Modeling Low-Volume Road Erosion

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Low-volume roads are recognized as one of the primary sources of sediment in many watersheds. The authors have carried out research on the details of the complex soil erosion processes occurring on low-volume roads for more than 10 years. An overview of their research summarizes the results of numerous past and ongoing field and computer modeling studies on road erosion processes and the effects of road design on road erosion. The authors have found that insloping and outsloping effects on roads are often overshadowed by the effects of rutting. Most soil erosion on roads is from concentrated flow in ruts or ditches. Adding gravel increases hydraulic conductivity and reduces erosion. Road erosion rates can also be decreased by reducing tire pressure or by removing roads. The authors are developing applications of the Water Erosion Prediction Project model as user-friendly erosion prediction tools for road managers. Further work is required to quantify the effects of current management techniques on water quality and to develop new low-impact road design and management technology.

Low-volume roads generally have a native soil surface or a graveled surface. Frequently they are located in watersheds in which the natural rates of erosion from rangeland or forests are extremely low and where erosion rates from agricultural activities are generally lower than from a road. The three dominant effects of roads on the environment are alteration of watershed runoff characteristics, mass wasting, and surface erosion. Sedimentation of streams is particularly serious in upland areas where salmonid species require gravel-covered stream bottoms for spawning. Sedimentation can also shorten the lives of reservoirs and water supply systems relying on surface sources for quality water for domestic and industrial uses. Peak discharges may be altered in basins following road construction. In watersheds with high infiltration capacity and where hillslope flow is dominantly subsurface, roads have the potential to increase surface runoff and intercept subsurface flow (*1*). Changing the hydrologic properties of a watershed will often change the upland stream sedimentation processes and adversely affect downstream structures, such as reservoirs, bridges, and other features in the stream's floodplain.

In steep terrain, where the climate may lead to saturated road prisms, slope stability failures may lead to greater sedimentation in streams than surface erosion (*2–4*). In many cases, the sediment particle sizes from stability failures may be much larger than from surface erosion and may include rocks and boulders larger than 1 m in diameter.

ROAD EROSION AND SEDIMENTATION PROCESSES

Soil erosion and sedimentation are the products of complex interactions among soils, climate, topography, and surface vegetation or management (Figure 1). On roads, the construction, maintenance, and level of traffic all affect the erosion rate.

A number of components make up a road, and the design and management of each component may influence the erosion of the road or delivery of sediment from the road to a stream system. Figure 2 presents the main road components that affect soil erosion. The design and management of a road determine the flow path that water follows to exit the road. All roads are designed to have a compacted foundation and to shed water. The main cross-sectional shapes of roads are crowned, insloping, or outsloping (Figure 2). On some forest roads, there is also a set distance in water bar spacing along the traveled way to limit erosion. In addition, a road designer can choose to add gravel, asphalt, or concrete to the surface. Designers may also consider methods to limit erosion from the road surface runoff, such as adding gravel to road ditches or specifying that cross drains deliver water to convex slopes, where the water will dissipate over the surface instead of incising a channel. Road erosion rates are influenced by the flow path that surface runoff follows along the road (*5,6*) and the hydraulic conductivity and soil erodibility of the road (*7,8*).

Flow Path

The flow path length across the traveled way depends on the shape of the road and the presence of wheel ruts. The minimum flow path occurs on a smooth road with a uniform cross slope. In this perfect geometry condition the flow path length increases with increasing road grade and decreases with increasing cross slope (*9*). Because cross slopes are rarely more than 4 percent, a road 4 m wide will rarely have a flow path length less than about 7 m for road grades of 5 percent or more. If the road receives heavy traffic, especially in wet weather, ruts will form in the road, and eroding water will follow the ruts instead of being diverted to the inside or outside of the road. With a rutted traveled way, any benefits from the initial design shape are lost. Even without a rutted traveled way, as wheel tracks begin to flatten, the cross slope the path length increases until it is equal to the spacing between any surface structures that divert the water from the road (*6*). These diversion structures may be called cross drains, water bars, or broad-based dips. Figure 3 shows the typical effects of flow path length on road surface erosion as predicted by the Water Erosion Prediction Project (WEPP) soil erosion model for a Lufkin, Texas, climate.

Insloping Versus Outsloping Roads

Debates continue about whether insloped or outsloped roads are better. Proponents of insloped roads point to the benefit of controlling the water in a ditch with planned outlets under the running surface. Erosion in the ditch can be minimized by lining the ditch with nonerodible rock. The benefit of outsloping is dispersed flow, but

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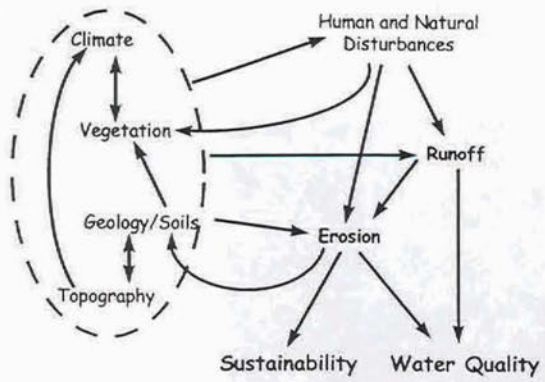

FIGURE 1 Complex interactions that lead to runoff, soil erosion, and sedimentation.

at the expense of water flowing over the less-erosion-resistant fill-slope (*10*). If the road is allowed to become rutted, the shape makes little difference because the ruts will have concentrated flow that may bypass drainage structures (*11*). In general, the correct road shape depends on the site conditions and road use.

Insloping road processes were studied in detail with field data and by modeling with the WEPP (*12,13*) model. Tysdal et al. (*14*) found that if roads are well maintained, the majority of erosion in a road prism is in the ditch (Figure 4), unless the ditch is graveled or has a protective cover of vegetation. The cutslope contribution to the erosion rate is small, unless the ditch has been treated to reduce erosion. One of the main contributions to the erosion process from both the cut and the road surface is in generating runoff that may then erode the ditch.

Concentrated Flow Erosion

Concentrated flow causes more erosion than dispersed flow. Wheel ruts and ditches are the primary sites of concentrated flow on low-volume roads. Wheel ruts are generated most quickly by heavy truck traffic during wet road conditions. Reid and Dunne (*2*) stated that the amount of traffic is probably the single greatest factor affecting sediment production. Comparing the sediment production for 2 years on identical road sections on which the major difference was frequent logging truck traffic versus no traffic, Foltz (*6*) found that sediment production increased by a factor of nine. In simulated high-intensity rainstorms, Foltz (*15*) reported a range of 5 to 2 times increase in sediment production for a wide range of soil types. Burroughs and King (*16*) recommended that sediment production for a rutted, unsurfaced traveled way be increased by a factor of 2, relative to the yield from a smooth, unsurfaced traveled way. Their recommendation was based on light use logging traffic. It is clear that keeping a road traveled way free of rutting is an important technique for reducing sediment. Seasonal road closures determined by road bearing capacities may be more effective than road maintenance with a grader by not allowing the ruts to form rather than removing the ruts after they have formed.

Roadside ditches convey runoff from the running surface and from the cutslope and cause concentrated flow. Luce and Black (*17*) reported the first year of results from a multiyear study on the effects of road length between water bars, road grade, and cutslope height on sediment production of entire road prisms. Observations from 74 plots in the Oregon Coast Range were that the condition of the ditch is an important determinant of sediment production in the first year after construction. They found a statistical relationship between the total sediment production and the product of the square of the road gradient and the segment length, factors that have been shown to correlate well in rill erosion studies (*18,19*). No relationship was found between sediment production and cutslope height. A few plots with severely disturbed cutslopes suggest that cutslope condition might become dominant after some recovery, mostly through the effect of cutslope sediment on the availability of readily eroded sediment on an otherwise stable ditch bottom.

Hydraulic Conductivity

The hydraulic conductivity of native-surfaced roads is much lower than for all other soils, including graveled roads, agricultural soils,

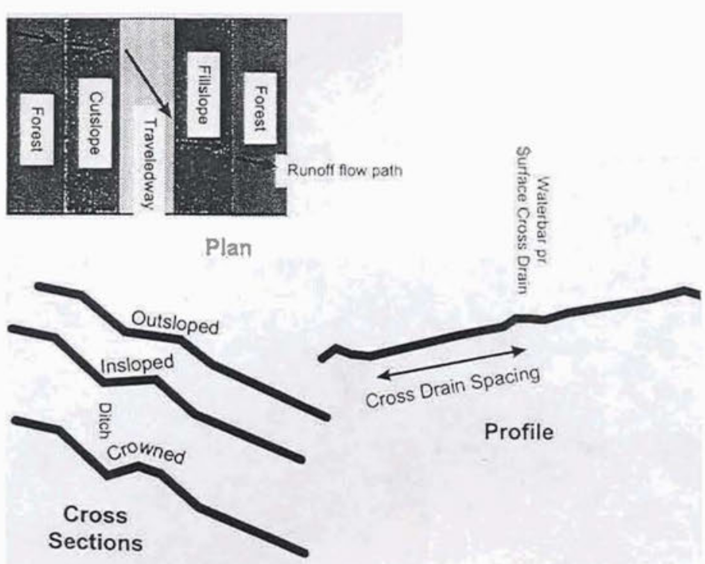

FIGURE 2 Main components of a road.

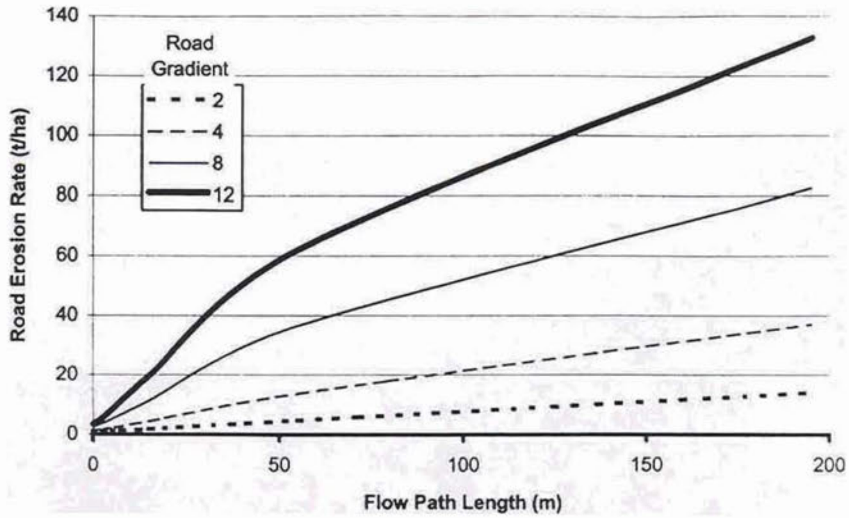

FIGURE 3 Typical effects of flow path length and percent road gradient on road erosion rates predicted with WEPP model.

and forest soils (*9,20,21*). The hydraulic conductivity of various forest conditions is shown in Figure 5. The conductivity varies from less than 1 mm/h for a native-surfaced or nongraveled road to more than 80 mm/h in an undisturbed forest. These differences are management effects that tend to overshadow effects caused by differences in soils. The presence of large amounts of vegetation and forest litter is responsible for the high infiltration capacity of undisturbed forest soils. Roads are highly compacted, resulting in near-zero conductivities on all soils.

Luce and Cundy (*22*) showed that roads without gravel have conductivities in the range of 0.1 to 0.5 mm/h, whereas roads with gravel have conductivities in the range of 3 mm/h (*9,21*). The result is a significant difference in runoff and erosion rates, especially in climates in which much of the runoff is from snowmelt. Snowmelt rates are less than rainfall rates (*23*), resulting in less runoff. Table 1 presents the difference in road runoff and sediment yield caused by this difference in conductivity for a snowmelt-dominated climate in the United States and a Texas climate with little snow. Gravel in the northwestern United States reduces predicted erosion by more than 80 percent, a commonly accepted figure by forest planners, whereas in Texas the model predicts that aggregate surfacing reduces road erosion by about 35 percent.

Erodibility

To determine the role of soil properties on road erodibility, a series of studies was initiated to collect field data from a wide range of native-surfaced roads. From these studies several researchers (*8,24,25*) determined that on native-surfaced roads, the interrill erodibility is similar to that of cropland soils, the rill erodibility is similar to that of rangeland soils, and the conductivity is near zero. Typical values are presented in Table 2.

MITIGATION

Researchers carrying out this project have been active in researching road erosion mitigation techniques. These techniques include reduced tire pressures, aggregate placement, road closure, and road maintenance.

Reduced Tire Pressures

In a 3-year study in the United States in the Cascade Mountains in Oregon, Foltz (*26*) found that sediment production was reduced by

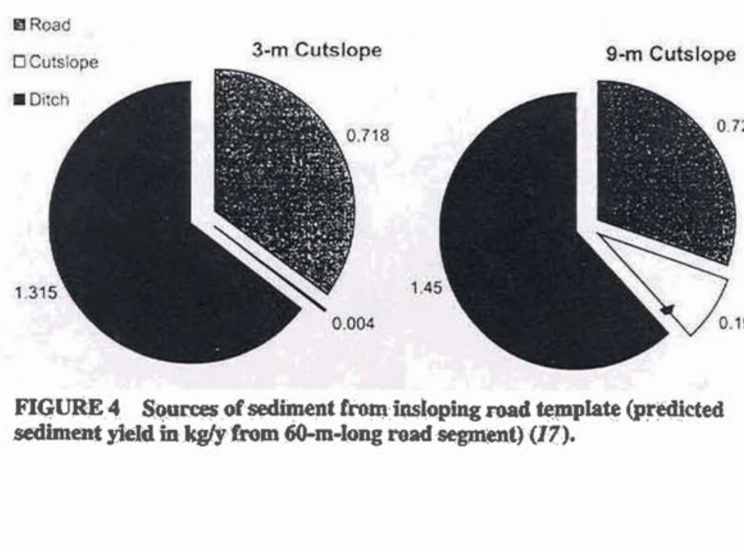

FIGURE 4 Sources of sediment from insloping road template (predicted sediment yield in kg/y from 60-m-long road segment) (*17*).

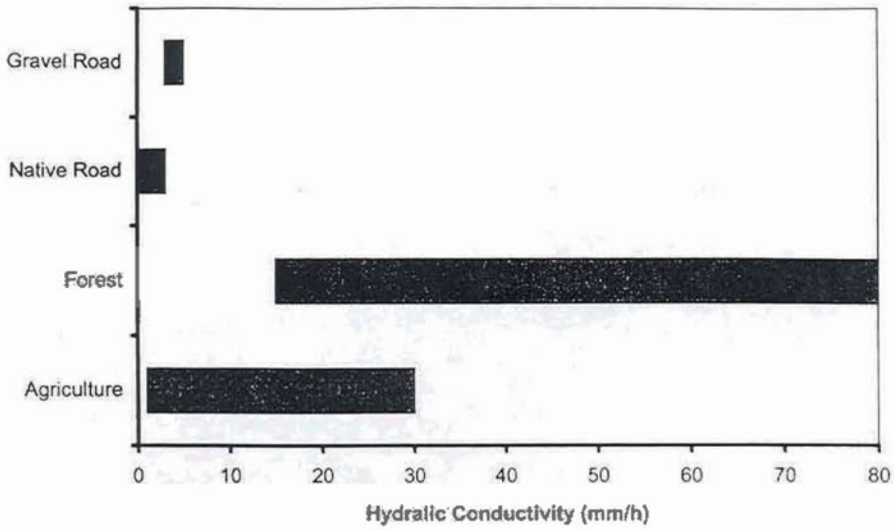

FIGURE 5 Typical hydraulic conductivities for roads compared with other soils (*7,8,12,21*).

45 percent when tire pressures were reduced from 620 kPa to 480 kPa on all axles, and by 80 percent when tire pressures were reduced to 480 kPa on the steering axles and 210 kPa or 340 kPa on all other axles (Table 3). Foltz and Elliot (*27*) observed on the study site that reduced tire pressures resulted in less rut formation. With less rutting, water tended to run over the edges of the road, instead of accumulating in flow directly down the ruts, which caused erosion from concentrated flow. Forest managers have accepted these results, and some timber sale contracts in central Idaho now include reduced tire pressures as one of the methods to reduce road erosion. Other benefits of operating at reduced tire pressures include longer hauling seasons, increased vehicle mobility, decreased truck maintenance, and improved operator comfort (*28*).

Aggregate Quality

Burroughs and King (*16*) reported that 150 mm of good quality aggregate reduced sediment production from a granitic surface road by 96 percent. Swift (*29*) found that the thickness of aggregate was important. A 50-mm depth provided no mitigation, whereas a 200-mm depth provided 97 percent mitigation. Neither of these studies was performed in the presence of traffic. For many years forests adopted these mitigation values with little consideration of aggregate quality or traffic. Foltz and Truebe (*30*), using loaded logging truck traffic, found that the quality of aggregate has an important effect on road soil erosion rates. An aggregate of marginal quality allowed erosion rates of 4 to 17 times greater than did an aggregate of good quality. The range depended on traffic and precipitation. Foltz and Elliot (*27*) believe that the differences are caused by the same effects observed for tire pressure impacts and gravel addition, namely conductivity and the presence of ruts.

TABLE 1 Impact of Graveling on Road Runoff and Erosion for Road 60 m Long and 4 m Wide with 12 Percent Slope, Predicted with WEPP Model

	Climate	
	Deadwood Dam, Idaho	Lufkin, Texas
Average Annual Precip (mm)	822	1116
Runoff (mm)		
Native Surface	450	841
Gravel Surface	78	516
Sediment Yield (kg)		
Native Surface	2312	3812
Gravel Surface	423	2468

Road Obliteration

The off-site impacts of altered runoff hydrographs and increased sedimentation have lead to the partial or complete removal of roads as a frequent practice in U.S. Department of Agriculture (USDA) Forest Service watershed restoration. There is, however, limited research data to support obliteration decisions. One practice associated with road obliteration is to rip the road with tines mounted on the back of a large crawler tractor. In a recent study on the effectiveness of ripping, Luce (*31*) found that road conductivity increased from 0 to 4 mm/h before ripping to 20 to 40 mm/h after. The improvement is modest compared with existing forest conductivities (Figure 5), but may lead to a substantial reduction in runoff in climates dominated by snowmelt and low-intensity precipitation. Although the initial ripping yielded infiltration capacities similar to forest soils, subsidence, consolidation, and surface sealing reduced capacities to these modest results. Soil amendments, such as straw, may improve performance. The long-term change in the conductivity of a closed road has not been measured, although in many cases, roads eventually become revegetated, leading to a more natural infiltration rate. The consolidated soils, however, may take many years to return to a natural state, if they ever do. Elliot et al. (*32*) observed that increased conductivity may lead to an increased likelihood of the road prism becoming saturated, resulting in an increased risk of failure from instability.

TABLE 2 Typical WEPP Erodibility Parameter Values for Forest Roads

Property	Soil				
	Clay Loam	Silt Loam	Sandy Loam	Gravelly Loam	Gravelly Sand
Gravel %	20	5	5	60	80
Sand %	30	30	60	40	70
Silt %	40	55	35	40	25
Clay %	30	15	5	20	5
Conductivity mm/hr	0.3	0.3	1.0	2.0	3.0
Interrill erodibility kg-s/m4	1e06	3e06	2e06	1e06	2e06
Rill erodibility s/m	0.0002	0.0006	0.0004	0.0003	0.0003

MODELING DEVELOPMENTS

Natural resource managers require tools to aid them in evaluating the environmental impacts of various decisions on the design and management of forest roads. Numerous soil erosion and road stability models have been developed to assist designers and managers. The authors' research in erosion modeling is mostly process-oriented and based on the WEPP model (*12,13*).

Water Erosion Prediction Project

WEPP is a process-based soil erosion model developed cooperatively by several federal agencies in the United States. WEPP predicts not only soil erosion rates, but also sediment delivery. USDA Forest Service research (*8,14,33*) has successfully validated WEPP for a number of forest road conditions, such as insloped roads with ditches, outsloped roads, roads draining to culverts, and roads with forest floor buffer strips. A number of templates have been developed for the WEPP model to aid in field applications (*9*). USDA Forest Service research is committed to develop applications of WEPP to more fully evaluate the impacts of current or proposed road management and mitigation practices.

Several workshops have been held to train more than 100 USDA Forest Service personnel on the application of the WEPP model to forest conditions. Because most potential users of WEPP are discouraged by the complex interface, the authors have focused on simplifying the interface to WEPP. An interface is being developed that will be applicable specifically to low-volume roads.

TABLE 3 Effects of Tire Pressures on Measured Soil Loss for Road Sections 61 m Long with 12 Percent Gradients (Average from 3 Years) (*26*)

Tire Pressures (kPa)		Sediment Yield
Front	Other	(kg)
620	620	2678
480	480	1466
480	210 Unloaded 340 Loaded	530

X-DRAIN

The X-DRAIN computer program is based on a study by Morfin et al. (*33*), in which a database was developed of more than 50,000 WEPP runs on road scenarios that included an eroding road surface and fillslope and a deposition area between the road and the nearest stream. The results of this study are accessed by a user-friendly interface called X-DRAIN. For a given climate, soil, and topographic condition, the X-DRAIN program presents the sediment delivery for 20 combinations of road gradient and water bar spacing values. Elliot et al. (*34*) describe how to apply this basic configuration to a range of field conditions.

RESEARCH NEEDS

Current road-related research includes continuing the road topography and cutslope height study in Oregon (*17*), developing a model to describe road erosion armoring and recovery processes, measuring the effects of aggregate quality on erosion rates, and developing methods to more easily apply WEPP and other models as aids to forest road design and management.

Areas that require further research include the following:

- Tools to aid managers in setting priorities for roads for maintenance, construction, or removal.
- Testing of current downslope mitigation techniques.
- Development of new techniques to minimize the transport of sediment from roads in a cost-effective and efficient manner.
- Development of road construction and road removal techniques that allow temporary access to remote sites with minimal long-term impacts.
- Development of models that better incorporate the impacts of roads on forest watershed hydrologic processes.
- Site-specific tools to assist in predicting risks of slope instability and impacts of failures on downslope streams.

SUMMARY

The authors have provided an overview of much of the recent research of their work units in predicting the impacts of low-volume roads on stream systems. Tools to predict soil erosion rates and off-site sediment delivery for low-volume roads have been developed. Current research will expand understanding of road erosion processes and the impacts of road design and management on road erosion and off-site impacts. Some future directions for research in road erosion also have been suggested.

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