Modeling erosion and sediment delivery on mountain roads in Upper Deep Creek

Rebecca Louise Franklin

MODELING EROSION AND SEDIMENT DELIVERY

ON MOUNTAIN ROADS IN

UPPER DEEP CREEK

A Project

Presented to the

Faculty of

California State University,

San Bernardino

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in

Environmental Sciences:

Professional Science Masters

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by

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December 2012

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December 2012

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ABSTRACT

Upper Deep Creek is a 250-square mile sub-watershed that is located in a mountainous, forested region of the San Bernardino National Forest in San Bernardino county in Southern California. A network of 156 miles of roads that are under state, county, and United States Forest Service jurisdiction traverse Upper Deep Creek. It is widely acknowledged that in mountainous, forested watersheds, roads are a primary source of excess sediment that can enter stream networks and cause environmental degradation. The goal of this project was to screen the Upper Deep Creek road network using two erosion prediction models, the Washington Road Surface Erosion Model (WARSEM) and the Watershed Erosion Prediction Project (WEPP:Road), in order to identify road segments that are contributing significant amounts of sediment to the stream system, and to test the predictions of the models using a field sediment collection method.

The data that was used for the erosion prediction models was obtained from attribute tables in GIS shape files, and field data was collected using silt fences. Due to the fact that the WARSEM model was found to be unusable for the purposes of this project, the WEPP:Road model was

used to generate all of the data that was used for analysis of the road network. The results of the WEPP:Road model indicate that it is possible to use an erosion prediction model to screen a road network in order to identify segments that are producing disproportionate amounts of sediment that is entering the stream system. The predictions of this model could not be tested in the field because the silt fences that were used to complete the field portion of this project did not collect any sediment. The accuracy of the predictions of a road erosion and sediment delivery model appear to be dependent on the accuracy of the model inputs, so future studies will need to be performed on the segments of the road network that were predicted to be contributing the most sediment to the stream system in order to accurately quantify the amount of sediment that is being produced.

ACKNOWLEDGMENTS

Thank you to the graduate committee and program coordinator for providing assistance with editing, guidelines, and formatting that were essential for completing this project. Thank you to Tracy Tennant of the United States Forest Service for providing numerous geospatial data files, without which this project could not have been performed. Thank you to Boykin Witherspoon III of the Water Resources Institute for providing guidance, expertise, and additional data files that were also essential to the completion of this project, and for assisting with field work. Thank you to Robert Taylor and Omero Torres for allowing me to complete this project in the San Bernardino National Forest. Thank you to George Henderson for providing support in the use of both computers and vehicles.

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CHAPTER ONE

INTRODUCTION

Background

In recent years, restoration of watershed and ecosystem health has become an increasing priority for land management agencies across the United States. In 2010, the United States Secretary of Agriculture announced in his "Vision for the Forest Service" that restoring watershed and forest health would be the primary management objective of the United States Forest Service (USFS) (USDA, 2011b). This was a reiteration of the United States Department of Agriculture's (USDA) *Strategic Plan for FY 2010-2015*, which targeted the restoration of watershed and forest health as core management objectives (USDA, 2011b). In forested ecosystems, sediment is the primary pollutant affecting stream systems (Elliot et al., 2009). In the absence of disturbance, most forest ecosystems do not produce much sediment outside of exceptional events such as natural flooding and landslides. However, any of a number of anthropogenic disruptions can alter the natural sediment flux and cause erosion and sedimentation in forest streams. Of these impacts, in the absence of fire, road construction is the primary factor causing increased sedimentation in forest ecosystems (Elliot et al., 2009).

In a forest road network, not all road segments contribute equally to sedimentation problems. This is because a variety of factors, including road design, geology, topography, and climate, all affect the amount of sediment that is produced from an individual road segment. Once a road segment has been identified as a significant source of sediment, it is possible to apply best management practices (BMPs) such as resurfacing, grading, or reducing traffic in order to decrease the volume of sediment that is produced. This project will evaluate a road network within a sub-watershed in a forest ecosystem using two physical erosion prediction computer models, in order to identify road segments that are disproportionately producing sediment that is affecting the stream system. The predictions of these models will then be tested by directly measuring sedimentation rates using a field method involving silt fences. The goal of this project is to establish that erosion prediction models may be used to analyze large road networks in order to identify problematic road segments. The results of this type of analysis can provide information that would allow a land management agency to target field work in a cost effective way, and provide an efficient and streamlined method for determining the best locations for applying BMPs. The prediction is that the portions of the road network that are contributing the largest volume of sediment to the stream network are road-stream crossings on unpaved roads that experience high levels of vehicular traffic and have large distance between cross-drains.

The United States Environmental Protection Agency and Erosion Control

The United States Environmental Protection Agency (USEPA) regulates erosion and sediment delivery from point sources through the Clean Water Act (CWA). The CWA authorizes USEPA-designated state regulatory agencies to administer a monitoring and reporting program for point source discharge through the National Pollutant Discharge Elimination System (NPDES). Under this system, sediment is regulated as a pollutant. The system requires BMPs to be incorporated into construction, manufacturing, industrial processes, and municipal systems such as storm water conveyance systems in order to prevent sediment from entering waterways (USEPA, 2012).

The United States Forest Service Approach to Protecting Ecosystem Health

The USFS is responsible for managing 193 million acres of land across the United States. These management areas include National Forests, National Grasslands, National Monuments, and wilderness areas. Known as "the land of many uses," the National Forest System manages its land to balance a variety of uses, including resource extraction, research, conservation, recreation, and wildlife habitat. Driving all of these management commitments is the USFS Mission, which is: "Sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations" (USFS, 2012). With major increases in spending on wildfire control and suppression in recent years (USFS, 2012), the USFS has been forced to cut spending on other forest management programs that could potentially help improve watershed health. Budget concerns will make it a challenge for the USFS to achieve the stated goal of "implementing practices to maintain or improve watershed condition" (USDA, 2011a).

In order to more effectively and efficiently target a range of watershed management projects across the country with a limited budget, the USFS has developed a method for rating and ranking the condition of watersheds across the country, with the goal of being able to allocate resources in a way that will return the best results for the least cost. Due to the vast variety of ecosystems and geographic locations that are included in the USFS system, developing an objective, universal method for evaluating watershed health is no small task. However, in 2011, the USFS published two documents that were aimed at creating an observation-based, consistent method for evaluating watershed health. The documents were published as the Watershed Condition Framework (WCF) and the Watershed Condition Classification (WCC) Technical Guide. The new framework "establishes a nationally consistent reconnaissance-level approach for classifying watershed condition, using a comprehensive set of 12 indicators that are surrogate variables representing the underlying ecological, hydrological, and geomorphic functions and processes that affect watershed condition" (USDA, 2011b).

The documents introduce the WCC system, which is used to classify the condition of watersheds in a way that is both quantitative and cost effective, focusing on the use of Geographic Information Systems (GIS) data to minimize the amount of work that needs to be performed in the field (USDA, 2011a). The goal of this new approach is to classify the health of the USFS forests on a watershed scale. This scale was chosen because "watersheds are easily identified on maps and on the ground, and their boundaries do not change much over time" and "are also readily recognized by local communities and resonate with members of the public" (USDA, 2011b).

In the United States, watersheds and hydrologic units can be identified by the United States Geological Survey (USGS) Hydrographic Unit Code (HUC) system. Under this system, the entire country has been divided into a series of progressively smaller watersheds that are contained within larger regions. The largest scale region is designated as HUC-2, and progressively smaller sub-regions, basins, sub-basins, watersheds, and sub-watersheds are contained within these largest units. The goal of the USFS is to evaluate all HUC-6 level basins, which are normally 10,000 - 40,000 acres in size, using the WCF in order to determine which watersheds are functioning normally, which are functioning at risk, and which are functionally impaired (USDA, 2011b). Resources will then be allocated to watersheds based on their condition, with the highest priority watersheds being those that are currently in the best condition. This is a fundamental change from previous management strategies, where the most resources were allocated to the watersheds in the worst condition (USDA, 2011b). This paradigm shift has been occurring since the Aquatic Conservation Strategy (ACS) was adopted in 1994 as part of the Northwest Forest Plan (Heller, 2004). The rationale for this shift stems from the reality that it is impossible for the USFS to restore every watershed under its jurisdiction, due to budget constraints and competing resource demands (USDA, 2011b). In order to maximize measurable ecological improvement with a limited budget, the management strategy is designed to protect "the best remaining, or most readily restorable, aquatic habitat in the plan area" and restore "watersheds most likely to positively respond to treatment" (Heller, 2004).

The WCF directs forests to follow the classification structure outlined in the WCC Technical Guide (USDA, 2011b). The goal of the WCC system is to determine if the underlying ecological processes of a watershed are functioning properly. In order to determine if a watershed is functioning properly, functioning at risk, or functionally impaired, the WCC system uses 12 indicators of ecosystem health that are composed of attributes that are directly related to watershed processes (USDA, 2011a). The USFS is able to then take action on indicators that show functional impairment in order to improve watershed condition.

Several indicators that are included in the WCC system could potentially affect erosion and sediment delivery processes. These indicators include Roads and Trails, Soils, Fire Regime or Wildfire, and Forest Cover. In most forest ecosystems, wildfire and roads are the top producers of sediment (Elliot et al., 2009). This means that in the absence of wildfire, roads are the top producer of sediment. For this reason, roads are the focus of the project presented in this paper.

Impact of Sediment on Forest Streams

Erosion and sedimentation are a major concern for watershed health because once sediment has entered a forest stream, it can negatively impact the stream ecosystem in a number of ways. Increased sediment volume can cause physical problems such as increased stream turbidity, changes in channel morphology, and destruction of spawning habitat (Owens et al., 2005). Increases in sediment can also cause water quality problems, as finer-grained sediment often contains a high percentage of nutrients and toxic pollutants, which can be detrimental to stream ecosystems by causing eutrophication and toxicity to organisms (Owens et al., 2005). Sediment flux can be difficult to study, however, because it is difficult to measure the amount of sediment that is transported in runoff, as well as the amount that is deposited throughout the forest, such as on the forest floor and in stream channels (Croke et al., 2005). Predicting the volume of sediment that will be delivered from a road segment requires understanding the hydrologic flow patterns of runoff from the road prism, as well as understanding the types of erosive processes that are occurring.

Types of Erosion on Road Surfaces

There are three major erosion processes that occur on road surfaces: surface erosion, gullying, and mass wasting (Dubé et al., 2004). While gullying and mass wasting occur in specific locations under specific conditions, surface erosion occurs on all roads. Surface erosion consists of two components: detachment and transport (Elliot et al., 2009). On a road surface, erosion can be caused by overland flow, raindrop impact, wind, or gravity (Dubé et al., 2004).

In undisturbed forest ecosystems, vegetation and vegetative matter that collects on the forest floor reduce erosion because they promote infiltration instead of runoff and help keep soil particles in place (Dubé et al., 2004). However, when a road is constructed, these natural systems are disturbed, the land is cleared of vegetation, and infiltration is disrupted due to soil compaction. The design of a road promotes erosion because road surfaces consist of compacted material, which reduces infiltration and promotes overland flow (Ziegler et al., 2001). This overland flow, which increases significantly in volume when roads are connected in a system, causes erosion, which can "contribute substantially to stream sedimentation, even during low magnitude rainfall events" (Ziegler et al., 2001).

Sources of Sediment in the Road Prism

Road design has a significant impact on the volume of sediment that a road segment produces and delivers to streams. The road prism of a cut-and-fill road in a mountainous area consists of four parts: the road surface, the cut slope, the fill slope, and the ditch (Figure 1). Some road segments have an additional component of a forested buffer between the fill slope and the stream channel. These cut-and-fill roads can be designed to be outsloped, insloped, or crowned (Figure 2), and these road designs will affect the patterns of overland flow and runoff (Figure 3), which can, in turn, affect erosion and sediment delivery. The presence of ruts on the road surface will also affect patterns of runoff and sediment delivery.

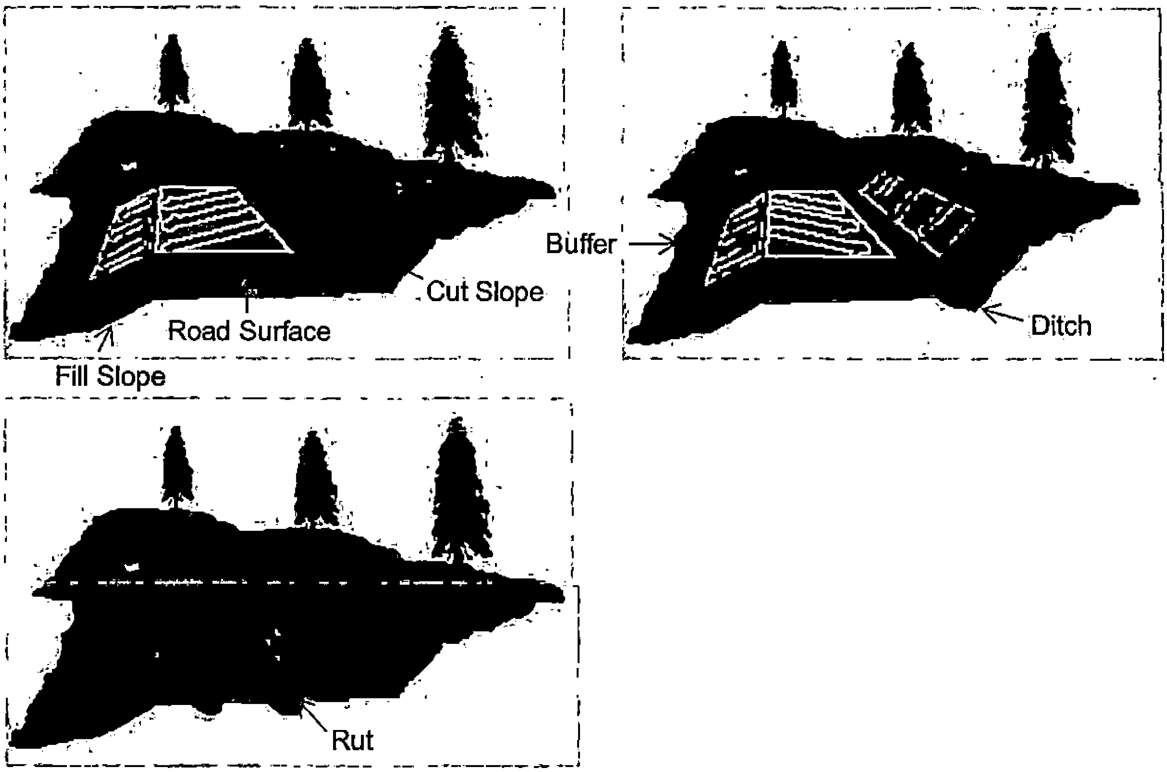


Figure 1. Portions of a Road Segment

Source: Adapted from Elliot, W.J.; Foltz, R.B.; Robichaud, P.R. *Recent findings related to measuring and modeling forest road erosion*; United States Department of Agriculture, Forest Service, Rocky Mountain Research Station: Moscow, ID, 2009.

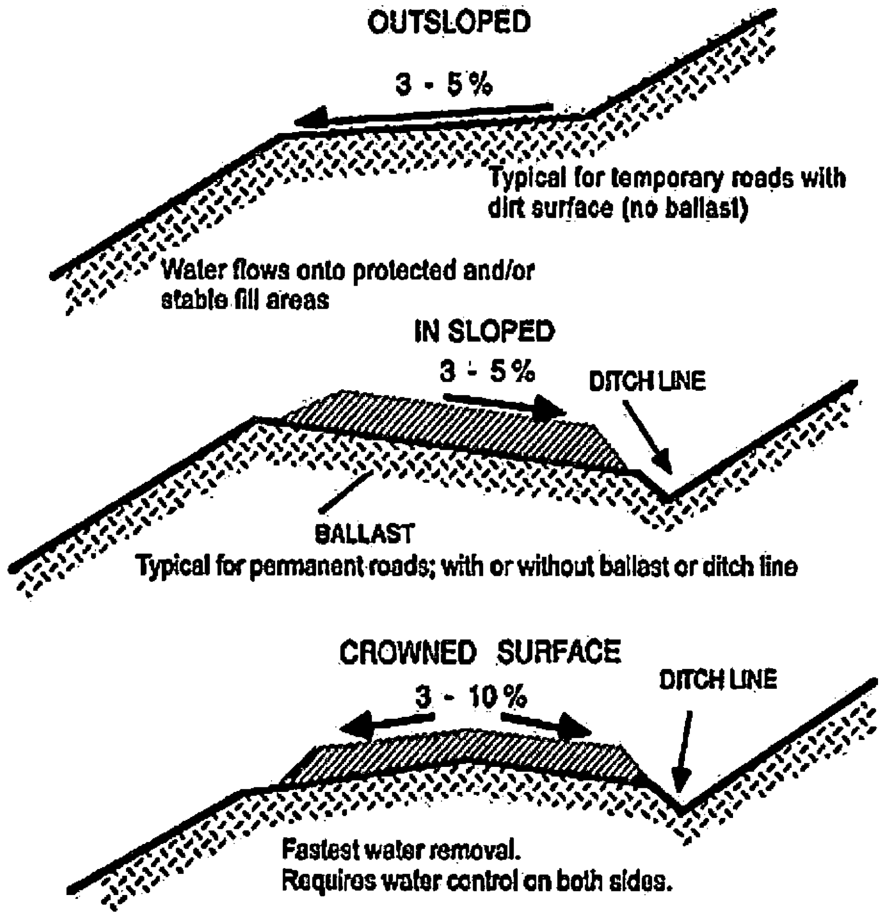


Figure 2. Road Designs for Cut-and-Fill Roads

Source: Adapted from *FAO Watershed Management Field Manual: Road Design and Construction in Sensitive Watersheds;* Food and Agriculture Organization of the United Nations, FAO Corporate Document Repository (Online). 28 May 2012.

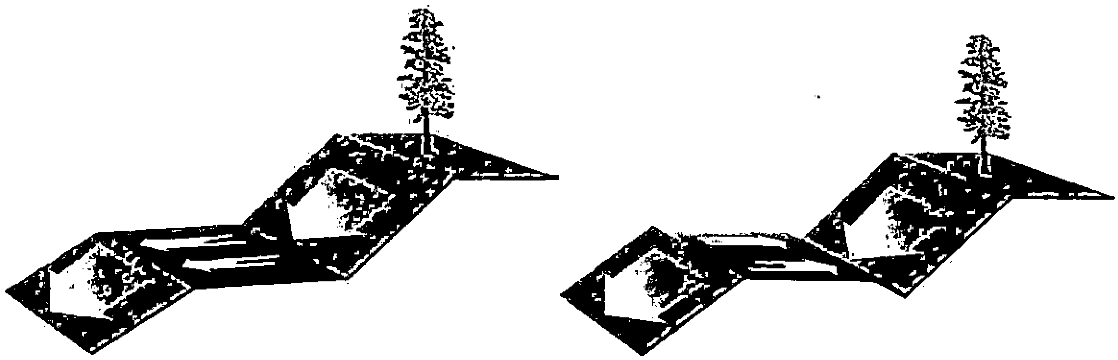


Figure 3. Runoff Patterns on the Cut-and-Fill Road Prism

Source: Adapted from Dubé, K.; Megahan, W.; McCalmon, M. *Washington Road Surface Erosion Model*; State of Washington Department of Natural Resources: Olympia, WA, 2004.

The outsloped road design is most commonly used on low-traffic roads, such as temporary roads and skid trails. This type of design directs runoff to the fill slope side, and generally uses a series of simple cross-drain structures to divert flow off of the road surface. This type of road design tends to promote dispersion of the water on the fill slope, and favors sediment deposition rather than erosion on the fill slope.

The insloped road design is more commonly used on higher traffic roads. In this type of road design, runoff is directed inwards to a ditch that runs along the cut slope. The runoff is then transported to the fill slope side of the road through a cross-drain structure such as a culvert. This type of road design can lead to more concentrated, higher-velocity flow that can cause erosion on the fill slope below the cross-drain structures, and favors channelized flow and gully formation (Croke et al., 2005).

Although portions of the road prism other than the road surface can contribute to the volume of sediment that is eroded off of a road segment, a study by Croke et al. (2006) showed that overland flow runoff from the cut slopes on cut-and-fill roads was a fairly small portion of the total runoff coming from a road segment.

Road Use and Surface Detachment

The amount of sediment that is eroded from an individual road segment, and its resultant impact on water quality, is also a function of sediment availability. One study found that graded roads produce sediment at a higher rate than background for a year after disturbance, while numerous other studies have shown a correlation between traffic usage and sediment production (Ziegler et al., 2001). Another study demonstrated that the amount of sediment that a road segment produces is a function of road use and maintenance, which indicates that the road surface, not the cut slope, fill slope, or ditch, will be the main contributor of sediment for most road segments (Croke et al., 2006). The correlation between road use and sediment production was also studied by Ziegler et al. (2001), who demonstrated that traffic use increased sediment production by several orders of magnitude over unused roads in the same area.

Road maintenance activities that are essential for usability, such as grading and filling of potholes and gullies, also generate loose material that can cause increases in erosion and sediment delivery (Ziegler et al., 2001). Cessation of maintenance activities and traffic use causes sediment production to rapidly decline, due to a process known as "consolidation" or "armoring" in which fine, easily removed particles are eroded and coarser particles remain (Ziegler et al., 2001). Consolidation can help unpaved road surfaces resist sediment detachment forces, such as raindrop impact and overland flow (Ziegler et al., 2001). However, once traffic increases or road maintenance is performed, new erodible particles can be generated by crushing and grinding forces. This is because "road erodibility is . . . controlled by both the erodibility of the underlying compacted road surface, and that of the loose surface material" that is generated by overland flow events, traffic, crushing and churning, and detachment processes (Ziegler et al., 2001).

Spatial Connectivity of Forest Roads and Streams

Once sediment has been eroded from a road segment, it can either be deposited on the forest floor, or it can be carried by the runoff into a stream channel. According to Croke et al. (2005), "the potential impact of road-related sediment on in-stream water quality can be better assessed in terms of the nature and connectivity of the delivery pathway" than in just the volume of sediment being eroded from a road segment. This hydrological connection is particularly significant at road-stream crossings, where the lack of a forested buffer between the road segment and the stream channel results in sediment being deposited directly into the stream. In addition, road-stream crossings are included in the WCC as an indicator of watershed health because "the greatest impact on in-stream water quality and biota is believed to occur" at these types of direct connections, where all sediment being removed from the road is delivered directly to the stream system (Croke et al., 2005).

Connectivity can be just as significant when cross-drain structures are gullied. Croke et al. (2005) demonstrated that gullied drainage pathways on fill slopes deliver sediment 2 to 3 times farther than dispersive pathways, and can be the major form of road-stream connection in certain watersheds. Gully formation itself is a function of road design; insloped roads on steep terrain with large distances between cross-drain structures favor concentrated flow and gully formation. Likewise, roads that have significant rut formation will favor channelized flow, which can increase the efficiency of sediment delivery. Croke et al. (2005) demonstrated that in their study, 90 percent of the gullied pathways that were studied were located at the outlet of culvert structures on insloped roads, rather than push-outs and mitre drains that are more common on outsloped or crowned roads. This indicates that the insloped road design that is favored on high-traffic roads in mountainous areas seems to promote gully formation, which in turn can lead to more sediment being delivered to streams.

Proximity of road segments to streams is another concern when predicting sediment delivery. The further a road segment is from a stream, the more likely that any eroded material will be deposited on the forest floor before the runoff reaches the stream network. For this reason, in the WCC system, roads that are more than 300 feet away from streams, and are not connected to the stream network by gullied drainage structures, are not considered hydrologically connected to the stream system. Similar assumptions have also been incorporated into several of the physical models that have been developed for estimating road erosion and sediment delivery.

Watershed-Scale Analysis of Erosion and Sediment Delivery

Because of the complex nature of erosion and sediment delivery from cut-and-fill roads, not all portions of a road network can be considered to have the same degree of impact on water quality and stream ecology. For example, a study of the Moruya-Deua and Tuross River watersheds in southeast Australia found that 35 to 50 percent of sediment was being contributed by 1.8 percent of the road network in the watershed (Fu et al., 2009). Sediment production can be reduced by applying BMPs, such as surfacing with gravel or asphalt, grading the road, or reducing traffic levels (Elliot et al., 2009). Applying BMPs to the portions of the road network that have a disproportionate impact on watershed health can return the most benefit to stream ecology with the least investment of capital. Determining which portions of a road network are contributing disproportionately large amounts of sediment to the stream system can be extremely beneficial to a land management agency such as the USFS, where funding can be limited and resource allocation takes place on a national scale.

One of the most efficient and effective ways to analyze large-scale watershed projects is to use GIS data and erosion prediction modeling. A good erosion prediction model can utilize data that is readily available in GIS databases and provide an analysis of an entire road network while requiring little additional data collection in the field. Models are categorized as either empirical or physical depending on how they are developed. Empirical models are developed by statistical analysis of empirical observations, while physical models are developed based on hydraulics and physical properties (Fu et al., 2010).

Empirical models can be very useful for the sites for which they were developed, but can be limited in their applicability to other locations. Physical models have the advantage that they can be applied universally, but tend to involve much more complex inputs and calculations than empirical models (Fu et al., 2010). For this project, two erosion and sediment delivery models, the Washington State Road Sedimentation Model (WARSEM) and the Watershed Erosion Prediction Project (WEPP) model, were utilized to analyze the road network within the study area.

Washington State Road Sedimentation Model

The first model that was used in this project was the WARSEM model. This model is an empirical erosion and sediment delivery prediction model that was developed by the Washington State Department of Natural Resources specifically for analysis of the forest road network in the state of Washington (Dubé et al., 2004). Although the model was originally designed for use in the state of Washington, it has been used for road research around the world (e.g. Akay et al., 2008; Fu et al, 2009). The model was designed to be used for different levels of analysis, including screening, planning-level assessment, detailed assessment and scenario playing, and site/segment level monitoring (Dubé et al., 2004). The various levels of analysis require increasingly detailed data inputs. The model outputs a long-term average amount of sediment that could be produced by a road with similar characteristics to the one entered in the model database (Dubé et al., 2004).

One of the main advantages of WARSEM is that it was designed to ease the process of performing large, watershed-scale analyses by allowing direct import of attribute table data from GIS files. This importation process can dramatically simplify the process of entering required data from each road segment, while also increasing the accuracy of the data entry process. The model was designed to allow data import from GIS data files, Excel files, or SEDMODL2 runs (Dubé et al., 2004). SEDMODL2 is a program that complements the WARSEM model by calculating road surface erosion. WARSEM, in turn, is designed to calculate the amount of road surface erosion that is delivered to streams.

Data can be entered into the model for one road or for an entire road system. The type of data required by the model includes the road segment dimensions, information about the cut slope and fill slope for each segment, maintenance frequency on each road segment, the distance of each road segment from streams, and traffic levels along the roads.

Water Erosion Prediction Project for Roads

The next model that was utilized for analysis in this project was the WEPP:Road model. This is a web-based interface that is one of several adaptations of the WEPP model, which was originally developed by the USDA Agricultural Research Service (ARS). The WEPP model is a complex, physics-based model that estimates soil erosion and sediment yield by simulating conditions that impact erosion. WEPP is designed to predict erosion from hill slopes for various types of food crops or other cover material (Flanagan and Nearing, 1995). The WEPP model has subsequently been adapted into the WEPP:Road model by an interagency group of scientists from the USFS, the Natural Resource Conservation Service (NRCS), the ARS, and the Bureau of Land Management (BLM). The model was modified to be specific to road segments and to represent the conditions that exist in a road prism (Elliot et al., 1999). The model predicts the amount of sediment eroded from the road surface and forest buffer for each modeled road segment in pounds per year. WEPP:Road has several advantages that make it easier to use than WEPP, including the fact that it incorporates simplifying assumptions that eliminate the need for some of the more complex algorithms used in WEPP, and does not require the installation of any software because it is internet based.

The original WEPP model requires inputs for soil texture, climate, vegetation cover, and topography. The model includes a built-in climate model called CLIGEN, developed by ARS, that allows the user to choose from over 1000 climate stations in the United States in order to create a customized climate for the modeled study area. Based on climate information generated by the CLIGEN model, WEPP predicts whether precipitation will occur on each day of the model run length, and whether or not the precipitation is in the form of rain or snow. The model then calculates the rates of infiltration and runoff for each precipitation day using inputs for soil, vegetation, and topography. When runoff is predicted, WEPP calculates the route that the runoff will take over the surface of the hill slope, while calculating erosion or deposition rates for at least 100 points on the surface. The average erosion rate is then calculated for the entire hill slope (Flanagan and Nearing, 1995).

In WEPP, the next input is a hill slope model. Landscape geometry is entered into the program by using data input files for slope, channel topography, watershed configuration, and impoundment characteristics. These files are used by the program to construct a series of hill slopes, which are divided into regions of homogenous soil, crops, and management called Overland Flow Elements (OFEs) (Flanagan and Nearing, 1995). For WEPP:Road purposes, this input is the actual road prism design. For simplification, the WEPP:Road model divides the road prism into three OFEs: the road surface, the fill slope, and a forested buffer between the road prism and the nearest stream channel (Figure 4) (Elliot et al., 1999). The OFEs are then used to calculate the paths that runoff will follow during a precipitation event. For further simplification, the WEPP:Road model includes only four road design options: insloped with a bare ditch, insloped with a vegetated ditch, outsloped, or rutted (see Figure 5). These road designs also affect the calculation of the travel length for runoff that may occur during a precipitation event.

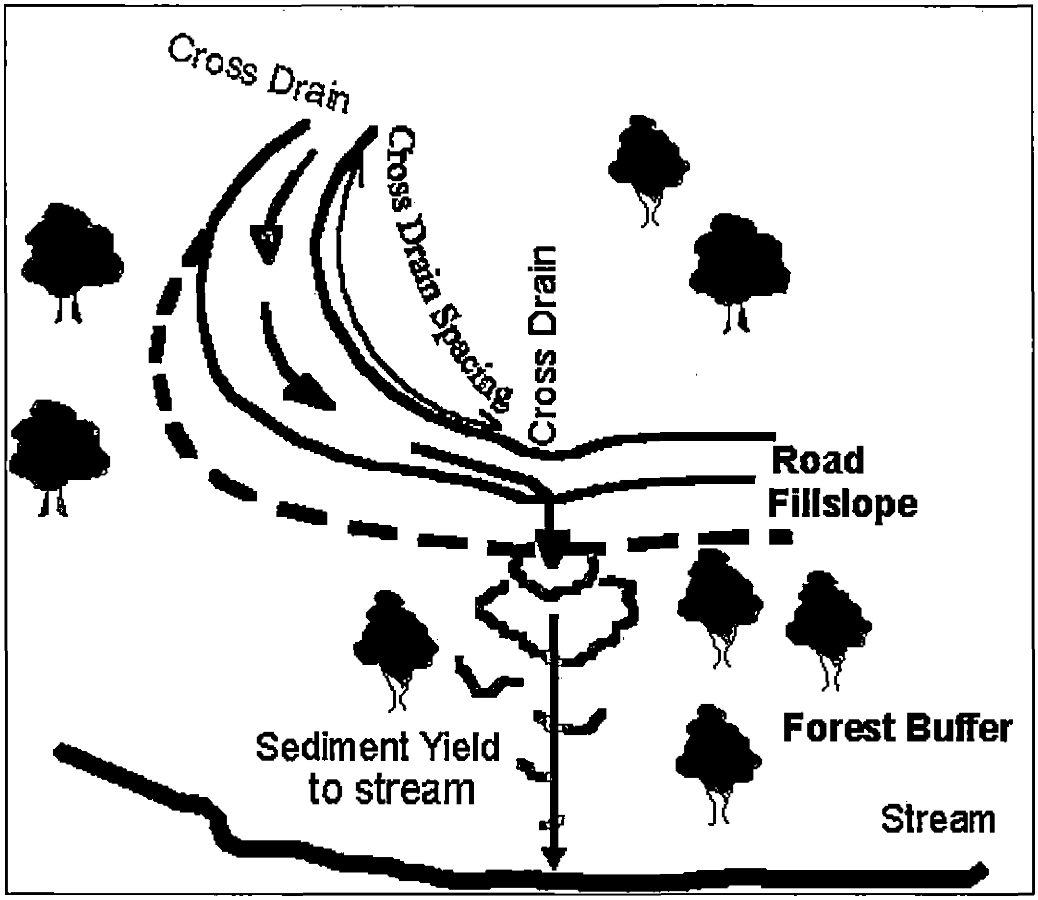


Figure 4. Overland Flow Elements in WEPP:Road

Source: Adapted from Elliot, W.J.; Hall, D.E.; Scheele, D.L. *WEPP Interface for Predicting Forest Road Runoff, Erosion and Sediment Delivery;* United States Department of Agriculture, Forest Service, DRAFT: 1999.

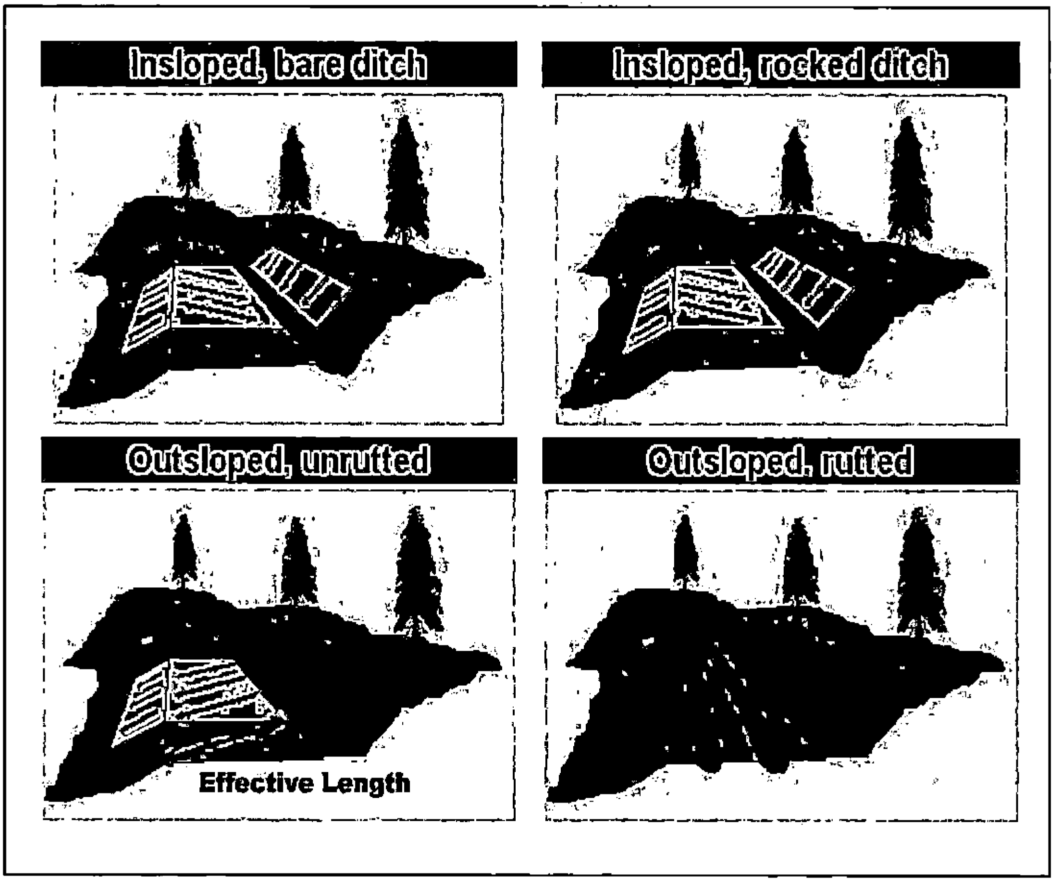


Figure 5. Road Designs in WEPP:Road

Source: Adapted from Elliot, W.J.; Hall, D.E.; Scheele, D.L. *WEPP Interface for Predicting Forest Road Runoff, Erosion and Sediment Delivery;* United States Department of Agriculture, Forest Service, DRAFT: 1999.

One of the most complicated algorithms used by the WEPP model is the vegetation cover algorithm. In WEPP, different types of crops and cover vegetation can be chosen to simulate different management practices on agricultural land (Flanagan and Nearing, 1995). WEPP vegetation modeling involves a complex set of algorithms that include calculations for a variety of variables, including species of vegetation, irrigation techniques, and respiration, transpiration, and infiltration rates. The WEPP:Road model simplifies this portion of the model by assuming that the road surface has no vegetation cover, that the fill slope has 50 percent forest cover, and the forested buffer has 20 years of accumulated vegetation (Elliot et al., 1999). These assumptions were included because it is assumed that the road surface will be free of vegetation. The model documentation does not provide an explanation for the vegetation cover amounts used for the fill slope and forest buffer. These assumptions that are built into the model for the fill slope and buffer OFEs will tend to decrease the amount of runoff predicted for these OFEs relative to the amount of runoff predicted for the road surface, causing the road surface to be the predominant contributor of sediment from the road prism. This assumption follows the findings of several studies on road designs and surface erosion (e.g. Croke et al., 2005; Croke et al., 2006; Ziegler et al., 2001).

An input for soil is also included in the algorithms used by the WEPP model. In the WEPP model, the soil algorithm is complex, and includes calculations for a number of factors, including hydraulic conductivity, vegetation, climate, and even worm holes (Elliot et al., 1999). The assumptions of the WEPP:Road model simplify this input into a choice of four soil texture types: loam, sandy loam, silt loam, and clay loam.

Overall, the WEPP:Road model is a vastly simplified version of WEPP. All of the simplifications that have been incorporated into this model make it efficient and easy to run, even for a fairly large-scale analysis. It is also web-based and does not require downloading or installing any software in order to run.

Empirical Analysis of Erosion and Sediment Delivery

A field study was conducted as a component of this project in order to test whether or not conditions in the field matched predictions of the erosion prediction models. The USFS has developed a method for estimating the volume of sediment being eroded from portions of a road network using silt fences (Robichaud and Brown, 2002).

This method provides guidance for the specific length of fencing that should be used for a given upslope contributing area and the number of fences that should be used to obtain a statistically-significant result, suggestions for a fence clean-out schedule, and recommendations for the types of precipitation collection devices that should be installed at each fence location. A modified version of this method was applied to three portions of the road network included in this study in order to attempt to test the predictions generated by the two erosion models.

CHAPTER TWO

METHODS

Study Area

This project was performed in the Upper Deep Creek HUC-6 level sub-watershed, which is located in the San Bernardino National Forest in San Bernardino County in Southern California (Figure 6). The San Bernardino National Forest includes watershed divides for ninety-five HUC-6 level sub-watersheds contained within five major HUC-3 level basins, which include the Santa Ana, Upper Mojave, Lower Mojave, Salton Sea, and Laguna-San Diego Coastal (Figure 7). Upper Deep Creek is contained within the boundary of the Upper Mojave HUC-3 basin (Figure 8).

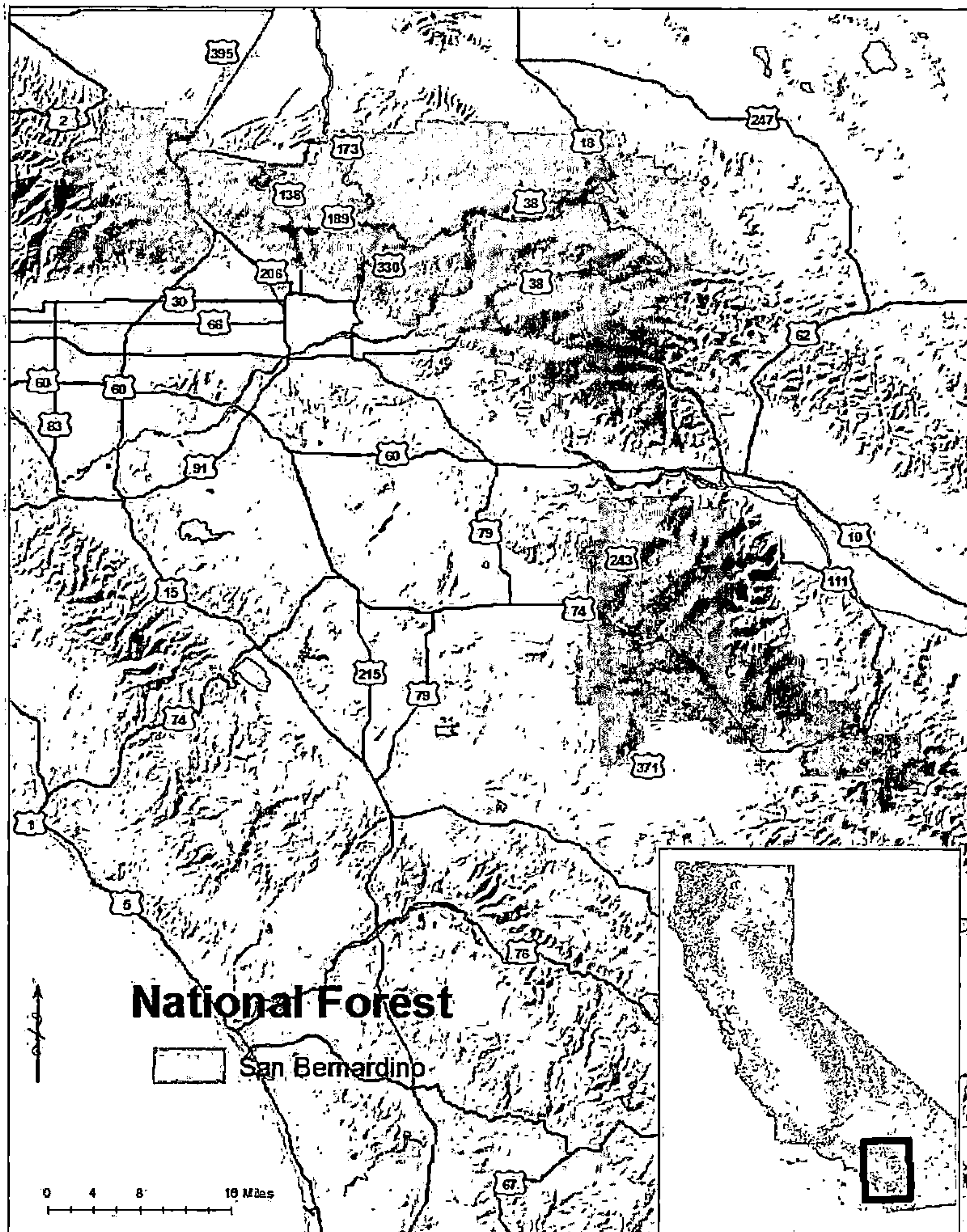


Figure 6. The San Bernardino National Forest

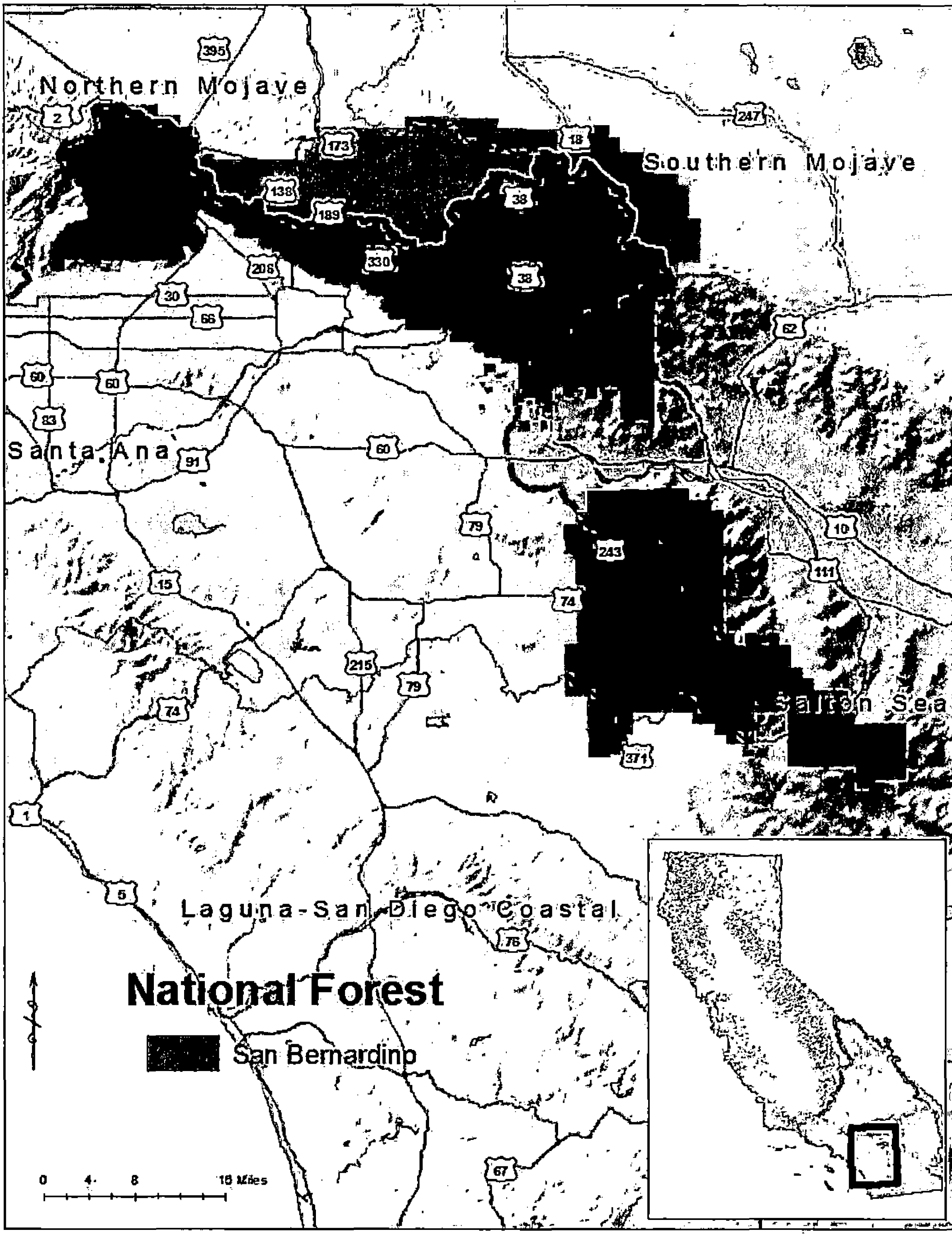


Figure 7. HUC-3 Basins in the San Bernardino National Forest

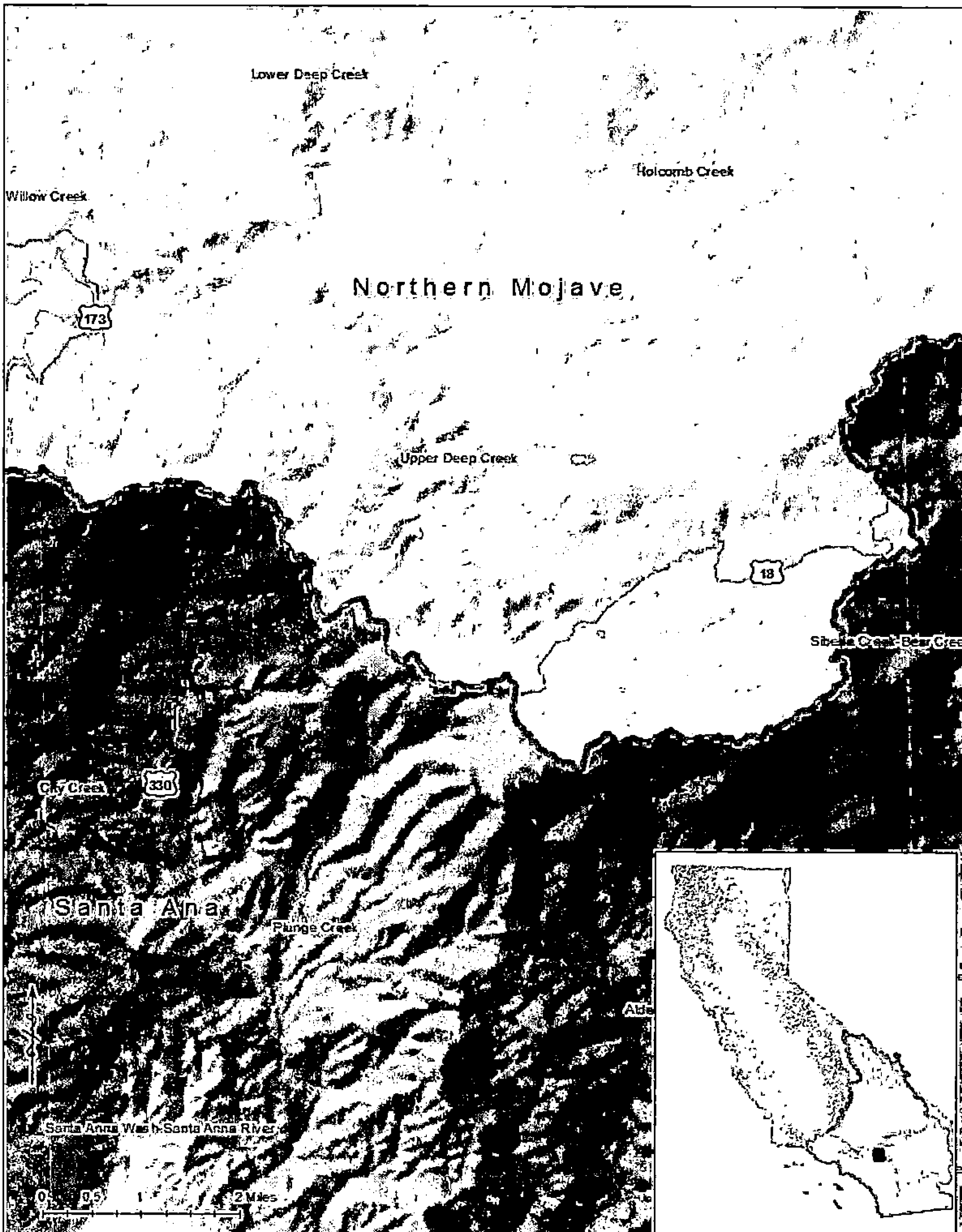


Figure 8: Upper Deep Creek Sub-Watershed

The elevation of the Upper Deep Creek sub-watershed ranges from approximately 4,600 to 8,400 feet above sea level, with a total land area of approximately 205 square miles. According to the information contained in attribute tables for the shape files used for this project, within this sub-watershed are approximately 156 miles of roads, including state, county, and USFS roads. USFS roads alone constitute 49 miles, or about 31 percent, of this road network. The total road density of the entire road network is 0.76 linear mi/mi^2, and the road density of the USFS road network is 0.24 linear mi/mi^2. Due to the fact that this is a mountainous, forested watershed, the majority of roads in this area are cut-and-fill, with various roads having either insloped or outsloped designs. There are about 79 miles of streams in this sub-watershed, and a local population of approximately 7,000 people lives on private land inholdings in this area (US Census, 2012).

The WCC guideline for road density within a highly functioning ecosystem is less than 1 linear mile of road per square mile of land area. Additional WCC guidelines also suggest that in order to protect watershed health, BMPs should be applied to 75 percent of all drainage structures in the road network, and that no more than 10 percent of the road network be located within 300 feet of a stream. In addition, the WCC suggests that in order to prevent the addition of sediment from landslides, very few roads should be built on areas that are at risk of mass wasting (USDA, 2011a). Using the shape files provided for the Upper Deep Creek sub-watershed, this project determined that 115 miles, or 73 percent, of the road network is within 300 feet of a stream. As mentioned above, the road density is 0.76 linear mi/mi^2, and 85 miles, or 54 percent, of the road network has been paved. From the GIS data used for this project, it is hard to determine much about drainage structures, or about how much of the road network is built in areas at risk of mass wasting, without extensive field checking and mapping that are beyond the scope of the immediate study.

Data Sources

The data used for the modeling portion of this project was obtained from attribute tables in GIS shape files that were provided by the San Bernardino National Forest staff and were downloaded from CalAtlas, the State of California's clearinghouse for geospatial data. Additional data was also provided by the Water Resources

Institute at the California State University, San Bernardino. A total of six different road shape files were used to represent the entire road network in the Upper Deep Creek sub-watershed. The shape files that were used to obtain this required information contained various amounts data, and the amount of detail that was provided for each road segment varied according to the source. Table 1 summarizes the attributes that were contained in road shape files from the USFS that were relevant for this project. Table 2 summarizes the attributes that were contained in road shape files that were obtained from CalAtlas that were relevant for this project.

Table 1. Fields Contained in the Attribute Tables for Forest Service Road Shape Files

Field	Description
ID	FS Route Number
Name	Road Name
Functional_Class	Type of road (Collector, Local, Arterial)
Lanes	Road width (single or double lane)
Oper_Maint_Level	Code related to maintenance frequency
Route_Status	Existing or decommissioned
Surface_Type	Surfacing (Native, Cement, Asphalt)
Passenger_Vehicle	Whether or not route is open to passenger vehicle traffic
Length	Length of road segment

Table 2. Fields Contained in the Attribute Tables for CalAtlas Road Shape Files

Field	Description
FeName	Road name
FeType	Type of road (Rd, Ln, St, etc.)

In order to obtain additional information needed to run the physical models used in this project, data from other shape files was joined to these tables, and additional analysis tools were used within the ArcMap software. ArcMap contains an analysis tool that allows attributes to be joined from different shape files based on spatial overlap. This spatial join was performed to add attribute data from shape files that contained information regarding geology and hydrologic features in the study area.

Slope data was gathered from a .tif file that was generated from aerial photographs of the study area. The .tif file was converted to a digital elevation model (DEM) using an analysis tool in ArcMap. The slope was projected in the DEM file, and then was assigned a code according to the parameters outlined in Table 3. The slope code was then spatially joined to the road shape files in order to estimate the gradient of the road surface. The slope code was also used to estimate the cut slope height, following a recommendation in the WARSEM model documentation. The WARSEM model automatically assumes a certain cut slope height based on the slope of the underlying topography of the hill slope. This information is also summarized in Table 3.

Table 3. Slope Codes and Cut Slope Heights Used for Modeling Upper Deep Creek Roads

Slope (%)	Slope Code	Value Modeled (% Slope)	Cut Slope Height (ft)
<5	1	2.5	2.5
5-10	2	7.5	2.5
10-30	3	20	5
30-60	4	45	10
>60	5	60	25

The WARSEM model assumes that all road segments that are greater than 200 feet from a stream are hydrologically disconnected from the stream, and therefore will not contribute any sediment to the stream system. Due to the fact that this project was only interested in road segments that could be contributing sediment to streams, all road segments that were greater than 200 feet from a stream were excluded from the analysis. In order to eliminate segments that were greater than 200 feet away from streams, two analysis tools were used in ArcMap. The "buffer" tool was used to create a polygon feature around all streams that extended 200 feet out from the streams. This polygon was then used along with the "clip" tool to clip the road shape file, which eliminated all road segments that were greater than 200 feet from streams from the road shape file attribute table. Road segment length was then re-calculated for all road segments after all of the geospatial processing functions had been performed.

For the WEPP:Road model, all segments were included in the analysis, regardless of their distance from the nearest stream. The distance between the road segment and the closest stream needed to be included as an attribute for each road segment. ArcMap contains a tool that calculates the shortest path between specified features called the "near" tool. This tool was used to measure the distance between all road and stream segments. This information was then added back into the attribute table for the road shape file. A flow chart showing all of the processing tools that were used in ArcMap is included in Figure 9.

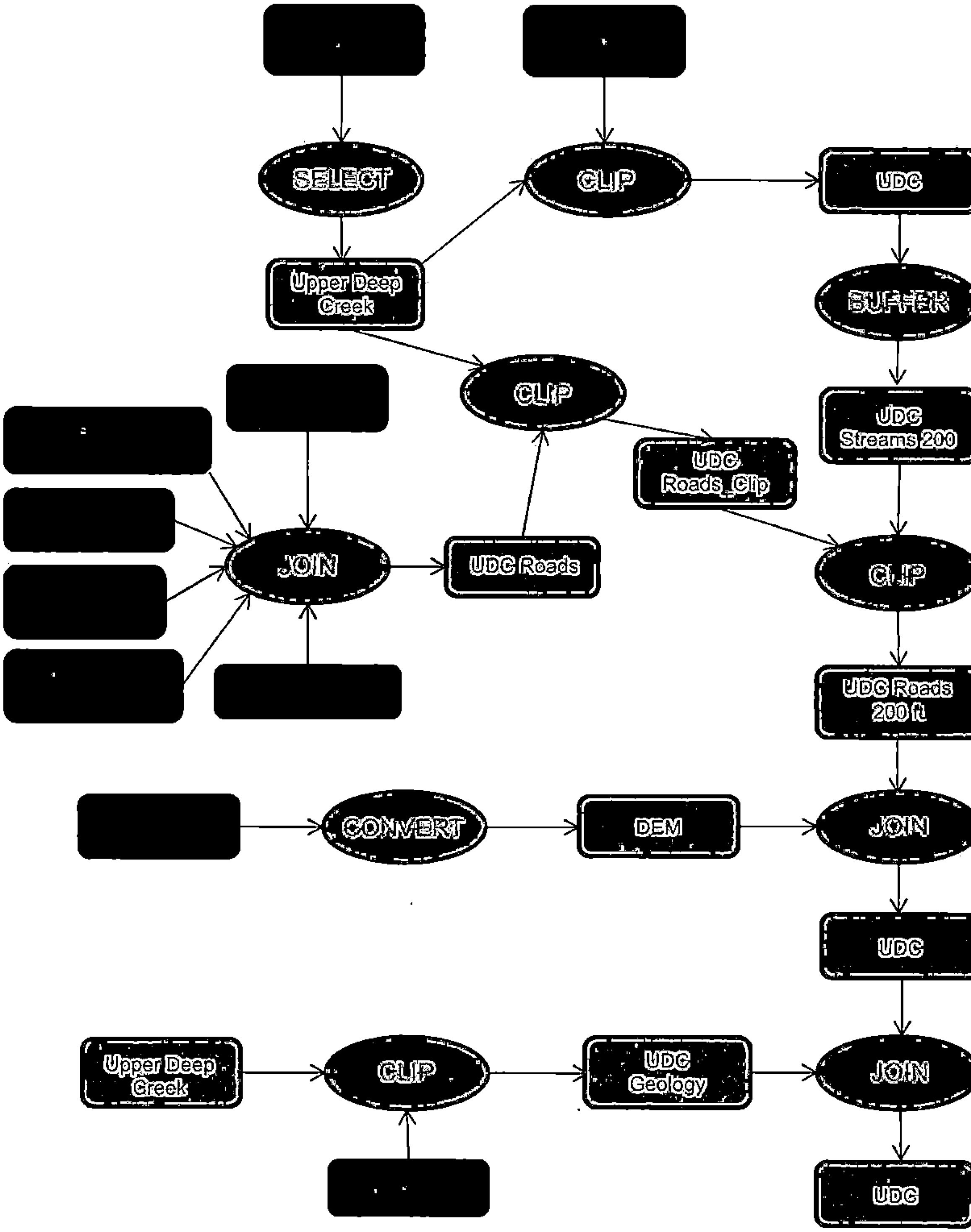


Figure 9. Flow Chart of Analysis Tools Used in ArcMap

WARSEM Modeling

The WARSEM model requires inputs for the following road attributes (Dubé et al., 2004):

Segment ID

Length of road segment (in feet)

Road surfacing

Road width

Road use

Road gradient

Cut slope height

Percent vegetation cover on cut slope

The WARSEM model has limitations on the values that it will accept for these attributes. For some attributes, including surfacing and road use, values need to be chosen from a list of acceptable entries. For other attributes, any integer number can be entered, but the model will simplify the entry by grouping values. This data was entered into the attribute table following the guidelines in Table 4.

Table 4. Data Import Format Requirements for the WARSEM Model

Field Name	Data Type	Max Length	Description and format requirements
Seg_ID	Long integer		Unique Identifier for road segment. Duplicates not allowed
Group_ID	Long integer		ID number for contiguous road segments with shared delivery route (extended drainage network)
RoadName	Text	30	User defined road name
ProjectArea	Text		Unique identifier for identifying the location of the road segment within a WAU
PrimTwp	Text	4	Township where the majority of the road exists, (Valid Format: T00N)
PrimRng	Text	4	Range where the majority of the road exists, (Valid Format: R00E, or R00W)
PrimSec	Integer		Section number where the majority of a road exists. (1-36)
Length	Single		Length of road segment in feet.
Flag	Integer		Indicator for application of updates or actions where Flag > 0.
RdClass	Text	17	Highway, Main haul, County road, Primary road, Secondary road, Spur road, Abandoned/blocked
RdSurf	Text	17	Asphalt, Gravel, Gravel with ruts, Pit run, Grassed native, Native, Native with ruts
TreadWidth	Integer		Width of road tread in

Field Name	Data Type	Max Length	Description and format requirements
			feet.
DitchWidth	Integer		Width of ditch in feet.
DitchDelType	Integer		Delivery type code for ditch (Valid Codes: 0 = No delivery; 1=Direct; 2=Indirect<=100 Ft.; 3=Indirect 101-200 Ft; 4=Direct via gully.)
DitchCond	Text	8	Condition of ditch (Valid Classes: ROCK/VEG, STABLE, ERODING)
RdUse Text		16	Typical road use: (Valid Classes: NONE, OCCASIONAL, LIGHT, MODERATE, MODERATELY HEAVY, HEAVY)
RdGradient	Integer		Actual values can be used but the model classifies the data into (0-5%, 5-10%, > 10%).
Rdcutslpht	Integer		Height of cut slope (in feet). Actual values accepted but classified into: 0 ft, 2.5ft, 5ft, 10ft, 25ft
Cutslpveg	Integer		Percentage of cover of vegetative or non-erosive material on road cut slope. (Whole number, 0-100)
Rdprism	Text	9	Road configuration (Valid Classes: Insloped, Outsloped, Crowned)
Constructyr	Integer		Year of road construction (Valid Format: yyyy)
Geology	Text	8	Description of geology as seen on the cut slope. (Valid Classes: Low, Medium, High)
Delcode	Integer		Delivery type code (Valid Codes: 0 = No delivery; 1=Direct; 2=Indirect<=100 Ft.; 3=Indirect 101-200

Field Name	Data Type	Max Length	Description and format requirements
			Ft; 4=Direct via gully.)
FieldVerified	Text	3	Have the road attributes been field verified? (Valid Codes: YES, NO)

Source: Adapted from Dubé, K.; Megahan, W.; McCalmon, M. *Washington Road Surface Erosion Model*; State of Washington Department of Natural Resources: Olympia, WA, 2004.

Once the data set included all of the attributes required by the WARSEM model, the attribute table was arranged according to the specifications in Table 3, as outlined in Dubé et al., 2004. After several failed attempts to use the data import feature, data from a subset of approximately 100 road segments was entered manually into the database for the WARSEM model.

Although the model documentation did not state that township, range, and section numbers are required by the model, when the data were entered manually, the model required inputs for these three variables. Because the model was designed for use in the state of Washington, it only accepted township, range, and section numbers from one of the state of Washington's land management areas.

Therefore, when this data was entered into the model, township, range, and section numbers were randomly chosen from the available options that had been programmed into the model. The same combination of township, range, and section numbers were used for all 100 segments that were entered into the WARSEM model.

WEPP:Road Modeling

Once the attribute tables for all of the road segments had been formatted according to the criteria for the WARSEM model, they were only minimally changed for the WEPP:Road model. The data did not require much additional re-formatting due to the fact that WEPP:Road has fewer input requirements than WARSEM, and makes similar simplifying assumptions to those made by the WARSEM model. Table 5 outlines the data input requirements and formatting limitations for the WEPP:Road model.

Table 5. Topographic Limitations in the WEPP:Road Interface

Variable	Range of Values
Road gradient	0.1 to 40 percent
Road horizontal length	1 to 300 m
Road horizontal width	0.3 to 100 m
Fill slope slope	0.1 to 150 percent
Fill slope horizontal length	0.3 to 100 m
Buffer gradient	0.1 to 100 percent
Buffer horizontal length	0.3 to 300 m

Source: Adapted from Elliot, W.J.; Hall, D.E.; Scheele, D.L. *WEPP Interface for Predicting Forest Road Runoff, Erosion and Sediment Delivery;* United States Department of Agriculture, Forest Service, DRAFT: 1999.

In order to make the data in the attribute tables fit the constraints of the WEPP:Road model, all road lengths that were greater than 1000 feet had to be changed to the maximum value, and all road lengths less than 1 foot had to be increased to the minimum value. The reason why the attribute table contained road lengths that were less than 1 foot is probably due to fragments left by the various spatial analyses performed in ArcMap, and most likely do not truly represent actual field conditions. Similarly, road lengths that are greater than 1000 feet may not represent field conditions, and may be due to the lack of information in attribute tables regarding cross-drain placement. However, all of these road lengths were calculated in ArcMap, and were modeled with the length as calculated.

Like the road length values, all buffer lengths that were less than 1 foot had to be increased to the minimum value, and all buffer lengths that were greater than 1000 feet had to be reduced to the maximum. Buffer lengths that were less than 1 foot were probably the result of road-stream crossings.

As mentioned previously in this chapter, due to the lack of road gradient data in the attribute tables, road gradients had been estimated based on underlying hill slope topography. Due to the fact that the road gradient input is limited to 40 percent, all road segments with slopes greater than 40 percent had to be changed to the maximum.

Several other assumptions were used when entering road segment data into the WEPP:Road model. The fill gradient was assumed to have a slope of 60 percent and to be 16 feet long. The buffer gradient was assumed to be 16 percent, and the percent rock fragment was assumed to be

20 percent. These assumptions were used because there was little information about fill slopes and buffers in the shape files used for this project, and these were the defaults that were present in the WEPP:Road data entry template. Acquiring more detailed information regarding these parameters would have required extensive field work that was beyond the scope of this project.

The WEPP:Road model includes an input for the CLIGEN model, which uses information from weather stations to generate weather data specific to the study area. For this project, the Lake Arrowhead climate station was used to model climate data. Depending on the type of weather in the area, the model documentation recommends running the model for a minimum of 30 years, with 100 years being preferable in areas with low amounts of precipitation (Elliot et al., 1999). For this project, 30 years of modeling was used, as this area receives enough precipitation for this to be an acceptable amount of time.

After running the WEPP:Road model, the data table containing the model output for predicted sediment production from the road surface and forest buffer was joined to the original attribute table. In order to identify portions of the road network that were disproportionately contributing sediment to the stream network, the road segments were classified in ArcMap according to the number of standard deviations the predicted sediment production was away from the mean value for all road segments. This classification was performed for four sets of data: the predicted erosion from road surfaces for all road segments, the predicted erosion from buffers for all road segments, the predicted erosion from road surfaces for only USFS road segments, and the predicted erosion from buffers for only USFS road segments. Breaks for this classification were placed at values that were 0.5, 1.5, and (in some cases) 2.5 standard deviations away from the mean predicted sediment production value.

Silt Fences

Three portions of the road network were chosen for silt fence installation. Silt fences were installed in sets, with one fence located above the road prism, and the other located below the road prism. Each location was chosen based on predicted traffic levels, road surfacing, and accessibility. One set of fences was located along a portion of the road network that had been completely closed to vehicles for three years. Another set was located along a portion of the road network that had been open to vehicles, and had been used by logging operations that had occurred over the previous three years. The third set of fences was located along a portion of the road network that was chosen because it was open to recreational users for part of the year. All three locations were on unpaved, single-lane USFS roads that had been burned 4 years prior to silt fence installation. The locations of the silt fences were captured using ArcPad and a Magellan Mobile Mapper hand-held GPS device. A map of the silt fence locations is presented in Figure 10.

Figure 10. Location of Silt Fences

The length of each silt fence was determined by examining the upslope contributing area above the fence location. Each fence was installed so that it would completely capture all runoff from the upslope area, so the locations were chosen based on the erosive patterns on the fill slope. Fence lengths are summarized in Table 6. The bottom 3 inches of each fence was buried so that all sediment would be trapped in the fence. The fences were originally installed on November 19, 2011, and were left intact until August 3, 2012. They were not cleaned out after any storm events, and were left undisturbed until they were removed. Due to the fact that no significant material was collected over the course of the project, the fences were simply removed once the study had been completed. Pictures of all of the silt fences on November 19, 2011 and August 3, 2012 are included in Appendix A.

Table 6. Summary of Dimensions and Locations of Silt Fences

Fence Number	Road	Road Surface	Road Width (ft)	Road Segment Length (ft)	Road Segment Slope (%)	Fence Location	Fence Length (ft)
1	2N19	Native	15	188	35	Below	9.5
1A	2N19	Native	15	188	35	Above	17
2	2N13	Native	12	383	5	Below	10
2A	2N13	Native	12	383	5	Above	17
3	2N19	Asphalt	17	82	5	Below	17
3A	2N19	Asphalt	17	82	5	Above	8

CHAPTER THREE

RESULTS

WARSEM Results

The WARSEM model was run for a subset of 100 road segments. Due to limitations of this model, results were an aggregate sum of all sediment from all road segments. This precluded the identification of road segments of particular concern, as will be described in more detail later in Chapter 4.

WEPP:Road Results

<u>Results for the Entire Road Network</u>

A total of 3,881 road segments were included in this analysis, which included state, county, and USFS roads. Road segment lengths ranged from 1 to 1,000 feet, averaging 212 +/- 229 feet. The WEPP:Road analysis predicted the total amount of sediment that will leave the road surface, as well as the total amount of sediment that will leave the buffer and enter the stream system each year. For the amount of sediment leaving the road surface, predictions range from 0 to 767,411 pounds per year, with a median value of 1,090 pounds of sediment per segment per year. The mean mass of sediment predicted to leave each road segment was 9,949 pounds per year, with a standard deviation of 36,434 pounds per year. A summary of this data is presented in Table 7 and Figure 11.

Table 7. Predicted Sediment Production from All Road Surfaces

Predicted Sediment Production Range (Number of Standard Deviations Above Mean)	Number of Segments	Total Road Length (ft)	Fraction of Road Network (%)	Total Sediment Leaving Road Surface (lb/yr)	Fraction of Total Sediment Production from All Road Surfaces (%)
< 0.5	3,573	602,865	73	10,886,522	28
0.5 - 1.0	119	76,290	9	4,537,022	12
1.0 - 1.5	48	26,672	3	2,591,513	7
1.5 - 2.0	26	21,527	3	1,788,640	5
2.0 - 2.5	49	39,508	5	4,137,403	11
> 2.5	66	55,675	7	14,669,947	38
Total	3,881	822,537		38,611,047	

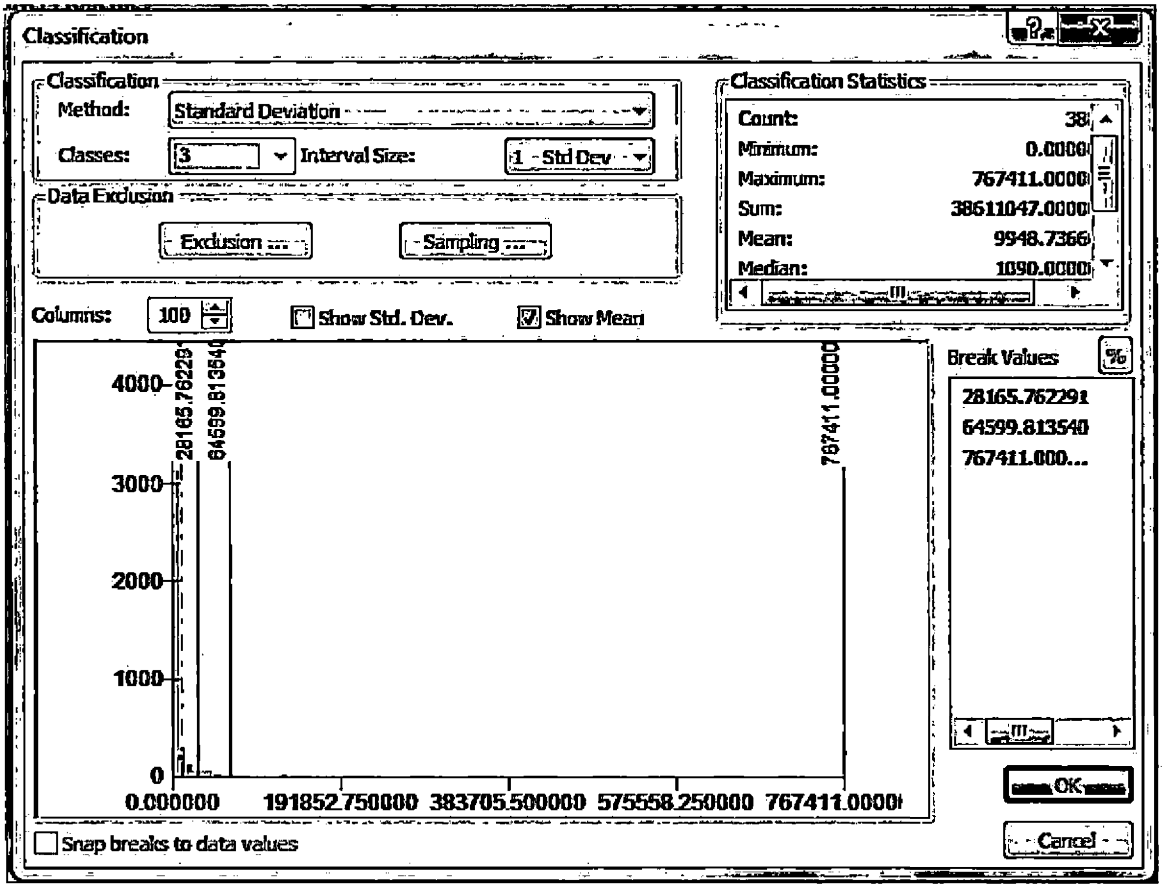


Figure 11. Histogram of Predicted Sediment Production from All Road Surfaces

Using this analysis, there were 66 road segments in the highest sediment production category, which included road segments that produce an amount of sediment that is > 2.5 standard deviations above the mean sediment production for all road surfaces. These roads had a total length of 55,675 feet, which is 7 percent of the total road network. The total sediment produced by roads in this category accounted for 38 percent of the total sediment production for the entire road network. The average length per road segment was 842 +/- 187 feet. The road segments were, on average, 393 +/- 338 feet from the nearest stream. Of these roads, 53 segments with a total of 43,499 feet, or 78 percent, had asphalt surfacing.

The predicted amounts of sediment leaving the buffer of each road segment and entering the stream network ranged from 2 to 296,102 pounds of sediment per year, with a median of 996 pounds per year, a mean of 3,556 pounds per year, and a standard deviation of 10,858 pounds per year. A summary of these results is presented in Table 8 and Figure 12.

Table 8. Predicted Sediment Production from All Road Segment Buffers

Predicted Sediment Production Range (Number of Standard Deviations Above Mean)	Number of Road Segments	Total Road Length (ft)	Fraction of Road Network (%)	Total Sediment Leaving Buffer (lb/yr)	Fraction of Total Sediment from All Segment Buffers (%)
< 0.5	3,570	596,650	73	5,374,560	39
0.5 - 1.0	112	70,638	9	1,246,437	9
1.0 - 1.5	58	40,570	5	977,481	7
1.5 - 2.0	30	22,926	3	674,633	5
2.0 - 2.5	36	30,001	4	1,000,713	7
> 2.5	75	61,752	8	4,526,167	33
Total	3,881	822,537		13,799,991	

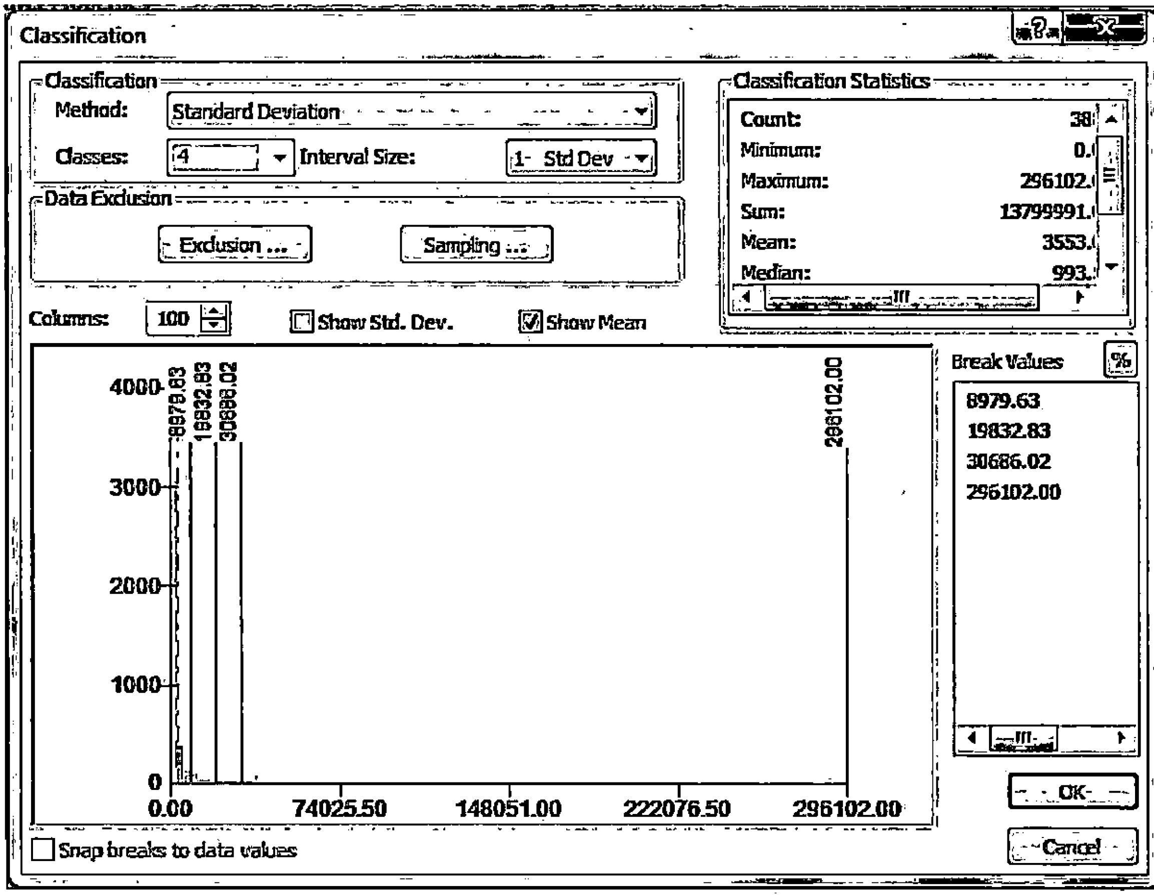


Figure 12. Histogram of Sediment Production from All Road Segment Buffers

When the predicted amount of sediment leaving the buffer of each road segment and entering the stream network was analyzed, 75 segments fell into the highest sediment production category, which included road segments that were predicted to produce an amount of sediment that was > 2.5 standard deviations above the mean sediment production for all roads. These roads had a total length of 61,752 feet, which is 8 percent of the total road network. The total sediment production for all roads in this category was 33 percent of the total predicted sediment production and delivery for the entire road network. The average length per road segment was 823 +/- 211 feet. The road segments were, on average, 103 +/- 118 feet from the nearest stream. Of these roads, 48 segments with a total of 37,565 feet, or 61 percent, had asphalt surfacing. The top ten segments producing sediment from their forest buffer constituted 9,547 miles, or 1 percent, of the total network, yet were predicted to contribute 11 percent of the sediment entering the stream network.

The results of these analyses are visually represented in Figures 13-14. In each figure, road segments are symbolized according to the number of standard deviations the predicted road sediment production is away from the mean predicted sediment production for all segments. The electronic data files for this analysis are included in the compact disk attached as Appendix B.

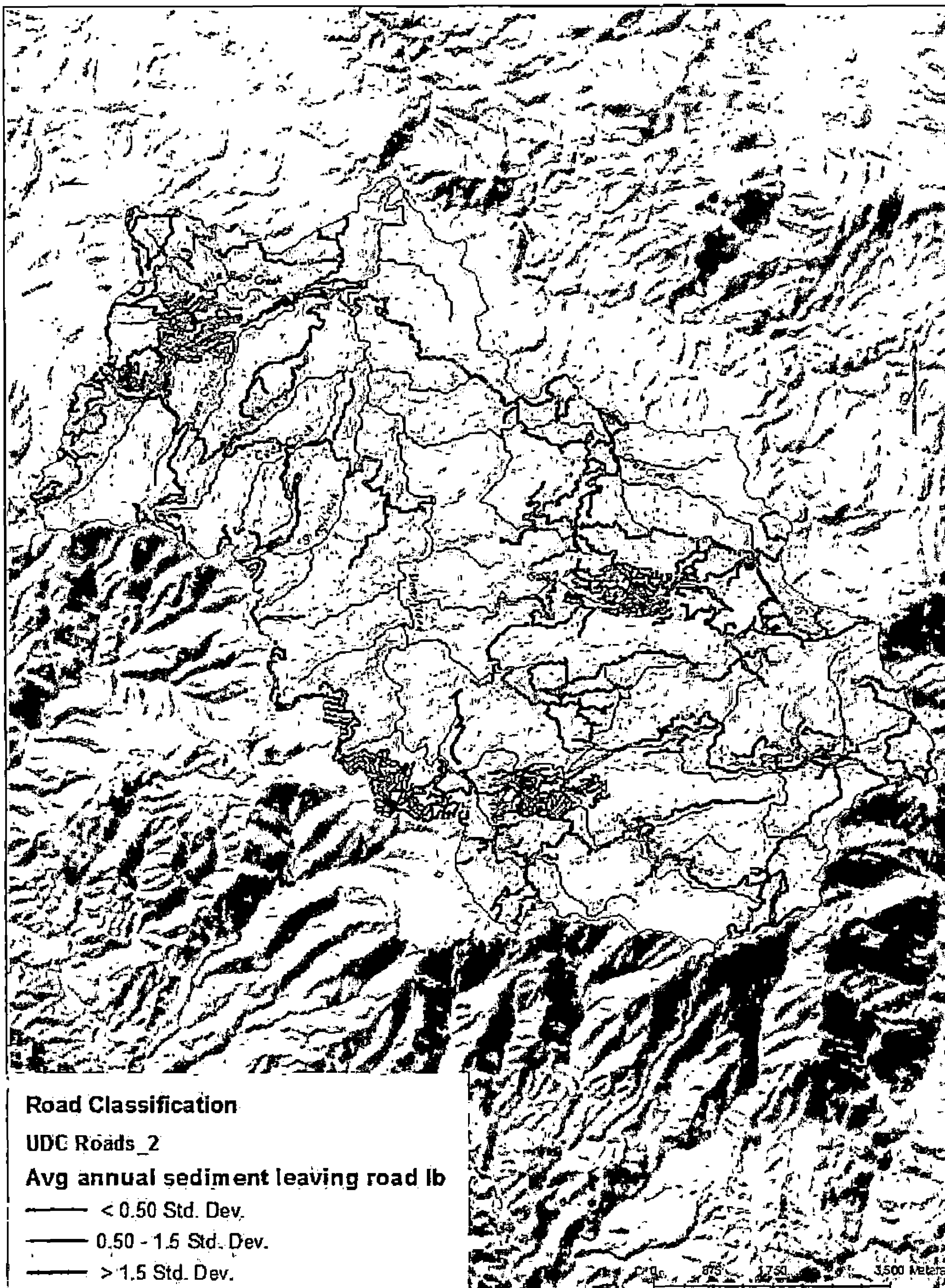


Figure 13. Predicted Sediment Production from All Road Surfaces

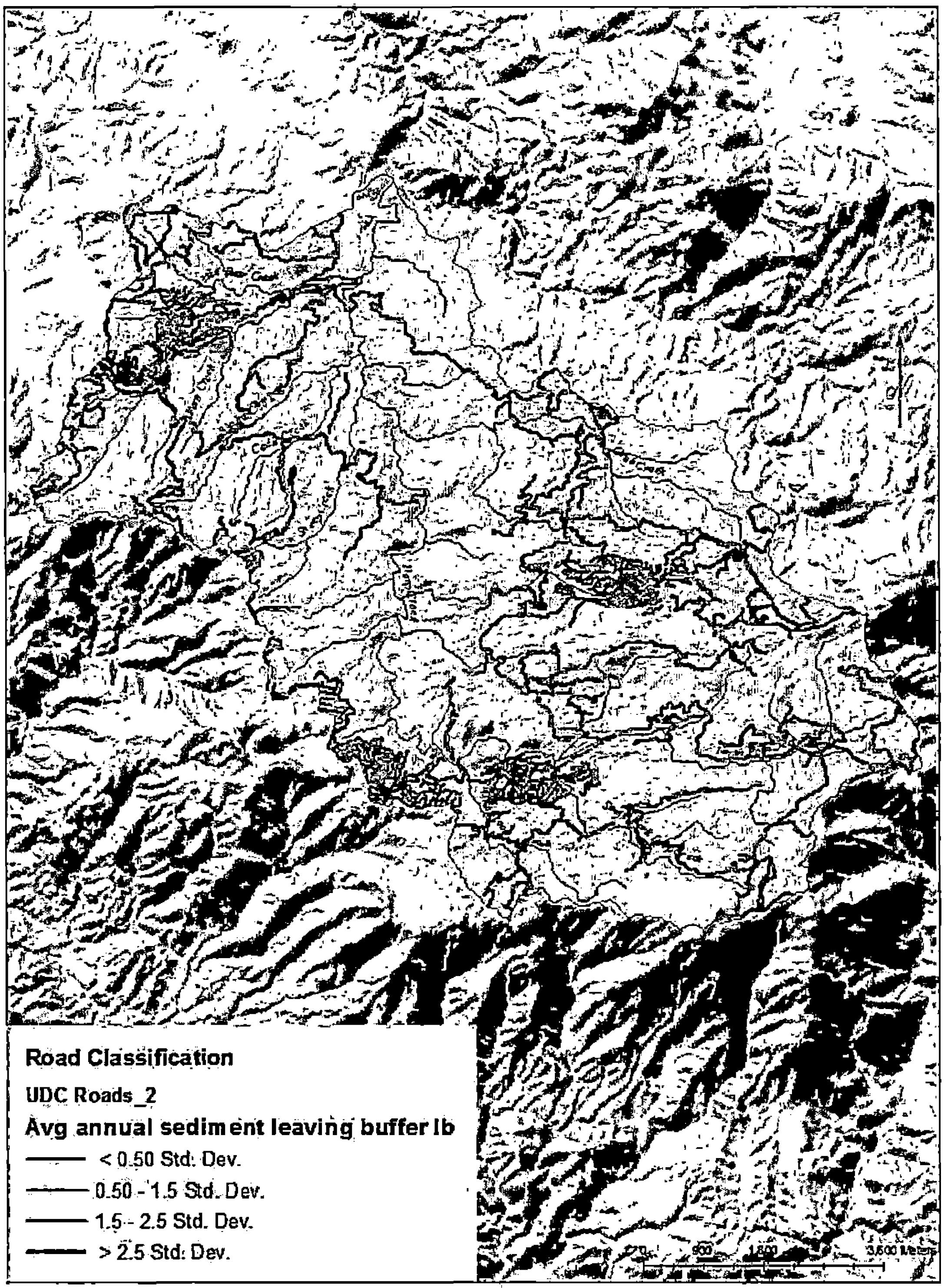


Figure 14. Predicted Sediment Production from All Road Segment Buffers

Results for Forest Service Roads

Out of all of the road segments, 945 are under USFS jurisdiction, and were analyzed as a separate subset of the road system. Road segment lengths for this subset ranged from 3 to 1,000 feet, with a mean of 273 +/- 282 feet. Of these road segments, the amount of sediment predicted to leave each road surface ranged from 3 to 389,642 pounds per year, with a median of 2,114 pounds per year. The mean predicted sediment production was 16,563 pounds per year, with a standard deviation of 40,740 pounds per year. A summary of these results is presented in Table 9 and Figure 15.

Table 9. Predicted Sediment Production from Forest Service Road Surfaces

Predicted Sediment Production Range (Number of Standard Deviations Above Mean)	Number of Segments	Total Road Length (ft)	Fraction of Road Network (%)	Total Predicted Sediment Production (lb/yr)	Fraction of Total Sediment Production for Road Network (%)
< 0.5	821	157,131	61	3,871,019	24
0.5 - 1.0	47	35,279	14	2,147,622	14
1.0 - 1.5	14	10,510	4	948,931	6
1.5 - 2.0	30	26,514	10	2,449,956	16
> 2.0	33	28,515	11	6,234,968	40
Total	945	257,949		15,652,596	

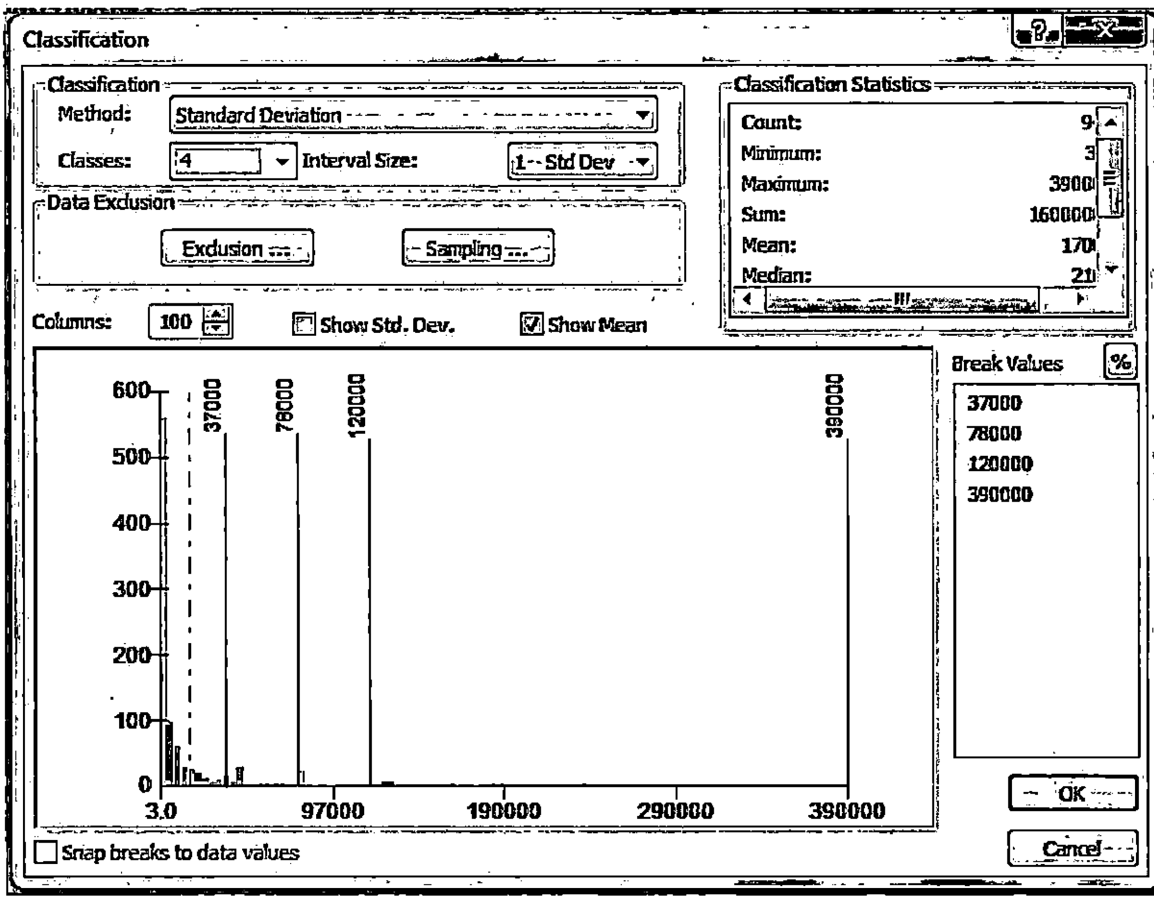


Figure 15. Histogram of Predicted Sediment Production from Forest Service Road Surfaces

Using this analysis, there were 33 road segments that were predicted to produce an amount of sediment that was > 2 standard deviations above the mean sediment production for all roads. These roads had a total length of 28,515 feet, which is 11 percent of the total road network. The total sediment production for all roads in this category was 40 percent of the total sediment production for all road surfaces in the USFS road network. The average length per road segment was 864 +/- 171 feet. Of these roads, 18 segments with a total of 14,741 feet, or 52 percent, had asphalt surfacing. The road segments were, on average, 338 +/- 327 feet from the nearest stream.

The predicted amounts of sediment leaving the buffer of each road segment and entering the stream system ranged from 3 to 296,102 pounds per year, with a median of 1,391 pounds per year, a mean of 6,141 pounds per year, and a standard deviation of 16,556 pounds per year. A summary of this data is presented in Table 10 and Figure 16.

Table 10. Predicted Sediment Production from Forest Service Road Segment Buffers

Predicted Sediment Production Range (Number of Standard Deviations Above Mean)	Number of Road Segments	Total Road Length (ft)	Fraction of Road Network (%)	Total Predicted Sediment from Buffer (lb/yr)	Fraction of Total Sediment Production from All Buffers (%)
< 0.5	849	179,042	69	1,966,378	34
0.5 – 1.0	27	19,770	8	493,959	9
1.0 – 1.5	28	24,480	9	765,600	13
1.5 – 2.0	8	6,047	2	283,403	5
> 2.0	33	28,610	11	2,293,821	40
Total	945	257,949		5,803,161	

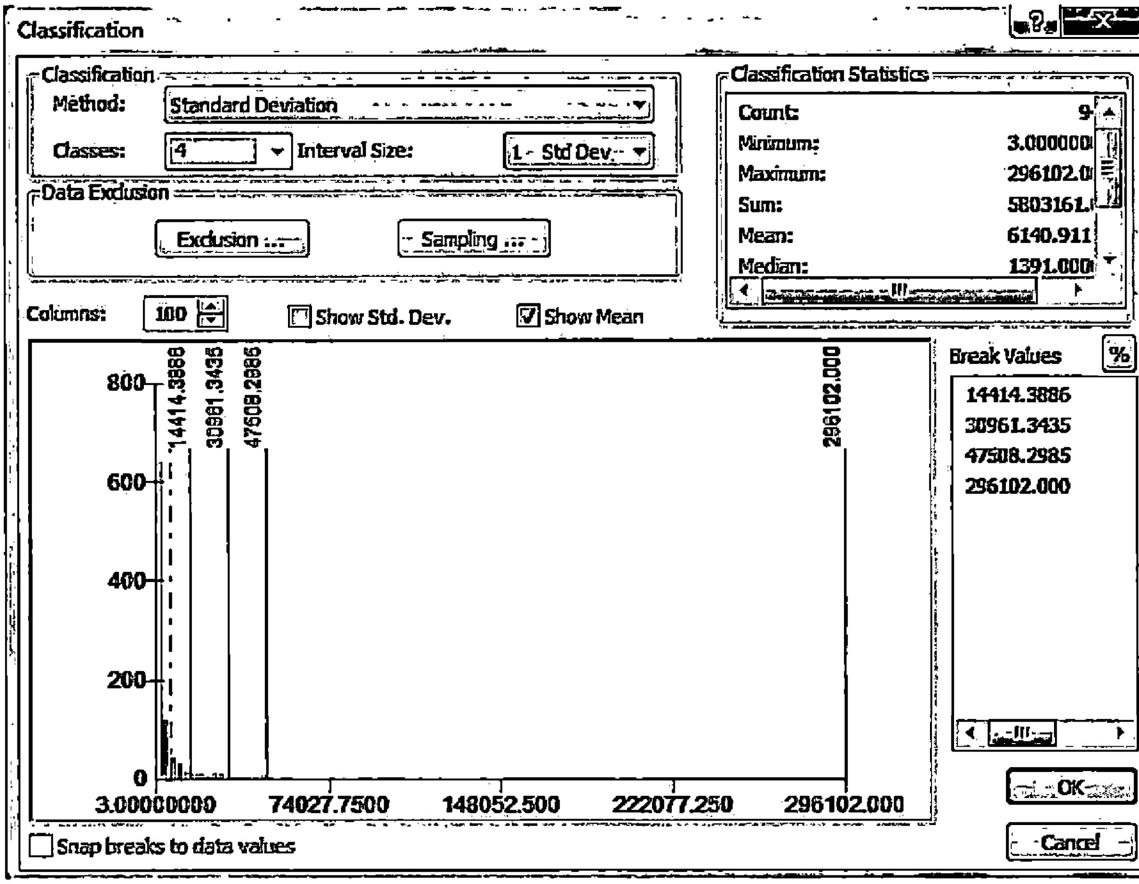


Figure 16. Histogram of Predicted Sediment Production from Forest Service Road Segment Buffers

When the predicted amount of sediment leaving the buffer of each road segment and entering the stream network was analyzed, 33 segments were predicted to produce an amount of sediment that is > 2 standard deviations above the mean sediment production for all roads. These roads had a total length of 28,610 feet, which is 11 percent of the total road network. The average length per road segment was 867 +/- 185 feet. Of these roads, 16 segments with a total of 12,573 feet, or 44 percent, had asphalt surfacing. The road segments were, on average, 53 +/- 64 feet from the nearest stream. The sediment that is produced and delivered from buffers for segments in this category accounts for 40 percent of the sediment delivery for the entire USFS road network.

The results of these analyses are visually represented in Figures 17-18. In each figure, road segments are symbolized according to the number of standard deviations the predicted road sediment production is away from the mean predicted sediment production for all segments. The electronic data files for this analysis are included in the compact disk attached as Appendix B.

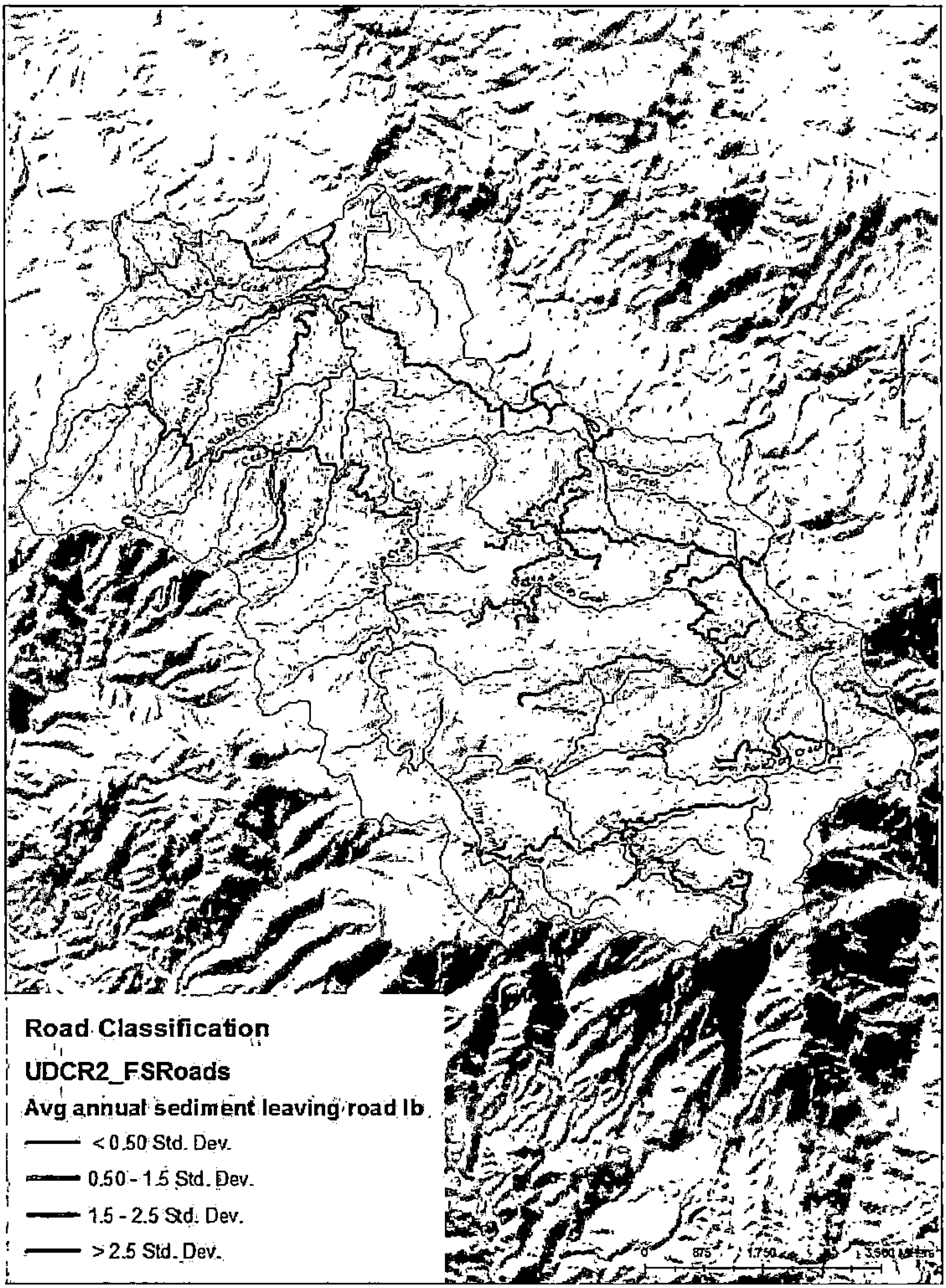


Figure 17. Predicted Sediment Production from Forest Service Road Surfaces

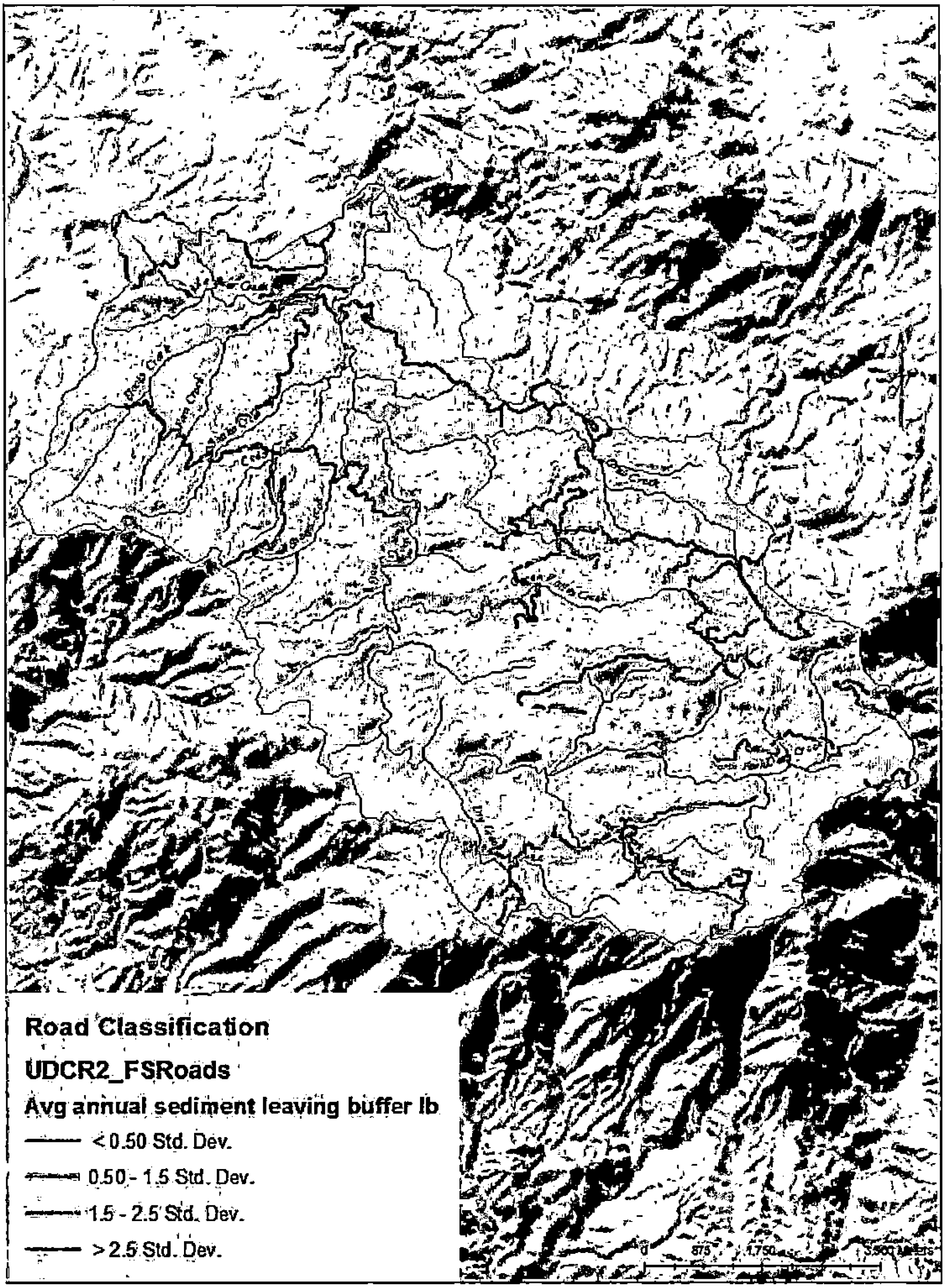


Figure 18. Predicted Sediment Production from Forest Service Road Segment Buffers

Empirical Results from Silt Fences

Silt fences were collected on August 3, 2012. Fences 1, 1A, and 2A had been removed, so no material was recoverable. Of the three fences that remained intact, none appeared to have collected significant sediment, and therefore no material was available to analyze. Pictures of the fences prior to removal are included in Appendix A.

CHAPTER FOUR

DISCUSSION AND CONCLUSIONS

Discussion of the WARSEM Model

Upon initial investigation, the WARSEM model contained several features that made it seem ideal for this project, including its compatibility with GIS data and its data import utility. However, after initiating this project, it was discovered that there were several aspects to the WARSEM model that made it less useful for accomplishing the goals of this project than originally thought, including the age of the software platform upon which the model was built, and challenges associated with the data import feature.

WARSEM Compatiblity with GIS Data

The fact that the WARSEM model is compatible with GIS data makes it very useful for a watershed-scale road network analysis, as GIS data is readily available to land and resource managers. However, it appears as if the version of Microsoft Access upon which the model is based is not compatible with current versions of dBASE files upon which the attribute tables in GIS shape files are built. The most recent version of the model that was available for download from the internet ran on a Microsoft Access 2000 platform, while the current version of Microsoft Access that was in use at the time this project was performed was the 2010 edition. Additionally, the most current version of ArcGIS software that that was used at the time of this study was ArcEditor 10, which was released in the year 2011 and was designed to be compatible with current computer operating systems. This version of ArcGIS software used dBASE III and IV files, while the early version of WARSEM was most likely using dBASE I files, as this would have been the type of file in use at the time that the Microsoft Access platform was current. This means that at the time that this project was completed, the version of software that was used for the geospatial analysis was incompatible with the version of software upon which the WARSEM model was built. This seemed to make the data in current GIS shape files unrecognizable to the WARSEM model.

WARSEM Data Import Feature

The WARSEM model contains a data import tool that is designed to ease the data entry process by allowing dBASE data files to be directly imported from attribute tables in GIS shape files (Dube et al., 2004). Using a model with a data import feature is an advantage because it can reduce the amount of time and resources used to initiate a modeling project, while also helping avoid potential data entry errors. However, the data import tool for the WARSEM model was never successful at importing data from the shape files that were used for this project. This was despite repeated attempts to format the attribute tables according to the specifications outlined in the model documentation provided by Dubé et al. (2004). The reason the data import tool did not work may be due to the lack of compatibility between the software that is required to run WARSEM, and the more recent versions of software designed to work with GIS data. As mentioned in the previous section, the version of Microsoft Access upon which the WARSEM model was built was much older than the current version of Microsoft Access in use at the time this project was completed, and was also designed to be used with a version of dBASE file that was much other than the version in use at the time this project was completed. The newer file versions used by current software may not have been recognizable to the WARSEM model.

This had the additional complication that the type of computer that was required to run the version of Microsoft

Access upon which the WARSEM model was based was incompatible with the type of computer required to run the ArcGIS software that was used for this project. Thus, all dBASE data files that were used for this project had to be formatted on one computer, and then transferred to another computer to attempt to import the data into the model. Due to the fact that the data import process was unsuccessful, the data was subsequently entered into the WARSEM database using the model template, without using the import feature.

Local Assumptions Built Into WARSEM

Manual data entry using the WARSEM's data entry template required entering data for additional inputs that were not specified in the model documentation. For example, data for township, range, and section information had to be entered for each road segment. Because the model was designed for use in the state of Washington, the township, range, and section numbers contained within drop-down menus in the data entry template did not match the actual township, range and section numbers of the study area. For this reason, a set of township, range, and section numbers were randomly chosen from the available options, and were used for all segments that were entered into this model. It is not clear what effect this could have had on the output that was generated by the model. Despite this data entry limitation, this model has been used in other studies that have taken place in various locations around the world (e.g. Akay et al., 2008; Fu et al., 2009). This implies that either the township, range, and section numbers are insignificant in terms of the model's predictions, or that other researchers may have been reprogramming the model to allow for different inputs to be entered in these fields.

Format of the WARSEM Output

Once data from the subset of 100 road segments had been entered into the model and the model had been run, the model predicted a quantity of sediment that would have been deposited as an aggregate sum of all contributing road segments. According to Fu et al. (2009), the output from the WARSEM model can be used on a watershed management scale to predict sediment contributions from individual road segments. However, for this project, the model delivered an output that presented sediment delivery data as an aggregate sum of all road segments, not predictions for individual road segments. This type of output was not useful for the purposes of this project, as the goal was to identify the portions of the road network contributing the most disproportionate amount of sediment to the stream network.

Overall Utility of the WARSEM Model

Despite the fact that the WARSEM model has been used in a number of recent studies around the globe for predicting erosion and sediment delivery from road networks(e.g. Akay et al., 2008; Fu et al., 2009). In the case of this project, a number of limitations to the model were identified that made it unusable. The types of limitations that were encountered suggest that other researchers may be using computer programming to adapt aspects of the model such as the data import feature to make the model compatible with current data formats and local geography, as well as making the output more useful for answering management questions. Unfortunately, modifying computer programming was beyond the scope of this project and was not feasible, so this model and its output were not useful for the purposes of this project.

Discussion of WEPP:Road Model

After the WARSEM model was determined to not be useful for this project, the project was continued with the WEPP:Road model. This model was chosen because WEPP:Road was easy to use and was compatible with GIS data that had already been formatted for the WARSEM model. The WEPP:Road model successfully generated predictions for erosion and sediment delivery from road surfaces and buffers of individual road segments. Several assumptions had to be incorporated into the data files in order to run the WEPP:Road model, and these may have affected the accuracy of the predictions of the model. However, the model predictions were useful in identifying portions of the road network that may be contributing disproportionate amounts of sediment to the stream network, and therefore were useful in answering some of the questions of this project. The accuracy of the output of the model can be improved in future studies by obtaining additional field measurements for attributes that were missing from the original shape files.

Results for the Entire Road Network

When the entire road network, including state, county, and USFS roads, was analyzed, the WEPP:Road model identified 66 road segments, or 7 percent of the total road network, that may be contributing a significant amount of sediment from their road surfaces. These road segments were, on average, over 300 feet away from streams. According to the WCF, road segments that are greater than 300 feet away from a stream can be considered hydrologically disconnected from the stream network (USDA, 2011b). Of these segments, only one appears to be a road-stream crossing; 36 were within 300 feet of a stream, and may be worth further field inspection for connectivity to the stream network.

The model also identified 75 road segments, or 8 percent of the total road network, that may be producing large amounts of sediment from their forested buffers. Because the sediment that is eroded from the forest buffer is predicted to enter streams (Elliot et al., 1999), these road segments probably deserve additional field investigation. These segments were, on average, only 100 feet from streams, and therefore can be considered hydrologically connected with the stream network. In this subset, the top 10 road segments, which account for 1 percent of the total road network, are predicted to be producing 11 percent of the sediment that is entering streams in Upper Deep Creek. These road segments probably also deserve additional field investigation, and would be good candidates for a future study.

Results for the Forest Service Road Network

The USFS roads were analyzed separately from the state and county roads due to the fact that the USFS road shape files contained substantial additional information regarding surfacing, maintenance, and road width that was not present in the shape files for the state and county roads. This meant that is was possible to obtain more accurate model predictions for the USFS subset than the entire road network. For this reason, the USFS roads were analyzed as a separate subset of the road network.

For the USFS road network, 33 road segments, or 11 percent of the road network, were identified as contributing significant amounts of sediment from their road surfaces. Like the results for the entire road network, this subset of road segments was, on average, more than 300 feet away from streams. However, 1 segment appears to be a road-stream crossing, and 20 segments are less than 300 feet away from streams. These segments may be worth additional field investigation in order to determine their real impact on the stream system.

The model also identified 33 segments, or 11 percent of the USFS road network; that were predicted to be contributing significant amounts of sediment from their forested buffers. These segments were, on average, only 54 feet away from streams, and therefore are much more likely to be contributing sediment to the stream network. These segments would be good candidates for additional field investigation.

Patterns Observed for Road Segments Contributing Sediment

One pattern that was noticeable among the segments that were predicted to contribute the most sediment to the stream network was the length of each road segment. For all 4 subsets discussed previously, the road segment length averaged over 800 feet for roads contributing the most sediment from either the road surface or the buffer. This was expected, as previous research has shown that having a large distance between cross-drains dramatically increases sediment production (Croke et al., 2005).

Another pattern that was not as consistent among all of the road segments was the length of the forest buffer. Segments that were predicted to be producing large amounts of sediment from the road surface were, in some cases, greater than 800 to 1,000 feet away from streams. Similarly, segments that were classified in the low production category were, in some cases, less than 1 foot away from a stream. Even if the segments in the latter category were not producing a large volume of sediment, all of this sediment could be directly entering a stream system, while the sediment from the former road segment could have been deposited in the forest buffer. and so would be contributing sediment directly to a stream. This implies that simply looking at the volume of sediment that a segment produces is not the only initial screening analysis that should be performed; identifying all segments that are within a certain distance of a stream is also a valuable analysis function. This is less of a concern with segments that are predicted to produce a large volume of sediment from the forest buffer, because all of this sediment is predicted to enter stream channels. These segments tended to be much closer to stream channels, too.

Road surfacing did not have a clear effect on predictions for erosion and sediment delivery. Between the 4 subsets of roads described in the previous sections, up to 78 percent of each subset of roads had asphalt surfacing. Paving a road surface is one BMP that has been shown to dramatically reduce sediment production (Ziegler et al., 2001). However, it is not the only BMP that can be effective at controlling sediment, and may not be affecting the most significant source of sediment for each road segment in a road network. Ultimately, each road segment must be examined in the field in order to determine the most effective BMP application.

Accuracy of the WEPP:Road Predictions

The actual predictions that were developed by the WEPP:Road model ranged from 0 to 767,411 pounds per year. These values seem much higher than expected. Similar studies predicted sediment delivery in the range of approximately 46,000,000 and 77,000,000 pounds for catchments that were 580 and 810 square miles, respectively (Fu et al., 2009). This amounts to approximately 80,000 to 95,000 pounds of sediment produced per square mile of watershed area. For this project, the amount of sediment being produced annually was predicted to be approximately 210,000 pounds per square mile. This is almost double the predictions in the other watershed. It is hard to know if this is due to underlying geology of the study areas or another compounding variable, but ultimately the variables included in this study will need to be examined in more depth in order to determine if the sediment predictions are accurate.

Effect of Assumptions on Predicted Sediment Production

Part of the reason why the model predicted such large amounts of sediment may have had to do with the assumptions that were made when road segments were input for modeling. Assumptions were incorporated into each segment due to a lack of detailed information regarding road design, fill slope height and gradient, buffer gradient, and percent rock cover in the original shape files. The shape files for county and state roads that were obtained from the CalAtlas database also lacked information regarding road surfacing, road width, and traffic levels. Since these parameters were all required by the WEPP:Road model, assumptions had to be made.

For the county and state roads, it was assumed that all roads were surfaced with asphalt. If any of these roads were not, in fact, surfaced with asphalt, this assumption would tend to underestimate the amount of sediment that was predicted to be eroded from these roads. Roads that are surfaced with asphalt do not require the frequent grading and maintenance required by unpaved roads, and so the ditches would tend to become rocked or vegetated over time. Thus, another assumption to model these roads with the "insloped, vegetated or rocked ditch" road design was also made.

The "insloped, vegetated or rocked ditch" design was also used to model all USFS road segments. This assumption was chosen based on the traffic and maintenance levels specified for the USFS roads included in this study. According to the original shape files, roads in this study area are generally maintained frequently enough in high traffic areas to avoid the formation of ruts. However, most roads are not maintained frequently enough to have bare ditches, which is why the "insloped, vegetated or rocked ditch" road design was applied to all road segments. A different assumption that could have been used would have been to model all roads with a higher maintenance frequency as "insloped, bare ditch," and all roads with infrequent or no maintenance as "rutted." This is because frequent grading often results in removal of all vegetation and rock from the road ditch, and no maintenance will almost always cause rut formation on an unpaved road (Elliot et al., 1999). Modeling the roads with bare ditches or ruts would have increased the amount of sediment produced from each road segment.

Other assumptions that were applied to all road segments related to fill slopes, buffers, and percent rock cover. The values of 16 feet for the fill slope length, 60 percent for the fill slope gradient, 30 percent for the buffer gradient, and 20 percent rock cover were applied to all road segments. Assumptions for these parameters had to be incorporated into the shape files due to the fact that there was no information in any of the shape files regarding these features. A better assumption may have been to base the buffer gradient off of the topography of the underlying hill slope, in a similar way as to how the road surface and cut slope gradients were determined when the data was analyzed for the WARSEM model. The high percentage of gradient used for the buffer would tend to overestimate the amount of sediment predicted to be generated by the buffer.

Another unknown that had be to assumed for the road segments was the slope of the road surface. In order to estimate this value, a DEM was created from a .tif file, and then was joined to the attributes of the road shape file. However, the true slope of the surface of a cut-and-fill road may have little to do with the underlying topography in a mountainous area. Using the underlying hill slope topography to estimate the road slope would tend to overestimate the slope of any given road segment, which would tend to increase the predicted volume of sediment that will be generated from each road segment. The magnitude of this potential overestimation is difficult to determine.

Another assumption that was built into the dimensions for each road segment was related to cross-drain spacing. There was no information in any of the original shape files regarding the spacing of cross-drains along each road segment. Previous studies have shown that the space between cross-drains can dramatically increase the volume of sediment being delivered to the stream network due to the fact that large spaces between cross-drains increase the upslope contributing area over which runoff must travel (Croke et al., 2005). For most of these shape files, the road segment lengths provided in the original shape files may have been up to several miles long, and were probably based more on road-road or road-stream crossings than on actual cross-drain spacing. Long segments of road were truncated during the various analyses that were performed in ArcMap, and then were further truncated when the data was modified in order to fit model parameters. This truncation made road segments smaller, which may have reduced overestimation of sediment production, but still failed to account for actual cross-drain spacing on the road segments. Using field-verified data for cross-drain spacing would have most likely decreased predictions for sediment production, and would have more accurately represented actual road conditions. However, the amount of time and resources required in order to gather this additional information in the field was beyond the scope of the current study. It is highly recommended that segments that are predicted to contribute the highest volumes of sediment be visited in the field, and that detailed road structure data be collected for these segments before attempting to determine which road segments would offer the greatest ecological benefit through BMP application.

Discussion of the Silt Fence Empirical Method

Three of the six silt fences that had been installed were removed prior to the completion of this project. This is probably due to the fact that the San Bernardino National Forest is a popular recreation area that serves over 2 million visitors each year (USDA, 2012). In addition, there are a number of local groups that voluntarily remove trash and repair trails in the area. The fences may have been removed by one of these groups, or by people recreating in the area. The fences may also have been knocked down and removed as debris. In the future, in order to avoid fence removal, it would be wise to include some kind of notice to the public about the importance of the fences and the fact that a research project is being conducted in the study area. This is something to note to anyone performing a similar project in the future.

Of the fences that remained intact at the end of the project, none had collected a significant amount of sediment. The reason for this is unclear. At the time that the fences were installed, they were designed to span obvious signs of runoff, such as gullies, that had formed on the fill slope of the study areas. They were designed following the methods outlined by Robichaud and Brown (2002). One reason that the fences did not collect much sediment may have been due to low amounts of precipitation, or else precipitation that predominantly fell as snow instead of rain. Snowmelt tends to melt slowly, favoring percolation over runoff (Elliot et al., 1999). It is difficult to know precisely how much precipitation fell during the length of the project because individual precipitation gauges were not installed at each fence location, and USGS weather data from the Lake Arrowhead station was missing for most of the 2011 water year. Precipitation data from the nearby Big Bear Lake climate station indicates a total of 33.71 inches fell in the area for water year 2011, which is 159 percent of normal (NOAA, 2012). This would suggest that more erosion should have occurred. However, a more accurate prediction for the amount of sediment that is eroded from a road segment on an annual basis could only come from several years of data collection. Robichaud and Brown (2002) recommend collecting 2 years of data in order to be able to determine results with statistical significance. A field project over this length of time was outside the scope of this study. However, field analysis could be very useful to forest managers for checking the predictions of a model and for narrowing down locations for BMP application, and would be a good area for future study.

Due to the limitations of time, the empirical method of measuring erosion and sediment delivery with silt fences was not explored as in depth as it potentially could have been. In terms of time and labor, this method is much more intensive than computer modeling, and requires resources such as silt fencing and rain gauges. For this reason, this method would seem to be better suited to examining limited portions of a road network in great detail, such as portions that are already suspected to be contributing large amounts of sediment to the stream network, rather than using it as a screening tool for the entire road network. This study also found that in areas with precipitation patterns that are highly variable, silt fences may need to be left in place for multiple years in order to establish a more accurate estimation for erosion and sediment delivery.

As with any experiment that is being performed in areas that could be accessed by the general public, it is important to inform the public about the scientific process, and to communicate the need for scientific equipment to remain undisturbed. Future researchers are advised to take this into consideration, and to attempt to locate areas that are less accessible to the public in the future, as well as to include signage regarding their project and the importance of leaving equipment intact.

Conclusions

The output from the WEPP:Road model was used for the majority of the analysis in this project. Using this model, it was determined that a small percentage of roads are disproportionately contributing sediment to the stream network, and can be targeted by land managers for further analysis and potential BMP application. This model is an effective tool that allows utilizing readily available GIS data for a preliminary scan of road networks within a watershed in order to target key segments that need additional analysis and potential BMP application.

Due to the fact that the predicted erosion and sediment delivery was much larger than expected by several orders of magnitude, the results of this study were not accurate enough to be used as the basis of future management decisions such as BMP application. However, the study did determine that there may be small portions of the road network that are disproportionately contributing larger amounts of sediment than the rest of the road network. This finding is worth exploring in more detail, perhaps by gathering additional data in the field, or by employing a more in-depth field study using silt fences.

This project underscored the fact that the quality of a model's output is dependent on the amount of detail and quality of data available for the model input. In future studies, predictions can be improved by obtaining more detailed field data, especially regarding fill slopes, cross-drain spacing, and forest buffers. Ultimately, using an erosion prediction model may be an effective way to screen a road network on a watershed scale, but cannot replace field inspection for actual sedimentation rates, and for evaluating the effect of BMP application.

APPENDIX A

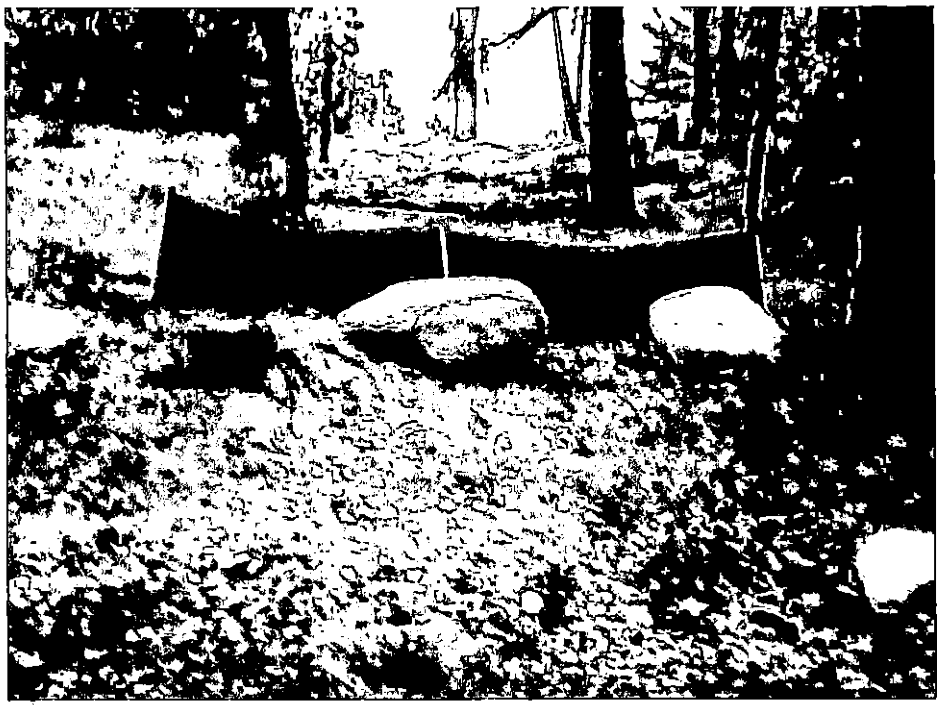
PHOTOGRAPHS OF SILT FENCES

Fence 1: Below Road Prism on FS Road 2N19

(a) On November 17, 2011

(b) On August 3, 2012

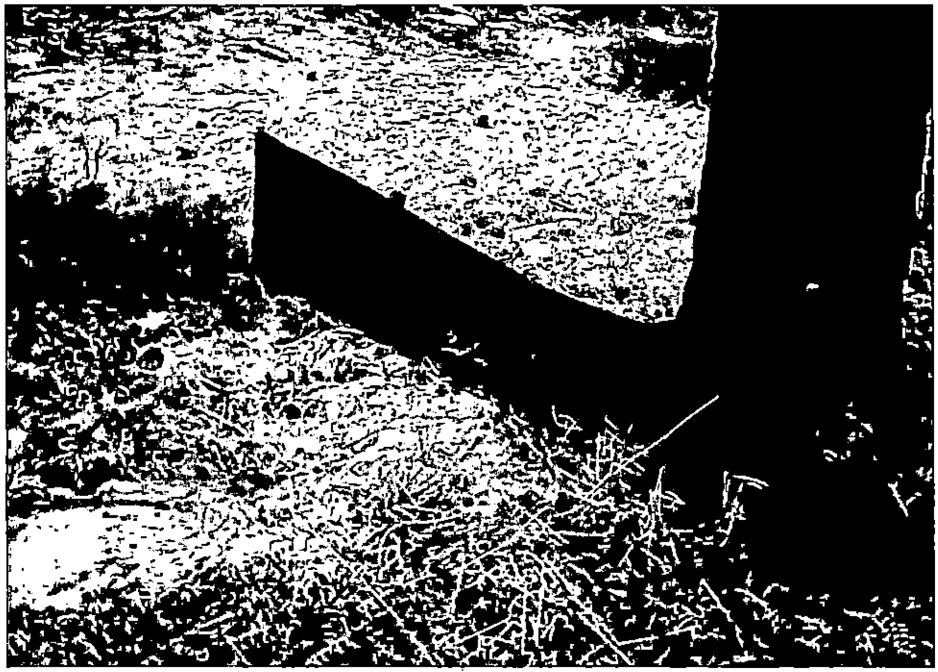
Fence 1A: Above Road Prism on FS Road 2N19



(a) On November 23, 2012

(b) On August 3, 2012

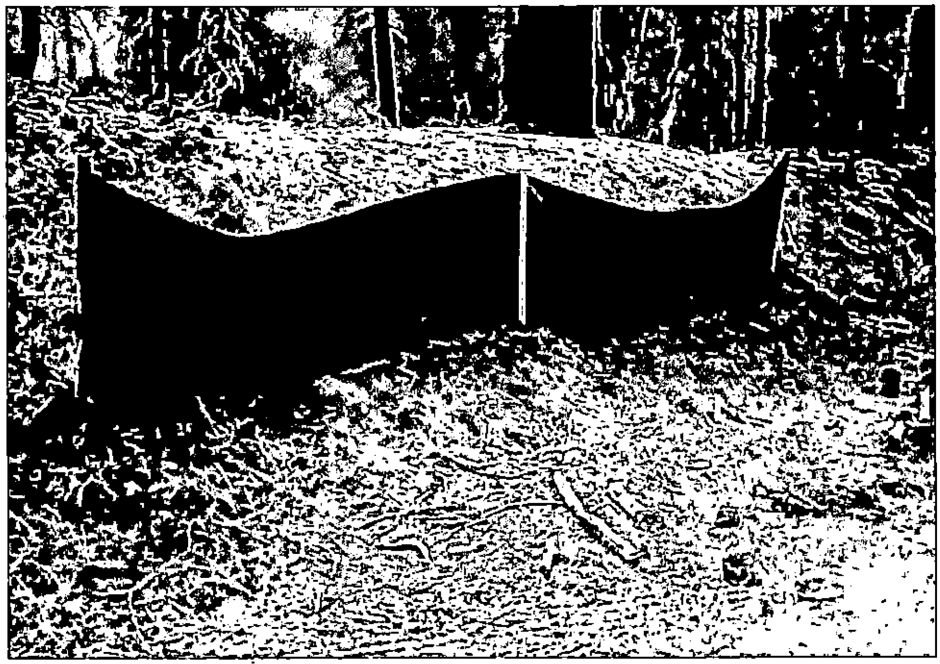
Fence 2: Below Road Prism on FS Road 2N13



(a) On November 23, 2011

(b) On August 3, 2012

Fence 2A: Above Road Prism on 2N13



(a) On November 23, 2011

(b) On August 3, 2012

Fence 3: Below Road Prism on FS Road 2N19

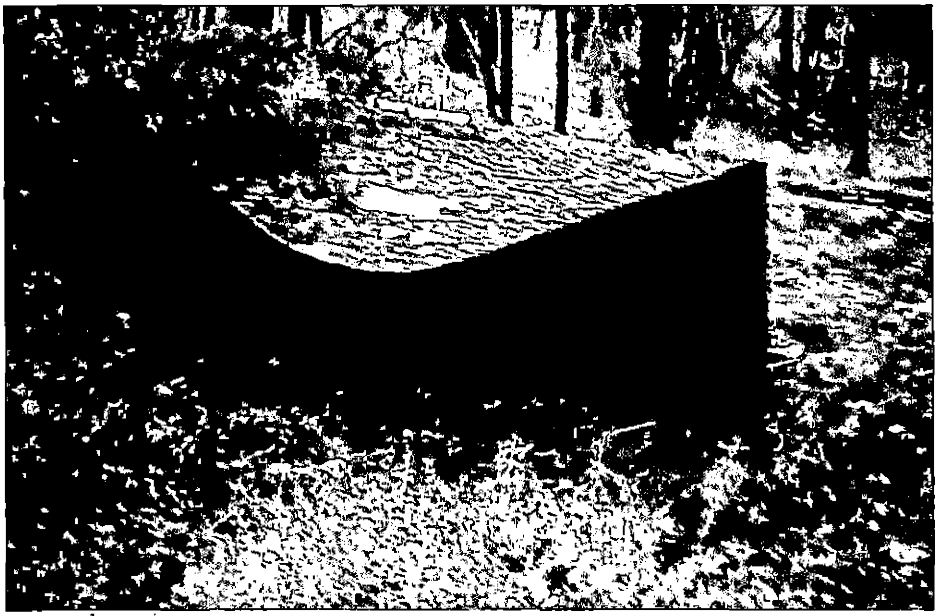
(a) On November 23, 2011

(b) On August 3, 2012

(c) On August 3, 2012

(d) On August 3, 2012

Fence 3A: Above Road Prism on FS Road 2N19



(a) On November 23, 2011

(b) On August 3, 2012

(c) On August 3, 2012

(d) On August 3, 2012

All photographs were made by Rebecca L. Franklin

APPENDIX B

ELECTRONIC DATA FILES

The attached compact disk contains the electronic data files that were used for discussion and conclusions in this project. Instructions for use of these files are also included on the disk.

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