UNDERSTANDING AND REDUCING EROSION FROM INSLOPING ROADS

A computer program can help managers anticipate erosion and sediment delivery attributable to forest roads. The watershed version of the water erosion prediction project (WEPP) predicts road erosion rates within the observed range but overestimates sediment plume lengths. The predicted sources of sediment from an insloping road are mainly from the road ditch and the downslope channel; less sediment comes from the traveled way and the cutslope. Mitigation measures to minimize ditch erosion and channel flow rates will have the greatest effects on reducing sediment delivered from insloped forest roads.

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Whether it comes in the form of slow surface erosion or catastrophic landslides, sediment from forest roads is a major pollutant of sensitive streams in forests. Managing roads to reduce sedimentation begins with an understanding of erosion processes.

The water erosion prediction project (WEPP) is a process-based model for predicting erosion and sedimentation. WEPP incorporates properties of vegetation, soil, and topography with local climate and management to predict runoff, soil erosion, and sediment delivery (Laflen et al. 1997). It can be applied to both hillslopes and small watersheds. The WEPP hillslope version has been developed to model some road conditions, including outsloped and rutted cross sections (Elliot and Hall 1997). The complex topography of an insloped road is better described as a small watershed than as a simple hillslope, so the watershed version must be used for complete analysis of the traveled way, cutslope, ditch, and channel erosion processes *(fig. 1)*.

This article evaluates the ability of WEPP to predict values that are reasonable approximations of observed runoff and erosion from insloping roads to improve our knowledge of erosion processes. Understanding the critical factors in erosion and the resulting management implications can assist in the design and maintenance of forest roads to reduce soil loss and sedimentation in watersheds.

Validation

Tysdal et al. (1999) presented field data from sites with similar insloped

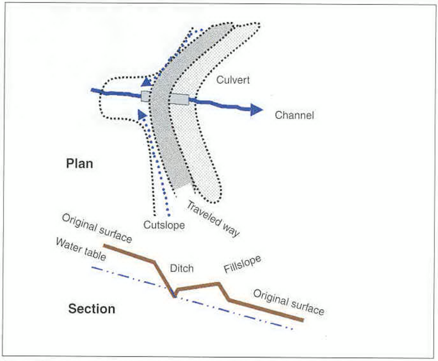

Figure 1. **Surfaces and flow paths associated with an insloped road cross section.**

road characteristics to assess the ability of WEPP to predict insloped road erosion. Sediment production data came from research plots in the Oregon coast range, west of Eugene, that measured the effects of cutslope height and cover, road length and grade, and ditch management on sediment delivery (Luce and Black 1998). *Figure 2* shows that the observed sediment yield measurements in western Oregon vary substantially and that WEPP's predictions are within this range. Both field and simulation observations revealed that longer, steeper roads produced more sediment and that grading in the ditch increased sediment yield by five to seven times (Luce and Black 1998; Tysdal et al. 1999). Most of the sediment from a road with an undisturbed ditch is from the traveled way, whereas most of the sediment from a road with a graded ditch is from the ditch. *Figure 2* illustrates that bare ditches (new construction, vegetation removal treatment, or grading) will cause more sediment production, especially as the road gradient increases. The cutslopes did not appear to be a source of sediment to the ditch in field observations (Tysdal et al. 1999).

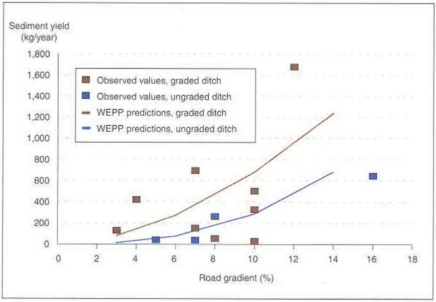

***Figure 2.* Average annual measured and predicted sediment yields for a 60-meter road at Low Pass in western Oregon (Luce and Black 1998; Tysdal et al. 1999).**

Sediment plume length data from a study in the Oregon coast range (Brake et al. 1997) were used to evaluate the ability of WEPP to predict plume length. The plume length is sensitive to the infiltration rate in the forested channel, the amount of vegetation present, and the obstructions that are in the path of the runoff (Ketcheson and Megahan 1996; Brake et al. 1997). In most cases WEPP overestimated the measured plume lengths *(table 1).*

The presence of a sediment plume does not necessarily mean that no sediment is carried beyond the plume. The observed plume lengths may have been underestimated on some sites because it is difficult to determine the extent of the plume under the dense vegetation. On other sites, the topography of the buffer may have greatly influenced plume length. For example, on one site, slope beneath the plume went from less than 10 percent to more than 100 percent about 10 meters from the road. In most cases, the fine materials may be carried some distance beyond the visible plume length.

Another factor not considered in this validation is that the channels may not act like grassed waterways, which concentrate road runoff. Some of the channels may be better represented as a flat or concave hillslope, over which the water spreads out (Tysdal et al. 1999). From these results, we concluded that the watershed version of WEPP could model the effects of road topography and management on soil erosion for insloped roads but tended to overpredict sediment plume

Table 1. Comparison of observed (Brake et al. 1997) and WEPP-predicted sediment plume lengths.

Measurement	Road 9	Road 120	Road 53	Road 94	Road 106
Road length (m)	223	248	366	177	213
Contributing road area (m^2)	645	889	125	81	290
Road gradient (%)	6.0	9.6	7.6	16.6	17.2
Ditch management	None	None	None	Graded	Graded
Observed plume length (m)	**7**	**13**	**15**	**5**	**33**
WEPP-predicted plume length (m)	**33**	**45**	**21**	**11**	**21**

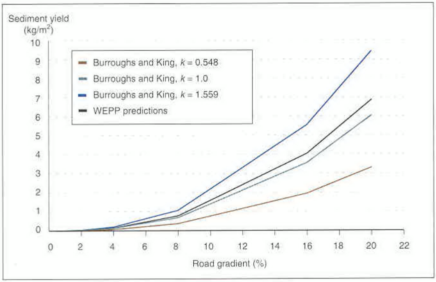

Figure 3. **Average annual sediment yield using the Burroughs and King (1985) equation and WEPP predictions for a similar soil and climate.**

length in channels.

Road traveled way. Having determined that WEPP predicted reasonable results for insloping road erosion, we carried out a study to determine the most important processes and factors affecting insloped road erosion. The elements of an insloping forest road are shown in *figure 1.* The runoff flow path on an insloping road follows a diagonal pattern across the road toward the ditch and depends on both the inslope gradient and the downslope gradient. This configuration ignores any rutting in the road and assumes a planar travel surface (Elliot and Hall 1997). Details of how the elements were described in WEPP are given in Tysdal et al. (1997).

In runs for one year of North Bend, Oregon, climate, WEPP predicted average sediment loss and runoff for a number of conditions describing different soils and topographies. Soil loss increased with both length and steepness, whereas runoff depth increased only slightly with steepness. Changes in road length did not affect the runoff depth. As gradient changes, the increase in runoff is likely due to the reduced surface storage capacity; the increase in erosion results from more runoff and the greater erosive capability of runoff water on steeper slopes. There was more erosion on the longer road slopes because the larger area increased runoff amount. Erosion was greatest for a silt loam soil, and runoff was greatest for a clay loam soil. Soil loss and runoff were least for the sandy loam with gravel (Tysdal et al. 1999).

Burroughs and King (1985) developed an empirical equation to predict sediment yield. It was based on road grade, surface density, and the D_{50} (diameter corresponding to 50 percent finer by weight) of the loose soil on the road traveled way in the granitic soils in central Idaho. Their relationship between sediment yield and gradient is

$$S = 0.00488kG^{2.3771} \qquad (1)$$

where S = sediment yield in kg/m², $k = D_{50}^{-0.9898}\,\text{Density}^{-0.7089}$, and G = road gradient in percent.

The variable k ranges from 0.548 to 1.559 in Burroughs and King (1985).

We completed a number of WEPP runs for a traveled way for a central Idaho climate with a sandy soil and carried out a regression on the results using the same equation. Our relationship is

$$S = 0.0055G^{2.38} - 0.0297 \qquad (2)$$

with an r² of 0.99 for the WEPP simulated runs *(fig. 3).* The Burroughs and King equation allows the sediment yield to be zero when the road gradient is zero, whereas our equation shows some soil deposition (negative sediment yield) on roads with no gradient—something we have observed (Elliot et al. 1994). The small differences in sediment yield from the two equations may be attributed to differences in road length, climate, soil characteristics, or natural variability. In our sensitivity study, we found that for a given gradient, predicted sedimentation varied by a factor of 3 from the least to the most erodible soil, similar to the range of the *k* factor in the Burroughs and King relationship. In a related work, Morfin et al. (1996) showed that a silt loam soil was about 1.5 times as erosive as a coarse sandy soil. All three studies appear to provide a similar range of soil loss and a similar relationship between soil loss and road gradient.

Road ditch. The next eroding element we evaluated was the ditch. For all of the topographies modeled, WEPP predicted road ditch erosion *(table 2).* Longer segments tend to experience relatively greater contributions from ditch erosion, whereas steeper segments tend to show fewer differences in the distribution of erosion between the road traveled way and the ditch.

Table 2. Average annual sediment yields from the traveled way with and without a ditch for several silt loam roads predicted by WEPP for a North Bend, Oregon, climate.

		Sediment yield		
Gradient	Road length	Traveled way	Ditch	Total
2%	60 m	523 kg	307 kg	830 kg
4	60	651	903	1,554
8	60	1,326	1,449	2,775
4	30	326	719	1,045
4	90	977	1,050	2,027

Road cutslope. Incorporating a cutslope element into the model, we found that in all cases approximately 30 percent of the sediment was from the road, 60 percent from the ditch, and less than 10 percent from the cutslope. Regardless of cutslope characteristics, the soil loss from the road was the same for a given road slope, and in our scenario, erosion from the graded ditch dominated the sediment budget. Erosion from the cutslope decreased slightly with more vegetation and increased with height. Greater cutslope height also caused more ditch erosion because the runoff was greater. The erosion from the cutslope was much less than from the road because of soil properties and the presence of vegetation. The soil on the cutslope was modeled as less compacted, with greater infiltration and a relatively short slope length, all of which reduced the potential for erosion.

Channel erosion. A culvert or surface waterbar generally diverts runoff from an insloped road to the channel below the road, where infiltration and sediment deposition occur in an ephemeral channel or in a sediment plume. This portion of the study investigates the complex interactions among road runoff, channel infiltration, and sediment delivery. To quantify the effect of the channel below the culvert on sediment delivery, we compared the predicted incoming with the outgoing sediment amounts and runoff volumes.

We found that channel discharge increased as road length increased and channel length decreased. This occurs because the larger surface area of the road produces more runoff, but a longer channel results in more infiltration, and thus less runoff.

The effect of channel length on runoff and sediment yield is shown in *table 3*. Sediment yield is generally less from short or long channels but greater for channels of moderate length. For short road segments, longer channels produce the least amount of sediment. As road length increases, however, runoff increases sufficiently to erode the entire length of the channel, and longer channels produce more sediment. WEPP predicts that erosion occurs in the channel for a certain distance before deposition begins to occur. From this point, the length of the channel limits sediment delivery. Longer channels with decreasing flow rates deliver less sediment.

Table 3. Average annual runoff and sediment yield data at different distances down the channel. Channel gradient is 8 percent and the road is 60 meters long at 3 percent gradient. The climate is Medford, Oregon.

Distance	Sediment yield	Runoff
1 m	0.3 tons	157 mm
3	0.4	144
9	0.5	113
20	0.8	72
40	1.0	40
80	1.2	14
120	1.1	7
160	0.2	1
180	0.0	0

Results from this study suggest that a short channel is better than one of "medium" length for controlling sedimentation when the channel has high potential for erosion, but a channel of extreme length is preferred in all cases. *Table 3* shows that in some cases there may be much more sediment eroded from the channel than from the road. This means that to minimize sedimentation for such conditions, channel treatment or reduction in channel flow may be more effective than altering the road profile.

The relationships between channel length and sediment yield were similar to those found by Morfin et al. (1996), who modeled the flow below the road as dispersed flow rather than channelized flow. The results from that study indicated sediment plume lengths shorter than those predicted with the WEPP watershed model, presumably because of the difference in channel geometry (Tysdal et al. 1999). An analysis based on predictions from the WEPP model of the effect of differing channel gradients indicated that neither sediment yield nor runoff was sensitive to changes in the gradient of the channel (Tysdal et al. 1997).

Discussion

The road analysis portion of this study suggests that road length, road gradient, and soil type are the driving factors in erosion. Erosion from the cutslope is relatively small compared with that from the road. When the soil is saturated, steep cutslopes may slump or collapse—something WEPP does not predict—rather than erode more gradually. A cutslope slump may supply a source of easily detached sediment to an otherwise stable ditch. Depending on the soil and management characteristics, erosion from the ditch may or may not be significant. If a ditch is stable but road ruts direct runoff along the traveled way, an increase in sediment delivery from the road will likely offset any reduction in ditch erosion.

The channel analysis portion of this study demonstrates that the most significant variable affecting sediment delivery from a channel is channel length. The density of vegetation and the channel infiltration capacity were also found to be important variables in determining channel erosion and sediment delivery rates. Comparing our results with those of Morfin et al. (1996) supports the recommended practice—to discharge from culverts on flat slopes rather than into channelized waterways. Many studies indicate that the most important factors affecting plume length are the obstructions oriented normal to the fall line of the slope (Ketcheson and Megahan 1996; Brake et al. 1997). The WEPP model does not incorporate obstructions at this time, but with further work, impoundment options or channel topographic details may be capable of modeling the effects of obstructions.

The findings of this study suggest that the most important mitigation measures depend on the location of the road with respect to the stream. If a road is far from the stream, little mitigation is required. If the road is close to a stream, then mitigation should focus on the road ditch or traveled way. If there is a moderate distance between the road and the stream, then mitigation to reduce both road erosion and channel erosion may decrease sediment delivery. Channel treatment options include lining the channel with rock or similar materials, establishing vegetation, or installing control structures. These mitigation techniques are expensive and may be ineffective during severe runoffs. A generally much better approach to reduce channel sediment delivery is to direct road runoff to hillsides or ridges where it is more likely to disperse and infiltrate, keeping channels free from excess runoff. Adding quality gravel to a road is another mitigation technique to reduce runoff (Foltz 1996) and subsequently both ditch and channel erosion, as well as erosion on the traveled way (Swift 1984; Burroughs and King 1989).

In carrying out this study, we had to determine the values of hundreds of input variables. Although values for most of these variables have been published (Morfin et al. 1996; Elliot and Hall 1997; Tysdal et al. 1999), users have difficulty in navigating through the complex and, in places, confusing interface in WEPP. The current watershed version is a useful tool for researchers seeking to better understand watershed processes, but not for widespread field use. USDA scientists in both the Agricultural Research Service and the Forest Service are developing interfaces that are intended to be more suitable for field applications (Elliot et al. 1999).

Recommendations

Our validation study demonstrates that the WEPP watershed predictions for insloping road erosion rates are reasonable approximations for the sediment yields from plots in the Oregon coast range. Ditch conditions greatly affect the sediment yield: sediment yield from road segments with freshly graded ditches is five to seven times greater than the yield from segments with vegetated ditches. In a sensitivity analysis, the sediment yield also varies with topography, soil type, and climate. WEPP appears to overestimate sediment plume length in channels. Following are the most important variables in sediment production that can be controlled by proper road planning and management, in order of effectiveness:

1. *Distance between the road and the nearest stream.* Very long distances are best, moderate distances may be the worst. Reducing flow in channels reduces channel erosion.
2. *Ditch management practices.* Vegetated and rocked ditches erode less.
3. *Road segment length.* Shorter lengths deliver less runoff and sediment.
4. *Road gradient.* Lower gradients have slightly less runoff and generate less sediment.
5. *Cutslope height and cover.* Shorter slopes and vegetated slopes have less runoff and erosion.

When used correctly, the WEPP watershed model can be useful in predicting runoff and sediment yields from roads by accounting for the main factors that cause low-volume road erosion. For more widespread use, however, the WEPP user interface needs to be improved.

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