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INCORPORATING FOREST ROAD EROSION INTO A RESOURCE TRANSPORTATION PLANNING MODEL FOR THE MICA CREEK WATERSHED, IDAHO

By

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Incorporating Forest Road Erosion into a Resource Transportation Planning Model for the Mica Creek Watershed, Idaho.

Chairperson: Woodam Chung WC

Most of the additional sediment generated during forest harvest operations comes from the road network. There is a need for improved forest road network planning systems that incorporate the environmental costs associated with this erosion into the planning process. This research incorporates the environmental impact of forest roads into an economic analysis for resource transportation planning. The USDA Forest Service WEPP: Road, a road erosion prediction model, was used to estimate road erosion rates and sediment delivery to streams. Based on the estimated sediment delivery, NETWORK2000, which is a forest transportation planning model, produced alternative road systems that simultaneously minimized both transportation costs and overall sediment delivery. The methodology was applied to the Mica Creek watershed in Northern Idaho. The results indicate incorporating environmental impacts into transportation planning can generate alternative road networks that minimize both transportation costs and overall sediment delivery from the network by as much as 39% at the expense of 10.2% cost increase compared to the least cost alternative.

Keywords: forest roads, timber transportation planning, environmental impacts, road erosion, network analysis

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Last, but most importantly I owe a big thanks my husband Tarn, my parents David and Mary, Tom and B.J., Brian and Emily, Jessa and Sophia, and all my friends and family that have kept me motivated throughout this project and have done nothing but encouraged me to keep at it. One last thank you goes to my pal Franklin who stood by my side for all of the data collection and protected me from all of the very large moose, bear, and other critters.

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PREAMBLE

This thesis consists of two parts. Part I is a discussion of environmental impacts from roads, forest road erosion, and a literature review of techniques used for incorporating environmental impacts into transportation planning. Part II is a manuscript prepared for publication. This part describes the study area, methodology, results and provides a discussion of the results.

PART I. INCORPORATING FOREST ROAD EROSION INTO FOREST TRANSPORTATION PLANNING

INTRODUCTION

Research by forest land managers and technical specialists nation-wide indicates that forest roads are the greatest single source of sediment delivered to streams (Burroughs 1991). Unfortunately, forest road networks are not currently optimized to minimize sediment delivery to streams. This is partially because there is currently no way to directly incorporate sediment delivery into the economics of forest transportation planning.

The decisions people make about ecosystems imply valuations; and people choose whether to make these valuations explicit or not (Costanza et al 1997). Forest transportation has been evaluated for its environmental impacts but these impacts have not been explicitly incorporated into economic analyses of forest transportation planning. The logic of market failure has led economists, and increasingly scientists as well, to argue that the critical environmental resources need to be incorporated into the market system (Hanemann 1988; McNeely 1988; Randall 1988). Putting a price on the environment is a controversial topic and has no existing standard method (Costanza 1997). The purpose of this study is to incorporate the environmental costs associated with road erosion into an economic analysis of forest road transportation planning. The goal is to simultaneously reduce both the environmental impacts and the economic costs associated with road network construction.

The overall sediment production in forested basins increases from road-related erosion process (Wemple 2001). Increased stream sedimentation, associated reductions in fish habitat productivity and mass road failures are just a few of the impacts that result from forest roads (USDA 1998, Klapproth 2000). Sediment delivery from roads results from surface erosion of the road bench, cutslope and fillslope, and by mass failures in the road prism. Sediment is delivered to streams directly when stream crossings intercept road ditches, and indirectly when sediment and runoff are routed to a culvert or other type of delivery point and reaches the stream channel (Figure 1) (Elliot 1999, Madej 2001).

The environmental costs for this study were incorporated as a dollar amount per pound of sediment leaving the road, and per pound of sediment leaving the forest buffer or delivered to the stream channel. The analysis was designed for the local conditions of the Mica Creek Watershed, in northern Idaho (Figure 2). The study area is owned and managed by Potlatch, a private timber extraction company.

Predicted sediment amounts were estimated using the United States Forest Service (U.S.F.S.) WEPP: Road erosion prediction model. This model is designed to predict forest road runoff, erosion and sediment delivery to stream channels. The model allows users to easily describe numerous road conditions, and can also be used for compacted log landings, skid trails and foot, cattle or off-road vehicle trails (Elliot et al.

1999). The methods to retrieve the input data for estimating sediment delivery were developed from Brooks et al. (2003), Girvetz and Shilling (2003), and from Riedel and Vose (2002).

The forest transportation economic analyses were executed using the NETWORK 2000 forest transportation planning model. Using the estimated sediment delivery from the WEPP: Road model along with information on road construction costs, NETWORK 2000 produces alternative road networks that minimize both transportation costs and overall sediment delivery as an environmental cost. Results for eleven different alternatives were attained and these are presented in Part II.

Our intention in this research is not to estimate the environmental cost of sediment, but rather to analyze the effects of considering sediment into forest transportation planning with optimal road networks. The major questions addressed in this study were: (1) Can an environmental cost in $/pound of sediment be effectively combined with an extensive transportation planning model?; (2) Will the alternative transportation networks result in reduced amounts of sediment delivered to stream channels, of reduced road length, or reduced costs for proposed roads?; (3) Are the results comparable in economic efficiency for forest managers for both the analyses of with, and without an environmental cost?

ENVIRONMENTAL IMPACTS FROM FOREST ROADS

Forest roads are a necessity in the timber industry to efficiently transport harvested timber to a mill. Although forest roads are built primarily for the timber industry, many forest roads are open to public use. Thousands of people use forest roads annually for recreation (i.e. ATV, biking, walking), and/or to access recreational areas. Forest roads provide an infrastructure in fire management as they allow better access to wildland fires, and can potentially act as a firebreak. However, sediment eroded from forest roads can negatively impact the hydrology, geomorphology, and ecosystem processes in the surrounding watersheds (Switalski et al. 2004).

Increased stream sedimentation, associated reductions in fish habitat productivity and mass road failures are just a few of the impacts that result from forest roads (USDA 1998). The impacts of roads on aquatic ecosystems have been primarily the deposition of sediment and contaminants from road surfaces to waterways, and disturbance of aquatic community processes (Girvetz and Schilling 2003). Road cuts and drainage structures can also affect the physical characteristics (i.e. channelization) and processes of stream systems and their ability to recover from other land use impacts (Girvetz and Schilling 2003, Madej 2001). Stream crossings have been associated with reduced overall riparian species richness (Girvetz and Schilling 2003). Roads can also directly affect terrestrial biodiversity through increased mortality and loss of habitat. They also cause indirect effects by hindering habitat connectivity causing habitat fragmentation or through associated human impacts from increased access (Girvetz and Schilling 2003, Switalski et al. 2004). Recognition of these wide-ranging effects has recently thrust roads into the forefront of research, resulting in the removal of roads to mitigate these problems (Switalski et al. 2004).

Forest Road Erosion

Forest transportation planning is currently lessening the erosion impacts from roads on a case-to-case basis through monitoring and road maintenance, or through the closure of roads deemed unnecessary. The prevention of soil erosion from forest roads requires an understanding of how construction (road design) and maintenance affect sediment production.

Forest road erosion is the result of the interplay between the ability of flowing water to remove sediment, transport capacity, and the availability of moveable sediment (Luce and Black 1999). The actual process of soil eroding from a forest road begins with a rainfall event. A forest road surface is generally not vegetated and is extremely compacted compared to the native hillslope in most situations, and this may reduce or eliminate infiltration on the road surface. Because of this reduced infiltration the surface area of roads within a watershed can directly contribute to surface runoff from storms or snowmelt (Hickenbottom 2000). Roads are designed to carry this water to a delivery point where it is either delivered directly to a stream or it is routed to the hillslope below. Jones and Grant (1996) found that roads modify water flow paths and speed the delivery of water to channels during storm events. Some flow paths are subsurface natural channels in bedrock in which water flows down a watershed until it is delivered to a stream or saturated and held in the soil. These flow paths can be modified and "converted to surface flow or runoff through the interception by road surfaces, cutbanks, ditches, and culverts" (Jones and Grant 1996). Once the flow is intercepted it may then be directly routed by ditches, road surfaces, and channels created from culvert outfalls, and delivered to a stream (Jones and Grant 1996). This can increase the sediment yield delivered to streams because there is usually a system of roads and this means an entire system of direct overland flow routing to streams within a watershed.

Wemple and Jones (2003) found that road segments whose road cuts intersected the entire soil profile were more likely to produce runoff; segments draining short slopes with shallow soils were more likely to produce rapid runoff response. Jones and Grant (1996) found that for the Cascades in Oregon, soil infiltration capacity is high and hillslope flow is dominantly subsurface. In these conditions discontinuous saturated zones can develop on steep slopes during storm events and contribute to along road cuts (Wemple and Jones 2003). This turns the subsurface flow to runoff or surface flow and if it is delivered or routed directly to a stream it could increase the delivery of sediment to stream channels. Short slopes are created from roads being built close together on a hillslope. The distance between roads on a hillslope is also the distance that runoff delivered from the upper road has to disperse into the hillslope. Therefore, having shorter slopes can lead to more frequent interception of subsurface flows, which is then creating more runoff and could increase delivery of sediment to stream channels.

Luce and Black (1999) found in their study of sediment production from forest roads in western Oregon, that the sediment production is correlated to the product of segment length times road slope squared. This means that the segment slope is more responsible for a higher sediment yield than the length of the segment, although length is an important attribute and should be considered in the assessment of sediment budgets. The length will generally have less effect when the gradient of the road is lower, and have the most effect when road segments have steep gradients (Luce and Black 1999). Road segments that are steep allow for water to be carried quickly over the road surface or through the ditch. A longer road segment in this situation will then increase velocity and will increase transport capacity or the amount of sediment able to be carried in the runoff. This quick movement of water can create rills on the road surface or hillslope channels when it is delivered through a culvert to disperse over the hillslope. These channels can then route surface flow and sediments to streams or to another road below.

Wheel tracks and ruts, which form on most forest roads, are more compacted then the rest of the road surface so infiltration is extremely low. Ruts can route the surface flow past delivery points and directly deliver it to streams via stream crossings. Roads made up of surface soils that are of high clay or silt content have a higher surface area than roads that are of a rocky soil or that have a gravel surface. Thus, the roads containing surface soils of higher clay or silt content will generate more runoff and contribute more fine sediments to streams.

Soil texture was found to have a strong effect on sediment yield with coarser soils producing much less sediment than finer soils(Luce and Black 1999). The maintenance of forest roads was found to temporarily increase sediment production when the cutslope and/or ditch were cleared of vegetation to eliminate blockages or to drain ponded water (Luce and Black 1999, Potlatch 2005). The grading of the road surface alone showed less effect in their study.

The results for Luce and Black's study (1999) did not consider the effects of time and traffic. High rates of sediment production from road surfaces occur in the years following road construction but diminish rapidly over time (Megahan and Kidd 1972). The role of traffic in forming ruts and disturbing the road surface is effective in interaction with processes occurring in the ditch and may increase the sediment yield from the road surface (Luce and Black 1999). The relationship between these concepts and sediment yield is in regards to the precipitation, road segment length, slope, soil texture, hillslope location and the maintenance schedule (Parker 2005, Luce and Black 1999).

Incorporating Environmental Impacts into Transportation Planning

Current Techniques to Reduce Sediment Yield from Road Surface

There are various approaches to minimizing the sediment delivery from road surfaces to stream channels. Short term approaches involve several types of drainage structure that are used to divert runoff from the road surface to the hillslope below. In the long term, road removal can reduce chronic erosion and the risk of landslides over time (Switalski et al. 2004).

Ditch relief culverts and/or rolling dips are generally used on primary roads or roads with higher traffic levels to minimize sediment yield. Ditch relief culverts are designed for insloped roads to directly route water from ditches to the hillslope below, but have been known to cause road failures through improper maintenance. Maintenance of culverts requires constant monitoring to prevent plugging from hillslope and ditch materials (i.e. soil, rocks, branches etc.). Rolling dips (Figure 3) are designed as a gentle outsloped dip in the road surface (4 to 6 inches) to divert water from the road surface to the hillslope below and are usually designed to discharge into a filter windrow or slash pile (Potlatch 2005). To be effective the sediment travel distance on the hillslope below the outfall of the structure must be less than the distance to the nearest stream channel (Parker 2005).

For secondary roads or roads with low traffic levels rolling dips, cross-ditches and water bars are generally used for the drainage of road surface runoff. Cross-ditches are designed specifically for low to restricted traffic levels because a vehicle must reduce speed to a crawl to drive over a cross-ditch. A cross-ditch is a twelve to eighteen inch cut into a road bed, with a twelve to twenty-four inch berm above the road bed (Figure 4). Heavy traffic or any traffic on saturated soils can be destructive for a cross-ditch and they generally require frequent monitoring to prevent gully erosion at the fillslope. Water bars are similar to cross ditches in that the bar acts as a barrier to the runoff and diverts it to the hillslope below.

All of these drainage structures are effective only if they are located appropriately (Parker 2005). The general maximum spacing of drainage structures is 90 meters (approximately 300 feet), and it is recommended that structures be installed on the uphill side of each road-stream crossing (Potlatch 2005). Road gradients in general should not exceed fifteen percent and should be at a minimum of a two percent gradient for stream crossings, curves, and approaching log landings and road intersections (Chung 2003). Although these approaches are regularly practiced in forest transportation planning, they are generally put into action after the forest transportation network has been designated and has not yet involved sediment yield predictions.

After a section of road has been deemed unnecessary or a high risk for impacts, decisions for the future of the road must be made. Erosion rates remain higher than background levels as long as roads remain in place, making them a chronic sediment source (Parker 2005). Road removal projects have been undertaken for several reasons: to restrict access, increase hillslope stability, minimize erosion, restore natural drainage patterns, protect endangered plants and wildlife, and restore aquatic and wildlife habitat (Switalski et al. 2004). There are several options for decommissioning a forest road and priorities include restricting access, restoring natural drainage patterns, increasing hillslope stability, and revegetating disturbed areas (Moll 1996).

Access restriction can be achieved through the use of gates or through less expensive natural road barriers such as rock barricades and earthen barriers (Haber 1982). The revegetation of a road surface is particularly important because of its influence on water and soil movement and should be considered a minimum objective of any road reclamation project (Bradley 1998). Most revegetation applications involve some ripping of the road bed to reduce soil strength, improve infiltration capacity and create drainage pathways (Chung 2003, Bradley 1998). Stream crossing restoration is another common decommissioning technique used to reduce the risk of washouts from plugged culverts and the associated impacts on aquatic habitats (Chung 2003). Full road recontouring, the most intensive form of road removal, is the most effective for Increasing hillslope stability, minimizing erosion, restoring natural drainage patterns, and restoring habitat (Switalski et al. 2004). Recontouring involves the removal of fill material and restoring the natural slope, mulching, seeding, and placement of woody debris on top (Potlatch 2005). Although this intensive approach is highly effective, it is also generally the most costly (Switalski et al. 2004).

Forest Transportation Planning with Environmental Concerns

The transportation network dictates or impacts the profitability of a forest management plan (Murray 1998). The road network incorporates into a forest management plan through the harvest schedule. Each harvest unit has log landings where logs are bucked, sorted, and loaded onto trucks. The number of landings depends on the terrain and harvest operations used (i.e. cable logging, ground-skidding). These landings are all points along a road network where access is required over a certain period of time. Research has shown there is a need for techniques and models to assist in the management planning of forest road networks, especially within the context of accessing timber harvest stands (Liu and Sessions 1993; Dean 1997). There is also a need for techniques to assess currently existing road networks, proposed road networks, and the impacts on the environment from both.

"Optimization models and methods have been applied to the solution of forest planning problems for over 30 years, and during this time the nature of the problems have evolved (Rönnqvist 2003)." Environmental impacts and resource sustainability have become more of a concern over the years and have created a more modernized type of forestry.

The trend of including environmental considerations in road management and design is evidenced by the growing discipline of road ecology (Coulter et al. 2006). Using optimization techniques such as heuristics and graph theories, road network planning models are created to find least-cost networks through forest transportation systems (Clark et al. 2000, Richards and Gunn 2000, Chung and Sessions 2003, Anderson and Nelson 2004). Although heuristics by definition, do not guarantee that the ultimate optimal solution will be identified, they are of significant value for computationally difficult problems (Murray 1998). The NETWORK 2000 economic analysis model uses heuristic algorithms for optimizing large fixed and variable cost transportation problems (Chung and Sessions 2003).

Currently, the U.S.F.S. relies on a process that incorporates consideration of the ecological effects of roads, forest transportation economics, the contribution of roads to management and the social and economic costs and benefits of roads (Girvetz and Schilling 2003). This process was applied to the Tahoe National Forest (TNF) using the Ecosystem Management Decision Support system (EMDS) to analyze the environmental impact of each section of road. The process assumed a variety of impacts could result from each road type and assumed a holistic approach using technical and scientific opinion to develop a spatially explicit assessment. The results were compared with past management decisions, road failure occurrences and the expert opinion of road impacts. The results were also used to achieve a minimum network of forest roads needed to access points of interest. The overall goal of this project was to test the usefulness of a custom-made knowledge base in the EMDS system for its usefulness in a roads analysis process for the Tahoe National Forest (Girvetz and Schilling 2003). This process used a potential environmental cost for each road segment in conjunction with the ArcView Network Analyst extension to weight them by their environmental impacts. This weight was then used to find a least-cost network to points of interest in the TNF (Girvetz and Schilling 2003). Their results showed that of the original road network of 8,233 km, only 3,483 km or 42% of the road network was needed. They concluded that a more thorough analysis of the road use in the TNF would present better results for locating and decommissioning unnecessary roads within the network.

Spatial data for the Tahoe National Forest project was derived from a 30 meter grid and combined with elevation data into a 30 meter digital elevation model (DEM) (Girvetz and Schilling 2003). Brooks et al. (2003) found that the accuracy of their approach was dependent on the accuracy and precision of the DEM. They found that the 30 meter DEM does not accurately predict the slope of the road, and recommended using a 10 meter DEM or smaller. The slope of the road segment has been found to play a significant role in the amount of sediment leaving the forest road surface (Luce and Black 1999).

Acquiring the physical road characteristics for each road segment and simulating the erosion using WEPP:Road for a large watershed is challenging for a land manager within time and budget constraints (Brooks et al. 2003). The technique of using information from global positioning system (GPS) and incorporating the data into a geographic information system (GIS) was developed by Brooks et al. (2003), to simplify the data collection and simulation processes. Their study evaluated the performance of this technique on 23% of the length of road or 1017 kilometers from the South Fork Clearwater River Watershed in Idaho, and overall modeled 6,955 road segments. This approach does require a detailed understanding of GIS, and has been well received and incorporated into other projects (Brooks et al. 2003).

Riedel and Vose (2002) used an erosion model, the Sediment Tool (Tetra Tech Inc. 2000), to facilitate decision-making in the restoration of forest roads for the Conasauga River Watershed in the southern Appalachians. The model needed to provide the sediment production and delivery assessment, and the model output had to allow the user to quantify the effectiveness of road restoration for reducing sediment production and delivery at local and watershed scales, locate high hazard areas and evaluate changes in future sediment production and delivery with the implementation of road improvement projects (Riedel and Vose 2002). The erosion model was applied along segments of thirteen mountain roads within the watershed. The segments provided replication of road types for unsurveyed roads under a variety of usage levels, road base materials and slope. Model results improved with digital elevation model resolution, and the model sensitivity was limited by the governing equations. The Sediment Tool model currently uses the universal soil loss equation (USLE) to estimate soil erosion and empirical equations to calculate sediment transport (Riedel and Vose 2002). The empirical equations were not developed for road surfaces with aggregate materials. Future research on this project will involve the adaptation of the U.S.F.S. WEPP model and the use of finer resolution DEM data.

Although these studies assess sediment production from roads at the watershed scale to guide their decision making process in restoration and road improvement efforts, only a few studies have directly incorporated environmental impacts into road management decision making. Our study assimilates forest transportation planning with a sediment yield environmental cost from roads to find optimal transportation routes that minimize both the transportation costs and environmental costs.

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PART II. MANUSCRIPT FOR PUBLICATION

Incorporating Forest Road Erosion Into Forest Resource Transportation Planning; A Case Study in the Mica Creek Watershed in Northern Idaho

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INTRODUCTION

Unpaved roads are the greatest single source of sediment delivered to streams in forested watersheds (Burroughs 1991), but forest road networks are not currently optimized to minimize sediment delivery to streams. This is partially because there is no method to directly incorporate sediment delivery into the economics of forest transportation planning.

The decisions people make about ecosystems imply valuations; and people choose whether to make these valuations explicit or not (Costanza et al. 1997). Forest transportation has been evaluated for environmental impacts (Girvetz and Shilling 2003), but these impacts are rarely incorporated into economic analyses for transportation planning. The logic of market failure has led economists, and increasingly scientists as well, to argue that the critical environmental resources need to be incorporated into the market system (Hanemann 1988; McNeely 1988; Randall 1988).

Increased stream sedimentation, associated reductions in fish habitat productivity and mass road failures are just a few of the impacts that result from forest roads (USDA 1998). Sediment delivery from roads results from direct delivery at stream crossings, indirect delivery at culverts or other drainage structures, and from mass wasting of the road prism (Madej 2001, Elliot et al. 1999).

This study was designed to develop alternative road network systems that minimize both the economic costs and environmental impacts represented by sediment yields for the Mica Creek Watershed (Figures 2 and 5). Predicted sediment amounts from each road segment were estimated using the United States Forest Service (U.S.F.S.)

WEPP: Road erosion prediction model (Elliot et al. 1999). The environmental costs were then calculated as a dollar amount per pound of sediment leaving the road and per pound of sediment delivered to the stream channel. The forest transportation economic analyses were carried out using the NETWORK 2000 forest transportation planning model. Based on the estimated sediment delivery, NETWORK 2000 produces alternative road systems that minimize both transportation costs and overall sediment delivery. Results for eleven different alternatives were attained; ten results employed an environmental cost, and one result with no environmental cost served as a control.

Our intention in this study is not to accurately estimate the environmental cost of sediment, but rather to analyze the effects of considering sediment into forest transportation planning with optimal road networks. The major questions addressed in this study were: (1) Can an environmental cost in $/pound of sediment be effectively combined with an extensive transportation planning model?; (2) Will the alternative transportation networks result in lesser amounts of sediment delivered to stream channels, and lesser amounts of existing or proposed roads?; (3) Are the results comparable in economic efficiency for forest managers for both the analyses of with, and without an environmental cost?

STUDY AREA

The study area is located within the Mica Creek watershed, which is part of the St. Joe River Basin in Idaho, about 68 kilometers (42 miles) southeast of Coeur d'Alene. Potlatch, a private timber company, owns and manages most of the watershed. The watershed is 13,046 hectares (32,238 acres) and includes 756 kilometers (470 miles) of roads. The study area is situated in the upper part of the Mica Creek watershed, and is 7,495 hectares (18,520 acres), or 58% of the entire watershed (Figure 5).

The study area elevation ranges from 818 to 1,688 meters (2,684 to 5,537 feet), and has a drainage density of 3.4 km/km² (5.49 miles/mile²). There are 453 inventoried secondary stream crossings and seven primary stream crossings within the watershed (Figure 6). The precipitation falls mostly in the form of rainfall with an average annual rainfall of 138.7 to 144.3 centimeters (54.6 – 56.8 inches), and an average annual snow water equivalent of 0 to 63.8 centimeters (0 - 25.1 inches) in the winter months (i.e. October - May) (NRCS 2005). The average annual air temperature ranges from 16.6 to 22.2 °C (NRCS 2005). The slopes are mostly gentle, but some areas have steep slopes up to 51.6 degrees. Parent materials consist of quartzite and schist (11%), quartzite (5%), siltite/argillite (16%), and siltite/quartzite (68%) (Potlatch 2005). The quartzite has very low mass wasting potential and surface erosion potential, and the quartzite and schist has the highest. Eighty-nine percent of the soils in the watershed are silt loam, and the rest is sandy loam (Figure 7). Roads made up of surface soils that are of high clay or silt content have a higher surface area than roads that are of a rocky soil or that have a gravel surface. A higher surface area results in less infiltration of precipitation and greater overland flow. Thus, the roads containing surface soils of higher clay or silt content will generate more runoff and contribute more fine sediments to streams.

There are 276 harvest units ranging from 0.4 to 77.3 hectares (1 to 191 acres) in size, and approximately 353 log landings (Figure 8). The road density is 4.4 km/km² (7.10 miles/mile²), and is greater than the drainage density for streams (Figure 9). The total length of the entire road network analyzed in this study is 779 km (484 miles) and includes highways and local roads used to access the mills, and existing and proposed roads within the study area. The total road length within the study area is 409 km (254 miles) (Figure 10), 335 km (208 miles) is existing roads, and 74 km (46 miles) is proposed roads. Proposed roads are analyzed in this study for the future access needs to timber sale locations. A total of 240 km (149 miles) of existing and proposed road segments were used in WEPP to estimate sediment yield leaving the road surface and leaving the forest buffer. While combining data layers using ArcGIS 169 km (105 miles) of road were unable to retain appropriate nodes to separate road segments and were unable to be analyzed using WEPP. Therefore, we have applied sediment yields of 0.0 tons leaving the road surface and leaving the forest buffer for these segments.

METHODS

Data Collection

A total of 3,889 sediment delivery points were identified throughout the field data collection and GIS analysis for surveyed, unsurveyed, and proposed roads (Figure 11). These delivery points represent stream crossings, drainage structure locations, or low elevation points along the road, where water collects and drains. These points were used to split roads into multiple segments along with intersection points and high points on the road that divert water into two opposite directions (Figure 12). Sediment yields from each road segment were estimated using WEPP:Road (Elliot et al. 1999), and converted into a dollar amount per pound. NETWORK2000 (Chung and Sessions 2003) was used to develop alternative road network systems that minimize both transportation costs and overall sediment delivery. Detailed methodology is described below.

Estimating Sediment Yields Using WEPP:Road

The U.S.F.S. WEPP:Road erosion model predicts runoff and surface erosion from a road segment, and the sediment yield to an adjacent stream channel. This physically-based model was developed from the original Water Erosion Prediction Project (WEPP) model that predicts hillslope erosion (Elliot et al. 1999). WEPP:Road is now one of several internet-based computer programs for calculating erosion and sediment yield. WEPP;Road is capable of running in batch mode (WEPP:Road Batch) where sediment yield for up to two hundred road segments can be evaluated at one time. Results from WEPP:Road consist of the mean annual sediment yield from the road surface and the amount of sediment leaving the forest buffer and delivered to stream channels, annually.

WEPP:Road assumes that there are three overland flow elements: a road, a fillslope, and a forest (Elliot et al.1999). Runoff and erosion from these elements varies with climate, soil and gravel addition to the road surface, local topography, drain spacing road design and surface condition, and ditch condition (Elliot et al., 1999). In order to provide the WEPP:Road model with information on these factors, the following input data are required:

- Road Segment Length, Width, and Gradient
- Surface Soil Texture: clay loam, sandy loam, silt loam, or loam.
- Road Design (Figure 13): outslope, outslope rutted, inslope vegetated or rocked ditch, or inslope bare ditch.
- Road Surface: gravel, native, or paved, and % rock content.
- Fill Slope (percent or degree)
- Fill Length (meters or feet)
- Buffer Slope (percent or degree)
- Buffer Length (meters or feet)
- Traffic level

The WEPP:Road model predicts sediment amounts with a custom interface that assumes certain inputs. The soil properties for each soil texture are generalized from research findings. The road is assumed to be free of vegetation, the fill slope has 50% ground cover, and the buffer contains forest litter of generally 100% (Elliot et al. 1999). Traffic levels are assumed to be high on primary roads and low on secondary roads. Error to model predictions may result from using ArcGIS and assuming accuracy from a segment of road represented by an average gradient and width (Brooks et al. 2003).

Field Data Collection for WEPP:Road

Using a Magellan Meridian GPS receiver, 1,298 points were surveyed along 136 kilometers, representing 41% of the existing roads within the study area (Figures 10 and 11). Each point was assigned a unique number to ensure that they could be tracked from field records, to Microsoft Excel, Arc GIS, and through both of the models utilized in this study. At each survey point, seven attributes were measured: road width, fill slope length, fill slope gradient, road design (Figure 13), road surface content, soil texture and percent rock content. Fill slope length, fill slope gradient, and road width were measured using a laser hypsometer. Road surface content was considered gravel if gravel was thick enough so that the underlying surface soil was not visible, and was considered native otherwise. Percent rock content was observed for rock particles greater than two millimeters in diameter, and was higher for segments with intermittent gravel.

There are four road design options in WEPP:Road: Insloped with a bare ditch, insloped with a vegetated or rocked ditch, outsloped and unrutted, and outsloped and rutted (Figure 13). The insloped, bare ditch option assumes there are no ruts in the road, and that all runoff is diverted to an inside road ditch. Road surface erosion is due to raindrop splash and shallow overland flow, and the bare ditch is experiencing rill erosion from concentrated flow. The insloped, vegetated or rocked ditch option assumes that the majority of erosion occurs on the road surface only due to raindrop splash and shallow overland flow. The function of the ditch is considered to be the transport of the sediment eroded from the road surface. Using this option will generally reduce road erosion by fifty to ninety percent (Elliot et al. 1999). The outsloped unrutted option is thought to best describe outsloped roads with light or restricted traffic and can be used for closed roads that were graded before closure. The outsloped rutted option assumes rill spacing equal to that of wheel tracks, an approximate distance of two meters.

Locations of high points were recorded along with any road failures (i.e. debris flows, land slides, slumping). High points are essential to capture situations where a high point in a road will direct water in two distinct directions (Figure 14). The elevation of the highpoint is needed to find the two segments gradients. These points were then displayed in ArcMap to acquire the rest of the spatial data and were linked with their specific attributes.

All stream crossings were recorded as delivery points but were noted as stream crossings in particular for later specifications in WEPP:Road. Sediment delivery was assumed equal to one hundred percent of the predicted erosion rate at stream crossings (Elliot et al. 1999). At stream crossings, fill and buffer attributes were assigned lengths of 0.03 meter (0.1 foot), and slopes of 0.3%. Sediment leaving the buffer can be used for this estimate, although deposition on the fill or buffer may be overestimated (Elliot et al. 1999).

At each survey point along the road, surface soil texture was determined by hand. Soil texture was found to be similar throughout the study area (Figure 7) and was compared to SSURGO Soil Survey database (NRCS 2003) to ensure that the field differentiation of textures were accurate. Comparisons revealed little differences, so SSURGO data were used for identifying soils for the non-existing proposed roads and roads that were not measured within the study area.

Climate data for WEPP:Road was generated from the St.Maries climate station approximately twenty miles from the Mica Creek Watershed. A fifty year simulation period was used for the WEPP:Road analysis to ensure that an adequate number of wet years was simulated.

Some sites on or along roads were observed as having major road surface erosion problems such as gully erosion, rills, deep ruts, and plugged culverts. These sites along with sites of road-related mass wasting events and debris slides were recorded using the GPS receiver and are used later to view communalities with the WEPP:Road results. Road-related mass wasting events and debris slides often exceed sediment production from road surfaces (Megahan et al., 1978; Reid et al., 1981), but generally only occur in response to extreme storms (Swanson and Dyrness, 1975; Coker and Fahey, 1993), steep hillslopes, and an unstable geomorphology (Wemple et al., 2001). Geomorphic effects of roads may include culvert plugging and gully erosion in some environments (Weaver et al., 1995; Flannagan, 1999). WEPP: Road does not consider hillslope geology and does not predict mass-wasting events. These sites were included only to find communalities and were not intended to validate WEPP.

Data Acquisition Using GIS

A 1-meter Digital Elevation Model (DEM) of the Mica Creek Watershed derived from LIDAR (Evans 2005) was used for GIS analyses in this study. Elevation and the length between each point were retrieved from the DEM. The data were used to find the segment gradient and the directional flow of runoff for each segment. The buffer slope and length were also retrieved from the DEM. Buffer lengths were measured from the delivery point location on the road to the nearest stream channel below and then the recorded fill slope length was subtracted from this. Buffer slopes were estimated using the elevation of the delivery point and the elevation of the nearest point on the stream channel below.

GIS data was used in post-sampling to provide replication of road segments from measured roads for 274 km (170 miles) of unsurveyed roads and proposed roads using techniques from Riedel and Vose (2002). Replication was focused on attributes such as road usage, slope, aspect, soils, geology and elevation. Replicated segments were assigned delivery points using the DEM. Using ArcGIS and the raster data from the DEM, the lowest points in elevation along the roads were located for every 90 to 150 meters (300-500 feet) depending on the averages applied to each road (Table 1). These low points became the delivery points, as well as any stream crossings visible from the map in ArcGIS. High points were located after the delivery points to divide segments into the appropriate directional flow.

Optimizing Road Networks Using NETWORK 2000

All of the predicted sediment amounts produced from WEPP:Road were incorporated into environmental costs, which were further combined with actual transportation costs and analyzed in NETWORK 2000.

NETWORK2000 is an economic analysis tool for forest transportation, which has been used by public agencies and forest industries to analyze alternative forest transportation routes and identify the least cost road network that connects timber sale locations (landing locations) to the mill (Chung and Sessions 2003).

NETWORK 2000 uses a heuristic algorithm for optimizing large fixed cost (road construction) and variable cost (timber hauling) transportation problems. It calculates the minimum cost network by using a shortest path algorithm to solve the variable cost problem similar to that proposed by Dijkstra (1959). The algorithm starts with sorting loading nodes by time and volume (Figure 15). Then, it solves for the shortest path from each loading node to the destination while considering only variable costs for the first iteration. After the first iteration, the algorithm adjusts variable costs to include consideration of fixed costs per link. For each link product volumes are summed across *i* periods, $\sum Vol_{ij}$ (where, j is a link ID.) The variable costs for each link, VC_j, are then recalculated using the concept of equivalent variable costs (Schnelle 1980) (revised variable cost = $VC_j + F_j/\sum Vol_{ij}$). The volume over all links is then reset to zero and the next iteration starts using the new set of variable costs. This process continues until the same solution is repeated for two consecutive iterations. This procedure generally results in a good solution, but there are cases where construction projects (links with fixed cost) are not undertaken which would improve the solution. To diversify the search, a negative value is substituted for each positive variable cost link not in the solution such that $VC_i < 0$ for all links with $Vol_i = 0$. The solution procedure is then repeated until the solution re-stabilizes with each time a link with a negative value is used its value returns to its original value. This process rapidly eliminates the substituted negative values while providing an additional opportunity to consider alternative routes. NETWORK 2000 has a problem capacity of 20,000 links, 20,000 nodes, and 5,000 timber harvests (sales) (Chung and Sessions 2003).

NETWORK 200 inputs require two data sets: link and sale data. Link data are arranged by road segments. These segments are identified by a beginning and ending node (Figure 12). Each link has a variable cost (hauling cost) which is defined by a road class factor (Table 2) multiplied by the length of segment. The variable cost units are set as dollar per thousand board feet (MBF) in this study. A fixed cost (road construction cost) can be also assigned to each proposed road segment. For proposed roads, a fixed cost is calculated and assigned using a construction cost of an assumed $15,500 per kilometer ($25,000 per mile) multiplied by the road segment length, whereas zero construction cost is assigned to existing road segments. In addition, in order to include the environmental impact of each road segment in the model the environmental cost for each road segment was added to the fixed cost as sediment yield in pounds from the road segment predicted from the WEPP:Road erosion prediction model, multiplied by a cost factor (Table 3).

Sale data was developed using the harvest schedule provided by Potlatch Corp. This data set includes entry nodes (landings), harvest volume, year of harvest, and destination (mill) for each sale (Figures 8 and 16). The harvest schedule from Potlatch for the Mica Creek Watershed is for seventy years, includes 276 harvest units (Figure 8), for 1,556 sales, and for 412 MMBF. The mills selected for the analysis are St. Maries, Medley Santa, and Clarkia (Figure 16), the three nearest mills to the Mica Creek watershed.

Developing Alternative Routes

NETWORK 2000 was run for the same harvest schedule for ten different alternatives with environmental cost factors ranging from ten dollars to one thousand dollars, and for one with no environmental cost for comparisons. The entire network of roads used for this program was 855 kilometers (531 miles), including all the primary, secondary, local roads, and highways that connect to the mills outside the watershed (Figure 16).

WEPP:Road gives two predictions, the annual sediment yield from the road segment surface and the annual sediment yield leaving the forest buffer or entering stream channels. Although the environmental concern is based from the sediment yield delivered to stream channels, to locate areas with high risk of potential erosion both of these predictions were used for the alternatives. The environmental cost factors were chosen without rationale other than to provide a scale for comparison (Table 3).

Alternative 1 does not use an environmental cost and provides comparison of optimal routes and associated costs. Alternatives 2 through 5 use the predicted sediment yield leaving the road surface with four different weighted environmental costs which vary from ten dollars to one hundred dollars per pound of predicted sediment yield. Alternatives 6 through 11 use the predicted sediment yield leaving the forest buffer or delivered to stream channels with six different weighted environmental costs ranging from ten dollars to one thousand dollars per pound of sediment predicted. WEPP:Road results for predicted sediment yields leaving the forest buffer were of much smaller amounts (by over 100,000 pounds) than for predicted sediment yields leaving the road surface. To ensure that costs were not too small to be effective in the NETWORK 2000 program, Alternatives 10 and 11 use higher cost factors.

The alternative transportation routes that resulted from NETWORK 2000 are compared in terms of road construction and hauling costs as well as total sediment yields from each road network alternative.

RESULTS

WEPP:Road Results

The WEPP:Road erosion prediction model results indicate that 96% of the road segments evaluated have sediment leaving the road surface, and 55% have sediment leaving the forest buffer and delivered to stream channels. The mean annual road erosion rate is 2.05 tons per hectare (0.83 tons per acre) and the mean annual sediment yield from the forest buffer is 1.57 tons per hectare (0.23 tons per acre). The mean annual total road erosion is 180.5 tons (397,853 lbs) and the mean annual sediment yield from the buffer is 49.2 tons (108,502 lbs). By using averages from observed data for some of the attributes of non-existing proposed roads and for the roads that were not measured, WEPP:Road results were for low sediment yield producing attributes (i.e. shallow gradient, average fill slope, ideal spacing for these roads) and therefore resulted in lower sediment predictions. Primary roads that were surveyed have an average predicted sediment yield of 7.16 tons per hectare (2.90 tons per acre) leaving the road surface, and 1.95 tons per hectare (0.79 tons per acre) delivered to stream channels, a higher average than the entire study area. Twenty-three percent of the road segments run through the WEPP:Road model were insloped with a vegetated or rocked ditch road design. This option in WEPP:Road can reduce erosion rates by fifty to ninety percent (Elliot et al 1999), and partially contributes to the low erosion estimates for predicted sediment yield delivered to stream channels.

WEPP:Road results for this study were used to rank road segments in magnitude of sediment delivery. WEPP predicted erosion rates were not validated by field measurements, so they do not necessarily represent actual erosion rates. However they do provide a reasonable indication of relative erosion rates within the road network. Areas that ranked highly based on the WEPP analysis coincided with areas of high erosion risk and documented road failure locations (Figures 17 and 18). Sediments yields predicted leaving the road surface (Figure 17) are separated into four groups: (1)> 1000 lbs, (2) 501-1000 lbs, (3) 101-500 lbs and (4) < 100 lbs, to view differences among road segments. Sediment yields predicted to be delivered to stream channels (Figure 19) are also separated into four groups: (1) > 500 lbs, (2) 251-500 lbs, (3) 101-250 lbs and (4) < 100 lbs. The sites of erosion overlay these groups in the figures to view communalities among road segments predicted to have greater erosion, and sites observed to be heavily eroding. Figures 17 and 18 also display percent slope for less than 20%, 20-40%, and greater than 40%. Areas with steep slopes coincide with areas of high predicted erosion (Figures 17 and 18). Road segments located close to streams also tended to have high erosion rates (Figure 18). Although, there are limitations in using WEPP:Road in that the accuracy of a predicted runoff or erosion rate is, at best, plus or minus 50% (Elliot et al. 1999). There were no paved roads measured for this analysis since there are no paved roads within the watershed. Evaluating roads outside the watershed for erosion was also beyond the scope of this research.

NETWORK 2000 Results

Eleven different alternative transportation routes were obtained from using the NETWORK 2000 program. For each alternative route a total variable cost, a total fixed cost and an overall network cost was reported. The total variable cost is the total hauling cost, and the total fixed cost is the construction costs for proposed roads added with the environmental costs, and the total network cost is all of these added together (Tables 4 and 5). To compare total network costs of all the alternatives only the total variable cost and the associated construction costs from the total fixed cost are used in Tables 6 and 7. The actual construction cost shown in Tables 6 and 7 is the total reported fixed cost minus the associated environmental cost since it is not an actual monetary value. All the alternatives have the same harvest schedule and same amount of timber volume passing through their networks. Tables 6 and 7 also show the total length of roads chosen in each road network alternative with the total sediment amounts estimated leaving road and delivered to streams from the alternative.

Alternative 1

This alternative used no environmental cost input for the NETWORK 2000 program (Figure 19). The length of this alternative network is 388.8 kilometers (241.6

miles) or 50% of the total road length analyzed. The total variable cost reported for this alternative is $17,847,200 (96% of the total network cost) or $43.30 per MBF, the total fixed cost reported is $835,475 (4% of the total network cost) or $2.03 per MBF, and the total network cost reported is $18,682,675 or $45.32 per MBF. Since this alternative did not use an environmental cost, the actual total cost for comparison is the same as the total network cost reported from NETWORK 2000. This alternative has the lowest overall associated costs reported and can be considered the optimal road network for the upper part of the Mica Creek Watershed without any consideration for environmental impacts.

The predicted sediment yield resulting for this alternative is 162.9 tons (359,001 pounds) of sediment leaving the forest road surface, and 44.5 tons (97,979 pounds) of sediment leaving the forest buffer and entering stream channels. Since this alternative has no associated environmental cost, it resulted in the highest overall sediment yield predicted from WEPP:Road to be leaving the forest buffer and entering stream channels.

Alternative 2

This alternative uses an environmental cost of $10 per pound of sediment from the road surface for input in the NETWORK 2000 program (Figure 20). The length of this alternative network is 379.6 kilometers (235.9 miles). The total variable cost reported for this alternative is $17,998,940 (85% of total network cost) or $43.66 per MBF, the total fixed cost reported is $3,262,260 (15% total network cost) or $7.91 per MBF, and the total network cost reported is $21,261,201 or $51.58 per MBF. The actual fixed cost or associated construction cost (fixed cost – associated environmental cost) considered is $836,011 (26% of the reported total fixed cost from NETWORK 2000), and the actual total network cost for comparison is approximately $18.8 million dollars. The actual total cost is for this alternative is approximately 0.5% greater than Alternative 1 with no associated environmental cost.

The predicted sediment yield resulting for this alternative is 110.1 tons (242,625 pounds) of sediment leaving the forest road surface, and 33.5 tons (73,723 pounds) of sediment leaving the forest buffer and entering stream channels. This alternative has a 32% lower sediment yield predicted from WEPP:Road to be leaving the forest road surface, and a 25% lower sediment yield predicted leaving the forest buffer and entering stream channels than for Alternative 1.

Alternative 3

This alternative uses an environmental cost of $25 per pound of sediment from the road surface for input in the NETWORK 2000 program (Figure 21). The length of this alternative network is 374.1 kilometers (232.4 miles). The total variable cost reported for this alternative is $18,152,716 (74% of total network cost) or $44.04 per MBF, the total fixed cost reported is $6,507,286 (26% total network cost) or $15.79 per MBF, and the total network cost reported is $24,660,003 or $59.82 per MBF. The actual fixed cost or associated construction cost (fixed cost – associated environmental cost) considered is $827,435 (13% of the reported total fixed cost from NETWORK 2000), and the actual total network cost for comparison is approximately $18.9 million dollars. The actual total cost is for this alternative is approximately 1.1% greater than Alternative 1 with no associated environmental cost.

The predicted sediment yield resulting for this alternative is 103.1 tons (227,194 pounds) of sediment leaving the forest road surface, and 32.1 tons (70,628 pounds) of sediment leaving the forest buffer and entering stream channels. This alternative has a 37% lower sediment yield predicted from WEPP:Road to be leaving the forest road surface, and a 28% lower sediment yield predicted leaving the forest buffer and entering stream channels than for Alternative 1.

Alternative 4

This alternative uses an environmental cost of $50 per pound of sediment from the road surface for input in the NETWORK 2000 program (Figure 22). The length of this alternative network is 375.8 kilometers (233.5 miles). The total variable cost reported for this alternative is $18,598,029 (61% of total network cost) or $45.12 per MBF, the total fixed cost reported is $11,936,801 (39% total network cost) or $28.96 per MBF, and the total network cost reported is $30,534,831 or $74.07 per MBF. The actual fixed cost or associated construction cost (fixed cost – associated environmental cost) considered is $853,303 (7% of the reported total fixed cost from NETWORK 2000), and the actual total network cost for comparison is approximately $19.5 million dollars. The actual total cost is for this alternative is approximately 4.3% greater than Alternative 1 with no associated environmental cost.

The predicted sediment yield resulting for this alternative is 100.6 tons (221,670 pounds) of sediment leaving the forest road surface, and 30.4 tons (67,035 pounds) of sediment leaving the forest buffer and entering stream channels. This alternative has a 38% lower sediment yield predicted from WEPP:Road to be leaving the forest road surface, and a 32% lower sediment yield predicted leaving the forest buffer and entering stream channels than for Alternative 1.

Alternative 5

This alternative uses an environmental cost of $100 per pound of sediment from the road surface for input in the NETWORK 2000 program (Figure 23). The length of this alternative network is 377.9 kilometers (234.8 miles). The total variable cost reported for this alternative is $18,722,487 (45% of total network cost) or $45.42 per MBF, the total fixed cost reported is $22,858,858 (55% total network cost) or $55.45 per MBF, and the total network cost reported is $41,581,345 or $100.87 per MBF. The actual fixed cost or associated construction cost (fixed cost – associated environmental cost) considered is $853,303 (4% of the reported total fixed cost from NETWORK 2000), and the actual total network cost for comparison is approximately $19.6 million dollars. The actual total cost is for this alternative is approximately 4.8% greater than Alternative 1 with no associated environmental cost.

The predicted sediment yield resulting for this alternative is 100.3 tons (220,971 pounds) of sediment leaving the forest road surface, and 30.2 tons (66,456 pounds) of sediment leaving the forest buffer and entering stream channels, which are similar to Alternative 4. This alternative has a 38% lower sediment yield predicted from WEPP:Road to be leaving the forest road surface, and a 32% lower sediment yield predicted leaving the forest buffer and entering stream channels than for Alternative 1.

Alternative 6

This alternative uses an environmental cost of $10 per pound of sediment leaving the forest buffer or entering the stream channel for input in the NETWORK 2000 program (Figure 24). The length of this alternative network is 383.6 kilometers (238.3 miles). The total variable cost reported for this alternative is $17,905,792 (95% of total network cost) or $43.44 per MBF, the total fixed cost reported is $967,728 (05% total network cost) or $2.35 per MBF, and the total network cost reported is $18,873,520 or $45.79 per MBF. The actual fixed cost or associated construction cost (fixed cost – associated environmental cost) considered is $875,649 (90% of the reported total fixed cost from NETWORK 2000), and the actual total network cost for comparison is approximately $18.8 million dollars. The actual total cost is for this alternative is approximately 0.5% greater than Alternative 1 with no associated environmental cost.

The predicted sediment yield resulting for this alternative is 115.0 tons (253,518 pounds) of sediment leaving the forest road surface, and 36.0 tons (79,258 pounds) of sediment leaving the forest buffer and entering stream channels. This alternative has a 29% lower sediment yield predicted from WEPP:Road to be leaving the forest road surface, and a 19% lower sediment yield predicted leaving the forest buffer and entering stream channels than for Alternative 1.

Alternative 7

This alternative uses an environmental cost of $25 per pound of sediment leaving the forest buffer or entering the stream channel for input in the NETWORK 2000 program (Figure 25). The length of this alternative network is 380.2 kilometers (236.2

miles). The total variable cost reported for this alternative is $18,006,340 (89% of total network cost) or $43.68 per MBF, the total fixed cost reported is $2,178,595 (11% total network cost) or $5.29 per MBF, and the total network cost reported is $20,184,936 or $48.97 per MBF. The actual fixed cost or associated construction cost (fixed cost – associated environmental cost) considered is $839,033 (39% of the reported total fixed cost from NETWORK 2000), and the actual total network cost for comparison is approximately $18.9 million dollars. The actual total cost is for this alternative is approximately 1.1% greater than Alternative 1 with no associated environmental cost.

The predicted sediment yield resulting for this alternative is 109.5 tons (241,393 pounds) of sediment leaving the forest road surface, and 32.2 tons (70,942 pounds) of sediment leaving the forest buffer and entering stream channels. This alternative has the a 33% lower sediment yield predicted from WEPP:Road to be leaving the forest road surface, and a 28% lower sediment yield predicted leaving the forest buffer and entering stream channels than for Alternative 1.

Alternative 8

This alternative uses an environmental cost of $50 per pound of sediment leaving the forest buffer or entering the stream channel for input in the NETWORK 2000 program (Figure 26). The length of this alternative network is 386.5 kilometers (240.2 miles). The total variable cost reported for this alternative is $18,079,219 (81% of total network cost) or $43.86 per MBF, the total fixed cost reported is $4,314,265 (19% total network cost) or $10.47 per MBF, and the total network cost reported is $22,393,485 or $54.32 per MBF. The actual fixed cost or associated construction cost (fixed cost –

associated environmental cost) considered is $845,458 (20% of the reported total fixed cost from NETWORK 2000), and the actual total network cost for comparison is approximately $19.0 million dollars. The actual total cost is for this alternative is approximately 1.6% greater than Alternative 1 with no associated environmental cost.

The predicted sediment yield resulting for this alternative is 106.4 tons (234,601 pounds) of sediment leaving the forest road surface, and 31.7 tons (69,955 pounds) of sediment leaving the forest buffer and entering stream channels. This alternative has a 35% lower sediment yield predicted from WEPP:Road to be leaving the forest road surface, and a 29% lower sediment yield predicted leaving the forest buffer and entering stream channels than for Alternative 1.

Alternative 9

This alternative uses an environmental cost of $100 per pound of sediment leaving the forest buffer or entering the stream channel for input in the NETWORK 2000 program (Figure 27). The length of this alternative network is 386.4 kilometers (240.1 miles). The total variable cost reported for this alternative is $18,201,617 (70% of total network cost) or $44.16 per MBF, the total fixed cost reported is $7,696,893 (30% total network cost) or $18.67 per MBF, and the total network cost reported is $25,898,511or $62.83 per MBF. The actual fixed cost or associated construction cost (fixed cost – associated environmental cost) considered is $851,699 (11% of the reported total fixed cost from NETWORK 2000), and the actual total network cost for comparison is approximately $19.1 million dollars. The actual total cost is for this alternative is approximately 2.1% greater than Alternative 1 with no associated environmental cost.

The predicted sediment yield resulting for this alternative is 108.2 tons (238,370 pounds) of sediment leaving the forest road surface, and 31.3 tons (68,978 pounds) of sediment leaving the forest buffer and entering stream channels. This alternative has a 34% lower sediment yield predicted from WEPP:Road to be leaving the forest road surface, and a 30% lower sediment yield predicted leaving the forest buffer and entering stream channels than for Alternative 1.

Alternative 10

This alternative uses an environmental cost of $500 per pound of sediment leaving the forest buffer or entering the stream channel for input in the NETWORK 2000 program (Figure 28). The length of this alternative network is 384.5 kilometers (238.9 miles). The total variable cost reported for this alternative is $19,335,944 (38% of total network cost) or $46.96 per MBF, the total fixed cost reported is $31,386,929 (62% total network cost) or $76.14 per MBF, and the total network cost reported is $50,742,874 or $123.10 per MBF. The actual fixed cost or associated construction cost (fixed cost – associated environmental cost) considered is $880,400 (2.8% of the reported total fixed cost from NETWORK 2000), and the actual total network cost for comparison is approximately $20.3 million dollars. The actual total cost is for this alternative is approximately 8.6% greater than Alternative 1 with no associated environmental cost.

The predicted sediment yield resulting for this alternative is 101.3 tons (223,209 pounds) of sediment leaving the forest road surface, and 27.7 tons (61,013 pounds) of sediment leaving the forest buffer and entering stream channels. This alternative has a 38% lower sediment yield predicted from WEPP:Road to be leaving the forest road surface, and a 38% lower sediment yield predicted leaving the forest buffer and entering stream channels than for Alternative 1.

Alternative 11

This alternative uses an environmental cost of $1000 per pound of sediment leaving the forest buffer or entering the stream channel for input in the NETWORK 2000 program (Figure 29). The length of this alternative network is 384.6 kilometers (239.0 miles). The total variable cost reported for this alternative is $19,651,808 (25% of total network cost) or $47.67 per MBF, the total fixed cost reported is $60,443,075 (75% total network cost) or $146.63 per MBF, and the total network cost reported is $80,094,883 or $194.30 per MBF. The actual fixed cost or associated construction cost (fixed cost – associated environmental cost) considered is $878,100 (1.5% of the reported total fixed cost from NETWORK 2000), and the actual total network cost for comparison is approximately $20.6 million dollars. The actual total cost is for this alternative is approximately 10.2% greater than Alternative 1 with no associated environmental cost.

The predicted sediment yield resulting for this alternative is 99.7 tons (219,800 pounds) of sediment leaving the forest road surface, and 27.0 tons (59,525 pounds) of sediment leaving the forest buffer and entering stream channels. This alternative has a 39% lower sediment yield predicted from WEPP:Road to be leaving the forest road surface, and a 39% lower sediment yield predicted leaving the forest buffer and entering stream channels than for Alternative 1.

DISCUSSION

The United States' average annual sediment yield from forest roads ranges from 0 to over 1000 tons per hectare per year (Dube et al., 2004). The results obtained from WEPP: Road in this study are at the lower end of this range with averages of 2.05 tons per hectare (0.83 tons per acre) annually leaving the road surface, and an average of 1.57 tons per hectare (0.23 tons per acre) annually leaving the forest buffer and entering the stream channels for the study area. A road surface erosion study located in the Appalachians in similar weathered gneiss and schist geology resulted in a range of 44 to 395 tons per hectare per year (18 to 160 tons per acre per year) (Swift, 1984). The lower end being from established roads with native surface, and light traffic. The average sediment yield of 395 tons per hectare per year is from a new road, with native surface, and moderate traffic. Their sediment yield range is higher than the averages in this most likely because the Appalachians receive almost twice as much precipitation annually than the Mica Creek Watershed. A similar study on sediment production from forest roads was done in western Montana, and found a mean annual sediment yield of 5.4 tons per hectare (Sugden and Woods, in press). Their study area was made up of coarse gravelly soils weathered from the Belt Supergroup and glacial tills, similar to the soils of the Mica Creek Watershed. The high proportion of coarse fragments (57.4 % of roadbed greater than 2 mm) is partially the reason for the relatively low mean annual sediment yield (Sugden and Woods, in press). The roads surveyed in the Mica Creek study area were found to have anywhere from 20 to 80 % coarse fragment content, and explains, in part, the lower annual sediment yield averages.

The results from NETWORK2000 for each alternative are shown in Figures 30 and 31, in terms of variable and fixed costs. The total variable costs do not vary much (10.1% at most) because the same timber volume, landing locations, and mill locations were used for all the alternatives. However, there are large changes in fixed costs because they include environmental costs associated with erosion as well as the road construction costs.

Actual costs used in cost comparison (Figures 32 and 33) are the total costs excluding the environmental costs. The environmental costs are used to weight the road segments based on sediment yield and is not an actual transportation cost in comparing the alternatives. The hauling costs are the same as the variable costs from the NETWORK 2000 output, and have an increasing trend with the increase of each environmental cost factor. This increasing trend is due to the increase of environmental costs. NETWORK 2000 considers road segments that produce much sediment less attractive, and this results in the model taking "go-around routes" that increase actual transportation costs, but reduce overall sediment yields from the network. The construction costs are the fixed costs from the NETWORK 2000 output minus the associated environmental costs for each alternative and do not vary by more than 6.7% (Tables 6 and 7). The total actual cost in Figures 32 and 33 is the hauling cost added to the construction costs for each alternative, and also has an increasing trend as variable costs increase with the increase of the environmental cost factors. Total actual costs for all eleven alternatives do not vary by more than 10%.

Alternatives 2 through 5, and alternative 1 show a decreasing trend in sediment yield with the increase of the environmental cost factors for both the total sediment yield leaving the road surface and delivered to stream channels (Figure 34). Alternatives 6 through 11 and alternative 1 show a decreasing trend in sediment yield delivered to stream channels with the increase of the environmental cost factors, but not for sediment yield leaving the road surface (Figure 34). This is because there are road segments that have more sediment predicted to be leaving the road surface (e.g., Segment A in Figure 35) than others (e.g., Segment B), could have a longer forest buffer (distance to stream channels), and therefore a lesser sediment yield delivered to stream channels than Segment B (Figure 35). Because alternatives 6 through 11 associated environmental costs were based on sediment yield delivered to the stream channels, the associated predicted sediment yield leaving the road surface does not follow a trend (See Alternatives 8 and 9 in Table 7).

Interestingly, the alternatives using sediment yields from the road surface (alternatives 2-5) have a lesser amount of sediment delivered to stream channels than their corresponding alternatives with same cost factors (alternatives 6 through 9) (Figure 34). This is because 96% of the total road segments evaluated by WEPP:Road have some sediment yield predicted to be leaving the road surface and only 54% of the segments have a predicted sediment yield delivered to stream channels. This means that 96% of the segments had an environmental cost for finding the alternatives 2 through 5, and only 54% of the segments had an environmental cost for finding alternatives 6 through 11. All road segments that have a predicted sediment yield delivered to streams also have a predicted sediment yield from the road surface. But not all segments that have a predicted sediment yield from the road surface have a predicted sediment yield delivered to streams. Therefore, minimizing sediment yield for more road segments (i.e. Alternatives 2 -5) results in less sediment yield delivered to streams.

Overall trends can be seen in the percent increase in cost from alternative 1 versus the percent decrease in predicted sediment yields (Figures 36 and 37). The trend follows a slow steady increase in cost with a rapid decrease in sediment yields. The total network costs for all the alternatives are within $1.9 million dollars of the total network cost for alternative 1 (Tables 6 and 7) or maximum 10% increase in cost compared to alternative 1 (Figures 36 and 37). However, these ten alternatives produce at least 47.9 tons less sediment yield (or 29% decrease) than alternative 1 for sediment predicted leaving the road surface, and at least 8.5 tons less sediment yield (or 19% decrease) than alternative for predicted sediment amounts leaving the forest buffer and delivered to stream channels. These results indicate that a large amount of sediment can be reduced at the expense of a relatively small cost increase.

Alternative 5 seems to be the most efficient alternative among 4 alternatives looking at sediment leaving the road surface because it reduces predicted sediment yields leaving the forest road surface and leaving the forest buffer, respectively, by 38% and 32%, while the increase in cost from alternative 1 is only 4.8%. In comparing the alternative routes 1 and 5 using ArcGIS (Figure 23), segments in alternative 1 and not in alternative 5 have an average 7.31 tons per hectare (2.96 tons per acre) leaving the road surface, and 1.67 tons per hectare (0.68 tons per acre) entering stream channels. Both these sediment yield averages are much greater than the current averages of 2.05 tons per hectare (0.83 tons per acre) annually leaving the road surface, and an average of 1.57 tons per hectare (0.23 tons per acre) leaving the forest buffer and entering the stream channels for the entire study area. Segments in alternative 5 and not in alternative 1 have an average of 0.48 tons per hectare (0.194 tons per acre) leaving the road surface and 0.11 tons per hectare (0.043 tons per acre) delivered to stream channels. Both of these sediment yields are lower than yields for segments in alternative 1 only, and for the current road network. NETWORK 2000 avoided the segments found only in alternative 1 for alternative 5 because the higher sediment yields from those segments increased the associated environmental costs considerably.

The two alternatives that show the greatest decrease in sediment yields among alternatives 6 through 11, are alternatives 10 and 11. Alternative 10 reduced sediment yields from alternative 1 by 38% from the forest road surface, and by 38% leaving the forest buffer and entering stream channels. Alternative 11 reduced sediment yields from alternative 1 by 39% from the forest road surface, and by 39% predicted leaving the forest buffer and entering stream channels. These two alternatives use the higher environmental costs of $500 and $1000 per pound of sediment yield respectively, and result in the highest actual network costs (8.6% and 10.2% greater than alternative 1, respectively).

All the alternative network lengths were within approximately 14.7 kilometers (9 miles) of each other (Tables 6 and 7). There is no obvious trend found in the lengths of the alternatives. This may be because actual transportation costs and sediment yields from road segments are influenced not only by segment lengths, but also by road gradient, driving speed, proximity to streams, and many other road attributes considered in WEPP:Road. The environmental cost or predicted sediment yield is generally greater for a longer segment especially where the gradient is steeper (Luce and Black 1999).

Therefore when using an environmental cost, it may cost less in the NETWORK 2000 program to choose a longer road segment that has a shallow gradient (i.e. less than 10%) than a steeper but short road. A graveled primary road has a lower hauling cost than for a secondary road due to its driving speed, and so the program may choose to take a longer primary route than a shorter secondary route. However, if the primary route has a higher associated environmental cost than the longer secondary route, then the program may choose the longer secondary route. Primary roads in the study area are often following the edge of a stream channel resulting in a continuous short forest buffer, while secondary roads are more often just crossing the stream channels. Primary roads also have heavier traffic than secondary roads, which results in a higher sediment yield coming from primary roads. Primary roads were estimated to have 7.16 tons per hectare leaving the road surface and 1.95 tons per hectare delivered to stream channels. Secondary roads were estimated to have 1.26 tons per hectare leaving the road surface and 0.35 tons per hectare delivered to stream channels, and are 82% lower on average than primary roads. Therefore, after the addition of an environmental cost, primary roads become more expensive to travel on average. Table 8 shows that all of the alternative transportation routes use more secondary roads than primary roads and the length of primary road is generally decreasing with increasing environmental costs.

Approximately 74 kilometers of proposed road were evaluated in this study. These proposed roads are either abandoned and proposed by Potlatch for reconstruction, or are non-existent and proposed to be constructed. The NETWORK 2000 results indicate that at most 56 km of roads need to be built to provide access to the given landing locations. In addition, all the alternatives show that at least 50% of the 779 kilometers of current total road network length in the study area can be reduced. These alternatives at the very least can guide Potlatch forest managers in locating roads that are unnecessary and identified having a high risk of erosion. The roads deemed unnecessary will continue to cause environmental impacts if left untreated and abandoned. Erosion rates remain higher than background levels as long as roads remain in place, making them a chronic sediment source (Parker 2005). Roads that are identified to have a potential high risk of erosion can increase maintenance costs and the associated environmental impacts. Road design improvements such as decreasing spacing between drainage structures can be used to reduce this risk. Seeding and mulching areas of disturbed soil and/or areas of potential erosion problems could be another way to decrease the risk of erosion (Potlatch 2005).

CONCLUSION

This study demonstrates that incorporating environmental impacts of forest roads into an economic analysis of road networks can provide improved road systems which reduce the environmental impacts while maintaining cost efficiency. The environmentally considerate alternatives were able to reduce sediment yields by as much as 39% at the expense of 10.2% cost increase compared to the least cost alternative. The roads that were evaluated and determined to no longer have an economic use in the study area could be closed or decommissioned upon the decisions of land managers.

A large amount of data was needed to successfully run the U.S.F.S. WEPP:Road and the NETWORK 2000 models together, but has shown to be an effective method of evaluating a large watershed. GIS knowledge of raster data from a DEM is required to accurately, and efficiently retrieve the data for these two models. The use of a 1 meter DEM is recommended for more accurate elevation and slope data, but may be difficult and/or expensive to attain.

This transportation planning method was not replicated and should be used for the Mica Creek Wathershed only as guidance for decision making on road management. This method does not currently consider maintenance costs, but incorporating the maintenance schedule and costs into this method would be more realistic in road management and could significantly improve the results. Results would also improve based on a more realistic economic cost associated with each road segment for NETWORK2000.

The eleven alternatives are all based on the assumed traffic levels and conditions of the current transportation network. The predicted sediment amounts are therefore also based on the current network conditions. Incorporating the alternative networks with adjustable traffic levels and road conditions may provide more realistic results in reducing sediment yields. Roads that were secondary may need to be used as a primary road in the new alternative road systems depending on traffic routes. A higher traffic level would also increase and could potentially cause a higher sediment yield than that of the current road network. Future research should include linking the outputs of NETWORK 2000 back to WEPP:Road to re-estimate sediment yields as new traffic routes are developed.

There is no obvious method for choosing an appropriate environmental cost factor for predicted sediment yields from the road surface and delivered to stream channels. A forest manager would need to assess the final network costs for all the alternatives relative to budget constraints, maintenance costs, willingness to reduce sediment yields at the expense of increasing costs, and would also need to assess the conditions of the actual routes in the field. These alternatives at the very least can guide forest managers in locating roads that are economically unnecessary and roads having a high risk of erosion. The integration of an environmental cost into forest transportation planning not only improves the economic efficiency of the transportation network, but it also adds conservation to forest transportation management.

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APPENDIX A

TABLES

Table 1. AVERAGES FOR UNSURVEYED AND PROPOSED ROADS

ROAD ClASS	ROAD WIDTH (m)	FILLSLOPE (%)	FILLSLOPE LENGTH (m)	ROCK FRAGMENT (%)
PRIMARY 1	3.7	71.816	3.393	20
PRIMARY 2	4.3	53.676	4.663	60
PRIMARY 3	3.7	98.090	2.708	40
PRIMARY 4	3.7	69.093	3.124	60
SECONDARY 1	3.7	71.614	4.378	40
SECONDARY 2	3.7	74.347	4.182	40
SECONDARY 3	3.7	73.851	3.804	80
SECONDARY 4	3.1	66.446	3.408	40
SECONDARY 5	3.7	72.922	2.770	20
SECONDARY 6	3.1	67.269	2.693	20
SECONDARY 7	3.1	78.052	2.748	60

Table 2. VARIABLE COST MULTIPLIERS

ROAD CLASS	MULTILPLIERS
PAVED HIGHWAY	$.60 / mile/ MBF
PAVED OR ROCKED LOCAL	$1.00 / mile/ MBF
PRIMARY	$2.00 / mile/ MBF
SECONDARY	$3.00 / mile/ MBF

Table 3. ENVIRONMENTAL COST FACTORS

Environmental Cost Factors Per Pound of Sediment	Used for Sediment Amount Leaving Road Surface	Used for Sediment Amount Leaving Forest Buffer
$10 / lb.	X	X
$25 / lb.	X	X
$50 / lb.	X	X
$100 / lb.	X	X
$500 / lb.		X
$1000 / lb.		X

Table 4. NETWORK 2000 RESULTS

Results for Sediment Leaving the Road Surface Environmental Costs

ALTERNATIVES	Total discounted variable cost	Total discounted fixed cost	Total discounted variable and fixed cost
1	17,847,200.80 (43.30 $/MBF)	835,475.17 (2.03 $/MBF)	18,682,675.97 (45.32 $/MBF)
2	17,998,940.55 (43.66 $/MBF)	3,262,260.55 (7.91 $/MBF)	21,261,201.10 (51.58 $/MBF)
3	18,152,716.43 (44.04 $/MBF)	6,507,286.90 (15.79 $/MBF)	24,660,003.33 (59.82 $/MBF)
4	18,598,029.59 (45.12 $/MBF)	11,936,801.59 (28.96 $/MBF)	30,534,831.18 (74.07 $/MBF)
5	18,722,487.07 (45.42 $/MBF)	22,858,858.84 (55.45 $/MBF)	41,581,345.91 (100.87 $/MBF)

Table 5. NETWORK 2000 RESULTS

Results for Sediment Leaving Forest Buffer Environmental Costs

ALTERNATIVES	Total discounted variable cost	Total discounted fixed cost	Total discounted variable and fixed cost
1	17,847,200.80 (43.30 $/MBF)	835,475.17 (2.03 $/MBF)	18,682,675.97 (45.32 $/MBF)
6	17,905,792.15 (43.44 $/MBF)	967,728.25 (2.35 $/MBF)	18,873,520.40 (45.79 $/MBF)
7	18,006,340.75 (43.68 $/MBF)	2,178,595.28 (5.29 $/MBF)	20,184,936.04 (48.97 $/MBF)
8	18,079,219.76 (43.86 $/MBF)	4,314,265.26 (10.47 $/MBF)	22,393,485.02 (54.32 $/MBF)
9	18,201,617.99 (44.16 $/MBF)	7,696,893.32 (18.67 $/MBF)	25,898,511.30 (62.83 $/MBF)
10	19,335,944.45 (46.96 $/MBF)	31,386,929.63 (76.14 $/MBF)	50,742,874.08 (123.10 $/MBF)
11	19,651,808.06 (47.67 $/MBF)	60,443,075.27 (146.63 $/MBF)	80,094,883.32 (194.30 $/MBF)

Table 6. COMPARISONS OF ACTUAL COSTS
Results for Sediment Leaving the Road Surface Environmental Costs

Alternatives	Environmental Cost	Hauling Costs (millions)	Construction Costs (thousands)	Total Network Cost (millions)	Total Road Length (km)	Total Sediment Leaving Road (tons)	Total Sediment Delivered to Streams (tons)
1	NONE	17.9	841.6	18.7	388.8	162.9	44.5
2	$10 / lb.	18.0	836.0	18.8	379.6	110.1	33.5
3	$25 / lb.	18.1	827.4	18.9	374.1	103.1	32.1
4	$50 / lb.	18.6	853.3	19.5	375.8	100.6	30.4
5	$100 / lb.	18.7	853.3	19.6	377.9	100.3	30.2

Table 7. COMPARISONS OF ACTUAL COSTS
Results for Sediment Leaving Forest Buffer Environmental Costs

Alternatives	Environmental Cost	Hauling Costs (millions)	Construction Costs (thousands)	Total Network Cost (millions)	Total Road Length (km)	Total Sediment Leaving Road (tons)	Total Sediment Delivered to Streams (tons)
1	NONE	17.9	841.6	18.7	388.8	162.9	44.5
6	$10 / lb.	17.9	875.7	18.8	383.6	115.0	36.0
7	$25 / lb.	18.0	839.0	18.9	380.2	109.5	32.2
8	$50 / lb.	18.1	845.5	19.0	386.5	106.4	31.7
9	$100 / lb.	18.2	851.7	19.1	386.4	108.2	31.3
10	$500 / lb.	19.4	880.4	20.3	384.5	101.3	27.7
11	$1000 / lb.	19.7	878.1	20.6	384.6	99.7	27.0

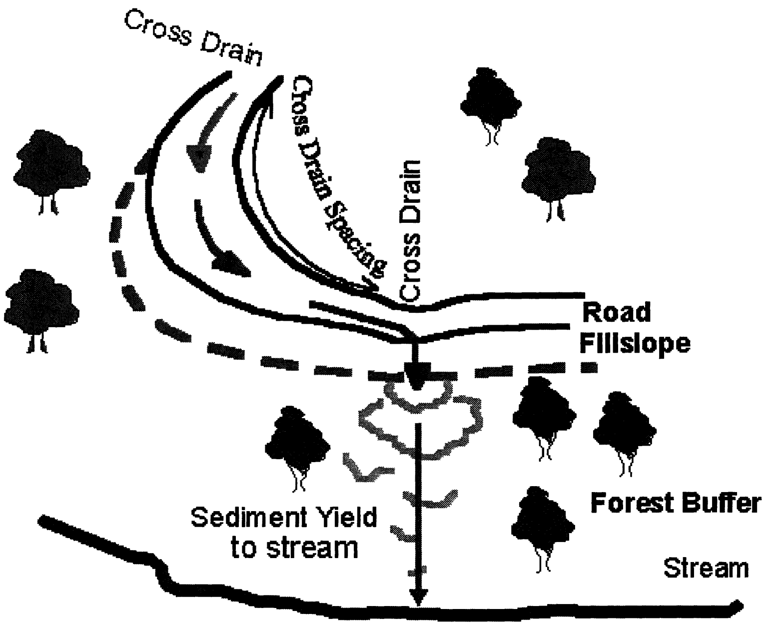
Table 8. LENGTH OF EACH ROAD CLASS FOR ALTERNATIVES

Alternatives	Primary (km)	Secondary (km)	Highways (km)	Unpaved Local (km)	Total Length (km)
1	89	214	37	49	389
2	86	208	37	49	380
3	83	205	37	49	374
4	80	207	37	52	376
5	80	209	37	52	378
6	86	212	37	49	384
7	85	210	37	49	380
8	84	214	37	52	387
9	85	213	37	52	386
10	78	218	37	52	384
11	77	220	37	52	385

APPENDIX B

FIGURES

Figure 1. FOREST ROAD EROSION **
Relationship of road, fill slope, forest buffer and stream for WEPP:Road

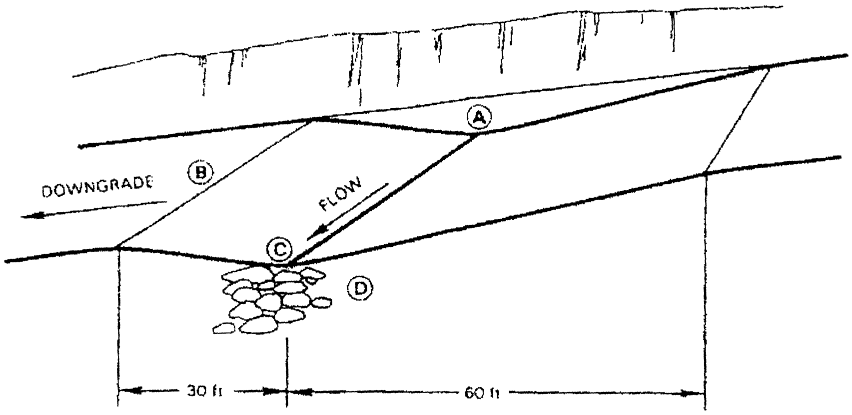


** From WEPP:Road Technical Documentation, Elliot et.al.

Figure 2. LOCATION OF MICA CREEK WATERSHED IN IDAHO

- Prepared by John Gravel, University of Idaho, 2003.

Figure 3. ROLLING DIP (Potlatch 2005)

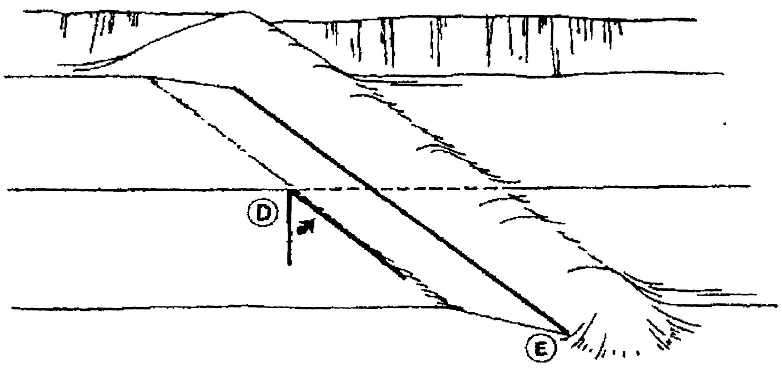


Design of outsloped dips for forest roads. A to C, slope about 4 to 6 inches to assure lateral flow, B. no material accumulated at this point — may require surfacing to prevent cutting; D. provide rock rip-rap to prevent erosion

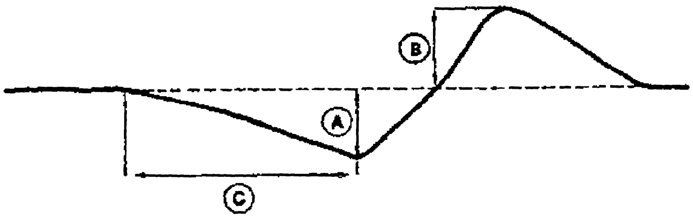
Figure 4. CROSS-DITCH (Potlatch 2005)

Cross-ditch for roads with limited or no traffic.

TOP VIEW



CROSS-SECTION AT CENTER LINE



Where ditch is present, cross-ditch should tie to ditch line and ditch should be blocked. **A**, 12 to 18 inch cut into roadbed; **B**, berm height 12 to 24 inches above roadbed; **C**, 3 to 5 feet; **D**, 30 to 45° downgrade; **E**, outlet obstructed.

Figure 5. MICA CREEK WATERSHED STUDY AREA

Prepared by: Jennifer Rackley
March 02, 2006

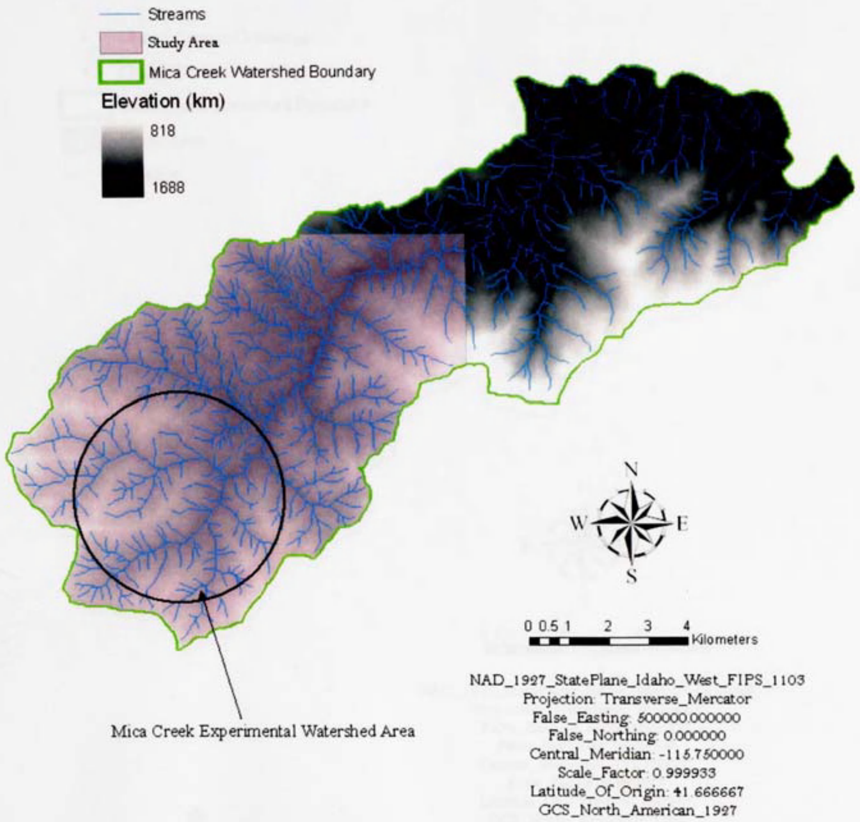
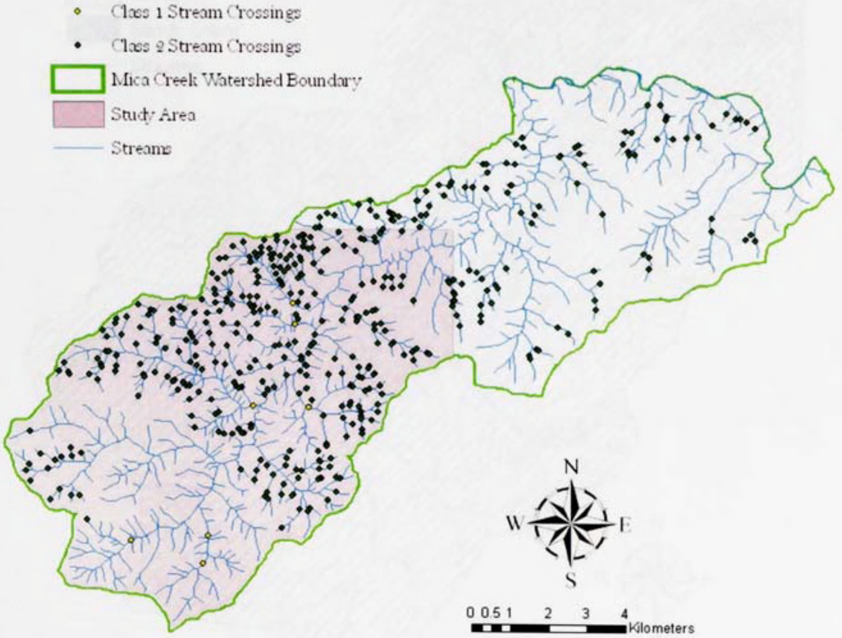


Figure 6. MICA CREEK WATERSHED STREAM CROSSINGS

Prepared by: Jennifer Rackley
March 02, 2006



NAD_1927_StatePlane_Idaho_West_FIPS_1103
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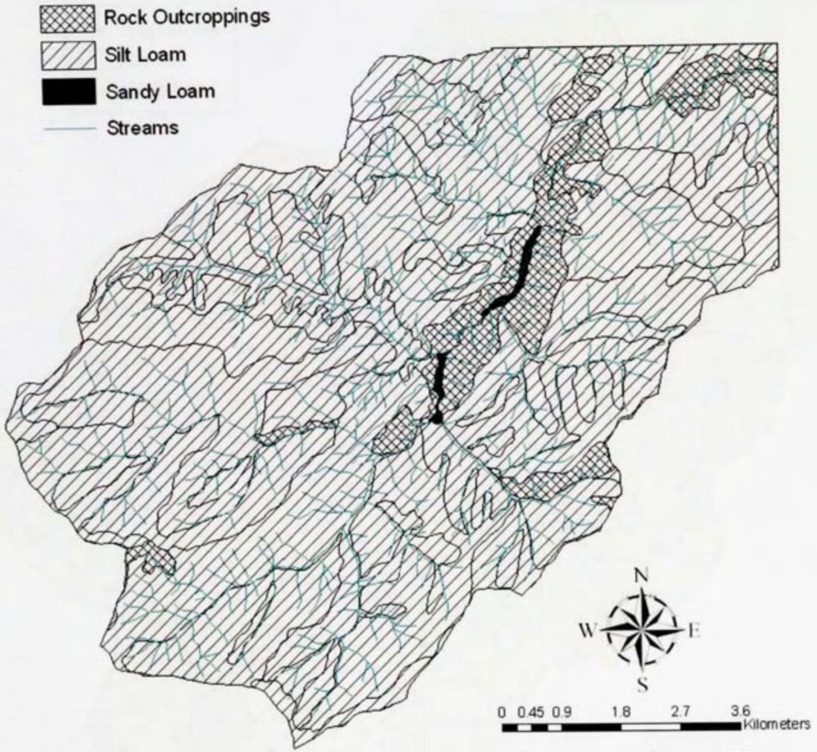
False_Easting: 500000.000000
False_Northing: 0.000000
Central_Meridian: -115.750000
Scale_Factor: 0.999933
Latitude_Of_Origin: 41.666667
GCS_North_American_1927

Figure 7. MICA CREEK SOILS

Prepared by: Jennifer Rackley
March 02. 2006



Metadata: Soil Survey Geographic (SSURGO)
Database for St. Joe Area, Idaho,
Parts of Benewah and Shoshone Counties
Originator: U.S. Department of Agriculture,
Natural Resources Conservation Service
Developer: National Cooperative Soil Survey 06/09/2005
URL:http://SoilDataMart.nrcs.usda.gov/

NAD_1927_StatePlane_Idaho_West_FIPS_1103
Projection: Transverse_Mercator
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False_Northing: 0.000000
Central_Meridian: -115.750000
Scale_Factor: 0.999933
Latitude_Of_Origin: 41.666667
GCS_North_American_1927

Figure 8. **Timber Harvest Stands and Designated Log Landings**

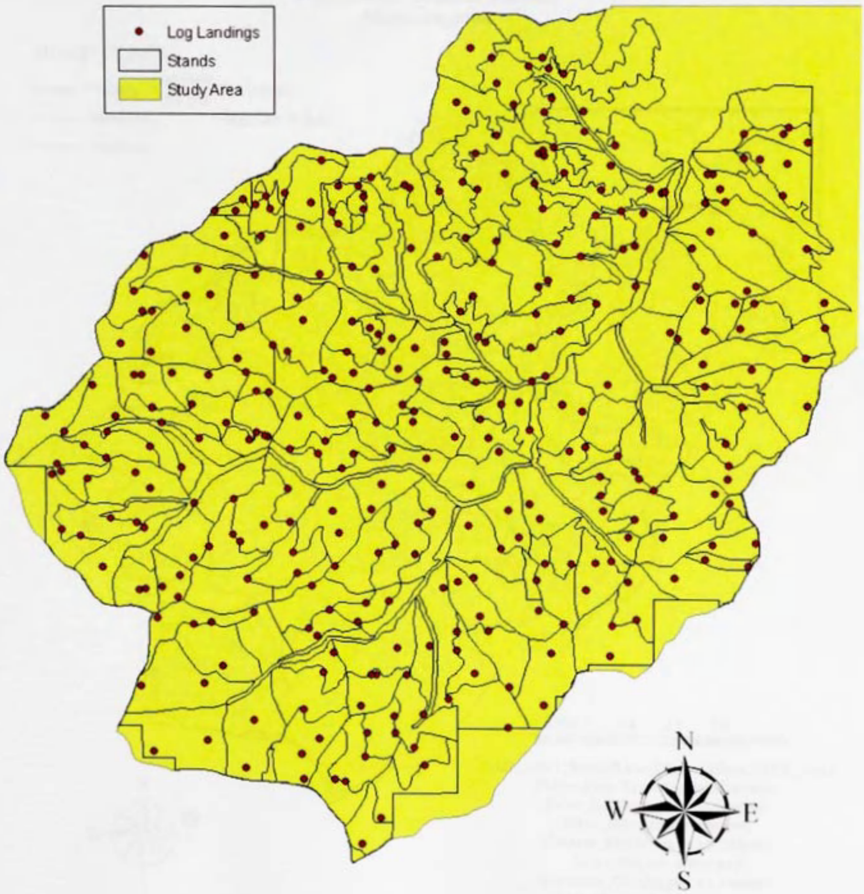


Figure 9.

STUDY AREA ROADS

Prepared by: Jennifer Rackley
March 02,2006

Figure 10.

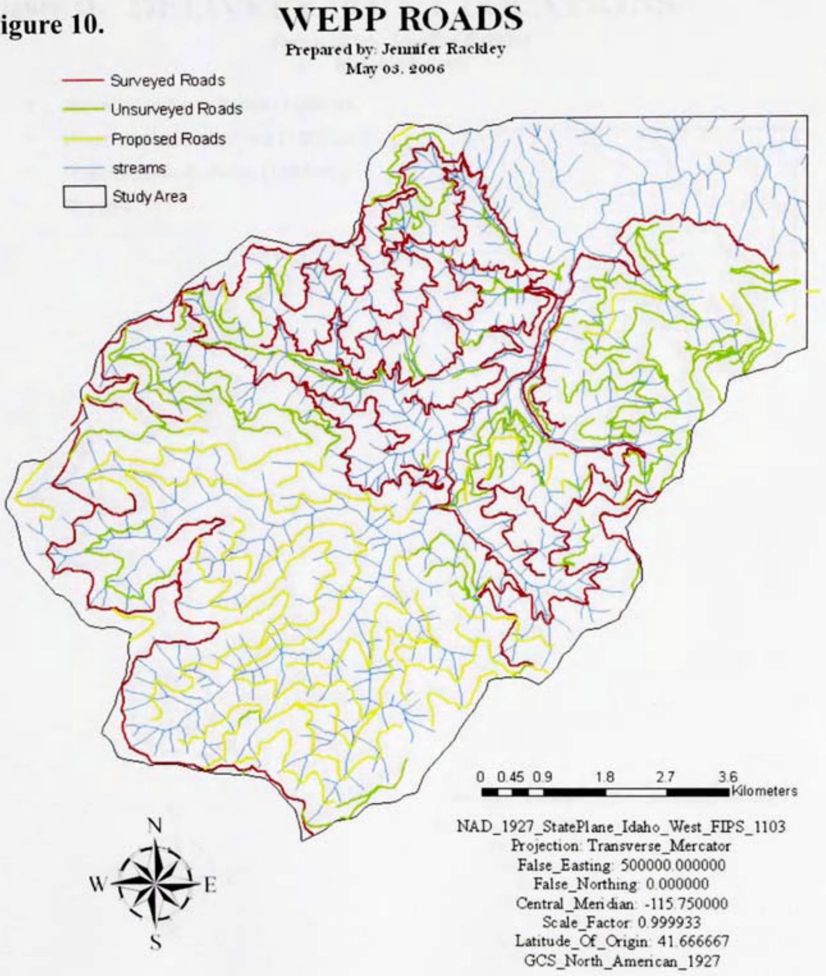

WEPP ROADS
Prepared by: Jennifer Rackley
May 03, 2006
Surveyed Roads
Unsurveyed Roads
Proposed Roads
streams
Study Area
0 0.45 0.9 1.8 2.7 3.6
Kilometers
N
W
E
S
NAD_1927_StatePlane_Idaho_West_FIPS_1103
Projection: Transverse_Mercator
False_Easting: 500000.000000
False_Northing: 0.000000
Central_Meridian: -115.750000
Scale_Factor: 0.999933
Latitude_Of_Origin: 41.666667
GCS_North_American_1927

Figure 11. **DELIVERY POINT LOCATIONS**

Prepared by: Jennifer Rackley
March 02, 2006

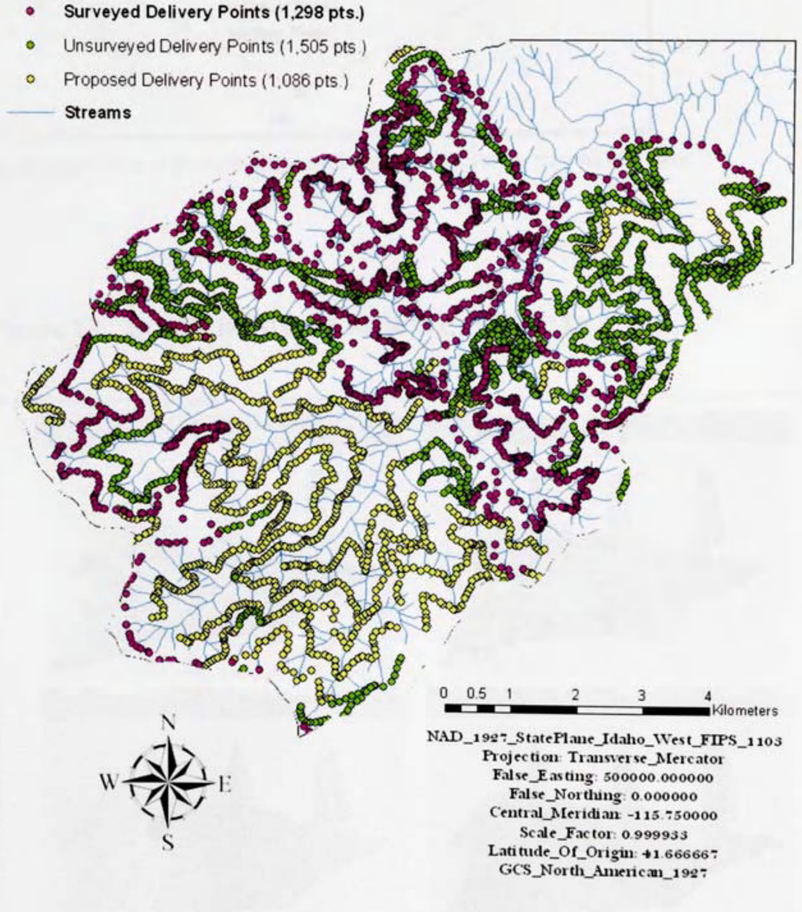
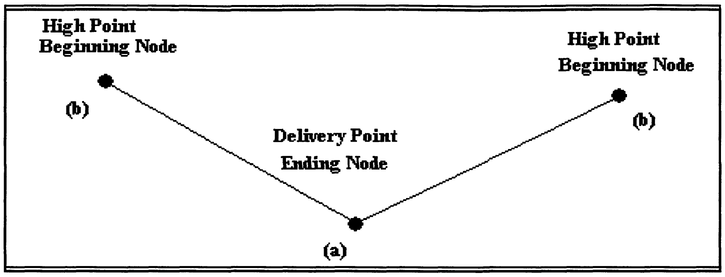
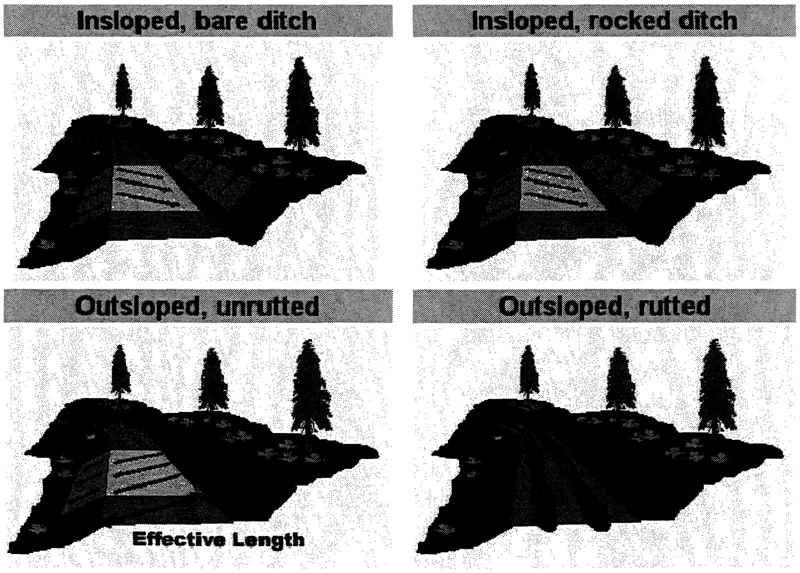


Figure 12. ROAD SEGMENT POINTS AND LINES CONCEPTS



Note. (a) Referred to as the To Node, and (b) is the From Node for NETWORK 2000.

Figure 13. ROAD DESIGNS FOR WEPP:ROAD**



**From WEPP:Road Technical Documentation, Elliot et al. 1999.

Figure 14. HIGH POINT & DIRECTIONAL FLOW

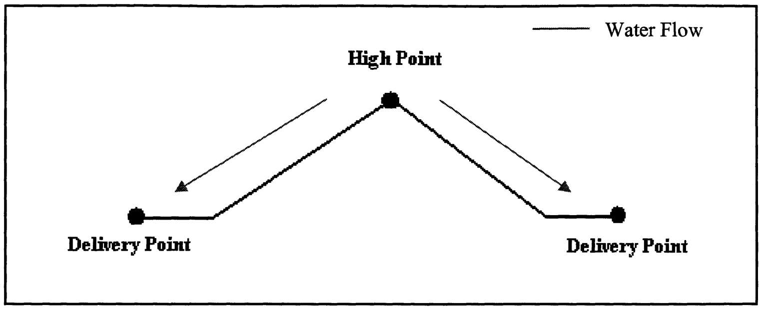


Figure 15. FLOWCHART OF THE HEURISTIC NETWORK ALGORITHM (Sessions 1985)

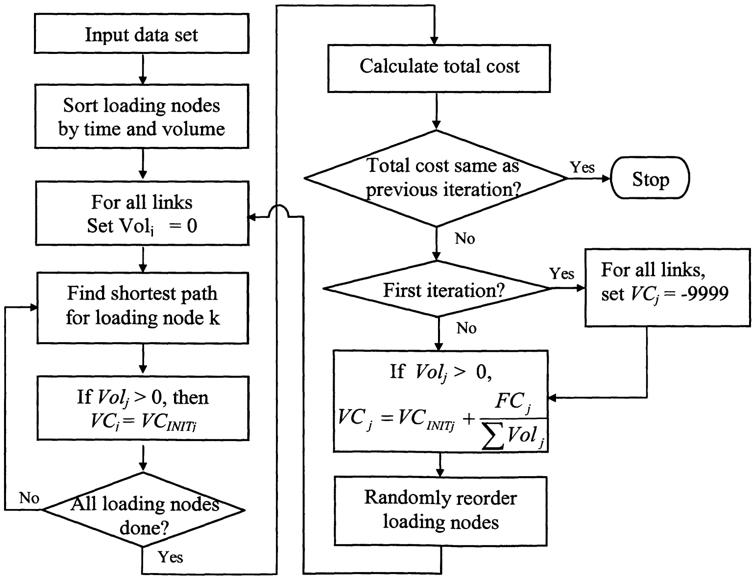


Figure 16. MILL LOCATIONS

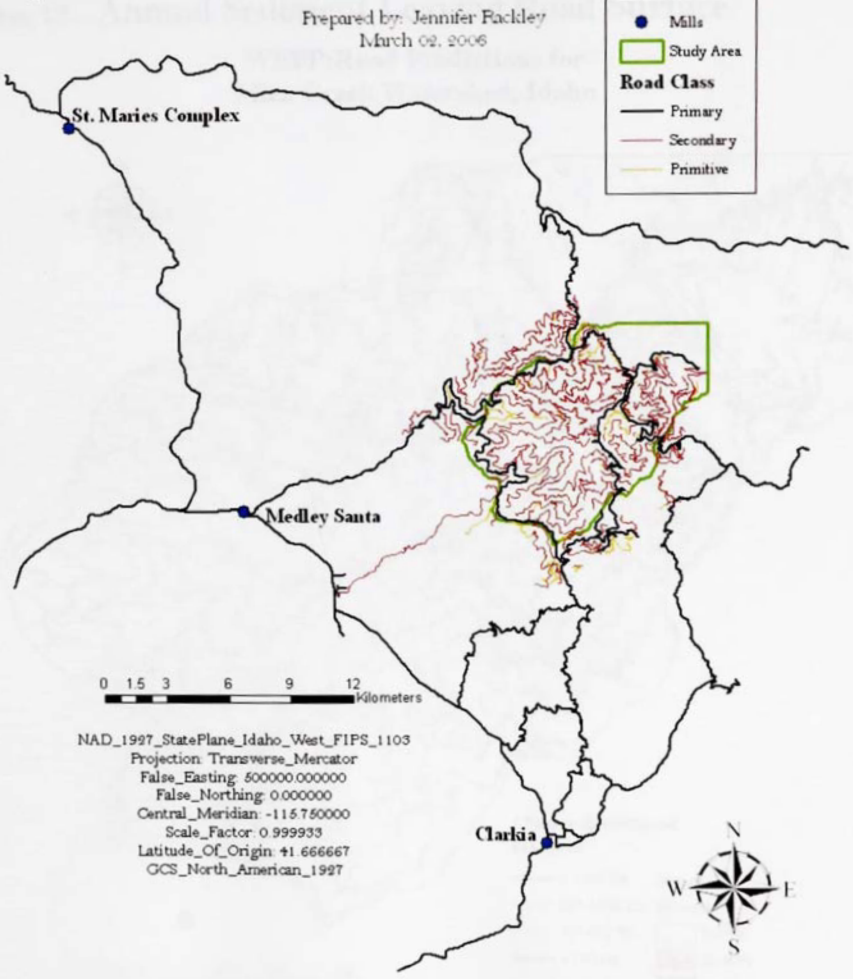


Figure 17. **Annual Sediment Leaving Road Surface**

WEPP:Road Predictions for Mica Creek Watershed, Idaho

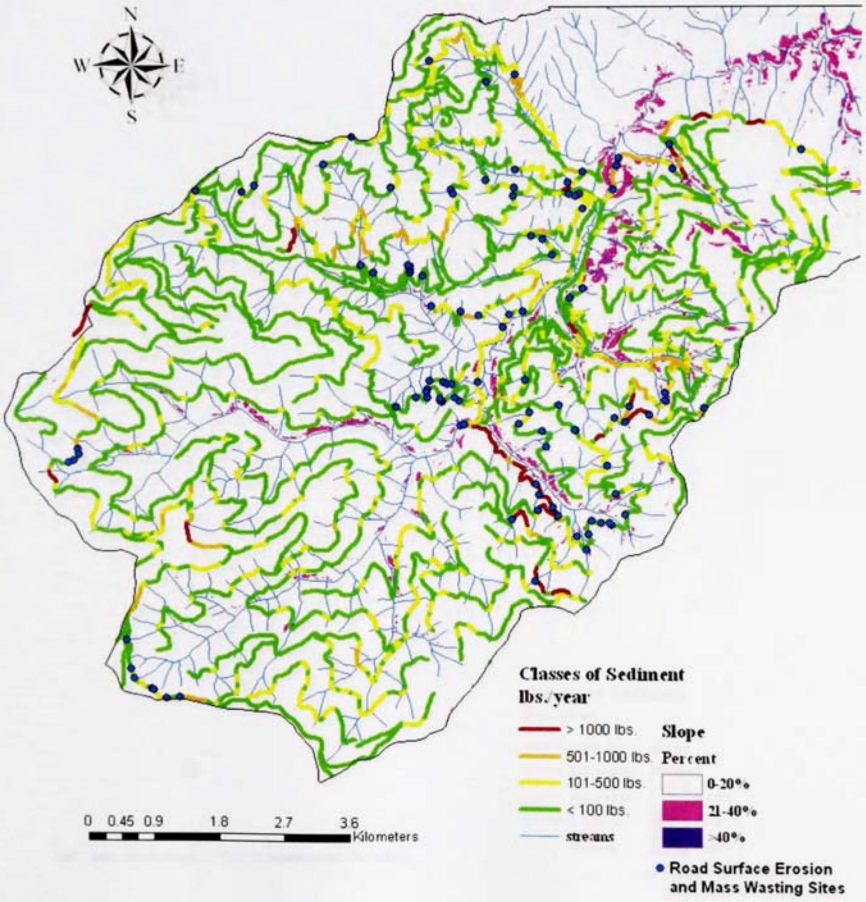


Figure 18. **Annual Sediment Leaving Stream Buffer and Delivered to Stream Channels**

WEPP:Road Predictions for Mica Creek Watershed, Idaho

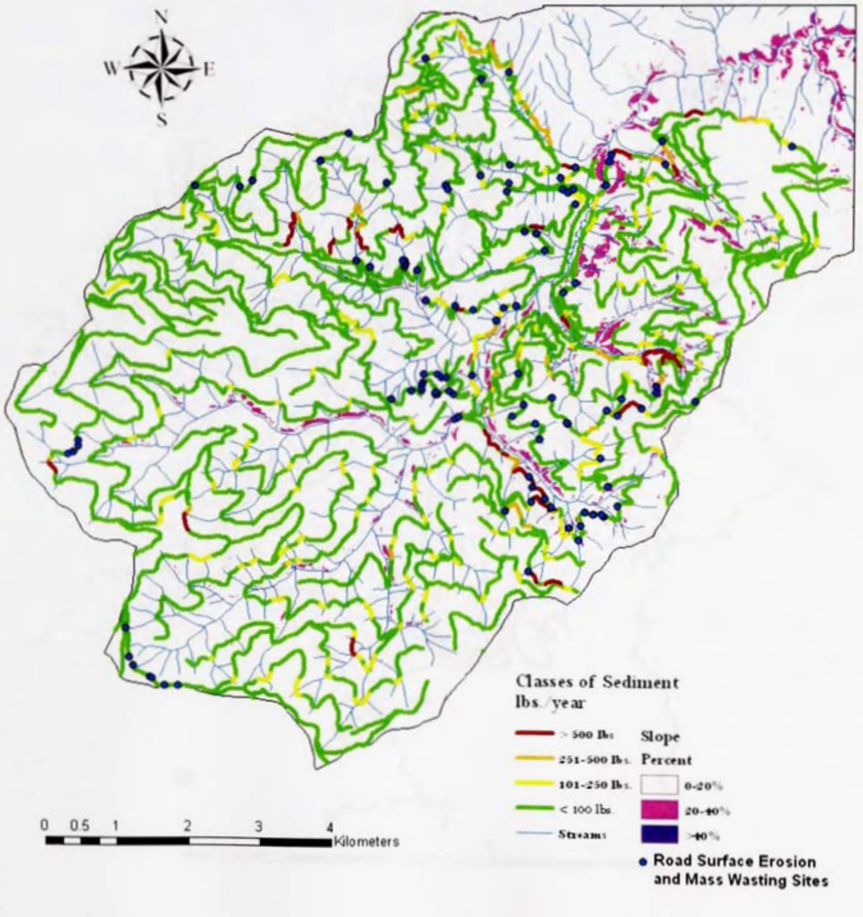


Figure 19. **ALTERNATIVE ROUTE 1**
NO ASSOCIATED ENVIRONMENTAL COST

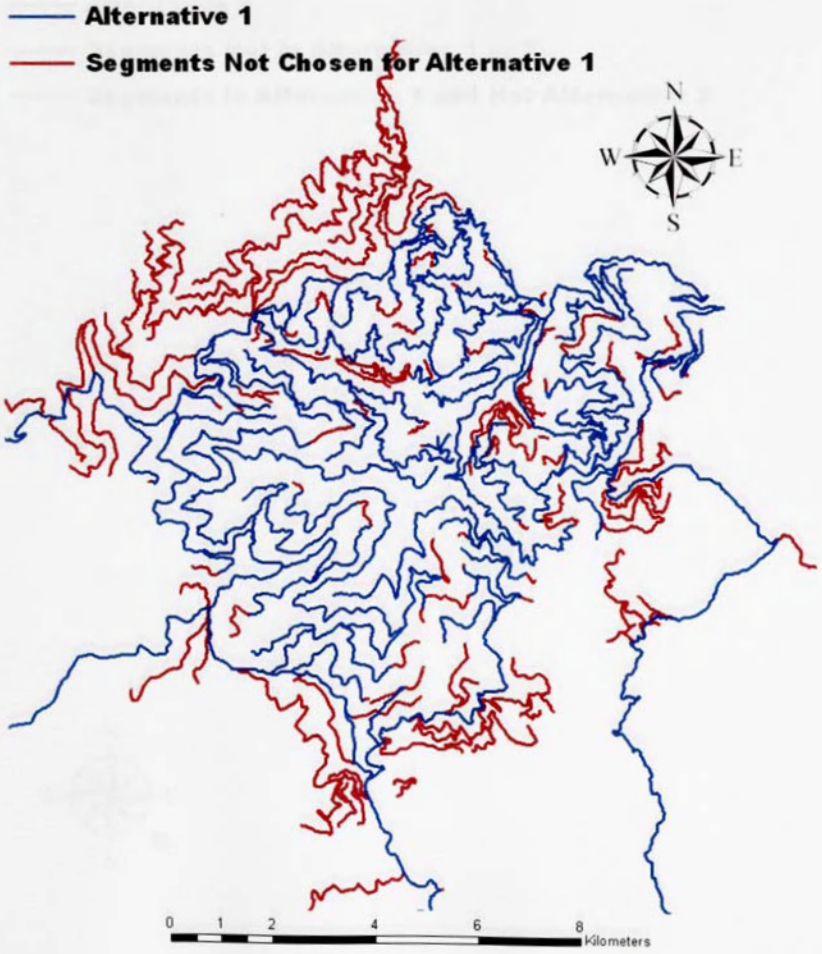


Figure 20. **ALTERNATIVE ROUTE 2 COMPARED WITH ALTERNATIVE 1**

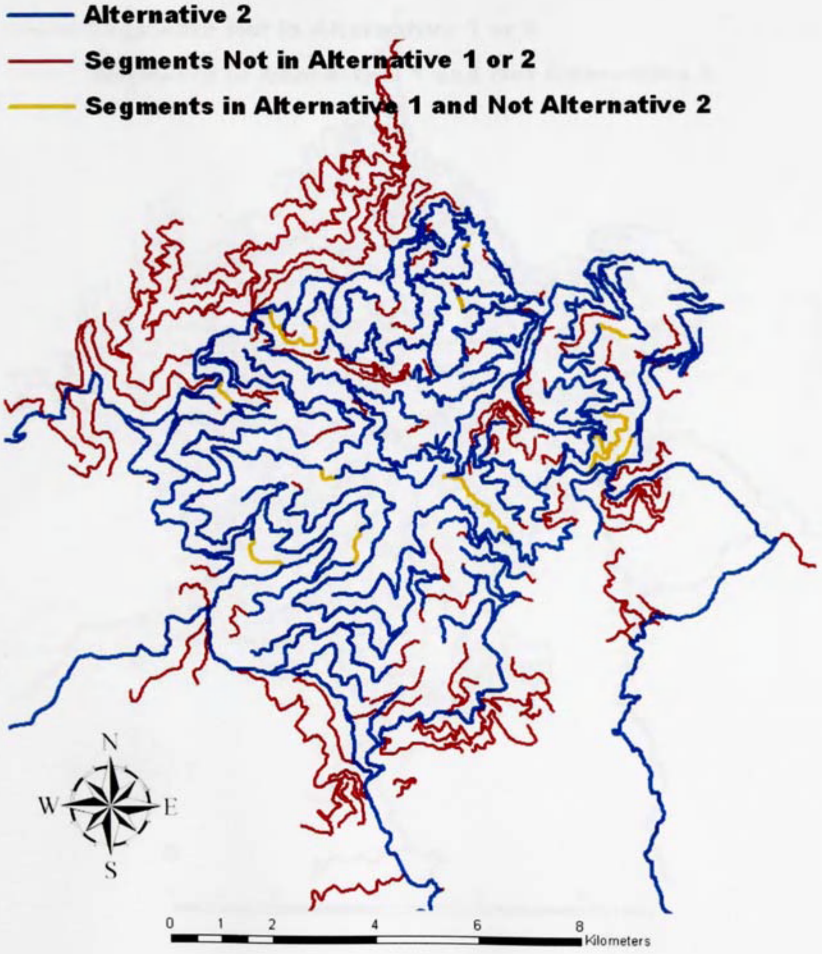


Figure 21. **ALTERNATIVE ROUTE 3 COMPARED WITH ALTERNATIVE 1**

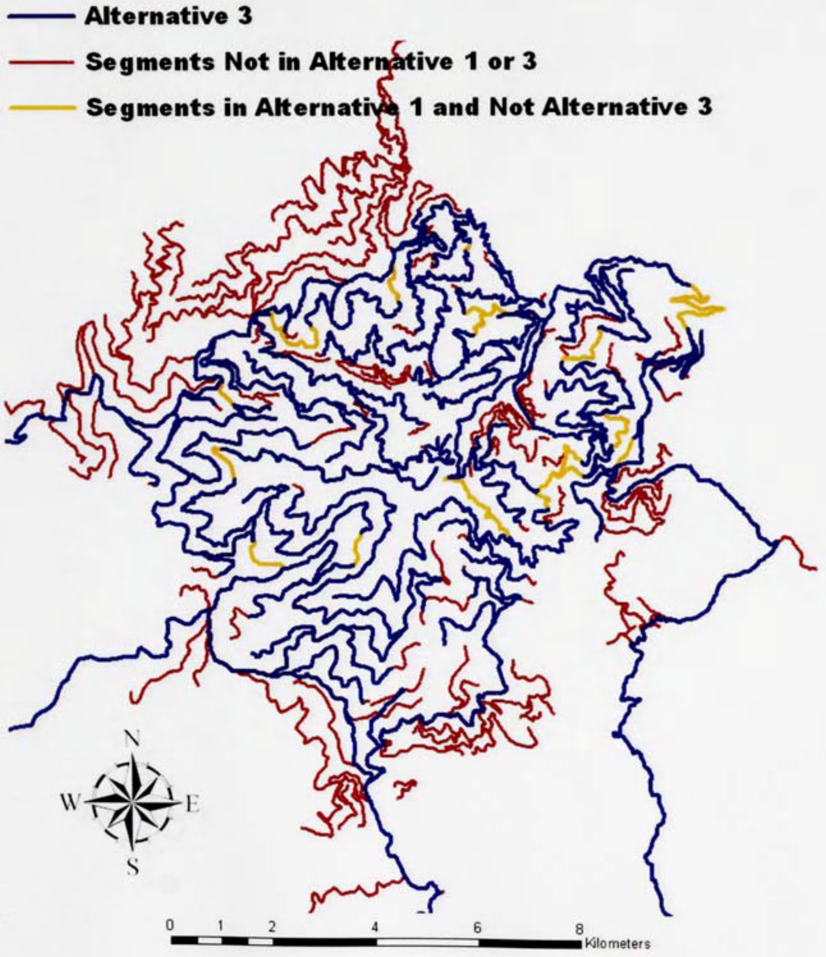


Figure 22. **ALTERNATIVE ROUTE 4 COMPARED WITH ALTERNATIVE 1**

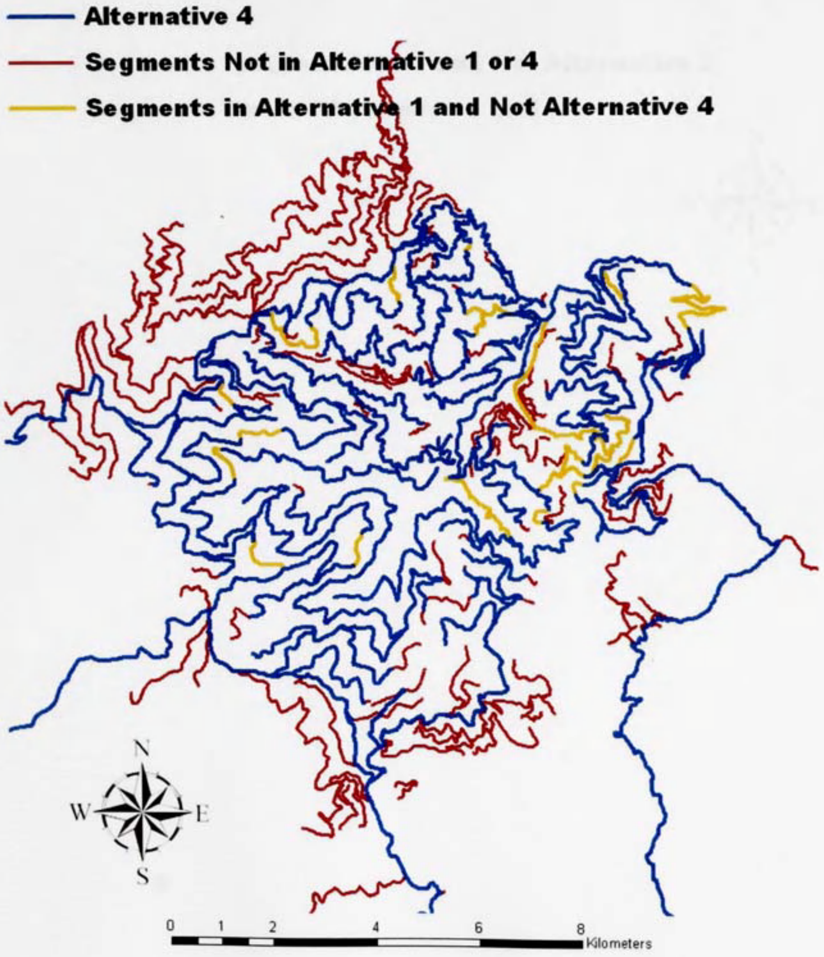


Figure 23. **ALTERNATIVE ROUTE 5 COMPARED WITH ALTERNATIVE 1**

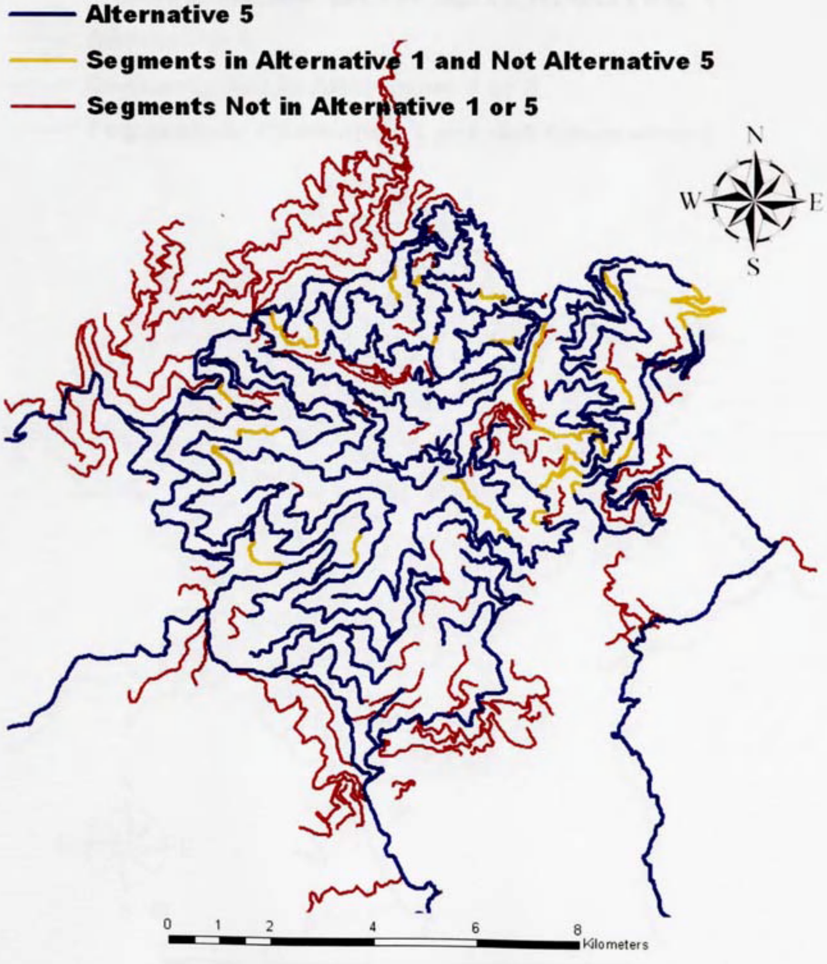


Figure 24. **ALTERNATIVE ROUTE 6 COMPARED WITH ALTERNATIVE 1**

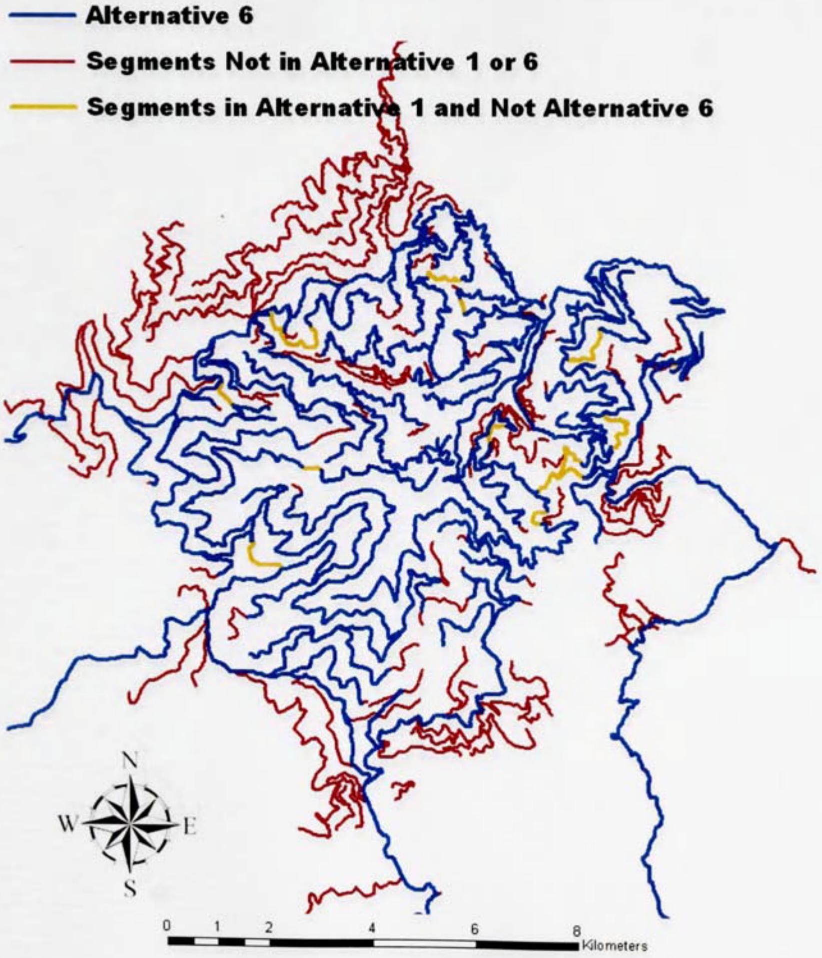


Figure 25. **ALTERNATIVE ROUTE 7 COMPARED WITH ALTERNATIVE 1**

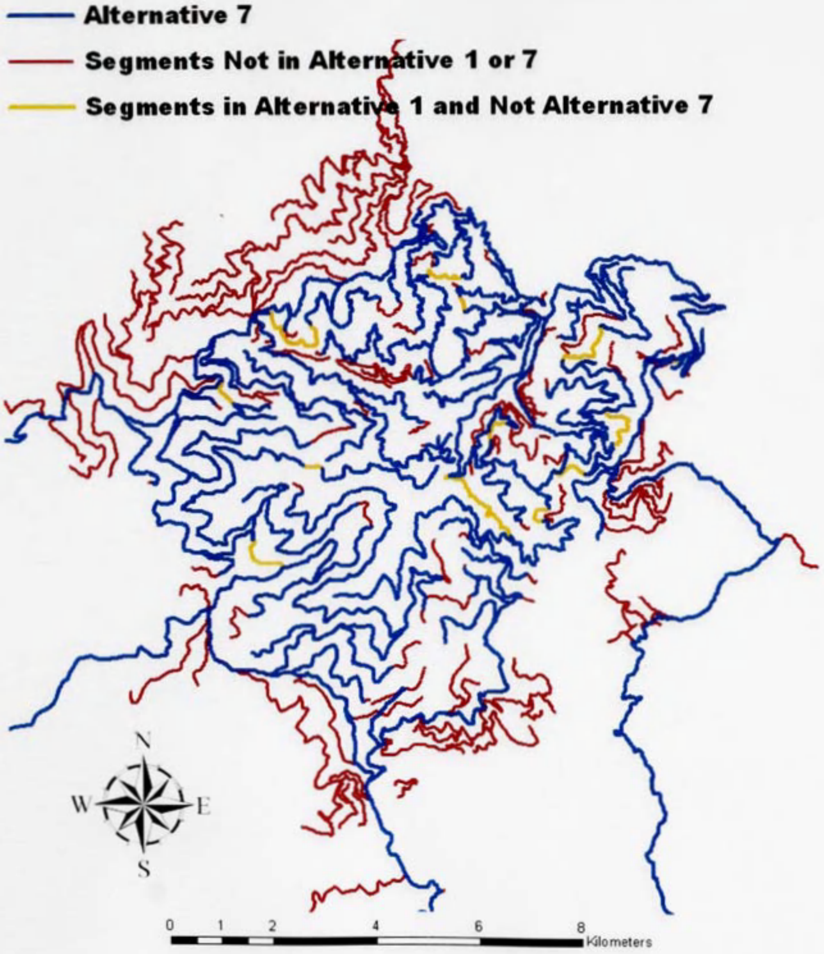


Figure 26. **ALTERNATIVE ROUTE 8 COMPARED WITH ALTERNATIVE 1**

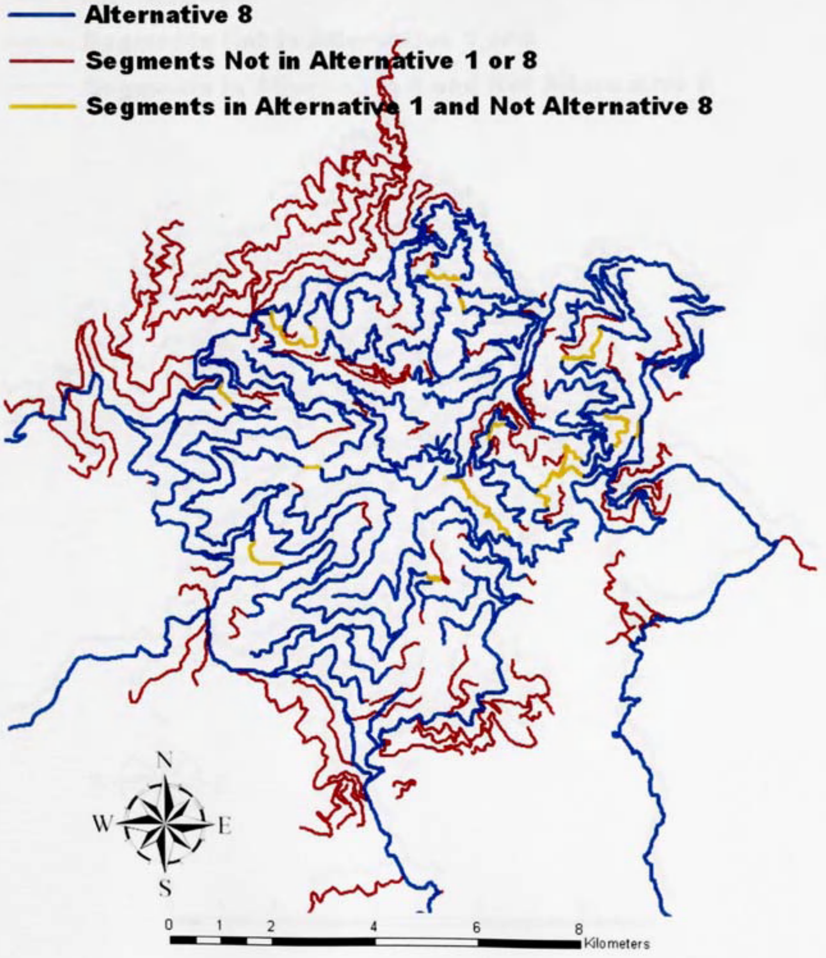


Figure 27. ALTERNATIVE ROUTE 9 COMPARED WITH ALTERNATIVE 1

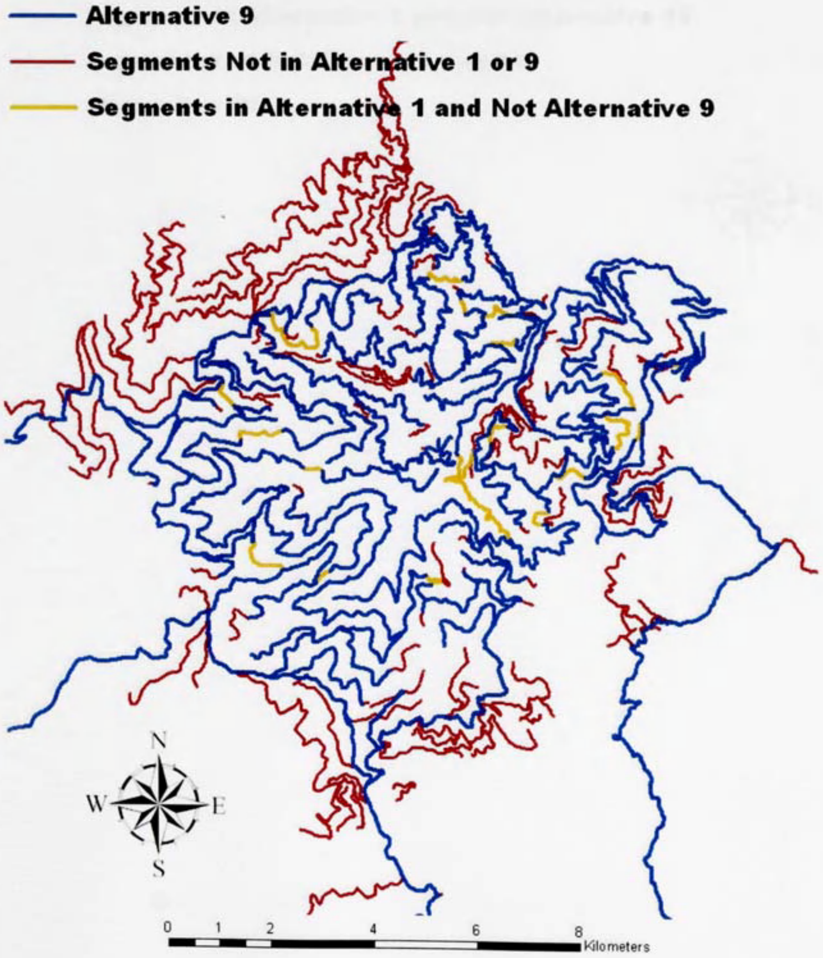


Figure 28. **ALTERNATIVE ROUTE 10 COMPARED WITH ALTERNATIVE 1**

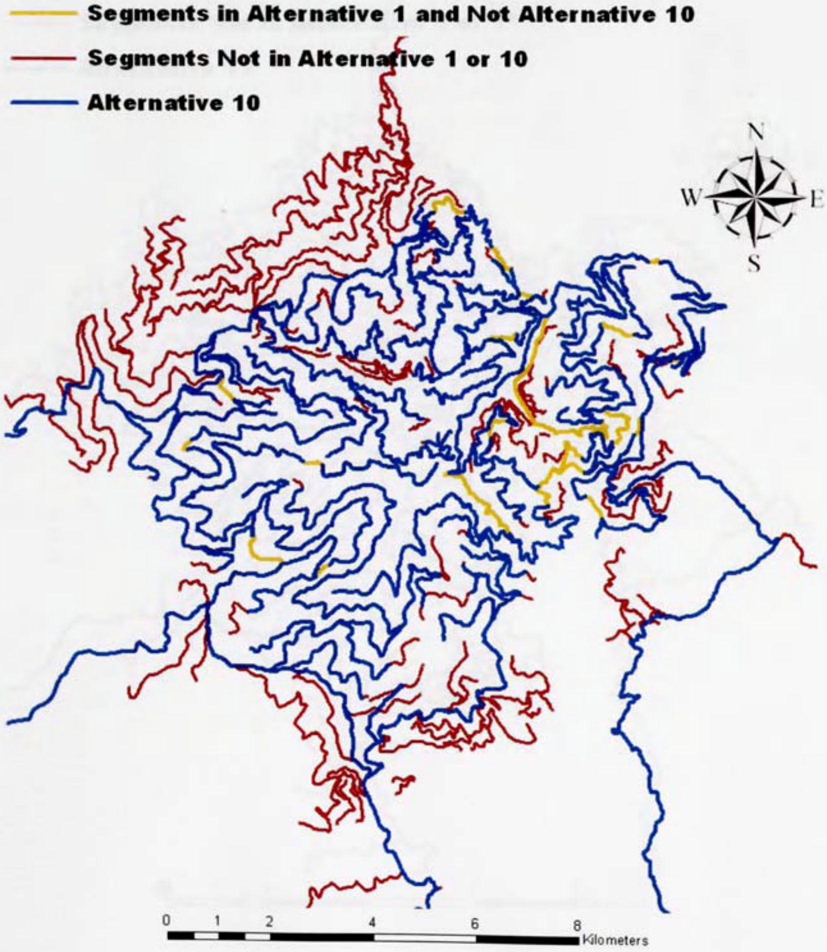


Figure 29. **ALTERNATIVE ROUTE 11 COMPARED WITH ALTERNATIVE 1**

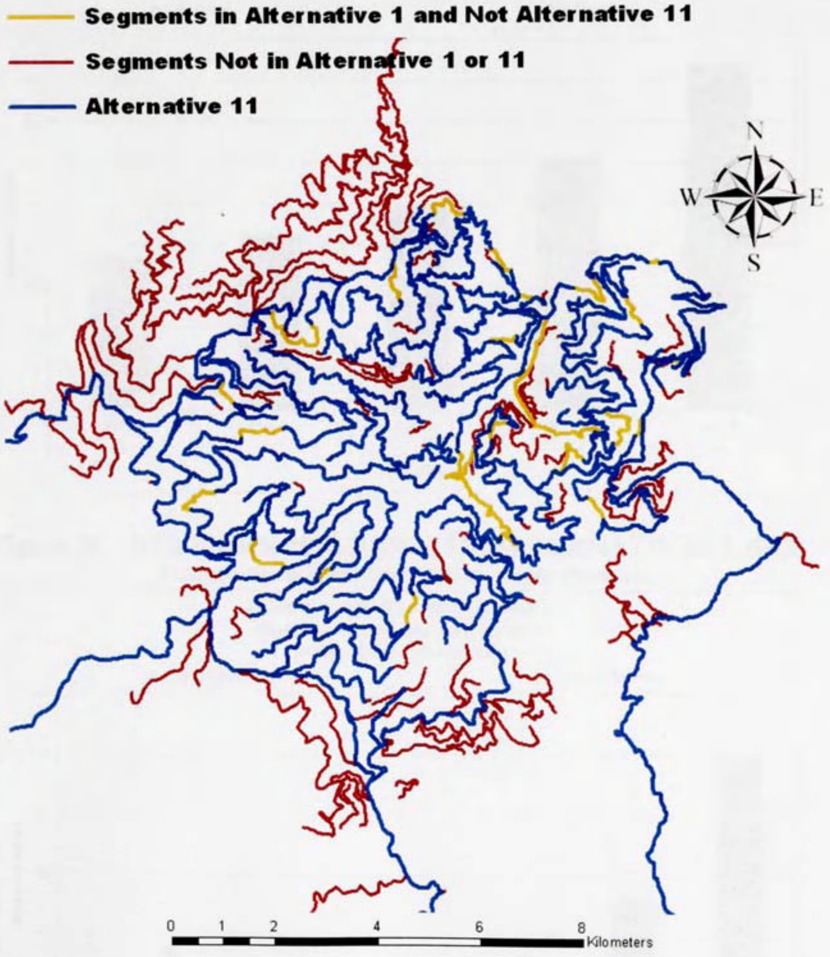


Figure 30. NETWORK 2000 RESULTS: ALTERNATIVES 1-5

Using Sediment Yield from Road Surface

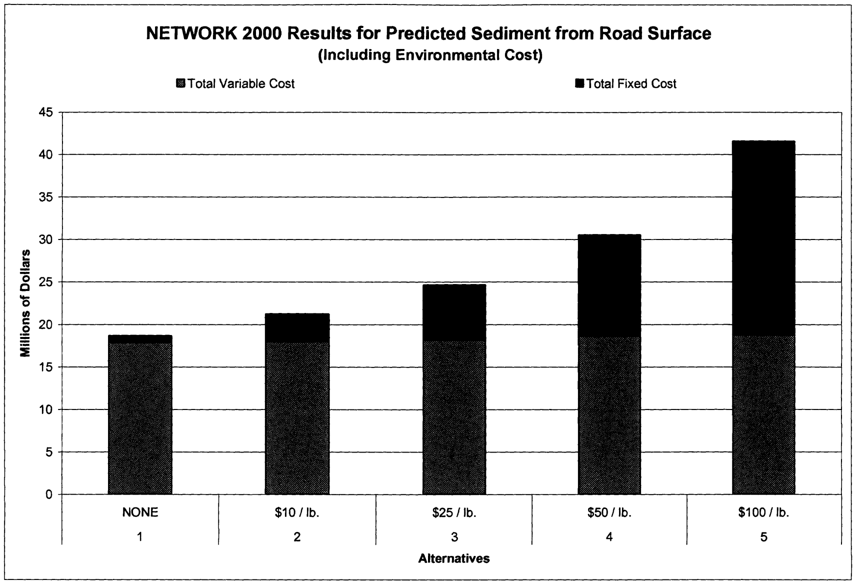


Figure 31. NETWORK 2000 RESULTS: ALTERNATIVES 1, 6-11

Using Sediment Yield Delivered to Stream Channels

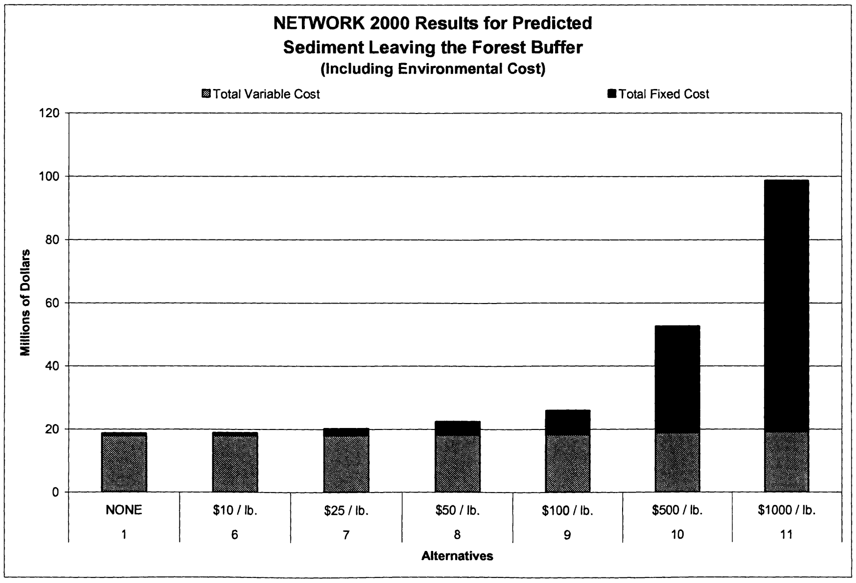


Figure 32. ACTUAL COST TOTALS FOR ALTERNATIVES 1-5

Using Sediment Yield from Road Surface

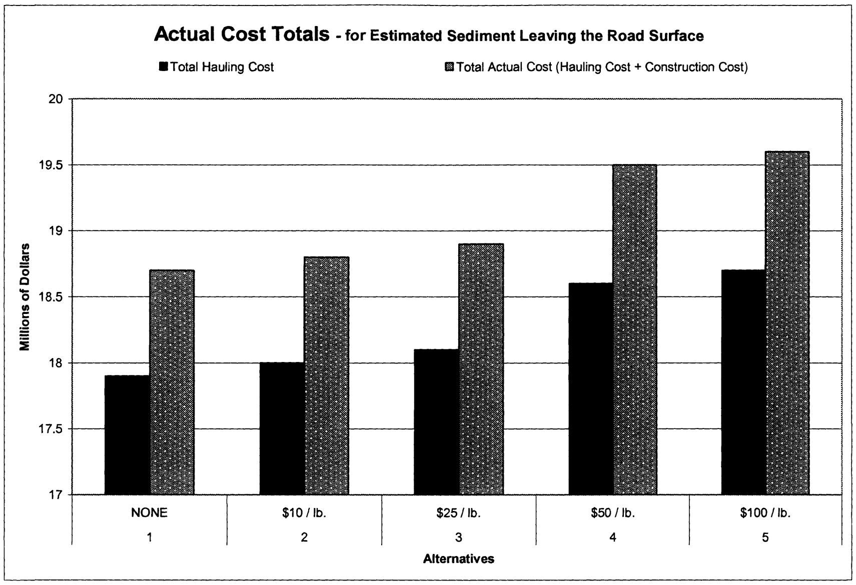


Figure 33. ACTUAL COST TOTALS FOR ALTERNATIVES 1, 6-11

Using Sediment Yield Delivered to Stream Channels

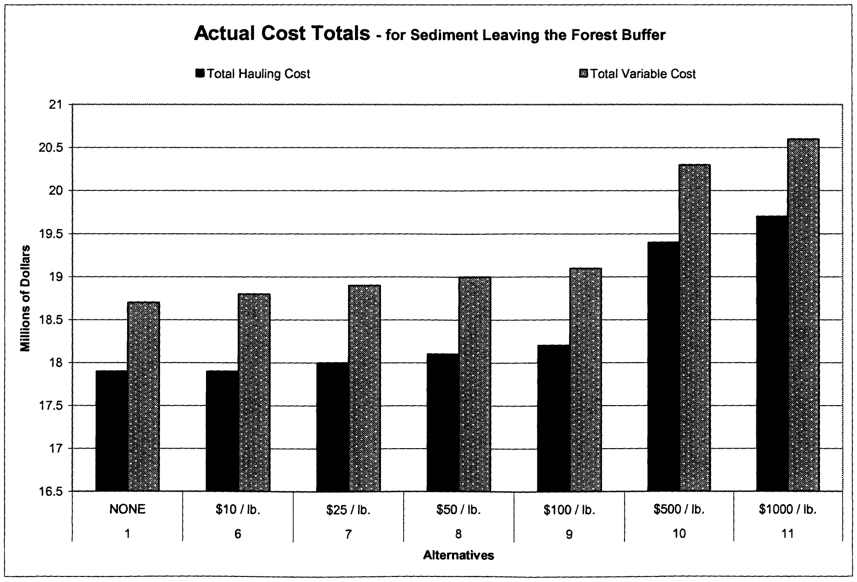


Figure 34. PREDICTED SEDIMENT YIELDS FROM ALTERNATIVES 1-11

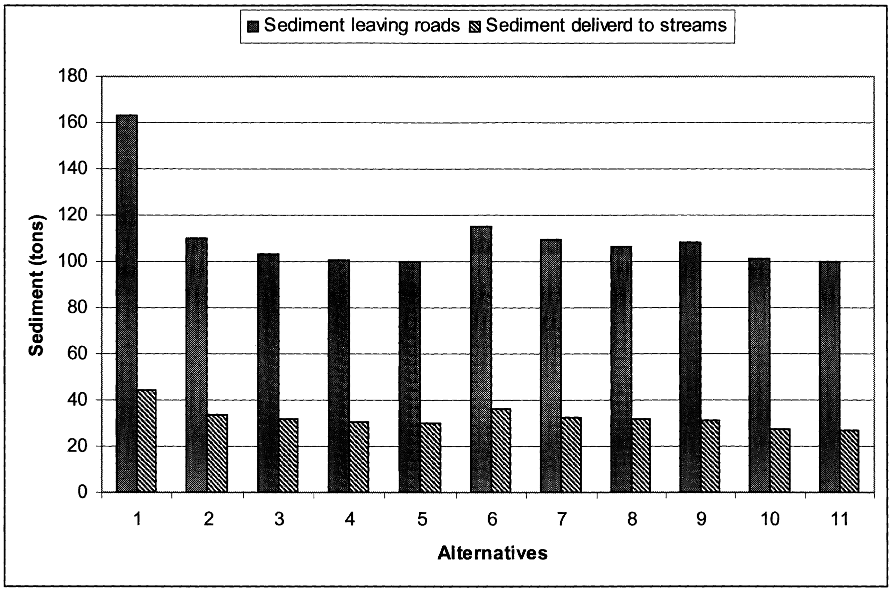


Figure 35. SEDIMENT YIELD EXAMPLE

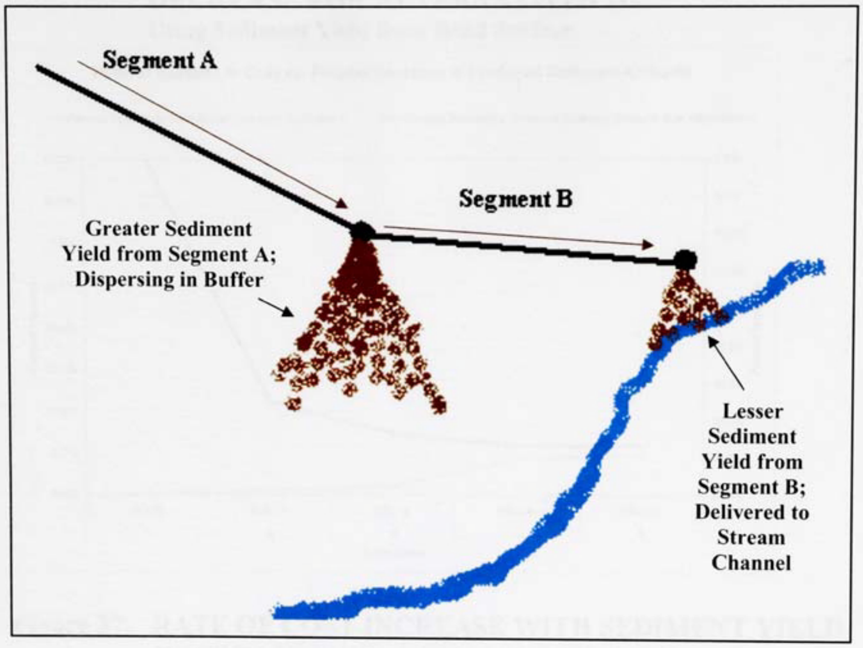


Figure 36. RATE OF COST INCREASE WITH SEDIMENT YIELD DECREASE FOR ALTERNATIVES 1-5

Using Sediment Yield from Road Surface

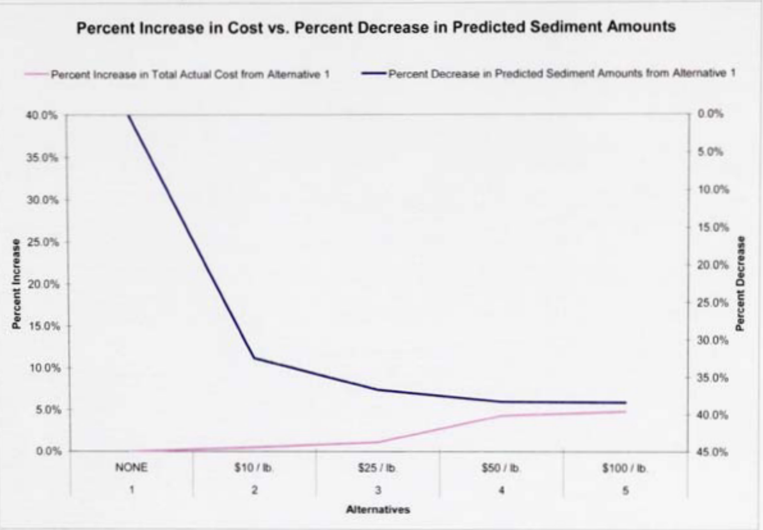
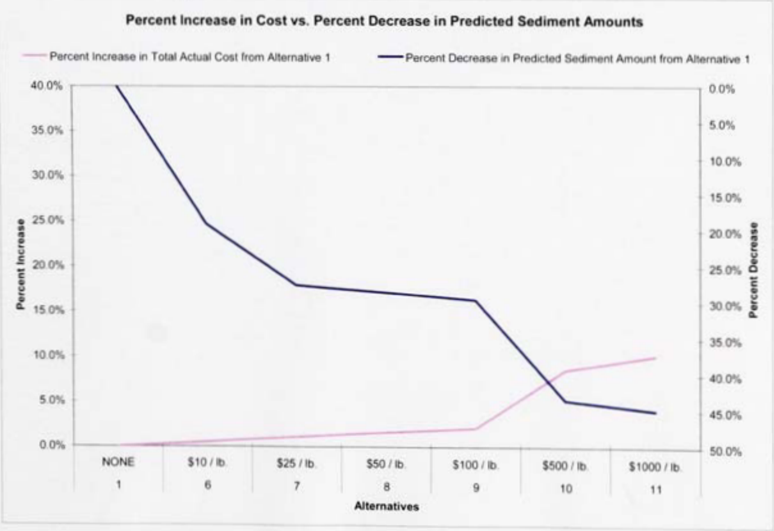


Figure 37. RATE OF COST INCREASE WITH SEDIMENT YIELD DECREASE FOR ALTERNATIVES 1, 6-11

Using Sediment Yield Delivered to Stream Channels



APPENDIX C

LITERATURE CITED SUMMARY

Author(s) and Publication Year	Literature Summary
Brooks, E.S., J. Boll, and W.J. Elliot. 2003.	The technique of using information from global positioning system (GPS) and incorporating the data into a geographic information system (GIS) was developed by Brooks et al 2003 to simplify the data collection and simulation processes. There study evaluated the performance of this technique on 23% of the length of road or 1017 km of road from the South Fork Clearwater River Watershed in Idaho, and overall modeled 6955 road segments. This approach does require a detailed understanding of GIS, and has been well received and incorporated into other projects.
Burroughs, E.R. 1991.	Disscussion of environmental impacts from forest roads and the development of an sediment production prediction model.
Chung, W., and J. Sessions. 2003.	This article is the introduction and discussion for the forest economics optimization transportation planning model NETWORK 2000. This program is used for optimizing transportation variable and fixed costs for multiple harvest schedule periods.
Costanza, et.al. 1997	This group of researchers has estimated economic values for 17 ecosystem services for 16 biomes. They have determined that the services of these ecological systems are critical to the functioning of the planet's life-support system.
Coulter, E.D., J. Sessions, and M.G. Wing. 2006.	This project combined heuristics, cost-benefit analysis, environmental impacts, and expert judgment to produce a road management schedule that better fits the current road network plan. They discuss the reasoning for including an environmental cost.
Elliot, W.J., D.E. Hall, and D.L. Scheele. 1999.	This document is a technical documentation for using the WEPP:Road model. It covers the purpose, assumptions, data inputs, and summarizing the results. This document contains multiple figures for displaying the concepts of WEPP:Road, as well road engineering designs.
Elliot, W.J., and R.B. Foltz. 2003.	Harvest operations are unlikely to decrease hillslope sediment yields but a more dense road network could increase it.
Gravel, John. 2003.	This webpage describes the history and ongoing projects in the Mica Creek Experimental Watershed.
Girvetz, E., and F Shilling. 2003.	This project uses spatial data for the Tahoe National Forest (TNF) to evaluate the road system for potential environmental impacts. They integrate a fuzzy-logic knowledge base, with an ArcGIS grid to evaluate the assertions about a roads impact. They used the modeled environmental impact to negatively weigh roads for a least-cost path network analysis. Results showed only 42% of the road network was needed to connect to the necessary points in their watershed area.
*Hanemann, 1998; McNeely 1998; Randall 1988. Cited in: Costanza et.al. 1997.	Costanza discusses the political controversy over putting a price on our environmental resources. Our water resources in specific are priceless and have to start being considered in industrial economic analysis.
Klapproth, J.C. 2000.	This paper discusses the point and nonpoint sources of pollution to the U.S. streams, lakes, and estuaries. Sediment is discussed as a source of pollution and that both forest and grass riparian buffers can effectively trap sediment.
Luce, C.H., and T. Black. 1999.	Luce and Black report from their results that sediment production is proportional to the product of road segment length and the square of the slope, and the slope is an important attribute in assessing sediment budget. Older roads are producing less sediment than the newer roads. Soil texture is a key area of uncertainty in most road erosion assessments.
Madej, M.A. 2001.	This project discusses many of the environmental problems roads can cause through their spatial locations with soils and geology, and the road engineering practices used to build them. The first step in their analysis was to map the geomorphic and hydrologic features of the road and adjacent hill slopes. To design road removal treatments they next had to identify erosion features, drainage structures, the stream network, and the location of all roads. These road removal treatments were then studied.

Murray, A.T. 1998.	This paper discusses the importance for new planning models that include the transportation network with the harvest schedule. They emphasize the importance of the transportation network and its influence on the profitability of a forest management plan. Discussion of heuristics reveals that this technique may not find the ultimate optimal solution, but will find a significant solution for a computationally difficult problem. These computationally difficult problems arise when assessing entire road networks such as in the Mica Creek Watershed.
Riedel, M.S., and J.M. Vose. 2002.	This project focuses on using an erosion model called the Sediment Tool, to aid in the decision-making in the restoration and management of roads in the Conasuaga Watershed. The Sediment Tool is GIS based, and generates estimates of soil erosion, sediment yield, and routing. The segments they surveyed provided for replication of road types based on road surface materials, slopes, and usage levels. This allows the model to be applied to a larger area without having to survey the road network in its entirety. They were able to qualitatively calibrate the model, and found that the model results improved with a finer resolution Digital Elevation Model (DEM).
Rönnqvist, M. 2003.	This paper discusses the history of optimization models and methods used in the forest industry. Also, describing some of the planning problems that are being modeled to find solutions.
Soil Survey Geographic (SSURGO) Database for Idaho. 2003.	SSURGO depicts information about the kinds and distribution of soils on the landscape. The soil map and data used in the product were prepared by soil scientists as part of the National Cooperative Soil Survey. 7.5 minute quadrangle format; scale = 1 : 24000.
U.S.D.A. Forest Service. 1998.	This paper describes the known impacts of forest roads on the environment.
Wemple, B.C., F.J. Swanson, and J.A. Jones. 2001.	This study discusses how roads are the net source of sediment in watersheds. They studied the different geomorphic features affecting forest roads including fluvial features, and mass movements. Eight of these geomorphic features were mapped and analyzed using geographic information systems (GIS), and sediment budgets were created for the road network. After an extreme storm event, actual road and hill slope failures were compared with analysis. Their results indicated that road failures are strongly influenced by the road location and construction practices, basin geology, and storm intensity.
Wemple, B.C., and J.A. Jones. 2003.	This study focuses on the interaction of subsurface flow with roads, and how this interaction can relate to road restoration efforts. They discuss the hydrologic behavior of a road network, and how it is dependent on the characteristics of individual road segments. Results showed that runoff from the road segments was related to its mapped characteristics, and that runoff is produced from sources other than intercepted precipitation on the road surface.