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GPS-ASSISTED ROAD SURVEYS AND GIS-BASED ROAD EROSION MODELING USING THE WEPP MODEL

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Summary:
Roads have been identified as a major source of sediment loading to streams in most forested watersheds. The Watershed Erosion Prediction Project (WEPP) model, as developed by the USDA-Forest Service, simulates the detachment and delivery of sediment through a road, fill, and buffer system. Time and budget constraints typically prevent a comprehensive sediment loading analysis using the WEPP model throughout a large watershed. We describe a step-by-step approach to allow use of the WEPP model to simulate erosion throughout a large road network. Road attributes are acquired from detailed global positioning system-assisted road surveys and mapped in a geographic information system (GIS). After data manipulation in GIS and Excel, the required input files for the WEPP model are developed. The approach was applied to 1017 km of road, divided into 6955 road segments, throughout a 3040 km^2 watershed, ranging in elevation from 377 m to 2706 m. The approach can be applied to insloped, outsloped, and crowned road designs, multiple climate regimes, and unique physical attributes for each road segment. Analysis of the WEPP results within a GIS provides a spatially explicit tool for the management and evaluation of sediment production throughout large road networks.

Keywords: sediment yield, runoff, low-volume roads, watershed modeling, TMDL

INTRODUCTION

In forested watersheds, road erosion can provide a large portion of the total sediment load to streams. Research on the sediment production and delivery from unpaved roads has lead to the development and application of the Water Erosion Prediction Project (WEPP; Flanagan and Livingston, 1995) model to forest roads (Elliot and Hall, 1997). The WEPP model is a physically based computer program that simulates the detachment, transport, and deposition of sediment by surface runoff. It can be applied to single hillslopes or to small watersheds (i.e., less than 2.6 km^2 or 1 mi^2). The model includes over 400 input parameters which tend to overwhelm and discourage use of the model in road and watershed management applications (Elliot et al., 1999b; Hall and Elliot, 2001). To address this problem, the U.S. Forest Service has adapted the hillslope version of the WEPP model into a suite of user-friendly internet-based models called FSWEPP (Elliot et al., 2000). Included in FSWEPP are the Rock:Clime and WEPP:Road models which allow for the simulation of road erosion using pre-defined forest templates to fix input parameters with long term, site-specific climate data. This has lead to more wide-spread use of the model (Hall and Elliot, 2001) for evaluating road erosion and sediment delivery from single road segments.

Although FSWEPP is proving to be a valuable tool for evaluating site specific impacts of a single road, fill, and buffer system, evaluation of sediment production from road networks in large watersheds can be daunting. The WEPP model simulates the runoff generation and sediment production from single road segments. A road segment is bound on the upper end by a high point in the road and on the lower end by the point where water leaves the road and enters the fillslope and buffer. Depending upon the topography of the watershed and the design of the road there can be thousands of road segments within a large watershed. The challenge for a watershed manager is acquiring the physical road characteristics of each road segment and simulating road erosion using the WEPP or FSWEPP models within time and budget constraints.

In this paper we incorporate information from global positioning system (GPS) assisted road surveys into a geographic information system (GIS). Feature attribute tables are used to develop the input files necessary to run and record the output from the WEPP hillslope model. Simple batch programming is used to automate repeated simulation of many road segments using the WEPP model. As with the WEPP:Road interface, input parameters are defined by easily measured road attributes using pre-defined forest template files based on key characteristics of each road segment.

We apply and evaluate the performance of this technique on 1017 km of road, throughout the South Fork Clearwater basin (3040 km^2), ranging in elevation from 377 m to 2706 m. Overall, 6955 road segments were modeled. The results of this study were included in the development of the total maximum daily load for sediment for the basin by the Idaho Department of Environmental Quality (IDEQ et al., 2003).

OBJECTIVES

The main objectives of this paper are to:

1) Develop an efficient approach for collecting WEPP input parameters for each road segment in a large road network;
2) Develop an automated procedure for applying and managing the WEPP model to large, complex road networks within a GIS;
3) Evaluate the production and delivery of sediment from a large forested road network using the developed approach.

We first describe the WEPP model and how it has been adapted to road erosion modeling through the WEPP:Road approach. Then we outline the methodology for data collection using a GPS unit and for processing the data in a GIS. Finally, the approach is applied and evaluated in the South Fork Clearwater River Basin in north-central Idaho.

THE WEPP MODEL

The WEPP model (Flanagan and Livingston, 1995; Flanagan and Nearing, 1995) is a physically-based computer program which simulates the detachment, transport, and deposition of sediment by surface runoff. WEPP uses daily weather data to simulate plant growth, residue decomposition, soil consolidation, infiltration, and track soil water content. Land management practices can also be incorporated into the model. It can be applied to single hillslopes or to small watersheds (i.e. less than 2.6 km^2 or 1 mi^2). In the watershed version, single hillslopes are topologically linked using channel networks. Here, we describe the hillslope version only.

Hillslope Version of WEPP

The hillslope version of the WEPP simulates the flow of water through a series of overland flow elements (OFEs). It is assumed in the hillslope version that all water and eroded material leaving a given OFE will be routed to the next downhill OFE. The hillslope version is limited to rill and interrill erosion and was not developed to simulate erosion from ephemeral gullies or channels.

The hillslope component of the model requires four input data files to run under the DOS operating system: 1) a climate file, 2) a slope file, 3) a soil file and 4) a plant/management file. The climate file includes daily weather data for the identified period of record. The slope file describes the topography of each OFE in the hillslope. The soil file identifies the textural and hydrologic properties of the soils in each OFE. The plant/management file lists the specific management scenarios and plant growth properties for each OFE. The model can be initiated manually through a user interface or a run file can be used. More specific information on each of these files can be found in Flanagan and Livingston (1995) and Flanagan and Nearing (1995).

- *WEPP:Road*

The WEPP:Road interface (Elliot et al., 2000) runs the hillslope version of the WEPP model using forest template files (Elliot and Hall, 1997) to fix input parameters based on soil type, road design, and road maintenance. The “hillslope” in WEPP:Road consists of three OFEs: the road surface, the fillslope, and the forested buffer. Users are required to enter in a road length, road width, road gradient, fillslope length, fillslope gradient, buffer length, and buffer gradient. Soil properties are dependent on soil type and whether the road is graveled or bare. Available road designs include insloped roads with either vegetated/rocked or bare ditches, or outsloped rutted or unrutted roads. Crowned roads are handled by a simulating each half of the road separately (Elliot et al. 1999a).

APPROACH

In this study we used the hillslope version of the WEPP model, following the strategy of the WEPP:Road model, to simulate the detachment, transport, and delivery of sediment from each road segment to a concentrated flow channel. As in the WEPP:Road approach surface runoff generated from a road surface can be routed to a ditch, over a fillslope, and through a forested buffer. Physical characteristics of each road were assigned using detailed GPS-assisted road surveys.

Data Collection: GPS-Assisted Road Surveys

A hand-held Trimble GEO3 Explorer GPS unit was used to collect road attribute data. The road network was broken down into "break points" and "road characteristic points". Physical features of the road, fill, and buffer were linked to each point through a data dictionary file in the GPS unit.

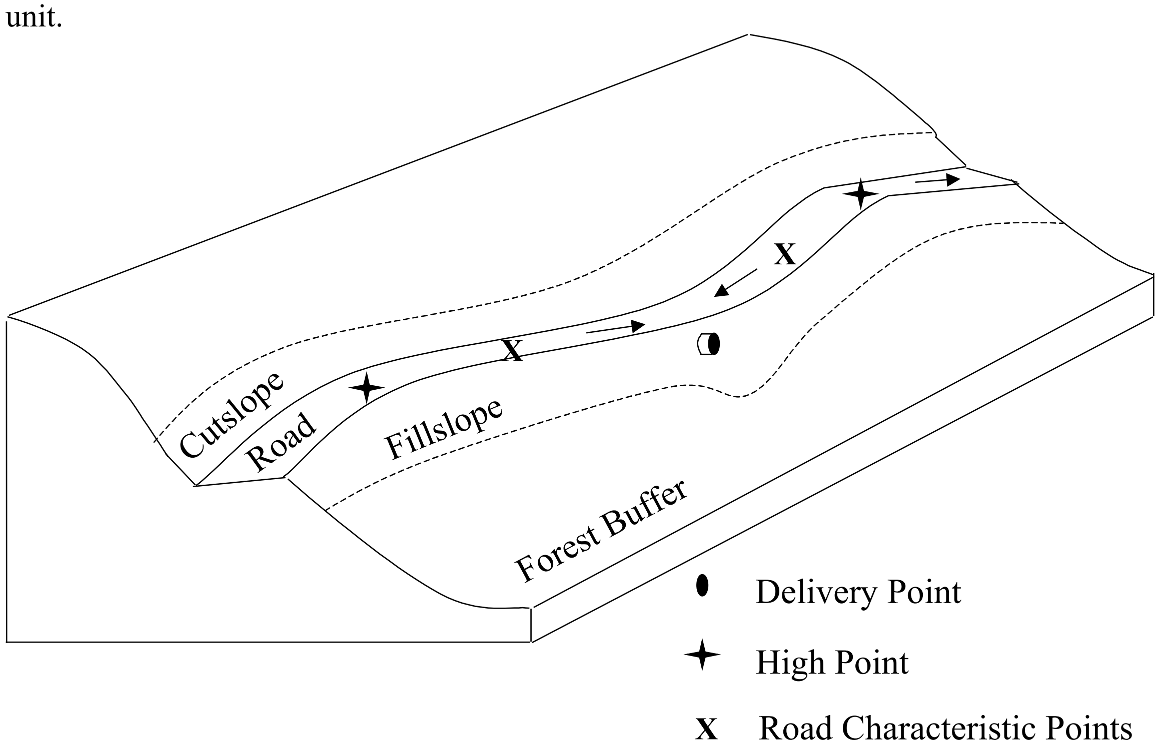

Figure 1. Conceptual model of a road network.

Break points consisted of "high points" and "delivery points" (Figure 1). High points are locations on the road where water diverges into two distinct directions. Delivery points are locations on the road network where water leaves the road prism (i.e. culverts, cross-drains, Kelly humps, water bars, or low points in the road). As described in the following section, these break points were used in the GIS to break up existing road coverages into road segments. Each delivery point also served to record physical features required in the WEPP model. These features include the fillslope gradient, length, and percent cover, as well as the forest buffer gradient and length (Table 1).

Road characteristic points were used to identify the physical road features required to run the WEPP hillslope version for each road segment. The physical features required at each road characteristic point depend on the road design. Four unique road designs were considered: insloped, outsloped, crowned with 1 ditch, and crowned with 2 ditches. All four road designs required the following road surface parameters: road width, road gradient, road cover type (i.e. bare, graveled, bare/gravel mix), and the presence of ruts, (see Table 1). Additional attributes depended on the overland flow path the water follows before reaching or passing through the forested buffer.

Insloped Roads

Surface runoff from an insloped road drains to a ditch and leaves the road at a fixed delivery point. In addition to the road surface parameters, therefore, the ditch width and the percent of the ditch covered by rock or vegetation were required by the model. The fillslope and buffer attributes were assigned at each delivery point.

Table 1. Physical attributes required for each road type and break point.

	Road Characteristic Points				**Break Points**	
Attribute	**Insloped**	**Crowned 2 Ditches**	**Outsloped**	**Crowned 1 Ditch**	**Delivery Point**	**High Point**
Road Width	X	X	X	X		
Road Gradient	X	X	X	X		
Road Cover	X	X	X	X		
Presence of Ruts	X	X	X	X		
Ditch Cover	X	X		X		
Ditch Width	X	X		X		
Fillslope Length			X	X	X	
Fillslope Gradient			X	X	X	
Fillslope Cover			X	X	X	
Buffer Length			X	X	X	
Buffer Gradient			X	X	X	

Outsloped Roads

Surface runoff from an outsloped road drains across the entire width of the road, through a fillslope, and into a forest buffer. In addition to previous road surface parameters, outsloped roads required fillslope length, gradient, and percent cover, and buffer length and gradient. The fillslope and buffer attributes were averaged along the entire road segment.

Crowned road with 1 Ditch

Surface runoff from crowned roads was assumed to be equally split between each side of the road. A crowned road with 1 ditch implies that half the road acts as an insloped road and half the road acts as an outsloped road. In this case all road, ditch, fillslope, and buffer attributes were required.

Crowned road with 2 Ditches

Crowned roads having two ditches implies that the road is effectively composed of two insloped roads each draining half the road width. Therefore, the physical attributes required by the model were identical to those required for insloped roads. To simplify data collection, a single average value was recorded for both the ditch width and the ditch cover.

Primary and Secondary Physical Attributes

As in the WEPP:Road model certain road attributes were used directly by the WEPP model and other attributes were used indirectly to assign secondary input parameters. Road length, road width, road gradient, fillslope length, fillslope gradient, buffer length and buffer gradient all were used directly in the model to define the topography and physical dimensions of the simulation. Road cover type (i.e. bare, gravel, gravel/bare) was used to fix the hydraulic conductivity and rock content of the road surface. This is important since it has been determined that graveled roads tend to increase infiltration and water storage and therefore reduce runoff and erosion (Foltz and Elliot 1998). The percent cover in the ditch and fillslope was used to set the critical shear stress of the model. As the percent cover increases the critical shear stress increases resulting in decreased erosion. The presence of ruts was used define the "rill" spacing in the model. As the number of rills increase, generally the erosion rate increases.

GIS Analysis

Both the road characteristic and break point maps, created by the road survey, were imported into a GIS to break out individual road segments and assign physical road features to each segment. Both Arc View 3.2 and Arc/Info 8.3 were used to process the data. The specific steps for breaking out road segments and assigning feature data to each segment are described below. A flow chart for each of these steps is given in Figure 2.

Breaking out road segments

To understand the GIS methodology used in the analysis we provide the following review of line coverage topology. In Arc/Info, a road coverage consists of arcs, nodes, and vertices. Arcs are line features which are defined by two node points: a "from" node point and a "to" node point. Each arc is also composed of vertices that define where each arc breaks and turns.

The first step to breaking up a road coverage into road segments was to dissolve any existing node points so that the only node points that existed in the coverage were at endpoints or intersection points of each line or arc. Vertices were added to each road segment every 10 m. The GIS software was then used to break arcs and add nodes at the closest vertex point to a point in the break point coverage. Each node was assigned the physical break point attributes recorded in the GPS survey. The 10 m resolution ensured that the road coverage was broken at a maximum distance of 5 m away from the nearest break point. By breaking up an existing road coverage, the horizontal error in the imported GPS coverage did not change the accuracy of the road coverage. Once the road segments were broken, the GIS software provided the road length for each road segment.

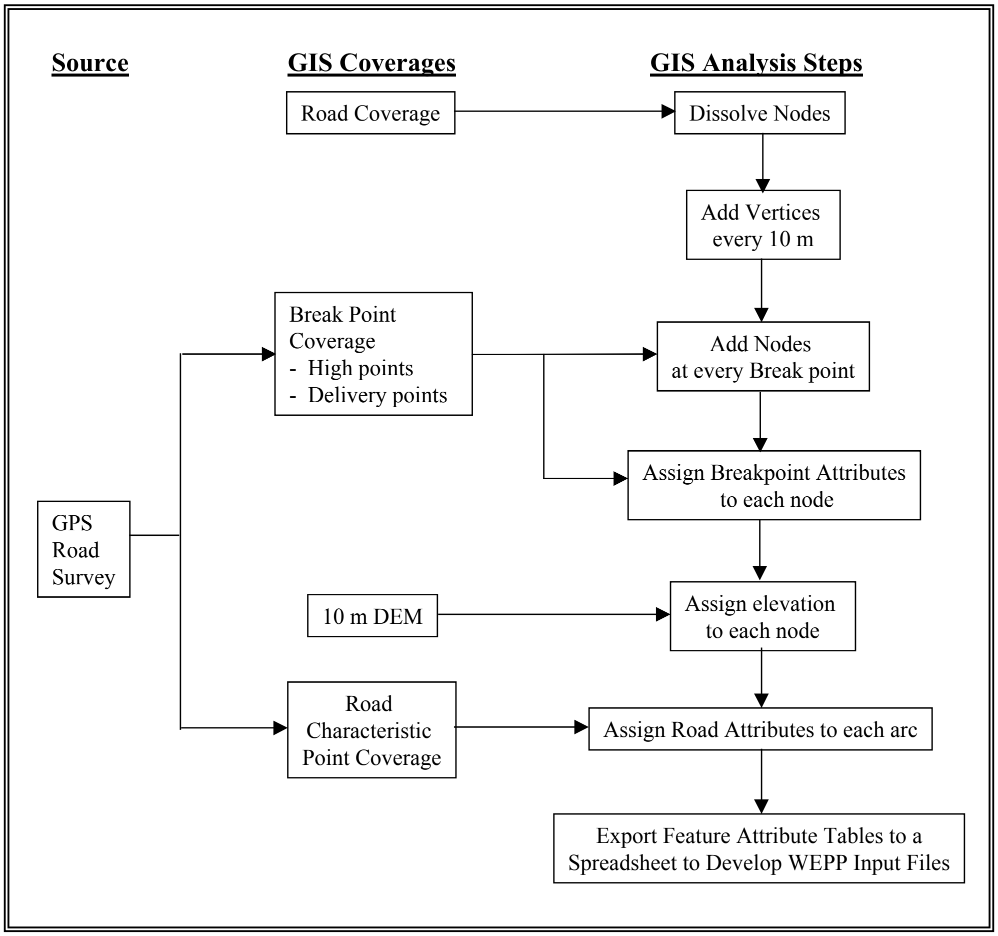

Figure 2. A flow chart describing the GIS analysis steps.

Determination of Drainage Direction

The elevation of each node point was used to determine the direction of water flow. Using the digital elevation model (DEM), the GIS software assigned elevation values to each node point. Since water should flow from a high point to a delivery point, the drainage direction was used as a check to see if break point attributes were properly assigned to each node point. On a constant downhill road segment with cross drains, a node point on the road coverage can represent both a delivery point for one segment and a high point for the next segment. In a case like this, the direction of flow would correctly indicate that the water was flowing from one delivery point to another delivery point.

Calculation of Road Slope

If the road slope was not directly measured in the road survey, the elevation of each node point and the road segment length was used to calculate the slope of each road segment. The accuracy of this approach depends on the accuracy and precision of the DEM. We recommend using a 10 m DEM (or higher resolution), which usually matched closely with direct clinometer measurements. We found that a 30 m DEM does not predict road slope accurately.

Passing Road Attributes to Road Segments

The physical road attributes of each road segment were assigned to the existing road coverage based on the nearest distance from a road characteristic point. In Arc/Info the distance from the road segment to the road characteristic point was provided in the feature attribute table. This distance was used as a quality control check to determine whether the road segment was close to a road characteristic point. Large distances indicated the road survey crew may have missed the road characteristic point.

The final product of the GIS analysis was a table of road segments each having a unique set of physical road characteristics and a table of node points which identify specific delivery point characteristics. These tables were imported in Excel for further processing.

Delivery Points with Multiple Contributing Road Segments

It is common in complex road networks for two road segments to drain and provide runoff and erosion to one delivery point. Since the delivery of sediment through a buffer is dependant upon the amount of runoff, simulating the erosion from each segment separately results in an under-prediction in amount of sediment delivered. Each segment, therefore, was simulated simultaneously. In this case, an effective road length and width were calculated and used in the WEPP hillslope model. The effective road length was set to the average distance of all road segments draining to the delivery point and the effective road width was determined by dividing the total area of all contributing roads by the effective road length (see Figure 3). The average road gradient used in the model was weighted by the contributing road length of each segment.

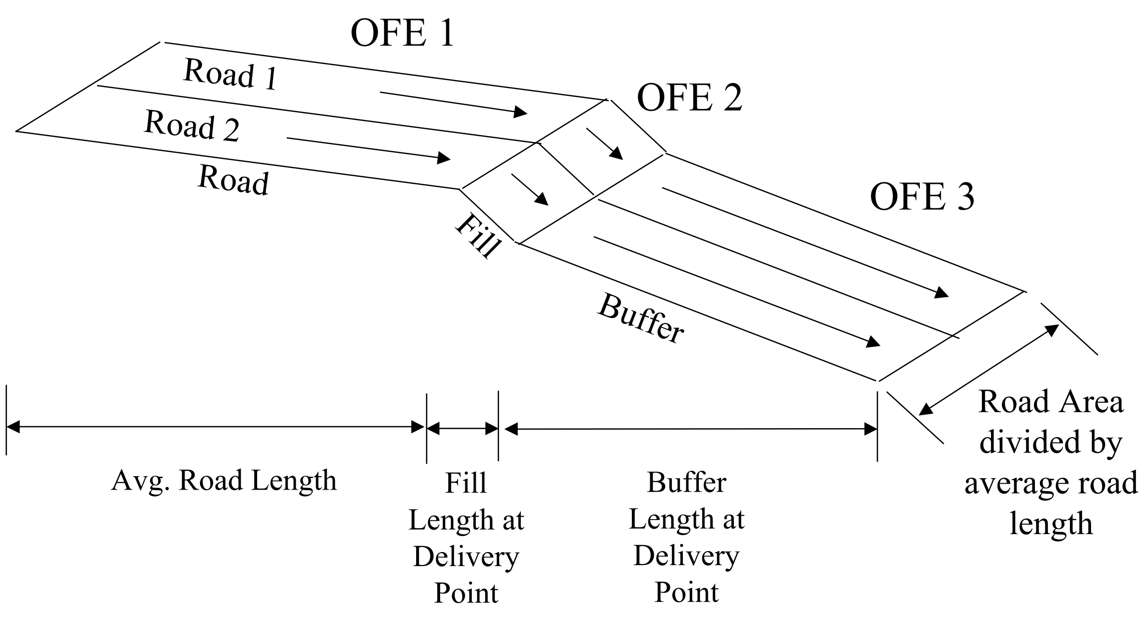

Figure 3. A conceptual model of multiple road segments draining to a single delivery point.

Creating Batch Files

To run the WEPP model repeatedly for each delivery point, batch files were created to pass variables and update the four input files used in the hillslope version of the model. Lookup tables were used to assign input parameters according to the secondary road attributes at each delivery point. Delivery points were sorted and grouped by elevation to represent multiple climate regimes through climate files generated using the Rock:Clim interface.

Output Files and Maps

Perl script files were used to extract specific values from WEPP output files which were then sorted and joined to feature attribute tables for each delivery point. Sediment detachment and delivery rates for each road segment were calculated in proportion to their effective length and contributing area. The final product of the analysis was soil detachment and delivery predictions by delivery point and road segment. These maps can be used to accumulate the total contribution of sediment by road erosion by basin or sub-watershed.

APPLICATION TO THE SOUTH FORK CLEARWATER RIVER WATERSHED

In 1998 the South Fork Clearwater River in north-central Idaho was placed on the 303(d) list for excessive sediment loading. The Idaho Department of Environmental Quality (IDEQ), the Nez Perce Tribe, and the U.S. Environmental Protection Agency under a Memorandum of Agreement (MOA) were involved with developing a subbasin assessment of sediment production. Sediment production from 4465 km of forested and county roads were considered to be a major source of sediment in the watershed. For this study 23% of the total road length, 1017 km, were surveyed and simulated using the WEPP model.

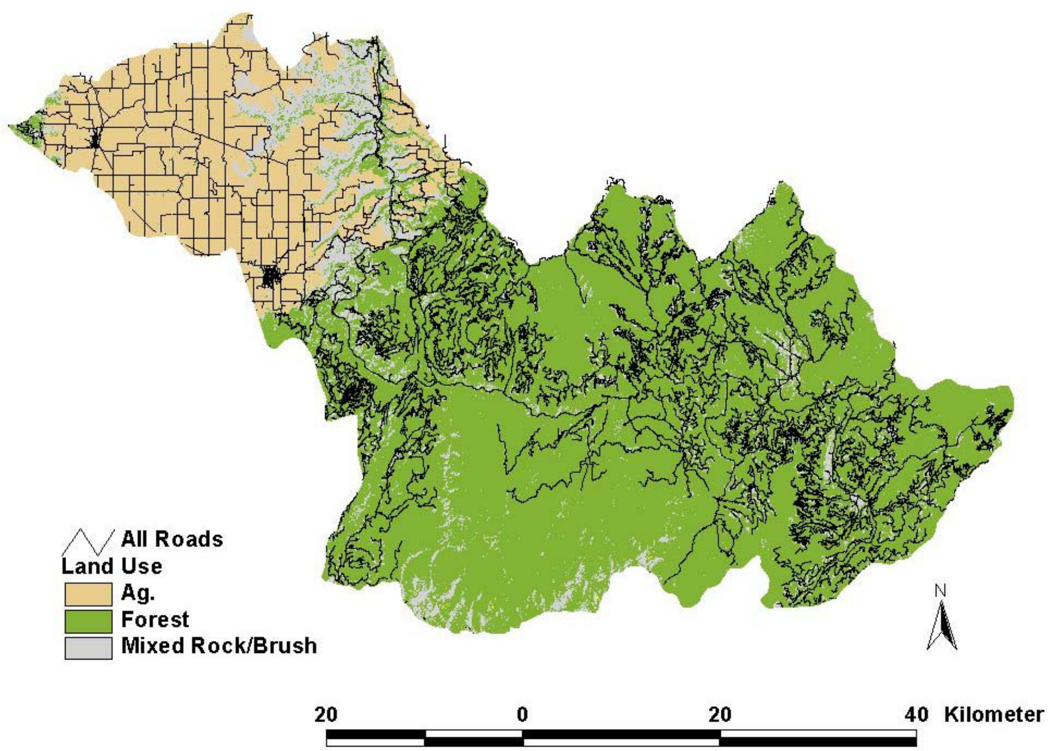

Figure 4. Landuse and roads map for the South Fork Clearwater Watershed.

The South Fork Clearwater watershed covers an area of 3043 km^2 (1175 mi^2) with elevations ranging from 377 m to 2706 m. The watershed is mostly forested with 79% of the total road length residing within the forested portion of the landscape (Figure 4). Three different climate files were used to represent regions of different climate as a function elevation within the watershed. The locations representing these regions are described in Table 2. The climate files were generated by modifying the Fenn Ranger Station climate file by elevation and position to account for regional differences in temperature and precipitation. The climate for roads having an elevation less than 1250 m were assumed to be described by the Grangeville climate file, the climate for roads having an elevation greater than 1250 m and less than 1750 m were assigned the Mid SF climate file, and the climate for roads having an elevation greater than 1750 m were assigned the Mtn. Meadows climate file. The DEM for the watershed is shown in Figure 5. All areas having shades of red, blue, and green were assigned the Grangeville, Mid. SF, and Mtn. Meadows climate files, respectively.

Table 2. Description of the three generated climate files used in the simulations.

Location	Elev. (m)	Avg. Yearly Precip (mm)	Avg. Max. March Temp. (C)	Avg. Min.. March Temp. (C)	Effective Elev. Range (m)
Grangeville	989	571	7.4	-3.5	< 1250
Mid. SF	1496	874	4.3	-6.1	1250 - 1750
Mtn. Meadows	1942	1202	1.7	-8.3	> 1750

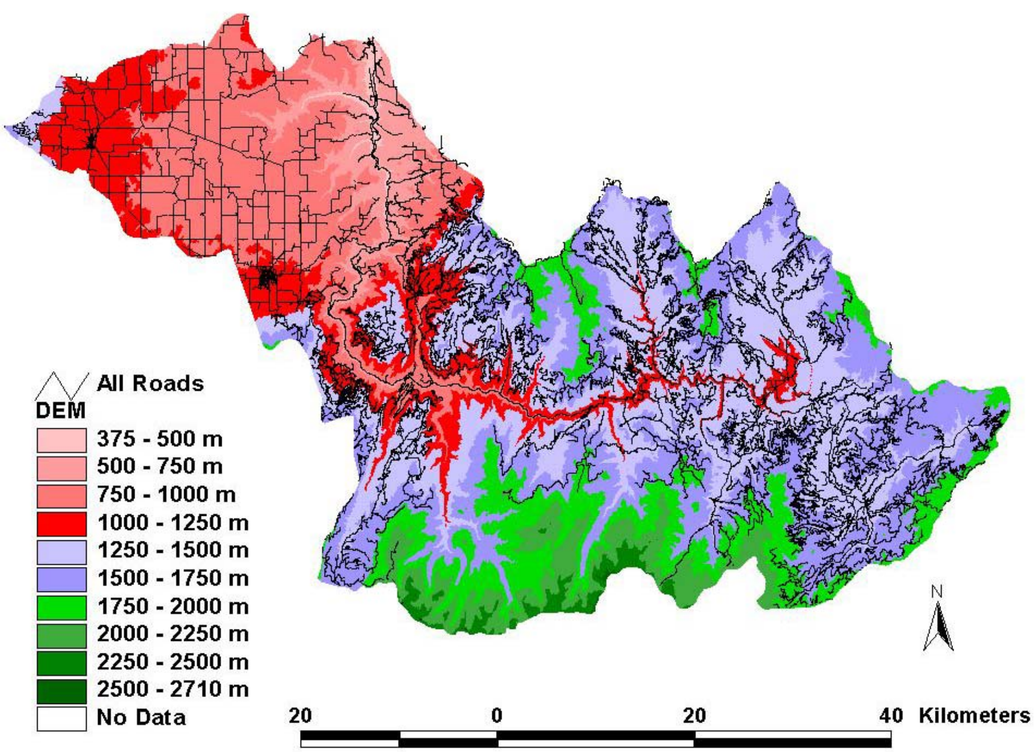

Figure 5. Digital elevation model for the South Fork Clearwater Watershed.

Table 3 summarizes the simulation results from the WEPP model. The road survey included roughly an equal proportion of forested and non-forest roads. Non-forested roads tended to be wider and flatter with shorter buffer lengths. As a result sediment detachment from non-forested roads was lower than from forested roads but the delivery percentage was larger. The average predicted sediment detachment rate for all roads was 5.75 tonnes/km (10.20 tons/mi).

Table 3. Summary of the road attributes and the soil detachment and delivery.

Attribute	All Roads	Forest Roads	Non-Forest Roads
Total Road Length (km)	4465.9	3543.0	922.9
Total Surveyed Road Length (km)	1017.2	754.8	262.4
Percent Surveyed	23%	21%	28%
Total Number of Delivery Points	5384	4385	999
Total Number of Road Segments	6955	5661	1294
Avg. Road Length (m)	146	133	203
Avg. Road Slope (%)	7.7%	8.2%	5.5%
Avg. Road Width (m)	3.95	3.67	5.2
Avg. Buffer Length (m)	81.1	81.4	51.4
Avg. Buffer Slope (%)	14.0%	15.9%	5.6%
Avg. Detachment (tonnes/km)	5.75	6.37	2.93
Avg. Detachment (kg/m2)	1.38	1.58	0.5
Total Detachment (tonnes)	6351	5361	990
Avg. Delivery (tonnes/km)	1.61	1.64	1.42
Total Delivery (tonnes)	1816	1274	541
Avg. Percent Delivery **	36.1%	33.9%	45.7%
Avg. Percent Delivery for the watershed ***	28.6%	23.8%	54.7%

** This average percent delivery is the average percent delivery for all the delivery points.
*** This average percent delivery is the total detachment for the watershed divided by the total delivery for the watershed.

The results of the WEPP simulation are presented in Figures 6 - 10 as either delivery point maps or road segment maps. Figures 6 - 8 present total sediment detachment and delivery at each delivery point. Figures 6 shows sediment detachment from the road in units of tonnes per km. Figure 7 shows the sediment delivery to the nearest stream or concentrated flow path in tonnes per km. The percent of the detached soil delivered to a stream is shown in Figure 8. In some cases, the WEPP model predicted soil detachment in long, steep, forested buffers resulting in a soil delivery percentages greater than 100%. This occurred on 11 road segments. Figure 9 shows the soil detachment in units of tonnes per km for each road segment. The difference between soil detachment and delivery was visualized by overlaying soil detachment and soil delivery (Figure 10).

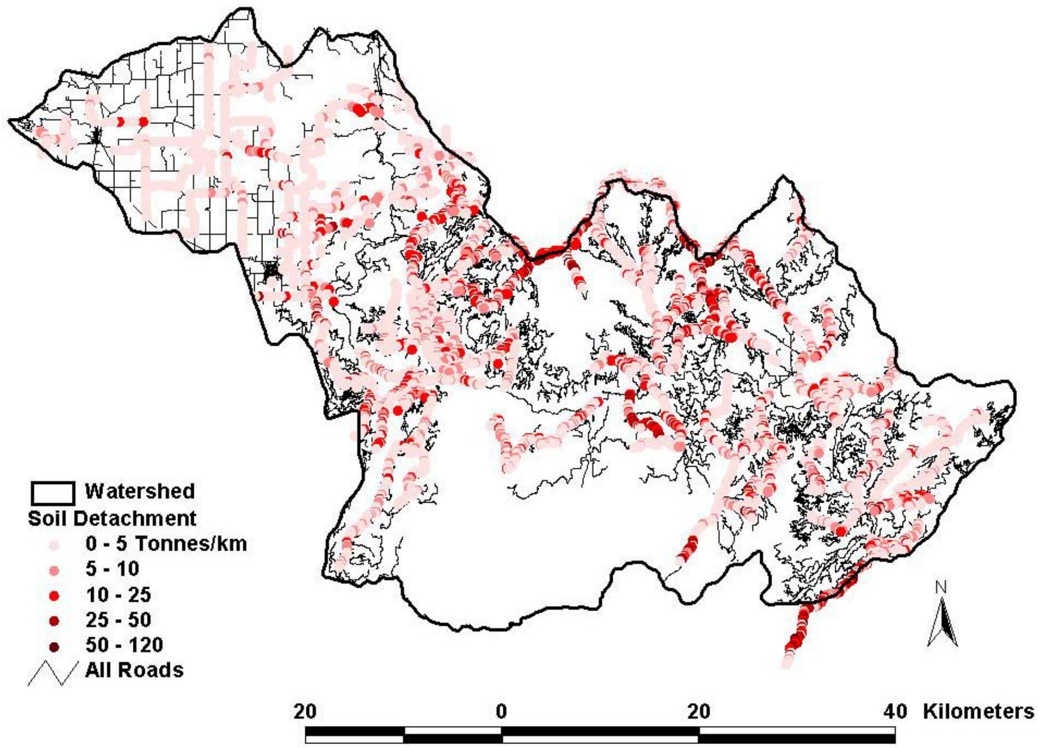

Figure 6. Average soil detachment at each delivery point in tonnes per km.

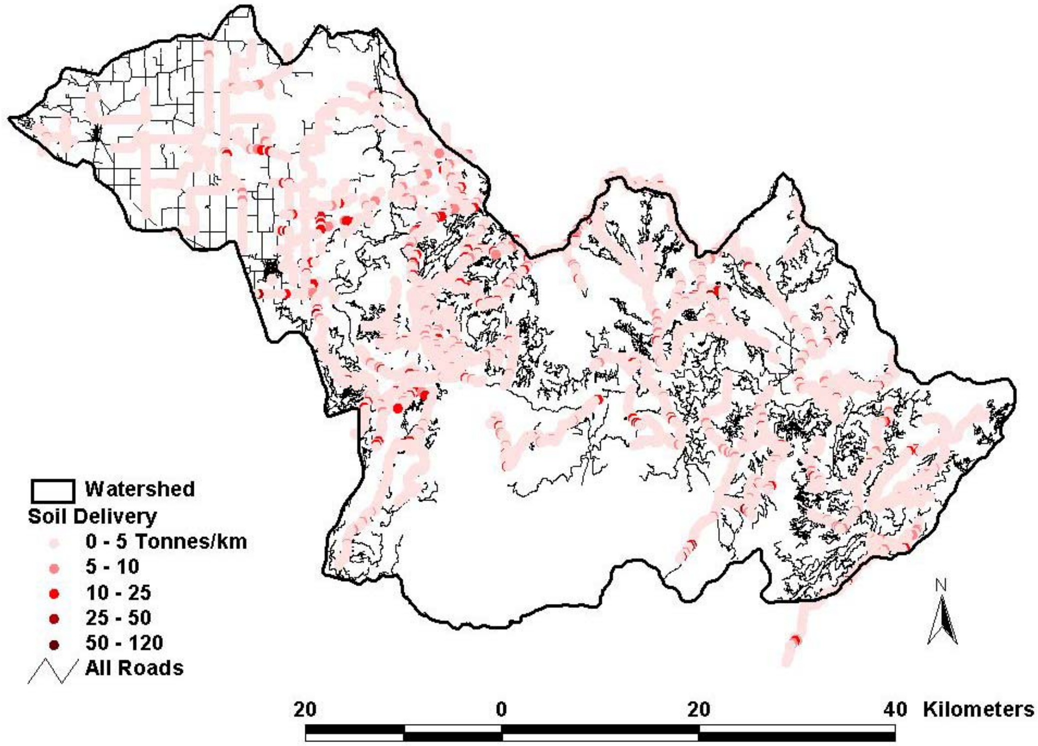

Figure 7. Average soil delivery at each delivery point in tonnes per km.

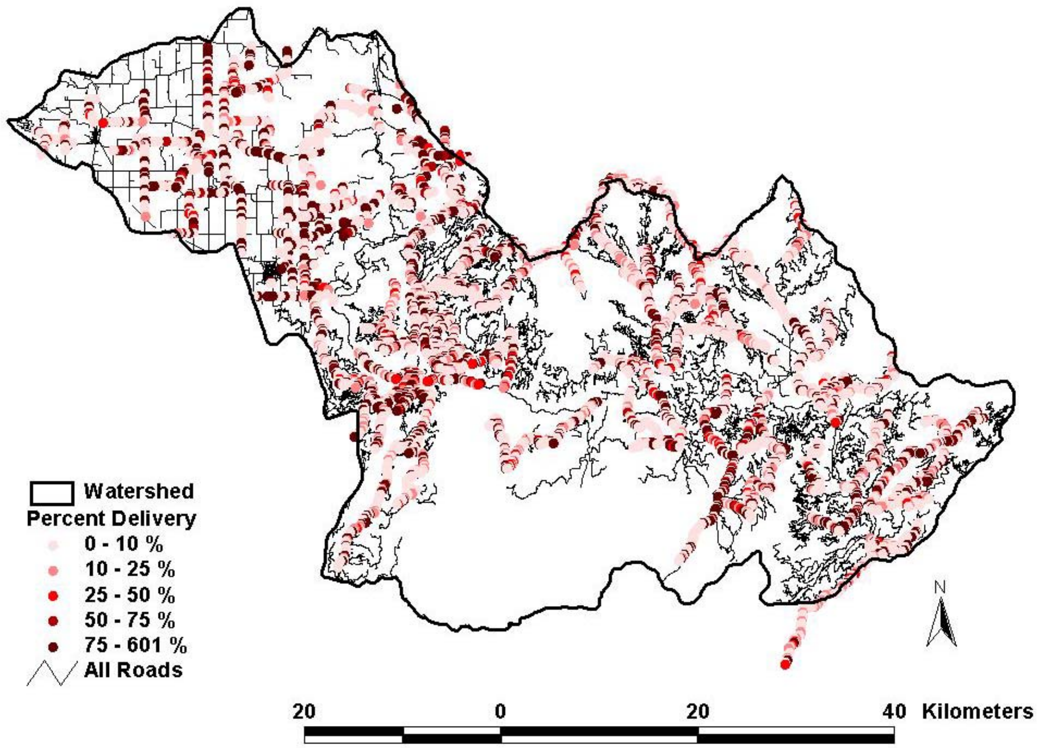

Figure 8. Average percent delivery to a stream at each delivery point.

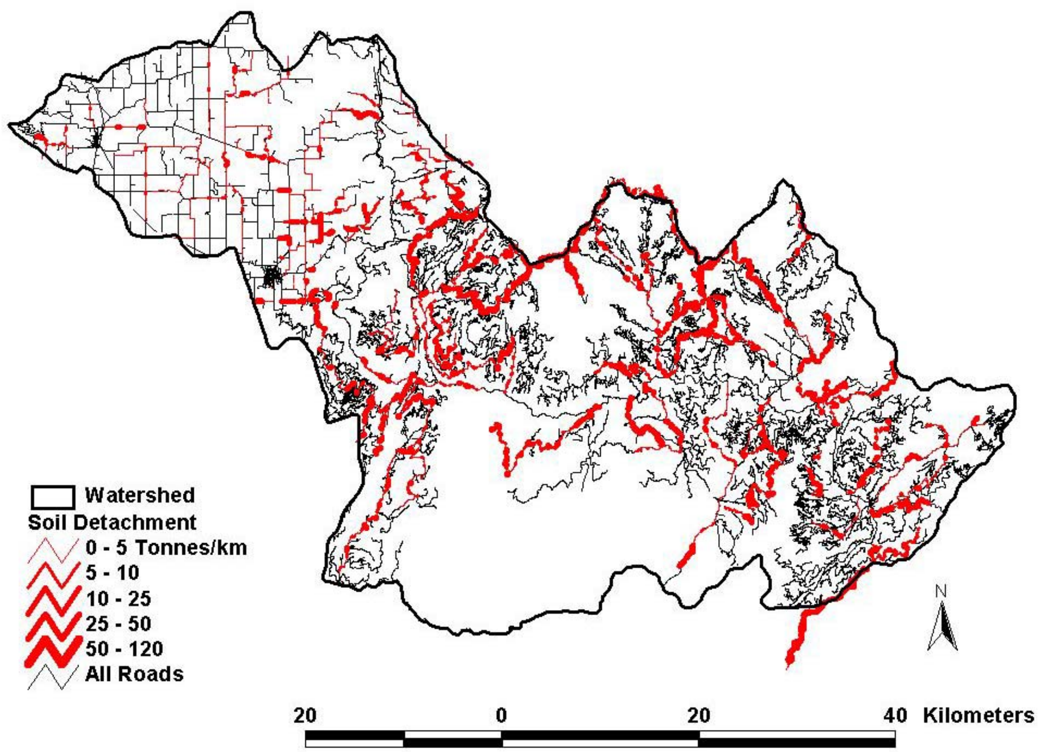

Figure 9. Average soil detachment for each road segment in tonnes per km.

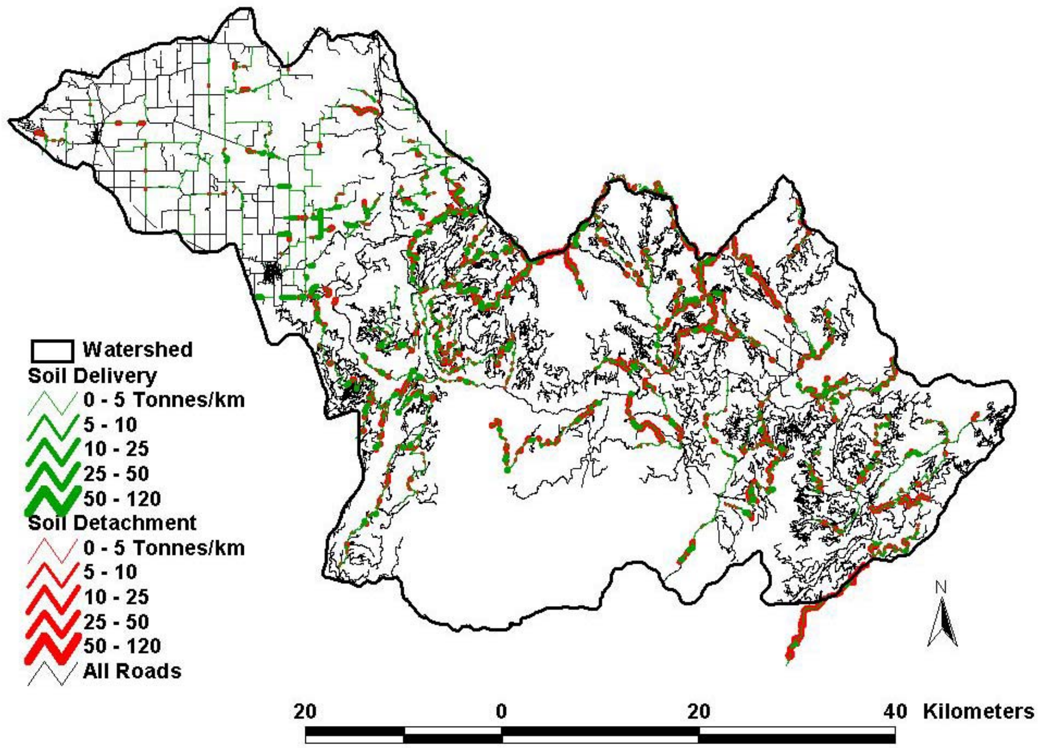

Figure 10. Difference between average soil detachment and delivery in tonnes per km for each road segment.

DISCUSSION

The assessment and evaluation of sediment production from large road networks using the WEPP model provided a physically-based technique for quantifying sediment erosion and delivery from specific road segments. By taking advantage of the tools available in GIS software, large batch files were created to simulate many road segments in a relatively short period of time. In batch mode, the WEPP model was able to simulate 30 years of weather data on 6955 road segments within a day. At this time, the pre- and post- processing steps in the GIS require an advanced user and have not been developed for wide-spread use. With training, however, it is possible, even with large data sets like the South Fork Clearwater basin, to import and develop the WEPP batch files within a day. The most time consuming step of the analysis was the field data collection of road attributes. After proper training and familiarity with the GPS unit a survey crew can cover up to 32 km (20 mi) of road per day on relatively flat county roads in rural regions of the watershed. Road segments in steep forested roads are typically broken by cross drains and can be considerably shorter and more fragmented than flat lowland roads, requiring a more detailed survey. Despite the time required for conducting road surveys this approach has been well received. It has been and is currently being applied in three watershed assessment projects throughout Idaho.

As with any model, the accuracy of the WEPP model is dependent upon how well the input parameters represent the true system. Several simplifications and assumptions may add error to model prediction. For example, in this approach it was assumed that the topography of each road segment can be represented by an average gradient and width. A single road segment can often have multiple gradients where a single slope does not truly reflect the actual topography of the road. The road width, fill length, and buffer slope can also vary greatly throughout a single road segment.

The WEPP model does not simulate mass wasting. In steep mountainous terrain the large majority of the sediment delivered can be due to land slides and bank failures from cutslopes (McClelland et al. 1999), which are not simulated in the WEPP model.

In addition the hillslope version of the model is not designed to simulate the detachment and transport of soil through established channels. As a rule of thumb while conducting road surveys, an established channel or concentrated flow path is defined by the presence of bed and banks. The delivery of sediment to a concentrated flow path is quite sensitive to the buffer slope and buffer length parameters. Figure 11 shows the variation in predicted percent delivery of sediment for various buffer slopes and buffer lengths.

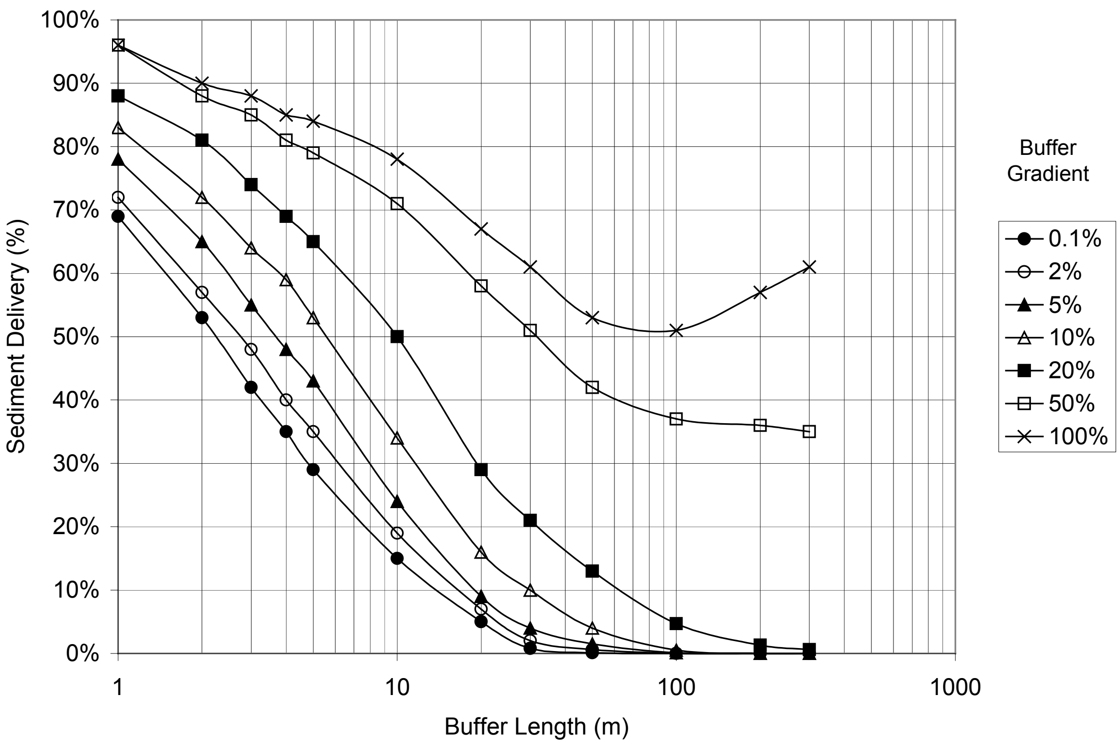

Figure 11. Percent of total detached sediment delivered through a forested buffer for an ungraveled, insloped road having a vegetated ditch with following dimensions: road length of 60 m, road width of 4 m, road gradient of 4%, a fillslope gradient of 50%, a fillslope length of 5 m, a sandy loam soil, using the Fenn R.S. climate file.

As seen in the Figure 11, even for a forested buffer with a 50% slope the sediment delivery is reduced by 50% within the first 30 m. It should be clear from this example that predicted amount of sediment delivered through a forest buffer is highly dependant upon whether the survey crew considers the buffer truly effective or whether it contains a concentrated flow path.

Ideally, the watershed version of the WEPP model should be used to determine the effectiveness of forested buffers having concentrated flow paths (Tysdal et al. 1999).

Even the natural variability of soil properties over a hillslope can cause substantial variability in soil erosion. It is for this reason that predicted erosion rates should not be assumed to be any more accurate than ± 50 percent (Elliot et al., 1999a).

CONCLUSIONS

This paper presents an automated approach for modeling the detachment and delivery of sediment from large road networks. The application of the procedure to the South Fork Clearwater Watershed resulted in maps that identify the location and amount of sediment produced by specific road segments in the watershed. Although the technique requires fairly detailed understanding of GIS analysis, the technique has the potential to be developed into a more user-friendly program. The approach has been well received and is currently incorporated into three ongoing watershed assessment projects with Tribal and State organizations.

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