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"R1-R4" AND "BOISED" SEDIMENT PREDICTION MODEL TESTS USING FOREST ROADS IN GRANITICS[1]

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ABSTRACT: Erosion and sedimentation data from research watersheds in the Silver Creek Study Area in central Idaho were used to test the prediction of logging road erosion using the R1-R4 sediment yield model, and sediment delivery using the "BOISED" sediment yield prediction model. Three small watersheds were instrumented and monitored such that erosion from newly constructed roads and sediment delivery to the mouths of the watersheds could be measured for four years following road construction. The errors for annual surface erosion predictions for the two standard road tests ranged from +31.2 t/ha/yr (+15 percent) to -30.3 t/ha/yr (-63 percent) with an average of zero t/ha/yr and a standard deviation of the differences of 18.7 t/ha/yr. The annual prediction errors for the three watershed scale tests had a greater range from -40.8 t/ha/yr (-70 percent) to +65.3 t/ha/yr (+38 percent) with a mean of -1.9 t/ha/yr and a standard deviation of the differences of 25.2 t/ha/yr. Sediment yields predicted by BOISED (watershed scale tests) were consistently greater (average of 2.5 times) than measured sediment yields. Hillslope sediment delivery coefficients in BOISED appear to be overly conservative to account for average site conditions and road locations, and thus over-predict sediment delivery. Mass erosion predictions from BOISED appear to predict volume well (465 tonnes actual versus 710 tonnes predicted, or a 35 percent difference) over 15 to 20 years, however mass wasting is more episodic than the model predicts.

(KEY TERMS: sediment model; BOISED; erosion; sediment prediction; test.)

INTRODUCTION

The "Guide For Predicting Sediment Yields From Forested Watersheds" (hereafter referred to as the "R1-R4 Model") was developed by specialists from U.S. Forest Service Regions 1 and 4 and the Rocky Mountain Experiment Station to provide land managers a procedure to evaluate sediment yield consequences of alternative land management practices on forested mountain lands (USDA Forest Service, 1981). The R1-R4 Model estimates average annual sediment yield for undisturbed forest conditions and following disturbances from road construction, logging and forest fire. Effects of land disturbances on both mass and surface erosion processes are evaluated. A number of National Forests have adapted the R1-R4 Model to their specific conditions utilizing locally derived information to adjust model coefficients. One such adaptation is the BOISED model developed by the Boise National Forest in Idaho (Reinig *et al.*, 1991).

Numerous studies have shown that most sediment resulting from timber harvest activities is caused by erosion on forest roads associated with the harvesting rather than by erosion on the areas disturbed by tree cutting and skidding. For example, Megahan *et al.* (1979) found 88 percent of 1418 landslides were associated with roads in the Boise and Clearwater National Forests of Idaho. Although landslides are an important erosion process in steep terrain, surface erosion on forest roads can also be very high (Megahan and Kidd, 1972; Ketcheson and Megahan, 1996). Surface erosion is much more widespread than mass erosion because it occurs on all slopes, not just the very steep. Megahan and Kidd (1972) reported on a six-year study of erosion from a logged area in typical mountainous terrain of the Idaho Batholith. The study included measurements of surface and mass erosion from road construction and timber harvest on three, small watersheds. Based on long term sediment yield data for the area, they found that average annual erosion was accelerated by a factor of 770 times on timber access roads as compared to a factor

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of 0.6 times on the area disturbed by cutting and skidding.

A test of road erosion and sediment production components in the R1-R4 Model and BOISED is an important need given the large and ubiquitous contribution of roads to erosion and sediment yields and widespread use of the models. However, such a test is difficult because it requires long term data documenting road erosion under ambient climatic conditions over relatively long stretches of road, as well as sediment yields from the watersheds containing the roads. In this paper, we evaluate the utility of the R1-R4 Model for predicting on-site road erosion and BOISED for predicting mass erosion and sediment yields. Model predictions are compared against four years of erosion and sediment yield data following road construction on three study watersheds in the Silver Creek Study Area located on the Boise National Forest in southwestern Idaho.

DESCRIPTION OF THE STUDY AREA

The study site is in the headwaters of the Silver Creek drainage, a tributary to the Middle Fork of the Payette River in southwestern Idaho. Coordinates of the approximate center of the study area are 44°25'N latitude and 115°45'W longitude. The study was conducted on new roads in the Ditch, No Name, and Cabin Creek study watersheds. A fourth study watershed, Eggers Creek, was maintained as a long term, undisturbed control watershed. Watersheds range in size from 102 to 130 hectares (Figure 1).

Annual precipitation averages about 900 mm with most of the precipitation occurring during the winter months. Summers are hot and dry with occasional, localized convective storms. More generalized frontal type rains are common in May and June and in late September and October. About 65 percent of the annual precipitation occurs as snowfall from mid

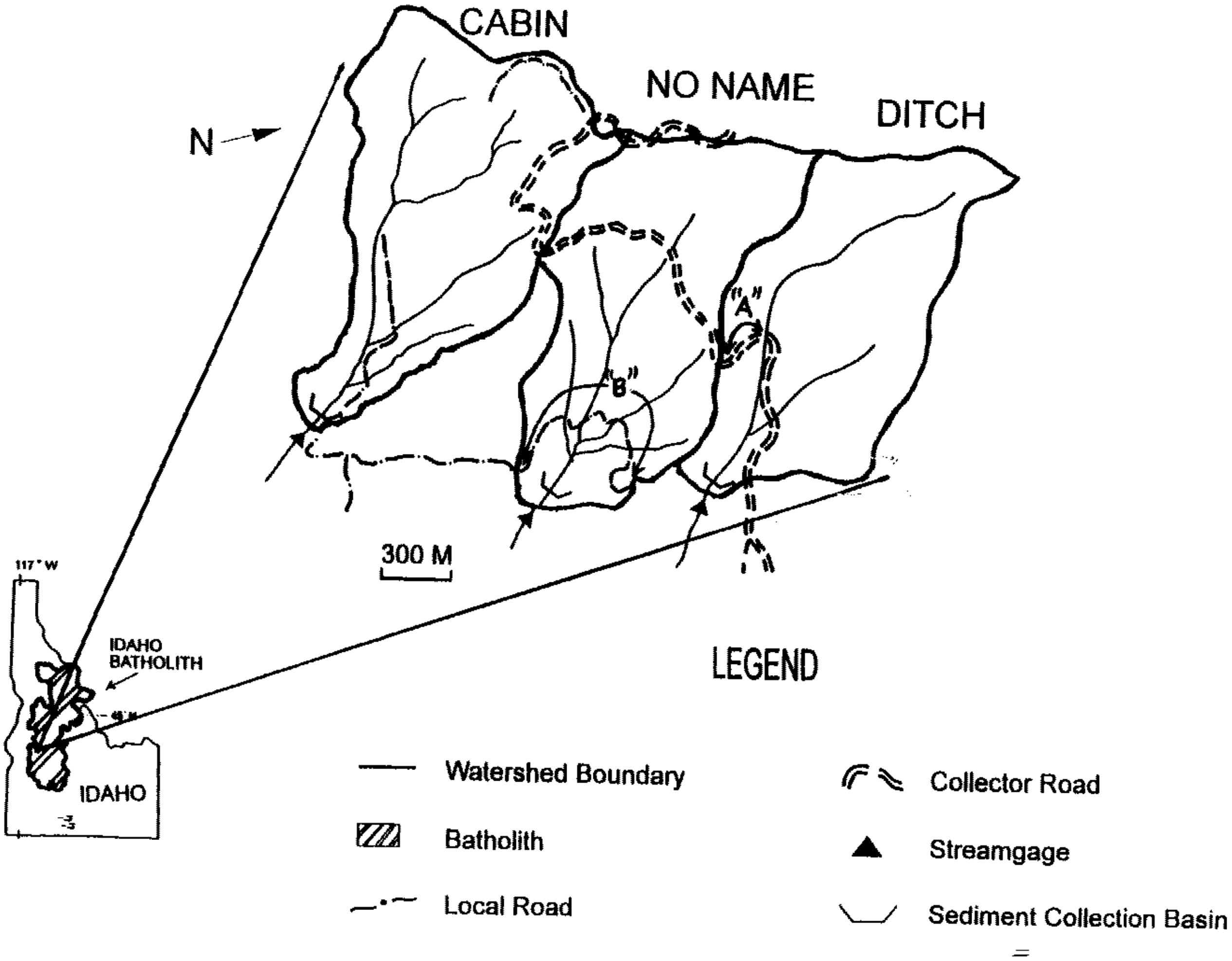

Figure 1. Study Area Location Map, Road Locations, and Instrumentation of the Three Study Watersheds.

November to mid April, and causes an average maximum snowpack water equivalent of about 55 cm. Streamflow is dominated by spring snowmelt.

Bedrock is primarily coarse-grained quartz monzonite that is typical of the central and southern portions of the Idaho batholith. Bedrock is moderately to well weathered (Clayton *et al.*, 1979). Soils are weakly developed with A horizons ranging from 5 to 25 cm thick overlying moderately weathered granitic parent material. Soil textures are loamy sands to sandy loams and depth to bedrock is usually less than 1.0 m. Soils less than 20 cm deep are common on ridges and south slopes. Scattered outcrops of granitic bedrock are found in the upper elevations of the watersheds. Four types of soils are found on the study watersheds. Sandy-skeletal mixed typic xerorthents predominate on south slopes. Sandy-skeletal, mixed typic cryorthents, sandy-skeletal mixed typic cryoborolls and mixed alfic cryopsamments are found at other locations (Clayton and Kennedy, 1985).

Hillslopes are relatively steep, ranging from 15 to 40 degrees, and are highly dissected. The mapping unit used to describe the landscape on the Boise National Forest is the land type. Land types are units of land having defined combinations of climate, slope morphology, and vegetation. Six land types are mapped in the study watersheds. Land type descriptions can be found in Wendt *et al.* (1975).

Vegetation varies primarily in response to changes in slope aspect and soil properties and is characterized by two principal vegetation habitat types (Steele *et al.*, 1981): Douglas-fir/white spirea, ponderosa pine phase [*Pseudotsuga menziesii* (Mirbel) Franco/*Spiraea betulifolia* Dougl., *Pinus ponderosa* Laws. phase] and Douglas-fir/ninebark, ponderosa pine phase [*Pseudotsuga menziesii* (Mirbel) Franco/*Physocarpus malvaceus* (L.) Maxim., *Pinus ponderosa* Laws. phase]. Timber stands are dominated by approximately equal volumes of mature and overmature ponderosa pine and Douglas-fir.

A total of 6.64 km of forest roads were constructed on the study watersheds between June and November 1980. The total planimetric area of disturbance from the top of the cut slope to the toe of the fill slope for the three study watersheds was 1.38 ha in Ditch Creek, 3.83 ha in Cabin Creek, and 4.54 ha in No Name Creek. Two types of roads were constructed (Figure 1): (a) a collector road designed for permanent access; and (b) local roads designed to support timber harvest only. Construction was generally cut and fill with some end-haul. Certain fills were layer-placed. Sustained grades characterized the collector road and gentle horizontal and vertical curves allow maximum speeds of 32 km/hr. The designed 4.3 m wide running surface was widened for curves, ditches, turnouts, and shoulders to as much as 8.6 m. Local roads used sharper curvatures and rolling grades that minimized excavation. Shoulders and occasional turnouts were added to the 3.7 m running surface. Two of the local roads also had an inside ditch, for a maximum width of approximately 6.0 m and a design speed of 8 km/hr. Road designs varied by road and by watershed.

Road design features used within the Ditch Creek watershed were representative of "typical" road design features for the area in 1980 and included: (1) a native material road surface, (2) native material berms to protect fill slopes from direct runoff on outsloped sections, (3) grass seed and fertilizer applied by hand to cut and fill slopes, and (4) small rock hand-placed at culvert outlets as energy dissipators.

Roads in Cabin Creek were designed for maximum erosion control and utilized: (1) asphalt pavement on the collector road and crushed rock surfacing on local roads; (2) grass seed, straw mulch, plastic netting, and transplanted shrubs and trees on fill slopes; (3) grass seed and hydromulch on cut slopes; and (4) cull logs placed across the hillslope immediately below the toe of fill slopes. Drainage was provided by concrete curbs and drains on asphalt road sections by either compacted earthen berms protected by rock or alternative insloping and outsloping of the road surface on roads where crushed rock surfacing was used. Energy dissipators were installed at the outlet of all road drainage culverts. Road fill slopes were protected by berms and downdrains or crushed rock in outsloped sections of the local roads.

Road design features on both roads in No Name Creek were similar to those used in Ditch Creek. However on the upper road, a series of experimental treatments were applied at selected road tread and road cut and fill slopes for detailed studies of erosion processes and erosion control treatment effectiveness (Vincent, 1979; Burroughs and King, 1985; Megahan *et al.*, 1991, 1992).

No additional activities took place on the study watersheds from 1980 through 1984. Traffic use on the local roads during this time was limited to normal administrative use and research access. Additional traffic occurred on the collector road for recreation and other purposes.

SEDIMENT YIELD PREDICTION PROCEDURES

Surface Erosion

The surface erosion component of the R1-R4 Model and its derivatives such as BOISED are empirically derived procedures for estimating erosion based on all pertinent data available at the time (USDA Forest

Service, 1980). Road surface erosion rates used in the models are based on a six-year study of road erosion on granitic soils of the Idaho Batholith (Megahan and Kidd, 1972). Surface erosion data were collected from a total of 0.3 km of roads located in two small watersheds in the headwaters of the South Fork of the Salmon River. Utilizing these data, Megahan (1974) developed an exponential model that describes the rate of road erosion as a function of time since construction.

Megahan's model was used to develop the basic annual road surface erosion rates used in the R1-R4 Model and BOISED. Model erosion rates decrease exponentially over time from 237 metric tons/hectare/yr (t/ha/yr) the first year to 18 t/ha/yr the third year after construction. Subsequent annual erosion continues at a sustained level of 18 t/ha/yr.

Basic erosion rates are applied to the total road prism area based on the horizontal distance from the top of the road cut to the toe of the road fill (Figure 2). This includes road subgrade, cut and fill slopes, ditches, berms, turnouts and any other constructed features when present. The basic erosion rate applies to an annually maintained "standard road" which is defined as a 4.9 m wide road with a 5 to 7 percent sustained grade, balanced construction, insloped with a ditch, native surface, cut and fill slopes dry seeded to grass, and cross drains at 150 m spacing, constructed in granitic materials on a 50 percent side slope. The assumption is made that the road area factor accounts for deviations in road width and hillslope gradient from the "standard" road. The basic erosion rate is adjusted to other geologic types by a geologic erosion factor which is based upon relative soil erodibility for different soil parent materials.

Mitigation measures are applied to basic road surface erosion rates (Figure 2) in the form of a percent reduction based on the nature of the practice used. A table of reduction factors is provided for a variety of erosion mitigation practices such as revegetation, mulching and road design features based upon road erosion control studies available at the time. Road design features can include deviations from the standard road such as road surfacing, reductions in road grade, road use and the placement of sediment retention structures below the road. Mitigation corrections are applied to the basic erosion rates at the time they are effective. Mitigation factors can be summed to a maximum of 80 percent except in the case of road obliteration which can be 95 percent.

Mass Erosion

For this study, we used the mass erosion module in BOISED which is based on an extensive survey of landslide occurrence (Megahan *et al.*, 1979) in areas of granitic parent material, including the Payette River watershed and present study area. The survey tabulated 228 landslides by road age and slide volume and provided an estimate of average annual mass erosion on roads by road age in years. Annual values

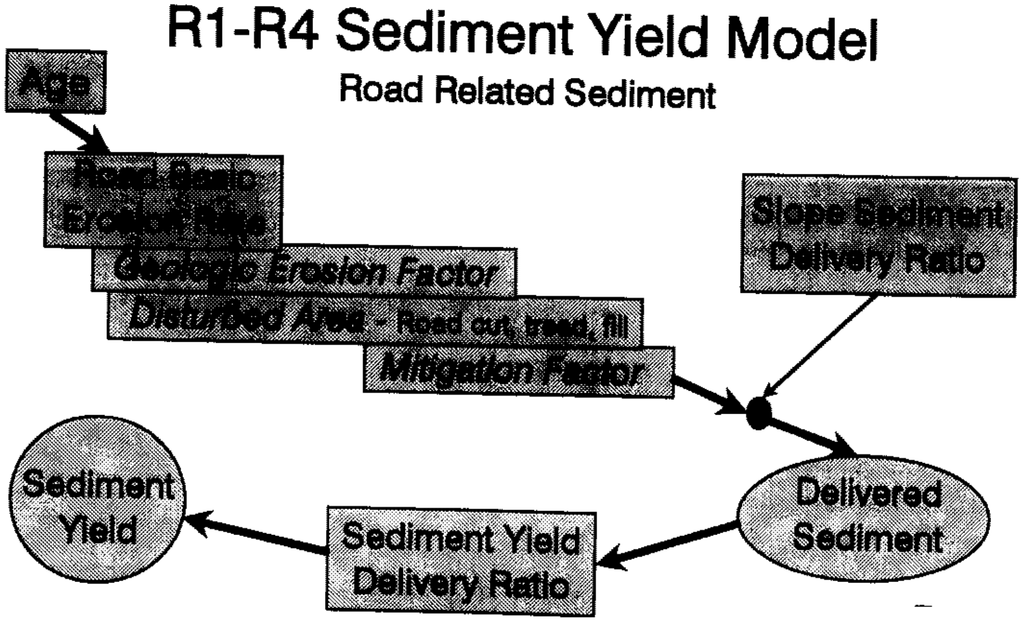

Figure 2. Schematic of Road Related Sediment Prediction, R1-R4 Sediment Yield Model.

from this survey were used to define the annual acceleration factor used in BOISED. Average annual mass erosion on roads is calculated as the product of the annual acceleration factor, the undisturbed natural erosion rate for the site and the area of road constructed on slopes greater than 45 percent (slopes less than 45 percent are assumed to have no mass erosion).

Sediment Delivery to Streams and Sediment Yields

Sediment is delivered from the erosion source to streams using a slope delivery ratio (Figure 2) for both surface and mass erosion. The R1-R4 Model suggests that these coefficients be derived using procedures in WRENSS (USDA Forest Service, 1980). For the present study, we used the procedure outlined in BOISED where coefficients for surface and mass erosion delivery were developed for individual landtypes based on local observations and data. Surface and mass erosion values are adjusted by the slope delivery coefficients to account for sediment storage on hillslopes. The remaining sediment is assumed to reach streams in the same year that the erosion occurs. For watersheds less than 259 ha (one square mile) sediment yield for the year is the sum of the adjusted erosion for all the landtypes in the watershed. For larger watersheds, sediment delivered to streams is adjusted by a sediment yield delivery ratio (Figure 2) that is a function of watershed size. This ratio accounts for sediment storage in channels and valleys.

METHODS

Field Data Collection and Analysis

Actual road erosion rates were determined by adding the amount of sediment from road surface erosion stored on hillslopes, the amount of mass erosion from the road, and the amount of sediment attributed to road construction that was yielded at the mouth of each study watershed. Such an approach ignores changes in channel sediment storage. However, observations of channel conditions and a sediment tracer study in these steep headwater watersheds (Ketcheson and Megahan, 1991) suggest that channel sediment storage effects are very minor.

Hillslope storage was determined from a complete survey of sediment deposits on the hillslopes below all roads on the study area as described in Megahan *et al.* (1986). This was possible because the light colored granitic sediment deposits are easily distinguished from the darker colored residual soils. Sediment deposits were monitored during June and July from 1981 through 1984.

Mass erosion of road fill material occurred at one location on the collector road the second year (1982). The following year a second, smaller failure occurred at the same site. We used surveyed cross sections at the failure site coupled with the original road design surveys and road fill bulk density measurements to document soil loss from mass erosion.

Sediment yield was measured in sediment collection basins behind dams located at the mouth of each study watershed (Figure 1). Sediment basins were operated from 1966 through 1984 in the Cabin, Ditch, and Eggers Creek watersheds and from 1979 through 1984 in the No Name watershed. Collected sediments were flushed in the spring after snowmelt as needed to maintain reservoir storage capacity. Detailed cross-section surveys in the spring (before and after flushing) and in the fall were used to determine the volume of sediment deposited in the basins. Accumulated sediments were core sampled to establish volume-weight relationships.

Some suspended sediment is transported through the basins and over the dams during spring snowmelt. Depth-integrated suspended sediment samples were collected at the spillway of the sediment dams in all study streams using a standard DH48 sampler during the snowmelt period for a total of seven years. Relationships between stream discharge and suspended sediment concentrations were used with mean daily discharges to estimate annual suspended sediment lost over the dams. Total annual sediment yields are the sum of the flux of sediment over the dams plus the sediment deposited in the sediment basins.

Sediment delivered to the mouth of each watershed, attributed only to road construction, was determined using a before-after, treated-control study design. Such a design corrects for natural annual variations in sediment yields caused by climatic differences between years. Regression relationships were developed between total annual sediment yields in the Cabin and Ditch Creek watersheds as compared to the undisturbed Eggers Creek watershed for the 14-year period of record before disturbance (Figures 3a and 3b). Log transformations of annual sediment yields were used to assure uniform variance over the range of data. Sediment yields following road construction that fell outside the 95 percent prediction interval for individual years indicated a statistically significant increase in sediment caused by road construction. The increase in sediment yield resulting from road construction is calculated as the difference between the measured sediment yield and the fitted regression line. An increase in the annual sediment yield amounting to 28 tonnes (Figure 3a) was found

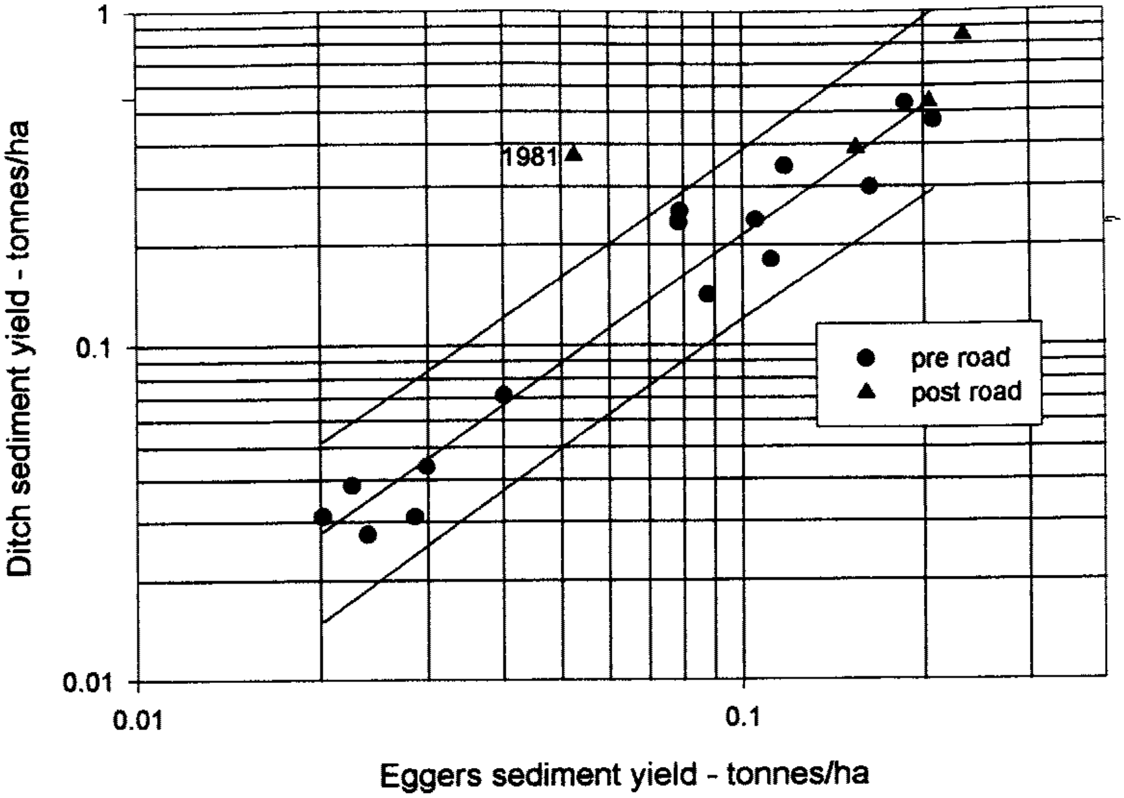

Figure 3a. Effect of Road Construction on Sediment Yield in Ditch Creek. Eggers Creek is the control watershed.

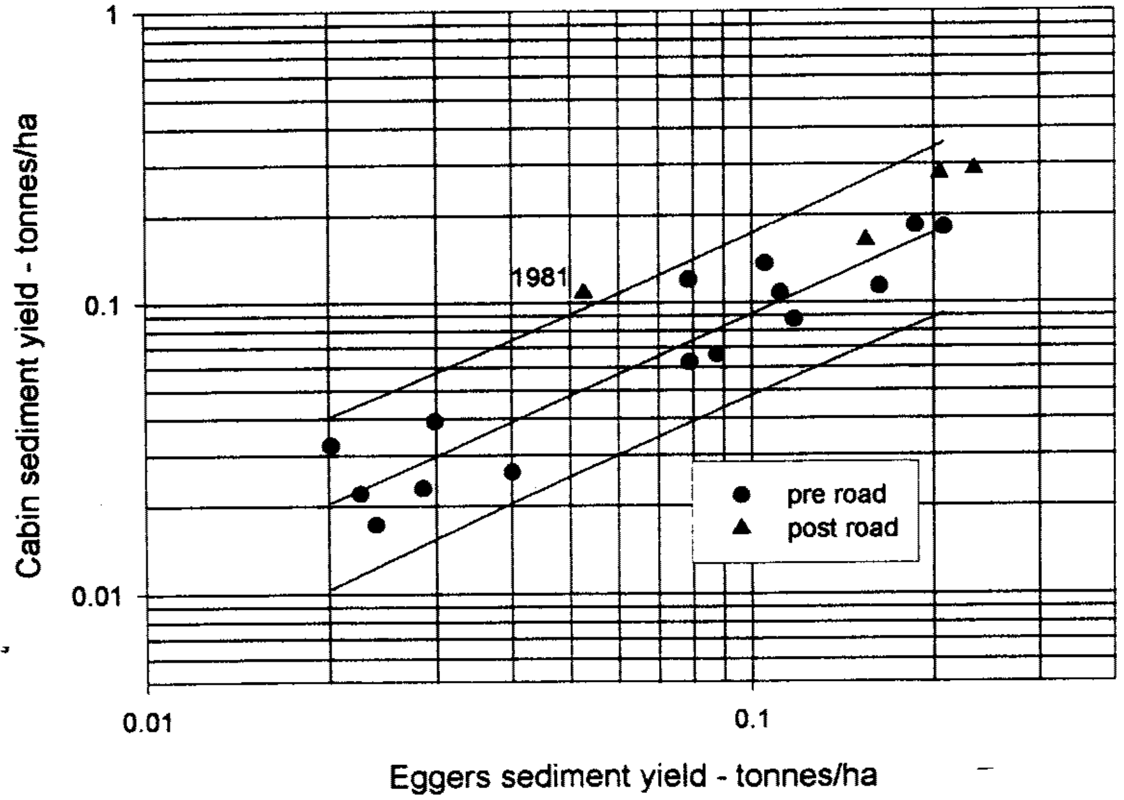

Figure 3b. Effect of Road Construction on Sediment Yield in Cabin Creek. Eggers Creek is the control watershed.

for the Ditch Creek the first year after road construction but no increases were found in subsequent years. A small increase in annual sediment yield amounting to 6.3 tonnes occurred the first year after road construction in Cabin Creek (Figure 3b).

The before-after, treated-control study design was not possible on No Name Creek because we only had two years of data from the sediment yield detention basin prior to road construction. We evaluated treatment effects by assuming that sediment yields in No Name Creek would have been the same as sediment yields from the undisturbed Eggers Creek if roads had not been built in the No Name Creek watershed. This appeared reasonable because of the similarity in watershed characteristics for the two basins and the close agreement between the sediment accumulated in the sediment basins for the two years of concurrent data before road construction (1.3 vs 1.6 tonnes the first year and 10.7 vs. 9.5 tonnes the second year for No Name and Eggers Creeks, respectively). A plot of the measured annual sediment yields for the two watersheds then reflects treatment effects (Figure 4). Note the small differences prior to road construction in 1979 and 1980 followed by large increases after construction until 1985 when differences began to fluctuate below and above the unroaded watershed, indicating no treatment effect. We estimated the increased sediment yields caused by roads in the No Name watershed by subtracting sediment yields in Eggers Creek from the corresponding annual sediment yield in No Name Creek for the years 1981-1984. Sediment yield differences in subsequent years were assumed to represent natural variability within the two watersheds (Figure 4). Using this procedure, roads increased sediment yields in No Name Creek by 40, 86.2, 24.3, and 4.6 tonnes in 1981 to 1984, respectively.

The 1981 sediment yield increase of 40 tonnes in No Name Creek was the direct result of surface erosion from road construction. However, in 1982 a rotational slump of 440 tonnes of road fill material occurred at a stream crossing in the headwaters of the watershed. This same site failed again in 1983 involving 83 tonnes of material. Field observations suggested that a small percentage (17 percent by calculation) of the slump material entered the stream. Therefore, sediment yields in No Name Creek in 1982 and 1983 were the result of both surface and mass erosion on the roads in the watershed.

We estimated the amount of sediment due to road surface erosion in 1982 and 1983 by assuming that sediment yields from 1981 to 1983 occurred in the

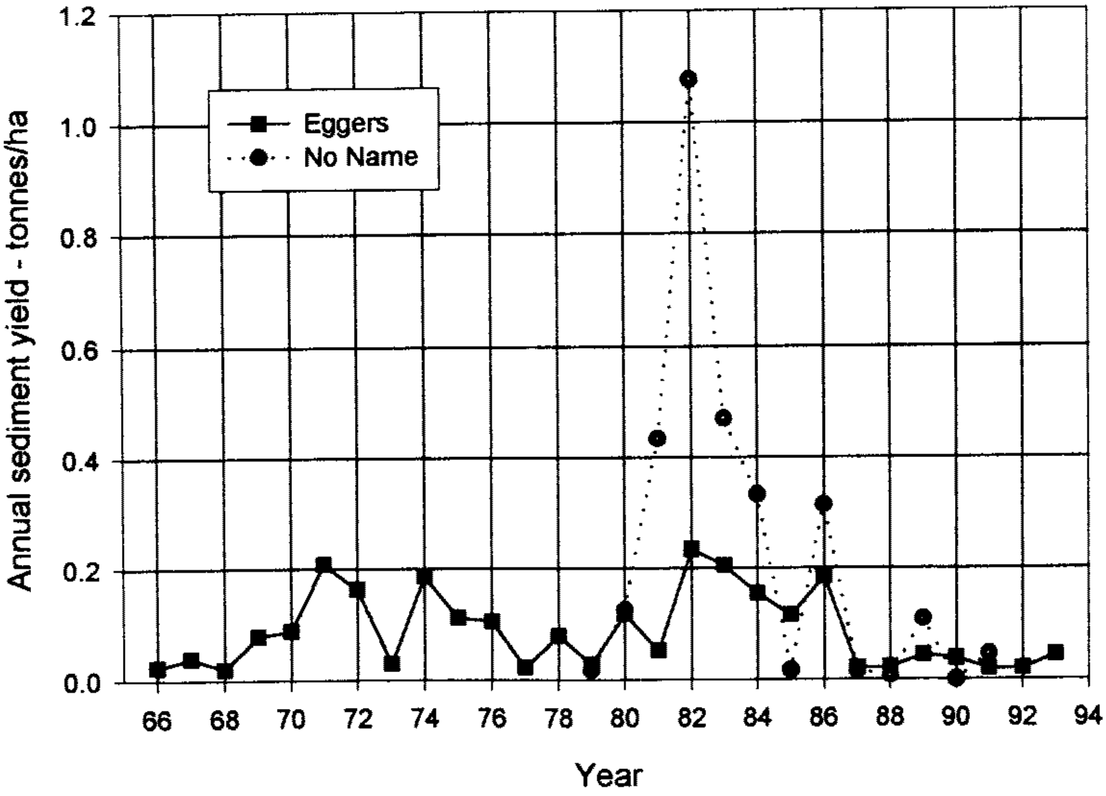

Figure 4. Effect of Road Construction on Sediment Yield in No Name Creek. Eggers Creek is the control watershed.

same proportion as the measured sediment slope storage caused by road surface erosion those same years. Thus, sediment yields caused by road surface erosion in No Name Creek amounted to 40 tonnes in 1981, 10.9 tonnes in 1982, 1.7 tonnes in 1983, and 4.6 tonnes in 1984. Sediment yields attributed to mass erosion amounted to 75.3 tonnes in 1982 and 22.6 tonnes in 1983.

Additional adjustments of sediment yield data were necessary in order to compare predicted and measured surface erosion for the "standard" roads in Ditch and No Name Creeks. This is because the standard road sections occupy only a portion of the total road length in each watershed but the sediment yields represent erosion from all roads. We estimated the proportion of sediment yields attributed only to the standard road sections in each watershed based on the relative percentages of the road length with direct sediment delivery to stream channels. Direct delivery is defined as that length of road adjacent to channel crossings that drains directly to live water stream crossings. Standard road adjustment factors were estimated to be 0.75 in Ditch Creek and 0.50 in No Name Creek based on the road design plans.

Predicted Values

Predictions of surface erosion from the roads in this study followed procedures in the R1-R4 Model. Detailed information about the specific design characteristics of all individual road lengths were available from the road plans. Sections of road were selected to test erosion rates for the "standard road." A 0.31 km section of the collector road in the Ditch Creek watershed and 1.41 km of the Lower No Name local road were selected as areas that best approximated the standard road described in the R1-R4 Model (road sections A and B, respectively, in Figure 1). No mitigation factors were applied to these road segments. We also aggregated all roads within a given watershed in order to test total watershed responses.

Surface erosion predictions for all non-standard road segments included a mitigation factor derived from Table 1. Road surface treatments (asphalt, crushed rock, and dust oil) and mulching and netting of fill slopes were considered effective the first year. Other cut and fill treatments that involve vegetation establishment were considered effective in year two. Table 2 shows the treatments and mitigation factors assigned to them in this analysis. Total erosion predictions are a composite of each section of road with

TABLE 1. Erosion Reduction Percentages for Various Mitigation Treatments [from R1-R4 Model (USDA Forest Service, 1981)].

Mitigation Measures	Reduction in Erosion (percent)
VEGETATIVE MEASURES	
Seed and Fertilizer Application	25
Plant Ponderosa Pine, Seed, and Fertilize	28
Wood Chip Mulch, Seed, and Fertilize	37
Straw Mulch, Seed, and Fertilize	43
Netting in Aspen Blanket, Seed and Fertilize	56
Asphalt and Mulch	57
Mulch and Net, Seed, and Fertilize	58
Sod	60
PHYSICAL MEASURES	
Road Tread Surfaced	20-25
Road Grade 5 Percent of Less	2
Rip Rap Fill	50
Road Partially Closed (no maintenance)	75
Road Permanently Closed (obliterated)	95
Buffer Strips Along Water Course	10-15
Filter Windrows (slash or baled straw) at Bottom of Fill Slope	35-40

TABLE 2. Road Treatments and Mitigation Factors (Silver Creek Roads).

Road Segment[1]	Mitigation Factor[2]	Segment Area (ha)	Road Treatment
10678			
Ditch Creek	(1.0)1.0	1.38	Native surface, grass seed, rocked culvert outlets
Cabin Creek	(0.25)0.20	1.52	Asphalt tread; seed, fertilizer, mulch, netting, and transplants on fills; hydromulch, seed and fertilizer on cuts
No Name Creek			
4678-5160	(0.32)0.32	0.36	Asphalt tread; seed, fertilizer, mulch, on fills; hydromulch, seed and fertilizer on cuts
5160-5742	(0.80)0.65	0.40	Native surface and berm; seed, fertilizer and mixed fill treatments, hydromulch, seed and fertilizer on cuts
5742-6740	(0.65)0.45	0.58	Dust oil on native surface; seed, fertilizer and mixed fill treatments, hydromulch, seed and fertilizer on cuts
6740-7405	(0.50)0.40	0.46	Dust oil on crushed rock tread; seed, fertilizer and mixed fill treatments, hydromulch, seed and fertilizer on cuts
7405-8208	(0.50)0.40	0.47	Crushed aggregate tread; seed, fertilizer and mixed fill treatments, hydromulch, seed and fertilizer on cuts
8208-9018	(0.25)0.20	0.4	Asphalt tread; seed, fertilizer, mulch, and transplants on fills; hydromulch, seed, fertilizer and transplants on terraced cuts
10678 I			
Cabin Creek	(0.25)0.20	0.53	Crushed aggregate tread; seed, fertilizer, mulch, netting, and transplants on fills; hydromulch, seed and fertilizer on cuts
10671 G			
No Name Creek	(1.0)1.0	1.87	Native surface, grass seed, rocked culvert outlets
10671 H			
Cabin Creek	(0.25)0.20	1.78	Crushed aggregate tread; seed, fertilizer, netting and transplants on fills, hydromulch, seed and fertilizer on cuts

[1] Road 10678 is the collector road that traverses all three watersheds; the No Name watershed is subdivided by road stations (e.g., 8208-9018).
Road 10678 I is a local road in the upper portion of Cabin Creek.
Road 10671 G is a local road in lower No Name Creek.
Road 10671 H is a local road in lower Cabin Creek.

[2] First year mitigation factor is in parentheses, years 2-4 follow. The factor is multiplied times the basic erosion rate, it is 1 minus the percent reduction in erosion.

given mitigation measures weighted by area. Where combinations of mitigation measures were applied, a combined factor was developed. Maximum mitigation, as described in the R1-R4 Model, was limited to 80 percent (mitigation factor of 0.20).

BOISED was used to predict mass erosion. As directed in BOISED, mass erosion calculations were limited to those road sections on hillslopes exceeding 45 percent slope. Annual mass erosion rates were determined using the locally derived average mass erosion versus time relationship developed for BOISED. Annual sediment yield predictions were also made using BOISED based on locally developed slope sediment storage coefficients for the landtypes found in the area.

RESULTS AND DISCUSSION

We tested all road erosion aspects of the R1-R4 Model and BOISED for small watersheds (less than 259 ha or one square mile) with data from the Silver Creek study except the mass erosion slope delivery coefficients. This includes two tests of predicted surface erosion rates for the "standard" road over four years, three tests of watershed scale responses over four years, one test of the mass erosion prediction component of BOISED, and three tests of the surface erosion sediment delivery coefficients and predicted sediment yields.

Surface Erosion on "Standard" Roads

Figure 5a shows the predicted erosion rates for the standard road in the R1-R4 Model as well as the measured erosion rates from the two road sections on the study area judged to best fit the criteria for the standard road. Predicted erosion rates compare favorably to measured for individual years with an average difference of -0.03 t/ha/yr and a standard deviation of the differences of 18.7 t/ha/yr. The average differences in predicted and measured erosion rates are essentially zero and indicate that the erosion estimates are not biased. Maximum deviations from predicted ranged from +31.2 t/ha/yr (+15 percent) on the lower No Name road the first year to -30.3 t/ha/yr (-63 percent) on the upper Ditch road the fourth year after construction. The largest percentage deviations occur at the lowest erosion rates, in years three and four. The R1-R4 Model projects long-term annual erosion at a static level after year two, however actual annual erosion may vary significantly due to climatic variability.

A network of rain gages in the study watersheds made it possible to calculate rainfall erosivity as described by Wischmeier and Smith (1958). A high intensity rainstorm in year four generated the highest erosivities in the 22-year climatic record for Silver Creek (exceedence probability of 0.01). The rain gage network showed that this event was centered over the Ditch Creek watershed where an erosivity of 610 MJ mm ha^{-1} h^{-1} was produced. This event caused the large increase in erosion on both road sections in year four. Erosivity in year three was also greater than average (exceedence probability of 0.21), again centered over Ditch Creek.

Factors other than climatic variability may account for some of the discrepancies. The difference in first year measured and predicted erosion on the lower No Name road is at least in part due to measurement error. Excessive tread and fill erosion occurred during the first snowmelt period on much of the lower No Name road. Before this sediment could be measured, the road was repaired and heavy equipment destroyed portions of the sediment deposits on the hillslope, making the measured erosion lower than actual erosion. Two additional factors affecting the outcome of the actual versus predicted comparison for the Upper Ditch Creek road segment are ineffective mitigation and variation from the standard road. Grass seeding did not establish ground cover on the weathered granitic cut slope and a high rate of erosion persisted. In addition, the Upper Ditch Creek road section averages 8.2 percent grade with a 100-foot piece that approaches 11 percent. This is steeper than the 5-7 percent grade of the standard road and undoubtedly caused some of the increase in road tread and ditch erosion. In normal use of the R1-R4 Model the station-by-station detail about roads is not known and the match to the standard road would be imperfect as well.

Our studies in Silver Creek show that cumulative erosion is the most significant variable influencing downslope transport of sediment below roads (Megahan and Ketcheson, 1996). Because of this, it is important that the R1-R4 model provide accurate estimates of long term cumulative road erosion if the estimates are used to predict downslope sediment travel using the Megahan and Ketcheson procedure. Plots of cumulative erosion (Figure 5b) show very close agreement. Predicted minus actual erosion resulted in a -11 percent difference for the upper Ditch road and +15 percent difference for the lower No Name road at the end of four years. The unmeasurable sediment for the first year along the lower No Name road likely accounts for some of the long term overprediction of road erosion.

Because the first year road erosion is by far the greatest annual amount, the comparison of predicted and actual cumulative erosion is greatly influenced by the agreement of the first year values. This agreement is quite good, in spite of the unmeasured sediment in lower No Name and the fact that the upper Ditch and lower No Name road sections do not perfectly match the standard road definition.

Watershed Scale Predictions of Surface Erosion

Another test of model performance is the prediction of erosion for all of the roads in each watershed. Such a test incorporates the effects of two or three roads in two of the watersheds, and thus provides an assessment of the cumulative effects of multiple roads. Watershed scale predictions also provide a coarse comparison of the mitigation measure coefficients in the model.

Figure 6a shows actual and predicted erosion for roads in the three study watersheds. Agreement is good for Cabin Creek and No Name Creek, less so for Ditch Creek. The predicted erosion is somewhat less than actual for the first year for the Cabin and No Name watersheds. The average annual difference between actual and predicted values for all years on all watersheds was -1.9 t/ha/yr with a standard deviation of 25.2 t/ha/yr and a range from -40.8 t/ha/yr to +65.3 t/ha/yr. Again, the average annual erosion rate difference is close to zero indicating a lack of bias in the erosion estimates. Average annual deviations from predictions for the three watersheds are -5.1 t/ha/yr in Cabin Creek, -8.0 t/ha/yr in No Name Creek and +7.5 t/ha/yr in Ditch Creek. For the Ditch Creek

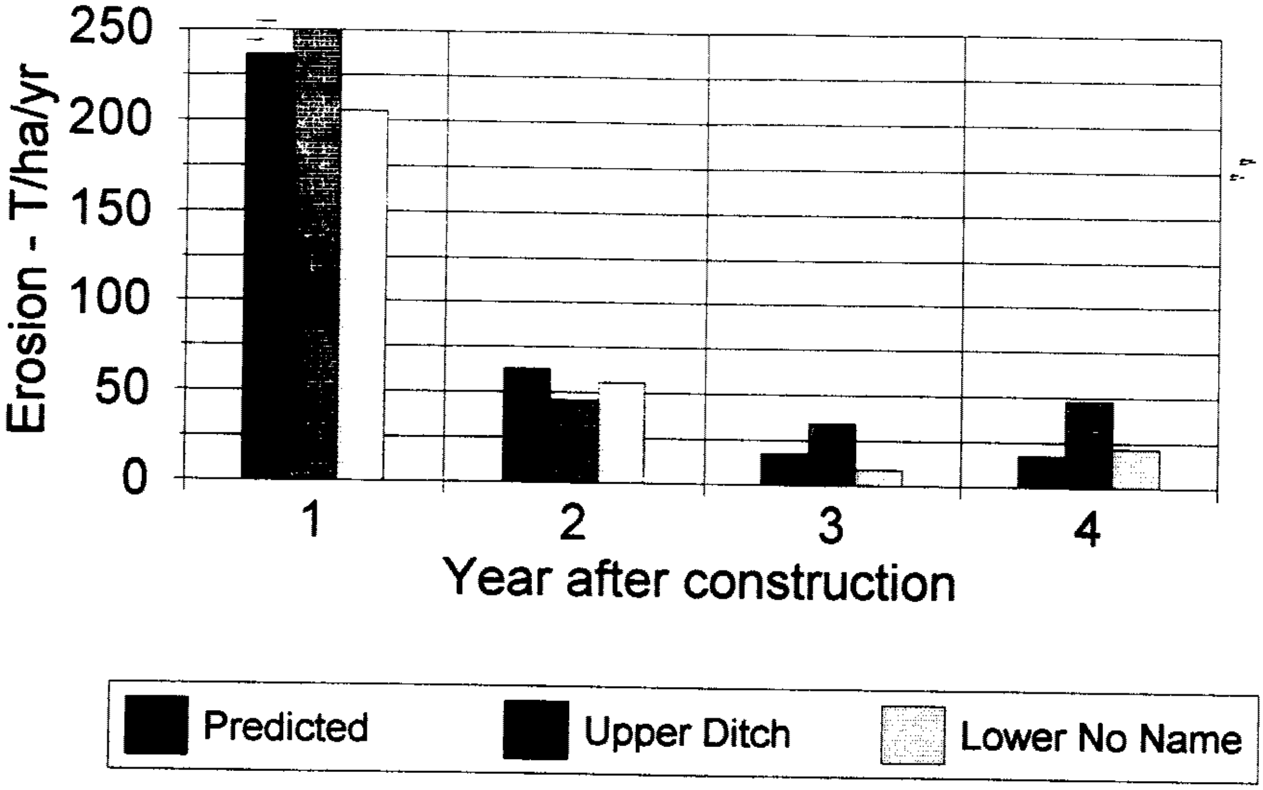

Figure 5a. Measured Versus Predicted Annual Surface Erosion from the "Standard" Road Sites.

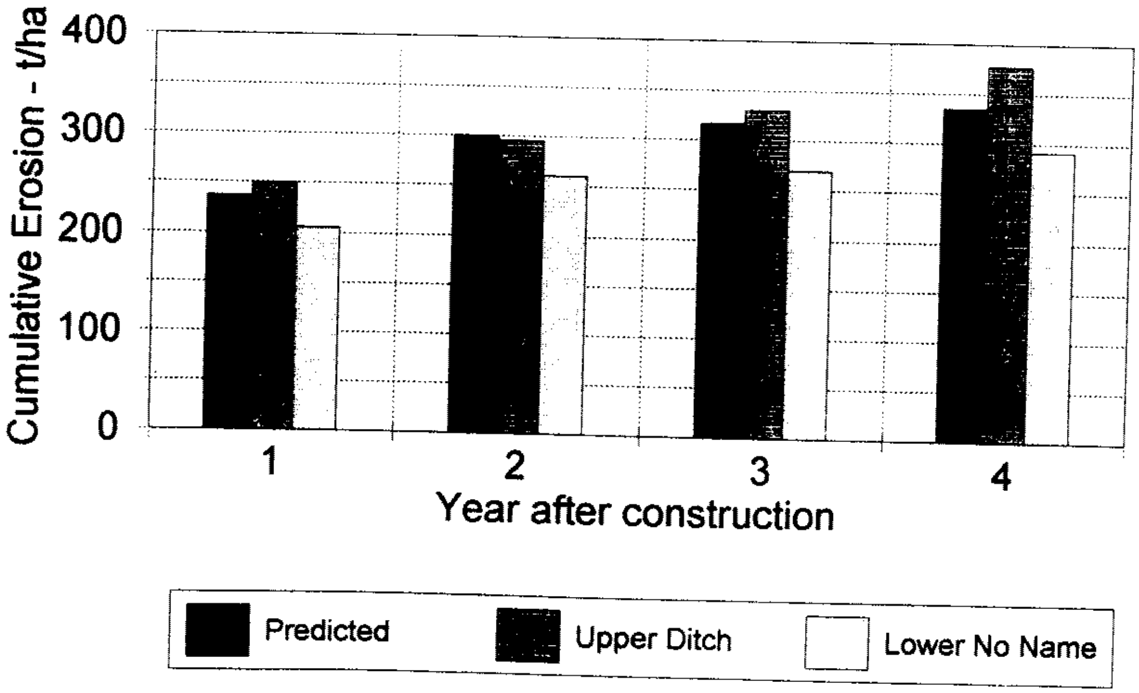

Figure 5b. Measured Versus Predicted Cumulative Annual Surface Erosion from the "Standard" Road Sites.

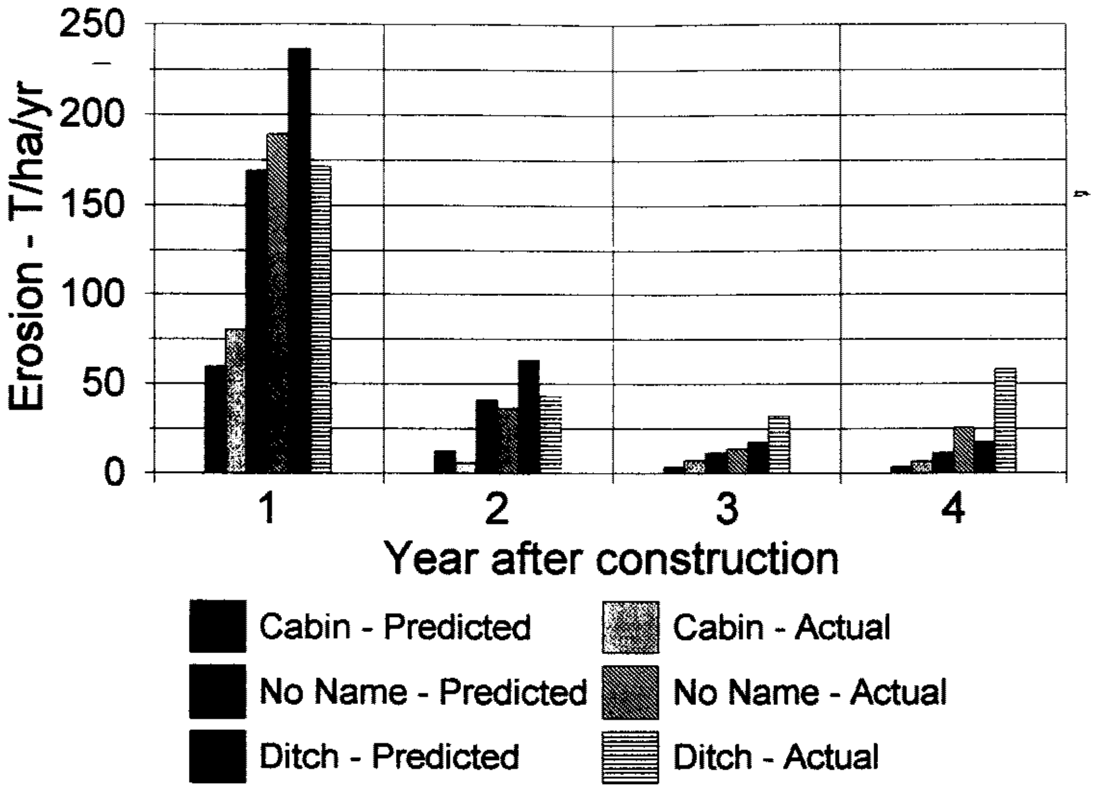

Figure 6a. Measured Versus Predicted Annual Surface Erosion from the Three Study Watersheds.

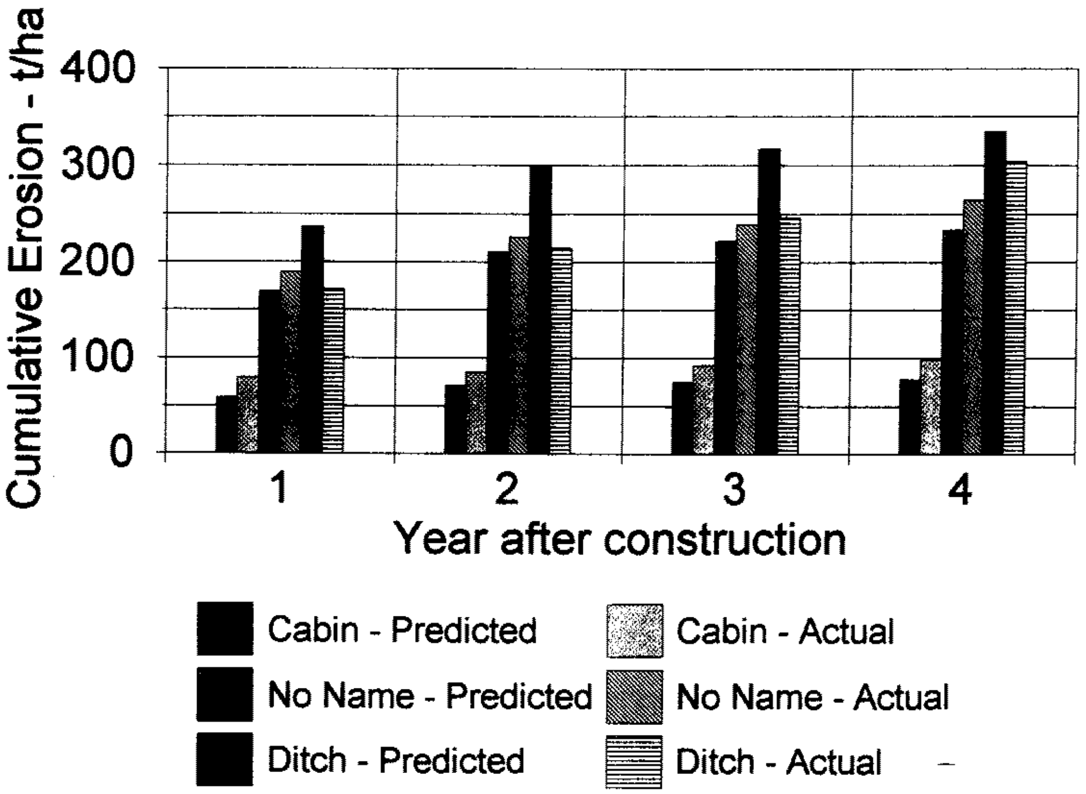

Figure 6b. Measured Versus Predicted Cumulative Annual Surface Erosion from the Three Study Watersheds.

watershed the maximum prediction error found in the study, amounting to +65.3 t/ha, was recorded in year one. Most of the road in Ditch Creek (that not used for the standard road tests above) is located in weathered colluvial materials that are considerably less erodible than typical granitic road materials so it is not surprising that overall erosion in Ditch Creek was lower than predicted in years one and two. Road erosion in Ditch Creek is underpredicted in year three and even more so in year four. As discussed in the section above on surface erosion on standard roads, unusual high intensity convective storms in those years, especially in year four, were centered in the Ditch Creek drainage and account for the under-predictions of road erosion in those years. The high intensity storm in year four also struck in No Name Creek although to a lesser extent and caused an under-prediction of erosion there as well. Since the model predicts average annual erosion, year to year variance due to changing weather is to be expected.

The plot of cumulative erosion by watersheds (Figure 6b) shows prediction errors for total erosion at the end of four years amounting to -21 percent in Cabin Creek, -12 percent for No Name Creek and +10 percent for Ditch Creek. Differences in annual cumulative erosion amounts range from +85 t/ha for Ditch Creek in year two to -32 t/ha for No Name Creek in year four. Considering the inherent variability in erosion data plus the variability of the terrain and road treatments in these watersheds, these predicted cumulative values are remarkably accurate.

Figures 6a and 6b also illustrate erosion mitigation treatment effectiveness and the use of mitigation factors in the R1-R4 Model. A maximum effort was made to reduce erosion on roads constructed in Cabin Creek whereas only scattered additional erosion control practices were used in No Name Creek and no extraordinary erosion control practices were used on the Ditch Creek roads (standard erosion control practices in existence at that time were used). An area weighted mitigation factor of 0.20 was used to model the effects of the additional erosion control practices used in Cabin Creek as compared to a factor of 0.41 in No Name Creek and 1.0 in Ditch Creek. While our study was not designed specifically to evaluate mitigation measures, the results support their general magnitudes. The least erosion occurred in the Cabin Creek watershed with the most aggressive erosion mitigation measures. The greatest amount of erosion occurred in Ditch Creek where mitigation measures were minimal.

Mass Erosion

Unlike road surface erosion which exhibits an exponential time trend, mass erosion occurrence is episodic in nature. Failures often occur when large volumes of water from precipitation events and/or snowmelt raise groundwater levels in road fills to the point that shear stress exceeds shear strength. Surveys of the mass erosion site in No Name Creek showed 440 tonnes of sediment were lost from the road fill in 1982 and 83 tonnes in 1983. The predicted and measured annual mass erosion rates are shown in Figure 7. This analysis is shown for a 17-year period (1980-1996) because no additional mass erosion has occurred at the study sites since 1984, and because of the episodic nature of mass erosion it is more meaningful when viewed over a longer time period. The measured erosion rates show a higher peak with a rapid decline over a two-year period. In contrast, the predicted erosion rates show a much lower rate prorated over the 17-year life of the roads. Such a difference is not surprising given the fact that the predicted rates are based on the average of many road segments, any one of which would likely show a sharp peak similar to what we measured. The best evaluation of prediction reliability for mass erosion is derived by comparing the total mass erosion for the 17-year life of the road. Total measured erosion was 465 tons as compared to a predicted value of 710 tons. Measured mass erosion rates were about 35 percent lower than predicted rates. Given the episodic nature of mass erosion on forest roads, a prediction error of 35 percent is very reasonable. However these results should be used carefully because this study involves a limited amount of road length and limited sample of climatic conditions that cause mass erosion. Years two and three (1982 and 1983) were relatively large runoff years, but 1984 through 1994 were drought years in the study watersheds.

Slope Delivery Coefficients and Sediment Yield

BOISED, like the R1-R4 Model, deliver sediment from erosion sources to streams the same year that the erosion occurs. Both surface and mass erosion are adjusted by delivery coefficients developed for each landtype in the watershed. For watersheds less than 259 ha (one square mile), annual sediment yield is then calculated as the sum of the adjusted erosion for all the landtypes in the watershed. Thus the sediment yield calculation assumes no loss of sediment to valley storage and no channel storage detention between

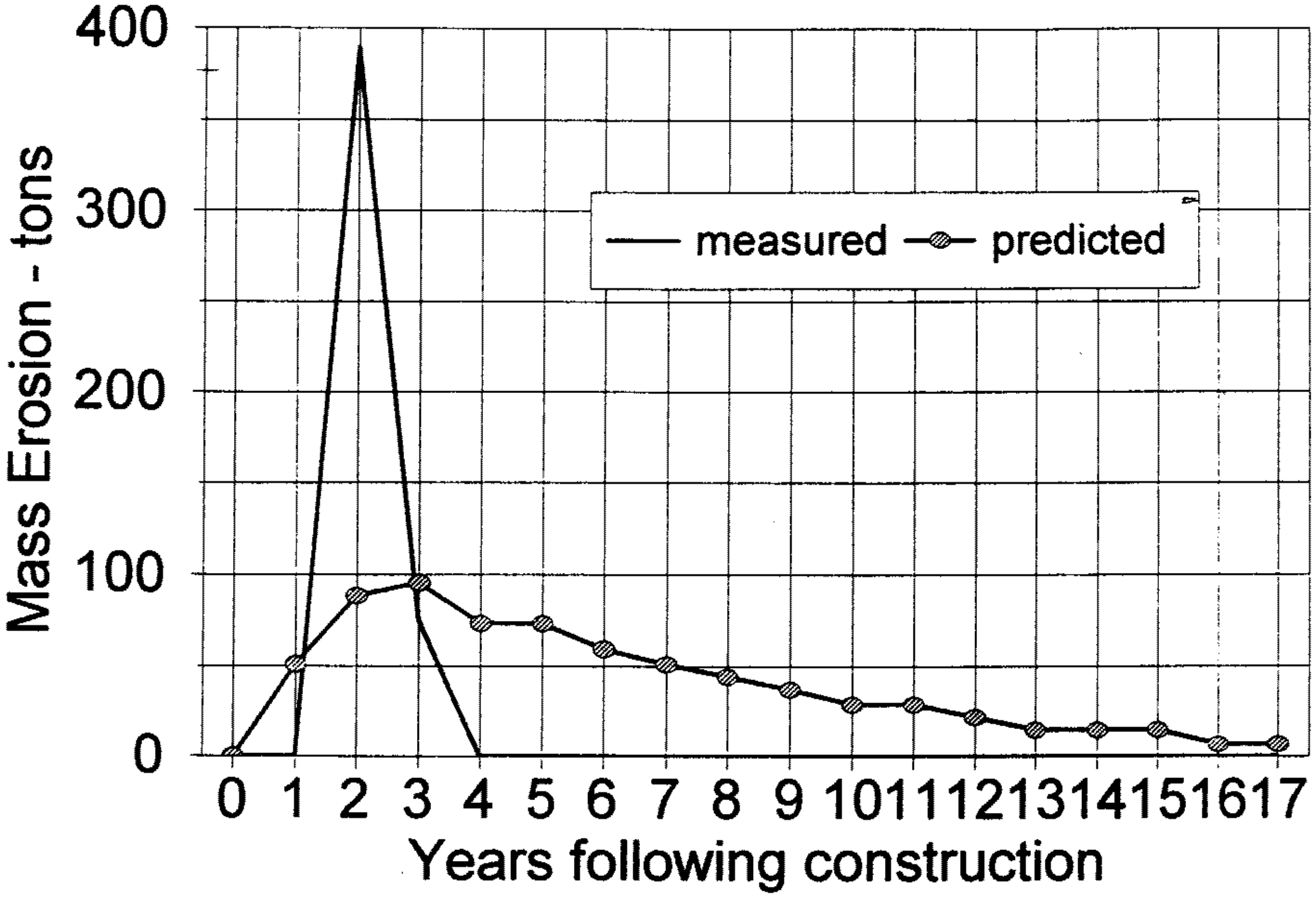

Figure 7. Measured Versus Predicted Annual Mass Erosion for Roads on the Study Area.

years. We were unable to evaluate the accuracy of the mass erosion delivery coefficients for the landtypes in the study watersheds because the failure in No Name Creek (a rotational slump) was not similar to the type of landslides (debris avalanche) used to develop the mass erosion coefficients. However, the data are available to check the surface erosion delivery coefficients.

Average landtype characteristics used to derive surface erosion delivery coefficients in BOISED include slope steepness, shape, dissection, roughness and length. We calculated an average surface erosion delivery coefficient for each watershed using an area weighted average of the BOISED surface erosion delivery coefficients for all landtypes within each basin. By comparing the total measured erosion to total measured sediment yield for the four years of data, we obtain an estimate of the measured surface erosion delivery coefficients for the study watersheds (Table 3). These coefficients include the effects of slope storage as well as long term valley storage and channel detention storage. Observations of channel conditions in these steep, headwater channels, as well as sediment tracer tests, show no significant channel detention storage or out-of-bank valley sediment storage over the life of the study. Sediment yield increases that could be attributed to road construction occurred only in year one after construction in Cabin and Ditch Creeks and in years one through four in No Name Creek with minimal amounts in year four. Thus, the measured surface erosion delivery coefficients averaged over the four-year study provide a reasonable estimate of the BOISED surface erosion delivery coefficients.

Measured surface erosion delivery coefficients range from 1.6 percent in Cabin Creek to 7.0 percent in No Name Creek. Surface erosion delivery coefficients are consistently overestimated by BOISED by factors ranging from about 1.5 times in the case of Ditch Creek to over seven times in the case of Cabin Creek. On average, the predicted BOISED surface erosion slope delivery coefficients are about 2.5 times greater than measured and result in about 2.5 times more sediment yield for the study watersheds (Table 3) than was measured.

The overestimation of slope delivery in BOISED is somewhat surprising given the fact that the landtype surface erosion delivery coefficients were derived from Silver Creek study area data (Reinig *et al.*, 1991, Appendix K). However, this work was done using preliminary sediment yield data and without the benefit of measured on-site erosion. Probably more important is the fact that average landtype characteristics of slope steepness, shape, dissection, roughness and length provide only an approximate index of surface erosion delivery to streams and no provision is made for the location of roads within the landtypes. For situations where more accuracy is needed, Megahan and Ketcheson (1996) show that placement of the road on the slope and total road erosion in relation to site conditions below the road is what regulates sediment supply to streams from roads. They found that the travel distance and sediment volume below roads can be estimated quite well using specific site conditions at and below individual road locations including the runoff source area, the amount of sediment storage obstructions on the slope, slope gradient and the volume of erosion from the road. The value of site specific predictions is apparent in Table 3. The highest predicted sediment yield occurred in Cabin Creek where only six tonnes of sediment increase was measured. This is because most of the road construction took place in the head of the drainage thus maximizing sediment travel distance to streams. Application of an average sediment delivery coefficient for a landtype in such situations maximizes the opportunity for error.

TABLE 3. Measured Versus Predicted Slope Surface Erosion Delivery Coefficients and Sediment Yields for the Silver Creek Study Watersheds.

	Measured Data		Predicted Data	
Watershed	Sediment Yield (tonnes)	Delivery Coefficient (percent)	Sediment Yield (tonnes)	Delivery Coefficient (yield)
No Name	57	4.2	69	9.7
Ditch	28	7.0	32	10.8
Cabin	6	1.6	118	11.4

CONCLUSIONS

The R1-R4 Model properly predicted the negative exponential time trends in surface erosion for all tests including the two standard road tests and the three watershed scale tests. The errors for annual surface erosion predictions for the two standard road tests ranged from +31.2 t/ha/yr (+15 percent) to -30.3 t/ha/yr (-63 percent) with a mean of zero t/ha/yr and a standard deviation of the differences of 18.7 t/ha/yr. Watershed scale predictions increase the opportunity for error because of the introduction of additional coefficients for erosion mitigation practices. Thus the annual prediction errors for the three watershed tests had a greater range from -40.8 t/ha/yr (-70 percent) to +65.3 t/ha/yr (+38 percent) with a mean of -1.9 t/ha/yr and a standard deviation of the differences of 25.2 t/ha/yr. In spite of the somewhat larger error band for the watershed scale predictions, it appears that the erosion mitigation coefficients are reasonable because the effects of the minimal, moderate and maximum efforts to control road surface erosion in the different watersheds were reproduced.

Variations in annual rainfall erosivity were the primary cause of annual prediction errors but other factors including variations from the standard road, ineffective or improperly applied erosion control measures, and measurement errors also contributed. However, the fact that prediction errors averaged at or near zero suggests that the model is predicting long term average erosion rates quite well.

Total erosion accumulated over the life of a road has been shown to be the most important site factor influencing the volume and distance of sediment transport below roads. Thus, the accuracy of the predicted cumulative erosion over the four-year study period is perhaps the most important test of the erosion prediction models. Cumulative erosion errors amounted to -11 percent and +15 percent for the two standard road tests and -21, -12, and +10 percent for the three watersheds tests. Such close agreement is remarkable given large differences in climatic conditions and the large variability in terrain and road conditions in the study area.

A comparison of measured mass erosion to that predicted using BOISED showed that the total volume of erosion could be predicted within 35 percent. Considering the variability associated with mass erosion on roads, such close agreement should not be considered as a validation of the BOISED procedure. Also, the measured erosion occurred over a two-year period whereas the model predicted erosion over a 17-year period. Unlike surface erosion, such disparities will always occur because the measured data at an individual study site reflect the episodic nature of mass erosion whereas the model is based on average landslide occurrence as a function of age.

Slope surface erosion delivery coefficients in BOISED averaged about 2.5 times greater than measured. It appears that the surface erosion delivery coefficients in BOISED are overly conservative in order to account for average site conditions and road locations within landtypes. The downslope sediment transport model developed by Megahan and Ketcheson (1996) may provide more accurate predictions of watershed sediment yields especially because the model is site specific and depends heavily on cumulative erosion values which are predicted very well with BOISED.

The R1-R4 and BOISED methodologies state that use of model predictions should be limited to comparing the relative effects of alternative activities. However, based on this test, it appears that the models provide reasonable estimates of actual road surface erosion rates, especially when accumulated over a period of years. Improvements in the slope sediment routing components of the models can make annual sediment yield predictions more realistic as well.

This test of the R1-R4 Model and BOISED was done in an area with geologic and climatic conditions similar to the area where the road erosion components of the models were originally developed. Thus, the results of the test are applicable to similar conditions, namely granitic soils with a Mediterranean climate (dry summers with occasional convective storms), annual rainfall ranging from about 600 to 1200 mm, and a permanent winter snowpack. Application of the model in other locations and to evaluate effects of other forest disturbances such as logging and wildfire still remain untested.

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