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Sediment Production and Downslope Sediment Transport from Forest Roads in Granitic Watersheds

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Research Summary

A mapping technique was used to measure the annual downslope deposition of granitic sediments eroded from forest roads constructed on three headwater watersheds in the mountains of central Idaho. Sediment deposits were identified by source and location of the deposit terminus. Over the 4-year study, a total of 1,659 m^3 of sediment was deposited on slopes from the 6.6 km of roads, 70 percent of the total occurred during the first year after construction. A total of 335 sediment deposits were measured, 85 percent from diffuse erosion on fill slopes and 8 percent from cross drains. However, the length and total volume of deposits from cross drains exceeded that from fills by about one and two orders of magnitude, respectively. The length and volume of deposits from other sources exceeded those for fills, but were still considerably less than culverts. Various erosion control practices on roads in one watershed reduced sediment deposits by about 65 percent compared to a companion watershed where standard erosion control practices where used. Frequency distributions were developed to define the probability of sediment travel distance by fill and cross drain sources. Also, a dimensionless relationship was developed to describe the percentage of total volume of sediment accumulated on the slope in relation to the percentage of the total length of the deposit. By combining the two relationships, land managers can assess the risk of sediment reaching streams to help guide road location and design.

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The health and viability of fish stocks in the northwest is a leading issue for politicians, regulatory and land management agencies, Indian tribes, organizations, and individuals. Human activities can affect the processes of erosion and sedimentation, with detrimental impacts to aquatic organisms. Many studies have identified roads as major contributors of sediment resulting from human actions in mountain environments (Fredriksen 1970; Megahan and Kidd 1972).

Concern about erosion from roads is especially high on granitic soils in the Idaho Batholith, a 40,000 km^2 expanse of granitic rocks in central Idaho (fig. 1) where sedimentation damage to valuable anadromous fishery resources in the headwaters of the Columbia River Basin is a critical issue (Seyedbagheri and others 1987). Forest resources in this mountainous region have supported extensive timber harvesting and associated road construction. The dominant erosion process on these landscapes is often surface erosion (Megahan and Kidd 1972), as opposed to other areas in the Pacific Northwest where mass erosion processes dominate (Swanston and Swanson 1976). Megahan and Kidd (1972) showed that, compared to undisturbed forest slopes, average surface erosion rates were increased 1.6 times on harvest units using a downhill cable yarding system, and 220 times on timber access roads.

Aquatic habitat is not impaired by excessive sediment from these areas unless eroded material reaches the stream network. Thus, sediment deposition on slopes below roads becomes an important issue. This paper presents the results of a study from highly erodible Idaho soils and provides information necessary to develop road design criteria and evaluate risks and trade-offs.

Objectives of the study were to:

- Quantify the volume of sediment deposition on slopes in relation to road features;
- Determine the probability distribution of sediment travel distance;
- Evaluate how sediment deposition occurs with respect to forest site conditions and downslope location of streams;
- Determine the volume and particle size distribution of sediment deposits on slopes in relation to sediment travel distance;
- Investigate time trends in sediment deposition.

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 lat. 44°25′ N. and long. 115°45′ W. The study was conducted on roads constructed across three study watersheds within the Silver Creek study area (fig. 1).

Annual precipitation averages about 890 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 late September and October. About 65 percent of the annual precipitation occurs as snowfall and causes a maximum snowpack water equivalent averaging

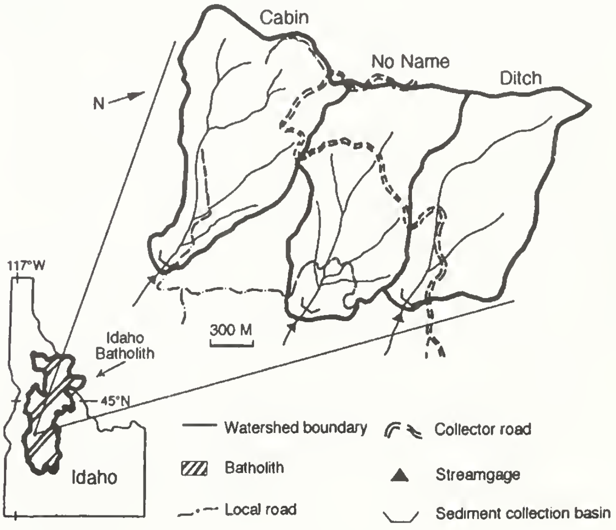

Figure 1—Location and detail of the study area.

about 55 cm. Streamflows from study watersheds are dominated by springtime melt of the snowpack that accumulates from about mid-November to mid-April.

Bedrock is primarily coarse-grained quartz monzonite and is typical of a large part of the central and southern portions of the Idaho Batholith. Bedrock is moderate-to-well weathered (Clayton and others 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. Shallow soils less than 20 cm deep are common on ridges and south slopes and scattered outcrops of granitic bedrock are found in the upper elevations of the watersheds. Four types of soils are found on the study watersheds depending on the gradient and aspect of the hillslopes. 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 in the area are relatively steep ranging from 15 to 40 degrees and are highly dissected. Vegetation varies primarily in response to changes in slope aspect and soil properties and is characterized by two principal vegetation habitat types (Steele and others 1981): Douglas-fir/white spirea, ponderosa pine phase (*Pseudotsuga menziesii* [Mirb.] Franco/*Spiraea betulifolia* Dougl., *Pinus ponderosa* Laws. phase) and Douglas-fir/ninebark, ponderosa pine phase (*Pseudotsuga menziesii* [Mirb.] Franco/*Physocarpus malvaceus* [L.] Maxim., *Pinus ponderosa* Laws. phase). Timber stands are dominated by approximately equal volumes of mature and over-mature ponderosa pine and Douglas-fir.

A total of 6.64 km of forest roads were constructed on the study watersheds. Construction began in June of 1980 and was completed by November. Two types of roads were constructed (fig. 1): a collector road designed for permanent access, and local roads designed to support timber harvest only. 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 minimize 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 on each study watershed. Road design features used on Ditch Creek were representative of typical road design features for the area in 1980 and included: a native material road surface, native material berms to protect fill slopes from direct runoff on outsloped sections, grass seed and fertilizer applied by hand to cut and fill slopes, and small rock hand placed at culvert outlets.

Roads in Cabin Creek were designed for maximum erosion control and used: asphalt pavement on the collector road and crushed rock surfacing on logging roads; grass seed, straw mulch, plastic netting, and transplanted shrubs and trees on fill slopes; grass seed and hydromulch on cut slopes; and cull logs placed across the hill slope immediately below the downhill toe of fill slopes. Drainage was provided by concrete curbs and drains on asphalt road sections and by alternative insloping and outsloping of the road surface where crushed rock surfacing was used. Energy dissipaters were installed at the outlet of all road drainage culverts. Road fill slopes were protected by crushed rock in outsloped sections of the logging roads.

Road design features on No Name Creek were similar to those used in Ditch Creek except a series of experimental treatments that were applied at selected sites on the road tread and road cut and fill slopes for detailed studies of erosion processes and erosion control effectiveness (Burroughs and King 1985; Megahan and others 1991, 1992; Megahan and others, unpublished report).

Methods

Complete surveys of all sediment deposits on hillslopes below all roads constructed on the study watersheds were made during the summers of 1981 through 1984 following the completion of road construction in November of 1980. Light colored granitic sediment deposits are easily distinguished from the darker colored disturbed and undisturbed soils (fig. 2a,b). Two measurement intensities were used. Slopes below ten randomly selected sites were mapped and monitored for sediment movement and deposition. These sites are referred to as "Intensive Sites", and were established to provide detailed descriptions of site factors and volume-distance relationships. Selected sites met two criteria: (1) there was no stream channel in proximity to the site so that no sediment would be lost to stream transport; and (2) sites were located in swales so that sediment did not move out of or into the area. Intensive sites were monitored twice a year; in June after spring snowmelt, and in October. Sediment deposits along the remainder of the roads in the study watersheds were also monitored once a year in June and with less precision. These "Other Sites" increased the

Figure 2a—Areal extent of the light colored granitic sediment is readily apparent.

Figure 2b—Depth of sediment deposits to a precision of about 0.5 cm is also easily determined by coring.

sample size for evaluating sediment transport distances and site conditions and allowed evaluation of sediment movement by source and treatment types.

Intensive Sites

The margins of the road fill slopes at the ten selected sites were staked and all sediment on the slope below the fills was measured. The sediment boundaries and depth measurement locations were marked with painted wooden stakes. Coordinates for each stake and any obstruction causing sediment deposition (log, tree, rock, mound) were recorded using an electronic surveying instrument. A hand held target rod limited precision of these measurements to approximately 7.5 cm.

Sediment deposits were segmented into pieces that could be approximated by geometric shapes for volume calculations. Long, narrow "arms" were segmented from the main "body" of the deposit. Sediment depth was measured by excavating a small hole through the sediment to mineral soil. The interface between the sediment and underlying soil or duff was usually very distinct (fig. 2b) and allowed measurement of undisturbed sediment thickness to 0.5 cm. The only criterion for the number of depth measurements was that the surveyor was confident that the average depth was represented. Segmenting the sediment deposit facilitated approximation of the average depth. Large, variable depth deposits were measured separately with a higher density of depth measurements than more uniform, shallow deposits. The frequency of depth measurements was generally between one for 1.3 m^2 and one for 10 m^2.

Base maps of 1:20 scale were prepared from the survey data (fig. 3). The base maps provide accurate determinations of sediment area and a visual representation of sediment movement. Sediment volume was obtained by digitizing individual segments on the maps and averaging the depth measurements for the segment. These subvolumes were then totalled for the site. Sediment deposits were partitioned into analysis increments spaced 4.6 m apart down the slope (fig. 3).

Data were also collected to characterize the source and disposition of sediment flows. Definition of source types are:

- Fill—sediment originates from erosion of the fill slope, either by direct rainfall or snowmelt on the fill slope or runoff from the road surface travelling over and down the fill slope.
- Cross drain—culverts that carry discharge from the road ditch and/or upslope runoff. Sediment sources include material eroded from the road tread, road cut, ditch, and fill material on the upslope side of the road.
- Berm drain—pipes draining curbs. These pipes collect only road tread runoff, except in a few cases where a curb was placed below cut slopes and cut slope runoff over-topped the curb.
- Rock drains—shallow rocked dips on certain roads provided drainage for the road tread and cut. The dips and short fill slopes were armored with rock rip rap.
- Landings—sediment that originated from erosion of log landing surfaces or their fill slopes.

Codes were used to describe the source of the sediment; fill, cross drain, berm drain, rock drain, or landing; and where sediment movement ended; on the slope, in a swale (a slope depression with no defined channel), in a channel (an overland flow path with a discernible bed and banks), or coalesced with another sediment flow. Sediment samples from each increment of sediment flow were obtained using a soil density core. Particle size distributions and sediment bulk densities were determined from these samples.

Other Sites

In addition to the intensive sites, data were collected to characterize all sediment deposits along the rest of the roads. All data except sediment volume weight and particle size distribution were collected at the other sites. However, instead of detailed maps for computing sediment volume, hand sketches were drawn, and instead of surveying average lengths and widths of sediment, segments were obtained using a tape measure. Sediment depth was obtained using the same technique of excavating a hole through the sediment as for the intensive sites. Sediment volume, length, and obstructions were totaled for each sediment deposit rather than for individual 4.6 m increments of the flows.

Results

We recorded 335 sediment deposits from the 6.64 km of roads constructed on the study watersheds over the 4-year study. The lower end of 13 of the deposits reached active stream channels and an additional 5 were captured in sediment traps installed below

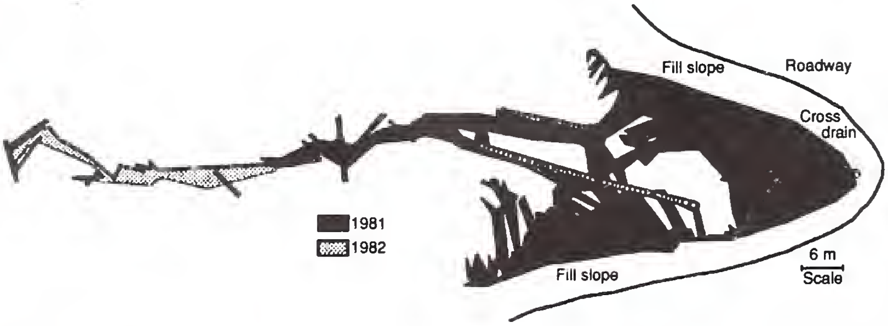

Figure 3—Map of a typical cross drain sediment deposit over time.

Table 1—Frequency of occurrence and average dimensions of sediment deposits by source, Silver Creek Road Study.

Source	*n*	Mean[1,2]	Standard deviation[1]	Range
Fills	264			
Volume (m^3)		0.2a	5.9	0.003 - 30.7
Length (m)		3.8a	2.6	0.4 - 66.1
Cross drains	26			
Volume (m^3)		11.4c	2.9	1.2 - 41.2
Length (m)		49.6c	2.0	10.7 - 183.6
Rock drains	17			
Volume (m^3)		0.3a	3.8	0.03 - 3.4
Length (m)		8.7a	2.5	1.2 - 33.9
Berm drains	6			
Volume (m^3)		1.7b	7.2	0.2 - 22.3
Length (m)		14.0a,b	2.6	3.7 - 54.6
Landings	4			
Volume (m^3)		3.2b	10.2	0.5 - 86.3
Length (m)		20.8a,b	3.1	8.8 - 106.3

[1] Calculated using $\log_{10}$ transformed values.
[2] Values with different symbols are statistically different ($P < 0.05$).

the roads as part of another study in the area. Of the remaining 317 deposits, a total of 264 or about 84 percent originated from road fill slopes (table 1). Cross drains account for 26 deposits or about 8 percent of the sediment flows. Of the 26 cross drains sampled, 13 were located in swales with no defined channel; the remainder discharged onto uniform slopes. Rock drains, a fairly unique drainage design featured on 1.48 km of local road, account for 17 (5 percent) of the sediment flows. Berm drains are common on the collector road, but in many cases sediment from them joined sediment discharging from cross drains so the deposit was counted as originating from a cross drain. There were only six distinct sediment deposits from berm drains comprising only 2 percent of the total. Finally, an additional 1 percent was contained in four sediment deposits originating from log landings (table 1).

The diffuse nature of sheet and rill erosion processes on road fill slopes resulted in short sediment travel distances and deposits were elongated laterally along the base of the fill slopes. In contrast, deposits from berm drains and culverts traveled much farther and often tended to funnel into the bottom of swales (fig. 3). Logs and other obstructions on the hillslope surface below the road stored sediment and sometimes caused changes in sediment flow direction, depending on the orientation of the obstruction relative to the fall line of the slope. As was typical for all sites, most of the sediment was deposited the first year with small increases in length and width occurring the second year (fig. 3). Sites with culverts showed significant increases in length the second year, but generally not in subsequent years. Most of the sediment in the second, and subsequent years, was deposited on top of the original sediment deposit.

Total Sediment Production

Total sediment delivered to slopes from all roads during the 4-year study was 1,659 m^3. About 300 m^3 or 18 percent of this total resulted from mass failures of a road fill embankment at the same site in 2 consecutive years. Of the 1,359 m^3 of sediment deposits, a total of 182 m^3 was contained in 18 sediment deposits that either reached a stream channel (13 deposits) or were trapped in sediment catchments used in a related study (5 deposits). The remaining 1,177 m^3 of sediment represents the total from 317 sediment deposits that did not reach stream channels and whose downslope transport were not impeded by sediment traps. An additional, unknown, volume of sediment was supplied to streams both from the 13 sediment deposits that reached streams and from sediment supplied to ten culverts in the immediate vicinity of road stream crossings.

Based on the volume of material stored on slopes, the average annual surface erosion rate from the 9.77 ha of road prism area was 34.8 m^3/ha/yr for the 4-year study. Average erosion rates varied considerably for the different roads and reflect differences in site factors, road design, and erosion control measures.

The lowest road erosion rate (6 m^3/ha/yr) was from a ridge-top logging road with maximum erosion control. The highest road erosion rate (49.5 m^3/ha/yr) was from a logging road located on the lower third of the slope with minimal erosion control.

Road erosion rates also varied by watershed and reflect the effectiveness of road design and erosion control measures on individual roads within the watersheds. We found an average annual road erosion rate in the Ditch Creek watershed of 50.4 m^3/ha/yr with typical erosion control practices, compared to a rate of 17.3 m^3/ha/yr for the Cabin Creek watershed with maximum road erosion control practices. Sediment production from the No Name Creek watershed averaged 44.8 m^3/ha/yr. Portions of the collector road in this watershed had a variety of experimental erosion control treatments, the remainder was treated as in Ditch Creek.

Sediment delivery to slopes varied dramatically by road source type. Considering only sediment deposits that were unimpeded and contained on the slope, fills account for a total volume of 181 m^3, cross drains 601 m^3, rock drains 12 m^3, berm drains 35 m^3, and landings 91 m^3. Normalizing for the numbers of each source, we found that the data were not normally distributed ($P > 0.05$) based on the D'Agostino (1990) test for normality. However, a log transformation of the data did adequately describe a normal distribution. Based on the mean of the log transformed values, average deposition volumes were; 11.4 m^3/cross drain, 0.2 m^3/fill, 0.3 m^3/rock drain, 1.7 m^3/berm drain, and 3.2 m^3/landing (table 1). Analysis of variance of the data shows that unit volumes of sediment deposition are greater from cross drains than from any other source ($P < 0.05$). Deposition volumes from berm drains and landings are similar and exceed deposition volumes from fills and rock drains that are also similar (table 1).

Annual and Seasonal Time Trends

A total of 943 m^3 or about 70 percent of the sediment deposition occurred the first year after road construction. Over one-fourth of the first-year sediment deposition occurred during road construction (Megahan and others 1986). The first year erosion rate of 96.5 m^3/ha decreased rapidly to 17.3 m^3/ha in year 2 and 9.5 m^3/ha in year 3. Erosion increased to 15.8 m^3/ha as a result of high intensity summer thunderstorms during year 4.

In the first year, 329 sediment flows were measured; 69 percent were active the next year, changing in (1) volume only, (2) volume and width, or (3) volume, length, and width (table 2). Seven new flows were documented the second year, and four flows that were distinct the first year flowed into another flow in year 2 and no longer could be counted separately. In the third year, 20 percent of the flows (now 332) changed and one new flow was added. In the fourth year, 23 percent of the flows changed and six new flows were recorded. Four more flows joined other flows, bringing the total number of distinct flows to 335.

The intensive site data allow an evaluation of seasonal relationships. Spring (over-winter) erosion rates were much greater than summer rates; 23 and 6 times greater during the first 2 years, respectively (table 2). While both rates dropped after the first year, summer rates dropped much less dramatically. Summer erosion was twice spring erosion in year 3. Ninety-six percent of the erosion this third summer occurred on native surface roads; nearly half (43 percent) from one landing. In year 4, the spring erosion rate exceeded the summer rate by over 2.5 times.

Sediment Travel Distance

For any given type of source, sediment travel distance varies greatly as shown by the ranges in table 1. The maximum travel distance for cross drains was about 275 m, considerably greater than any other source where maximum distances barely exceeded 100 m. Like sediment volumes, sediment travel distances were log normally distributed ($P < 0.05$) based on the D'Agostino (1990) test for normality. An analysis of variance of the log transformed sediment travel distance values shows that the average travel

Table 2—Sediment flow changes and erosion rates over time, Silver Creek Road Study.

		Changes in						Erosion rates	
Year	No change	Volume only	Volume and width	Volume and length	New flows	Total flows	Joined flows	Spring	Summer
								- - - - (m^3/ha/yr) - - -	
1					329	329		149.9	6.6
2	98	184	21	22	7	332	4	12.2	2.0
3	264	38	20	10	1	333	0	2.2	4.9
4	254	47	16	12	6	335	4	5.0	1.9

distance for sediment from cross drains of 49.6 m was significantly greater ($P < 0.05$) than any other source (table 1). There were no significant differences ($P > 0.05$) between average sediment travel distances of 3.8 m for fills and 8.7 m for rock drains. At 14.0 and 20.8 m, sediment travel distances for berm drains and landings were not statistically different from each other, but were statistically greater than for fills and rock drains ($P = 0.05$ level).

Empirical probability distributions were developed for sediment travel distance by source type using the plotting position equation of Weibull (1939). Data were grouped according to the results of the statistical tests for average travel distance as fills plus rock drains ($n = 281$) or cross drains ($n = 24$). The sample sizes for berm drains ($n = 6$) and landings ($n = 4$) were too small for use in this analysis. Least squares regression analysis was used to develop a prediction equation for each data set that makes it possible to define the probability of exceeding any given sediment travel distance (fig. 4). For example, there is a 50 percent chance of sediment travel distance exceeding 50 m from cross drains, but only about a 1 percent chance of sediment traveling the same distance from fills or rock drains.

Distribution of Sediment Volume

Data from the 10 intensive study sites makes it possible to describe the distribution of sediment volume on the slope. No downslope sediment transport occurred on one of the sites so data from only nine sites are used here. Data from three sites, representing a range in travel distance from relatively short to long, show that all sediment deposits rapidly decrease in volume as they move downslope (fig. 5). Although deposition patterns varied considerably, a general pattern emerges using a dimensionless plot of all sediment volume versus travel distance data (fig. 6). A least squares regression fit to the data is highly significant ($P < 0.01$) and has an r^2 of 0.90. The regression fit included the 0 and 100 percent data points in order to force the fitted line towards these logical endpoints. This process reduces the variance to zero at the endpoints thus inflating the value of r^2. A regression fit without the 0 and 100 percent data included is still highly significant but the r^2 value drops to 0.76. This data set makes it possible to determine the proportion of sediment volume deposited in relation to the proportion of travel length.

Distribution of Sediment Particle Size and Volume Weight

Core samples from each volume increment were taken to evaluate particle size and volume weight. The D_{50} value (median particle size) shows a weak ($r^2 = 0.28$) but statistically significant ($P < 0.05$) relationship to travel distance (fig. 7). No relationship was found between sediment volume weight and distance. Volume weight averaged 1.40 gm/cm^3, ranged from 1.12 gm/cm^3 to 1.51 gm/cm^3 and had a standard deviation of 0.078 gm/cm^3.

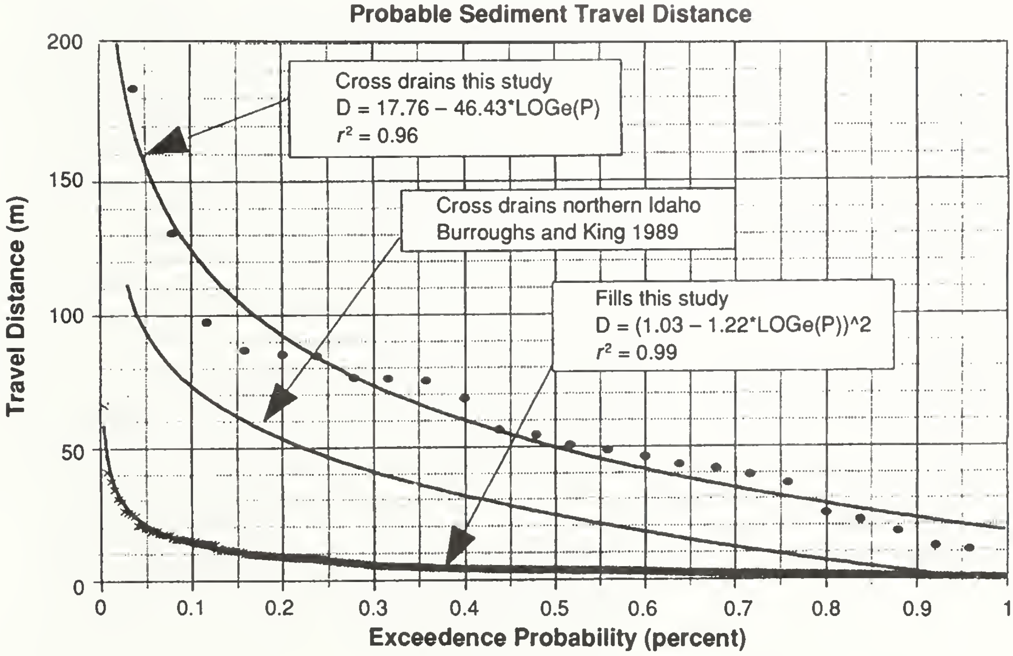

Figure 4—Probability of sediment travel distance for cross drains and fills.

Discussion and Conclusions

This study shows the same time trends in erosion as earlier studies that documented large volumes of erosion during the first year after road construction followed by a rapid reduction in erosion in subsequent years (Dyrness 1970; Megahan 1974; Megahan and Kidd 1972; Swift 1984). The first year erosion rate averaged 96.5 m^3/ha and amounted to 70 percent of the total erosion measured during the 4-year study. About one-forth of the first year erosion occurred from rainstorms during construction (Megahan and others 1986); the remainder occurred during the subsequent winter and spring. Much of this over-winter erosion resulted from sloughing of surface materials disturbed by construction primarily from micro-scale mass erosion processes (Megahan and others 1991; Megahan and others, unpublished report). Swift (1984) reported similar erosion during the first winter after forest road construction on granitic parent materials in North Carolina. Subsequent average annual erosion rates on our study area were considerably lower ranging from a high of 17.3 m^3/ha in year 2 to a low of 9.5 m^3/ha in year 3. Erosion rates after the initial high over-winter erosion vary by site conditions such as ground cover density, slope gradient, aspect, and rainfall erosivity on road cut and fill slopes (Megahan and others 1991; Megahan and others, unpublished report; Swift 1984) and on gradient (Vincent 1979), effects of grade, traffic-induced rutting, and type of surfacing (Burroughs and King 1985; Burroughs and others 1984; Swift 1984) on road treads.

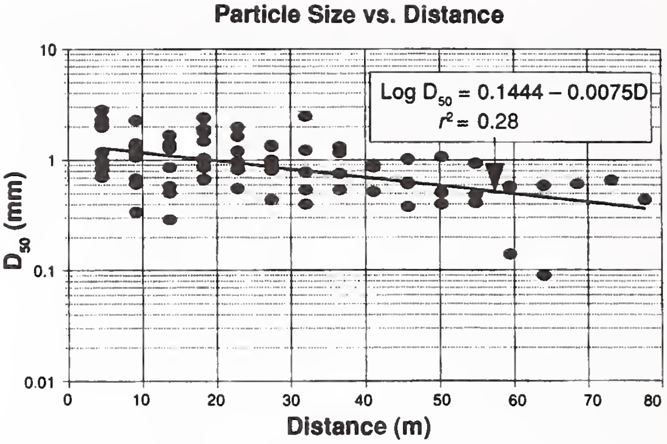

Figure 7—Median sediment particle size (D_{50}) as a function of travel distance.

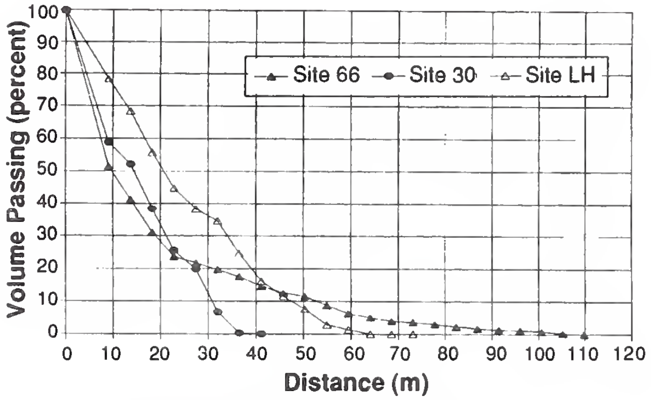

Figure 5—Representative plots of sediment volume with distance downslope.

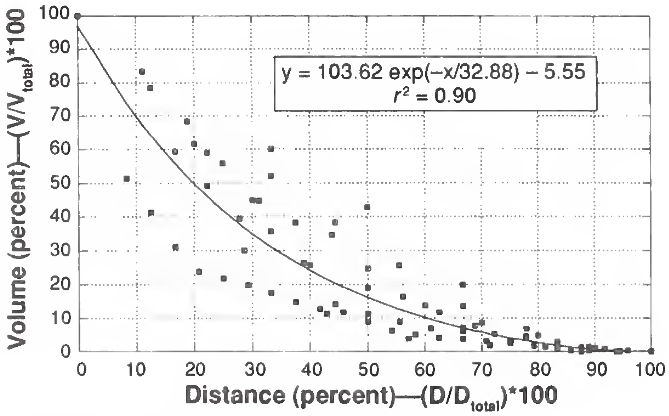

Figure 6—Dimensionless plot of volume of sediment deposition as a function of travel distance.

Erosion control treatments effectively reduce erosion. Other research has documented the amount of erosion reduction and costs of specific erosion control treatments such as revegetation measures and surface protection on road fill slopes (Megahan and others 1991), seeding, mulching, and terracing on cut slopes (Megahan and others, unpublished report), and road surfacing (Burroughs and others 1984). In this study we determined the average effectiveness of all treatments by study watersheds. Road construction on the Ditch Creek watershed used standard road construction practices (circa 1980) and resulted in erosion rates averaging 50.4 m^3/ha/yr for the 4-year study. Intensive erosion control practices in the Cabin Creek watershed reduced average annual erosion rates by 66 percent to 17.1 m^3/ha/yr. Much of the soil loss from road sections treated by intensive erosion control measures occurred during the first over-winter period when erosion control measures were least effective (for example, vegetation growth had not yet occurred). Thus, the long term percentage reductions in erosion as a result of these treatments should increase over time.

Sediment deposits measured in this study include all road surface erosion, except for that sediment supplied directly to the streams at points where roads cross active stream channels and where sediment deposits extended far enough downslope to reach active streams. Coarse soil texture over moderate-to-high weathered granitic bedrock, coupled with relatively low annual precipitation (890 mm) that occurs mostly as snow, causes low drainage densities ranging from 2.7 km^{-1} to 4.9 km^{-1} for the three study watersheds. As a result, many of the drainage dissections crossed by the roads do not sustain perennial water flow and show no signs of concentrated flow as shown by the lack of development of a channel bed and banks. For example, only four perennial stream crossings are encountered along the 3.2 km mid-slope collector road, yet there are 13 cross drains in swales containing no active stream channels. Low drainage density, plus the fact that only 18 of the 335 sediment deposits measured on the 6.64 km of roads extended downslope far enough to reach streams, suggests that sediment delivery ratios are low for the study basins.

Sediment budgets are needed to determine delivery ratios but such data are not yet available for the 4-year study period. However, a sediment budget was developed for the three study watersheds for the road construction period (Megahan and others 1986). Results of that work showed an average of 8 percent of the total sediment produced during road construction was stored in channels and 7 percent had reached the basin outlets. The remaining 85 percent of the sediment was stored as sediment deposits on slopes. Much of the sediment supplied to streams resulted from a high intensity rainstorm that occurred during construction, at a time when the road drainage and road erosion control measures where not in place. Both erosion rates and delivery to channels are lower after construction is completed to the specified design. We show that post construction erosion continues at a reduced rate but that few changes in sediment flow length occur. This is because most sediment drops out on top of the original sediment deposits. Sediment accumulates because of normal deposition processes and the fact that the storage capacity of the surface is rejuvenated to some degree by vegetation growth on and through the sediment and by the accumulation of new forest debris on the surface. Barring extreme climatic events, we expect future annual sediment deposition to continue at a rate between 10 to 15 m^3/ha of road area and that less than 10 percent of the eroded material will be supplied to channels.

Cross drains are by far the largest source of sediment from roads and travel the farthest. This is to be expected given the fact that runoff for sediment transport is greater from cross drains than from other road sources. One of the reasons for greater runoff from cross drains is the larger source area for runoff, both from the road prism itself and from upslope watershed areas (table 3). Increased runoff causes greater erosion within the road prism and provides greater energy for sediment transport below slopes. The watershed portion of the source area mostly affects the length of sediment movement by supplying transport energy. The other components of source area, road and fill area, affect the volume of sediment since they constitute the area exposed to erosion. Distances are consistently greater for cross drains by approximately one order of magnitude (fig. 4). Length of sediment deposits for cross drains also vary by site conditions. A probability distribution of sediment travel distance for cross drains was developed by Burroughs and King (1989) for study watersheds in the Horse Creek drainage located on weathered gneiss and schist parent materials in northern Idaho. Notice that although the frequency distribution appears similar, travel distances are less in northern Idaho. Much of the reduced travel distances can be attributed to a greater density of obstructions on the soil surface in northern Idaho (J. G. King, personal communication).

The dimensionless relationship between sediment volume and sediment length is limited in that it represents only nine sample sites; four from cross drains, four from fills, and one from a log landing. It is very probable that deposition patterns vary by type of source. For example, our data suggest that a smaller proportion of sediment volume extends downslope at longer proportional sediment lengths from cross drain sources than from fill sources. However, more data are needed to detect these trends.

The analysis above includes only those sites along the roads that represent typical conditions following road construction in the Idaho Batholith. Two atypical, but significant, situations existed along the roads that deserve discussion. These two sites are not included in the analysis presented above because they are considered outliers based on the circumstances

Table 3—Mean contributing area by source, Silver Creek Road Study.

Source	Mean contributing area			
	Fill	Road[1]	Watershed	Total
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Fills	0.02	0.02	0.004	0.04
Cross drain	0.04	0.09	3.25	3.34
Berm drain	0.01	0.04	0.02	0.06
Rock drain	0.01	0.06	0.21	0.28

[1] Road area includes the road cut, ditch, and tread area.

that created them. They are presented to show that more extreme situations may be encountered.

Concrete drop inlets were used to receive runoff contained between curbs on paved road sections. In one instance, the fill supporting the drop inlet settled slightly during construction and separated the drop inlet from the pavement. The fill slope rapidly eroded sending 66 m^3 of sediment through a nearby cross drain. Sediment traveled 218 m downslope of the road, to within a couple of meters of Cabin Creek. This failure would have delivered about 20 m^3 of sediment into the channel system had the small stream been within 30 m of the road. Another situation not included in the analysis resulted in the longest travel distance (274 m) and greatest volume (116 m^3) measured in the study. This resulted from two cross drains and two berm drains discharging into the same micro-watershed. The individual flows coalesced the first year after construction. The excess water discharged from these culverts caused gullying of the slope below the road that added an additional 18 m^3 of sediment. In this case, an estimated 85 m^3 of sediment would have been delivered to the channel system had the stream been within 30 m of the road.

The methodology outlined in this study provides a useful tool for land managers concerned about sediment hazards associated with road location and design in granitic parent materials. Probability distributions of sediment travel distance for road fill slopes and cross drains provide a measure of the risk of total sediment travel distance by road source condition. The dimensionless relationship between sediment travel distance (D) relative to total travel distance D_{total}, and sediment volume (V) relative to total sediment volume V_{total} (fig. 6) allows a land manager to estimate the risk of sediment travel below the road to a stream, and how much sediment reaches the stream. If the risk of sediment delivery is too high, alternative road design or location can then be planned or provision can be made to catch additional sediment below the road. An estimate of volume of erosion is needed to make such assessments. Procedures are available to estimate erosion volumes for roads constructed in granitic materials for road fills (Megahan and others 1991), road cuts (Megahan and others, unpublished report), and total road prisms (U.S. Forest Service 1981). The Revised Universal Soil Loss Equation (Renard and others 1991) could also be used to estimate erosion volumes. In a companion paper (Megahan and Ketcheson 1996) we describe a procedure to predict sediment travel distance from site conditions. Such an approach makes it possible to estimate sediment travel distance from specific site conditions and removes the need to select a probability value for sediment transport distance.

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A mapping technique was used to measure the annual downslope deposition of granitic sediments eroded from forest roads on three headwater watersheds in the mountains of central Idaho. Frequency distributions were developed to determine sediment travel distance, and a dimensionless relationship was developed to describe the relation between the percentage of total volume and total length of sediment deposit. By combining the two relations, land managers can assess the risk of sediment reaching streams to help guide road location and design.

Keywords: sediment deposition, sediment delivery, sediment storage, erosion control, road erosion

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