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Modeling Insloping Road Erosion Processes With the WEPP Watershed Model

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Summary:

A sensitivity analysis and validation was carried out to determine the ability of the WEPP watershed model to predict erosion from insloping forest roads. The validation study reflected that WEPP predictions were reasonable approximations of sediment yield for insloping roads, but tended to underpredict sediment plume length. The model behaved in a predictable manner in the sensitivity analysis and we developed a set of insloped road scenario templates with different topographies, soils, and management practices.

Keywords:

Insloping forest roads, Sediment yield, Sensitivity analysis, Forested waterways

Modeling Insloped Road Erosion Processes

With the WEPP Watershed Model

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Introduction

Roads can be a major source of sediment in sensitive forest watersheds. In order to economically mitigate soil erosion from roads, we need to be able to understand the processes that cause erosion. The Water Erosion Prediction Project (WEPP) has been shown to be valid for predicting erosion from some forest roads [Elliot et al. 1994, Elliot et al. 1995] that can be described as hillslopes. WEPP incorporates land characteristics and topography with physical activities such as precipitation or road maintenance in a model to simulate erosion processes. Input files describe management, soil, slope, channel, and climate. A variety of output information is available, including runoff amounts and sediment detachment and delivery. Watershed applications of WEPP can predict erosion and sedimentation values for small watersheds [Flanagan and Livingston 1995].

Forest roads are generally designed to be either outsloped, where water flows across the road prism and down the hillslope without concentrating, or insloped, where water flows into a ditch and then across the road in a waterbar or through a culvert as concentrated flow. The complex topography of an insloped road is better described as a watershed than as a simple hillslope. WEPP's hillslope version is able to model the outsloped road [Elliot and Hall 1997], but the watershed version must be employed when modeling the insloped road for complete analysis of cutslope, ditch, and channel erosion processes.

A segment of an insloping forest road with a cutslope and ditch may be modeled as a small watershed which drains through a culvert and filters down a forested waterway. The purposes of this paper are to discuss how well WEPP models insloping roads, to improve our understanding of insloping road erosion processes, and to determine whether or not the WEPP-predicted values are a good approximation of observed runoff and erosion from forest roads. This paper describes the insloped road structure as modeled in WEPP, presents the sensitivity to the input parameters, and provides validation. This information may contribute to design or maintenance of forest roads to meet erosion and soil loss goals.

Validation

Field data from studies with similar roadcut characteristics were used to assess the validity of the WEPP watershed roadcut scenario. We are monitoring 85 plots in the

Oregon Coast Range Resource Area, west of Eugene, to assess the effects of cutslope height and cover, road length and grade, and ditch management (Table 1).

Table 1 illustrates that sediment volume measurements in western Oregon vary naturally by a significant amount and that WEPP's predictions fall in this range. The climate data utilized was from a station near the sites. The ranges shown for the road and ditch length, road gradient, and cutslope height were measured in the field for two different road segments with similar topography, soil, and management characteristics. The cutslopes did not contribute any sediment to the ditch in any of the runs in either the field study or the WEPP simulations. Measurements show that longer, steeper roads produce more sediment and that grading in the ditch increases sediment yield by a substantial amount.

Table 1. *Comparison of some field observations to simulated WEPP outputs*

	Run 1	Run 2	Run 3	Run 4	Run 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	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
Total Sediment Production (kg)	163-234	5-67	503-1197	39-167	154-696
WEPP Erosion from Road (kg)	166.8	18.3	52.7	36.3	40.5
WEPP Erosion from Outlet (kg)	172.3	18.8	829.6	39.8	338.5

Figure 1 shows the distribution of the field data in comparison to the trends that WEPP predicts for a 60 meter road at various gradients for the sites in western Oregon. It illustrates, for both the predicted and measured roads, the marked effect of grading the ditches. This suggests that bare ditches (new construction or a vegetation removal treatment) will cause more sediment production from these roads.

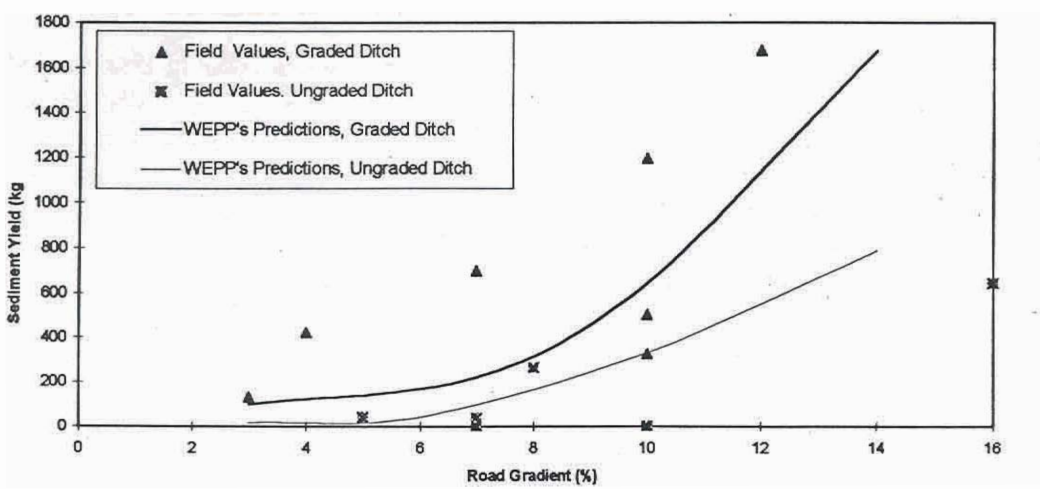


Figure 1. *Measured and Predicted sediment yields for a 60-m road at Low Pass in western Oregon.*

A study by Brake [1997] investigating sediment plume length was conducted in the Oregon Coast Range near our sites. WEPP does not directly predict the sediment plume length, but rather the sediment yield for a given set of conditions. In order 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 monitored. The length where most of the sediment was deposited on the waterway was compared to the site observations. The plume length is sensitive to both the hydraulic conductivity and the amount of vegetation on the forested waterway channel, as well as the different obstructions that are present in the path of the runoff. The vegetation was set at a fairly dense level to correspond to the Coast Range characteristics and the conductivity on the waterway was set at 80 mm/hr, which corresponds to some field measurements.

Table 2. *Comparison of Brake's [1997] measurements to simulated WEPP outputs.*

	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%
Measured Plume Length (m)	15	7	5	13	33
WEPP Predicted Plume Length (m)	44	28	6	54	14

Table 2 shows that WEPP overestimates the measured plume lengths in most cases. The most significant factor in plume length is the contributing area and the presence and type of obstructions in the flow path. It is difficult to predict where, at what orientation, and how large obstructions are and therefore modeling such occurrences is difficult. WEPP currently does not provide such a scenario, although with further work some of the impoundment options may be capable of modeling the effects of some of these obstructions. Also, the presence of a sediment plume does not necessarily mean that there is no sediment carried beyond the plume. There is currently a field study underway to determine the amount of sediment carried beyond the observed plume [Brake 1997].

Figure 2. *Channel Structure*

Another factor not considered in this validation is the fact 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 cannot be used for this scenario. Different flow patterns result in different sedimentation properties, as shown in figures 3 and 4. Figure 3 shows sedimentation occurring in a wide flat channel best represented as a hillslope below the culvert, while figure 4 shows a definite rill forming below the culvert, which is best represented as a channel. Figure 3 also shows a large woody obstruction, causing the sediment to deposit in a shorter plume.

The validation studies indicate that the current version WEPP can model the effects of different road topographies and treatment conditions on the erosion processes for insloping forest roads, but does not model sediment plume length in channels.

Figure 3. *Waterway with a dispersed flow pattern*

Figure 4. *Waterway with a concentrated flow pattern*

Sensitivity

Having determined that WEPP predicts reasonable results for road erosion, we performed a sensitivity study to determine the most important processes in insloped road erosion. The elements of an insloping forest road are the cutslope, a ditch, the road, culverts spaced at desired intervals, and the hillslope or gully below the culvert where sediment follows an ephemeral vegetated channel toward a perennial stream. To model this scenario in WEPP, each element was developed individually and then linked together in a watershed structure.

The road travelway was modeled with an inslope of 3 percent, diverting all runoff to an inside ditch rather than onto the hillslope below. Road gradients of 2, 4, 8, and 16 percent were combined with road lengths of 10, 20, 40, 60, and 100 meters for a total of 20 road-length combinations. These 20 combinations, each simulated for five different soil types, produced 100 different runs. The soils represented a range of typical soil types observed on forest roads and included a silt loam, clay loam, sand loam, loam with gravel, and sandy loam with gravel (Table 3).

Table 3. *General Road Input Parameters*

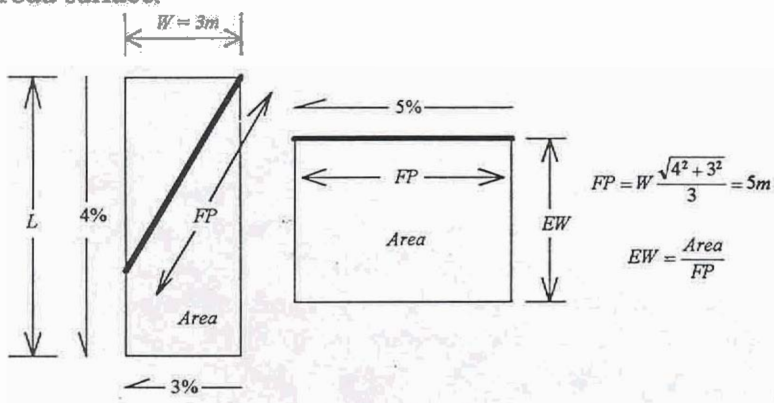
Gradient	Length	Soil Type
2%	10 m	Silt Loam
4%	20 m	Clay Loam
8%	40 m	Sand Loam
16%	60 m	Loam with Gravel
	100 m	Sandy Loam with Gravel

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.

Forest Travelways

Because a forest road has little or no vegetation, the management file in WEPP describes a fallow system with seasonal blading. The runoff flow path (FP) 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 (figure 5). In order to accurately model this as a hillslope element in WEPP, the road segment has been described with a length of the flow path, rather than the physical road width. Subsequently, to maintain the same surface area for precipitation and evapotranspiration, an effective road segment width (EW) was determined by dividing the physical road area by the flow path length. This configuration neglects any rutting in the road and assumes a planar travel surface. A rutted road would increase the flow path, thus increasing the erosion from the road surface.



Travelway as Measured Travelway as Modeled

Figure 5. *Flow Pattern Description of Road Element*

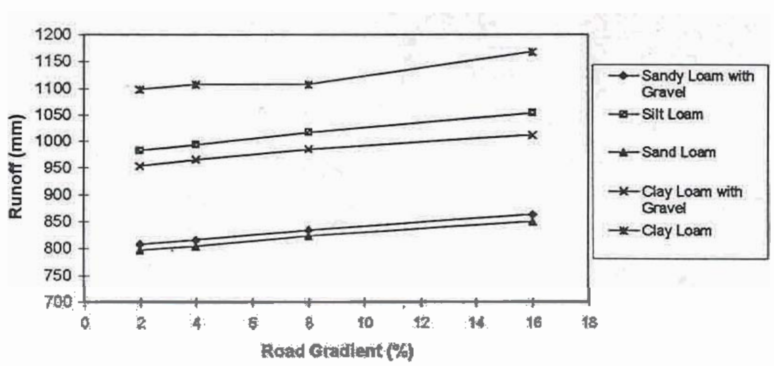


Figure 6. *Average Annual Runoff values predicted by WEPP for one year in North Bend, OR*

WEPP performed the 100 runs for a North Bend, Oregon climate for one year, and output values for average sediment loss and average runoff were recorded. These results are summarized in figures 6 and 7. Other climates had similar trends. Using generally the same variable inputs, Burroughs and King [1985] developed an empirical equation to predict sediment yield based on road grade, surface density, and the D_{50} of the loose soil for the road element of the roadcut scenario. This equation produces a curve with similar trends to figure 7. For more erosive soil properties and higher road gradients, soil losses were higher and increased in an exponential manner with road length.

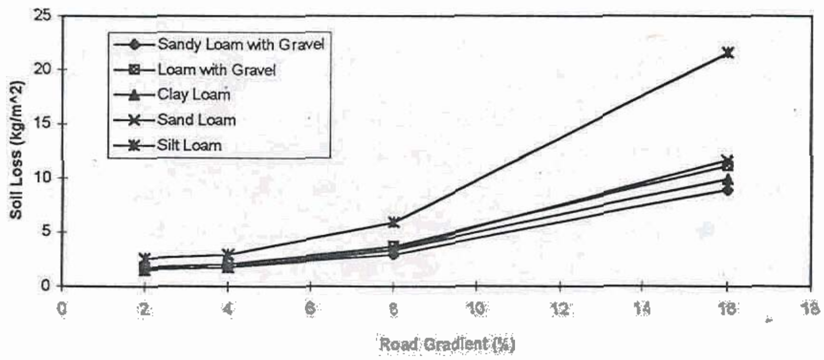


Figure 7. *Average Annual Erosion values for one year predicted by WEPP for a 60 m road segment in North Bend, OR*

The increased runoff is likely due to the reduced surface storage capacity, while increased erosion results from deeper runoff and greater erosivity of the runoff water because of higher water energy. There was more erosion on the longer roadslopes due to a larger area contributing. Changes in road length did not affect the runoff depth. Erosion and runoff were greatest for the silt loam and clay loam soils, respectively (figure 8). Soil loss and runoff were both the least for the sandy loam with gravel.

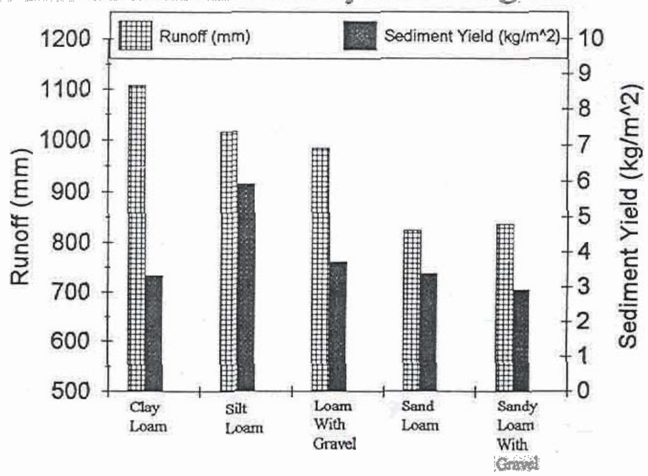


Figure 8. *Runoff and Soil Loss for roads with different soils for 8% gradient and 60-m length in North Bend, OR*

Ditch Characteristics

The next element to be incorporated into the watershed was the ditch, which WEPP models as a seasonal channel. Since the road shape was changed to accommodate the flow path, the question arose as to where along the ditch to place the road element. WEPP uses structure elements and places them side by side or above and below one another. Several different configurations were simulated with the road element at different locations along the ditch. The results suggested that the best way to configure the road and channel was to center the modified road segment at the midpoint of the channel (figure 9). This configuration was not only easy to build, but gave more consistent outputs. The sedimentation from Channel 1 in this configuration may be underpredicted and the sedimentation from Channel 3 overpredicted, but the overall effective yield falls in the observed range, as shown in figure 1.

These runs were performed using the same climates as the single-element road, and two soils, clay loam and silt loam with gravel. Four different length and slope combinations were selected for the runs. In all cases, the road ditch was eroding. Table 4 shows some typical results for one soil type.

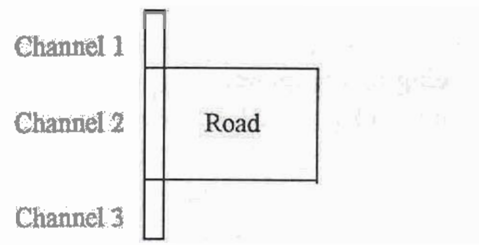


Figure 9. *Channel and Road Configuration*

Table 4. *Sediment yields from the travelway and the travelway with ditch in one year for several silt loam roads predicted by WEPP for a North Bend climate*

Gradient	Road Length (m)	Sediment Yield from Travelway (kg)	Total Sediment Yield (kg)
2%	60	523	830
4%	60	651	1554
8%	60	1326	2775
4%	30	326	1045
4%	90	977	2027

Cutslope Characteristics

The cutslope was modeled with three different amounts of vegetation, which were named Much, Some, and None for simplicity. Vegetation characteristics are described in the management file and include a number of variables such as stem diameter, plant height and spacing, and rill and interrill cover. In order to reduce repetitive runs, the road length was fixed at 60 meters and the soil type as the silt loam. Cutslopes generally have steep slopes, so the slope was fixed at 100 percent and the height was varied at one, two, and three meters. This made a total of 36 runs: four different road slopes, three different vegetation covers, and three different cutslope heights.

The soil characteristics are different for each element because of compaction and disturbance. Table 5 shows the modeled soil properties in the WEPP soil file for the silt loam soil.

Table 5. *Soil Characteristics of Watershed Elements for Silt Loam Soil*

Element	ki $kg*s/m^4$	kr s/m	tau_c N/m^2	Conductivity mm/hr
Travelway	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 10 summarizes what portion of the sediment eroding comes from the road, channel, and cutslope for the four 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 ditch dominates. It is apparent from figure 10 that erosion from the cutslope decreases slightly with more vegetation and increases with height. Greater cutslope height also causes more channel erosion due to greater runoff. Dependent upon soil characteristics and road and ditch management, other scenarios may show erosion being driven by the road, but the general relationship of cutslope vegetation and height and road gradient and length holds.

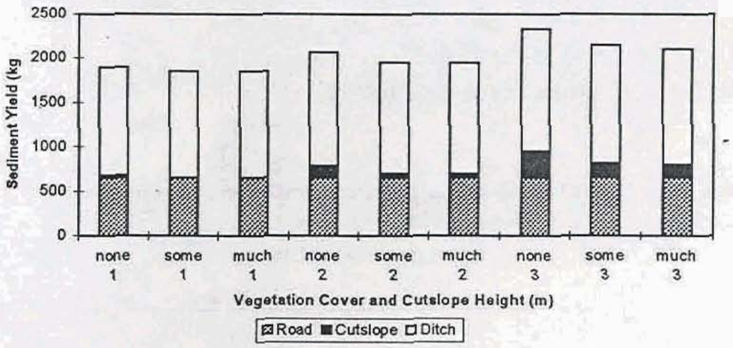


Figure 10. *WEPP's predicted sediment yield for different cutslope heights and vegetation amounts for a watershed consisting of a 4% silt loam road 60m long, with a channel and a cutslope for one year in North Bend, OR*

Below the Culvert: Forested Waterways

A corrugated metal pipe culvert is usually used to divert runoff from an insloped road to the waterway below, where water infiltration and sediment deposition occur in a concentrated channel. The WEPP Watershed Version includes several templates that simulate impoundments, including culverts under roadways, but the sensitivity analysis approach revealed several problems with the impoundment routines. In order to bypass these problems, we chose to model the culvert as a nonerodible open channel with a roughness and gradient similar to a corrugated metal pipe culvert. This portion of the study investigates the complex interaction of discharge and infiltration below the road [Morfin et al 1996]. We assume in this section 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 (figure 11). Recall that since the road is insloped, the road-hillslope length and width were altered to account for the diagonal overland flow of the water toward the ditch. 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 may vary with road length and gradient, as well as waterway length, gradient, side-slope and roughness. In this study, we have developed sets of WEPP runs to examine volumes and sediment amounts first with waterway length and gradient, and second with waterway roughness, holding other variables constant. A similar set of runs showed that waterway channel side slope had no effect on sediment yield or runoff.

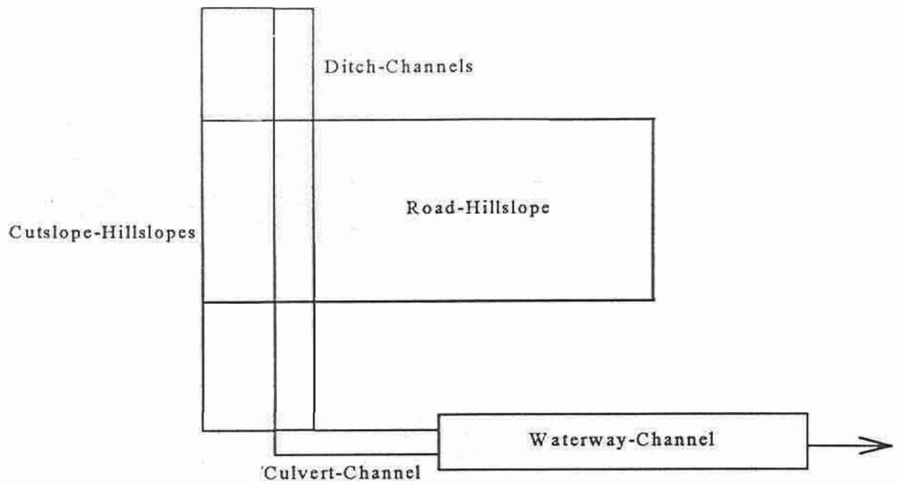


Figure 11. *Plan view of complete watershed structure.*

To illustrate the effect of waterway length and road length for attenuating discharge, the gradient of the waterway was fixed at 10 percent and the road gradient at 4 percent. Waterway discharge increased as road length increases and/or waterway length decreases. This occurs because the larger surface area of the road leads to more runoff, but a longer waterway results in more infiltration, or less runoff.

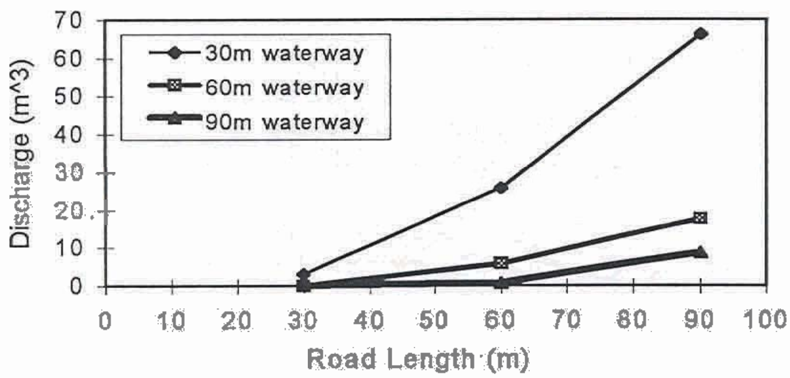


Figure 12. *WEPP's predicted waterway discharges for different road and waterway lengths for Charleston, WV. Road gradient is 4%.*

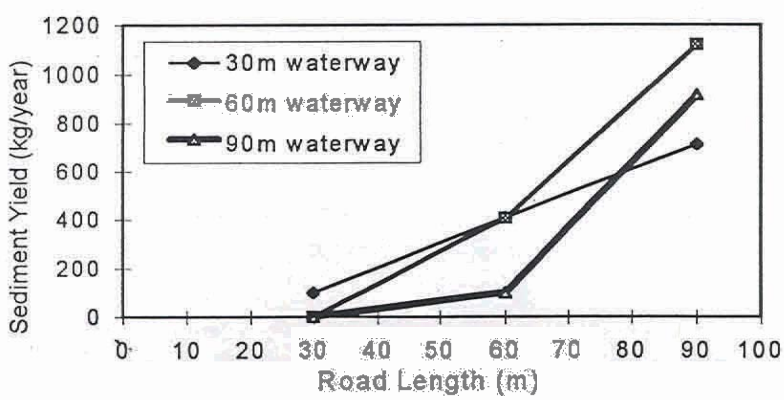


Figure 13. *WEPP's predicted sediment yields for one year for different roads and waterways in Charleston, WV. Road gradient is 4%.*

Figure 13 shows that as road length increases, sediment yield increases. Sediment yield is generally less for roads which have longer waterways. It appears that for short road 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. This concept is further illustrated in figures 14 and 15.

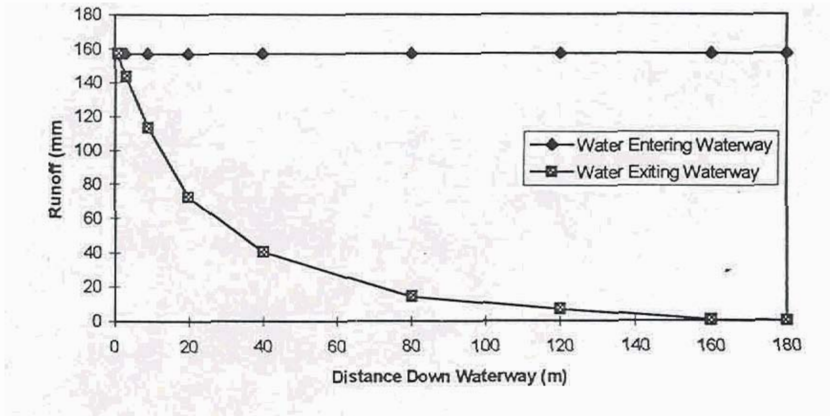


Figure 14. *Runoff attenuation over waterway length with gradient of 8% for one year in Medford, OR for a 60m long road.*

Figure 14 shows volume entering the waterway as the upper line and volume leaving the waterway as the lower curve for one roadcut scenario where the road is 60 m long at 3 percent and the waterway is of varying length with a gradient of 8 percent. This graph suggests that 160 m are needed to infiltrate the runoff from the road and cutslope section.

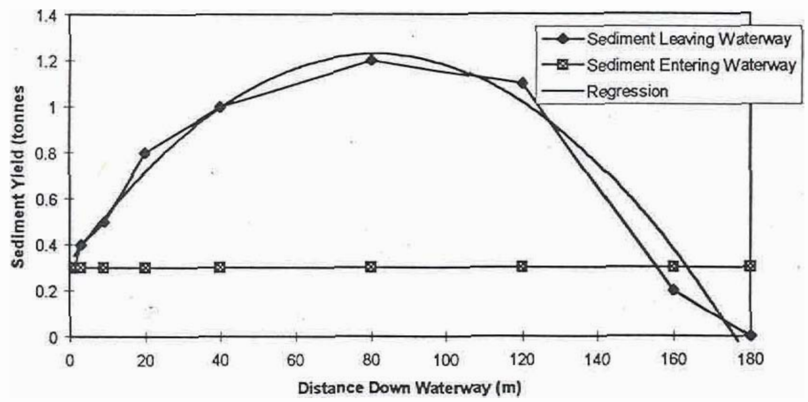


Figure 15. *Sediment Yield for varying waterway length with 8% gradient for one year in Medford, OR for a 60m long road.*

The effect of waterway length on sediment yield shows a different initial trend than the runoff discharge. Figure 15 shows that erosion occurs in the waterway channel for a distance of about 80 meters before deposition begins to occur. A regression analysis resembles a second order equation with the y-intercept as the incoming sediment for this trend. This graph insinuates that, for this scenario, a waterway length of at least 180 meters is needed between a 60 meter road length and a stream channel if no road sediment is to enter the stream for this climate and soil. The peak of the curve shifts with changes in road segment length, gradient, soil type, and climate.

Figures 13 and 15 both suggest that a short waterway is better for controlling sedimentation than a waterway of "medium" length in some cases, while a waterway of extreme length is preferred in all cases. For the scenario depicted in figure 15, sediment delivery is limited by the length of the waterway until 80 m is reached. Beyond 80 m, sediment delivery is transport-limited in that the energy of the runoff is too low (fig. 14) to transport all of the sediment previously eroded.

The relationships between waterway length and sediment yield were different from those presented by Morfin et al. [1996], who modeled the flow downstream from the road as dispersed flow rather than channel flow. We used their overland flow model to study the impact of the channel on erosion and sediment delivery from roads. The WEPP waterway channel has a discrete side slope, so the channel flow pattern is different from the dispersed flow pattern portrayed by Morfin et al. [1996] in the hillslope model (fig. 2).

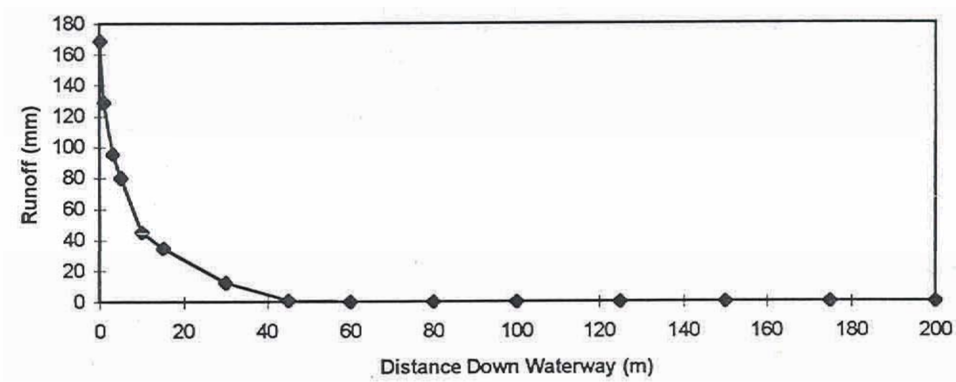


Figure 16a. *Runoff from a dispersed waterway.*

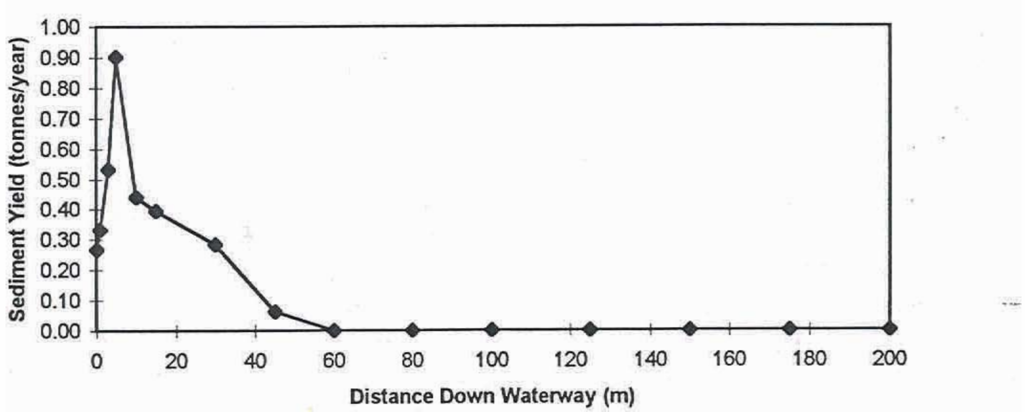


Figure 16b. *Sediment Yield from a dispersed waterway.*

The runoff attenuation and sediment yield for the hillslope waterway has a shape somewhat similar to that of the channel waterway. In both figures 14 and 16a, the flow depth decreases with waterway length as the runoff infiltrates into the forest floor.

However, because the waterway is a channel in figure 14, a longer waterway is needed to infiltrate all the runoff. Properties of flow in a triangular channel are different from properties of overland flow, causing this discrepancy. Figures 15 and 16b show that both types of waterway initially erode and then begin to deposit sediment some distance down the slope. The channelized waterway erodes the slope for a longer distance before depositing while the dispersed flow hillslope begins deposition sooner, thus making the distance that the eroded soil travels less. The deposition rates are proportional to the volume of runoff in both cases. The lengths and peaks of the curves will change with different climates, road topographies, and soil characteristics.

To measure the effects of differing waterway gradients, the waterway length was fixed at three meters in the model and the gradient varied from zero to sixty percent. The results of both sediment yield and discharge volume showed that as the gradient of the waterway increased, runoff and erosion both increased, but the changes were relatively small. Table 6 illustrates that a waterway gradient of 8 percent will yield about 4 cubic meters per year less water volume than a gradient of 60 percent. It also shows that the 8 percent gradient will yield 0.1 tonnes of sediment per year less than the 60 percent gradient. These small changes indicate that neither runoff nor sediment yield are sensitive to the waterway gradient in WEPP.

Table 6. *Discharge and Sediment Yield data for varying waterway gradients. Waterway length is 3m while road is 60m long at 3% in Medford, OR for one year.*

Waterway Gradient	2%	8%	30%	60%
Discharge Entering Waterway (m^3/year)	89.2	89.2	89.2	89.2
Discharge Exiting Waterway (m^3/year)	78.4	78.9	82.2	82.8
Sediment Entering Waterway (tonnes/year)	0.3	0.3	0.3	0.3
Sediment Exiting Waterway (tonnes/year)	0.3	0.3	0.4	0.4

Lastly, changes in waterway roughness were examined to determine the effects of channel roughness on discharge and sediment yield. WEPP calculates roughness effects from a bare Manning's n and a total Manning's n. In this analysis, waterway length was fixed at 100 m and 8 percent and five different bare n's were chosen. The road was fixed at 60 m and 3 percent, while the total n varied from 0.05 to 0.70. The high Manning's n values are more common for the shallow flows found in these ephemeral waterways. A value of 0.05 is representative of coarse vegetation or a stony channel and a value of 0.70 would be representative of a channel with large boulders. Figure 17 shows that as bare roughness increases, sediment yield increases proportionally. Changes in total n caused little variation in sediment yield and curves looked similar to the one shown. The analysis showed no change in runoff for changes in either roughness. It was noted that for very short waterways, changing roughness causes unpredictable trends in sediment yield and runoff discharge.

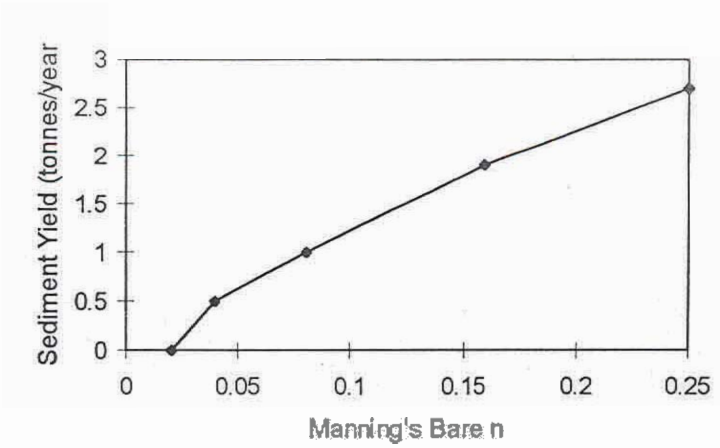


Figure 17. *WEPP's predicted sediment yields for various bare Manning's n and a total Manning's n of 0.3 for a 60-m road at 3% gradient and 100-m waterway at 8% gradient near Medford, OR*

Discussion

The road portion of this study points to road length, road gradient and soil type as the driving factors in erosion. Erosion from the cutslope element is relatively small compared to that from the road element. Depending on the soil and management characteristics of the ditch, erosion from the ditch may or may not be of significance.

The waterway study demonstrates that the most significant variable driving erosion on a waterway is downslope waterway length and to a lesser extent, bare roughness. The amount and density of vegetation are important, as well as the hydraulic conductivity. Factors such as waterway gradient, channel sideslope, and total roughness are of negligible importance when modeling with WEPP. The presence and orientation of obstructions drives where and how much sediment is deposited in the waterway, as well. Also important is how the road prism watershed is modeled, as demonstrated in the comparison between the hillslope waterway and channel waterway. It is uncommon and is not a recommended practice for culverts outlets to discharge directly into a channel waterway. There is a need to develop a watershed model that incorporates overland flow below channels to be able to model the more common hillslope waterway.

The large variability in sediment yield patterns shows the high complexity of modeling a roadcut watershed scenario. Even with a model such as WEPP, it is difficult to account for all the variables and their boundary conditions, but WEPP allows many of these type of variables to be accounted for that past studies have "lumped" into "factors" in simpler models. For example, we found soil erodibility to be an important parameter when validating field measurements. Without knowledge of soil erodibility and conductivity, WEPP runs can be useful for comparison relative to other WEPP scenarios in establishing trends, but may not approach values that one may observe in the field.

Conclusions

We developed a set of insloped road scenario templates with different topographies, soils, and management practices. These templates can be modified for site specific roadcut scenarios in different climates for practical application by forest engineers and managers. A validation study reflected that WEPP's predictions were reasonable approximations for the sediment yields at our plots and the ditch treatment made substantial increases in the sediment yield. This yield also varies with topography, soil type, and climate. WEPP did not appear to predict sediment plume formation in waterways. It appears that factors such as obstructions and channelization are critical in plume formation, and modeling these features requires further investigation. A sensitivity analysis was performed and the applicability of these templates was tested using the field validation. The most important variables in terms of sediment production are, in order:

* Road segment length
* Road slope
* Ditch management practices
* Waterway properties

The cutslope topography and management had minimal effect on the sediment yield of the road scenario.

When used correctly, the WEPP Watershed Model can be useful in predicting runoff and sediment yields for insloped forest roads. WEPP can account for such variations as topography, soil properties, management practices, and climate, all of which cause substantial differences in the forest road erosion process. Because WEPP is sensitive to several input variables, it is important to have site specific details for comparison or calibration for the areas of interest.

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