

Erosion, Sedimentation, and Cumulative Effects in the Northern Rocky Mountains

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ABSTRACT: Erosion and sedimentation are natural geomorphic processes characterized by large temporal and spatial variability. Recent radionuclide studies suggest that rare episodic events, such as large wildfires, produce massive sediment yields over time scales of thousands of years, thereby causing long-term average sediment production to exceed present-day average erosion rates by a factor of about 10. Even today, in undisturbed forested watersheds, sediment production is highly variable. Early studies of the effects of grazing and wildfire and surveys of river basins provided a foundation for much of the subsequent research on the effects of forest practices on erosion and sedimentation. The erosional and sedimentation effects of wildfire have been documented in many locations — ranging from none to minimal for low-intensity burns to catastrophic for high-intensity burns. Management of forestlands to regulate the risk of wildfire effects on erosion and sedimentation is an important present-day concern throughout the region.

Research consistently has shown that roads have the greatest effect of all practices associated with forest management on both surface and mass erosion. A large body of research shows, however, that much of the erosional impact of roads is manageable through proper land-use planning, location, design, construction, maintenance, and road closure. Considerable empirical data exists to illustrate surface erosion rates on roads, including time trends following construction as well as the effectiveness of a variety of erosion control practices. Effects of harvesting and associated site preparation activities on surface erosion are generally minimal and usually are controlled by providing downslope buffers. An exception is broadcast burning on harsh sites with highly erodible soils. Mass erosion, usually in the form of debris avalanches and torrents, is managed through risk assessment that uses inventory data and/or slope stability models to identify high-hazard site conditions. The primary management option for minimizing mass erosion resulting from roads or timber cutting is avoiding high-risk sites. Where avoidance is not possible, special design features are used, in the case of roads, or cutting and site preparation practices are modified, in the case of timber harvesting.

Several empirical and process-based models have been developed to predict surface erosion rates, the effectiveness of a variety of erosion control practices, and downslope sediment delivery. Empirical data are the primary

source of information for occurrence, magnitude, and downslope delivery of landslide material. Examples of downstream cumulative effects have been documented in terms of sediment delivery and associated channel responses. Methods to predict downstream cumulative effects are crude, however, limited primarily to sediment delivery, and are more applicable to smaller basins. Linkages between downstream cumulative effects and the impacts on beneficial uses, especially fish habitat, are poorly defined.

KEYWORDS: allowable impacts, channel cross-section, cosmogenic isotopes, cumulative effects, episodic events, erodible soils, erosion, erosion control, fish, legislation, particle size distribution, prescribed burning, roads, routing, salmon, sedimentation, sediment delivery, sediment supply, site preparation, surface erosion, timber harvest, time trends, variability, wildfire

Introduction

In this chapter we describe some of the key information developed over the past 100 years about erosion, sedimentation, and associated cumulative effects in relation to forestland management in the northern Rocky Mountains (NRM). For purposes of this review, we define the NRM to include the states of Idaho and Montana. It is impossible to include all of the important studies that have been conducted. We include enough references to provide an overview of some of the important lessons learned and present our impressions of relevant research needs.

Erosion, sedimentation, and associated downstream cumulative effects issues have long been a concern in the NRM. Prior to about 1950, the effects of sheep and cattle grazing on erosion and associated sedimentation were the primary problem. At issue was not only the potential for downstream sedimentation damages but also the effects of erosion on on-site range productivity. After World War II, grazing pressures decreased, and demand for construction lumber led to increasing timber harvest during the 1950s. As the harvesting progressed from more easily accessed forestlands to steeper terrain, there was increasing concern about erosional effects and associated sedimentation damages from timber harvesting and road-building activities.

A variety of legislation since the 1960s focused these concerns. Important federal legislation for managing National Forest lands such as the Multiple Use-Sustained Yield Act, the Forest and Rangeland Renewable Resources Planning Act, and the National Forest Management Act include protection of soil and water resources as a central theme. Additional legislation — including the Watershed Protection and Flood Prevention Act, the Resource Conservation Act, the National Environmental Policy Act, the Federal Water Pollution Act, and subsequent revisions to the Clean Water Act — was designed to protect soil and water resources on all lands, not just national forests. Last, but certainly not least, the potential for sedimentation effects on threatened and endangered fish and amphibians identified under the Endangered Species Act is a widespread

concern throughout the NRM. Furthermore, both NRM states have developed statutes directed at erosion and sedimentation issues.

Early Range Studies

Most early studies were directed at the effects of wildfire or grazing on erosion and sediment production; these studies provide the basis for much of the subsequent work on forestlands. One of the earliest studies, by Connaughton (1935), documented the effects of wildfire on erosion of granitic soils in the Payette River basin of southern Idaho. He reported increasing erosion with burn intensity and slope gradient and greater erosion on previously logged areas compared to unlogged areas. Other fire-related studies documented the effects of wildfire on runoff and downstream damages. For example, Curtis and Packer (1951) described the effects of a 100-acre range fire that caused a flood peak large enough to close a highway with sediment deposits.

Much of the early range research was carried out in southern Idaho in conjunction with watershed surveys in the Boise River drainage (USDA 1940). The work was done to assess runoff and erosion source areas within the basin, in order to develop watershed management plans to protect large irrigation and flood control works. Using a sprinkling infiltrometer, Craddock and Pearce (1938) found that runoff and erosion were least on perennial wheatgrass range sites and greatest on annual weed sites and tended to increase with rainfall intensity, soil disturbance, and slope gradient in all cases. In 1939 and 1940, the US Geological Survey, working in cooperation with the US Department of Agriculture, collected daily runoff and sediment loads at several stations on streams in the Boise River basin (Love and Benedict 1948). Rosa and Tigerman (1951) used these data to relate sediment production to watershed conditions within the river basin through the use of sediment rating curves.

The sprinkling infiltrometer proved to be an important tool for several subsequent researchers for determining the effects of site factors on erosion rates. Packer (1951) showed that erosion on rangeland was inversely proportional to ground cover density plus litter and directly proportional to size of bare soil openings. A second study (Packer 1953) documented increased erosion by the simulated trampling of livestock. Meeuwig (1969, 1971) found that erosion on rangeland depends chiefly on ground cover and slope gradient, with lesser effects from soil organic matter content and texture.

Natural Variability

Erosion and sedimentation are characterized by large spatial and temporal variability. Spatial variability results from differences in site conditions, including geology, climate, topography, soils, vegetation, and proximity to erosion source. Temporal variability results from varying short-term weather conditions and longer-term climatic trends, as well as natural and human-caused disturbances. Interactions between spatial and temporal components occur as sediments are routed down the watershed system.

Surface Erosion

Early studies showed the effects of spatial variability on erosion on rangeland in response to changing site conditions such as ground cover density, slope gradient, and soil properties. On most undisturbed forested slopes in the NRM, surface erosion is negligible because dense vegetative cover and surface litter prevent soil movement. However, surface erosion can occur on undisturbed, erodible, coarse-textured soils, especially on south exposures where vegetation cover is sparse as a result of low soil-moisture-holding capacities. Clayton and Megahan (1997) report annual surface erosion rates on undisturbed forest sites on granitic soils in southern Idaho averaging 0.09 tons per acre. Erosion rates varied from to zero to 1.6 tons per acre, depending on site factors such as ground cover density, rainfall erosivity, solar radiation loading, and soil depth. Natural disturbance, such as by fire, can increase surface erosion rates. Megahan and Molitor (1975) recorded annual erosion rates of 0.6 tons per acre the first year after wildfire on north-facing granitic slopes where there was no evidence of surface erosion prior to the fire. By the third year after the fire, erosion rates were negligible because of rapid regrowth of understory vegetation.

Mass Erosion (Landslides)

The vast majority of mass failures of concern to forest managers consist of debris avalanche landslides that occur on shallow soils overlying an impermeable layer, usually bedrock (Megahan, Day, and Bliss 1978). In some cases, slumps may also be a problem, especially on roads. Both of these types of mass failures are episodic in nature and occur when shear stresses within a slope exceed shear strength. Thus, landslide occurrence is highly variable over both time and space, almost by definition. Inventories of hundreds of landslides (Megahan, Day, and Bliss 1978; McClelland et al. 1997) show that landslides occur almost exclusively during very large storm events and vary on the basis of a variety of site conditions, such as type of bedrock, slope gradient, and slope location. Natural disturbances such as wildfire, earthquakes, insects, and disease can increase the occurrence of landslides (Croft and Adams 1950).

Although landslides are a major concern in some areas of the NRM, landslide risks and occurrences are considerably less there than in other areas in the Northwest, such as the Coast Range of California, Washington, and Oregon. In a survey of slope stability problems in the western United States, Burroughs (1985) classifies about 10 percent of national forest lands in northern Idaho and western Montana and 12 percent in southern Idaho forests as having a "high potential" for landslide occurrence.

The potential for mass erosion problems on landscapes may be evaluated through risk assessment, utilizing the results of landslide inventories to assist in the identification of high-hazard site conditions. Inventories of landslide occurrence and associated site characteristics have identified specific factors associated with high mass erosion hazard, including geologic,

soil, topographic, vegetation, and land-use characteristics (Megahan, Day, and Bliss 1978; McClelland et al. 1999).

Potential mass erosion problems have been evaluated more recently through risk assessment that uses slope stability models to identify landslide hazards at specific locations on the landscape. The infinite slope stability model accounts for the destabilizing effects of gravity and the components of friction and cohesion that resist failure. The LISA model (Hammond et al. 1992) uses the infinite slope stability model to determine a probability of failure and is useful for relative landslide hazard evaluation. More recently, slope stability models have been developed that combine the infinite slope model with hydrologic models. These models include SHALSTAB (Montgomery and Dietrich 1994) and SINMAP (Pack, Tarboton, and Goodwin 1998). Local information on soils and geology and available landslide inventory data are used to calibrate these models.

Considerable empirical data are available to illustrate the amount of sediment delivery to streams from landslides. Megahan, Day, and Bliss (1978) found an overall sediment delivery of 23 percent to channels in a survey of 629 landslides on the Clearwater National Forest in Idaho. A subsequent inventory of landslides on the Clearwater National Forest evaluated the effects of large storm events in 1995 and 1996 (McClelland et al. 1997). An average of approximately 57 percent of the landslide material was delivered to streams from 907 landslides.

Ward (1994) developed a two-step approach for estimating landslide delivery to streams. In the first step, site characteristics of landslide length, distance to the stream, and slope gradient are entered into a logistic model to determine whether a landslide will reach a stream. If the landslide is predicted to reach the stream, a multivariate model is used to estimate the percentage of slide volume being delivered. Site variables that are important for predicting delivery percent include slope gradient, distance to the stream, slide length, and ratio of slide length/distance to stream, depending on the type of disturbance at the landslide site (road prism location or natural slopes).

Sediment Yields

Numerous publications document that sediment yields can vary considerably from year to year in response to varying weather conditions and that episodic climatic events can increase sediment yields. However, long-term sediment yield data are limited to decades at best on undisturbed watersheds. Such data are available from 28 undisturbed study watersheds in Idaho ranging in size from 0.09 mi² to 6.5 mi² (USDA Forest Service, unpublished report). Lengths of records for the watersheds vary from 4 to 28 years. Records for all stations were adjusted statistically to a common 17-year period from 1966 to 1982. The average annual sediment yield from all watersheds for this dataset was 33.1 yds³ mi⁻² year⁻¹ and the range was 7–76 yds³ mi⁻² year⁻¹. Statistically significant differences in sediment yield were explained mostly by differences in average annual streamflow (82

percent of variability) and watershed relief (3 percent of variability) between the study watersheds. These average sediment yields represent essentially pristine conditions without any human-caused or natural disturbances or major episodic climatic events.

Granger, Kirchner, and Finkel (1996) showed that cosmogenic nuclide concentrations in stream sediments accurately reflect the area-averaged long-term (thousands of years) erosion rates of whole watersheds. Kirchner et al. (1998) compiled sediment data from 34 essentially undisturbed, forested watersheds in Idaho ranging in size from 0.1 mi² to 13,550 mi², including 25 of the basins identified above. Lengths of records for the watersheds ranged from 4 to 79 years and averaged about 20 years. Sediment samples were collected from each watershed and analyzed for cosmogenic nuclide content to determine long-term average sediment yield. On average, the long-term sediment rates exceed the measured short-term rates by a factor of about 10.

The Idaho watersheds had little or no glaciation, nor can the large differences between long- and short-term sediment rates be explained by climatic differences between Pleistocene and current climatic conditions. Apparently, long-term erosion rates and associated channel responses are driven by relatively rare episodic events that overshadow the short-term conditions represented by the available data sets. Episodic events are caused by large storms, often coupled with natural disturbances — especially wildfire — and result in very large sediment yields that can have major impacts on channel systems. Several such episodic events have occurred in Idaho in recent years from landslides during large storm events (Megahan, Day, and Bliss 1978; McClelland et al. 1997) and from intense wildfires (USDA Forest Service 1996; Pacific Watershed Associates 1998).

Effects of Timber Harvest

Timber harvest practices used in the NRM have minimal effects on erosion, which are small in comparison to the effects of the road system used to support the timber harvest. For example, jammer and skyline logging on steep granitic soils in central Idaho had a six-year average annual surface erosion rate of 0.06 tons per acre — only about 1.6 times the natural rate. In contrast, surface and mass erosion rates from the associated logging roads were 220 and 550 times natural rates, respectively (Megahan 1975). Megahan (1980) summarizes the reported soil disturbance from various studies of logging systems in the Pacific Northwest and British Columbia; he found an average of 21 percent from tractor logging, 13 percent from ground cable logging, 8 percent for skyline logging, and 4 percent for aerial logging systems such as helicopter logging. Thus, one means of controlling surface erosion is selection of a harvesting system that minimizes ground disturbance and exposure of soil. Soil losses usually are small on harvest areas because most logging systems disturb less than about 30 percent of the soil surface, and bare areas are small, rough, and discontinuous (Rice, Rothacher, and Megahan 1972).

Site preparation activities can have more effect on the potential for surface erosion than logging itself. Prescribed burning is the most commonly used technique for site preparation in the NRM; it also is used to reduce the hazard for wildfire. The erosional consequences of burning depend on the severity of the burn and resulting reduction in vegetation, slash, litter, and humus. One plot study in the mixed conifers of northern Idaho found that a spring prescribed burn under relatively moist conditions retained sufficient ground cover to cause only minimal amounts of erosion (Robichaud, Graham, and Hungerford 1994). At the other extreme, broadcast burning of clearcuts on south-facing slopes on granitic soils in southern Idaho accelerated erosion on the burned portions to about 8 tons per acre — 66 times natural rates (Megahan, King, and Seyedbagheri 1995). At this harsh site, much of the sustained erosion is attributed to slow vegetation recovery. Clayton (1981) attributed 32 percent of the first-year postlogging erosion to the broadcast burning. Thus, use of fire for site preparation and fuel reduction is not appropriate for all sites. Lopping and scattering slash or a silvicultural practice that retains more of the residual stand may be more appropriate at sites with steep slopes and highly erodible soils or at harsh sites where revegetation rates are slow.

Sediment travel distance from surface erosion in areas of diffuse runoff such as timber harvest units is minimal and easily controlled by providing downslope buffers of vegetation and debris on the ground. Both Idaho and Montana have rules and regulations that provide for streamside management zones and regulate activities within these areas. We are not aware of any studies in the NRM to determine appropriate buffer widths below harvest units as a function of site characteristics. However, sediment travel from other areas with diffuse sources of runoff, such as road fills, averaged only about 8 feet below the toe of the fill in one study in northern Idaho (McMurtray-Carlton, King, and Tennyson 1982) and 12 feet in a study in southern Idaho (Ketcheson and Megahan 1996) and varied with the volume of erosion and the amount of obstructions on the slope (Megahan and Ketcheson 1996).

Forest vegetation often provides the margin of safety between a secure slope and a landslide by providing root strength, removing soil water by evapotranspiration, anchoring the soil mass into the fractured bedrock, and buttressing and soil-arching action behind embedded tree trunks (Gray and Megahan 1981; Ziemer 1981). Studies of loss of root strength over time following timber harvesting (Burroughs and Thomas 1977) and frequency of landslide occurrence with time after timber harvesting (Megahan, Day, and Bliss 1978) suggest that landslides are most frequent 4–10 years after logging. Unlike in coastal areas, mass erosion resulting from timber harvest is not a serious problem in the NRM. Megahan, Day, and Bliss (1978) found that only 2 percent of the landslides on the Clearwater National Forest occurred on cutting units, compared to 3

percent on undisturbed areas. In a later study on the same area, McClelland et al. (1997) found that 12 percent of landslides occurred on cutting units, compared to 29 percent on undisturbed slopes. In areas where landslide risks are high, modifications to harvest practices can reduce landslide potential. Practices might include selection logging in preference to clearcutting, reduction in the size of clearcuts, establishment of vegetation leave areas, and integration of road drainage measures with vegetation leave areas (Gray and Megahan 1981).

Effects of Roads

Road construction results in exposure of bare soil, placement of unconsolidated material on the slope, soil compaction, destruction of soil aggregation, interception of subsurface flow, and concentration of surface runoff, all of which increase the potential for erosion and off-site sedimentation. Thus, it is not surprising that research has consistently shown that roads have the greatest effect on erosion of all practices associated with forest management. Although other management activities, such as timber harvesting, usually occur on a larger percentage of the landscape, erosion rates on roads are large enough that they are the dominant source of sediment in the NRM.

Magnitude of Road Effects

Surface erosion from roads generally is highest during the first year following construction and decreases rapidly with time (Figure 9-1). Erosion rates during the first year following road construction of standard-design roads on highly erodible granitic soils have been measured to exceed natural rates by up to 2,000–3,000 times, with erosion rates exceeding 90 tons per acre (Megahan and Kidd 1972; Ketcheson, Megahan, and King 1999). The amount of surface erosion in the first year following construction accounted for 66–86 percent of total erosion measured over a four- to six-year period. Both armoring of the soil surface and reestablishment and growth of vegetation reduce surface erosion over time. The initial high road erosion rates following construction often are attributed to erosion of unconsolidated fill material (Megahan and Kidd 1972; King 1984). At many sites, however, fillslope revegetation is sufficient after a year or two, so the long-term source of sediment is from the cutslopes, road tread, and ditch system. Moreover, traffic, road grading, and ditch cleaning rejuvenate a supply of finer sediments, and ditch cleaning may reinitiate an increase in cutslope erosion. Thus, most road systems represent a potential continuous source of sediment, although the source of the sediment will change over time. For example, a road built in the 1930s in one small study watershed was still producing about two tons per acre of erosion 37 years after construction—about a 50-fold increase over natural rates (Megahan 1974). Much of the erosion was attributed to continuing erosion of the cutslopes (Megahan, Seyedbagheri, and Dodson 1983).

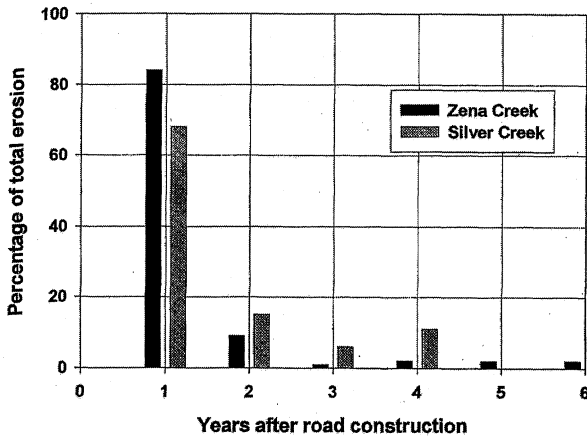


Figure 9-1. Erosion after construction of roads in Zena Creek and Silver Creek, Idaho.

Roads have also consistently been shown to have the greatest effect on mass erosion of all practices associated with forest management. Inventories of landslides conducted on two national forests in Idaho following major climatic events showed that landslides associated with roads accounted for 88 percent (Megahan, Day, and Bliss 1978) and 57 percent (McClelland et al. 1997) of total landslide occurrences, respectively. In the earlier study, delivery of material to streams from road-associated landslides varied with location of the slide source in the road prism; cutslope slides delivered an average of 33 percent, whereas fillslope slides delivered 44 percent. In the later study, delivery of material to streams from road-associated landslides averaged about 25 percent.

Controlling Road Erosion

Although roads represent an important potential source of sediment, a large body of research shows that many of the erosional impacts of roads are manageable through proper land-use planning, location, design, construction, maintenance, and closure. Application of four basic principles can reduce the erosion and sedimentation impacts of roads (Megahan 1977). A thorough knowledge of site conditions is required in applying these principles and deciding which combination of applications is best for the site and the planned activities.

The first principle is preventive; it involves recognition and avoidance of high-erosion hazard areas (Megahan and King 1985). These areas include excessively steep slopes, highly erodible soils, areas with a high risk of landslide, and areas with a high potential to deliver sediment to streams.

The second principle, also preventative, is to minimize the total amount of landscape disturbed by roads. This goal is accomplished in two ways: by minimizing the total length of roads and by keeping the roads as narrow as possible to accommodate transportation and drainage needs. The total mileage of roads necessary often is related to the type of yarding system used in the timber harvest operation. Some tractor and short-lead cable systems have had more than 25 percent of the area in roads, whereas

skyline and helicopter yarding systems typically require less than 4 percent of the area in roads (Megahan 1985) (Figure 9-2). Thus, selection of the logging system can be used to reduce road length. Minimizing total road disturbance also is accomplished by making roads as narrow as possible and rolling the grade to conform to the topography. This technique reduces surface erosion by minimizing the road disturbance width and the heights of cut- and fillslopes. Minimizing total road disturbance also reduces the occurrence of landslides. Landslide occurrence on roads is directly related to the amount of excavation required for the design standard of the road (Megahan, Day, and Bliss 1978), so landslide occurrence on larger main arterial roads is considerably higher (3.5 slides per mile of road) than for narrower terminal roads (0.3 slides per mile of road).

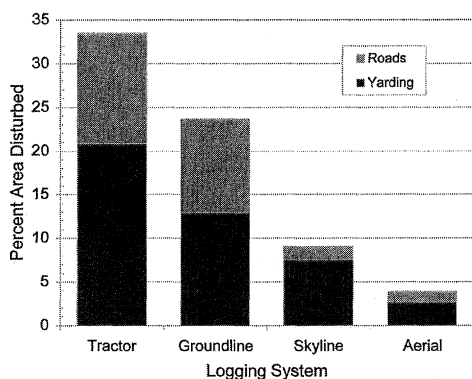


Figure 9-2. Percentage of area disturbed by different logging systems.

The third principle is to provide for design or treatments on road features that reduce erosion. In the case of surface erosion, a considerable amount of research has gone into quantifying the effectiveness of a variety of road erosion control practices. Guidelines have been developed that describe the effectiveness of many of these treatments (Burroughs and King 1989). Fillslope treatments that combine a surface amendment, typically a mulch, with a revegetation measure, seeding, sprigging, or transplanting are more successful than either a surface amendment or revegetation measures alone (Megahan et al. 1992). Treatments that include an application of mulch with a means of holding the mulch in place on the slope (e.g., asphalt tackifier, net, or crimping) in combination with seeding or seeding and transplanting can reduce fillslope erosion more than 90 percent. Much of this effectiveness can be lost, however, if direct runoff from the road tread is diverted to fillslopes (King 1979). Thus, maintenance of the designed drainage system also is critical in reducing fillslope erosion. Cutslopes, which typically are constructed with steeper gradients than fillslopes, are prone to dry ravel and sloughing processes. Erosion control treatments on cutslopes are less successful; reported reductions in erosion for terracing and mulch applications, both with seed and fertilizer, are in the range of 30–60 percent (King 1994; Megahan, Wilson, and Monsen 2001). The road tread also is a source of sediment, and rutting of the road

tread from traffic concentrates runoff and increases surface erosion. Surfacing forest roads effectively reduces erosion, and plot studies of applications of gravel, bituminous surfacing, and dust oil have shown reductions in road tread erosion exceeding 77 percent (Burroughs and King 1985). Use of lowered tire pressures on logging trucks also results in reduced surface erosion, partly because it causes less-defined wheel ruts (Foltz 1995). Plot studies on short road segments indicate a twofold to more than a fourfold increase in sediment production from freshly graded roads that become rutted (Foltz and Burroughs, 1990). Thus, routine grading or road closures to minimize rutting are additional options for erosion control.

In the case of mass erosion on roads, special design features often are used to reduce sidecast material, bench roads, compact fills, control drainage, and retain cut- and fillslopes. Excellent technical guidelines describing these and other road construction techniques in high-risk areas are available (Burroughs, Chalfant, and Townsend 1976; Chatwin et al. 1994). Control of drainage is critical in minimizing slope failures.

The fourth principle is to minimize the delivery of road-derived sediments to streams. This approach requires careful planning of road locations to minimize the number of stream crossings and maximize slope travel distance to streams. Several empirical studies make it possible to estimate sediment travel distance below roads on the basis of local site characteristics. Haupt (1959) defines sediment travel distance from roads constructed on granitic materials in southern Idaho as a function of the amount of obstructions on the slope below the road, cross-ditch spacing on the road, fillslope embankment length, and road gradient. Packer (1967) found sediment travel distance to be controlled by cross-drain spacing on the road, slope obstruction characteristics, fillslope cover density, soil particles greater than 2 mm (characterized by type of geology), and road age. Both of these studies provide prediction equations for total sediment travel distance. Other researchers have defined the probability of sediment travel distance below road culverts on border zone geology in northern Idaho (Burroughs and King 1989) and on granitic soils in southern Idaho (Ketcheson and Megahan 1996). Additional studies make it possible to define not only how far sediment travels below roads but also how much travels how far. Wasniewski (1995) developed relationships between cumulative sediment volume and travel distance below roads on granitic and gneiss/schist soils in northern Idaho. King (1979) presents data for the percentage of eroded sediment volume that travels given distances below roads on border zone soils in northern Idaho, and Ketcheson and Megahan (1996) present similar data for granitic soils in southern Idaho. Megahan and Ketcheson (1996) developed a prediction equation for sediment travel distance based on the volume of road erosion, runoff source area, hillslope gradient, and obstructions below the road, and they provide a relationship showing sediment volume in relation to

total flow length of sediment. Use of both equations makes it possible to predict the volume of sediment reaching channels and to evaluate the effects of alternative erosion control measures or road locations on the volume of sediment delivered to streams. One additional treatment — placement of slash generated from road-clearing operations on or below fillslopes — has been shown to be very effective in capturing sediment and reducing sediment transport distance (Cook and King 1983).

Many older roads were located in areas with a high potential delivery of sediment to streams, such as in valley bottoms paralleling streams, often constricting the channel, or on unstable slopes with a high potential for landslides. In these cases, some form of road obliteration may be desirable. Although road obliteration is becoming more widely used, little information is available at this time to quantify either short- or long-term effects on sediment production.

Predicting Road Erosion

The number of empirical studies of surface erosion on roads conducted over the years in the NRM has led to the development of empirical models for predicting on-site erosion rates, the effectiveness of erosion control practices, and downslope delivery of eroded materials. Available empirical studies have been assembled into a methodology (known as the R1-R4 Sediment Yield Prediction model) for estimating the effects of roads and other forest disturbances on erosion and sediment yields (Cline et al. 1981). Further discussion of the R1-R4 model is presented in the “Cumulative Watershed Effects” section below.

In addition to empirical models, there has been considerable effort devoted to the development of process models for predicting road erosion. Simons, Li, and Shiao (1977) developed the first physically based process model for predicting sediment production from forest roads from individual storm events. The ROSED (ROad SEDiment) model was applied to mine haul roads in Montana as well as forest roads in other locations (Ward 1985). The model considers all components of the road prism, including cutslopes and fillslopes, the running surface, ditches, and culverts. Hydrologic processes evaluated include interception, infiltration, overland flow routing, and sediment detachment and transport using rain-drop splash and overland flow shear stress.

More recently, the Watershed Erosion Prediction Project (WEPP) model has been applied to forest roads, areas of timber cutting, and burned forest areas (Elliot and Hall 1997). The model is physically based and includes an evaluation of runoff and erosion processes similar to those considered in the ROSED model. WEPP also uses a long-term climate generator to simulate storm events as well as snowfall and melt, and it provides estimates of vegetation growth and the production of litter. The model was developed to replace the empirically based Universal Soil Loss Equation (USLE) and its successor the Modified Universal Soil Loss Equation (MUSLE). The current version of the model evaluates erosion and downslope sediment

movement from small areas (road sections or cutting units); a watershed-scale version of the model for application on forest lands is under development. A simplified version of the model called X-DRAIN (Elliot et al. 1998) provides estimates of sediment deposition below forest roads for selected conditions of cross-drain spacing, road gradient, length of forest buffer area below the road, steepness of the buffer, and soil texture. The model has been tested on forest roads in Idaho and elsewhere (Elliot, Hall, and Graves 1999) for both erosion rate on the road and sediment travel downslope below roads.

Cumulative Watershed Effects

Cumulative effects for the purposes of this chapter are the erosion and sedimentation consequences, both on and off site, of one or more forest practices (harvesting, road building, or fire) over time. Because the Clean Water Act mandates the assessment of cumulative watershed effects of land management activities, this issue is very relevant. Watershed case studies, process studies, and paired watershed studies are different strategies for addressing cumulative effects in basins of concern and for developing methods to predict cumulative watershed effects elsewhere (Reid 1993). All three of these approaches have been used in the NRM.

Case Studies

The best example of a case study on cumulative effects is the South Fork Salmon River basin. Historically, the South Fork Salmon River was the single most important summer Chinook salmon spawning stream in the Columbia River basin (Mallet 1974). Intensive logging and road construction took place between 1945 and 1965. The combination of highly erodible soils, steep slopes, soil disturbance from road building and timber harvest, and large climatic events in 1955, 1962, 1964, and 1965 delivered large quantities of sediment to the river, and by 1965 sediment quantities were in excess of the stream's transport capacity. There was deposition of predominantly sand-sized material throughout much of the river system, and prime salmon spawning and rearing areas were buried with sand. As a result, a moratorium on logging and road construction was imposed by the USDA Forest Service in 1966 for much of the basin. Assessments of the basin were performed in 1965 to estimate sediment volumes by source (USDA 1965), and over time rehabilitation practices were installed to reduce surface erosion and mass erosion. More than 400 miles of roads were closed and stabilized.

River responses following the moratorium were monitored through photographic documentation, channel cross-section surveys, and transects to evaluate the particle size distribution of the river bed in spawning and rearing areas (Megahan, Platts, and Kulesza 1980). The watershed rehabilitation program reduced sediment supply to a level at which the river began to remove excess sediments. Conditions within the river improved with time (Figure 9-3) (Platts and Megahan 1975; Megahan, Platts, and Kulesza 1980). In 1978 the moratorium was lifted, and a new land-use plan

allowed cautious reentry into the basin. Monitoring continued to assure continuing improvement of the river conditions. A comparison of sediment storage in the river channel between 1965 and 1989 indicated that about 78 percent of the sand and gravel had been transported out of the river (Bohn and Megahan 1991). Such case studies or basin-wide assessments provide useful information on types and magnitudes of problems, sources of sediment, rehabilitation needs and priorities, and quantified time trends in recovery.

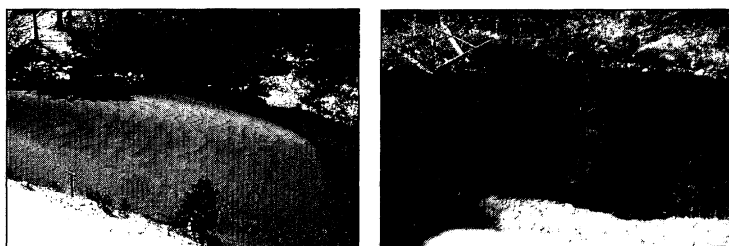


Figure 9-3. (a) 1966: Glory Hole almost completely filled with sand; (b) 1972: most sand is gone, and original rubble-boulder streambed surface is revealed. Source: Megahan, Potyondy, and Seyedbagheri (1992). Reprinted with permission of the publisher.

Paired Watershed Studies

A second strategy for assessing cumulative sedimentation effects is paired watershed studies, which usually are carried out in conjunction with other studies to define and describe processes of erosion, sediment delivery, and sediment transport. Much research in the NRM relative to the cumulative effects issue has been conducted in small, paired watersheds — most less than 1 mi² in area — on granitic and metasedimentary geology. Management treatments have been evaluated on 11 watersheds (Horse Creek and Silver Creek study areas), representing 102 station-years of data for pretreatment conditions and 109 station-years following treatment. Paired watershed approaches typically compare the effects of selected forest practices in treated watersheds with an undisturbed control watershed. These watersheds typically are monitored for a sufficient number of years in an undisturbed condition to determine natural rates and variability in erosion and sedimentation processes. Various forest activities are applied to each watershed, and conditions and processes are monitored for a sufficiently long period to allow for substantial recovery of disturbed areas. The types of practices that have been monitored include different types of yarding systems, different sizes of clearcuts and amounts of timber harvested, different site preparation techniques, and different types of road standards and treatments. Measurements of conditions and processes vary by watershed but have included climatic variables, streamflow variables, sediment production, channel storage of sediment, hillslope storage of sediment, and erosion and site conditions on undisturbed slopes, harvest units, and road features. These small watershed and process studies have

been extremely useful in understanding processes and developing relationships that can be extrapolated to other areas in the NRM.

Prediction Methods

In the late 1970s Forest Service researchers and soil scientists and hydrologists from the Northern and Intermountain Regions of the National Forest System collaborated in integrating information from small watershed studies and process studies with relevant research from other geographic areas to develop a methodology for estimating the erosional and sedimentation consequences of land management activities (Cline et al. 1981). This *Guide for Predicting Sediment Yields from Forested Watersheds* estimates average sediment production over time from harvesting, road building, and fire activities.

This methodology, known as the R1-R4 Sediment Yield Prediction model, was developed principally for national forests and similar lands on watersheds in or generally associated with the Idaho batholith, but it has been applied elsewhere in the NRM. A landscape stratification procedure (Wendt, Thompson, and Larson 1975) provides the basic geomorphic response units for assessing erosion and sediment delivery to channels. The procedure provides an estimate of on-site erosion for a given management activity, modifies the amount of erosion according to erosion mitigation measures (best management practices) and general land-unit characteristics, delivers the eroded material to the stream system, and routes it through the watershed to a critical stream reach. The sediment delivery ratio approach used for sediment routing through channels provides unrealistic sediment supplies in larger watersheds because the effects of channel storage on the attenuation of the sediment wave are not considered. The procedure is widely used on national forest lands, primarily as a land-use planning tool to compare the effects of alternative land management activities on sediment production. It is structured so that new information and local data can be used to refine the procedure; thus, many variations of this procedure now exist.

Megahan, Potyondy, and Seyedbagheri (1992) document application of the sediment yield prediction methodology, as adapted to the Boise National Forest in southern Idaho (Reinig et al. 1991), to compare sediment production from alternative timber harvest activities and wildfire in a major tributary of the South Fork Salmon River (Figure 9-4). Potts, Peterson, and Zuuring (1985) used the R1-R4 model to illustrate the possible effects of wildfire and post-fire timber salvage on sediment yields in the NRM. There has been limited comparison of modeled versus actual erosion or sediment yields using this procedure (Gerhardt 1992; Ketcheson, Megahan, and King 1999). The latter comparison was done on a research study area in the southern part of the Idaho batholith. The evaluation showed that model predictions of on-site erosion were very close to that measured but that predicted sediment delivery to and down streams was substantially higher than that recorded on study watersheds. The

researchers conclude that the primary reason for overprediction of sediment delivery to streams is the fact that the R1-R4 procedure assumes average conditions for landscape units and ignores road location in relation to proximity to streams.

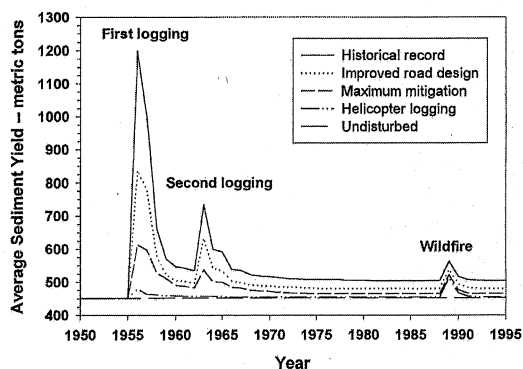


Figure 9-4. Comparison of modeled time trend in sediment yields for alternative land management practices for South Fork of the Salmon tributary. Source: Megahan, Potyondy, and Seyedbagheri (1992). Reprinted with permission of the publisher.

An effort has been made to develop a basin-scale physical process model to evaluate cumulative effects of alternative land management activities in the Gospel Hump area of the Nez Perce National Forest in Idaho. This model consisted of an expansion of the original ROSED model to a watershed scale; it was adapted to snowmelt hydrology conditions that are common in central Idaho. The model, called SNOSED (SNOwmelt-SEDiment) (Simons et al. 1981), included routines for sediment routing on the basis of measured channel conditions. The model was used to compare expected consequences of various long-term land management scenarios on streamflow and sediment production. However, SNOSED was evaluated on a small watershed for which sediment, streamflow, and climatic data were available. The results of the evaluation suggested the need for improvement of the model, especially with regard to how it models subsurface flow, before it can be considered sufficiently reliable (Barber 1982).

Defining What's Allowable

One major problem facing forest managers dealing with sedimentation effects of alternative management practices is to define how much sediment, of what kind, is allowable. There has been some effort toward such assessments in the NRM, but much more needs to be done. Wilson, Patten, and Megahan (1982) used an adaptation of the R1-R4 model on the Clearwater National Forest to develop a methodology to define how much change in annual sediment yield is needed to upset the geomorphic equilibrium of channels in headwater basins. First they made a comparison of R1-R4 predicted versus measured annual sediment yields for nine basins; there was reasonable agreement. Next, watershed characteristics for 65 watersheds were used to predict annual sediment yields for undisturbed conditions and the existing disturbance condition. Low-gradient channel reaches at the mouth of each watershed were sampled for evidence of channel aggradation. The researchers developed a scattergram by plotting

predicted undisturbed sediment yield for each watershed against predicted sediment yield increase from management activities, expressed as a percentage over natural. Points on the scattergram were labeled for evidence of aggradation in the channel. There was a clear break between channels with and without aggradation that suggested that increases in annual sediment yields of about 100 percent were needed to cause channel aggradation.

Defining allowable sediment yield increases is linked most often to the need to know the impacts on beneficial uses, especially aquatic habitat and fish populations. In response to this need, fisheries biologists with the USDA Forest Service and the University of Idaho developed the *Guide for Predicting Salmonid Response to Sediment Yields in Idaho Batholith Watersheds* (Stowell et al. 1983). This procedure uses the predicted average annual sediment yields from the R1-R4 model as input. Relationships were developed between predicted sediment yield and existing habitat conditions on selected watersheds and combined with relationships between habitat conditions and fish population responses from field and laboratory studies. This procedure is useful in land management planning to compare relative differences between management alternatives on fish populations. However, our ability to predict temporal and spatial responses in downstream habitats resulting from sediment yield increases from upstream land management practices is lacking.

Only limited studies have been done to develop process-based models of sediment transport and habitat conditions. In one study of a Chinook salmon spawning reach of the South Fork Salmon River, a "salmonid spawning analysis model" was developed to model streamflow and sediment transport through the spawning reach, intrusion of fine sediment into Chinook redds, redd attributes of temperature, particle size distribution, interstitial velocities, and dissolved oxygen concentration (Havis et al. 1993). This model performed well relative to data collected in artificial and natural redds within the reach, but it does require calibration and known inputs of upstream streamflow, sediment, and stream temperature. This model is not directly linked to upstream erosion and sediment generated from forest activities.

Research Needs

Watershed scientists in the NRM region have made tremendous strides in understanding watershed processes and functions. This understanding has led to the development of useful sediment control methods and assessment tools that find application in management in this region and elsewhere. Nevertheless, we recognize the need for some additional research on erosion and sedimentation in the NRM. Variability in outputs of water and sediment from watersheds was recognized early in the research in this region. There is a need to develop a better understanding of natural variability and the factors influencing it, as well as how natural variability should be factored into decisions about forest management activities. Sediment delivery from upslope erosion sites and sediment

routing connect hillslopes to streams and critical reaches. Progress has been made in understanding the factors influencing routing of sediment, but there is a need to develop practical methods for routing sediment through channel conditions that are representative of mountainous forested watersheds. In addition, we need to know how the delivered sediment affects different channel types or habitats and how this sediment impacts beneficial uses. Although assessment tools such as SNOSED and R1-R4 have been developed in the NRM, there is a need to improve and test prediction models at the watershed scale. Watershed managers are being challenged to provide increasingly precise and robust assessments and to evaluate the cumulative effects of multiple management activities. Watershed models and watershed assessment tools provide the most effective means of meeting those demands.

KEY LESSONS LEARNED IN THE NORTHERN ROCKY MOUNTAINS

- Erosion on rangeland is inversely proportional to ground cover and increases with slope gradient.
 - Natural surface erosion rates in the NRM region are low.
 - Long-term (1,000-year) erosion rates are an order of magnitude greater than background erosion rates measured at gaging stations, probably reflecting rare major hydrologic or disturbance events.
 - In the NRM, mass erosion from harvest units is not a major problem.
 - Roads are a major source of sediment to streams from both surface erosion and mass wasting.
 - Four principles for minimizing erosion from roads are avoiding high-hazard (steep, erodible) areas; reducing disturbance caused by roads by minimizing their length and width; designing and treating roads to reduce erosion; and minimizing delivery of sediment to streams.
 - Cumulative effects have been studied using case studies, paired watershed studies, and process studies.
 - Tools are available to predict sediment impacts from forest operations in this region.
 - More research is needed to define allowable impacts from forest operations, but one study suggests that an increase of about 100 percent in background sediment loads is needed to cause measurable changes in channel aggradation.
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Editors

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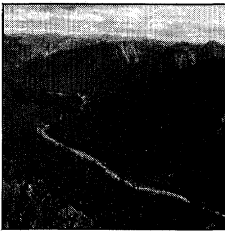
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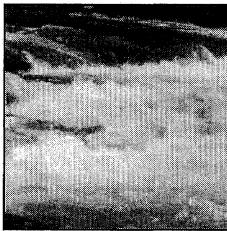
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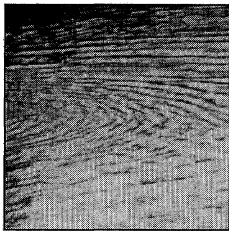
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