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Land–Water Interactions: The Riparian Zone

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INTRODUCTION

The interface between aquatic and terrestrial environments in coniferous forests forms a narrow riparian zone. Until recently, structure, composition, and function of the riparian zone had received little consideration in ecosystem level research, because this zone forms the interface between scientific disciplines as well as ecosystem components. In some climate-vegetation zones particular aspects of riparian zones have received much study. The conspicuous riparian plant communities in arid lands have been studied extensively, primarily in terms of wildlife habitat (Johnson and Jones 1977; Thomas et al. 1979). Research on riparian vegetation along major rivers has dealt mainly with forest composition and dynamics (for example, Lindsey et al. 1961; Sigafoos 1964; Bell 1974; Johnson et al. 1976). Riparian vegetation research has been largely neglected in forested mountain land, where it tends to have smaller areal extent and economic value than upslope vegetation. From an ecosystem perspective, however, the riparian zone is an integral part of the forest/stream ecosystem complex.

This chapter synthesizes general concepts about the riparian zone in northwest coniferous forests and the results of coniferous forest biome research on: (1) structure and composition of riparian vegetation and its variation in time and space; and (2) functional aspects of the riparian zone in terms of physical, biological, and chemical terrestrial/aquatic interactions. We emphasize conditions observed in mountain streams and small rivers.

The riparian zone may be defined in a variety of ways, based on factors such as vegetation type, groundwater and surface water hydrology, topography, and ecosystem function. These factors have so many complex interactions that defining the riparian zone in one sense integrates elements of the other factors. We prefer to define the riparian zone functionally as that zone of direct interaction between terrestrial and aquatic environments. Vegetation, hydrology, and topography all determine the type, magnitude, and direction of functional relationships. The direction of riparian interactions refers to the notion that the terrestrial system may affect the aquatic or vice versa. In arid land systems, where streams may recharge groundwater, as well as in floodplain situations, streams and rivers are often viewed as exercising important control over streamside vegetation. Steep terrain and massive forests in the Pacific Northwest emphasize effects of forests on streams.

The riparian zone can be viewed on three distinct scales. In the strictest sense the zone of direct interaction could be considered the water's edge. This restricted zone is preferentially occupied by bank and large wood-dwelling beetle adults, *Diptera* larvae, Collembola, and hydrophilic plants. Such a narrowly defined, linear view of terrestrial/aquatic interactions ignores many important characteristics of the riparian zone.

In a slightly broader sense, the aquatic/terrestrial interface includes the areas of the streambed, banks, and floodplain that may be submerged only part of the year. At different times of the year these sites may be subjected to processes and be habitats for species that are typical of either terrestrial or aquatic environments or some mix of the two. This type of interface occurs as a result of both headward and lateral expansion and contraction of stream area on the time scales of storms and seasons. This planar view of the riparian zone accounts for only limited aspects of aquatic/terrestrial interactions.

The third and largest scale on which we view riparian vegetation is more three-dimensional and incorporates the concept that at any point in time a forested stream is directly influenced biologically, physically, and chemically by aboveground and belowground components of streamside vegetation. If the riparian zone is defined functionally in terms of the area of direct interaction between aquatic and terrestrial environment, then it forms a zone of interaction extending upward and outward from the stream through the overhanging canopy. In the Pacific Northwest, structure and composition of riparian vegetation include herbaceous groundcover, understory shrubby vegetation (commonly deciduous), overstory trees on the floodplain (generally a mix of deciduous and coniferous), and possibly the upper parts of trees rooted at the base of adjacent hillslopes (generally coniferous). Each of these components of riparian vegetation is involved in a variety of terrestrial/aquatic interactions, many of which are summarized in Table 9.1.

We choose to consider the land/stream interface on this broad scale and in terms of compositional, structural, and functional aspects of riparian vegetation. This perspective offers a conceptual basis for examining the full range of terrestrial/aquatic interactions. Discussion of the riparian zone begins with composition and structure of the vegetation, because these two factors determine the character of functional relationships.

STRUCTURE AND COMPOSITION OF RIPARIAN VEGETATION

Hydrologic, climatic, and substrate factors determine the composition and therefore the structure and function of riparian vegetation. Relative to upslope

TABLE 9.1 *Function of riparian vegetation with respect to aquatic ecosystems.*

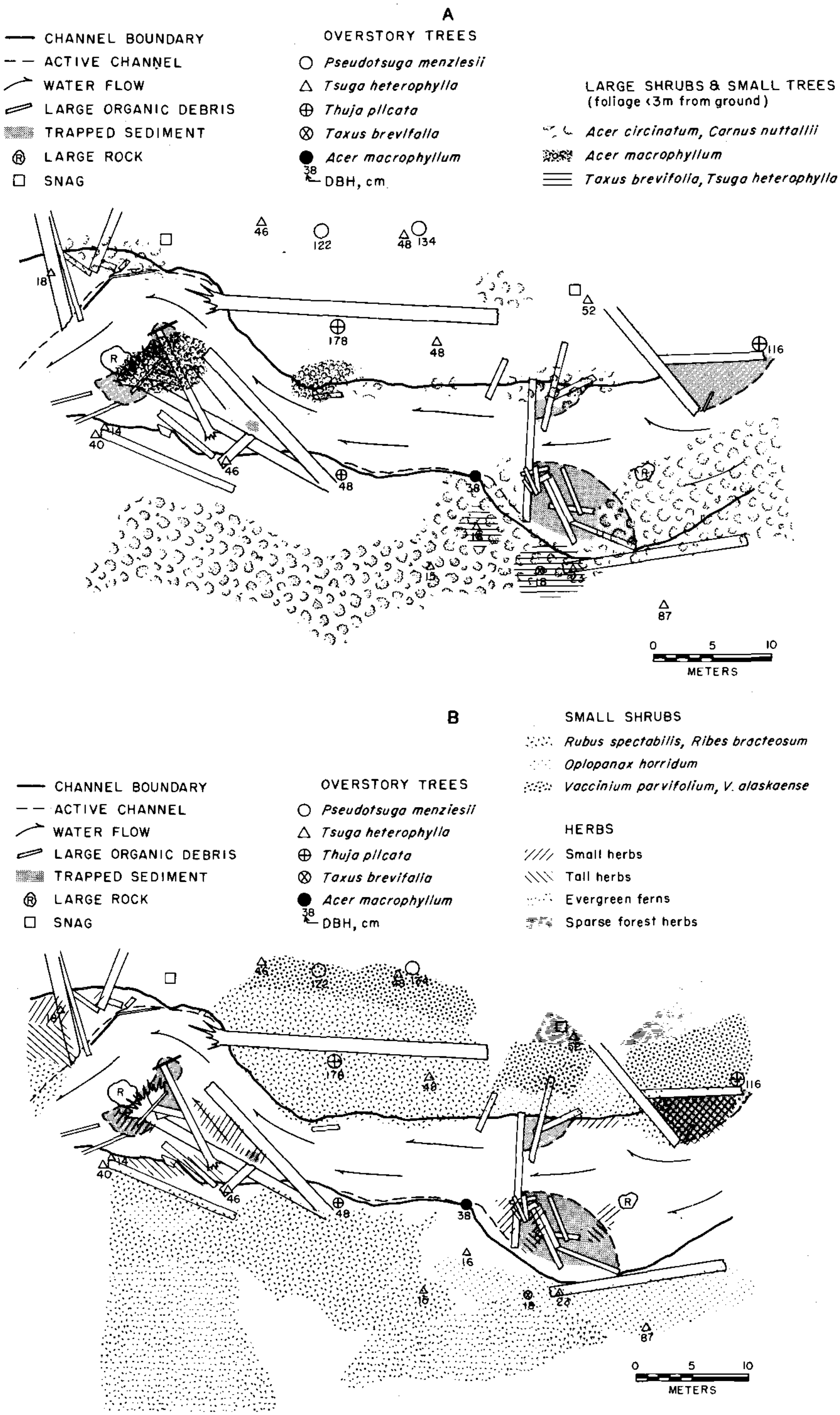
Site	Component	Function
Aboveground/ above channel	Canopy and stems	1. Shade controls temperature and in stream primary production 2. Source of large and fine plant detritus 3. Wildlife habitat
In channel	Large debris derived from riparian vegetation	1. Control routing of water and sediment 2. Shape habitat—pools, riffles, cover 3. Substrate for biological activity
Streambanks	Roots	1. Increase bank stability 2. Create overhanging banks—cover 3. Nutrient uptake from ground and streamwater
Floodplain	Stems and low-lying canopy	1. Retard movement of sediment, water and floated organic debris in flood flows

sites, the riparian environment is protected from high winds and extremes of summer drought. It is subjected to periodic flooding, however, that causes inundation, destruction of some vegetation, and creation of fresh sites for establishment of vegetation. These physical factors result in some distinctive structural and compositional attributes of riparian vegetation.

Riparian-zone vegetation in the Douglas-fir region has been characterized in terms of: (1) stream/stand relations in a variety of forest age classes and stream sizes; and (2) types of riparian plant communities along streams of different sizes and disturbance histories. Much of the descriptive ecology and geomorphology dealing with riparian vegetation in the Pacific Northwest has been carried out in the H. J. Andrews Experimental Forest, the primary site for the IBP stream ecology research (Sedell et al. 1974, 1975; Sedell and Triska 1977; Swanson et al. 1976; Swanson and Lienkaemper 1978; Anderson et al. 1978; Campbell and Franklin 1979). Mack Creek, a principal study stream, offers examples of riparian vegetation structure and composition in steep, intermediate-sized streams of this region.

Maps of large shrub and small tree (Figure 9.1A) and small shrub and herb (Figure 9.1B) vegetation and a vegetation valley bottom cross profile (Figure 9.2) portray the distribution of plants along a section of Mack Creek. Here the streams flow over boulders and large organic debris through a 450- to 500-year-old *Pseudotsuga menziesii/Tsuga heterophylla* forest.

Vegetation along Mack Creek and other small and intermediate-sized streams has a pronounced stratification from low-lying herbs and shrubs to


A
CHANNEL BOUNDARY
ACTIVE CHANNEL
WATER FLOW
LARGE ORGANIC DEBRIS
TRAPPED SEDIMENT
LARGE ROCK
SNAG
OVERSTORY TREES
Pseudotsuga menziesii
Tsuga heterophylla
Thuja plicata
Taxus brevifolia
Acer macrophyllum
DBH, cm
LARGE SHRUBS & SMALL TREES
(foliage <3m from ground)
Acer circinatum, Cornus nuttallii
Acer macrophyllum
Taxus brevifolia, Tsuga heterophylla
0 5 10
METERS
B
SMALL SHRUBS
Rubus spectabilis, Ribes bracteosum
Oplopanax horridum
Vaccinium parvifolium, V. alaskaense
HERBS
Small herbs
Tall herbs
Evergreen ferns
Sparse forest herbs
CHANNEL BOUNDARY
ACTIVE CHANNEL
WATER FLOW
LARGE ORGANIC DEBRIS
TRAPPED SEDIMENT
LARGE ROCK
SNAG
OVERSTORY TREES
Pseudotsuga menziesii
Tsuga heterophylla
Thuja plicata
Taxus brevifolia
Acer macrophyllum
DBH, cm
0 5 10
METERS

small trees, and large overstory trees. Large trees that shade streams are predominantly *Pseudotsuga menziesii, Thuja plicata,* and *Tsuga heterophylla,* which may be rooted adjacent to the channel or well away from it, and lean out over the stream. Development of small trees along a stream may be greater than in upslope areas in response to greater light availability where streams are wide enough to have at least partially broken canopy above the channel. In old-growth forests of the H. J. Andrews Forest this lower-tree stratum is mainly composed of deciduous trees that lean over the stream into the light. In the western Cascade Mountains, streamside herb and shrub communities also typically have greater biomass per unit area than the same vegetation strata in upslope areas (C. C. Grier, pers. comm.). This may be due to lower plant moisture stress in the streamside area.

In a broad sense, streamside vegetation is composed of generalist species that inhabit upslope areas as well as specialists whose range is restricted to the very moist streamside habitats. For example, generalists in the Mack Creek area include *Acer circinatum, Acer macrophyllum, Vaccinium parvifolium,* and *Oxalis oregana,* whereas *Oplopanax horridum* and *Rubus spectabilis* are specialists restricted to the streamside area and other very wet sites (Figure 9.1). Plants that are specialists along Mack Creek may be widely distributed on hillslope areas in other climatic settings.

A variety of site factors such as substrate type, frequency and intensity of scouring, light availability, and site area constrain the types and distributions of riparian zone plant communities. On small, steep, first-order streams riparian habitats are so restricted in area that only fragments of synusiae may form, while full-scale forests are found on floodplains of larger streams and rivers. The amount of sunlight reaching the vicinity of a stream also influences the type and degree of development of herb, shrub, and small tree components of riparian vegetation. Aspect, stream width, and stand crown condition all regulate light penetration to the stream and adjacent areas.

Riparian plant associations within the herb and shrub layers are commonly limited by substrate type. For example, in the central western Cascade Range of Oregon clans of seed-disseminated herbs such as *Circaea alpina* and *Montia sibirica* are common on fresh deposits of sand and fine gravel. Other species, such as *Petasites frigidus* and *Stachys cooleyea,* sustain themselves by spreading their root systems below the level of frequent scour among small boulders in sunny areas. Wet cliff faces may support communities dominated by *Adiantum pedantum, Tolmiea menziesii,* and mosses. *Oplopanax horridum* or *Ribes bracteosum* and *Rubus spectabilis* are common components of the shrub layer

FIGURE 9.1 *Components of riparian vegetation along a third-order section of Mack Creek, H. J. Andrews Experimental Forest. Watershed area is 600 ha; channel gradient is about 10 percent. (A) Map of large shrubs (>2 m high) and low-lying canopy (<3 m) of small-tree strata. (B) Map of herb and small-shrub (50 cm to 2 m high) strata.*

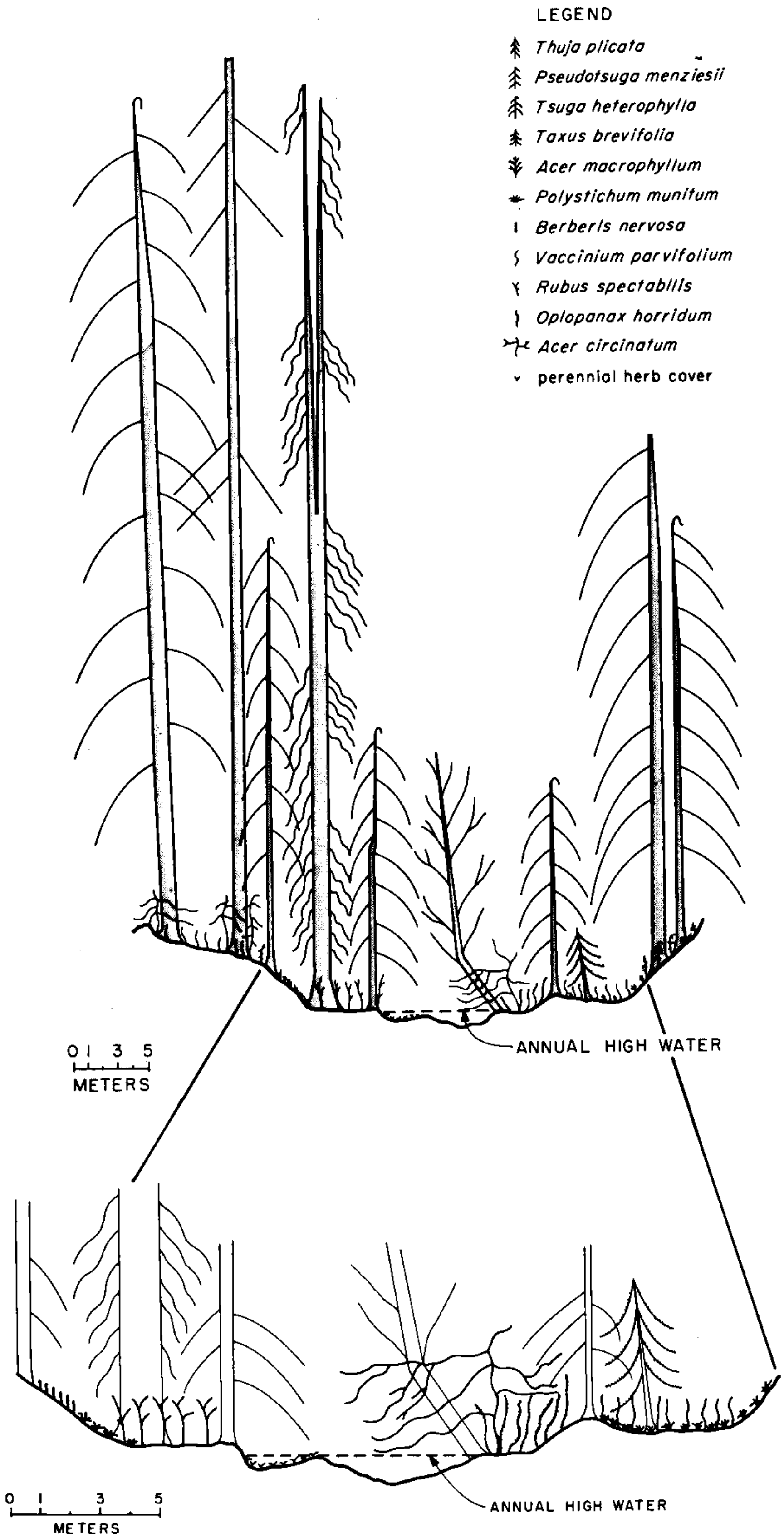


FIGURE 9.2 *Generalized vegetation/valley bottom cross profile of Mack Creek, H. J. Andrews Experimental Forest.*

where subsoil remains wet and scouring is not a problem. Farther from the stream, the understory is dominated by the same synusiae found in the wettest of typical forest plant communities—*Vaccinium parvifolium, Oxalis oregana, Polystichum munitum,* and others (Zobel et al. 1976).

The effects of variation in substrate type, availability of sunlight, and scouring history on riparian plant community development are evident in surveys of community types on nine first- through third-order streams in the H. J. Andrews Experimental Forest and vicinity, summarized in Table 9.2 by stratigraphic groups of riparian plants. Communities dominated by shrubs, *Acer circinatum,* and other small trees increase in percentage of cover with increasing stream size. This trend appears to be a response to greater sunlight penetration to middle strata of the forest where stream width is sufficient to cause opening of the overstory canopy. The small and large herb classes show no consistent change in cover over the three stream orders, possibly because the increased light availability in larger streams is utilized by higher vegetation strata. Plant cover conditions along the watershed 2 stream are very different from those of the other inventoried streams. High herb layer cover reflects the abundance of bedrock and very small, localized pockets of soil along the stream. A debris torrent scoured this channel in the late 1940s, leaving a steep-sided bedrock notch in the second-order portion of this watershed. Opportunity for rooting by larger plants is severely limited.

Several features of the riparian zone tend to retard development of streamside vegetation. As in the case of the watershed 2 stream, erosion along small

TABLE 9.2 *Percent cover of stratigraphic classes of riparian communities in small tree, shrub, and herb strata along four first-order, three second-order, and one third-order stream with predominantly gravel, boulder, and substrates, and along watershed 2 stream, a second-order bedrock-dominated channel.*[a]

Stratigraphic class[b]	Percent cover: Stream order 1	2	3	Watershed 2 (second-order)
Small herb	6	6	2	23
Large herb	5	14	9	39
Shrub	2	19	25	
Large shrub/small tree		3	13	
Acer circinatum	26	31	37	9

[a]Campbell and Franklin 1979.

[b]Small herbs are up to 30 cm tall, for example, *Tolmiea menziesii;* large herbs, 30 cm to 2 m tall, for example, *Aralia californica;* small shrubs, 50 cm to 2 m, for example, *Oplopanax horridum;* large shrubs/small trees, 2 to 6 m tall, for example, *Osmaronia cerasiformis.*

and intermediate-sized streams may leave a channel bordered by steep bedrock slopes with soil cover sufficient to support only patchy herbaceous vegetation. Large woody debris in channels is also an unsuitable substrate for establishment of many plant species, so it may suppress development of riparian vegetation where it is heavily concentrated, particularly in logged or burned areas. Streamside vegetation subject to periodic wetting is also vulnerable to partial or complete destruction during major floods when stream-transported debris, ice, or both may severely batter plants along streams and rivers. Therefore a riparian plant community at a particular time reflects both long- and short-term histories of channel changes.

FUNCTIONS OF THE RIPARIAN ZONE

Discussion of terrestrial/aquatic interactions proceeds from physical to biological to chemical factors. The physical environment forms a template on which the biota develops and both physical and biological factors determine the type and rates of changes in soil-water and stream-water chemistry that occur across the terrestrial/aquatic interface.

Physical Terrestrial/Aquatic Interactions

Much of the classic work on physical characteristics of the stream environment has been concerned with the shaping of channel pattern and bedforms by flowing water (Leopold et al. 1964). Most of this work has dealt with meandering, low-gradient streams and rivers where sediment type and hydraulic forces clearly control fluvial morphology. Mountain streams and small rivers in the coniferous forests of the Pacific Northwest, however, are primarily shaped by external factors—hillslope erosion processes, bedrock control of channel position and geometry, channel stabilization by riparian vegetation, and large organic material derived from terrestrial vegetation.

Hillslope erosion processes determine the rate of supply of sediment and large organic debris to the channel, frequency of catastrophic flushing by debris torrents, and rates of channel constriction (see Chapter 8). These factors control channel geometry, streambed substrate, and the character of riparian vegetation in a variety of ways. Abundance and size distribution of alluvium in a channel reflect, in part, the balance between sediment supply by hillslope processes and removal by channel processes. Sediment type determines the channel bedforms, bed roughness, bed stability (frequency and depth of scour and fill), and habitat for benthic organisms. In addition to supplying sediment to a channel, slow, deep-seated mass-erosion processes also disrupt riparian zone vegetation by tipping big trees and contributing to the occurrence of small streamside slides that destroy established riparian vegetation and create an opportunity for the development of new plant communities. Over the course of years, these processes of creep, slump, and earthflow progressively close channels until they are reopened by floods (Swanson and Swanston 1977). Rapid mass erosion events from hillslope areas have the potential for greater, more immediate impact on streams and the riparian zone. Debris avalanches may completely destroy riparian vegetation at the base of a slope, and they are the prime triggering mechanism of debris torrents (Swanson et al. 1976). Movement of debris torrents down steep channels often completely obliterates streamside vegetation.

Channel erosion and downstream transport of organic and inorganic detritus are also influenced by streamside vegetation. Studies in agricultural systems indicate that vegetation in shallow channels reduces sediment transport (Karr and Schlosser 1978). Smith (1976) and others argue that root networks of streamside plants retard bank erosion, and, in the Colorado River system, Graf (1978) documents reduced channel width due to sediment entrapment and stabilization by invading *Tamarix chinensis.* Channel geometry differs for forest and pasture vegetation along several small streams in northern Vermont (Zimmerman et al. 1967). During floods, streamside vegetation is both a source of transportable woody debris and a device for trapping transported material. Large amounts of leaves, twigs, and small limbs trapped in riparian vegetation are evidence that floating organic matter is combed from floodwaters by streamside brush. Streamside vegetation also reduces water velocity and therefore erosive capability by increasing roughness (Petryk and Bosmajian 1975).

The input of large organic debris to streams from the surrounding forest is a complex and important link between terrestrial and aquatic components of the forest ecosystem. The quantity of large organic debris in a stream at any specific time is a result of the balance between input and output processes over the previous several centuries (Figure 9.3). Debris input is regulated by the dynamics of the surrounding forest and landscape, which involve biotic factors such as episodes of stand thinning and the abiotic processes of blowdown, debris avalanche, and streambank cutting. Debris input processes interact in several ways (Figure 9.3), such as wind stress on the tree canopy that may trigger streamside debris avalanches. Debris avalanching may also occur in response to bank cutting by the stream or by debris torrents. Undercutting of streamside trees makes them more susceptible to being blown down.

Large woody debris may be moved out of a channel section by: (1) flotation of individual pieces or "rafts" of debris during floods; (2) debris torrents involving rapid, turbulent movement of masses of soil, alluvium, and organic matter down stream channels; and (3) transport of dissolved and fine particulate matter following decomposition, leaching, and processing by aquatic invertebrates.

Standing crops of coarse woody debris (>10-cm diameter) in western Oregon streams have been measured by Froehlich (1973) and J. R. Sedell and

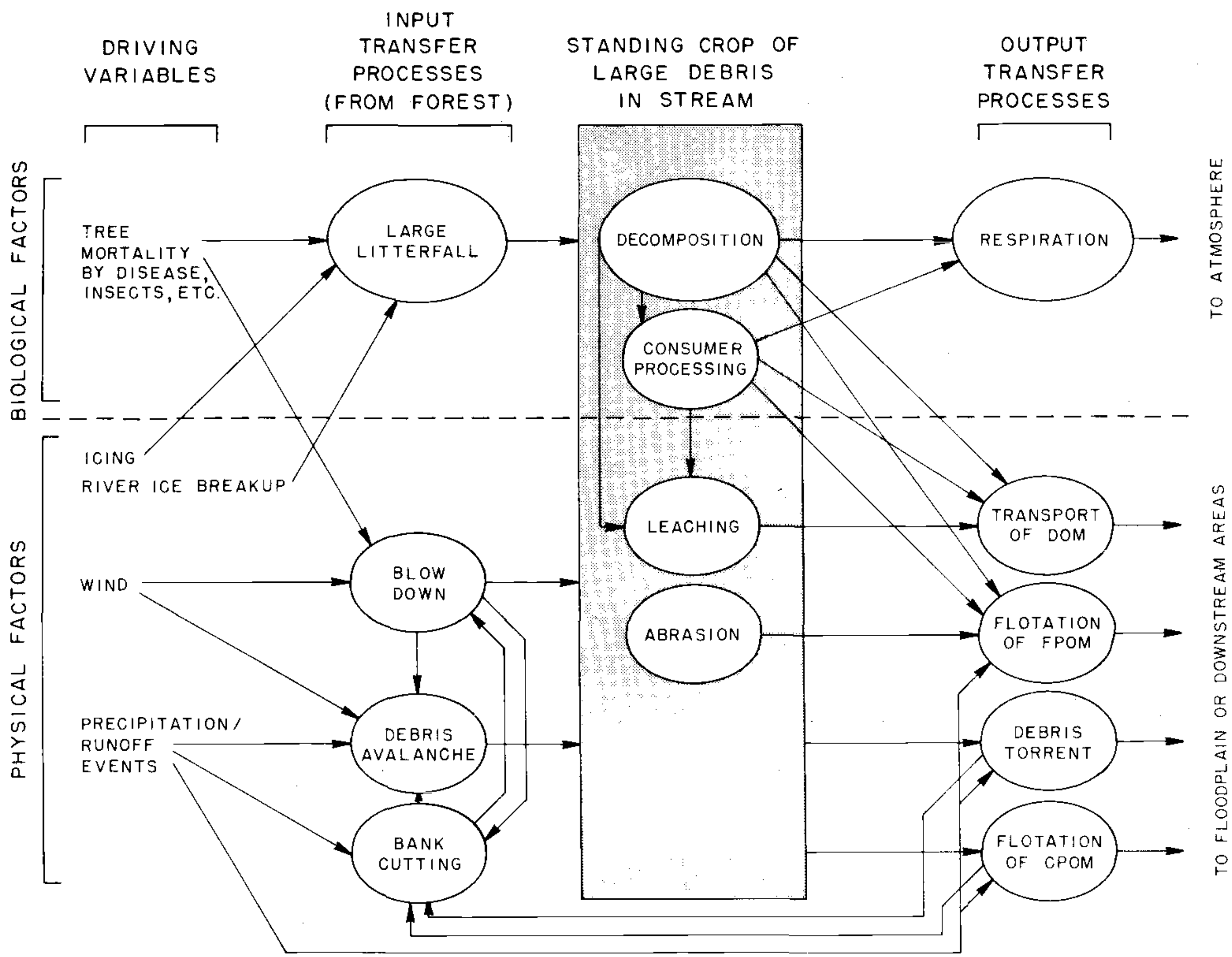


FIGURE 9.3 *Dynamics of large woody debris in streams (from Keller and Swanson 1979).*

G. W. Lienkaemper (pers. comm.). Eleven small streams flowing through old-growth forests and draining areas of 3 to about 50 ha contain coarse debris ranging from 2.8 kg/m^2 in a channel recently flushed by a debris torrent to 90.2 kg/m^2. These figures include both the channel and bank areas immediately adjacent to the stream. Average standing crop of debris, excluding the recently cleared channel, was 50.4 kg/m^2.

The standing crop of coarse debris in channels decreases downstream due to increased stream transport capability and reduced influence of adjacent forests on progressively wider streams. Standing crop of coarse debris decreases systematically in a series of samples taken along a gradient of stream sizes from first to sixth order in the upper McKenzie River system (Table 9.3). Coarse organic debris levels exceed 30 kg/m^2 at sample sites on first- through third-order stream reaches, but the sixth-order McKenzie River site at Rainbow, Oregon, has only about 1 percent of the standing crop of the first-order channel.

The spatial distribution of coarse debris also varies systematically from small streams to large rivers (Keller and Swanson, 1979). Maps of stream channels (Figures 9.1, 9.4, and 9.5) reveal the generally lower debris concentrations and greater clumping of debris pieces in larger streams. The distribution of debris reflects in part the balance between stream size and debris size. Debris in small streams is large relative to channel dimensions and volume of flood flows, so it cannot be floated and redistributed (Figure 9.4). Consequently, the debris is randomly distributed and located where it initially fell; however these small channels are in the steepest part of the drainage network, and are most prone to catastrophic flushing by debris torrents. Intermediate-sized streams are large enough to redistribute coarse woody debris but narrow enough that debris accumulations crossing the entire channel are common

TABLE 9.3 *Coarse (> 10 cm diam) debris loading sampled in sections of five streams flowing through old-growth Douglas-fir forests in McKenzie River system, western Oregon. Specific gravity of wood assumed to be 0.50 g/cm^3.*[a]

Stream	Coarse debris loading (kg/m)	Length of sampled station (m)	Channel width (m)	Channel gradient (%)	Stream order	Watershed area (km^2)
Devil's Club Creek	43.5	90	1	40	1	0.2
Watershed 2 Creek	38.0	135	2.6	26	2	0.8
Mack Creek	28.5	300	12	13	3	6.0
Lookout Creek	11.6	300	24	3	5	60.5
McKenzie River at Rainbow	0.5	800	40	0.6	7	1024

[a]From Keller and Swanson 1979.

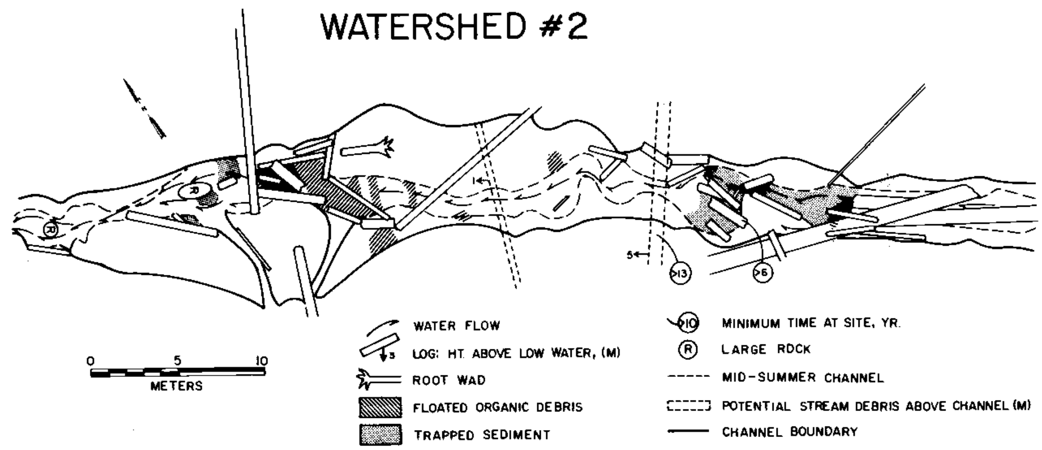


FIGURE 9.4 *Map of large organic debris in an upper second-order section of watershed 2 stream (mapped by G. W. Lienkaemper).*

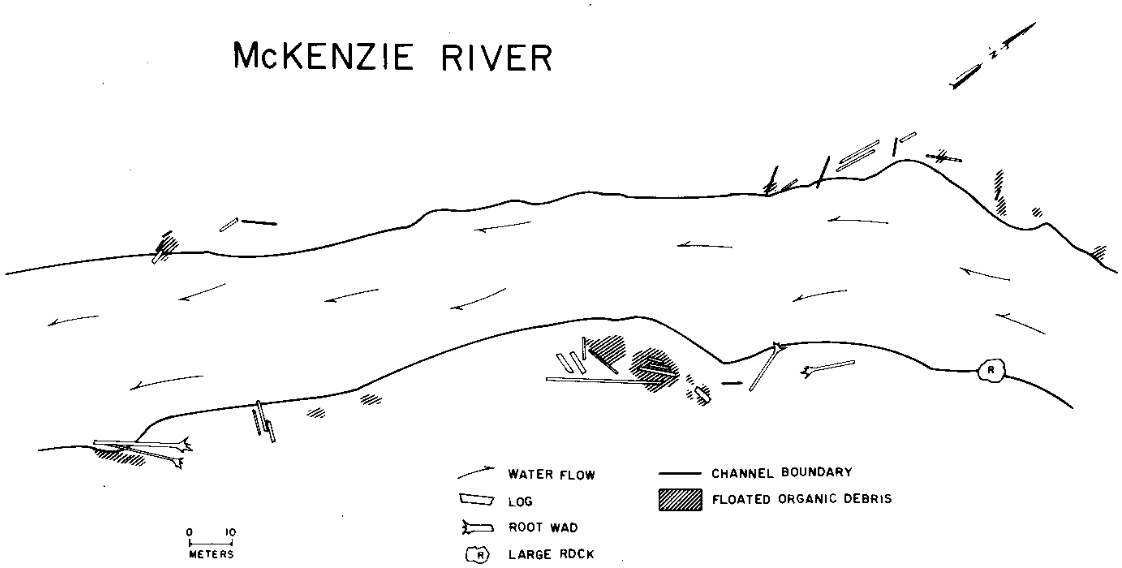


FIGURE 9.5 *Map of large organic debris in a sixth-order section of McKenzie River (mapped by G. W. Lienkaemper).*

(Figure 9.1). The debris tends to be concentrated in distinct accumulations spaced several channel widths apart along the stream. In large rivers, debris is commonly collected in scattered, distinct accumulations at high water (Figure 9.5) and particularly on upstream ends of islands and at bends in the river.

Large debris in streams controls channel morphology as well as sediment and water routing (Keller and Swanson 1979). Debris helps form a stepped gradient in streams up to about the third order (Heede 1972). The streambed is made up of long, low gradient sections separated by relatively short, steep falls or cascades. Therefore much of the streambed may have gradient less than the overall gradient of the valley bottom, because much of the stream drop, or decrease in potential energy, takes place in the short, steep reaches. This pattern of energy dissipation in short stream reaches results in less erosion of bed and banks, more sediment storage in the channel, slower routing of organic detritus, and greater habitat diversity than in straight, even gradient channels.

Comparison of volumes of stored sediment and volume of annual sediment export suggests that small forested streams annually export only a small fraction of sediment in storage in the channel system. In the case of the 60-ha watershed 2 in the H. J. Andrews Experimental Forest, average bedload export measured in a sediment basin for 1957 through 1976 has been 3.8 m^3/yr (R. L. Fredriksen, pers. comm.). In a 100-m channel section upstream of the basin, 20.1 m^3 of sediment is stored behind organic debris. The entire length of perennial and intermittent channel is about 1700 m, so in this watershed annual sediment yield is probably much less than 10 percent of material in storage. Megahan and Nowlin (1976) have made similar observations in several small, forested watersheds in central Idaho where sediment yield was only about 10 percent of sediment stored in the channel systems. Woody materials made up 75 to 85 percent of the obstructions that trapped sediment in the Idaho streams.

Unfilled storage capacity serves to buffer the sedimentation impacts on downstream areas when pulses of sediment enter channels. Scattered debris in channels reduces the rate of sediment movement and routes sediment through the stream ecosystem more slowly, except in cases of catastrophic flushing events.

Debris has both positive and negative effects on bank stability, on the lateral mobility of channels, and on stability of aquatic habitats. Debris-related bank stability problems in steep-sided, bedrock-controlled streams result from undercutting of the soil mantle on hillslopes by debris torrents. Undercut slopes are subject to progressive failure by surface erosion and small-scale ($<$ 100-m^3) mass erosion over a period of years. Both bank instability and lateral channel migration may be facilitated by debris accumulations in channels with abundant alluvium and minimal bedrock influence. Change in channel conditions and position often occurs as a stream bypasses a debris accumulation and cuts a new channel. Where channels flow through massive depositional areas behind and through debris accumulations, streamflow may be subsurface much of the year. In areas of active creep and earthflows, lateral stream cutting may undermine banks and encourage further hillslope failure and accelerated sediment supply to the channel. On balance, however, large debris generally stabilizes small streams by its roles in stream energy dissipation and bank protection.

Large organic debris may be the principal factor in determining characteristics of aquatic habitats in small and intermediate-sized mountain streams in the northwest. In classic meandering channels, hydraulic factors regulate the formation of pools and riffles, which are the major contrasting habitat components of low-gradient streams and rivers. Large organic debris, however, may regulate the distribution of fast-water areas and slow-water depositional sites in steep forested streams. Logs and riparian vegetation in all types of forest streams provide cover and offer other benefits as well as negative effects for fish habitat (Narver 1971; Hall and Baker 1977). Wood itself also serves as a habitat or substrate for a great deal of biological activity by microbial, invertebrate, and other aquatic organisms (Anderson et al. 1978; Sedell and Triska 1977).

The influence of wood on aquatic habitats has been measured in several streams in the H. J. Andrews Experiment Forest. Along a third-order stretch of Mack Creek flowing through old-growth forest, 11 percent of the stream area is covered with wood, 16 percent is wood-created habitat (primarily depositional sites), and 73 percent is nonwood habitat, mainly boulder-dominated areas of fast water. Wood composes 25 percent of the stream area and another 21 percent is habitat-influenced by wood in Devil's Club Creek, a first-order stream. Much of the biological activity by detritus processing and other consumer organisms is concentrated in the areas of wood and wood-related habitat.

Biological Terrestrial/Aquatic Interactions

Riparian vegetation controls both the energy base and physical structure of low-order streams in coniferous forests. In addition, this vegetation may influence the chemistry of soil solution and stream water. Composition of riparian communities determines both the quantity and food quality of organic matter contributed to the aquatic environment. Through these influences the riparian zone also regulates the composition of the aquatic community in terms of relative importance of functional groups (Cummins 1974).

Biotic communities in streams are supported by dual energy sources, autochthonous primary production and allochthonous detritus. Both energy sources are always present but their relative magnitudes are determined largely by conditions of surrounding vegetation and landscape. Inputs of allochthonous detritus to small streams flowing through old-growth forests account for more than 95 percent of organic matter inputs (see Tables 10.3 and 10.4). Shading by riparian vegetation restricts the amount of primary production in a stream by reducing the amount of sunlight reaching the streambed. Sunlight is the energy base for photosynthesis and a source of energy for warming stream water (Brown and Krygier 1970). Both of these factors enhance primary production. Primary production by algae and diatoms in open streams contributes greatly to the energy base of the stream and may well be a more important source of organic matter than streamside vegetation.

Allochthonous detrital inputs range from rapidly-processed, fine particulate inputs, such as leaves, needles, and twigs, to large, slowly-processed, woody debris. Though woody material has lower food quality than nonwoody detritus, the high standing crop and physical stability of logs and branches in Pacific Northwest streams make wood an important and relatively reliable food source for stream organisms over the long term. The energy base of the stream is constantly supplied with refractory fine organic material from wood. This process provides a buffer for the energy base of the biota during periods when few leaves or needles are available.

The function of large organic debris to provide retention structures and longer residence time for fine detritus benefits aquatic organisms by increasing opportunity for detritus processing. Adequate time for detritus processing is critical in headwater streams because microbial conditioning of important food sources such as conifer needles may take more than one hundred days (Sedell et al. 1975).

The species composition of riparian vegetation affects the timing and quality of food resources of aquatic systems. Deciduous vegetation has a more seasonally pulsed and readily decomposed litter input to streams than coniferous trees (Sedell et al. 1974; F. J. Triska pers. comm.). Decomposition of woody debris from the dominant coniferous species in the region is also slower than that of wood of common riparian deciduous species. Therefore, the diversity of food resources, both heterotrophic and autotrophic, reflect a variety of characteristics of the riparian zone.

The position of riparian zones in watersheds makes them potentially effective in modifying the chemistry of groundwater as it approaches streams. The shallow position of bedrock in many mountain streams of the Pacific Northwest results in flow of groundwater through the rooting zone of streamside vegetation. Nutrients that have either escaped the rooting zone of upslope vegetation or entered solution as a result of mineral weathering below the rooting zone may be incorporated into this last terrestrial site for nutrient retention. Additionally, the extensive contact between riparian zone soils and groundwater and stream water accommodates leaching of chemicals into the water. Thus riparian zones have high potential for regulating nutrient fluxes.

The physical environment of riparian zones is well suited for vigorous extended plant growth and nutrient uptake. The position of the riparian zone along streams ensures adequate soil moisture for plant utilization throughout the most of the year. During summer, it is buffered against evapotranspiration stress because of relatively higher humidity and lower temperature in the area along streams. The streamside corridor does not experience the high temperatures of upslope areas, because of cooling by evaporation along the stream. During winter it is not exposed to the winds more prevalent at higher elevations of watersheds. The combination of these factors makes the riparian zone one of the best suited portions of watersheds for seasonally prolonged metabolic activity. Longer periods of growth increase the potential for retention of nutrients from groundwater.

Riparian vegetation dominated by *Alnus rubra* can provide nitrogen to nitrogen-poor aquatic ecosystems of the Pacific Northwest as a result of nitrogen fixation and nitrogen-rich litter. *Alnus rubra,* a common component of riparian stands, converts atmospheric nitrogen gas to reduced or organic nitrogen forms. This species competes best on wet, disturbed sites and thus is often found in the wet bottom areas at the bases of steep slopes in the Cascade and Coast ranges (Newton et al. 1968). Its litter contains approximately 2 percent nitrogen (dry weight) while most other deciduous or coniferous litter contains approximately 0.5 percent to 1 percent nitrogen.

These and other factors, including the high rate of *Alnus rubra* litter production, result in greater standing crop of nitrogen in litter and soil and much faster rates of nutrient cycling in *Alnus rubra* stands contrasted with *Pseudotsuga menziesii* stands (Bollen and Lu 1968). Cole et al. (1978) observed these patterns in thirty- to fifty-year-old *A. rubra* and *P. menziesii* stands on level ground in the Washington Cascades. Zavitkovski and Newton (1971) measured even higher rates of leaf litterfall in younger *A. rubra* stands on more mesic sites in western Oregon.

The high nutrient quality of this litter affects its rate of processing. Since microbial processing of litter is limited by the nitrogen content of the organic matter (Alexander 1961), the higher nitrogen content of *Alnus*-dominated riparian litter results in faster turnover of organic matter within this zone (Cole et al. 1978). In addition, the nitrogen quality of leaf litter in streams has been shown to limit the decomposition by the litter microbes (Kaushik and Hynes 1971). In view of the fact that aquatic invertebrate utilization of leaf litter depends on microbial conditioning (Barlocher and Kendrick 1973), the quality of litter from the riparian zone has a significant impact on dynamics of the stream ecosystem.

Food resources and physical habitat opportunities, which we have suggested are controlled by riparian vegetation, determine much of the structure of aquatic invertebrate communities. Particular functional groups of organisms are adapted to processing specific materials under certain habitat conditions (Chapter 10; Cummins 1974). For example, "gougers," such as beetle larvae, utilize large woody debris (Anderson et al. 1978), "shredders" consume leaves and needles, and "scrapers" eat algae on the surfaces of rocks. Consequently, changes in relative proportions of these food and substrate types in a stream trigger shifts in aquatic communities. Compositional, structural, and functional changes in riparian vegetation trigger changes in structure and composition of stream communities. Biological consequences of terrestrial/aquatic interactions are described in greater detail in Chapter 10.

SPATIAL VARIATION OF TERRESTRIAL/AQUATIC INTERFACES

The character of the terrestrial/aquatic interface changes systematically with variation in stream size. The forest dominates small headwater streams and suppresses development of herb, shrub, and small tree components of the riparian community. The canopy is partially open over intermediate-sized streams (third through fourth or fifth order), permitting greater expression of deciduous riparian plants. Larger rivers in western Oregon are bordered by stands dominated by deciduous trees, principally *Alnus rubra* and *Populus trichocarpa,* developed on fresh substrates prepared by major floods. Although the transition is gradual and varies with regional physiography and vegetation, the energy base shifts from heterotrophy in small streams to autotrophy in rivers because of reduced shading and litter input by riparian vegetation. In western Oregon this energy base shift occurs in the range of third- to fourth-order streams.

In general, the intensity of terrestrial/aquatic interactions under flow conditions up to bank-full diminishes with increasing stream size. Wider streams receive less litter input per unit of stream surface area and less shading by streamside vegetation and have greater capability for transporting large organic material.

TEMPORAL VARIATION IN THE RIPARIAN ZONE

Temporal variation in the riparian zone occurs on time scales of storm and seasonal changes of water level and successional response to severe disturbance of streamside and upslope vegetation. These sources of variation are common under the general climatic conditions of the Pacific Northwest, which are characterized by mild, wet winters and warm, dry summers. Large floods occur rather commonly in response to heavy rains and warm rain on snow cover. Consequently, small forested watersheds in the H. J. Andrews Experimental Forest, such as the 60-ha watershed 2, have an average August streamflow of only about 2.5 percent of average January runoff. Peak discharge of a 10-year return period flood in watershed 2 is more than one hundred times larger than average August runoff (R. D. Harr, pers. comm.).

In order to contrast the wet and dry seasons of an active stream area, we surveyed the 6400-ha Lookout Creek drainage, H. J. Andrews Experimental Forest, at two streamflow levels. The stream network was mapped and channel widths were measured in the spring when discharge at the Lookout Creek gauging station was 2.26 m^3/sec (80 cfs) to characterize winter baseflow, which is typical minimum flow for the wettest six to eight months of the year. (G. W. Leinkaemper pers. comm.) Remapping of the network and measuring of channel widths was done in late summer when discharge of Lookout Creek was 0.71 m^3/sec (25 cfs) to characterize summer baseflow conditions. This fifth-order drainage network experiences a 28 percent reduction in total length between winter and summer baseflow (Figure 9.6). Decrease in average width ranges from 60 percent for first-order streams to 16 percent for the fifth-order stream segment. Total wetted stream area is reduced 45 percent between early spring and late summer. Of course, maximum annual change in stream area is much greater; in the 19 year period of record on Lookout Creek maximum and minimum discharges have been 189 m^3/sec (6660 cfs) and 0.18 m^3/sec (6.4 cfs).

Extremes of climate and runoff contribute to occurrence of a variety of disturbance mechanisms that affect streamside areas and/or upslope vegetation. During floods on large and intermediate-sized rivers, large, floating or-

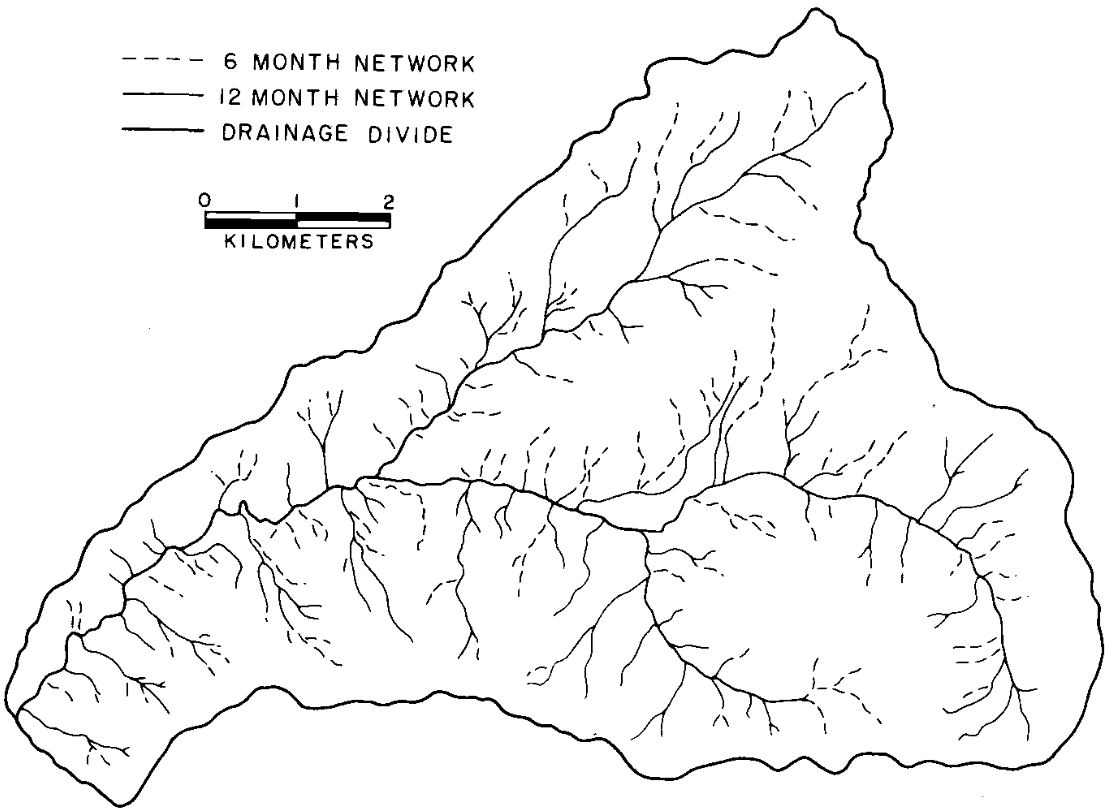


FIGURE 9.6 *Drainage networks of Lookout Creek watershed for six- and twelve-month periods in a year (mapped by G. W. Lienkaemper).*

ganic debris and ice may trim, batter, and destroy vegetation along the riparian corridor, thereby initiating sprouting from many species of damaged residual trees and shrubs (Sigafoos 1964). Lateral cutting by streams and rivers wipes out existing riparian communities and sets the stage for development of new ones by invading plants. Summer drought contributes to the occurrence of wildfire that may destroy vegetation in both riparian and upslope areas. In the steep terrain of the western Cascade Mountains, however, wildfire commonly leaves natural streamside buffer strips (F. J. Swanson, pers. comm.), apparently because of more moist conditions along streams and the natural tendency for fires to burn upslope. These conditions reduce the impact of a severe disturbance of the forest on the stream environment. Similarly, current forest practice rules call for buffer strips along third-order and larger streams.

Severe disturbances of riparian vegetation initiate successional redevelopment of the plant communities. Both streamside and upslope vegetation in many situations in western Oregon have been disturbed simultaneously and equally. Riparian and upslope communities in these cases follow successional sequences with contrasting compositional and structural development. Field observations of stands up to forty years in age after clearcutting have led to the following conceptual model or relative riparian and upslope vegetation development (Figure 9.7) that is now being tested quantitatively. We hypothesize that in the first five to ten years following disturbance, deciduous riparian species, notably *Alnus rubra* and *Salix* spp., may develop more rapidly than

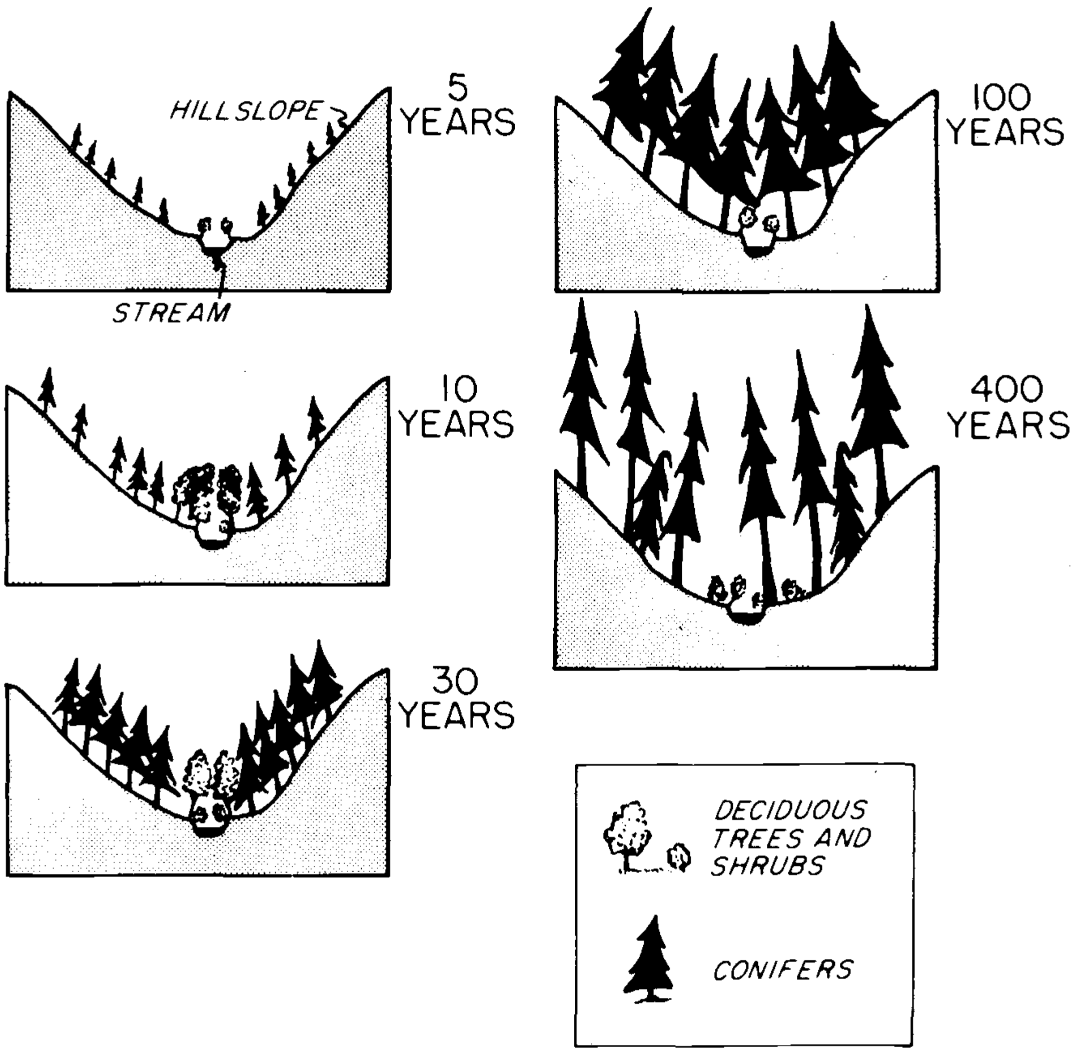


FIGURE 9.7 *Hypothetical changes in the riparian zone through succession.*

shrubs and conifer seedlings and saplings on upslope sites. This rapid expansion of riparian vegetation would return the aquatic ecosystem to a detrital energy base typical of forested streams more quickly than it would if the stream were solely dependent on upslope vegetation communities for shading and detrital inputs. As a stand reaches an age of about thirty to sixty years, upslope conifers close canopy over small streams, shade out lower strata of streamside vegetation, and gradually suppress this component of riparian zone vegetation. Establishment of shade-tolerant conifers may also occur at this stage, further enhancing the switch from deciduous to coniferous dominance along streams. Blowdown and other mortality may open the canopy in old-growth stands, permitting greater development of riparian vegetation than in intermediate-age stands.

This hypothetical phasing of deciduous and coniferous dominance during successional development of riparian zone vegetation would result in progressive changes in the quality, quantity, and seasonal timing of litter inputs to the stream. Figure 9.8 schematically depicts temporal variation of organic matter

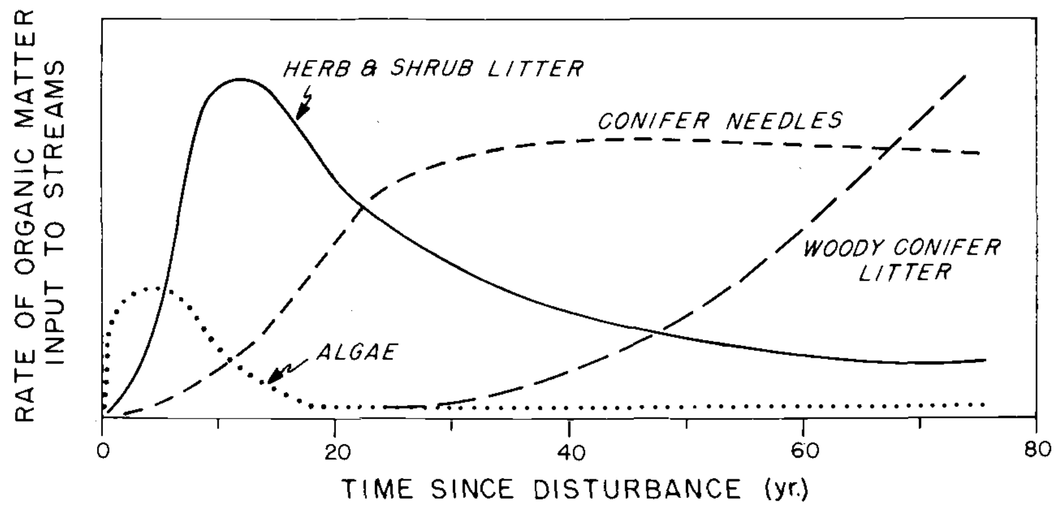


FIGURE 9.8 *Hypothetical phasing of organic matter inputs into a small stream following removal of riparian and upslope vegetation (after Turner and Long 1975; S. V. Gregory pers. comm.; F. J. Triska pers. comm.).*

inputs to a small stream during eighty years of stand development. The initial pulse of algae is a response to high light levels, which are quickly reduced by shading of herbaceous and shrubby vegetation. Herbs and shrubs dominate litter production in the second decade following disturbance; then conifer needles, followed in time by conifer woody litter, are major types of organic matter inputs (Turner and Long 1975).

The pattern and timing of response of the riparian zone to disturbance depends both on the type of disturbance and the rate of recovery of various components and related functions of riparian zone vegetation (Table 9.1). Events such as debris torrents primarily damage the lower strata of riparian vegetation, reducing shade and litter inputs from deciduous and annual components of streamside vegetation for five to fifteen years, but the role of undamaged overstory conifers in performing the same functions may be unaltered.

If upslope vegetation is removed by wildfire or clearcutting, its role as a source of large debris may be reduced or eliminated for decades. Large debris, however, commonly has sufficient residence time in a channel to continue controlling structure of the stream environment until the postdisturbance stand begins to contribute large organic material. Based on dendrochronologic dating of downed logs, we have commonly observed pieces of debris that have been in channels from twenty to more than a hundred years (Swanson et al. 1976). *Thuja plicata* is particularly long-lasting, followed by *Pseudotsuga menziesii, Tsuga heterophylla,* and *Alnus rubra* in order of increasing rate of breakdown (Anderson et al. 1978).

The postwildfire phasing of debris loading has been studied in small streams flowing through a chronosequence of stands ranging from 75 to 135 years in age (Swanson and Lienkaemper 1978). Debris from prefire and postfire stands may be distinguished by evaluating debris size, residence time in channel, and other factors. Some of these relations are evident in Figure 9.9,

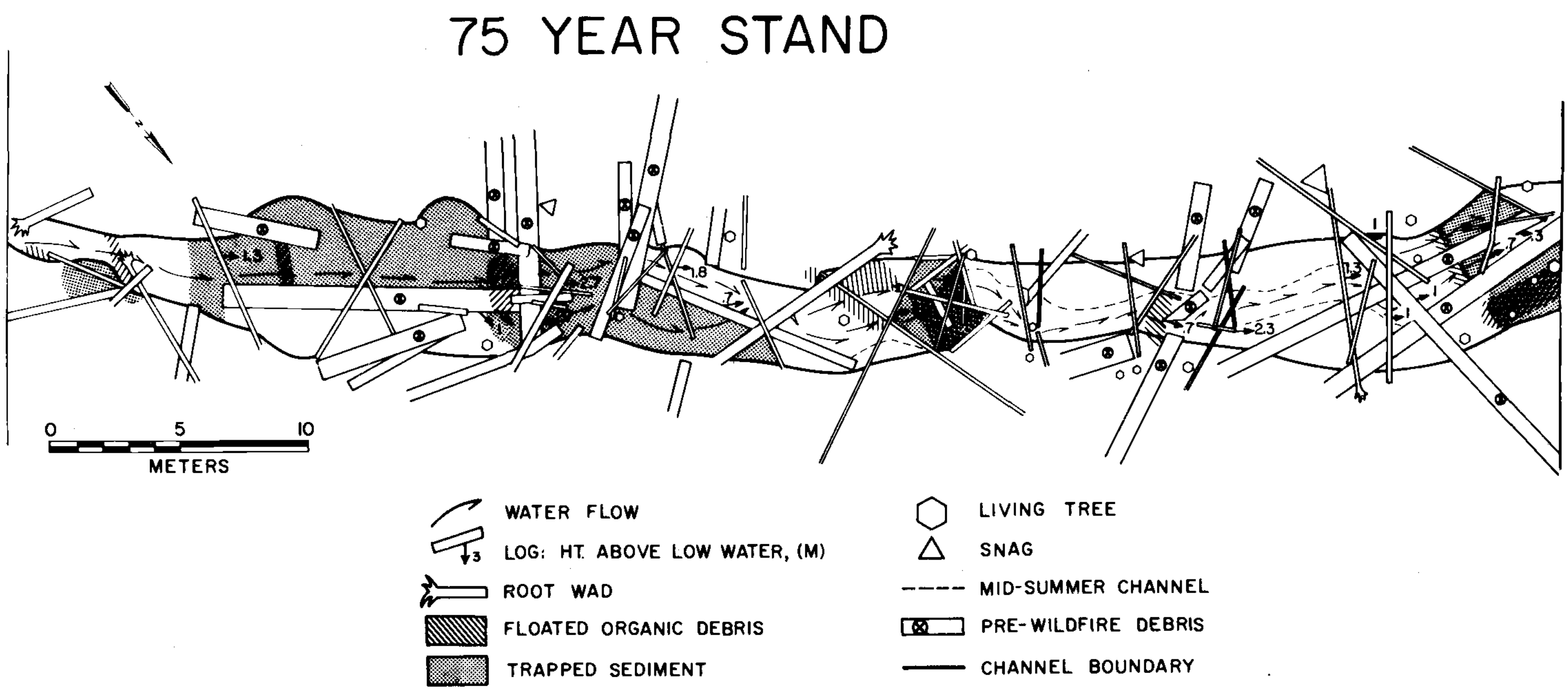


FIGURE 9.9 *Map of large organic debris in a first-order stream flowing through a seventy-five-year-old postwildfire stand (mapped by G. W. Lienkaemper).*

which shows debris in a stream section in a seventy-five-year-old stand. The large-diameter pieces were introduced from the prefire, old-growth stand, and the small pieces were derived from the postfire stand. Observations in streams such as this indicate that the change in dominance of debris of prefire and postfire origin is gradual, occurring over more than a century.

Although this discussion emphasizes infrequent, catastrophic disturbances and subsequent succession, numerous small-scale disturbances are more common in streamside areas. This frequent mortality of individual and small groups of trees results in complex, mixed-age-class stands of streamside vegetation.

SUMMARY

The riparian zone is subject to many definitions. Based on a functional rather than vegetative or topographic definition, the riparian zone is the area of direct interaction between aquatic and terrestrial environments. This zone includes low-lying vegetation in and adjacent to channels as well as higher vegetation strata forming the overhanging canopy. Riparian zone vegetation in coniferous forests of the Pacific Northwest is typically composed of low strata of herbs and deciduous shrubs and small trees beneath a canopy of large conifers.

The composition and structure of riparian plant communities are largely determined by light availability; substrate conditions such as wetness, frequency and intensity of scouring; and availability of sites for rooting. Specific plant associations are adapted to fresh alluvial deposits, wet cliffs, wet flat subsoil conditions, and other types of sites. In a sampling of first- through third-order sites, larger streams have higher cover of shrub, and large shrub/small tree strata, apparently in response to greater light availability due to opening of the overstory. Variation in the small and large herb strata is particularly sensitive to substrate type and disturbance history.

Vegetation along small and intermediate-sized streams (up to about fourth-order) exercises important controls over physical conditions in the stream environment. Rooting by herbaceous and woody vegetation tends to stabilize streambanks, retard erosion, and determine bank morphology. Aboveground riparian vegetation is an obstruction to highwater streamflow and sediment and detritus movement and is a source of large organic debris for streams. Large pieces of woody debris in streams: (1) control routing of sediment and water through channel systems; (2) dissipate stream energy; (3) define habitat opportunities; and (4) serve as substrates for biological activity by microbial and invertebrate organisms.

Riparian vegetation regulates the energy base of the aquatic ecosystem by shading and supplying plant and animal detritus to streams. Shading affects both stream temperature and light availability to drive primary production. Thus multiple functions of riparian vegetation determine the balance between autotrophy and heterotrophy in aquatic ecosystems. By controlling this balance and the quantity, food quality, and seasonal timing of litter inputs, riparian vegetation also influences the composition of the aquatic community in terms of relative importance of functional groups.

Riparian vegetation and organic detritus derived from it may also alter the chemical composition of water as it moves through the aquatic/terrestrial interface and as it flows through the stream ecosystem. The forest/stream interface is a zone of numerous interactions. Living vegetation takes up nutrients from stream-adjacent soil solution and, in the case of hydrophytic roots, from stream water itself. Nutrients are released from dead organic matter by leaching and decomposition. Decomposition also involves nutrient uptake.

All of these functions of riparian vegetation vary in time and space. Temporal variation occurs on the time scale of vegetative succession following major disturbances such as wildfire, clearcutting, and floods. Spatial variation of riparian characteristics takes place along the continuum of increasing stream size from small headwater streams to large rivers.

The forest/stream interface is a zone of numerous interactions important to both terrestrial and aquatic components of watershed ecosystems. Understanding of this ecosystem should not be viewed as the sum of strictly aquatic and strictly terrestrial components that meet in an abrupt interface. The transfer of materials and energy between these two components is mediated by a riparian zone distinctive in composition and structure from upslope vegetation.

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