Modeling Erosion from Insloping Low-Volume Roads with WEPP Watershed Model

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Low-volume roads can be a major source of sediment to streams in forest watersheds. For soil erosion from roads to be economically mitigated, the processes that cause erosion need to be understood. The Water Erosion Prediction Project (WEPP), a physically based erosion and sedimentation model, was used for predicting erosion from forest roads that can be described as hillslopes. Watershed applications of WEPP predicted erosion and sedimentation values for insloping roads that can be described as microwatersheds. How well WEPP models insloping roads through a sensitivity analysis and validation process using two studies in the Oregon Coast Range is discussed.

The Water Erosion Prediction Project (WEPP) (*1*) is a process-based model for prediction of erosion and sedimentation. It can be applied to hillslopes and small watersheds. Although it was developed for agricultural scenarios, some federal agencies and universities are expanding its use for roads, forests, and rangeland applications. Modeling roads in other settings, such as developed rural areas or agricultural areas, is also possible with WEPP. Low-volume roads are generally designed to be outsloped, insloped, or crowned. On an outsloped road, water flows across the road prism and down the hillslope without concentrating. On an insloped road, water flows into a ditch and then across the road in a waterbar or through a culvert as concentrated flow. Crowned roads are a combination of insloped and outsloped roads. WEPP has been shown to be valid for some forest road erosion conditions (*2,3*).

The complex topography of an insloped road is better described as a small watershed than as a simple hillslope. WEPP's hillslope version is able to model the outsloped road (*4*), but the watershed version must be used for modeling the insloped road for complete analysis of cutslope, ditch, and channel erosion processes. WEPP incorporates land characteristics and topography with physical activities, such as precipitation or road maintenance, to simulate erosion processes. Input files needed to run WEPP describe management, soil, slope, channel, and climate.

A segment of an insloping road with a cutslope and ditch may be modeled as a small watershed that drains through a culvert and filters down a forested waterway. A crowned road may be modeled as an insloped road segment and an outsloped road segment that can be separated by dividing the road at the crown. In this paper, the ability of WEPP to predict values that are a good approximation of observed runoff and erosion from roads is evaluated. The ability to accurately predict runoff and erosion will improve understanding of insloping road erosion processes. The authors describe the insloped road structure as modeled in WEPP, present the sensitivity to the input parameters, and provide validation. This information may contribute to the design and maintenance of low-volume roads to meet erosion and soil loss goals.

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VALIDATION

Field data from sites with similar insloped road characteristics were used to assess the validity of the WEPP watershed road prism scenario. Sediment production data came from 74 research plots in the Oregon Coast Range Resource Area, west of Eugene, measuring the effects of cutslope height and cover, road length and grade, and ditch management on sediment delivery (*5*).

Table 1 shows that the observed sediment yield measurements in western Oregon vary substantially and that WEPP's predictions are within this range. The WEPP predictions fall in the range of 24 to 74 percent of the maximum measured values. For each WEPP run, the road and ditch lengths, road gradients, and cutslope heights were measured in the field for two road segments with similar topography, soil, and management characteristics. The climate data were from a nearby weather station. The cutslopes did not appear to be a source of sediment to the ditch in either the field observations or the WEPP simulations. Both field and simulation observations revealed that longer, steeper roads produce more sediment and that grading in the ditch increases sediment yield by five to seven times. Most of the sediment from roads with no ditch treatment is from the traveled way, whereas most of the sediment from a road with a graded ditch is from the ditch.

Figure 1 shows the observed data and WEPP predictions for a road 60 m long at various gradients for the sites in western Oregon (*5*). It shows that bare ditches (new construction, vegetation removal treatment, or grading) will cause more sediment production, especially as the road gradient increases.

Brake et al. (*6*) investigated sediment plume length in the Oregon Coast Range near these sites. WEPP does not directly predict the sediment plume length, but instead predicts the sediment yield for a given set of conditions. To estimate plume length using WEPP, the forested waterway element below the culvert was divided into several sections of variable length, and the sediment leaving each section was recorded. The segment in which most of the sediment was deposited on the waterway was compared with the site observations. The plume length is sensitive to the hydraulic conductivity of the forested waterway channel, the amount of vegetation present, and the different obstructions that are present in the path of the runoff. The

TABLE 1 Comparison of Average Annual Sediment Yield Field Observations with Simulated WEPP Outputs (*5*)

Measurement	Site 1	Site 2	Site 3	Site 4	Site 5
Road Length (m)	87	33-40	60	59	60
Ditch Length (m)	88	34-41	60	60-62	58-60
Road Gradient (%)	12-13	3-5	10	5-7	7
Cutslope Height (m)	1.2-4.9	0.6-2.0	1.2-3.0	6.1-7.0	2.3-5.5
Ditch Management	None	none	Graded	none	graded
Observed Sediment Production (kg/yr)	163-234	5-67	503-1197	39-167	154-696
WEPP Erosion from Road Travelledway (kg/yr)	167	18	53	36	40
WEPP Erosion from Road Travelledway and Ditch (kg/yr)	172	19	830	40	339

vegetation was fairly dense, which corresponds to observations in the coast range. Hydraulic conductivity on the waterway was 80 mm/h, derived from field measurements in the area of the sites. Hydraulic conductivity may vary a great deal for different slopes and soil types.

WEPP overestimates the measured plume lengths in most cases (Table 2). The most important factors contributing to plume length are the road's contributing area, road gradient, and the presence and type of obstructions in the flow path (*6,7*). Unlike WEPP, the field observations presented in Table 2 do not show any relationship between plume length and road gradient or road area. Because it is difficult to model the location, orientation, and size of obstructions, modeling such occurrences is difficult. WEPP currently does not provide such a scenario, although with further work, its impoundment options may be capable of modeling the effects of these obstructions. The presence of a sediment plume does not necessarily mean that there is no sediment carried beyond the plume. The fines may be carried some distance further than the visible plume length. A field study is under way to determine the amount of sediment carried beyond the observed plume (*6*).

Another factor not considered in this validation is that these waterways may not act like grassed waterway channels, which concentrate road runoff. One or more of the channels may be better represented by a hillslope waterway element with a dispersed flow pattern (Figure 2), in which case the current WEPP watershed version is not appropriate. Different flow patterns result in different sedimentation patterns. A wide, flat channel is best represented as a hillslope below the culvert (*8*), whereas a rill forming below the culvert is best represented as a triangular channel.

From these results, the authors concluded that the current version of WEPP can model the effects of different road geometry and treatment conditions on the erosion processes for insloping low-volume roads, but it does not readily model observed sediment plume length in channels.

SENSITIVITY

Having determined that WEPP predicts reasonable results for road erosion, the authors performed a sensitivity study to determine the most important processes and parameters affecting insloped road erosion. The elements of an insloping forest road are the cutslope, ditch, road, culvert spacing, and hillslope or waterway below the culvert where runoff and sediment follow an ephemeral vegetated channel toward a perennial stream. To model this scenario in WEPP, each

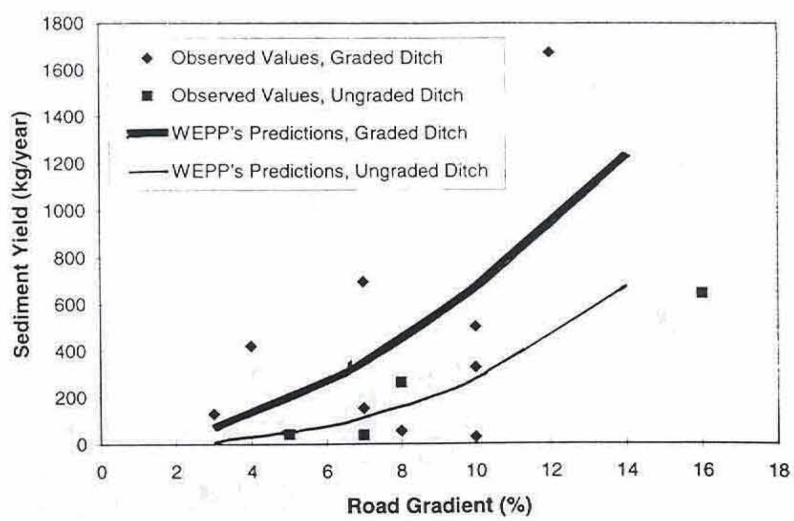

FIGURE 1 Average annual measured and predicted sediment yields for 60-m-long road (*5*).

TABLE 2 Comparison of Measurements by Brake et al. (6) of Average Annual Sediment Plume Lengths with Simulated WEPP Outputs

Measurement	Road 53	Road 9	Road 94	Road 120	Road 106
Road Length (m)	366	223	177	248	213
Contributing Road Area (m^2)	125	645	81	889	290
Road Gradient (%)	7.6	6.0	16.6	9.6	17.2
Ditch Management	None	None	Graded	None	Graded
Observed Plume Length (m)	15	7	5	13	33
WEPP-Predicted Plume Length (m)	21	33	11	45	21

FIGURE 2 Channel structure used in WEPP hillslope and watershed models.

element was developed individually and then linked in a watershed structure.

The road traveled way was modeled with an inslope of 3 percent, diverting all runoff to an inside ditch instead of directly onto the hillslope below. The details of how the elements were described in WEPP are discussed elsewhere by Tysdal et al. (9). Road gradients of 2, 4, 8, and 16 percent were combined with road lengths of 10, 20, 40, 60, and 100 m. The soils used in the analysis represented a range of typical soil types and included a silt loam, clay loam, sandy loam, loam with gravel, and sandy loam with gravel, for a total of 100 road-length-soil combinations. Table 3 presents the soil characteristics of the five soil types.

Of the 20 road-length combinations for the silt loam soil, several were chosen and combined further in the watershed scenario with a cutslope, ditch, culvert, and waterway. These combinations were analyzed in WEPP to establish trends for future scenarios and validation.

Road Traveled Ways

Because the traveled way of a low-volume road has little or no vegetation, the management file in WEPP describes a fallow system with annual blading. The runoff flow path on an insloping and downsloping road follows a diagonal pattern across the road toward the ditch and is dependent on both the inslope gradient and the downslope gradient. This configuration neglects any rutting in the road and assumes a planar travel surface. A rutted road would increase the flow path length by diverting the runoff down the ruts for a distance, increasing the erosion from the road surface (*10,11*).

WEPP performed all the combinations for a 1-year North Bend, Oregon, climate, and average sediment loss and runoff were calculated (Figures 3 and 4). Other climates were run for some conditions and had similar trends. For higher road gradients, soil losses were higher and increased exponentially with road length.

The increase in runoff with gradient is likely a result of the reduced surface storage capacity, whereas increased erosion with gradient results from more runoff and the greater erosivity of runoff water because of higher water energy. More erosion occurred on the longer roadslopes because a larger area contributed. Changes in road length did not affect the runoff depth. Erosion was greatest for the silt loam soil, and runoff was greatest for the clay loam soil. Soil loss and runoff were both least for the sandy loam with gravel.

Using generally the same variable inputs, Burroughs and King (*12*) developed an empirical equation to predict sediment yield on the basis of road grade, surface density, and the D50 (diameter corresponding to 50 percent finer by weight) of the loose soil for the road traveled way element of the insloped road scenario in the granitic soils of the Idaho Batholith. The Burroughs and King relationship is

$$S = 0.00488kG^{2.3771}$$

where

S = sediment yield (kg/m^2),
$k = D_{50}^{-0.9898}\ \text{Density}^{-0.7089}$, and
G = road gradient (%).

The variable k ranges from 0.548 to 1.559 in Burroughs and King's work.

Using the same exponent and data from the WEPP runs for a sandy loam soil in a central Idaho climate, the authors' relationship is

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

with an r^2 equal to 0.99 with respect to the WEPP simulated runs (Figure 5). The Burroughs and King equation allows the sediment yield to be zero when the road gradient is zero, whereas the authors' equation shows some soil deposition (negative sediment yield) on roads with no gradient, which the authors have observed to be true (*5*). The differences in sediment yield from the two equations can be attributed to differences in road length, climate, and soil characteristics, which the Burroughs and King equation cannot address. In a related

TABLE 3 General Road Input Parameters

Soil Type	% Gravel	% Sand	% Silt	% Clay
	(2.0mm-6.0in)	*(0.06-2.0mm)*	*(0.002-0.06mm)*	*(<0.002mm)*
Silt Loam	5	30	55	15
Clay Loam	20	30	40	30
Sandy Loam	5	60	35	5
Loam with Gravel	60	40	40	20
Sandy Loam with Gravel	80	70	25	5

NOTE: Gravel is percent by weight of sand, silt, and clay (4).

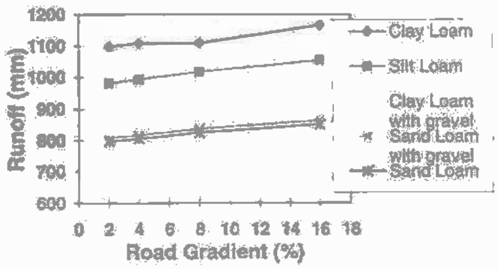

FIGURE 3 Average annual runoff values predicted by WEPP for 60-m road segment.

work, Morfin et al. (*8*) showed that a silt loam soil is about 1.5 times as erosive as a coarse sandy soil. These combined differences account for most of the difference between the authors' regression and that of Burroughs and King.

Ditch Characteristics

The next element to be incorporated into the watershed was the ditch, which WEPP models as a seasonal channel. These model runs were performed using the same climates as the single-element road and a silt loam soil. Four length and slope combinations were selected for the analysis. The ditch experienced the same seasonal grading as the traveled way. In all cases, the road ditch eroded (Table 4).

Cutslope Characteristics

The cutslope was modeled with three amounts of vegetation, which were called "much," "some," and "none" for simplicity. Vegetation characteristics are described in the WEPP management file and include a number of variables such as stem diameter, plant height and spacing, and rill and interrill cover. To reduce repetitive runs, the road length was fixed at 60 m and the soil type as the silt loam. Cutslopes in the Oregon Coast Range generally have steep slopes, so the slope was fixed at 100 percent and the height was varied at 1, 2, and 3 m.

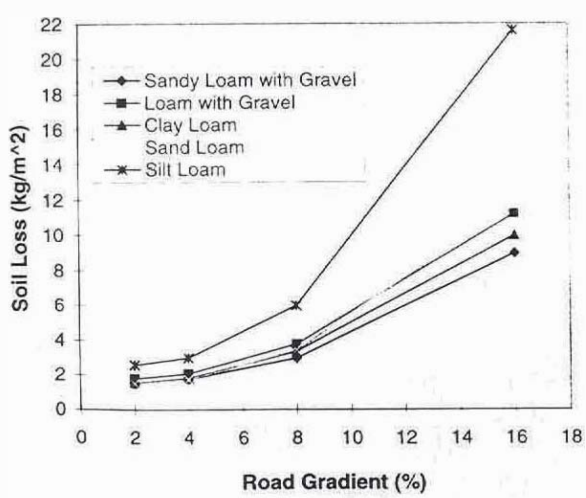

FIGURE 4 Average annual erosion values for 1 year predicted by WEPP for 60-m road segment.

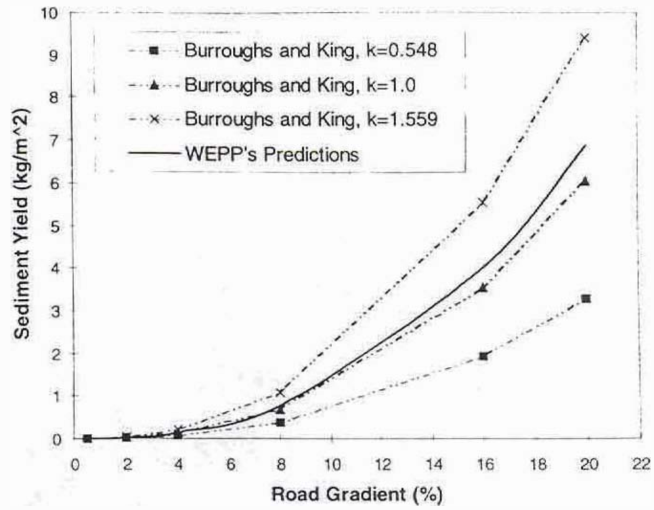

FIGURE 5 Average annual sediment yield using Burroughs and King (*12*) equation and WEPP's predictions for similar soil and climate.

The soil characteristics are different for each element because of compaction and disturbance. Table 5 presents the modeled soil properties in the WEPP soil file for the silt loam soil for each element. Figure 6 shows what portion of the detached sediment comes from the road, channel, and cutslope for a 4 percent road gradient. Regardless of cutslope characteristics, the soil loss from the road is the same for a given road slope and, in this case, erosion from the graded ditch dominates. It is apparent that erosion from the cutslope decreases slightly with more vegetation and increases with height (Figure 6). Greater cutslope height also causes more ditch erosion because of greater runoff. The erosion from the cutslope differs from the road because of soil properties and the presence of vegetation. The soil on the cutslope has less compaction and allows more infiltration, reducing potential for erosion. Depending on soil characteristics and road and ditch management, other scenarios may show erosion being driven primarily by the road, but the general relationship between cutslope vegetation and height and erosion would probably remain unchanged.

Below the Culvert: Waterways

A corrugated metal or high-density polyethylene pipe culvert or a surface waterbar generally diverts runoff from an insloped road to the waterway below, where water infiltration and sediment deposition occur in a concentrated channel or in a plume formation. During this portion of the study, the complex interaction between discharge and infiltration below the road and sediment delivery was investigated. The authors assumed that the portion of the forest floor where the runoff infiltrates has formed an ephemeral V-shaped channel (Figure 2).

The structure of the watershed as perceived by WEPP is a series of hillslopes and channels. The importance of the waterway below the culvert can be quantified by comparing incoming sediment amounts and water volumes to outgoing sediment amounts and water volumes. These amounts and volumes may vary with road length and gradient, as well as with waterway length, gradient, sideslope, and roughness.

TABLE 4 Average Annual Sediment Yields from Traveled Way and Traveled Way with Ditch for Several Silt Loam Roads Predicted by WEPP for North Bend, Oregon, Climate

Gradient	Road Length	Sediment Yield from Travelledway	Total Sediment Yield	Difference
(%)	(m)	(kg)	(kg)	(kg)
2	60	523	830	307
4	60	651	1554	903
8	60	1326	2775	1449
4	30	326	1045	719
4	90	977	2027	1050

In this study, the authors developed sets of WEPP runs to examine volumes and sediment yields with these waterway variables, holding other variables constant.

To allow the effect of waterway length and road length for attenuating discharge to be understood, the gradient of the waterway was fixed at 8 percent and the road gradient at 3 percent. Waterway discharge increases as road length increases, waterway length decreases, or both. This result occurs because the larger surface area of the road produces more runoff, but a longer waterway results in more infiltration, or less runoff.

The effect of waterway length on sediment yield in WEPP shows a different initial trend than that for the runoff discharge. Sediment yield is generally less from longer waterways. For short road segment lengths, longer waterways produce the least amount of sediment. As road length increases, however, runoff increases sufficiently to erode the entire length of the waterway, and longer waterways result in more sediment production (Table 6). In WEPP, erosion occurs in the waterway channel for a certain distance before deposition begins to occur. From this point, sediment delivery is limited by the length of the waterway and is transport-limited in that the energy of the runoff is too low to transport all of the sediment previously eroded. Results from this study suggest that a short waterway is better than one of medium length for controlling sedimentation when the waterway has high potential for erosion, although a waterway of extreme length is preferred in all cases.

The relationships between waterway length and sediment yield were similar to those by Morfin et al. (*8*), who modeled the flow downstream from 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 (Figure 2).

An analysis based on data from the WEPP model of the effect of differing waterway gradients indicated that neither sediment yield nor runoff is sensitive to changes in the gradient of the waterway. A similar set of runs showed that waterway channel sideslope had no effect on sediment yield or runoff and that the roughness in the channel as quantified by Manning's "*n*" showed some effect on channel erosion events (*9*).

DISCUSSION OF RESULTS

The road analysis portion of this study suggested that road length, road gradient, and soil type are the driving factors in erosion. Erosion from the cutslope element is relatively small compared with that from the road element. This study examined cutslopes with heights up to 3 m and found that they contribute little sediment. Cutslopes found in mountainous areas may be higher, and therefore may contribute more runoff and sediment yield. Depending on the soil and management characteristics of the ditch, erosion from the ditch may or may not be of significance. A graded ditch eroded more than an undisturbed ditch.

The waterway analysis portion of this study demonstrated that the most significant variable driving erosion on a waterway is waterway length. The amount and density of vegetation are important, as is the hydraulic conductivity. The presence and orientation of obstructions can also affect how much sediment is deposited in the waterway and where. The outlet channel or plume is also important. Factors such as waterway gradient, channel sideslope, and roughness are less important. Comparing the authors' results with those of Morfin et al. (*8*) supports the recommended practice to generally discharge from culverts on flat slopes rather than into channelized waterways. Many studies indicate that the most important factor affecting plume length is the obstructions oriented normal to the fall line of the slope (*13*), but the WEPP model does not incorporate obstructions at this time, making them impossible to quantify in the results.

Crowned roads often have a ditch on both sides of the road and can be modeled by bisecting the road at the crown and modeling each side separately. This method decreases the contributing surface area for each ditch, reducing the erosion potential in those channels. The adverse effects of grading ditches and the impact of waterway length on sediment delivery are also applicable to crowned roads. Some low-volume roads are only bladed every several years, and thus the man-

TABLE 5 Soil Erodibility Characteristics of Watershed Elements for Silt Loam Soil

Element	Interrill Erodibility	Rill Erodibility	Critical Shear	Hydraulic Conductivity
	(kg*s/m^4)	(s/m)	(N/m^4)	(mm/hr)
Travelledway	3000000	.0006	1.8	0.3
Ungraded Ditch	2000000	.0003	4	10
Graded Ditch	3000000	.0100	1.8	10
Cutslope	2000000	.0003	2	10
Waterway	3000000	.0006	1.8	80

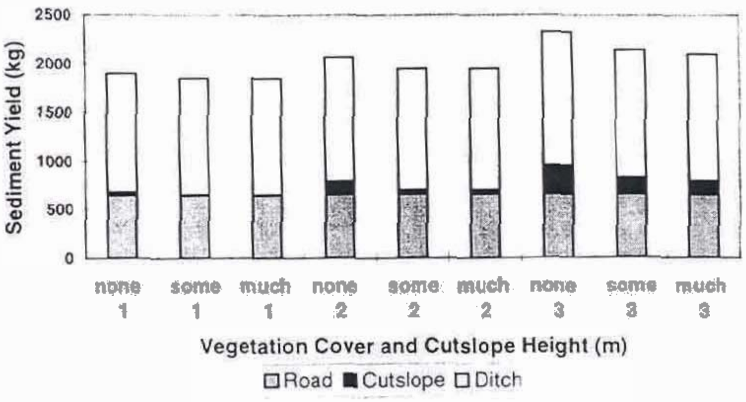

FIGURE 6 WEPP's predicted sediment yield for different cutslope heights and vegetation amounts for 1 year for watershed consisting of 4 percent silt loam road 60 m long, with channel and cutslope.

agement file would need to be altered slightly to accommodate these conditions.

The large variability in observed sediment yield shows the complexity of modeling an insloped road watershed scenario. Even with a model such as WEPP, it is difficult to account for all the variables. However, WEPP allows many of these variables to be considered, whereas past studies have grouped them into factors in simpler models. For example, the universal soil loss equation has a factor for soil type that describes a variety of soil characteristics, including erodibility and hydraulic conductivity, whereas WEPP allows these two variables and others to be considered separately. WEPP runs can be useful for comparison with other WEPP scenarios in establishing trends, but may not predict values that one knowledgeable in soil erodibility and conductivity may observe in the field.

CONCLUSIONS

The authors developed a set of insloped road scenarios with different geometries, soils, and management practices. These scenarios can be modified for site-specific roadcuts in different climates for practical application by road engineers and managers. They can also be adapted to other areas. A validation study determined that WEPP's predictions were reasonable approximations for the sediment yields from plots in the Oregon Coast Range and that the ditch conditions greatly affected the sediment yield. This sediment yield also varies with topography, soil type, and climate. WEPP appeared to overestimate sediment plume length in waterways. It appears that factors such as obstructions and runoff dispersion are critical in plume formation, and modeling these features requires further investigation. A sensitivity analysis was performed, and the applicability of these scenarios was tested using the field validation. The most important sediment production variables that can be controlled to some degree are as follows (in order):

1. Road segment length,
2. Road slope,
3. Ditch management practices,
4. Waterway properties, and
5. Cutslope height and management.

When used correctly, the WEPP watershed model can be useful in predicting runoff and sediment yields for insloped low-volume roads. WEPP can account for such variations as topography, soil properties, management practices, and climate, all of which cause differences in low-volume road erosion.

TABLE 6 Average Annual Runoff and Sediment Yield Data at Different Distances Down Waterway

Distance (m)	Sediment Yield (tonnes)	Runoff (mm)
1	0.3	157
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

NOTE: Waterway gradient is 8 percent, and road is 60 m long at 3 percent gradient near Medford, Oregon.

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