Measuring and Modeling Soil Erosion Processes in Forests

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Abstract:

A prime forest resource is clean water for downstream beneficial uses. Sediment from forests may impair those beneficial uses. Sedimentation by water erosion is rare unless road activities, timber harvesting, or fire disturb the forest. We have been researching forest soil erosion processes and developing erosion prediction models for over 10 years. This paper presents an overview of some of our findings.

Rut formation dominates road erosion processes. Road maintenance practices that reduce rutting also reduce erosion rates. Road ditches can also be a major source of sediment if the ditches are recently disturbed from construction or maintenance. Generally, if roads are properly designed and located at a sufficient distance from nearby streams, then stream sedimentation is minimal.

Forest harvesting activities can lead to increased erosion due to the exposure of mineral soil or the alteration of soil properties due to compaction. Fires can lead to major erosion in forests, especially during the first few years after the fire. Spatial variability of the severity of disturbance is common after fire. Fire effects include a reduction in soil hydraulic conductivity and a loss of the protective organic layer on the soil surface. These two impacts can increase erosion rates by several magnitudes.

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The Water Erosion Prediction Project (WEPP) model can model disturbed forest erosion processes. WEPP can be a powerful tool to provide quantitative estimates of the amount of sediment entering forest streams for many management activities. Templates for the current WEPP model and user-friendly interfaces have been developed to assist field managers to apply this technology to various forest conditions.

Introduction

Soil erosion results from complex interactions of climate, topography, soils and geology, vegetation, and management activities. Rainfall is inadequate to cause major erosion problems in many of the non-agricultural forested areas managed by federal agencies in the western U.S. The soil surface litter layer prevents surface runoff, so there is little concern from upland erosion processes. In these areas, much of the runoff is from near-surface flow, and shallow groundwater dominates stream flow. The net result of these processes is that natural erosion rates within most U.S. forests is low, in the range of 0.04 to 0.1 Mg ha^{-1} yr^{-1} (Hickey, 1997; Megahan and Kidd, 1972; Patric, 1976) (1 Mg = 1000 kg). Forest disturbances, however, can increase erosion rates to 100 Mg ha^{-1} yr^{-1} (Megahan and Molitor, 1975). These disturbances include roads, forest operations including harvesting, and fire. The objective of this paper is to describe research activities and findings about measuring and modeling soil erosion resulting from forest disturbances.

Roads are the greatest human-induced disturbance on a forested landscape. The soil disturbance and compaction caused during road construction considerably reduces the hydraulic conductivity of roads (from 40 mm h^{-1} or more to under 1 mm h^{-1}). The resulting increased runoff coupled with the absence of vegetation are responsible for the increased erosion rate observed on road surfaces. Harvesting activities and fire have similar effects in increasing runoff and decreasing surface cover but to a much lesser extent. The degree to which conductivity is decreased, and surface cover reduced, determines the level of erosion that will follow. Even though erosion rates may not be as high as on roads, the larger spatial extent of the disturbance may result in an overall greater delivery of sediment. The forest vegetation, however, can soon return following a forest disturbance, reducing erosion rates back to undisturbed levels. The process-based Water Erosion Prediction Project (WEPP) model has the ability to model most of these processes, but building the input files for such complex conditions has been too time-consuming for many forest specialists.

Road Erosion Processes

Rut formation dominates road erosion processes. Roads with ruts caused by traffic produced two to four times as much sediment as freshly graded roads in studies using rainfall simulation (Figure 1) or natural rainfall (Foltz and Burroughs, 1991; Foltz, 1993). These studies reported on ruts that were deep (50 mm) and continuous (greater than 15 m long). In these studies with well defined continuous ruts, the dominant process responsible for the increased sediment was a change from short overland flow paths across the road to long concentrated flow paths down the road. Figure 2 shows Forest Service professionals measuring the degree of rutting on a road in a recent study in Oregon.

Overland flow occurs along a path that is a combination of the road grade and the cross slope on a recently maintained road without ruts (Figure 3). Even before deep ruts form on a road, traffic causes changes in the road surface topography that may increase erosion. On most forest roads, traffic tends to reduce the cross-slope, so that runoff follows the road surface for a greater distance (Figure 3). The increase in surface erosion due to this increased flow path length may be doubled, or more, even before rutting occurs.

Road maintenance practices to remove ruts can result in major reductions in erosion rates. Elimination of ruts and reestablishment of cross-slope reduces overland flow path length, which reduces erosion rates. Road maintenance practices can leave erodible material on the surface ready to be washed off in the next storm. The shorter overland flow path leads to lower accumulated runoff, resulting in lower sediment detach and transport rates of this loose material and less surface erosion.

A decrease in sediment production over time is an important characteristic of road erosion. Two time scales can be distinguished: within a single runoff event, and over several years. In rainfall simulation studies, sediment concentrations start high and decline during a runoff event even though the runoff rate remains constant (Figure 4). Foltz (1993) reported sediment concentration declines of 67 to 78 per cent during high intensity, long duration simulated rainfall storms (50 mm hr^{-1}, 90-minute duration). The reason for this decrease appeared to be a sediment supply deficiency. We postulate that the sediment supply recovers between storms by a combination of desiccation of the surface and additional traffic. Desiccation causes larger aggregates to break into more transportable sizes. Traffic crushes the surface into smaller, more transportable sizes. In a study of these recovery mechanisms, Foltz and Elliot (1999) estimated the time scale for desiccation to be approximately one week. The amount of traffic needed to regenerate a similar sediment supply was 50 to 100 passes of a pickup truck (3.6 Mg) or a single pass of a fully loaded logging truck (22.5 Mg).

The long time scale decrease in sediment production represents a period of several years (Figure 5). Megahan (1974) measured erosion from a new logging road in central Idaho for a period of six years. Sediment production from the entire road prism decreased exponentially from 175 Mg ha^{-1} yr^{-1} to 4.6 Mg ha^{-1} yr^{-1} for the sixth year of the study where traffic on the road was minimal after the first year. Megahan discounted both variations in rainfall and re-vegetation as causative agents in the observed sediment decline. He postulated that armoring of the surfaces was responsible. Classical armoring occurs in mountainous rivers where the smaller size particles are washed away by the flow leaving the larger ones undisturbed. The larger sizes subsequently shield the smaller ones from detachment until a higher flow removes the protective layer. Similar decreases of sediment production with time have been incorporated into U.S. Forest Service regional erosion models and Washington [State] Forest Practices (1997).

If roads are free from ruts, then road ditches can be another major source of sediment if they have been disturbed by construction or maintenance. When routine forest road maintenance is performed, the ditch is often cleared of vegetation and accumulated sediment. This operation increases the water velocity by removing the retarding vegetation and makes detachable sediment more freely available. However, the faster water is more erosive. In a study of ditch linings in central Idaho, Foltz (1996) found water velocities two to three times higher in bare ditches than in grass-lined ditches. Luce and Black (1998) reported that road segments in Western Oregon with recently cleared ditches produced seven times as much sediment as well vegetated segments.

A bare or vegetated fill slope, and a forested buffer area are generally located between roads and streams (Figure 6). If roads are located at a sufficient distance from nearby streams, then sediment delivery to the stream is minimal. The erodibility, transportability, and conductivity of soils vary with parent materials. Burroughs and King (1989) studied travel distances below ditch culvert outlets in gneiss and schist parent materials on 30 to 40 per cent hillside gradients. They reported that if the objective was to prevent 80 per cent of the culverts from contributing sediment to streams, a distance of 50 m would have to be provided between the culvert outlet and the stream. In another study in central Idaho, Wasniewski (1994) found that 95 per cent of the sediment travel distances below culverts did not exceed 45 m for gneiss and schist, and 60 m for granitic parent material, which had a higher hydraulic conductivity. Rhee et al. (1998) reported on a WEPP model study of a 4.4 km road in granitic parent materials that had been designed to minimize sediment delivery. No sediment delivery to the stream occurred from segments totaling 2.21 km. The maximum delivery of only 1.2 per cent of the sediment that was detached on the road occurred over a forest floor with a length of 180 m and a gradient of 40 per cent.

State and federal regulatory agencies recognize the role of forest buffers in trapping sediment. In a recent document, an interagency group of managers recommended buffers of 92 m around fish bearing streams and 46 m around permanent non-fish-bearing streams (USDA FS and USDI BLM, 1995). Washington [State] Forest Practices (1997) Watershed Analysis assigns roads draining directly into streams a delivery of 100 per cent. For forest buffers up to 60 m, a delivery of 10 per cent is estimated; for buffers greater than 60 m, the sediment delivery is assumed zero. Any sediment delivery across a buffer will vary with climate and topography. Consideration to local factors therefore is necessary, and caution is recommended before transferring any remotely developed prediction technology to local conditions (Morfin et al., 1996).

Erosion from forest operations

Roads are not the only source of erosion in forests. Forest lands are generally stable and do not erode unless disturbed by forest operations, prescribed fire, or wildfire. Forest operations such as thinning, harvesting, and site preparation activities may influence onsite erosion. Erosion from timber harvest areas generally is less per unit area than erosion from roads, but since these areas are much larger, the total erosion from timber harvested areas and roads may exceed that from roads alone (Figure 7). Spatial variability is a complicating factor in determining the effects of forest operations. The variability of inherent site characteristics, (Robichaud, 1996), spatial extent of the disturbance (Robichaud and Monroe, 1997), and proximity to sensitive areas such as stream corridors and riparian zones (O'Laughlin and Belt, 1995) all impact upland erosion and sediment delivery.

Four common harvesting systems are skidder, ground cable, skyline and helicopter. Skidder logging systems cause the most disturbance (Figure 8). The logs are dragged, disrupting the forest floor. The skidder tires disrupt the forest floor, and repeated passes are common. Skidders displace the forest floor and compact the mineral soil. In addition to compaction, on slopes greater than 20 per cent, the slippage of the skidder tires may remove the litter cover and loosen the mineral soil beneath. Compaction increases runoff and soil erosion and adversely impacts productivity by reducing the water holding capacity of the soil. Litter removal increases the erosion rate of the mineral soil. The most erodible soils within a harvest area are skid trails because these soils have reduced infiltration, disturbed litter cover, and compacted soil (Robichaud et al., 1993a). Cable systems and helicopter logging cause far less disturbance with erosion rates approaching undisturbed rates, depending on how much care is taken during the operations.

The location of skid trails on a hillslope can also influence the rate of erosion and sediment yield. Skid trails near the top of a hill, and those following natural contours, are unlikely to cause any significant erosion or offsite sediment delivery. Skid trails nearer the bottom of the hill, with minimal undisturbed buffer zones, are more likely to erode. They are exposed to additional overland flow from uphill and are more likely to deliver sediment to streams. In Elliot et al. (1996), a skid trail near the bottom of the hill concentrated surface and subsurface runoff, leading to erosion in a channel that was stable prior to the disturbance.

Fire

Forest management activities impact the natural processes of fire and erosion, particularly fire suppression and timber harvesting. Fire suppression on steep terrain has increased for many decades in the western U.S. Fire suppression leads to fuel loads that exceed natural levels and may cause plant species composition changes (Agee, 1993). These changes in the plant community and fuel result in conditions that are more susceptible to high severity fires. High severity wildfires, especially on steep slopes, can have a major impact on erosion, mass wasting, and hydrologic processes. The result is often loss of soil mantle (from generally poorly developed soils), sediment movement and flooding, loss of nutrients held in organic matter and mineral soil, damage to fish habitat, and damage to structures such as roads, bridges, and water storage systems. Studies with both rainfall simulation on small plots and natural runoff studies on small watersheds (under 10 ha) are used to measure erosion rates from these disturbed areas (Figure 9).

The most common method of site preparation for tree regeneration in the United States is prescribed burning. Prescribed fires are conducted alone, and in combination with other treatments, to dispose of slash, reduce the risk of insect and fire hazards, prepare seedbeds, and suppress plant competition from natural and artificial regeneration. The use of prescribed fire is likely to increase during the next decade as forest managers reintroduce fire into fire-dependent ecosystems.

Erosion following fires, either prescribed or wildfire, can vary from extensive to minimal, depending on the fire severity and areal extent. Erosion from high severity fire can cover large areas and fires may create water repellent soil conditions. Erosion from low severity fires may be 0.1 Mg ha^{-1} or less (Robichaud et al., 1993b), whereas erosion from high severity fires can range from 6 to 38 Mg ha^{-1} (Robichaud and Brown, 1999; Robichaud and Waldrop, 1994). Variation in erosion is due to the variability of fire effects, ground cover differences, inherent variability in soil properties (Robichaud, 1996), and the weather patterns the year following the fire.

The Water Erosion Prediction Project (WEPP) Model

The WEPP model was developed by an interagency team of scientists including the U.S. Department of Agriculture's (USDA) Agricultural Research Service (ARS), Natural Resource Conservation Service (NRCS, formerly the SCS), and the Forest Service. Participants from the U.S. Bureau of Land Management and numerous universities also have contributed to the development of the WEPP model (Laflen et al., 1996). WEPP is a process-based soil erosion model that uses a daily time step for water balances and vegetation growth. When a day has a precipitation or snowmelt event, WEPP predicts the runoff, distribution of sediment detachment on a given hillslope, and sediment yield from the bottom of the hill. WEPP can be run for a hillslope, with up to 10 different soils and/or vegetation conditions along the flowpath, or for a small watershed of up to about 100 ha. WEPP simulates rill and interrill erosion in the hillslope version and adds channel erosion or deposition in the watershed version.

WEPP is available with a MS-DOS text-based interface. A Windows 95 interface is under development by the USDA-ARS. Both of these interfaces allow the user to alter every input variable describing soil layer properties and vegetation conditions in great detail. It is not uncommon to have 400 variables for a given scenario, plus 10 daily climate descriptors. This considerable amount of input data allows users to describe a large number of conditions including agriculture, range land, disturbed forests, mining sites, and construction sites. Typical values for soil erodibility properties are presented in Table 1 for forest conditions. Values to describe forest vegetation conditions can be found in Elliot and Hall (1997), which is available from our internet web site (http://forest.moscowfsl.wsu.edu/4702/forwepp.html). Templates for a number of forest conditions are available from our internet web site for downloading and installing within the WEPP MS-DOS file structure.

The complexities of the input data have discouraged widespread application of the model. The authors, therefore, have begun development of simple interfaces for specific applications such as forest roads, harvested and burned forest areas, and range land. These interfaces can be accessed at our web site (http://forest.moscowfsl.wsu.edu/fswepp/) (or through the Forest Service Intranet for Forest Service users; Elliot et al., 1999).

Typical Field Observations and Modeling Results

Forest Roads

The importance of an undisturbed buffer to minimize sediment production was described earlier. Figure 10 presents the predicted amount of sediment delivered to a stream from a forest road in Idaho as a function of buffer width. WEPP predicted an average annual road erosion rate on the 100-m road of 20 Mg ha^{-1}. Ketcheson and Megahan (1996) measured an average annual erosion rate of 24 Mg ha^{-1} in a four-year study on 24 km of roads in northern Idaho, in close agreement with the predicted value. The predicted length of sediment deposition downhill from the 100-m road was about 45 m. Ketcheson and Megahan (1996) found the mean length of observed sediment travel from 26 sites to be 49.6 m in Idaho. These predictions and similar comparisons have led us to believe that WEPP predicts reasonable values for road erosion and sediment plume length. We, therefore, believe that WEPP also predicts reasonable values for sediment entering a stream, although we do not have direct measurements for comparison.

Some managers have assumed that if a sediment plume is evident, then there has been no transport of sediment to the stream. We have observed, however, that WEPP often predicts sediment delivery to a stream from a buffer area, even when there is significant predicted deposition. WEPP has shown that sediment commonly carried beyond the observed depositional area from the occasional large storm, which transports most detached sediment all the way to the stream.

Disturbed Forests

One of the features of predicting erosion from a disturbed forest is that the disturbance only lasts for one to three years before revegetation occurs. If high rainfall or snow melt rates occur before revegatation, then erosion rates may be very high. If the weather is less severe, there may be no erosion. For these revegetating forest conditions, predicting a mean erosion rate is inappropriate even though it is common in all agricultural erosion prediction methods. The dynamic nature of vegetation regeneration means that the forest vegetation cover is likely to be different each year. A design storm approach to predicting erosion rates has limitations in that the impact of the storm depends on the hydrologic and vegetative recovery condition when the event occurs. In many remote, high elevation forests, runoff and erosion are driven by snow melt rather than rainfall, and little information exists to aid in deriving design storms for snow melt. We are evaluating alternative strategies to address this situation. Our current approach is to predict the probability of erosion occurring after a disturbance by running the WEPP model for 50 or 100 years of stochastic climate. WEPP generates a detailed annual output file giving the precipitation, runoff, erosion, and sediment yield for each year of simulation. Our interface accesses this file to estimate annual probabilities for given magnitudes of precipitation, runoff, and erosion. The predicted probable erosion rates and sediment yields can then be evaluated by managers relative to other watershed characteristics, such as value of fisheries, property risks, and soil quality to determine the level of mitigation to recommend following a disturbance. A web browser accesses our web site for the entire analysis (Elliot et al., 1999). Results of an example of such a study that was recently carried out for a forest in the Sierra Madre Mountains in California is presented in Table 2. Table 2 presents the exceedance probabilities, the mean values, and the probabilities of zero values for both undisturbed and thinned forests, as predicted by the WEPP model.

WEPP can differentiate between upland erosion rates, which impact productivity, and sediment delivery from the toe of the slope, which impacts off-site water quality (Table 2). Timber harvesting by thinning increases erosion and sediment yields in the years with the greatest precipitation. However, Table 2 shows that there is a 96 per cent probability that the runoff and erosion associated with thinning operations will not be greater than the undisturbed condition. Reasons for this minimal difference may be due to greater transpiration and earlier, slower snow melt rates after thinning. Table 2 also presents the probability that the runoff, erosion, and sediment delivery will be greater than zero ($P(x>0)$). In many forest conditions, surface runoff and erosion rates are zero in most years, and WEPP provides a tool to estimate the probability of non-zero years.

The values in Table 2 predict average erosion rates in Northern California of 500 to 600 kg ha^{-1} for undisturbed forest, and 500 to 900 kg ha^{-1} for disturbed forests (not including roads). These values are similar to those observed by Rice et al. (1979) in Northern California after harvesting of 630 kg/ha, and Betscha (1978) for a similar wet climate in the Oregon Coast range of 600 to 1100 kg/ha (both include roads). The similarity of these values gives us confidence that WEPP predictions are reasonable for disturbed for conditions.

Summary and Conclusions

We have provided an overview of some of the recent findings in our research program to determine the erosion processes, and measure the factors associated with those processes, in forests. An understanding of the sites of erosion and deposition, and the flow paths followed by runoff, is essential in estimating erosion amounts. In addition to topography, soils, climate, and vegetation cover, spatial and temporal variability are important factors in erosion processes in disturbed forests. We believe that the average values may be suitable for road erosion since roads tend to be permanent features on the landscape. With the epochal nature of erosion events, however, we suggest that probabilities of erosion are more appropriate for forest disturbances such as harvesting or fires, because the site quickly returns to pre-disturbance hydrologic conditions.

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Tables

Table 1. Typical WEPP soil erodibility values for forest conditions for a sandy loam soil.

Condition	Interrill erodibility ($kg\ s\ m^{-4}$)	Rill erodibility ($s\ m^{-1}$)	conductivity ($mm\ h^{-1}$)
Forest	500,000	0.0005	42
Low severity fire	1,100,000	0.0006	25
High severity fire	2,800,000	0.0007	16
Skid trail	1,000,000	0.0005	10
Ungravelled road	3,000,000	0.0003	0.3
Gravel road	3,000,000	0.0003	3.0

Table 2. Results from a WEPP to analysis for a timber thinning operation in the Sierra Nevada Mountains in California. The slope was assumed to be 260 m long and 30 per cent steep, with a 60-m buffer at the bottom.

Exceedance probability (per cent)	Precipitation (mm)	Runoff (mm)	Upland erosion (Mg ha^{-1})	Sediment delivery (Mg ha^{-1})
Undisturbed forest				
2	2475	130	7.1	5.2
4	2462	114	5.3	4.6
10	2239	46	2.1	1.9
20	2006	13	0.8	0.6
Average*	1695	13	0.6	0.5
P(x>0) †		0.90	0.86	0.90
After thinning				
2	2475	105	18.0	13.7
4	2462	53	8.1	5.3
10	2239	30	3.9	0.6
20	2006	6	0.9	0.2
Average*	1695	7.5	0.9	0.5
P(x>0) †		0.98	0.74	0.92

* Average erosion predicted from 50 years of WEPP simulation for site.

† Probability that the value is greater than zero.

Figures

Figure 1. Measuring road erosion rates in central Idaho with a rainfall simulator.

Figure 2. Measuring rutting on a road in the Willamette National Forest, OR.

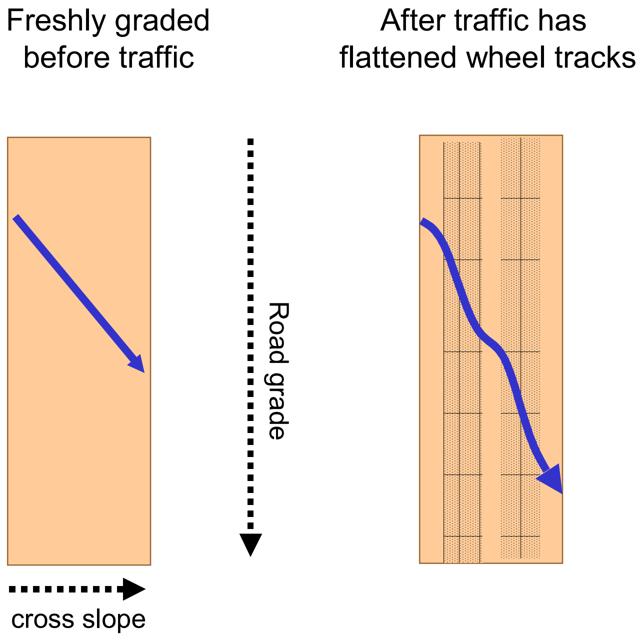

Figure 3. Impact of traffic flattening an outsloping road on flow path length

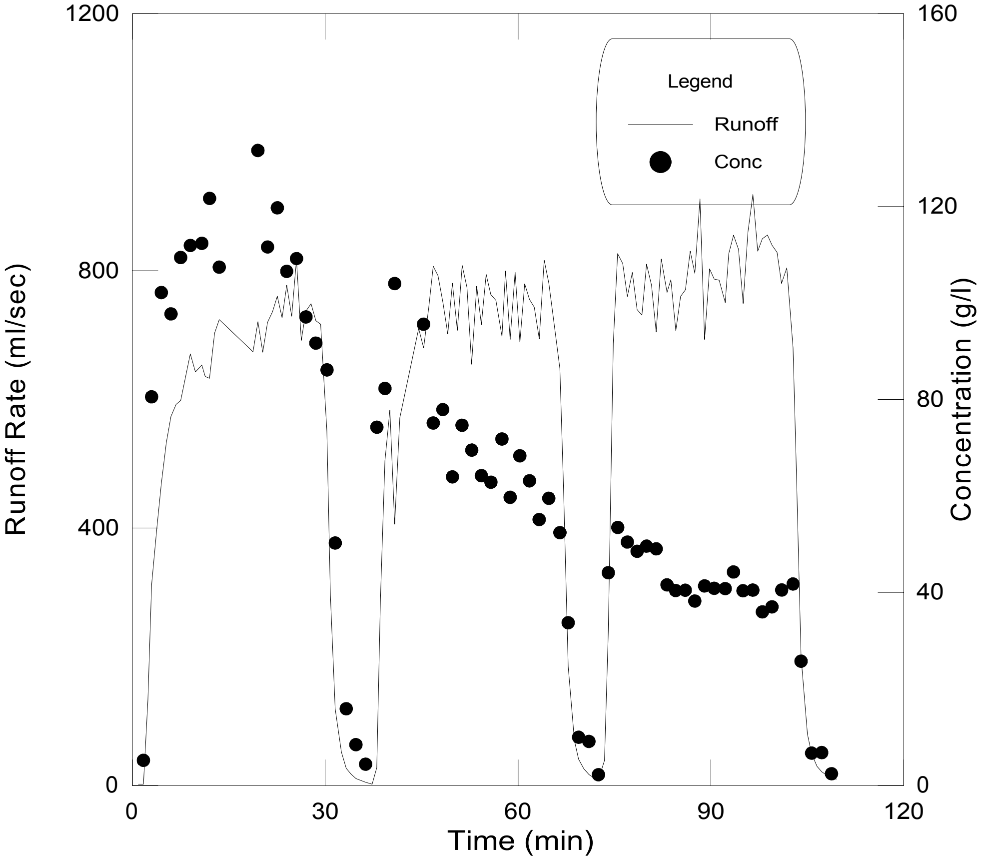

Figure 4. Typical rainfall simulation data showing the relationship between road runoff and sediment concentration and time during a sequence of three constant-intensity rainfall events.

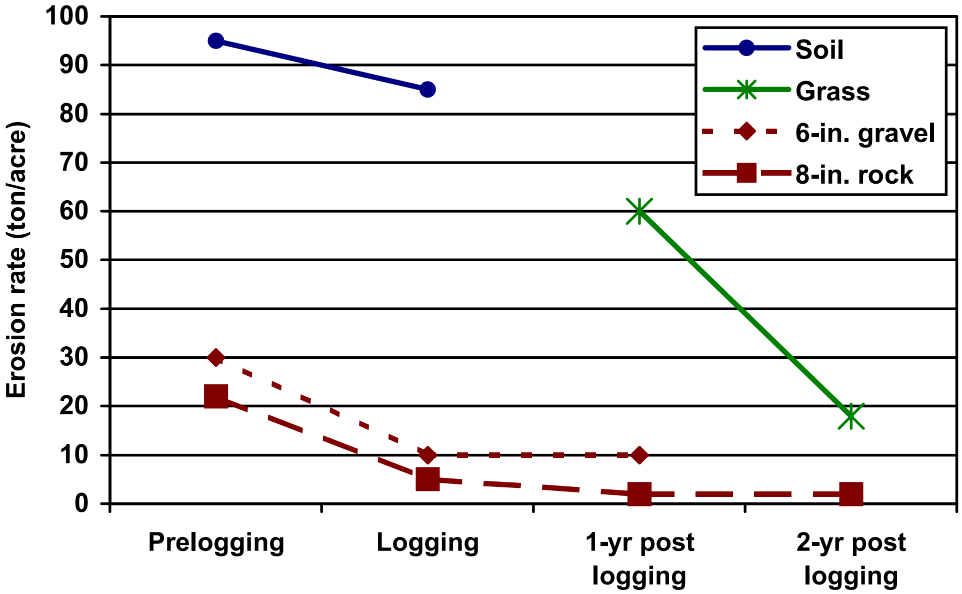

Figure 5. Decline in road surface erosion rate over several years in the southeastern U.S. (Swift 1984).

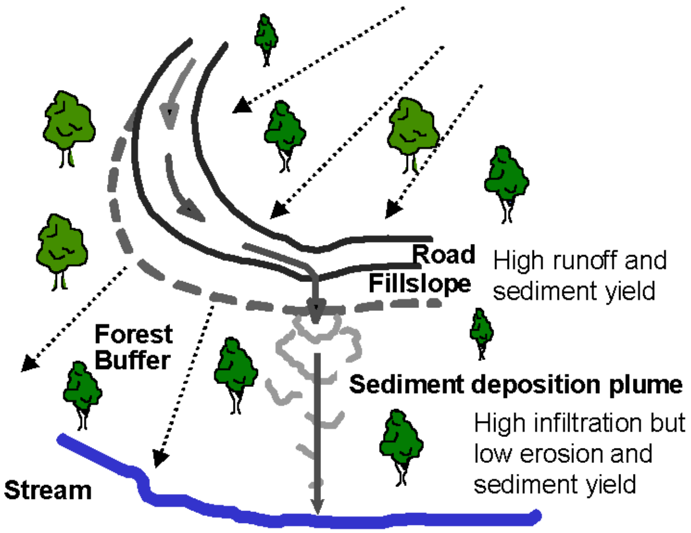

Figure 6. Dominant erosion processes on roads with forest buffers.

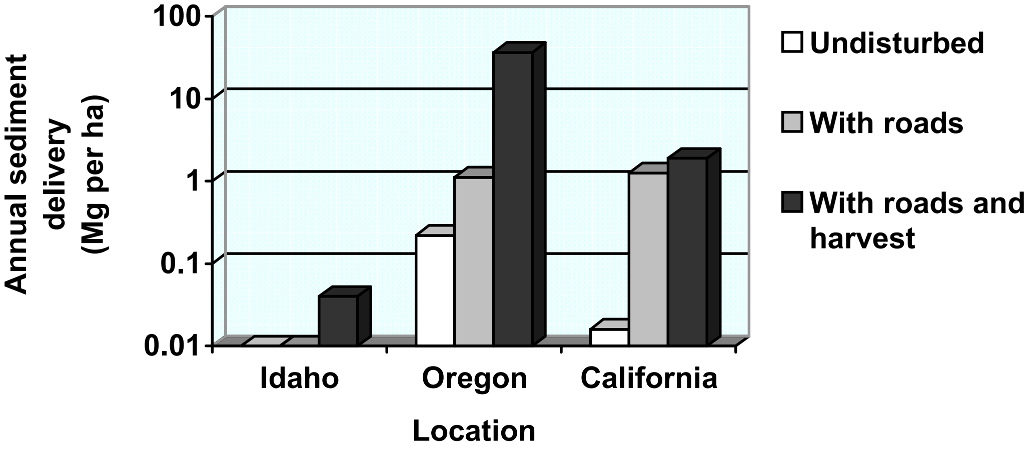

Figure 7. Effect of roads and timber harvesting on annual watershed sediment yields (After Megahan and Kidd, 1972; Fredriksen, 1970; Rice et al., 1979)

Figure 8. Skidder at work in a Georgia forest.

Figure 9. Installing a weir and sediment collector on a site following a wildfire in the Wenatchee National Forest, Washington.

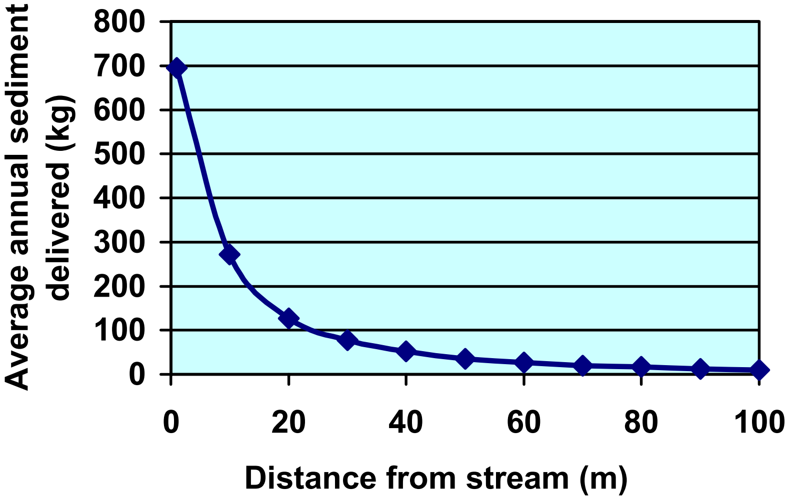

Figure 10. Effect of distance from a road to the stream on predicted annual sediment yield to the stream (for a 100-m long road in northern Idaho). See Figure 6 for a diagram of the relationship between the road and the stream.

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