREVENTION: SIDE HILL CONSTRUCTION DRAIN

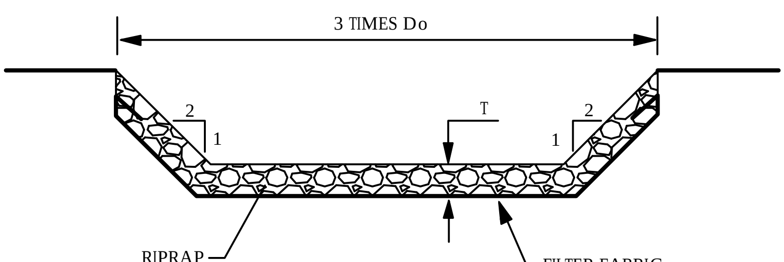
Outlet protection structures prevent scour and erosions at discharge outlets by dissipating the energy and reducing velocities. The illustration below show a typical application of an apron lined with rock riprap.



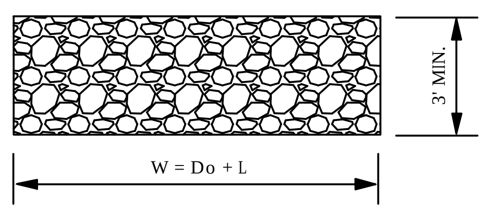
PLAN VIEW



SECTION A-A



SECTION B-B



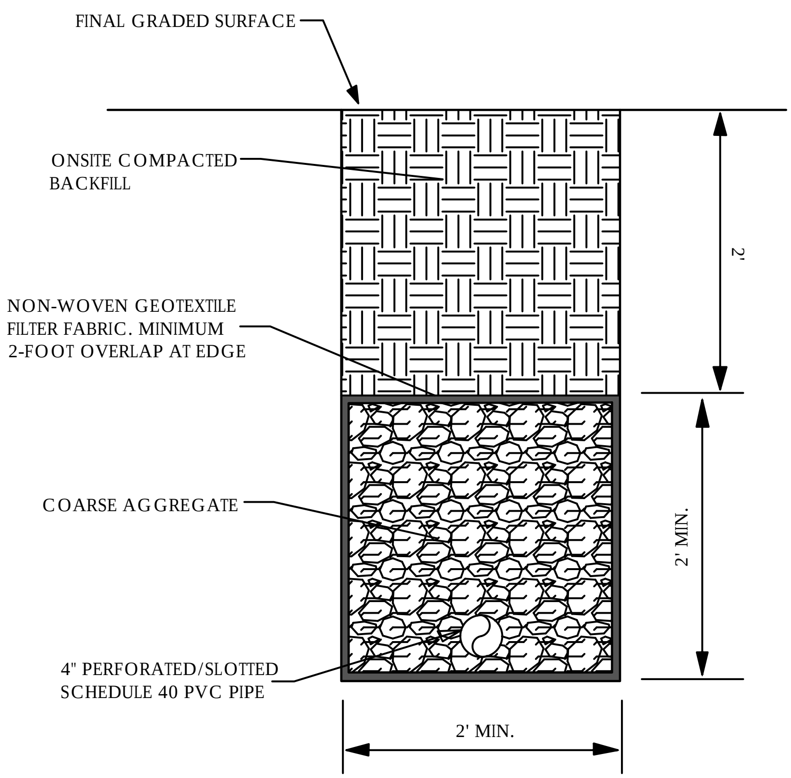
SECTION C-C

APRON ID	L* (FT)	W1 (FT)	W2 (FT)	D50 (IN)	T (FT)	RIPRAP	CY OF STONE
DRAIN OUTLET	4	2	6	3	1	R - 3	2.00

NOT TO SCALE

SLIP PREVENTION: DRAIN OUTLET RIP-RAP OUTLET

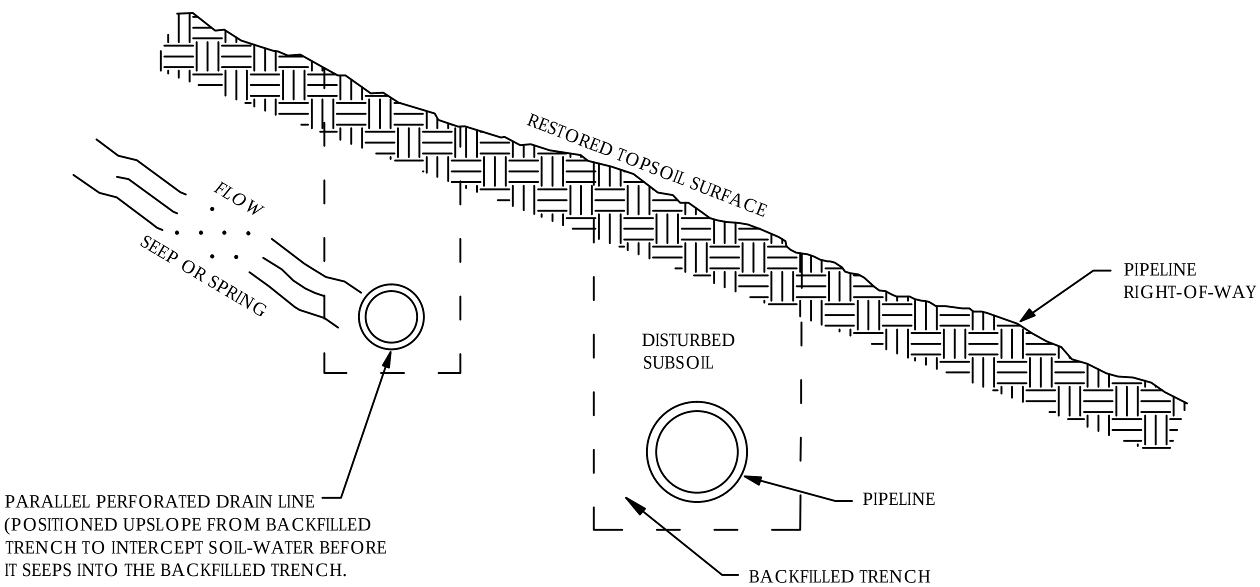
French drains can be constructed to passively drain water away from the trench area. These drains can be installed at seepage areas encountered during construction. These drains should be sloped at a minimum of 2% to the outlet locations



NOT TO SCALE

SLIP PREVENTION: SUBSURFACE DRAIN (FRENCH DRAIN)

Parallel drainage tiles can be installed at seepage areas encountered during construction. The drains may be perforated PVC or geocomposite drain strips placed between the seepage area and the pipeline to intercept soil-water before it seeps into the open or backfilled trenchline. These drains should be sloped at a minimum of 2% to the outlet locations.



NOT TO SCALE

SLIP PREVENTION: SEEP INTERCEPT DRAIN PARALLEL TO TRENCH

APPENDIX A
GLOSSARY

GLOSSARY

AASHTO - American Association of State Highway & Transportation Officials (Formerly AASHO.)

ACCEPTABLE OUTLET - That point where storm water runoff can be released into a watercourse or drainage way of adequate capacity without causing scour or erosion.

ACID SOIL - A soil giving an acid reaction throughout most or all of the portion occupied by roots. (Precisely, below a pH of 7.0; practically, below a pH of 6.6.)

ALLUVIAL FAN - A sloping, fan shaped mass of sediment deposited by a stream where it emerges from an upland onto a plain.

ALLUVIUM - A general term for all detrital material deposited or in transit by streams, including gravel, sand silt, clay and all variations and mixtures of these. Unless otherwise noted, alluvium is unconsolidated.

ANGLE OF REPOSE - The stable angle between the horizontal and the maximum slope that a soil assumes through natural processes that will not slough.

ANTI-SEEP COLLAR - An impermeable diaphragm usually of sheet metal or concrete constructed at intervals within the zone of saturation along the conduit of a principal spillway to increase the seepage length along the conduit and thereby prevent piping or seepage along the conduit.

ANTI-VORTEX DEVICE - A device, usually a vertical or horizontal plate, carefully designed and placed at the entrance of a pipe to prevent the formation of a vortex in the water at the pipe entrance.

APRON - A floor or lining to protect a surface from erosion, for example, the pavement below chutes, spillways, or at the toes of dams.

ASPECT - The direction a slope faces - a physiographic feature of steep slopes which influences plant growth and adaptation.

ATTERBERG LIMITS - Atterberg limits are soil properties measured for soil materials passing the No. 40 sieve.

Liquid Limits (LL) - the liquid limit is the water content corresponding to the arbitrary limit between the liquid & plastic states of consistency of a soil.

Plastic Limits (PL) - The plastic limit is the water content corresponding to an arbitrary limit between the plastic andsemisolid states of consistency of a soil.

Plasticity Index (PI) - The plasticity index is the numerical difference between the liquid limit and plastic limit.

BAFFLES - Vanes, guides, grids, grating or similar devices placed in a conduit to deflect or regulate flow and effect a more uniform distribution of velocities.

BARREL - The usually mild sloping closed conduit used to convey water under or through a dam; part of a principal spillway.

BASE FLOW - The stream discharge from ground water accretion.

BEDLOAD - The sediment that moves by sliding, rolling or bounding on or very near the streambed; sediment moved mainly by tractive or gravitational forces or both but at velocities less than the surrounding flow.

BERM - A shelf that breaks the continuity of a slope.

BIODEGRADABLE - Capable of being broken down (degraded) by common soil organisms.

BLIND DRAIN - A type of drain consisting of an excavated trench refilled with pervious material, such as coarse sand, gravel or crushed stone, through whose voids water percolates and flows to an outlet. Often referred to as a French drain because of its initial development and widespread use in France.

BRACKISH (WATER) - Slightly to moderately salty water.

BULKHEAD - A wall made from wood, steel, concrete, etc. for protection of shoreline from waves or currents.

CALCIUM SULFATE - Gypsum. A hydrated form used to treat high sodium soils. CaS04

CHANNEL - A natural stream that conveys water; a ditch or channel excavated for the flow of water.

CHANNEL IMPROVEMENT - The improvement of the flow characteristics of a channel by clear
ing, excavation, realignment, lining, or other means in order to increase its water carrying capacity.

CHANNEL STABILIZATION - Erosion prevention and stabilization of velocity distribution in a channel using jetties, drops, revetments, structural linings, vegetation and other measures.

CHANNEL STORAGE - Water temporarily stored in channels while en route to an outlet.

CHECK DAM - A small dam construction in a gully or other small watercourse to decrease the stream flow velocity (by reducing the channel gradient), minimize channel scour, and promote deposition of sediment.

CHUTE - A high velocity, open channel for conveying water to a lower level without erosion.

CLAY (SOILS) - 1. A mineral soil separate consisting of particles less than 0.002 millimeter in equivalent diameter. 2. A soil texture class. 3. (Engineering) A fine grained soil (more than 50 percent passing the No. 200 sieve) that has a high plasticity index in relation to the liquid limit. (Unified Soil Classification System)

COMPACTION - To unite firmly. With respect to construction work with soils, engineering com tion is any process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the weight of solid material per unit of volume, increasing the shear and bearing strength and reducing permeability.

CONDUIT - Any channel intended for the conveyance of water, whether open or closed.

CONTOUR - 1. An imaginary line on the surface of the earth connecting points of the same el tion. 2. A line drawn on a map connecting points of the same elevation.

COOL (SLOPE EXPOSURE) - A slope facing north or east, or a slope shaded during the hot part of the day.

CORE TRENCH - A trench, filled with relatively impervious material intended to reduce seepage of water through porous strata.

CRADLE (ENGINEERING - A structure usually of concrete shaped to fit around the bottom and sides of a conduit to support the conduit, increase its strength and in dams, to fill all voids between the underside of the conduit and the soil.

CREST - 1. the top of a dam, dike, spillway or weir, frequently restricted to the overflow portion. 2. The summit of a wave or peak of a flood.

CRITICAL AREA OR SITE - Sediment producing, highly erodible or severely eroded areas.

CRITICAL DEPTH (HYDRAULICS) - Depth of flow in a channel of specified dimensions at which specific energy is a minimum for a given discharge.

CROWN (OF SLOPE) - Top of slope; apex.

CRUSHED STONE - Aggregate consisting of angular particles produced by mechanically crushing rock.

CULM - The stem of grasses, sedges and rushes which is jointed and usually hollow in grasses and usually solid in sedges and rushes.

CULTIPACKER SEEDER - A farm tool equipped with a seed box which drops the seed between cultipacker rollers to place the seed to firm soil where they will be pressed into soil by the second corrugated roller.

CUT - Portion of land surface or area from which earth has been removed or will be removed by excavation; the depth below original ground surface to excavated surface.

CUT-AND-FILL - Process of earth moving by excavating part of an area and using the excavated material for adjacent embankments or fill areas.

CUTOFF - A wall or other structure, such as a trench, filled with relatively impervious material intended to reduce seepage of water through porous strata.

CUTTINGS - A small shoot cut from a plant to start a new plant.

CYCLONE (SEEDER) - A hand turned or tractor drawn seeder that broadcasts seed onto the seed bed by a rotary motion that slings the seed outward from the seeder.

DAM - A barrier to confine or raise water for storage or diversion, to create a hydraulic head, to prevent gully erosion, or for retention of soil, sediment or other debris.

DEBRIS - Broken remains of plants, objects and rocks that form trash or remains.

DECIDUOUS - Plants that shed their leaves annually as opposed to evergreen.

DEPOSITION - The accumulation of material dropped because of a slackening movement of the transporting agent, water or wind.

DESICCATION - Drying out as of root systems of plants before they are planted.

DESILTING AREA - An area of grass, shrubs or other vegetation used for inducing deposition of silt and other debris from slowing water, located above a pond, field or other area needing protection from sediment accumulation. (See filter strip.)

DETENTION DAM - A dam constructed for the purpose of temporary storage of stream flow or surface runoff which releases the stored water at controlled rates.

DIKE (ENGINEERING) - An embankment to confine or control water, for example, one built along the banks of a river to prevent overflow or lowlands; a levee.

DISTURBED AREA - An area in which the natural vegetative soil cover has been removed or altered and, therefore, is susceptible to erosion.

DIVERSION - A channel with a supporting ridge on the lower side constructed across the slope to divert water from areas where it is in excess to sites where it can be used or disposed of safely. Diversions differ from terraces in that they are individually designed.

DOLOMITIC (LIMESTONE) - Liming materials that contain more than 6 percent magnesium (mg); high magnesium lime.

DRAIN (NOUN) - 1. A buried pipe or other conduit (subsurface drain). 2. A ditch or channel (open drain) for carrying off surplus surface water or groundwater.

DRAIN (VERB) - 1. To provide channels, such as open ditches or closed drains, so that excess water can be removed by surface flow or internal flow. 2. To lose water (from the soil) by pertion.

DRAINAGE - 1. The removal of excess surface water or ground water from land by means of surface or subsurface drains. 2. Soils characteristics that affect natural drainage.

DRAINAGE AREA (WATERSHED) - All land and water area from which runoff may run to a common (design) point.

DRAUGHTY (SOIL OR SLOPE) - Lacking moisture during part of the growing season during a typical year.

DROP INLET SPILLWAY - An out fall structure in which the water drops through a vertical riser connected to a discharge conduit.

DROP SPILLWAY - An out fall structure in which the water drops over a vertical wall onto an apron at a lower elevation.

DROP STRUCTURE - A structure for dropping water to a lower level and dissipating surplus energy; a fall. The drop may be vertical or inclined.

DRY STORAGE - The 1800 cubic feet of storage in a trap or basin that is dewatered after rain events.

EMERGENCY SPILLWAY - A dam spillway designed and constructed to discharge flow in excess of the principal spillway design discharge.

ENERGY DISSIPATOR - A designed device such as an apron of rip rap or a concrete structure placed at the end of a water transmitting apparatus such as pipe, paved ditch or paved chute for the purpose of reducing the velocity, energy and turbulence of the discharged water.

ENTRANCE HEAD - The head required to cause flow into a conduit or other structure, including both entrance loss and velocity head.

EROSION - 1. The wearing away of the land surface by running water, wind, ice, or other geo cal agents, including such processes as gravitational creep. 2. Detachment and movement of soil or rock fragments by water, wind, ice or gravity. The following terms are used to describe different types of water erosion:

Accelerated erosion - Erosion much more rapid than normal, natural or geological erosion, primarily as a result of the influence of the activities of man or, in some cases, of other animals or natural catastrophes that expose base surfaces, for example, fires.

Gully erosion - The erosion process whereby water accumulates in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths, ranging from 1 or 2 feet to as much as 75 to 100 feet.

Rill erosion - An erosion process in which numerous small channels only several inches deep are formed. See rill.

Sheet erosion - The spattering of small soil particles caused by the impact of raindrops on wet soils. The loosened and spattered particles may or may not subsequently removed by surface runoff.

EROSIVE VELOCITIES - Velocities of water that are high enough to wear away the land surface. Exposed soil will generally erode faster than stabilized soils. Erosive velocities will vary according to the soil type, slope, structural or vegetative stabilization used to protect the soil.

ESTHETIC (AESTHETIC) - Pleasing in appearance; showing good taste.

EVERGREEN - Plants that have leaves or needles yearlong as opposed to those that lose their leaves during part of the year.

EXCELSIOR BLANKET - An erosion retardant material made from excelsior strands held together with net
like stands of plastic or other material.

EXPOSURE (SLOPE) -

North - Slopes facing in any compass direction clockwise between N45W and S45E.

South - Those slopes that face in any compass direction clockwise between S45E and N45W.

FILTER STRIP - A strip of permanent vegetation above ponds, diversions and other structures to retard flow of runoff water, causing deposition of transported material, thereby reducing sediment flow.

FINES (SOIL) - Generally refers to the silt and clay size particles in soil.

FREEBOARD (HYDRAULICS) - The distance between the maximum water surface elevation anticipated in design and the top of retaining banks or structures. Freeboard is provided to prevent overtopping due to unforeseen conditions.

GABION - A flexible woven-wire basket composed of two to six rectangular cells filled with small stones. Gabions may be assembled into many types of structures such as revetments, retaining walls, channel liners, drop structures and groins.

GABION MATTRESS - A thin gabion, usually six or nine inches thick, used to line channels for erosion control .

GRADE - 1. The slope of a road, channel or natural ground. 2. The finished surface of a canal bed, roadbed, top of embankment, or bottom of excavation; any surface prepared for the support of construction, like paving or laying a conduit. 3. To finish the surface of a canal bed, roadbed, top of embankment or bottom of excavation.

GRAFTING - A method of propagating plants by joining wood from one plant to another plant to get more desirable growth on the second plant.

GRASSED WATERWAY - A natural or constructed waterway, usually broad and shallow covered with erosion resistant grasses, to convey surface water down the slope.

GRAVEL - 1. Aggregate consisting of mixed sizes of 1/4 inch to 3 inch particles which normally occur in or near old streambeds and have been worn smooth by the action of water. 2. A soil having particle sizes, according to the Unified Soil Classification System, ranging from the No. 4 sieve size angular in shape as produced by mechanical crushing.

GRAVEL FILTER - Washed and graded sand and gravel aggregate placed around a drain or well screen to prevent the movement of fine materials from the aquifer into the drain or well.

GROIN - A shore protection structure built (usually perpendicular to the shoreline) to trap littoral drift or retard erosion of the shoreline.

GROUND COVER - Plants which are low-growing and provide a thick growth which protects the soil as well as providing some beautification of the area occupied.

GULLY - A channel or miniature valley cut by concentrated runoff through which water commonly flows only during and immediately after heavy rains or during the melting of snow. The distinction between gully and rill is one of depth. A gully is sufficiently deep that it would not be obliterated by normal tillage operations, whereas a rill is of lessor depth and would be smoothed by ordinary farm tillage.

HEAD (HYDRAULICS) - 1. The height of water above any plane of reference. 2. The energy, either kinetic or potential, possessed by each unit weight of a liquid expressed as the vertical height through which a unit weight would have to fall to release the average energy possessed. Used in various terms such as pressure head, velocity head, and head loss.

HERBACEOUS PERENNIAL (PLANTS) - A plant whose stems die back to the ground each year.

HERBICIDE - Chemical formulation used to control weeds or brush.

HULLED (SEED) - Hullless seed, such as sericea lespedeza. Seed are usually processed after threshing to take off outer hull to facilitate scarification and quicken germination.

HYDRAULIC GRADE LINE - In a closed conduit a line joining the elevations to which water could stand in risers or vertical pipes connected to the conduit at their lower end and open at their upper end. In open channel flow, the hydraulic grade line is the free water surface.

HYDRAULIC GRADIENT - The slope of the hydraulic grade line. The slope of the free surface of water flowing in an open channel.

HYDRAULIC JUMP - The sudden turbulent rise in water level from a flow stage below critical depth to flow stage above critical depth, during which the velocity passes from super critical to sub-critical.

HYDROGRAPH - A graph showing variation in stage (depth) or discharge of a stream of water over a period of time.

H-3 l -6

HYDROSEEDER - A machine designed to apply seed, fertilizer, lime and short fiber wood or paper mulch to the soil surface.

HYDRO-SEEDING - Seeding with a hydroseeder.

INFLOW PROTECTION - A water handling device used to protect the transition area between any water conveyance (dike, swale, or swale dike) and a sediment trapping device.

INTERCEPTOR DRAIN - A surface or subsurface drain, or a combination of both, designed and installed to intercept flowing water.

LIME - Basic calcareous materials used to raise pH of acid soils for benefit of plants being grown. May be either ground limestone or hydrated lime.

LITTORAL DRIFT - The sedimentary material moved in the littoral zone under the influence of waves and currents.

MANNING'S FORMULA (HYDRAULICS) - A formula used to predict the velocity of water flow in an open channel or pipeline:

MULCH - Covering on surface of soil to protect and enhance certain characteristics, such as water retention qualities.

MULCH ANCHORING TOOL - A tool that looks like a dull disk designed to press straw and similar mulches into the soil to prevent loss due to wind, water or gravity.

NETTING (MULCH) - Paper or cotton material used to hold mulch material on the soil surface.

NITROGEN - FIXING (BACTERIA) - Bacteria having the ability to fix atmospheric nitrogen, making it available for use by plants. Inoculation of legume seeds is one way to insure a source of these bacteria for specified legumes.

NON-EROSIVE VELOCITY - Controlling the velocity of water to prevent detachment and movement of soil or rock. Erosive velocity will vary according to the soil type, slope, structural or vegtive stabilization used to protect the soil.

NORMAL DEPTH - Depth of flow in an open conduit during uniform flow for the given con tions. (See uniform flow.)

NOXIOUS WEEDS - Harmful; undesirable; hard to control.

a. Restricted - May be sold in the trade but are limited to very small amounts as undesirable connates.

b. Prohibited - Prohibited from sale.

OUTFALL - The point where water flows from a conduit, stream or drain.

OUTLET - The point at which water discharges from such things as a stream, river, lake, tidal basin, pipe, channel or drainage area.

OUTLET CHANNEL - A waterway constructed or altered primarily to carry water form man-made structures such as terraces, subsurface drains, diversions and impoundments.

OVERFALL - Abrupt change in stream channel elevation; the part of a dam or weir notch over which the weir notch over which the water flows.

PAPER FIBER - A short fiber mulch material usually applied by hydroseeder along with fertilizer and seed.

PARENT MATERIAL - The unconsolidated rock material from which the soil profile develops.

PENDULOUS - More or less hanging or inclined downward.

PERMANENT SEEDING - Results in establishing perennial vegetation which may remain on the area for many years.

PERMISSIBLE VELOCITY (HYDRAULICS) - The highest average velocity at which water may be carried safely in a channel or other conduit. The highest velocity that can exist through a subtial length of a conduit and not cause scour of the channel. A safe, non-eroding or allowable vety.

pH - A number denoting the common logarithm of the reciprocal of the hydrogen ion concentration. A pH of 7.0 denotes neutrality, higher values indicate alkalinity, and lower values indicate acidity.

PHREATIC LINE - The upper surface of the zone of saturation in an embankment is the phreatic (zero pressure) surface; in cross-section, this is called the phreatic line.

PIPING - Removal of soil material through subsurface flow channels or pipes developed by seepage water.

PLUGS - Pieces of turf or sod, usually cut with a round tube, which can be used to propagate the turf or sod by vegetative means.

PROJECTION - In sediment basins or other dams the perpendicular distance that the anti-seep collar extends from the outside surface of the pipe or pipe cradle.

RECP – See Rolled Erosion Control Products

RETENTION - The amount of precipitation on a drainage area that does not escape as runoff. It is the difference between total precipitation and total runoff.

REVETMENT - Facing of stone or other material, either permanentor temporary, placed along the edge of a stream or shoreline to stabilize the bank and to protect it from the erosion action of water.

RHIZOME - Any prostrate, more or less elongated stem growing partly or completely beneath the surface of the ground; usually rooting at the nodes and becoming upcurved at the apex.

RIGHT-OF-WAY - Right of passage, as over another's property. A route that is lawful to use. A strip of land acquired for transport or utility construction.

RILL - A small channel cut by concentrated runoff but through which water commonly flows only during and immediately after rains or during the melting of snow. A rill is usually only a few inches deep (but no more than a foot) and, hence, no obstacle to tillage operations.

RIP RAP - Broken rock, cobbles, or boulders placed on earth surfaces, such as the face of a dam or the bank of a stream, for protection against the action of water (waves); also applies to brush or pole mattresses, or brush and stone, or similar materials used for soil erosion control.

ROLLED EROSION CONTROL PRODUCTS - Rolled Erosion Control Products (RECPs) are temporary or permanent erosion control nets, blankets and three-dimensional matrixes made from a wide variety of natural (such as jute, coir and straw) and manmade materials alone or in combination.

ROUGHNESS COEFFICIENT (HYDRAULICS) - A factor in velocity and discharge formulas representing the effect of channel roughness on energy losses in flowing water. Manning's is a commonly used roughness coefficient.

RUNOFF (HYDRAULICS) - That portion of the precipitation on a drainage area that is discharged from the area in the stream channels. Types include surface runoff, ground water runoff or seepage.

SALINE SOIL - A non-alkali soil containing sufficient soluble salts to impair plant growth.

SAND - 1. (Agronomy) A soil particle between 0.05 and 2.0 millimeters in diameter. 2. A soil textural class. 3. (Engineering) According to the Unified Soil Classification System, a soil particle larger than the No. 200 sieve (0.074mm) and passing the No. 4 sieve (approximately 1/4 inch).

SCD - Soil Conservation District.

SEDIMENT - Solid material, both mineral and organic, that is in suspension, is being transported, or has been moved from its site of origin by air, water, gravity, or ice and has come to rest on the earth's surface either above or below sea level.

SEDIMENTATION - Deposition of detached soil particles.

SEDIMENT DISCHARGE (SEDIMENT LOAD) - The quantity of sediment, measured in dry weight or by volume, transported through a streamcross-section in a given time. Sediment discharge consists of both suspended load and bedload.

SEEPAGE - 1. Water escaping through or emerging from the ground. 2. The process by which water percolates through the soil.

SEEPAGE LENGTH - In sediment basins or ponds, the length along the pipe and around the anti-seep collars that is within the seepage zone through an embankment. (See phreatic line.)

SHA - Maryland State Highway Administration.

SHEET FLOW - Water, usually storm runoff, flowing in a thin layer over the ground surface.

SIDE SLOPES (ENGINEERING) - The slope of the sides of a canal, dam or embankment. It is customary to name the horizontal distance first, as 1.5 to 1, or frequently, 1 1/2: 1, meaning a hortal distance of 1.5 feet to 1 foot vertical.

SILT - 1. (Agronomy) A soil separate consisting of particles between 0.05 and 0.002 millimeter in equivalent diameter. 2. A soil textural class. 3. (Engineering) According to the Unified Soil Clas
tion System a fine grained soil (more than 50 percent passing the No. 200 sieve) that has a low plasticity index in relation to the liquid limit.

SLURRY - A thickened, aqueous mixture of such things as seed, fertilizer, short fiber mulch or soil.

SMALL GRAIN MULCH MATERIAL - Straw material from oats, barley, wheat, or rye.

SOD - A piece of earth containing grass plants with their matted roots. Turf.

SOIL - 1. (Agronomy) the unconsolidated mineral and organic material on the immediate surface of the earth that serves as a natural medium for the growth of land plants. 2. (Engineering) Earth and rock particles resulting from the physical and chemical disintegration of rocks, which may or may not contain organic matter. It includes fine material (silts and clays), sand and gravel.

SOIL TEST - Chemical analysis of soil to determine needs for fertilizers or amendments for species of plant being grown.

SPECIFIC ENERGY - The average energy per unit weight of water at a channel section as ex pressed with respect to the channel bottom.

SPILLWAY - An open or closed channel, or both, used to convey excess water from a reservoir. It may contain gates, either manually or automatically controlled to regulate the discharge ofexcess water.

SPREADER (HYDRAULICS) - A device for distributing water uniformly in or from a channel.

STABILIZATION - Providing adequate measures, vegetative and/or structural that will prevent erosion from occurring.

STABILIZED AREA - An area sufficiently covered by erosion resistant material such as a good cover of grass, or paving by asphalt, concrete, or stone, in order that erosion of the underlying soil does not occur.

STABILIZED GRADE - The slope of a channel at which neither erosion nor deposition occurs.

STABLE (STREAM OR CHANNEL) - The condition of a stream, channel or other water course in which no erosion or deposition occurs; adequately protected from erosion.

STAGE (HYDRAULICS) - The variable water surface or the water surface elevation above any chosen datum.

STATIC HEAD - Head resulting from elevation differences, for example, the difference in elevation in headwater and tailwater in a hydroelectric plant.

STILLING BASIN - An open structure or excavation at the foot of an outfall, conduit, chute, drop, or spillway to reduce the energy of the descending stream of water.

STOLON - A trailing or reclining above ground stem capable of rooting and/or sending up new shoots from the nodes.

STRUCTURAL - Relating to something constructed or built by man.

STRUCTURAL (SOIL) - The combination or arrangement of primary soil particles into secondary particles, units or peds. (Dune sand is structureless)

SUBCRITICAL FLOW - Flow at velocities less than critical velocity.

SUBGRADE - The soil prepared and compacted to support a structure or a pavement system.

TAILWATER (HYDRAULICS) - Water, in a river or channel, immediately downstream from a structure.

TEMPORARY SEEDING - A seeding which is made to provide temporary cover for the soil while waiting for further construction or other activity to take place.

TERRACE - An embankment or combination of an embankment and channel constructed across a slope at a suitable spacing to control erosion by diverting or storing surface runoff instead of per ting it to flow uninterrupted down the slope. Normally used only on cropland.

TEXTURE (SOIL) - The relative proportions of various soil separates in a soil material.

THATCH - A tightly intermingled layer of living and dead stems, leaves and roots of grasses.

TIME OF CONCENTRATION - Time required for water to flow from the most remote point of a watershed, in a hydraulic sense, to the outlet.

TOE (OF SLOPE) - Where the slope stops or levels out. Bottom of the slope.

TOE WALL - Downstream wall of a structure, usually to prevent flowing water from eroding under the structure.

TOPSOIL - Fertile or desirable soil material used to top dress roadbanks, subsoils, parent material, etc.

TRAP EFFICIENCY - The capability of a reservoir to trap sediment. The ratio of sediment trapped to the sediment delivered, usually expressed in percent.

TRASH RACK - Grill, grate or other device at the intake of a channel, pipe, drain or spillway for the purpose of preventing oversize debris from entering the structure.

UNHULLED (SEED) - Seed still encased with a hull. Example: Sericea lespedeza before it is rendered hulless by mechanically removing the hull.

UNIFIED SOIL CLASSIFICATION SYSTEM (ENGINEERING) - A classification system based on the identification of soils according to their particle size, gradation, plasticity index and liquid limit.

UNIFORM FLOW - A state of steady flow when the mean velocity and cross-sectional area are equal at all sections of a reach.

UNIVERSAL SOIL LOSS EQUATION - An equation used for the design of water erosion control system: A=RKLSCP where A is average annual soil loss in tons per acre per year; R is rainfall factor; K is soil erodibility factor; L is length of slope; S is percent of slope; C is cropping and management factor; and P is conservation practice factor.

UPLIFT (HYDRAULICS) - The upward force of water on the base or underside of a structure.

VARIETY - A variant within a species which reproduces true by seed or vegetative propagation.

VELOCITY HEAD (HYDRAULICS) - Head due to the velocity of a moving fluid, equal to the square of the mean velocity divided by twice the acceleration due to gravity (32.16 feet per second per second).

WATER SURFACE PROFILE (HYDRAULICS) - The longitudinal profile assumed by the surface of a stream flowing in an open channel; the hydraulic grade line.

WEEP-HOLES (ENGINEERING) - Openings left in retaining walls, aprons, linings or foundations to permit drainage and reduce pressure.

WET STORAGE - The wet storage area is the 1800 cubic feet in the permanent pool of water in a sediment trap or basin.

WETTED PERIMETER (HYDRAULICS) - The length of the line of intersection of the plane or the hydraulic cross-section with the wetted surface of the channel

WING WALL - Side wall extensions of a structure used to prevent sloughing of banks or channels and to direct and confine overfill.

WOOD FIBER - A short fiber mulch material, usually applied with a hydro-seeder in an aqueous mixture.

From VA

APPENDIX B

MISCELLANEOUS

Appendix B

Endangered species by stream

Applicants should notify the US Fish & Wildlife Service due to the presence or possible presence of endangered/threatened species when projects will discharge to the stream segments shown below:

- Kanawha River (Kanawha Falls to river mile 89.0 near Boomer) – Fayette County (Tubercled-blossom pearlymussel, *Epioblasma torulosa torulosa*; Pink mucket pearlymussel, *Lampsilis abrupta*; and Fanshell, *Cuprogenia stegaria*)

- Potts Creek – Monroe County (James spinymussel, *Pleurobema collina*)

- South Fork Potts Creek – Monroe County (James spinymussel, *Pleurobema collina*)

- Elk River – Braxton, Clay and Kanawha Counties (Pink mucket pearlymussel; *Lampsilis abrupta;* Northern riffleshell, *Epioblasma torulosa rangiana;* and Clubshell, *Pleurobema clava*)

- Meathouse Fork Middle Creek – Doddridge County (Clubshell, *Pleurobema clava*)

- Middle Island Creek – Doddridge, Tyler and Pleasants Counties (Clubshell, *Pleurobema clava*)

- Ohio River – Cabell, Mason and Wood Counties (Pink mucket pearlymussel, *Lampsilis abrupta*; and Fanshell, Cyprogenia stegaria)

- Gauley River – Nicholas and Fayette Counties (Virginia spiraea, *Spiraea virginiana*)

- Bluestone River – Mercer and Summers Counties (Virginia spiraea, *Spiraea virginiana*)

- Greenbrier River – Pocahontas and Greenbrier Counties (Virginia spiraea, *Spiraea virginiana*)

- Meadow River – Greenbrier and Fayette Counties (Virginia spiraea, *Spiraea virginiana*)

- Dingess Branch of Marsh Fork and associated palustrine emergent and scrub-shrub wetlands – Raleigh County (Virginia spiraea, *Spiraea virginiana*)

- Millers Camp Branch of Marsh Fork and associated palustrine emergent scrub-Shrub wetlands – Raleigh County (Virginia spiraea, *Spiraea virginiana*)

- South Fork Hughes River – Ritchie County (Clubshell, *Pleurobema clava*)

- Sleepy Creek – Morgan County (Harperella, *Ptilimnium nodosum*)

- Cacapon River – Morgan County (Harperella, *Ptilimnium nodosum*)

- Back Creek – Morgan County (Harperella, *Ptilimnium nodosum*)

- Hackers Creek of West Fork River – Lewis County (Clubshell, *Pleurobema clava*)

- Wetlands – Berkeley County Northeastern bulrush, *Scirpus ancistrochaetu*

West Virginia MS4 Communities

WVR030011
Village of Barboursville
P.O. Box 266
Barboursville, WV 25504-0266
CABELL COUNTY

WVR030009
City of Beckley/Beckley Sanitary Board
P.O. Box 2494
Beckley, WV 25802 – 2492
RALEIGH COUNTY

WVR030015
Town of Belle
1100 East Dupont Avenue
Belle, WV 25015 [waiver]
KANAWHA COUNTY

WVR030026
City of Benwood
430 Main Street
Benwood, WV 26031
MARSHALL COUNTY

WVR030019
Berkeley County Public Service Sewer District
P.O. Box 944
Martinsburg, WV 25402
BERKELEY COUNTY

WVR030025
Village of Bethlehem
P.O. Box 6339
Wheeling, WV 26003
OHIO COUNTY

WVR030008
City of Bluefield/Bluefield Sanitary Board
P.O. Box 4100
Bluefield, WV 24701
MERCER COUNTY

WVR030014
City of Ceredo
P.O. Box 691
Ceredo, WV 25507
WAYNE COUNTY

WVR030006
City of Charleston
P.O. Box 2749
Charleston, WV 25330-2749
KANAWHA COUNTY

WVR030040
Town of Chesapeake
12404 MacCorkle Ave, SE
Chesapeake, WV 25315 [waiver]
KANAWHA COUNTY

WVR030034
City of Clarksburg
222 West Main Street
Clarksburg, WV 26301
HARRISON COUNTY

WVR030031
City of Dunbar/Dunbar Sanitary Board
P.O. Box 483
Dunbar, WV 25064
KANAWHA COUNTY

WVR030038
City of Fairmont
200 Jackson Street
Fairmont, WV 26555-1428
MARION COUNTY

WVR030045
Fairmont State University
1201 Locust Avenue
Fairmont, WV 26554
MARION COUNTY

WVR030012
Federal Correctional Institution – Morgantown
446 Greenbag Road
Morgantown, WV 26507
MONONGALIA COUNTY

WVR030018
City of Follansbee
P.O. Box 606
Follansbee, WV 26037 [waiver]
BROOKE COUNTY

WVR030024
City of Glen Dale
402 Wheeling Avenue
Glen Dale, WV 26038 [waiver]
MARSHALL COUNTY

WVR030033
City of Huntington
P.O. Box 1659
Huntington, WV 25717
CABELL COUNTY

WVR030010
City of Hurricane/Storm Water Board
P.O. Box 1086
Hurricane, WV 25526
PUTNAM COUNTY

WVR030039
City of Kenova
P.O. Box 268
Kenova, WV 25530
WAYNE

WVR030037
City of Marmet
P.O. Box 15037
Marmet, WV 25315 [waiver]
KANAWHA COUNTY

WVR030043
Marshall University
One John Marshall Drive
Huntington, WV 25755
CABELL COUNTY

WVR030017
City of Martinsburg
P.O. Box 828
Martinsburg, WV 25401
BERKELEY COUNTY

WVR030036
City of McMechen
47 Ninth Street
McMechen, WV 26040 [waiver]
MARSHALL COUNTY

WVR030003
Town of Milton
1139 Smith Street
Milton, WV 25541
CABELL COUNTY

WVR030007
City of Montgomery
706 Third Avenue
Montgomery, WV 25136 [waiver]
FAYETTE COUNTY

WVR030030
Morgantown Utility Board
P.O. Box 852
Morgantown, WV 28507-0852
MONONGALIA COUNTY

WVR030013
City of Moundsville/Moundsville Sanitary Board
P.O. Box 480
Moundsville, WV 26041
MARSHALL COUNTY

WVR030027
City of Nitro
20th Street & 2nd Avenue
Nitro, WV 25143
KANAWHA/PUTNAM COUNTY

WVR030029
City of Parkersburg
One Government Square
Parkersburg, WV 26102
WOOD COUNTY

WVR030035
Town of Poca
P.O. Box 586
Poca, WV 25159 [waiver]
PUTNAM

WVR030005
City of St. Albans
1499 MacCorkle Avenue
St. Albans, WV 25177
KANAWHA COUNTY

WVR030001
City of South Charleston
4th Avenue & D Street
South Charleston, WV 25303
KANAWHA COUNTY

WVR030023
Town of Star City
370 Broadway Avenue
Star City, WV 26505
MONONGALIA COUNTY

WVR030046
Veterans Administration – Huntington Medical Center
1540 Spring Valley Road
Huntington, WV 25704
WAYNE COUNTY

WVR030047
Veterans Administration – Martinsburg Medical Center
510 Butler Avenue
Martinsburg, WV 25413
BERKELEY COUNTY

WVR030032
City of Vienna
P.O. Box 5097
Vienna, WV 26105
WOOD COUNTY

WVR030021
City of Weirton
200 Municipal Plaza
Weirton, WV 26062
HANCOCK COUNTY

WVR030028
City of Wellsburg
70 Seventh Street
Wellsburg, WV 26070 [waiver]
BROOKE COUNTY

WVR030022
City of Westover
500 Dupont Road
Westover, WV 26505
MONONGALIA COUNTY

WVR030016
City of Wheeling
1500 Chapline Street
Wheeling, WV 26003
OHIO COUNTY

WVR030020
City of Williamstown
100 West 5th Street
Williamstown, WV 26187
WOOD COUNTY

WVR030004
WV Department of Transportation
1900 Kanawha Boulevard East
Bldg. 5, Room A-125
Charleston, WV 25305
STATEWIDE COVERAGE

WVR030041
WV Turnpike Authority
P.O. Box 1469
Charleston, WV 25325-1469
KANAWHA, RALEIGH & MERCER COUNTIES

WVR030042
West Virginia University
P.O. Box 6551
Morgantown, WV 26506
MONONGALIA COUNTY

WVR030044
West Virginia *State* University
P.O. Box 1000
Institute, WV 25313
KANAWHA COUNTY

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APPENDIX C
REFERENCES

APPENDIX C

REFERENCES

Applied Polymer Systems, Inc. Floc Log. Available at: http://www.siltstop.com/.

Austin, Texas. Environmental Criteria Manual. City of Austin, Texas..

Bidelspach and Jarrett, Delayed Dewatering of Sediment Basins Improves Water Quality. Penn State University

California Stormwater Quality Association (CASQA).. California Stormwater BMP Handbook - Construction. www.cabmphandbooks.com 2003

Caltrans. Storm Water Quality Handbooks, Construction Site Best Management Practices Manual. 2003

Center for Watershed Protection, The Practice of Watershed Protection - Watershed Protection Techniques. 2000

Center for Watershed Protection. Construction Standards/Specifications for Ponds.

Connecticut Department of Transportation, Storm Drainage Systems. 2000 Drainage Manual

Dane County Wisconsin, Office of Lake and Watersheds. Dane County Erosion Control and Stormwater Management Manual. 2004

Douglas County Colorado. Department of Public Works. Grading, Erosion and Sediment Control Manual. 2004

Erosion Control Technology Council (ECTC).. Erosion Control Technology Council Guidance. 2006

Faircloth and Son. Faircloth Skimmer. A Manual for Designing, Installing, and Maintaining Skimmer Sediment Basins. 2005

Federal Energy Regulatory Commission, Office of Pipeline Regulation. Upland Erosion Control, Revegetation, and Maintenance Plan. Washington, D.C. 1994.

Federal Energy Regulatory Commission, Office of Pipeline Regulation. Wetland and Waterbody Construction and Mitigation Procedures. Washington, D.C. December 2, 1994.

Georgia Environmental Protection Division. Erosion and Sediment Control Manual. 2000

Illinois Environmental Protection Agency. 1995 Illinois Urban Manual. Illinois EPA, Division of Water Pollution Control. Prepared by USDA, NRCS, Champaign, Illinois. 1995.

Indian Department of Environmental Protection. Indiana Handbook for Erosion Control

Indian Department of Environmental Protection. Erosion & Sediment Control for Individual Building Sites.

Iowa Department of Natural Resources. Iowa Construction Site Erosion Control Manual.

Iowa State University/Iowa Statewide Urban Design and Specifications. Iowa Statewide Urban Design Standards Manual. 2005

King County, Washington, King County, Department of Natural Resources and Parks, Surface Water Design Manual, 2004.

Knoxville Tennessee, Stormwater Engineering Division, Best Management Practice Manual, 2003.

Maine Department of Environmental Protection, Maine Erosion and Sediment Control BMP Manual. 2005

Maine Forest Service, Best Management Practices for Forestry: Protecting Water Quality. 2003.

Maryland Department of the Environment,. Maryland Standards and Specifications for Soil Erosion and Sediment Control. 1991

Maryland Department of the Environment, 2000. Maryland Stormwater Design Manual.

Massachusetts Department of Fish and Game. Stream Crossings Handbook. 2005

Massachusetts Department of Environmental Protection. Nonpoint Source Management Manual. 1994.

McLaughlin, Richard, "SoilFacts: Baffles to Improve Sediment Basins." N. C State University Cooperative Extension Service. 2005

McLaughlin R. A.. Using Baffles to Improve Sediment Basins. N. C State University Cooperative Extension Service. 2005

Michigan Department of Environmental Quality. Guidebook of Best Management Practices for Michigan Watersheds. 1998

Michigan Department of Environmental Quality. Soil Erosion and Sediment Control Training Manual. 2005

New York State Department of Environmental Conservation, Division of Water. New York Standards and Specifications for Erosion and Sediment Control. 2004.

Nilex. GeoRidge Specifications, http://www.nilex.com/Products.aspx?ProductID=23

North American Green. Products & Design Software.Available at: http://www.nagreen.com..

North Carolina Department of Environment and Natural Resources. Division of Land Resources. Erosion and Sediment Control Planning and Design Manual.1988 and 2006 Draft.

Oregon Department of Environmental Quality. Erosion and Sediment Control Manual, 2005

Pennsylvania Department of Environmental Protection. Erosion and Sediment Pollution Control Program Manual. 2000

Profile Products Terra-Tubes Brochure

Reid, Scott M. and Anderson, Paul G..Alliance-Pipeline. Effects of Sediment Released During Open-cut Pipeline Water Crossings.

South Carolina Department of Health and Environmental Control, Storm Water Management and Sediment Control Handbook for Land Disturbing Activities. 2005

Southeast Pennsylvania Association of Conservation Districts. Erosion and Sedimentation Pollution Control Plan Guide for Small Projects. 1995.

Sullivan, Brian. City of High Point Erosion Control Specifications. 2005

Tacoma Washington, Surface Water Management Manual. 2003

Tennessee Department of Environment and Conservation, Tennessee Erosion and Sediment Control Handbook. 2002.

U.S. Army Corps of Engineers. Engineering and Design – Handbook for the Preparation of Storm Water Pollution Prevention Plans for Construction Activities. 1997

U.S. Department of Agriculture, Forest Service. A Landowners Guide to Building Forest Access Roads., Radnor, PA 1998

U.S. Department of Agriculture - Natural Resources Conservation Service. Field Office Technical Guide. Champaign, IL

U.S. Department of Agriculture - Natural Resources Conservation Service. Engineering Field Handbook. Washington D.C.

U.S. Department of Agriculture - Natural Resources Conservation Service. National Engineering Handbook, Washington D.C.

U.S. Department of Agriculture. Urban Hydrology for Small Watersheds. Technical Release 55 (TR-55). National Technical Information Service. 1986. 2005.

U.S. Department of Transportation, Federal Highway Administration. Design of Stable Channels with Flexible Linings, HEC-15. NTIS PB89-122584/AS. 1975.

U.S. Department of Transportation, Federal Highway Administration. Hydraulic Charts for the Selection of Highway Culverts, HEC-5. 1965.

U.S. Department of Transportation, Federal Highway Administration. Design of Energy Dissipators for Culverts and Channels, HEC-14. NTIS PB86-180205/AS. 1983.

U.S. Department of Transportation, Federal Highway Administration. Capacity Charts for the Hydraulic Design of Highway Culverts, HEC-10. 1972.

U.S. Department of Transportation, Federal Highway Administration. Hydraulic Riprap for Bank Protection, HEC-11. 1967.

Vermont Department of Environmental Quality. Vermont Standards and Specifications for Erosion Prevention and Sediment Control. 2006 Draft

Virginia Department of Conservation and Recreation. Division of Soil and Water Conservation. Virginia Soil and Erosion Control Handbook, Third Edition. 1992

Virginia Department of Forestry. Virginia's Forestry Best Management Practices for Water Quality. 2002.

Washington Department of Ecology, WA. Stormwater Management Manual for Western Washington. 2005

West Virginia Division of Highways. Standard Specifications for Roads and Bridges, 2000 and 2003 Supplement.

West Virginia Division of Highways. Erosion and Sediment Control Handbook, 2003 and 2004 Addendum 1.

Wisconsin Department of Natural Resources. Construction Site Erosion and Sediment Control.

Zwim, Michael. Wild Salmon Center. Pipeline-Stream Crossing: Best Management Practices. 2002.

EPA has a page that lists numerous Storm Water Management Manuals, some which cover sediment control, at this address

http://yosemite.epa.gov/R10/WATER.NSF/0/17090627a929f2a488256bdc007d8dee?OpenDocument

Links change over time; if you find a broken link please notify the Stormwater Program.

APPENDIX D

West Virginia High Slip Potential Soils by County

BARBOUR		
Name	**Symbol**	**Soil Slip Potential**
Belmont and Cateache gravelly silt loams, 20 to 35 percent slopes, very stony	BcE	HIGH
Belmont and Cateache gravelly silt loams, 35 to 65 percent slopes, very stony	BcF	HIGH
Bethesda channery silt loam, 15 to 35 percent slopes	BeE	HIGH
Bethesda-Rock outcrop complex, very steep, very stony	BoF	HIGH
Clarksburg silt loam, 15 to 25 percent slopes	ClD	HIGH
Dekalb channery loam, 25 to 35 percent slopes	DaE	HIGH
Dekalb channery loam, 35 to 65 percent slopes	DaF	HIGH
Dekalb channery loam, 15 to 35 percent slopes, very stony	DbE	HIGH
Dekalb channery loam, 35 to 65 percent slopes, very stony	DbF	HIGH
Ernest silt loam, 15 to 25 percent slopes	EnD	HIGH
Ernest silt loam, 3 to 20 percent slopes, extremely stony	ErC	HIGH
Gilpin channery silt loam, 25 to 35 percent slopes	GcE	HIGH
Gilpin channery silt loam, 25 to 35 percent slopes, severely eroded	GcE3	HIGH
Gilpin channery silt loam, 35 to 65 percent slopes	GcF	HIGH
Gilpin-Dekalb complex, 15 to 35 percent slopes, very stony	GdE	HIGH
Gilpin-Dekalb complex, 35 to 65 percent slopes, very stony	GdF	HIGH
Gilpin-Upshur complex, 15 to 25 percent slopes	GuD	HIGH
Gilpin-Upshur complex, 15 to 25 percent slopes, severely eroded	GuD3	HIGH
Gilpin-Upshur complex, 25 to 35 percent slopes	GuE	HIGH
Gilpin-Upshur complex, 25 to 35 percent slopes, severely eroded	GuE3	HIGH
Gilpin-Upshur complex, 35 to 70 percent slopes	GuF	HIGH
Itmann channery clay loam, very steep	ItF	HIGH
Janelew channery silt loam, 15 to 35 percent slopes	JnE	HIGH
Janelew-Rock outcrop complex, very steep, very stony	JoF	HIGH
Westmoreland silt loam, 25 to 35 percent slopes	WmE	HIGH
Westmoreland silt loam, 25 to 35 percent slopes, severely eroded	WmE3	HIGH
Westmoreland silt loam, 35 to 60 percent slopes	WmF	HIGH
Westmoreland silt loam, 35 to 60 percent slopes	WmF3	HIGH

BRAXTON		
Name	**Symbol**	**Soil Slip Potential**
Vandalia silt loam, 25 to 35 percent slopes	VaE	HIGH
Vandalia silt loam, 15 to 35 percent slopes, very stony	VxE	HIGH

BROOKE		
Name	**Symbol**	**Soil Slip Potential**
Berks channery silt loam, 25 to 35 percent slopes, severely eroded	BeE3	High
Berks soils, 35 to 65 percent slopes	BkF	High
Brooke silty clay loam, 15 to 25 percent slopes	BoD	High
Brookside silt loam, 15 to 25 percent slopes	BrD	High
Clarksburg silt loam, 15 to 25 percent slopes	CkD	High
Guernsey silt loam, 8 to 15 percent slopes	GuC	High
Guernsey silt loam, 15 to 25 percent slopes	GuD	High
Guernsey silt loam, 15 to 25 percent slopes, severely eroded	GuD3	High
Westmoreland silt loam, 25 to 35 percent slopes	WeE	High
Westmoreland silt loam, 35 to 60 percent slopes	WeF	High

CABELL		
Name	**Symbol**	**Soil Slip Potential**
Gilpin silt loam, 25 to 35 percent slopes	GlE	HIGH
Gilpin-Upshur complex, 15 to 25 percent slopes	GuD	HIGH
Gilpin-Upshur complex, 25 to 35 percent slopes	GuE	HIGH
Gilpin-Upshur complex, 35 to 70 percent slopes	GuF	HIGH
Vandalia silt loam, 15 to 25 percent slopes	VaD	HIGH

CALHOUN		
Name	**Symbol**	**Soil Slip Potential**
Vandalia silt loam, 15 to 25 percent slopes	VaD	HIGH

CLAY		
Name	Symbol	Soil Slip Potential
Cedarcreek very channery loam, very steep, very stony	CeF	HIGH
Fairpoint channery loam, very steep, very stony	FpF	HIGH
Gilpin-Upshur silt loams, 15 to 25 percent slopes	GuD	HIGH
Gilpin-Upshur silt loams, 25 to 35 percent slopes	GuE	HIGH
Gilpin-Upshur complex, 35 to 70 percent slopes, very stony	GxF	HIGH
Itmann channery clay loam, very steep	ItF	HIGH
Vandalia silt loam, 15 to 25 percent slopes	VaD	HIGH
Vandalia silt loam, 25 to 35 percent slopes	VaE	HIGH

DODDRIDGE		
Name	Symbol	Soil Slip Potential
Gilpin-Upshur silt loams, 15 to 25 percent slopes	GuD	HIGH
Gilpin-Peabody complex, 25 to 35 percent slopes	GpE	HIGH
Gilpin-Peabody complex, 15 to 35 percent slopes, very stony	GsE	HIGH
Gilpin-Peabody complex, 35 to 70 percent slopes, very stony	GsF	HIGH
Gilpin-Upshur-Urban land complex, 15 to 25 percent slopes	GyD	HIGH
Vandalia silt loam, 15 to 25 percent slopes	VaD	HIGH
Vandalia silt loam, 25 to 35 percent slopes	VaE	HIGH
Vandalia silt loam, 15 to 35 percent slopes, very stony	VsE	HIGH
Vandalia-Urban land complex, 15 to 25 percent slopes	VuD	HIGH

FAYETTE		
Name	Symbol	Soil Slip Potential
Berks-Highsplint-Sharondale complex, 35 to 80 percent slopes, very stony	BhG	High
Cateache-Pipestem complex, 35 to 80 percent slopes, very stony	CcG	High
Gilpin-Highsplint-Berks complex, 35 to 90 percent slopes, extremely stony	GhG	High
Layland-Clifftop complex, 35 to 70 percent slopes, very stony	LdF	High
Layland-Dekalb-Guyandotte complex, 35 to 70 percent slopes, extremely stony	LeF	High
Layland-Dekalb-Rock outcrop complex, 55 to 80 percent slopes, extremely stony	LgG	High

Name	Symbol	Soil Slip Potential
Layland-Rock outcrop complex, 35 to 70 percent slopes, very rubbly	LkF	High
Lithic Udorthents-Rock outcrop complex, cut land, 5 to 100 percent slopes	LxG	High
Udorthents, graded, 15 to 55 percent slopes	UgF	High

GILMER		
Name	**Symbol**	**Soil Slip Potential**
Vandalia silt loam, 15 to 25 percent slopes	VaD	High
Vandalia silt loam, 15 to 35 percent slopes, very stony	VsE	High

HARRISON		
Name	**Symbol**	**Soil Slip Potential**
Clarksburg silt loam, 15 to 25 percent slopes	ClD	HIGH
Clarksburg silt loam, 15 to 25 percent slopes, severely eroded	ClD3	HIGH
Culleoka silt loam, 25 to 35 percent slopes	CuE	HIGH
Culleoka silt loam, 25 to 35 percent slopes, severely eroded	CuE3	HIGH
Culleoka silt loam, 35 to 60 percent slopes, severely eroded	CuF3	HIGH
Dekalb extremely stony sandy loam, very steep	DSF	HIGH
Ernest silt loam, 15 to 25 percent slopes	EnD	HIGH
Ernest very stony silt loam, 15 to 35 percent slopes	EsD	HIGH
Faywood silty clay loam, 15 to 25 percent slopes	FaD	HIGH
Faywood silty clay loam, 25 to 35 percent slopes	FaE	HIGH
Faywood silty clay loam, 35 to 60 percent slopes	FaF	HIGH
Gilpin silt loam, 25 to 35 percent slopes	GlE	HIGH
Gilpin silt loam, 35 to 70 percent slopes	GlF	HIGH
Gilpin very stony silt loam, 15 to 35 percent slopes	GsE	HIGH
Gilpin very stony silt loam, very steep	GTF	HIGH
Gilpin-Upshur complex, 15 to 25 percent slopes	GuD	HIGH
Gilpin-Upshur complex, 15 to 25 percent slopes, severely eroded	GuD3	HIGH
Gilpin-Upshur complex, 25 to 35 percent slopes	GuE	HIGH
Gilpin-Upshur complex, 25 to 35 percent slopes, severely eroded	GuE3	HIGH
Gilpin-Upshur complex, 35 to 70 percent slopes, severely eroded	GuF3	HIGH
Guernsey silt loam, 8 to 15 percent slopes	GyC	HIGH

Name	Symbol	Soil Slip Potential
Guernsey silt loam, 15 to 25 percent slopes	GyD	HIGH
Guernsey silt loam, 15 to 25 percent slopes, severely eroded	GyD3	HIGH
Upshur silty clay, 15 to 25 percent slopes, severely eroded	UhD3	HIGH
Vandalia silty clay loam, 15 to 25 percent slopes	VaD	HIGH
Vandalia silty clay loam, 15 to 25 percent slopes, severely eroded	VaD3	HIGH
Westmoreland silt loam, 25 to 35 percent slopes	WmE	HIGH
Westmoreland silt loam, 25 to 35 percent slopes, severely eroded	WmE3	HIGH
Westmoreland silt loam, 35 to 60 percent slopes	WmF	HIGH

HANCOCK		
Name	**Symbol**	**Soil Slip Potential**
Berks channery silt loam, 25 to 35 percent slopes, severely eroded	BeE3	High
Berks soils, 35 to 65 percent slopes	BkF	High
Brooke silty clay loam, 15 to 25 percent slopes	BoD	High
Brookside silt loam, 15 to 25 percent slopes	BrD	High
Clarksburg silt loam, 15 to 25 percent slopes	CkD	High
Guernsey silt loam, 8 to 15 percent slopes	GuC	High
Guernsey silt loam, 15 to 25 percent slopes	GuD	High
Guernsey silt loam, 15 to 25 percent slopes, severely eroded	GuD3	High
Westmoreland silt loam, 25 to 35 percent slopes	WeE	High
Westmoreland silt loam, 35 to 60 percent slopes	WeF	High

JACKSON		
Name	**Symbol**	**Soil Slip Potential**
Culleoka-Lowell complex, 25 to 35 percent slopes	CuE	High
Gilpin-Peabody complex, 35 to 65 percent slopes, severely eroded	GlF3	High
Gilpin-Peabody complex, 35 to 65 percent slopes, very stony	GmF	High
Gilpin-Peabody-Rock outcrop complex, 35 to 65 percent slopes, very stony	GoF	High
Gilpin-Upshur silt loams, 15 to 25 percent slopes	GpD	High
Gilpin-Upshur complex, 15 to 25 percent slopes, severely eroded	GpD3	High

Name	Symbol	Soil Slip Potential
Gilpin-Upshur silt loams, 25 to 35 percent slopes	GpE	High
Gilpin-Upshur complex, 25 to 35 percent slopes, severely eroded	GpE3	High
Peabody-Gilpin complex, 35 to 65 percent slopes	PgF	High
Peabody-Gilpin complex, 35 to 65 percent slopes, severely eroded	PgF3	High
Upshur silt loam, 15 to 25 percent slopes	UeD	High
Upshur-Gilpin complex, 15 to 25 percent slopes	UgD	High
Upshur-Gilpin complex, 15 to 25 percent slopes, severely eroded	UgD3	High
Upshur-Gilpin complex, 25 to 35 percent slopes	UgE	High
Upshur-Gilpin complex, 25 to 35 percent slopes, severely eroded	UgE3	High
Vandalia silt loam, 15 to 25 percent slopes	VdD	High
Vandalia silt loam, 25 to 35 percent slopes	VdE	High
Vandalia silty clay loam, 15 to 25 percent slopes, severely eroded	VsD3	High
Vandalia silty clay loam, 25 to 35 percent slopes, severely eroded	VsE3	High
Vandalia silt loam, 15 to 35 percent slopes, very stony	VtE	High
Vandalia silt loam, 15 to 35 percent slopes, bouldery	VxE	High

MASON		
Name	**Symbol**	**Soil Slip Potential**
Culleoka-Lowell complex, 25 to 35 percent slopes	CuE	High
Gilpin-Peabody complex, 35 to 65 percent slopes, severely eroded	GlF3	High
Gilpin-Peabody complex, 35 to 65 percent slopes, very stony	GmF	High
Gilpin-Peabody-Rock outcrop complex, 35 to 65 percent slopes, very stony	GoF	High
Gilpin-Upshur silt loams, 15 to 25 percent slopes	GpD	High
Gilpin-Upshur complex, 15 to 25 percent slopes, severely eroded	GpD3	High
Gilpin-Upshur silt loams, 25 to 35 percent slopes	GpE	High
Gilpin-Upshur complex, 25 to 35 percent slopes, severely eroded	GpE3	High
Peabody-Gilpin complex, 35 to 65 percent slopes	PgF	High
Peabody-Gilpin complex, 35 to 65 percent slopes, severely eroded	PgF3	High
Upshur silt loam, 15 to 25 percent slopes	UeD	High
Upshur-Gilpin complex, 15 to 25 percent slopes	UgD	High

Name	Symbol	Soil Slip Potential
Upshur-Gilpin complex, 15 to 25 percent slopes, severely eroded	UgD3	High
Upshur-Gilpin complex, 25 to 35 percent slopes	UgE	High
Upshur-Gilpin complex, 25 to 35 percent slopes, severely eroded	UgE3	High
Vandalia silt loam, 15 to 25 percent slopes	VdD	High
Vandalia silt loam, 25 to 35 percent slopes	VdE	High
Vandalia silty clay loam, 15 to 25 percent slopes, severely eroded	VsD3	High
Vandalia silty clay loam, 25 to 35 percent slopes, severely eroded	VsE3	High
Vandalia silt loam, 15 to 35 percent slopes, very stony	VtE	High
Vandalia silt loam, 15 to 35 percent slopes, bouldery	VxE	High

JEFFERSON		
Name	**Symbol**	**Soil Slip Potential**
Bagtown very flaggy sandy loam, 25 to 45 percent slopes, extremely stony	BgE	High
Bagtown very flaggy loam, 25 to 65 percent slopes, rubbly	BnF	High
Bagtown-Stumptown-Rock outcrop complex, 25 to 65 percent slopes	BoF	High
Hagerstown-Opequon-Rock outcrop complex, 15 to 35 percent slopes	HgE	High
Rock outcrop-Opequon complex, 25 to 60 percent slopes	ReF	High
Weverton-Rock outcrop complex, 15 to 45 percent slopes, very stony	WoE	High
Bagtown very flaggy sandy loam, 25 to 45 percent slopes, extremely stony	BgE	High

KANAWHA		
Name	**Symbol**	**Soil Slip Potential**
Vandalia silt loam, 15 to 25 percent slopes	VaD	High
Vandalia silt loam, 25 to 35 percent slopes	VaE	High
Vandalia silty clay loam, 15 to 25 percent slopes, severely eroded	VdD3	High

LEWIS		
Name	**Symbol**	**Soil Slip Potential**
Bethesda-Rock outcrop complex, steep, very stony	BrE	High
Gilpin silt loam, 25 to 35 percent slopes	GaE	High
Gilpin silt loam, 35 to 70 percent slopes	GaF	High
Gilpin-Dekalb association, very steep, very stony	GDF	High
Gilpin-Upshur silt loams, 15 to 25 percent slopes	GuD	High
Gilpin-Upshur silt loams, 25 to 35 percent slopes	GuE	High
Gilpin-Upshur silt loams, 35 to 70 percent slopes, severely eroded	GwF3	High
Janelew channery silt loam, steep	JaE	High
Vandalia silt loam, 15 to 25 percent slopes	VaD	High
Vandalia silt loam, 25 to 35 percent slopes	VaE	High
Westmoreland-Upshur complex, 25 to 35 percent slopes, severely eroded	WuE3	High

LINCOLN		
Name	**Symbol**	**Soil Slip Potential**
Beech loam, 15 to 25 percent slopes	BeD	High
Beech loam, 25 to 35 percent slopes	BeE	High
Gilpin silt loam, 25 to 35 percent slopes	GiE	High
Gilpin-Upshur silt loams, 15 to 25 percent slopes	GpD	High
Gilpin-Upshur silt loams, 25 to 35 percent slopes	GpE	High
Gilpin-Upshur silt loams, 35 to 70 percent slopes	GpF	High

MARSHALL		
Name	**Symbol**	**Soil Slip Potential**
Brookside silt loam, 15 to 25 percent slopes	BrD	High
Brookside silt loam, 25 to 35 percent slopes	BrE	High
Culleoka-Dormont-Peabody complex, 15 to 25 percent slopes	CpD	High
Culleoka-Dormont-Peabody complex, 25 to 35 percent slopes	CpE	High
Culleoka-Dormont-Peabody complex, 35 to 65 percent slopes, very stony	CrF	High
Culleoka-Peabody complex, 15 to 25 percent slopes	CyD	High
Dormont silt loam, 25 to 35 percent slopes	DoE	High
Dormont-Culleoka complex, 25 to 35 percent slopes	DrE	High
Dormont-Culleoka complex, 35 to 70 percent slopes, very stony	DsF	High

Name	Symbol	Soil Slip Potential
Gilpin-Dormont silt loams, 35 to 70 percent slopes, very stony	GdF	High
Guernsey silt loam, 15 to 25 percent slopes	GuD	High
Guernsey silt loam, 8 to 15 percent slopes	GuC	High
Urban land-Brookside complex, 15 to 25 percent slopes	UmD	High

MARION		
Name	**Symbol**	**Soil Slip Potential**
Buchanan and Ernest very stony soils, 15 to 25 percent slopes	BeD	High
Clarksburg silt loam, 15 to 25 percent slopes	CkD	High
Culleoka-Westmoreland silt loams, 25 to 35 percent slopes	CwE	High
Culleoka-Westmoreland silt loams, 35 to 65 percent slopes	CwF	High
Dekalb channery loam, 25 to 35 percent slopes	DaE	High
Dekalb very stony loam, 15 to 35 percent slopes	DdE	High
Dekalb very stony loam, 35 to 65 percent slopes	DdF	High
Dormont and Guernsey silt loams, 8 to 15 percent slopes	DgC	High
Dormont and Guernsey silt loams, 15 to 25 percent slopes	DgD	High
Ernest silt loam, 15 to 25 percent slopes	ErD	High
Gilpin silt loam, 25 to 35 percent slopes	GaE	High
Gilpin silt loam, 35 to 65 percent slopes	GaF	High
Gilpin-Culleoka silt loams, 25 to 35 percent slopes	GcE	High
Gilpin-Culleoka silt loams, 35 to 65 percent slopes	GcF	High
Gilpin-Culleoka-Upshur silt loams, 15 to 25 percent slopes	GuD	High
Gilpin-Culleoka-Upshur silt loams, 25 to 35 percent slopes	GuE	High
Gilpin-Culleoka-Upshur silt loams, 35 to 65 percent slopes	GuF	High
Gilpin-Culleoka-Upshur complex, 15 to 25 percent slopes, severely eroded	GwD3	High
Gilpin-Culleoka-Upshur complex, 25 to 35 percent slopes, severely eroded	GwE3	High
Upshur-Belmont very stony silt loams, 35 to 65 percent slopes	UbF	High
Westmoreland silt loam, 25 to 35 percent slopes	WeE	High
Westmoreland silt loam, 35 to 60 percent slopes	WeF	High

MONONGALIA		
Name	**Symbol**	**Soil Slip Potential**
Buchanan and Ernest very stony soils, 15 to 25 percent slopes	BeD	High
Clarksburg silt loam, 15 to 25 percent slopes	CkD	High
Culleoka-Westmoreland silt loams, 25 to 35 percent slopes	CwE	High
Culleoka-Westmoreland silt loams, 35 to 65 percent slopes	CwF	High
Dekalb channery loam, 25 to 35 percent slopes	DaE	High
Dekalb very stony loam, 15 to 35 percent slopes	DdE	High
Dekalb very stony loam, 35 to 65 percent slopes	DdF	High
Dormont and Guernsey silt loams, 8 to 15 percent slopes	DgC	High
Dormont and Guernsey silt loams, 15 to 25 percent slopes	DgD	High
Ernest silt loam, 15 to 25 percent slopes	ErD	High
Gilpin silt loam, 25 to 35 percent slopes	GaE	High
Gilpin silt loam, 35 to 65 percent slopes	GaF	High
Gilpin-Culleoka silt loams, 25 to 35 percent slopes	GcE	High
Gilpin-Culleoka silt loams, 35 to 65 percent slopes	GcF	High
Gilpin-Culleoka-Upshur silt loams, 15 to 25 percent slopes	GuD	High
Gilpin-Culleoka-Upshur silt loams, 25 to 35 percent slopes	GuE	High
Gilpin-Culleoka-Upshur silt loams, 35 to 65 percent slopes	GuF	High
Gilpin-Culleoka-Upshur complex, 15 to 25 percent slopes, severely eroded	GwD3	High
Gilpin-Culleoka-Upshur complex, 25 to 35 percent slopes, severely eroded	GwE3	High
Upshur-Belmont very stony silt loams, 35 to 65 percent slopes	UbF	High
Westmoreland silt loam, 25 to 35 percent slopes	WeE	High
Westmoreland silt loam, 35 to 60 percent slopes	WeF	High

MORGAN		
Name	**Symbol**	**Soil Slip Potential**
Blackthorn very gravelly sandy loam, 35 to 55 percent slopes, rubbly	BqF	High
Buchanan loam, 15 to 35 percent slopes, extremely stony	BxE	High

Name	Symbol	Soil Slip Potential
Caneyville silt loam, 8 to 15 percent slopes	ClC	High
Caneyville silt loam, 15 to 25 percent slopes	ClD	High
Caneyville silt loam, 25 to 35 percent slopes	ClE	High
Caneyville silty clay loam, 35 to 65 percent slopes	CnF	High
Hazleton-Dekalb complex, 15 to 35 percent slopes, extremely stony	HaE	High
Hazleton-Dekalb complex, 35 to 65 percent slopes, extremely stony	HaF	High
Hazleton-Dekalb-Rock outcrop complex, 35 to 65 percent slopes, rubbly	HdF	High
Hazleton-Dekalb-Rock outcrop complex, 35 to 65 percent slopes, very rubbly	HeF	High
Hazleton-Lehew-Dekalb complex, 35 to 65 percent slopes, extremely stony	HlF	High
Murrill gravelly loam, 15 to 25 percent slopes	MrD	High
Murrill loam, 15 to 35 percent slopes, extremely stony	MsE	High
Rock outcrop-Opequon complex, 55 to 100 percent slopes	ReG	High
Rock outcrop-Rough complex, 55 to 100 percent slopes	RgG	High
Rushtown channery silt loam, 35 to 65 percent slopes	RuF	High
Schaffenaker-Vanderlip loamy sands, 15 to 35 percent slopes, very bouldery	SnE	High
Schaffenaker-Vanderlip loamy sands, 35 to 65 percent slopes, very bouldery	SnF	High
Sideling gravelly loam, 15 to 35 percent slopes, extremely stony	SxE	High
Sideling gravelly loam, 15 to 35 percent slopes, rubbly	SyE	High

NICHOLAS		
Name	**Symbol**	**Soil Slip Potential**
Clifftop channery silt loam, 35 to 70 percent slopes, very stony	CnF	High
Clifftop-Buchanan complex, 35 to 70 percent slopes, extremely stony	CoF	High
Clifftop-Dekalb complex, 15 to 35 percent slopes, extremely stony	CpE	High
Gilpin silt loam, 35 to 70 percent slopes	GlF	High
Layland-Clifftop complex, 35 to 70 percent slopes, very stony	LdF	High
Pineville-Clifftop complex, 55 to 70 percent slopes, extremely stony	PfG	High

Name	Symbol	Soil Slip Potential
Berks-Highsplint-Sharondale complex, 35 to 80 percent slopes, very stony	BhG	High
Highsplint channery loam, 15 to 35 percent slopes, very stony	HgE	High
Laidig-Clifftop complex, 15 to 35 percent slopes, very stony	LcE	High
Layland-Laidig complex, 15 to 35 percent slopes, rubbly	LhE	High
Layland-Laidig complex, 15 to 35 percent slopes, very rubbly	LkE	High
Layland-Rock outcrop complex, 35 to 70 percent slopes, very rubbly	LmF	High
Lithic Udorthents-Rock outcrop complex, cut land, 5 to 100 percent slopes	LxG	High
Udorthents, graded, 15 to 55 percent slopes	UgF	High

OHIO		
Name	**Symbol**	**Soil Slip Potential**
Berks channery silt loam, 25 to 35 percent slopes, severely eroded	BeE3	High
Berks soils, 35 to 65 percent slopes	BkF	High
Brooke silty clay loam, 15 to 25 percent slopes	BoD	High
Brookside silt loam, 15 to 25 percent slopes	BrD	High
Clarksburg silt loam, 15 to 25 percent slopes	CkD	High
Guernsey silt loam, 8 to 15 percent slopes	GuC	High
Guernsey silt loam, 15 to 25 percent slopes	GuD	High
Guernsey silt loam, 15 to 25 percent slopes, severely eroded	GuD3	High
Westmoreland silt loam, 25 to 35 percent slopes	WeE	High
Westmoreland silt loam, 35 to 60 percent slopes	WeF	High

PLEASANTS		
Name	**Symbol**	**Soil Slip Potential**
Cedarcreek channery silt loam, steep, stony	CeE	High
Gilpin-Upshur complex, 15 to 25 percent slopes	GpD	High
Gilpin-Upshur complex, 25 to 35 percent slopes	GpE	High
Gilpin-Upshur complex, 35 to 70 percent slopes	GpF	High
Gilpin-Upshur complex, 15 to 25 percent slopes, severely eroded	GwD3	High

Name	Symbol	Soil Slip Potential
Gilpin-Upshur complex, 25 to 35 percent slopes, severely eroded	GwE3	High
Gilpin-Upshur-Rock outcrop complex, 35 to 70 percent slopes	GxF	High
Vandalia silt loam, 15 to 25 percent slopes	VaD	High
Vandalia silt loam, 15 to 25 percent slopes, very stony	VbD	High

PUTNAM		
Name	**Symbol**	**Soil Slip Potential**
Gilpin-Upshur complex, 15 to 25 percent slopes	GuD	High
Gilpin-Upshur complex, 25 to 35 percent slopes	GuE	High
Gilpin-Upshur complex, 35 to 70 percent slopes	GuF	High
Vandalia silt loam, 15 to 25 percent slopes	VaD	High
Vandalia silt loam, 25 to 35 percent slopes	VaE	High
Vandalia silty clay loam, 15 to 25 percent slopes, severely eroded	VdD3	High

Raleigh		
Name	**Symbol**	**Soil Slip Potential**
Berks-Highsplint-Sharondale complex, 35 to 80 percent slopes, very stony	BhG	High
Cateache-Pipestem complex, 35 to 80 percent slopes, very stony	CcG	High
Gilpin-Highsplint-Berks complex, 35 to 90 percent slopes, extremely stony	GhG	High
Layland-Clifftop complex, 35 to 70 percent slopes, very stony	LdF	High
Layland-Dekalb-Guyandotte complex, 35 to 70 percent slopes, extremely stony	LeF	High
Layland-Dekalb-Rock outcrop complex, 55 to 80 percent slopes, extremely stony	LgG	High
Layland-Rock outcrop complex, 35 to 70 percent slopes, very rubbly	LkF	High
Lithic Udorthents-Rock outcrop complex, cut land, 5 to 100 percent slopes	LxG	High
Udorthents, graded, 15 to 55 percent slopes	UgF	High

RITCHIE		
Name	Symbol	Soil Slip Potential
Vandalia silty clay loam, 20 to 30 percent slopes, severely eroded	VdD3	High

ROANE		
Name	Symbol	Soil Slip Potential
Vandalia silt loam, 15 to 25 percent slopes	VaD	HIGH

TAYLOR		
Name	Symbol	Soil Slip Potential
Clarksburg silt loam, 15 to 25 percent slopes	ClD	HIGH
Clarksburg silt loam, 15 to 25 percent slopes, severely eroded	ClD3	HIGH
Culleoka silt loam, 25 to 35 percent slopes	CuE	HIGH
Culleoka silt loam, 25 to 35 percent slopes, severely eroded	CuE3	HIGH
Culleoka silt loam, 35 to 60 percent slopes, severely eroded	CuF3	HIGH
Dekalb extremely stony sandy loam, very steep	DSF	HIGH
Ernest silt loam, 15 to 25 percent slopes	EnD	HIGH
Ernest very stony silt loam, 15 to 35 percent slopes	EsD	HIGH
Faywood silty clay loam, 15 to 25 percent slopes	FaD	HIGH
Faywood silty clay loam, 25 to 35 percent slopes	FaE	HIGH
Faywood silty clay loam, 35 to 60 percent slopes	FaF	HIGH
Gilpin silt loam, 25 to 35 percent slopes	GlE	HIGH
Gilpin silt loam, 35 to 70 percent slopes	GlF	HIGH
Gilpin very stony silt loam, 15 to 35 percent slopes	GsE	HIGH
Gilpin very stony silt loam, very steep	GTF	HIGH
Gilpin-Upshur complex, 15 to 25 percent slopes	GuD	HIGH
Gilpin-Upshur complex, 15 to 25 percent slopes, severely eroded	GuD3	HIGH
Gilpin-Upshur complex, 25 to 35 percent slopes	GuE	HIGH
Gilpin-Upshur complex, 25 to 35 percent slopes, severely eroded	GuE3	HIGH
Gilpin-Upshur complex, 35 to 70 percent slopes, severely eroded	GuF3	HIGH
Guernsey silt loam, 8 to 15 percent slopes	GyC	HIGH
Guernsey silt loam, 15 to 25 percent slopes	GyD	HIGH
Guernsey silt loam, 15 to 25 percent slopes, severely eroded	GyD3	HIGH

Name	Symbol	Soil Slip Potential
Upshur silty clay, 15 to 25 percent slopes, severely eroded	UhD3	HIGH
Vandalia silty clay loam, 15 to 25 percent slopes	VaD	HIGH
Vandalia silty clay loam, 15 to 25 percent slopes, severely eroded	VaD3	HIGH
Westmoreland silt loam, 25 to 35 percent slopes	WmE	HIGH
Westmoreland silt loam, 25 to 35 percent slopes, severely eroded	WmE3	HIGH
Westmoreland silt loam, 35 to 60 percent slopes	WmF	HIGH

TYLER		
Name	**Symbol**	**Soil Slip Potential**
Cedarcreek channery silt loam, steep, stony	CeE	High
Gilpin-Upshur complex, 15 to 25 percent slopes	GpD	High
Gilpin-Upshur complex, 25 to 35 percent slopes	GpE	High
Gilpin-Upshur complex, 35 to 70 percent slopes	GpF	High
Gilpin-Upshur complex, 15 to 25 percent slopes, severely eroded	GwD3	High
Gilpin-Upshur complex, 25 to 35 percent slopes, severely eroded	GwE3	High
Gilpin-Upshur-Rock outcrop complex, 35 to 70 percent slopes	GxF	High
Vandalia silt loam, 15 to 25 percent slopes	VaD	High
Vandalia silt loam, 15 to 25 percent slopes, very stony	VbD	High

UPSHUR		
Name	**Symbol**	**Soil Slip Potential**
Gilpin-Upshur silt loams, 15 to 25 percent slopes	GuD	High
Gilpin-Upshur silt loams, 25 to 35 percent slopes	GuE	High
Gilpin-Upshur silt loams, 35 to 65 percent slopes	GuF	High
Gilpin-Upshur complex, 15 to 25 percent slopes, severely eroded	GwD3	High
Gilpin-Upshur complex, 25 to 35 percent slopes, severely eroded	GwE3	High
Vandalia silt loam, 15 to 25 percent slopes	VaD	High
Westmoreland-Upshur silt loams, 25 to 35 percent slopes	WuE	High
Westmoreland-Upshur silt loams, 35 to 65 percent slopes	WuF	High

WEBSTER		
Name	**Symbol**	**Soil Slip Potential**
Clifftop channery silt loam, 35 to 70 percent slopes, very stony	CnF	High
Clifftop-Dekalb complex, 15 to 35 percent slopes, extremely stony	CpE	High
Clifftop-Laidig association, very steep, extremely stony	CSF	High
Pineville-Clifftop complex, 55 to 70 percent slopes, extremely stony	PfG	High

WETZEL		
Name	**Symbol**	**Soil Slip Potential**
Gilpin-Peabody complex, 15 to 25 percent slopes	GpD	High
Gilpin-Peabody complex, 25 to 35 percent slopes	GpE	High
Gilpin-Peabody complex, 35 to 70 percent slopes	GpF	High
Gilpin-Rock outcrop complex, very steep	GrF	High
Vandalia silty clay loam, 15 to 25 percent slopes	VaD	High
Vandalia silty clay loam, 25 to 35 percent slopes	VaE	High
Vandalia silty clay loam, 15 to 25 percent slopes, extremely stony	VbD	High
Vandalia-Urban land complex, 15 to 25 percent slopes	VuD	High

WIRT		
Name	**Symbol**	**Soil Slip Potential**
Peabody-Gilpin complex, 40 to 55 percent slopes	PgF	High
Peabody-Gilpin complex, 30 to 55 percent slopes, severely eroded	PgF3	High
Peabody-Gilpin complex, 30 to 55 percent slopes, very stony	PvF	High
Upshur-Gilpin complex, 20 to 30 percent slopes	UgD	High
Upshur-Gilpin complex, 20 to 30 percent slopes, severely eroded	UgD3	High
Upshur-Gilpin complex, 30 to 40 percent slopes	UgE	High
Upshur-Gilpin complex, 30 to 40 percent slopes, severely eroded	UgE3	High
Vandalia silty clay loam, 20 to 30 percent slopes, severely eroded	VaD3	High

WOOD		
Name	**Symbol**	**Soil Slip Potential**
Peabody-Gilpin complex, 40 to 55 percent slopes	PgF	High
Peabody-Gilpin complex, 30 to 55 percent slopes, severely eroded	PgF3	High
Peabody-Gilpin complex, 30 to 55 percent slopes, very stony	PvF	High
Upshur-Gilpin complex, 20 to 30 percent slopes	UgD	High
Upshur-Gilpin complex, 20 to 30 percent slopes, severely eroded	UgD3	High
Upshur-Gilpin complex, 30 to 40 percent slopes	UgE	High
Upshur-Gilpin complex, 30 to 40 percent slopes, severely eroded	UgE3	High
Vandalia silty clay loam, 20 to 30 percent slopes, severely eroded	VaD3	High

Counties with no known High Slip Potential Soils:

Berkeley, Boone, Grant, Hardy, Greenbrier, Hampshire, Mineral, Logan, Mingo, McDowell, Mercer, Monroe, Pendleton, Pocahontas, Preston, Randolph, Summers, Tucker, Wyoming