Predicting Effects of Climate, Soil, and Topography on Road Erosion with the WEPP model[1]

S. Morfin — Geologist
W. Elliot — Project Leader
R. Foltz — Research Engineer
Intermountain Research Station, USDA Forest Service
1221 South Main, Moscow, ID 83843

S. Miller — Professor
Dept. of Geologic Engr
Univ. of Idaho
Moscow, ID

Introduction

Natural erosion and sedimentation in forest streams help keep the streams functioning properly. However, forest development, harvest, and management require roads to be built and maintained, and these roads may create excess sediment. Erosion from roads has become a greater concern as forests are developed and as the demand for forest management increases. Sediment added from these human activities can be harmful to natural stream habitats.

Compared to naturally accumulated sediment, road sediment generally is more fine grained with a higher percentage of silt and clay. It can also carry oils and contaminants from the road surface. This excess sediment affects the morphology of a stream, as well as the habitat for local and migratory fish (Burroughs and King, 1989; Bilby, 1985). Reducing the amount of road-derived sediment to streams with erosion and sediment control techniques is necessary for maintaining healthy stream systems.

There are many techniques for reducing erosion and sediment transport on roads. Graveling travelways, installing water bars or cross drains, and establishing riparian buffer zones are usually the most cost effective. Field tests have shown that spacing recommendations for these types of controls should be based on soil type, topography, road dimensions, road aspect, and climate (Copstead and Johansen, 1996; Burroughs and King, 1989). Therefore, design recommendations for these controls cannot be made on a nationwide or statewide level. Few agencies, however, have the resources necessary for site specific studies for every road segment they build or maintain.

Roads

It is estimated that 50 to 90 percent of excess sediment from forest activities originates on the road systems (Elliot et al., 1994). The largest sediment loss occurs in the first two or three years after construction. Sediment loss usually decreases substantially after those initial few years, as the cut and fillslopes stabilize and become revegetated (Burroughs and King, 1989; Ketcheson and Megahan,1996).

After this initial time period, most of the excess sediment comes from the travelway of a road. This area lacks the protection of vegetation which reduces sediment production on the cutslope, fillslope, and forest floor. The bare soil on the travelway is highly susceptible to rain-drop detachment and rill erosion, which can detach large amounts of sediment as water runs over the road surface (Foster, 1982). Erosion control treatments such as buffer zones, cross drains, gravel surfacing, pavement, wood chips, and oil treatment have been developed to reduce erosion and sediment yield on the travelway. These treatments can be expensive and, if applied incorrectly, may be ineffective. Usually, the most cost effective techniques for reducing sediment are: graveling, installing cross drains, and allowing for riparian buffer zones. To ensure that they reduce water transport energy, thereby reducing sediment carrying capacity of the water, proper design spacing is particularly important.

A physically based erosion prediction model, such as the Water Erosion Prediction Project (WEPP), may be used to establish spacing for water bars and buffer zones (Elliot et al., 1994). The model also can be used to evaluate the effectiveness of gravel surfacing on the travelway. If WEPP can be shown to produce reasonable results, then engineers can use it to assist with and verify their road construction and erosion control designs.

The WEPP model

The WEPP model is based on physical input parameters that describe processes that affect erosion. These parameters estimate infiltration, interrill erosion, and rill erosion to predict runoff and sediment yield. WEPP can model a hillslope with a given width and various soil, vegetation, and management characteristics. The Hillslope version is suitable for simple road design studies (Elliot et al., 1994).

The WEPP Hillslope version has four main input files: management, soil, slope, and climate. In the management file, the number of different overland flow elements (OFEs) can be set. An OFE is an area on the hillslope where the soil types, vegetation types, and management practices are homogeneous. One hillslope can be modeled with up to ten OFEs. The soil file describes texture, rill and interrill erosion coefficients, soil hydraulic conductivity, cation exchange capacity, and critical shear. The slope file defines the topography, width, and aspect of the hillslope. The climate file contains weather scenarios generated for any number of years by the CLIGEN weather simulator (Nicks et al., 1995). The climate file is not limited to CLIGEN information; observed weather data may be input (Flanagan et al., 1995).

The WEPP model can provide a variety of outputs, including plots, graphs, and estimates of sediment loss, sediment size distributions, and deposition along a hillslope. The output can contain either annual or single storm summaries for runoff, erosion, and sediment yield (Flanagan et al., 1995).

Methods

The goal of this study is to predict the effects of climate, soil, and topography on road erosion, downslope deposition, and sediment yield, using the WEPP model. This information can assist engineers in determining the effectiveness of gravel surfacing, cross drains, and buffer zones. This paper provides an overview of a study in progress, and reports a sensitivity analysis of the key input parameters for the WEPP model under these conditions.

We began by defining the parameters for the study and estimating the amount of time it would take to process the information using the WEPP model. We simulated a simple road configuration of three components: travelway, fillslope, and forest floor (Figure 1). We assumed that a negligible amount of sediment was contributed by the cutslope and hillslope above the travelway. The road was flat so that a road-side ditch was not necessary, and the shoulder and travelway were considered to be one unit.

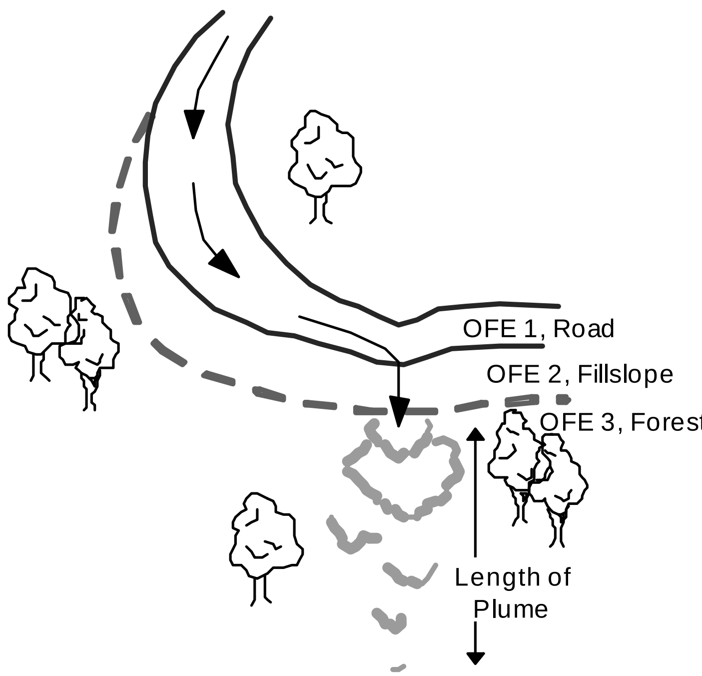


Figure 1. *Diagram of the WEPP road scenario: 1. travelway, 2. fillslope, 3. forest buffer.*

We developed a set of files to define road slopes, buffer slopes, road lengths, buffer lengths, soil types, climates, and a basic vegetation scenario that covers 9600 different situations (Table 1). Thirteen combinations of buffer and road slopes were created from the parameters, because it is not possible to have a road slope steeper than a buffer slope. With the 20 different buffer and road length combinations, there was a total of 260 different slope files. Five soil files-clay, silt, sand, sandy gravel and clayey gravel (Table 2)-were built and six climate files, representing a range of climates in the United States-Sappo, WA; North Bend, OR; Deadwood Dam, ID; Lancaster, NH; Cullowhee, NC; and Heber, AZ.

Table 1. *Study parameters.*

Road length (m)	10	20	40	80	100	
Road slope (%)	2	4	8	16		
Buffer Length (m)	10	40	80	200		
Buffer slope (%)	4	10	25	60		
Climates	Sappo, WA	North Bend, OR	Deadwood Dam, ID	Heber, AZ	Cullowhee, NC	Lancaster, NH
Soil	Silt loam(slt)	Clay loam(cly)	Sand loam(snd)	Clay gravel(cg)	Sand gravel(sg)	

Table 2. *Soil properties of the different road types in this study.*

	CLY	SLT	SND	CG	SG
Thickness	200	200	200	200	200
%Gravel	20	5	5	60	80
%Sand	30	30	60	40	70
%Silt	40	55	35	40	25
%Clay	30	15	5	20	5
k sat	0.3	0.3	1	2	3
Ki	1000000	3000000	2000000	1000000	2000000
Kr	0.002	0.0006	0.0004	0.0003	0.0003
tc	1.5	1.8	2	1.8	2
Organics	0.01	0.01	0.01	0.01	0.01
%Gravel	20	5	5	40	40
%Sand	30	30	60	35	65
%Silt	40	55	35	40	30
%Clay	30	15	5	25	5
k sat	5	8	10	25	40
Ki	1000000	3000000	2000000	1000000	2000000
Kr	0.0002	0.0006	0.0004	0.00025	0.00035
tc	1.5	1.8	2	1.6	2
Organics	2	2	2	2	2
%Gravel	20	5	5	20	5
%Sand	30	30	60	30	60
%Silt	40	55	35	40	35
%Clay	30	15	5	30	5
k sat	10	15	20	50	80
Ki	1000000	3000000	2000000	1000000	2000000
Kr	0.0002	0.0006	0.0004	0.0002	0.0004
tc	1.5	1.8	2	1.5	2
Organics	4	4	4	4	4

We found that it took approximately 15 minutes to run a 30-year climate and approximately that long to record, delete, and prepare another run on a 486-33mhz MS-DOS computer. If the 9600 runs were made manually, it would require 600, 8-hour days to run all the combinations and complete the data generation part of the project. This seemed to be an unreasonable amount of time, so other options were explored.

Because the runs were systematic and repetitive, a command program was designed to create the various input file combinations on a Unix workstation. We also created a data recording program to record only the necessary information from the Unix output files into a separate file for easy access. We compared the results from MS-DOS machine to the Unix workstation and found that they were within 1-2% of each other. The Unix machine processes approximately 1200 runs per day and completed all the runs in 8 days. The final data set took 120MB to store on the workstation.

An overview of the results indicated that most roads with low slopes and short lengths produced little or no sediment, so in the sensitivity analysis, we focused on the steeper slopes and longer roads so the predicted differences could be evaluated more easily. The standard scenario was the climate from Deadwood Dam, ID, a silt loam native road surface, with a road length of 100 m, buffer length 10 m, road slope 8%, and buffer slope of 25%.

Results and Discussion

Road parameters that affect sediment loss

The road travelway contributes most of the excess sediment; therefore, the first analysis was to determine how slope and length affect runoff and erosion from the road alone. The results are shown in Figure 2.   The sediment loss is in kilograms of sediment per meter width of road per year.

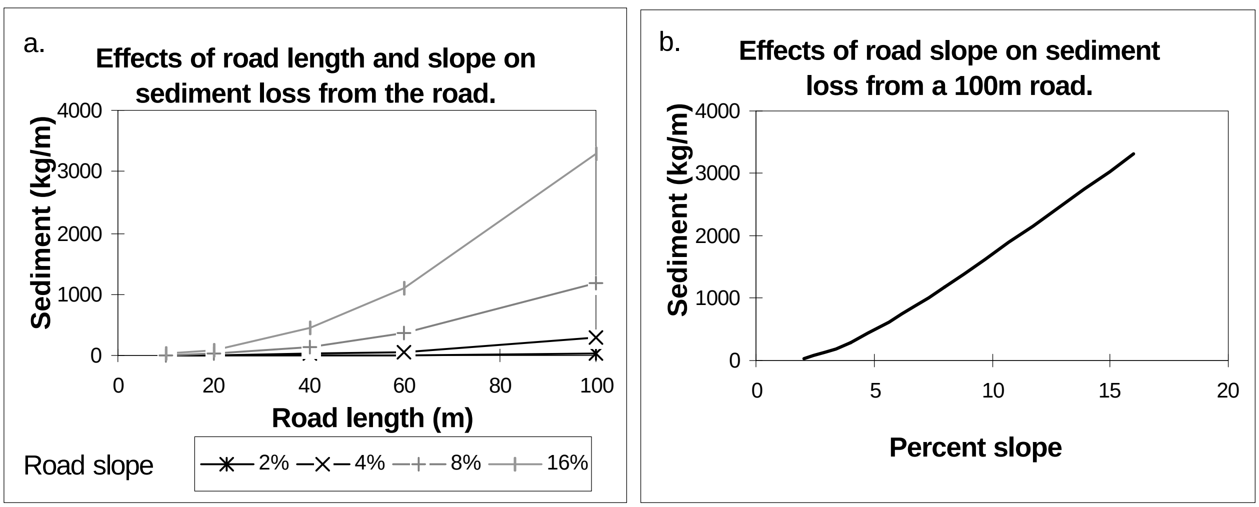


Figure 2. *a. Slope has greater effect as the length of the road increases.*
b. As the road slope increases sediment loss increases.

Effect of adding a buffer to the profile

Most roads have a fillslope or buffer, so our next step was to add a short buffer strip to see how that affects the amount of sediment leaving the site. A buffer strip with a 25% slope and 10 m in length was placed at the base of the road prism; there was deposition on the buffer. Different amounts of deposition occurred on the same buffer for different road lengths and slopes. Therefore, it was more difficult to relate sediment yield directly to the road geometry. Figure 3 shows that the buffer strip substantially reduced the sediment yield.

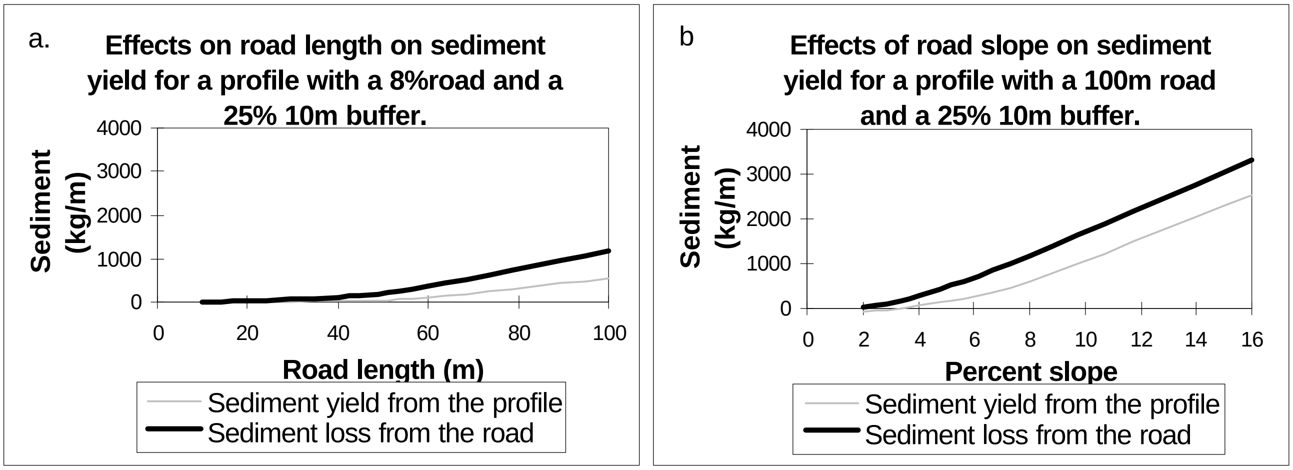


Figure 3. *a. Deposition on the buffer increases with road length.*
b. Deposition increases with slope.

Buffer strip effects

Because the buffer strip reduced sediment losses significantly, the buffer strip parameters were varied to determine the optimal configurations for each road type (Figure 4). Under most conditions, a steep buffer slope needs to be longer to retain the same amount of sediment as shorter buffers. Figure 4a also shows that there is little sedimentation benefit from having a buffer wider than about 75 m for this scenario. Figure 4b shows that for this scenario the effect of the buffer slope is small for slopes greater than 30%.

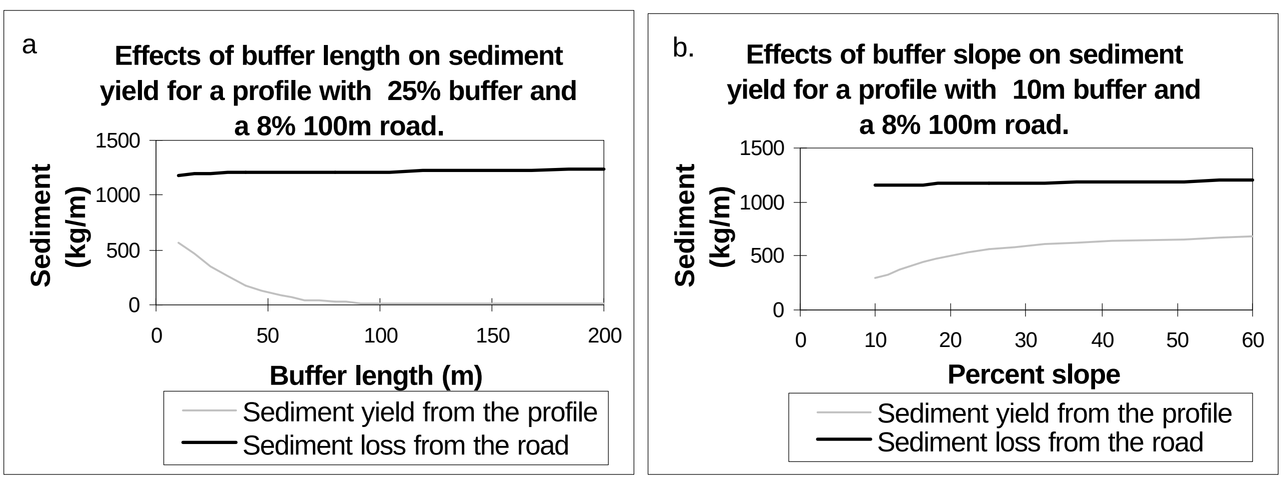


Figure 4. *a. Effect of buffer length on sediment loss.*
b. Effect of buffer slope on sediment loss.

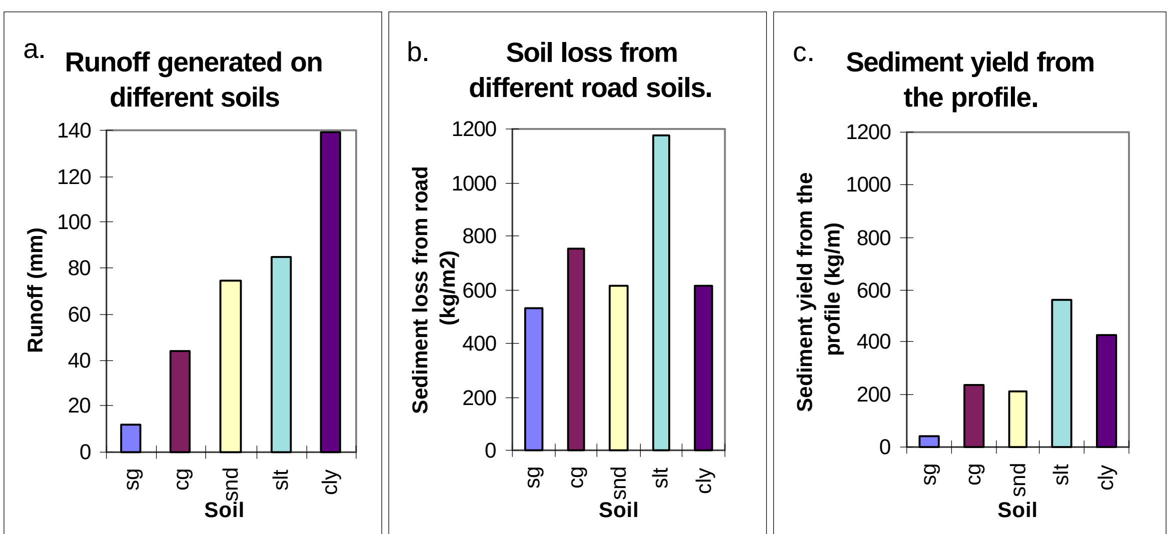
It appeared that 10 m roads had no noticeable sediment yield at any slope as long as a 10 m buffer was in place. Calculations indicated that 80-100% of the sediment was trapped on a buffer strip 40 m wide for any road length or slope in the Idaho climate. According to the WEPP model, general recommendations for maximum road lengths and minimum buffer lengths are presented in Table 3 for the silt in the Idaho mountains. Similar tables can be developed for other soils, climates, and buffer slopes.

Table 3. *Maximum road lengths for the given road slopes and buffer lengths for a silt soil type, and a 25% buffer slope in the Idaho climate.*

Appropriate road lengths (m) for given buffer lengths				
Buffer slope 25%	Road slope %			
Buffer lengths (m)	2	4	8	16
10	20	20	20	20
40	60	40	40	40
80	100	60	60	40
200	100	60	60	40

Soil effects

The soil files for three ungraveled roads and two roads with added gravel were evaluated so that the effects of surface graveling could be analyzed (Table 2). The WEPP values agree with Burroughs and King's (1989) field data that stated that adding gravel decreased runoff (Figure 5a). However, sediment yield was not always reduced by reducing runoff. In Figure 5b, the sandy gravel road had a lower sediment yield than the sand, but the clay graveled road had a greater sediment yield than the clay road.



sg-Sandy Gravel, cg-Clayey Gravel, snd-Sand, slt-Silt, cly-Clay.

Figure 5. *a. The amount of runoff from each different soil type.*
b. The amount of soil loss from each different road surface.
c. The amount of sediment yield from the profile with the buffer.

Figure 5c shows the sediment yield decreased by about 50 percent when a 10 m 25% buffer slope was added. The buffer was most effective for the sandy gravel road and least effective for the clay road. The most sediment was deposited on the silt slope buffer, and the least on the clay slope.

Table 4 presents the results from our WEPP analysis compared to Copstead's draft publication (1996) on cross drain spacing. These spacings are based on road grade and soil types. WEPP recommend slightly shorter spacing between cross drains than did Copstead for most soil types. This difference may be from different climates or soil properties, however, we are very encouraged by these results. Work is being done to narrow the margin of difference.

Table 4. Recommended lengths between culverts as recommended by the WEPP model and Copstead's paper.

Lengths between cross drains (m) as recommended By WEPP and Copstead (1996)						
WEPP	Road grade	Sandy gravel	Clayey gravel	Clay	Silt	Sand
	2	100	60	40	40	40
	4	60	40	30	30	40
	8	60	40	20	20	30
	16	50	30	20	20	20
Copstead						
(1996)	2	120	100	80	50	30
	4	100	80	70	50	30
	8	70	60	50	30	20
	16	40	30	30	20	10

Climate effects

Climate variations make statewide and nationwide recommendations inappropriate, especially in mountainous terrain, where climate may vary with a road's aspect, relative location, and elevation. Rainfall duration, rainfall intensity, rainfall amount, snow fall, snowmelt, and antecedent moisture conditions all affect the amount of runoff and sediment yield from a road profile. Accurate climate information for a site is essential to the design of road sediment control systems.

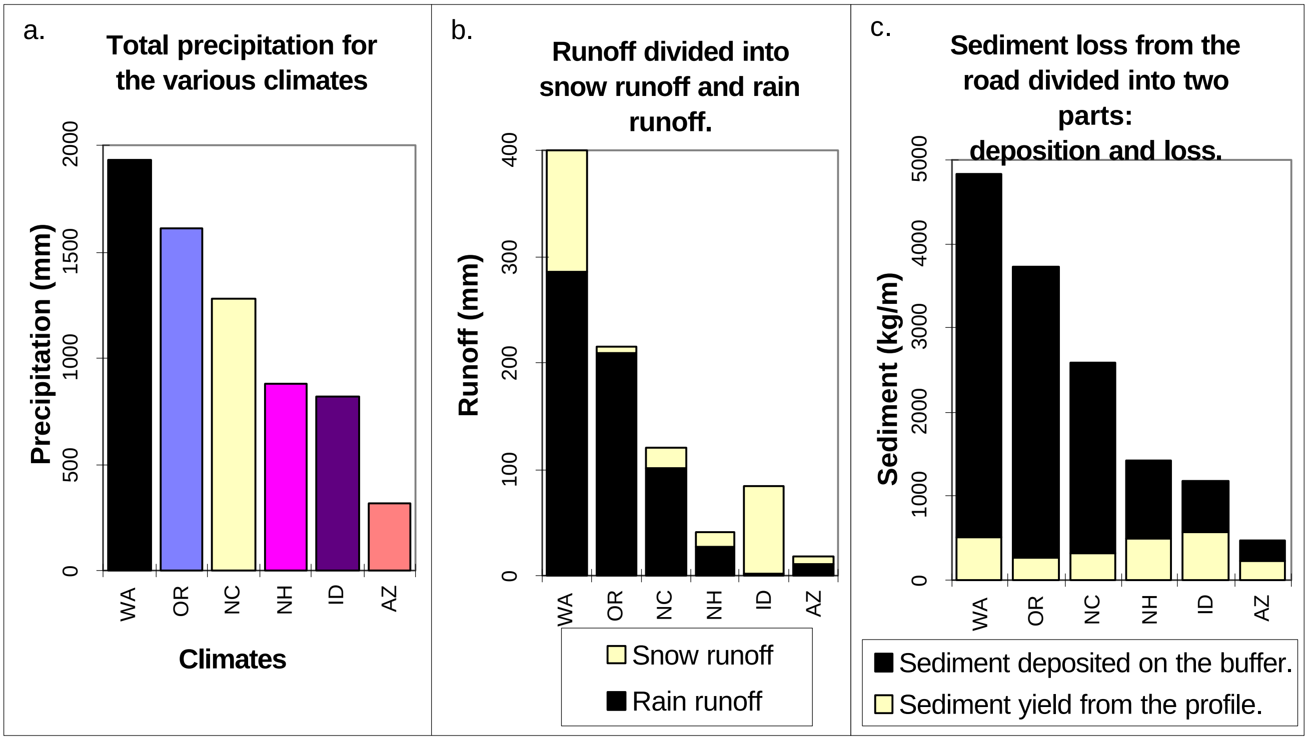


Figure 6: *a. Precipitation varies for different climates.*
b. Runoff is not always directly related to precipitation possibly because of the different sources of the runoff: snow and rain.
c. Sediment loss from the road surfaces for different climates increased with precipitation. Sediment deposition also increased with the increase of precipitation, but sediment yield tended to be less predictable.

Figure 6 illustrates that the annual precipitation does not necessarily determine the amount of runoff, road erosion, or the sediment yield. For example we see that although Idaho has less precipitation than New Hampshire, it has more runoff. It is likely that the runoff in Idaho climate, Deadwood Dam, is larger than expected, because the runoff was a result of snowmelt. In snow driven climates, most precipitation falls as snow in the winter. With the arrival of spring rains and warmer weather, the snow melts quickly and saturates the ground, resulting in large amounts of runoff as saturation overland flow (Elliot et al., 1996).

Runoff from snowmelt tends to have less sediment in suspension, because snowmelt rates are slow and steady with a lower, but more constant intensity than rainfall climates (Elliot et al., 1996). In rain driven climates where rainfall intensity is higher and rain drop splash assists flow shear in picking up sediment, more sediment can be detached and transported (Foster, 1982). Figure 6c shows that the second driest climate, Idaho, generates the greatest amount of sediment for the standard topographic scenarios.

The results in Figure 6 are reinforced in Figure 7. This figure illustrates that sediment loss from roads is related to the amounts of precipitation and runoff, but that sediment loss from the entire profile with the buffer zone does not appear to be related. Although sediment yield does not appear to have any correlation with precipitation and runoff, the relationships with the buffer are complicated by antecedent moisture conditions, infiltration rates, vegetation cover, runoff velocities, and sediment transport capacity.

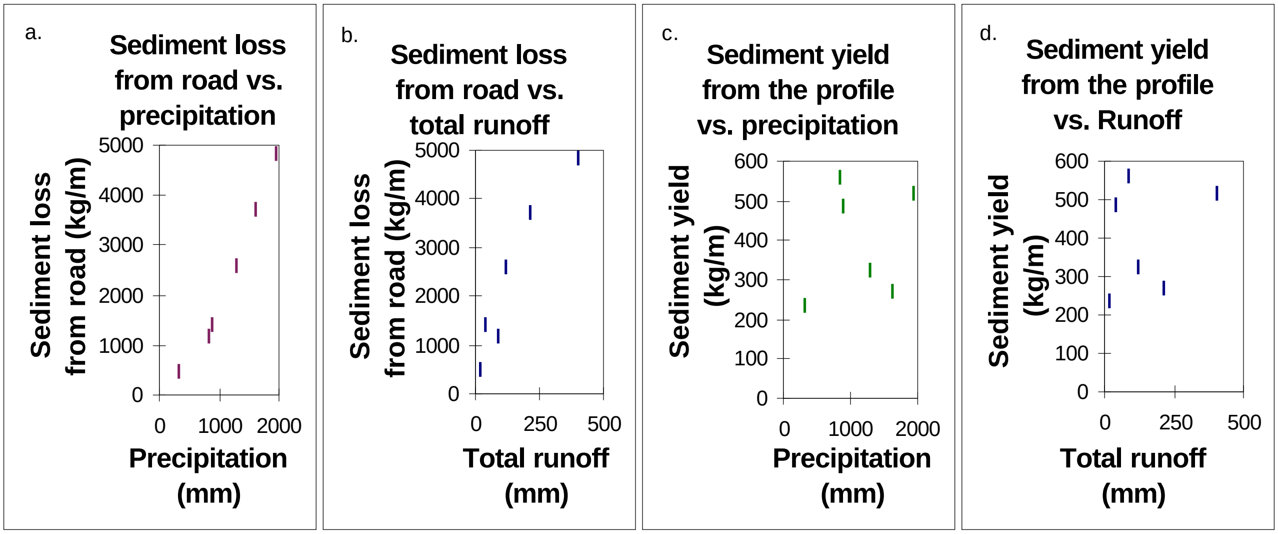


Figure 7. *a. Sediment loss from the road appears to increase with the increase of precipitation.*
b. Sediment loss from the road also appears to be related to the amount of runoff.
c. Sediment yield from the profile does not appear to be related to the amount of precipitation.
d. Sediment yield from the profile also does not appear to be related to the amount of runoff.

Summary and Conclusions

Excess sediment from roads is becoming a larger problem as more roads are being built to develop and manage the forests. Erosion and sedimentation controls are only effective if properly spaced and applied. The WEPP model is a physically based modeling program that may help in road and erosion control design.

We have completed 9600 computer runs with WEPP to study the sensitivity of WEPP to various parameters. The topographic effects on the road were as might be suspected, with the buffer zone being less sensitive to length and steepness. The soils responded as expected, with only one exception--less benefit came from graveling a clay road than anticipated. Optimal cross drain spacings determined from our WEPP runs were only marginally smaller than those in common use in some Northwestern forests. The differences may have been because the WEPP climate used for the comparison may have been more erosive than the climate where the recommendations were developed. This reinforces the need for site specific road studies. Climate effects on road travelways were predictable. However, no easily developed relationship between climate and sediment yield for the entire road prism could be established.

It appears that WEPP is capable of considering differences due to soil, topography, and climate to provide site-specific recommendation for combinations of cross-drain spacing and buffer zone width.