Predicting Sedimentation from Roads with the WEPP Model

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Roads cause Sedimentation

Roads are the dominant source of sediment in Eastern U.S. forests (Swift, 1985; Swank and Crossley, 1988), and a major source of sediment in Western Forests (Reid, 1981). It is estimated 50 to 90% of sediment in a forest comes from roads. Landslides are the other single major contributor to sediment.

Sedimentation lowers the quality of normally pristine forest streams, adversely affecting the habitat. Salmon spawning beds are adversely affected, and deep pools essential for many freshwater species may be filled in. Life of reservoirs is shortened, and natural geomorphic channel processes are perturbated with excessive sedimentation. Sediment from roads is often more damaging to the environment than from landslides because it has a higher concentration of the fine sediment that clogs spawning beds, whereas sediment derived from landslides contains more coarse sediments, which may improve spawning habitats in some situations.

The WEPP Model

The Water Erosion Prediction Project (WEPP) model is a physically based soil erosion model (Laflen et al., 1991b). It continuously models climate, soil water, and plant growth, on a daily time step. For each storm, the model predicts runoff, sediment detachment, sediment deposition, and sediment yield from the bottom of the hillslope. Currently, only a hillslope version of the model is available. The Hillslope Version predicts the distribution of erosion along a hillslope profile, as well as the sediment yield, and eroded sediment size distribution in the runoff at the bottom of the hillslope.

The WEPP model allows the user to describe up to ten overland flow elements (OFEs) along a hillslope (Figure 1). OFEs allow the description of different soils, different types of vegetation, and different combinations of soil and vegetation.

The soil erosion processes modeled in WEPP are interrill and rill. Interrill erosion is the detachment and transport of sediment by raindrop splash and shallow overland flow. Rill erosion is the detachment and transport of sediment by concentrated channel flow. Interrill erosion is described by the equation:

$$Di = Ki\ i\ q\ \mathrm{f(slope)\ f(canopy)\ f(surface\ cover)} \tag{1}$$

where Di is the interrill erosion rate (Kg/s/m^2), Ki is the interrill erodibility (Kg-s /m^4) i is the rainfall intensity (m/s), q is the runoff rate (m/s) and the final three terms are factors that influence interrill erosion due to slope, canopy, and surface cover (both vegetation and rocks).

Rill erosion is predicted by the equation:

$$Dr = Kr(\tau - \tau c)\left(1 - \frac{Qs}{Tc}\right) \tag{2}$$

where Dr is the rill erosion rate (kg/s/m^2), Kr is the rill erodibility (s/m), τ is the hydraulic shear due to the flow in the rill channel (Pa), τc is the critical shear of the soil (Pa), Qs is the rate of sediment being transported down the rill (kg/s/m^2) and Tc is the sediment transport capacity of the rill (kg/s/m^2).

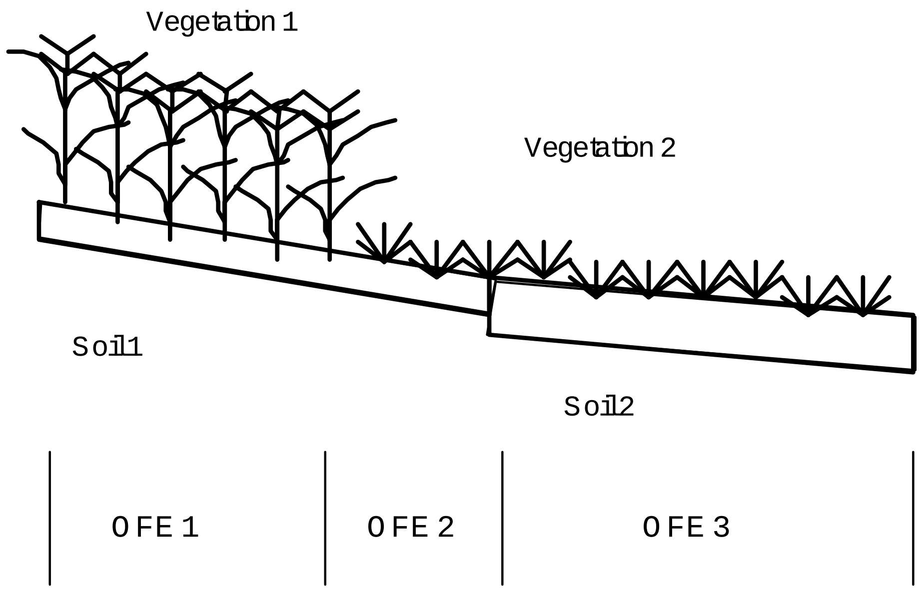

Figure 1 An example of a hillslope with three overland flow elements (OFEs) to describe a combination of two types of vegetation and two soils.

The three critical soil properties in the above erodibility equations are Ki, Kr, and τc. In addition, the effective hydraulic conductivity (Ke) is another critical soil property required for the WEPP model to determine runoff, which influences both interrill and rill erosion. Further discussion on predicting these values for forest roads will be presented in this paper.

WEPP Input Files

The WEPP model requires four input files: Slope, Soil, Climate, and Management. File builders are provided with the model to assist the user in building each of these files, and we have developed a set of standard files to assist the user in initially running the model.

Slope. The slope file specifies the length and width of the hillslope, and at least two pairs of points specifying the percent distance from the top of the slope, and the percent slope at that point. Up to ten pairs of points can be specified for each overland flow element, making it possible to describe complex slopes in great detail.

Soil. The soil file describes the surface layer percent saturation at the start of the simulation, as well as the erodibility and conductivity. It then allows the user to describe up to ten layers of soil, up to 2 m deep, with the texture and Cation Exchange Capacity (CEC). The CEC is used by the model to determine the clay mineralogy, and the effects of relative stability of soil aggregates on temporal soil properties.

Climate. The climate file provides input of daily maximum, minimum, and dew point temperatures, rainfall amount, intensity, duration, and time to peak, solar radiation, and wind speed and direction. Observed climate files can be formatted and used with the model, but generally, a stochastic climate generator (CLIGEN) is used to generate a climate using statistics from a 100-km grid of weather stations. If there is some information on the climate at the site desired, it is also possible to modify the statistical input to the CLIGEN generator to generate longer term climates for the area of interest.

Table 1. Typical Erodibility values for native surface forest roads, freshly bladed, with compacted wheel ruts (Elliot et al., 1993b).

Soil	Interrill Erodibility, Ki, kg s/m^4	Rill Erodibility Kr s/m	Critical Shear τc, Pa	Conductivity Ke mm/hr
Loamy Sand	2,300,000	0.0004	0.1	2.9
Sand	800,000	0.0003	0	0.004
Sandy Loam	3,100,000	0.0005	1.9	0.15
Silt Loam	3,500,000	0.0003	2.2	0.002

Most of these weather stations are located in valleys, and may not be representative of climates at higher elevations in mountainous regions. To address such mountainous areas in the western United States, a mountain climate generator (MCLIGEN) is being developed which will use mesoscale climate modeling principles to estimate a climate on a 10-km grid. The MCLIGEN technology will also have the ability to interpolate between 10-km grid points to any point desired with consideration of local elevation and vegetation.

Management. The management file includes the description of the vegetation, and the timing and effects of tillage operations on soil erodibility properties. The file contains an initial conditions loop, a number of loops describing scenarios of vegetation and tillage, and a section describing the dates of operations during each year of simulation. The file builder provided with the WEPP model is almost essential to successfully create a management file.

The initial conditions scenario of the management file allows the user to specify a fixed or variable rill spacing, whether or not ridge tillage is practiced, and whether or not the width of the rill is fixed.

Estimating Soil Erodibility

Research has been carried out with rainfall simulation on 36 tilled cropland soils, 20 untilled rangeland soils (Laflen et al., 1991a; Elliot et al., 1993a), and eight forest road soils (Elliot et al., 1993b; Foltz, 1994). Equations based on easily measured soil properties have been developed to predict erodibility for cropland and rangeland soils on which the erodibility is unknown. Generally, the observed erodibility values varied by about 30 percent around the mean, so trying to predict an erodibility value any closer than ± 30 percent is not necessary. There were insufficient forest road soils to develop predictive equations. Studies were carried out, however, on the forest road erosion data, to determine the best method for predicting erodibility of native surfaced forest roads (Elliot et al., 1993b).

On graveled roads, validation studies are ongoing to determine the best method for predicting erodibility of graveled forest roads from rainfall simulation and natural rainfall studies. The data indicate that erodibility of a graveled road with traffic depends on the quality of gravel, and the tire pressure of the traffic (Foltz, 1994). Additional studies will be required to determine the effects of traffic intensity on erodibility.

Interrill Erodibility Ki: On native-surface forest roads, the interrill erodibility is best predicted by the rangeland prediction equations presented in the WEPP User Summary (Flanagan, 1994) furnished with WEPP program, or available for Internet downloading. Table 1 contains some typical values determined for native-surface roads from validation studies by Elliot et al. (1993b). They found that for roads that were bladed and then had a rut formed by traffic had interrill erodibility values similar to cropland soils with similar properties. The saturated hydraulic conductivity was predicted well by equations presented in Lane and Nearing (1989) for six of the seven soils.

Studies are underway to determine interrill erodibility of graveled roads. Current studies indicate that values similar to rangeland may be adequate, if the surface rock content is also included. The rock content contributes to the surface cover function (f(surface cover)) of Equation 1, reducing the interrill

Table 2. Typical erodibility values for graveled forest roads as a function of aggregate quality and tire pressure.

Surface Condition	Interrill Erodibility, Ki, kg s/m^4	Rill Erodibility Kr s/m	Critical Shear τc, Pa	Conductivity Ke mm/hr
Good Aggregate with highway pressure, or Marginal aggregate with reduced pressure	2,000,000	0.0003	2	9
Marginal Aggregate with highway pressure	4,000,000	0.0003	2	3

erodibility. Preliminary values for *Ki* for graveled roads are given in Table 2, based on preliminary validation studies.

Rill Erodibility. On native-surfaced roads, Elliot et al. (1993b) assumed that only the wheel tracks were subject to rill erosion. They found that rill erodibility properties were similar to rangeland soils with similar properties (Table 1).

Validation is ongoing to determine the rill erodibility of gravel roads with traffic. Field observations indicated that wheel traffic tends to force gravel into the rut bed, with more easily detached sediment extruding up and around the gravel. Under these trafficked conditions, the rill erodibility values would be similar to cropland soils. In the absence of traffic, it is believed that the rut area would soon armor or consolidate, resulting in a rangeland level of erodibility.

Critical Shear. Predictions of critical shear have not been particularly successful (Elliot et al., 1993a). Table 1 presents values predicted with rangeland algorithms for native surfaced roads.

On graveled surface roads in Oregon, we are finding that runoff is seldom great enough to exceed critical shear because of the greater conductivities of the gravel surfaces between the wheel tracks. A value of 2 Pa is recommended pending further field research on the erodibility of wheel tracks on graveled roads.

Hydraulic Conductivity. Generally, the conductivity on native surfaced roads was low, under 1 mm/hr. On graveled roads, however, the conductivity varied depending on the tire pressure of the traffic. Typical values ranging from 8 to 9 mm/hr are presented in Table 2. On the graveled, trafficked roads, the conductivity of the wheel tracks will be similar to the native-surfaced roads. The untrafficked area between ruts would appear to have a conductivity in the range of 15 to 20 mm/hr.

Management File

On forest roads, there are several vegetation conditions to consider: the road, the cut slope, the fill slope, and the undisturbed vegetation beyond the road prism. Generally, roads are best described with the "agricultural" format because it allows the inclusion of "tillage" operations which can be used to simulate the effects of blading or traffic on erodibility. Forests are better described with the "Rangeland" format as it allows for a description of layers of grass, shrubs, and trees.

If using more than one OFE, the current version of WEPP requires that all of the OFEs have the same type of vegetation, either cropland or rangeland. The current version of the WEPP model does not allow tillage operations in the Rangeland format, so if any operations are occurring on the road surface, the cropland version of the management input file must be used.

On roads, fallow can be selected for the vegetation scenario, so that no plants will be allowed to grow. Users may wish to depart from this if a closed road has been seeded with grass.

Blading can be considered a tillage operation that disturbs 100 percent of the surface to a depth of 5 to 10 mm. Traffic can also be considered a tillage operation which disturbs about 50 percent of the surface at a depth of about 1 mm. Dates of blading and traffic can be entered into the management file, although the current version of the model allows only ten operations per year. Alternatives to allow more operations are being considered.

On the cutslope and fillslope, a perennial grass vegetation can be described, varying the density of the vegetation to match the field conditions. Work is ongoing in determining the best set of descriptors to model a forest situation with the cropland file. Generally, the large litter layer in a forest prevents any erosion occurring, and if the residue amount entered is high (over 1 kg/m^2), the model will predict no erosion. In forests in northern Idaho and North Carolina, surface residue amounts of 7 kg/m^2 have been measured.

Describing a Road with the Hillslope Version of the Model

Field observations of the relationship between roads and streams have shown a number of different configurations. Validation studies have shown the importance of determining the correct flow paths to be able to predict erosion rates similar to those observed in field studies. Several typical configurations will be described as examples of how the Hillslope Version can be used to describe the erosion processes observed on forest roads.

In climates where the dominant form of precipitation is low intensity rainfall, as in the west coast mountains, most erosion will be from interrill erosion, and the description of the topography will not be as important as it is in those areas where precipitation is dominated by heavy rainfall intensities or high snow melt rates. In these areas, rill erosion of the road or inside ditch may be the dominant contributor to sediment yield, particularly on steeper or longer slopes.

Roads Parallel to Streams. Roads parallel to streams may either be insloped, outsloped, or rutted. If they are insloped or rutted, the modeling techniques described for roads crossing streams can be followed, assuming that sediment delivered to relief culverts or dips would be deposited into the stream.

Outsloped roads can be described as a series of overland flow elements (OFEs) (Figure 2). In most conditions, the forest above the road and the cutslope will not contribute to the erosion processes, and can be ignored. If these areas are contributing to runoff because they have been cleared of vegetation, then they should be included in the OFEs. The riparian area below the fill slope may not exist in many situations, making the fillslope the last element.

In the Slope File, the slopes of the various overland flow elements is entered. If there is a gradient to the road as well as an outslope, as shown on OFE3 in Figure 2, the slope of the road element is:

$$\text{Element Slope} = \sqrt{(\text{Road Gradient})^2 + (\text{Outslope Slope})^2} \qquad (3)$$

and the length of the road element is:

$$\text{Element length} = \text{Road Width} \times \frac{\text{Element Slope}}{\text{Outslope Slope}} \qquad (4)$$

Generally, the slopes of the fillslope and cutslope are sufficiently steeper than the road gradient that the above calculations are unnecessary, and their slopes and lengths can be determined directly from the road prism cross section.

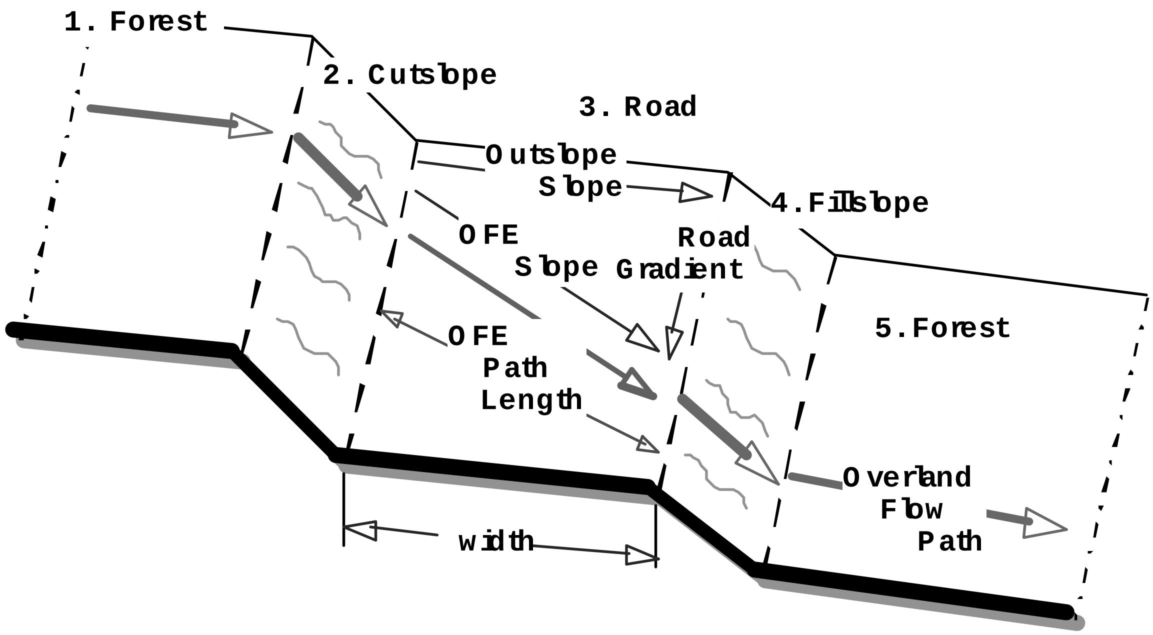

Figure 2 Use of multiple Overland Flow Elements (OFEs) to describe an outsloped road parallel to a stream.

Roads Crossing Streams. Roads crossing streams or upland drainage channels may be insloped or rutted. Insloped roads can be modeled by describing the road as a large ridge, and the inside ditch as the furrow (Figure 3). The ridge spacing can be considered to be the width of the road if the cutslope is fully vegetated and contributing little sediment to the ditch, or may be considered the combined width of the road and the cutslope. If the road is cambered, then only half the width of the road would be contributing to the erosion entering the ditch. Sediment from the outside half of the road could be predicted from an outslope model (Figure 2). The rill erodibility of the ditch would generally be similar to the wheel track as predicted by rangeland values, unless it was regularly disturbed by grading. The length of the slope is equal to the length between ditch relief culverts. The width of the hillslope is equal to the width of the road, and maybe the cutslope if it is eroding. The slope of the hillslope profile would be the same as the gradient of the road ditch, which generally is the same as the road.

Rutted roads that cross streams may also be modeled as a ridge and furrow system (Figure 4). The distance from the inside ditch to the first rut, and from the first rut to the second rut could be used to determine a "ridge" spacing. The ridge height can be estimated from the depth of the ruts and the depth of the ditch. The WEPP model is sensitive to the ridge height. The width of the rill should be set to be equal to the width of the wheel ruts. The rill width value can affect the predicted erosion rates. The road gradient is entered into the Slope file.

Factors Influencing Wheel Track Development. The presence of wheel tracks can increase rill erosion by concentrating runoff rather than shedding it from the road surface. Studies by the Army Corps of Engineers (COE) (Witcomb, et al., 1990) have found that wheel track development is a function of traffic density, axle loads, tire pressures, aggregate quality, and strength of the subgrade. Currently we are researching methods to apply the COE model to track formation to see if a model can be developed to more directly relate road design and management techniques to track formation and sedimentation.

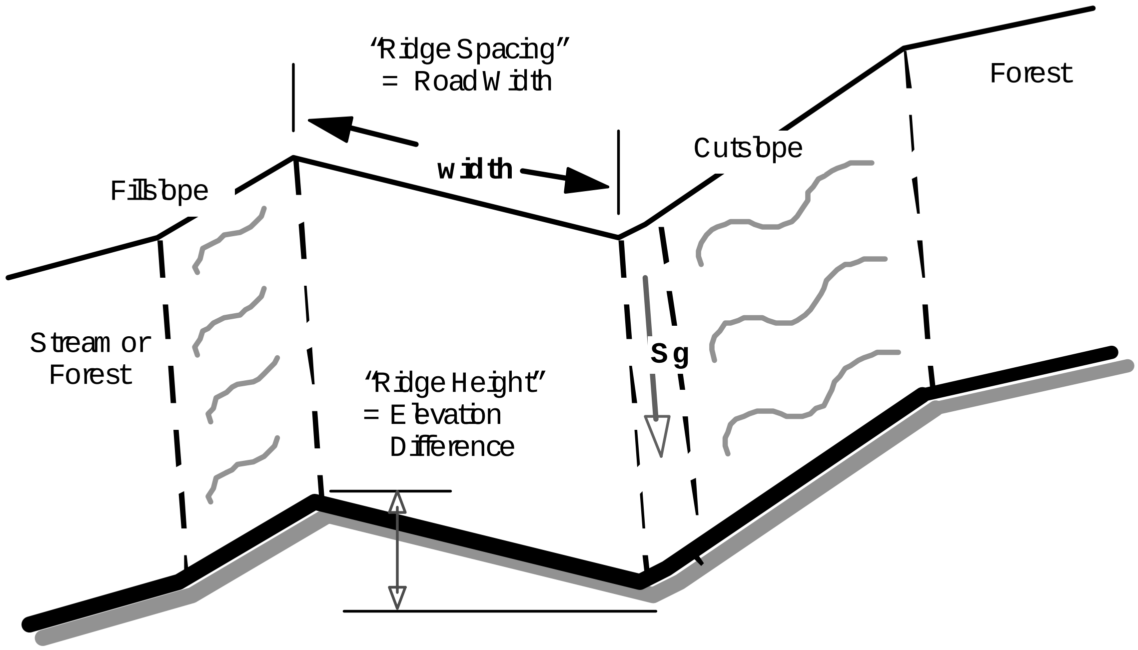

Figure 3 Diagram of an insloped road that may be crossing a stream, or have regularly-spaced culverts that guide the ditch flow to a stream parallel to the road, modeled as a "ridge and furrow" element.

Off-Road Deposition. One of the concerns of ecosystem managers is the width of riparian zone or buffer zone that may be necessary to ensure that sediment eroded from roads does not enter streams. It is possible to use the Hillslope Version of the WEPP model to assist in predicting the critical relationships between the road, the riparian area, and sediment transport. Figure 5 shows these relationships. The problem can be modeled as three overland flow elements: an insloping or rutted road, a fillslope (or culvert), and a riparian area.

Each of the elements can be modeled as described previously, with the riparian area described as an additional OFE. To simplify the modeling process, it is necessary to assume that the width of flow is the same on the road as it is on the fillslope and the riparian area. Care is necessary to determine the hydraulic conductivities of both the road and the riparian area. An undisturbed forest has a conductivity in the range of 80 to 120 mm/hr, but once deposition on top of the forest litter layer begins, this value may decrease.

Validation of the Model

Validation of the WEPP model for forest road conditions is an ongoing process for us. The current version of the WEPP model is a research version, and has received limited use outside of research projects. We will present the results of some of the validation studies that we have completed to date.

Validation for a Rutted Road with Rainfall Simulation. Elliot et al. (1993b) carried out a validation study for native surface roads with ruts using the geometry similar to Figure 2. The site was initially bladed, a wheel track dug by hand, and the bottom of the track consolidated by driving over the track several times with a pickup. Some of the results of this study are discussed above. Generally, the validation study showed that equations in Lane and Nearing (1989) could predict conductivities and rill erodibilities for consolidated wheel tracks with rangeland equations. Interrill erodibilities of bladed native surface roads could be predicted from the cropland prediction methods of Elliot et al. (1993a).

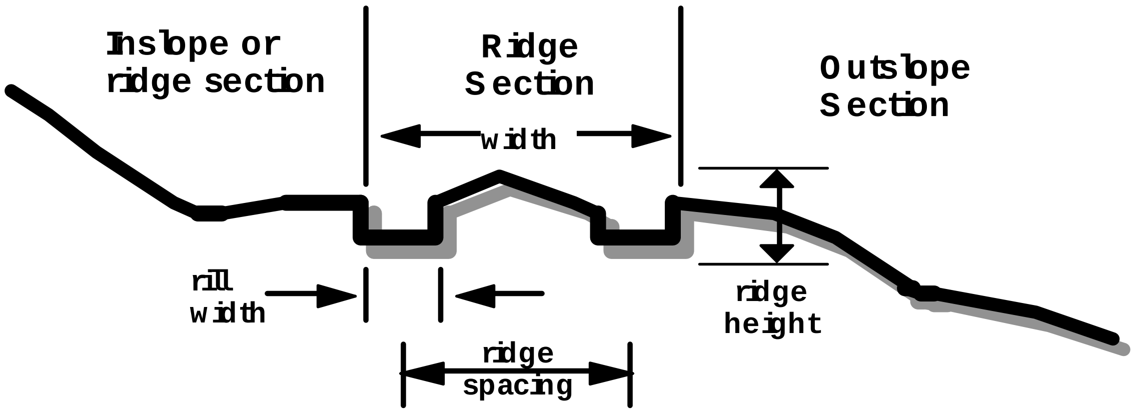

Figure 4 Diagram of a rutted road that crosses a stream as described by a WEPP ridge and furrow scenario.

Validation on Insloping/Outsloping Roads. A road parallels the environmentally-sensitive South Fork of the Salmon River in the Payette National Forest in Idaho. The road has been in existence for approximately 40 years. From the amount of sediment covering the road culverts, it was estimated that approximately 250 mm of sediment had been eroded during the past 40 years, or about 6 mm per year. It was observed during a site visit, and from previous observations, that on insloping sections, blading is employed twice each season to remove sediment that has been deposited in the ditch, to spread it back across the road.

The WEPP inslope/outslope model was applied to this section of road. The outslope model (using the geometry of Figure 2) predicted a net erosion rate that was approximately 6 mm/yr for those reaches of road that were outsloping. Some sections of the road were insloping to bank the road for curves. On one of these insloping sections, the WEPP model (using the geometry of Figure 3) predicted a net sediment yield less than the predicted interrill erosion rate. This would indicate that the interrill erosion was greater than the sediment transport capacity of the ditch, resulting in deposition in the ditch. Both results were similar to the long term field observations.

Validation on Roads Crossing Streams with Rainfall Simulation. A study with rainfall simulation was carried out on graveled roads having different qualities of aggregate, and different levels of tire pressures (Foltz, 1994) using the geometry of Figure 3 with and without incised wheel tracks. The study found that roads that were rutted had erosion rates that were dominated by rill erosion. Roads with higher quality aggregate, or reduced tire pressures had no significant rill formation, and the erosion was dominated by interrill erosion over the road shoulder. Cropland erodibility values were adequate to describe the observed interrill erosion rates, and rangeland values the observed rill erosion rates, once the flow paths (down the rut or over the shoulder) were adequately described.

Validation on Roads Crossing Streams with Natural Rainfall. Runoff from natural rainfall was collected from the graveled roads in an Oregon study over several seasons. Our studies show that the low intensity storms typical of the Cascade Mountains causes mainly interrill erosion. Observed sediment yields varied from 30 kg/m^2 on reduced tire pressure plots to 430 kg/m^2 on highway pressure, marginal aggregate plots. Validation with these data is ongoing. Our experience indicates that traffic is an important contributor to erodibility, and that quality of aggregate and tire pressure affect both erodibility and hydraulic conductivity. We have been able to obtain predicted erosion rates similar to the observed rates, and are currently studying methods to best describe the effects of traffic with the WEPP model.

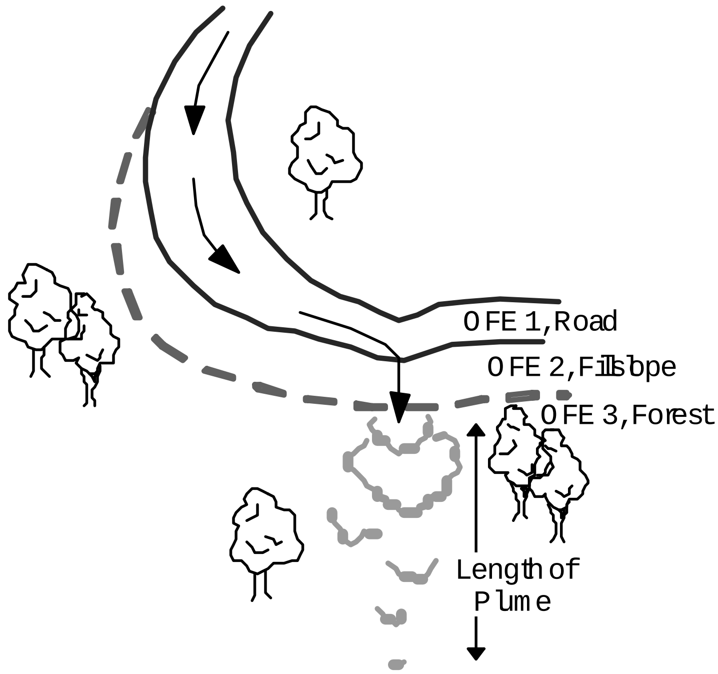

Figure 5 Relationship between an eroding road, a riparian area, and a plume of sediment deposition.

Deposition Validation. A study of the length of a deposition plume is being carried out in the Wine Creek Watershed in the Appalachians in North Carolina. A length of road of approximately 200 m was contributing runoff and sediment to a plume of sediment forming on the 50 percent slopes below a broadbase dip in the road. After six storms in 1994, the extent of the sediment plume was approximately 30 m. The site was modeled as three OFEs similar to Figure 5, and conductivities of the road and forest were estimated from other work. With the initial estimates, after the same six storms, a plume length of 20 m was predicted. Additional studies measuring flow rates and conductivities of the three OFEs would allow closer prediction of the extent of the deposition plume.

Summary

Roads are a major source of sediment in most forests. The WEPP model is a process-based soil erosion model that may be applied to such forest roads. Example applications of the WEPP model to different road/stream configurations were presented. Validation results have been encouraging.

Conclusions

The WEPP model shows considerable promise in assisting ecosystem managers to predict the impact of forest roads on sedimentation in forest streams.

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