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A Methodology for Planning Road Best Management Practices Combining WEPP: Road Erosion Modeling and Simulated Annealing Optimization

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A METHODOLOGY FOR PLANNING ROAD BEST MANAGEMENT PRACTICES

COMBINING WEPP: ROAD EROSION MODELING AND SIMULATED
ANNEALING OPTIMIZATION

By

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B.S. Resource Conservation, The University of Montana, Missoula, MT, 2006

Thesis

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A Methodology for Planning Road Best Management Practices Combining WEPP: Road Erosion Modeling and Simulated Annealing Optimization

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Erosion from forest roads is a known problem in mountainous terrain. To abate these negative consequences, physical Best Management Practices (BMPs) are implemented, sometimes with no knowledge of erosion hot spots. With the need to minimize water quality impacts while at the same time accounting for multiple considerations and constraints, road BMP planning at the watershed scale is a difficult task. To assist in this planning process, a methodology is presented here that combines WEPP: Road erosion predictions with simulated annealing optimization. Under this methodology, erosion predictions associated with BMP options for a segment comprise the objective function of an optimization problem. This methodology was tested on a watershed in the Lake Tahoe Basin. WEPP: Road input data was gathered through road surveys. Modeling results predicted relatively little sediment leaving the forest buffer, as a result of numerous well-maintained BMPs and the dry climate found in the watershed. A sensitivity analysis for all WEPP: Road input parameters is presented, which provides insight into the general applicability of these erosion estimates as well as the relative importance of each input parameter. After evaluating erosion risk across the entire watershed, applicable BMPs were assigned to problem road segments and WEPP: Road was used to predict change in sediment leaving the buffer with BMP implementation at a given site. These predictions, combined with budget constraints as well as equipment scheduling considerations, were incorporated into an algorithm using simulated annealing as its optimization engine. Three modeled scenarios demonstrate the viability of this methodology in reducing total sediment leaving the road buffer over a planning horizon. Of the 173 segments surveyed, 38 segments could be treated using generic BMPs. For all three scenarios, BMP-SA reduced sediment leaving the buffer by as much as 70% over the course of a 20-year planning horizon. For the 38 segments treated with BMPs, sediment was reduced by greater than 90% over the planning horizon. This methodology is a viable approach for streamlining watershed-scale road network BMP planning, despite its heavy reliance on road erosion estimates.
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1. INTRODUCTION/LITERATURE REVIEW

1.1 Introduction

Forest roads fulfill a critical service through providing access to public lands. If road mileage is a metric of perceived importance of remote land access, the 380,000 miles of United States Forest Service (USFS)-administered forest roads could be interpreted as invaluable (USDA Forest Service 2009). Negative impacts of these roads, however, are extensive. These impacts encompass biological effects as well as hydrologic and geomorphic changes.

To minimize negative road impacts, managers frequently implement Best Management Practices (BMPs). In practice, physical BMPs (e.g. drain dips, cross-draining culverts, rip rap) are installed based on professional judgment in the field. Often, no data on sediment leaving the road surface or sediment leaving the buffer- thereby entering a stream- is used to guide judgment. One way to address this issue is to apply some form of road erosion prediction model. These models range from relatively simple, two or three variable empirically-based prediction equations (such as those reported by Megahan and Ketcheson (1996)) to complicated, process-based computer models such as WEPP: Road (Elliot et al. 1999). By applying some form of erosion prediction model to road segments, managers can identify erosion hot spots and prioritize treatment.

While applying hydrology models to road segments provides insight into where treatment is most critical, these models do not provide any help in determining what treatment is most effective. In addition, given budget constraints, managers must decide what BMPs are most cost-effective to install right now and what BMPs can be installed on other sites in the future. Existing BMPs must be maintained to ensure continued
effectiveness; otherwise catastrophic road failure could result. Further challenges stem from the logistics associated with project planning for BMP installation, since it is cheaper to install and maintain BMPs in near proximity in the same time period. At a small scale, these issues are tractable. Planning BMPs for large watersheds, however, while taking into account all possible treatment options and management considerations, becomes exceedingly difficult.

Heuristic optimization provides a starting point from which these problems can be addressed. Heuristic optimization, in solving an objective function while taking into account numerous side constraints, allows complicated planning problems to be solved over relatively short computation time. A variety of heuristic optimization techniques have been applied to forest planning issues for several decades, but have only more recently been incorporating environmental constraints (Weintraub et al. 2000).

Presented in this thesis is a methodology that combines road erosion modeling with heuristic optimization with the intent of improving watershed-scale road BMP planning. Since the study site for demonstrating this methodology was in the Lake Tahoe Basin, literature references and procedures used herein cater to those conditions found in the Lake Tahoe Basin. Note, however, that the general concept can be applied to any watershed.

The following section is a literature review of road prism and adjacent hill slope hydrology, erosion modeling, road BMP implementation, and optimization techniques. Following the literature review is a manuscript presenting a WEPP: Road sensitivity analysis. The final section of this thesis, also a manuscript, presents model results for WEPP: Road erosion modeling combined with simulated annealing optimization.
Simulated annealing optimization, through iterative comparison of neighborhood solutions, was used here to find a near-optimum BMP implementation and maintenance scenario while accounting for multiple constraints (for a complete description of simulated annealing, see Chapter 1.2e). With this research, I demonstrate that combining road erosion prediction modeling with heuristic optimization techniques can improve road BMP planning and implementation over a planning horizon.

1.2 Literature Review

1.2a Effects of Road Construction

Forest roads (hereafter referred to as “roads”) can be defined as a subset of roads that “are characterized as being narrow, not covered with asphalt, lightly traveled, and remote (Forman and Alexander 1998).” While more primitive and designed to access rougher terrain than other roads (Forman and Alexander 1998), these roads must also accommodate larger vehicles to facilitate activities such as timber harvest, recreation, grazing, and mining (Akay et al. 2005, Switalski et al., 2003, Forman, 2000). While Forman and Alexander’s definition excludes asphalt surfaced roads, the definition used through the course of this thesis will include paved road segments, since the Lake Tahoe Basin provides a notable exception to this definition by using asphalt paving on its road network.

The effects of road erosion begin with the first groundbreaking for a roadbed. Vegetation is removed from the future road bed, exposing soil to greater raindrop impact. Nutrient-rich topsoil is also removed, creating a positive feedback loop that leads to less plant regeneration and greater exposure of organic matter-deficient soils to erosive forces.
Soil compaction aggregates the soil’s susceptibility to erosion (Grismer and Hogan 2004, Switalski et al. 2004).

Roads crosscutting hillslopes reroute groundwater to the surface through the road’s cutslope, causing an increase in overland flow (Luce 2002). With increases in road density (number of roads per unit area) come increases in drainage density, since roads can become drainage paths themselves (Wemple et al. 1996). Roads tend to increase the amount of runoff delivered to streams and also increase in-stream erosion (Jones et al. 2000, Maholland 2002). As a result, frequency and magnitude of small stream peak flows increases (Maholland 2002, Luce 2002).

Roads become a chronic fine source of sediment in a watershed (Luce 2002) and can greatly increase the potential for landslides and mass flows in forested watersheds (Grigal 2000, Jones et al. 2000), at times to such an extent that mass flow becomes the predominant sediment source for streams (Megahan and Hornbeck 2000).

Culverts are potentially responsible for several of the hydrologic, geomorphic, and biological consequences of roads. If improperly sized, culverts will increase water speed and subsequent erosive potential of runoff (Maholland 2002). With this increase in erosive potential, new channels may form as a result of culvert placement and permanently alter stream network structure (Wemple et al. 1996). In addition, culverts have been found to be entry points for sediment and other stream pollutants (Forman and Alexander 1998). Improperly placed culverts can become plugged, rerouting water to other stream channels or directly down the road, and potentially causing washouts, severe gully erosion, or potentially even landslides when the drainage system becomes
completely overwhelmed (Forest Practices Advisory Committee (FPAC 2000)). Culverts may serve as an impediment to upstream fish passage (FPAC 2000).

Beyond fish passage issues, other biological impacts are also of concern when discussing roads and their effects on the landscape. Roads create a medium for introduction of invasive plant species (FPAC 2000, Switalski et al. 2004). Chronic inputs of fine sediment tend to cause increased stream turbidity, which can cause problems for fish, aquatic vegetation, and macro-invertebrates (Forman and Alexander 1998). Roads, especially at culverts, can block movement of large wood pieces downhill, which are important for stream habitat. A buildup of wood and debris above a culvert could eventually result in a culvert blowout and debris flow downhill (FPAC 2000). In terms of wildlife, roads disrupt contiguous habitat sections and create barriers to movement and migration (Forman and Deblinger 2000). Noise pollution is also an issue, causing more problems for some species than others (Forman and Alexander 1998).

1.2b Factors Affecting Severity of Road Impacts

Parent materials and soil type influence road erosion potential. Sugden and Woods (2007) found that the average annual sediment yield from Belt Metasediments is similar to the amount of erosion found in basalt, sandstone, and other sedimentary materials in the Northwest United States, but far less than for granitic parent materials like those tested in the Idaho Batholith by other researchers. Research in the Lake Tahoe Basin has shown volcanic parent materials to be even more erodible than the granitic parent materials that also dominate the basin’s lithology (Grismer and Hogan 2005a). Glacial till parent materials are similar in sediment contribution to the Belt Supergroup studied by
In general, finer soils tend to contribute more sediment for runoff than coarser-textured soils (Luce and Black 1999, Grismer and Hogan 2005a).

Physical location and construction of a road also plays a role in a road’s susceptibility to erosion. Packer (1967) found that the distance to the closest obstruction below the road prism is directly related to how much sediment reaches a stream channel from the road. Greater distance between roads and streams means, in all likelihood, more obstructions, and therefore less sediment delivered. This fact, however, is also contingent upon the degree of hydrologic connectivity to the stream network (Wemple et al. 1996).

Presence or absence of aggregate surfacing, depth of that surfacing, and quality of that surfacing can affect road erosion rates (Swift 1984, Foltz and Truebe 2003). Steeper slopes and longer road segments will increase road erosion rates (Sugden and Woods 2007, Luce and Black 1999). Aspect of slope will influence available water, and as a result will also control potential surface erosion (Packer 1967). In addition, road geometry (insloped versus outsloped or crowned road profile, road width) will also serve as a control on sediment production (Luce and Black 1999, Packer 1967). Location of sediment origin on the road prism partially regulates road sediment travel distance (Megahan and Hornbeck 2000).

Cutslope height and angle will vary sediment yield, as will presence or absence of vegetation on the cutslope, in the ditch, and on the road’s fill slope (Luce and Black 1999). The amount of cutslope runoff contribution relative to the road bed itself is not generally agreed upon by researchers (Luce 2002). Cutslope interception of subsurface flow and the consequent contribution of subsurface flow to road runoff and surface erosion may be a major contributor to road surface erosion in wetter climates and
landscapes (Wemple and Jones 2003, Luce 2002). Slope length, soil depth, subsurface topography, and cutslope height relative to total depth of cutslope to bedrock all dictate degree of groundwater interception and surface runoff (Wemple and Jones 2003).

Road location on a slope can play an important role in determining erosion potential. Roads located high on a slope are more susceptible to erosion as a result of receiving a greater amount of precipitation due to orographic effect (Maholland 2002). Roads high on a slope, however, tend to be minimally connected to streams (due to minimal stream channel formation) and therefore have a lower proportional impact on stream sedimentation (Jones et al. 2000, Bloom 1998). Roads, however, can concentrate flow, creating channels higher on the slope than if no roads were present (Forman and Alexander, 1998). Roads located on the mid- and low-slope can be major contributors of sediment to stream channels (Maholland 2002, Bloom 1998). In western Oregon, mid-slope roads tend to be net sources of sediment, whereas valley floor roads tend to be net sinks (Jones et al. 2000).

New roads tend to produce more sediment than old roads, and newly disturbed roads (for example, roads that have been recently graded) produce more sediment than undisturbed roads (Megahan and Kidd 1972, Swift 1984, Grigal 2000).

Traffic on forest roads is a dominating factor in the amount of sediment produced (Reid and Dunne 1984). Ruts, by channeling runoff directly down the road grade, increase erosion potential (Swift 1984, Grigal 2000). With these factors in mind, road maintenance regimen will influence road erosion potential (Swift 1984).

Climate plays a major role in controlling road erosion potential. Rainfall intensity and duration affect surface erosion (Grigal 2000). In areas where snowmelt is not the
dominant form of precipitation, snowmelt runoff may not exceed forest soil infiltration rates or soil critical shear stress values, making it a minor contributor to sedimentation (Elliot 2006). In contrast, the majority of sediment reaching downstream water bodies from upland sources may come during spring snowmelt in environments where snow is the dominant form of precipitation (Simon et al. 2006).

Adjacent forest management practices can affect sediment production from roads. Fewer trees adjacent to a given road section will produce more water yield than a thicker forest stand and consequently shed more water to the road grade (Luce and Black 1999, Megahan and Hornbeck 2000, Grigal 2000). In most cases, sediment production from roads has been found to greatly exceed the amount of sediment produced by the timber harvest for which they were built to access (Megahan and Kidd 1972, Sugden and Woods 2007).

With all of these factors taken into consideration, it is clear that transportation network planning plays a crucial role in how much sediment is produced by forest road networks (Krogstad and Schiess 2000, FPAC 2000).

1.2c Mitigation of Road Impacts Using Best Management Practices

To address and minimize effects of road erosion, scientists and managers have formulated standards, or Best Management Practices (BMPs), as guidelines for how projects should be conducted and constructed. “Best Management Practices or ‘BMPs’ are those principals and engineering design practices that will protect water quality as well as the function of the road when properly applied (Keller and Sherar 2007).” Besides roads, BMPs practices have also been formulated for a number of landscape management
practices, for example agriculture (Brown et al. 2007), hazard fuel reduction (O’Connell 2006), grazing (Wyoming Department of Environmental Quality 1997), and mining (U.S. EPA 2000).

Road BMPs can be structural/physical or planning in nature. Examples of structural/physical road BMPs include culverts, drain dips or waterbars, and resurfacing. Planning BMP examples include maintenance frequency or limiting what length of road surface can be graded at one time (USDA Forest Service 2000).

Physical BMPs used in the Lake Tahoe Basin: Since Lake Tahoe is a unique management situation (spanning two states, multiple national forests, and being susceptible to heavy user traffic), the Lake Tahoe Basin has its own USFS management district- the Lake Tahoe Basin Management Unit (LTBMU)- along with a number of other planning agencies. To ensure compliance with its BMPs, the LTBMU has initiated an annual monitoring program to evaluate effectiveness of mandated BMPs. In general, LTBMU BMPs have been effective according to their evaluation criteria (Brill et al. 2009, Heller and Norman 2005).

Structural/physical BMPs used frequently in the Lake Tahoe Basin include (but are not limited to) culverts, gravel, native and rocked ditches, riprap, drain dips, and pavement. Discussions pertinent to those BMPs assigned to problem road segments in the Lake Tahoe Basin study watershed are below (for further detail, see Chapters 2 and 3).

Pavement: In terms of surfacing, paving roads will prevent sediment entrainment from the road bed, but in turn will create an impervious surface that may concentrate water and sediment into drainage structures (Maholland 2002). Nonetheless, paving may
be the best sediment mitigation solution for high-traffic roads (Reid and Dunne 1984, Clinton and Vose 2004). Paving short road segments in mountainous terrain is a costly endeavor (USDA Forest Service 2008), and as such is used relatively infrequently.

**Drain dips:** Drain dips fall into the broad category of surface cross drains. By interrupting hydraulically contiguous sections of road, segment length, which has been found to be an important variable in determining sediment production on forest roads (e.g. Luce and Black 2001a, Coe 2006), is minimized. Beyond segment length, appropriate drain dip spacing is dictated by a number of different factors, including (among others) surfacing material characteristics, climate, and road grade (Copstead et al. 1998).

**Outsloping:** Under this road profile design, runoff is not concentrated into a point source; rather, runoff is dispersed off the shoulder along the entire length of the road segment. By dispersing runoff and sediment in this fashion, sediment is less likely to reach a stream (Luce and Black 2001a, Elliot et al. 2009). While a highly effective BMP, outsloping is not appropriate in all situations (such as on wet or steep roads with heavy truck traffic) and requires more intensive maintenance than other BMPs (USDA Forest Service 2008).

**Road decommissioning:** If a road segment is unnecessary, it can be permanently removed from the road network (Switalski et al 2004). Road decompaction and prism restoration are becoming more popular options following decommissioning (Luce 2002, Switalski et al. 2004). The Lake Tahoe Basin recently finished a period of extensive forest road decommissioning, and as such is no longer widely applying this BMP (P. Potts personal communication).
1.2d Road Erosion Prediction Using Models

**General overview of hydrologic models:** To assess runoff and erosion, researchers and managers have enlisted the help of mathematical hydrologic models for many years (Sorooshian et al. 2008, Loague and VanDerKwaak 2004). These models fall into several broad categories: empirical versus process (physics)-based, stochastic versus deterministic, and lumped versus distributed.

In use since the 1970’s, the Universal Soil Loss Equation (USLE) is a widely used empirically-based erosion prediction model (Wischmeier and Smith 1978). The Revised Universal Soil Loss Equation (RUSLE) and the Modified Universal Soil Loss Equation (MUSLE) are two more recent improvements on the original model (Brooks et al. 2003). Empirical models do not make full use of our understanding of hydrologic system dynamics. Process-based models, in contrast, incorporate knowledge about the physics of a system to derive more detailed yet generalizable predictions of runoff and sediment (Renschler 2003).

As a sub-category of process-based models, stochastic models draw variable inputs from probability distributions. In contrast, deterministic models define input variables as being free from random variation (Loague and VanDerKwaak 2004). A further subdivision within hydrologic models stems from whether the model treats spatial watershed variability in a lumped versus distributed fashion. While distributed models allow for spatial variability in climate and hydrologic processes across a watershed, lumped models do not. Accounting for spatial variability produces a more accurate representation of watershed-scale hydrologic processes. As a tradeoff, these models can
be highly complex as a result of requiring detailed spatially-explicit data and may demand greater computation resources (Sorooshian et al. 2008).

Distributed Hydrology-Soil-Vegetation Model (DHSVM) (Wigmosta et al. 1994), and Système Hydrologique Européen Sediment Yield Component (SHESED) (Wicks and Bathurst 1996) are examples of fully process-based models currently in use. The Water Erosion Prediction Project (WEPP) (Flanagan and Nearing 1995), also a fully process-based hydrologic model, has over 400 input parameters. Originally designed for agriculture, it has been adapted for use in forest conditions (Elliot et al. 2006) and has been applied to a variety of watersheds with success at a variety of scales (Amore et al. 2004).

Hydrologic modeling and road erosion: Empirical and process-based models alike have been developed to predict road erosion. Several studies have developed road sediment volume and travel prediction equations from empirical data (e.g. Megahan and Ketcheson 1996, Anderson and MacDonald 1998). These empirical models are computerized in some instances; ROADMOD and STJ-EROS, two GIS-based models capable of predicting road erosion, calculate erosion using empirical relationships (Ramos-Scharron and MacDonald 2007).

As process-based hydrologic models have become more prevalent, so too have process-based road erosion prediction tools. SWAT, while not spatially-explicit, is capable of predicting road erosion (Neitsch et al. 2005) (Despite being generally considered a physics-based model, SWAT’s erosion computations are based on empirical
models). Doten and others’ (2006) modification of DHSVM to accommodate road sediment was the first spatially-explicit physics-based model to incorporate road erosion.

With process-based models have come complexity and inaccessibility to untrained users. WEPP: Road, a user-friendly web-based interface for WEPP, has been developed by the Rocky Mountain Research Station (Elliot et al. 2004) to address this problem. This marks the first adaptation of a process-based model specifically for predicting sediment from road segments. WEPP: Road requires few input parameters, many of which can be acquired without field surveys. The interface allows users from a variety of technical backgrounds to effectively predict impacts associated with road-related management decisions. By providing a range of climates (and the option to alter climates to represent site-specific conditions), surface types, traffic levels, and road designs, WEPP: Road is applicable virtually anywhere in the U.S.

1.2e Natural Resource Planning and Decision Support Tools

Forest and natural resource planning, especially when accounting for multiple uses, has become ever more complex over time (Rönnqvist 2003). Optimization strategies (including application to forest roads) have been employed since the 1970’s to address multiple management goals and environmental constraints in forest planning (Weintraub et al. 1995, Rönnqvist 2003, Weintraub 2006).

Optimization strategies consist of either exact solutions or heuristics (Kirkpatrick et al. 1983). Linear programming, integer programming, and mixed integer programming are all common exact solution methods. While exact solutions are often preferred, problem complexity may require excessive computation power or time (Kowalski 1995).
In these cases, heuristics are favorable. While not guaranteed to find the exact solution, heuristics produce near optimum solutions during multiple process repetitions with less computing time (Lin and Kernighan 1973).

With increasing concern for environmental impact of forest operations has come incorporation of impact mitigation strategies into the planning process (Weintraub et al. 2000). Sedimentation associated with timber harvest has been accounted for since the 1970’s using linear programming techniques (Hof and Bevers 2002). Application of heuristic optimization specifically to environmental concerns, including sedimentation associated with roads, has only occurred more recently (Chung 2002, Weintraub et al. 2000).

**Optimization and road impact analysis:** Multiple projects to date have incorporated BMPs and/or associated erosion potential into cost-benefit analyses for road management planning. Aruga and others (2005) optimized road alignments using a Tabu Search algorithm. To incorporate road impact concerns, road sediment was accounted for with empirically-derived erosion equations. BMPs assigned to road segments included road surface material, culvert location (segment length), and outsloped road design. This research emphasized new road construction and incorporated erosion concerns as a side constraint.

Taking a stream restoration perspective, Madej and others (2006) compared the effectiveness of a genetic algorithm (a heuristic technique) with dynamic programming (an exact solution technique) to assess the cost effectiveness of road removal treatments on a watershed scale. While both search techniques provided similar answers, the genetic
algorithm was deemed to have several advantages over dynamic programming because it provides a set of effective solutions rather than only one solution. As a result, managers have a choice of which solution to use when wishing to account for other factors besides just sediment savings. Sediment savings associated with various treatments was accounted for by physically measuring voids left in road prism, native hillslopes, and channels following a 12-year storm event.

Modeled road erosion predictions have been incorporated into forest transportation planning problems. To date, all research incorporating these predictions has used WEPP: Road to model road sediment. Rackley and Chung (2008) applied a dollar amount to WEPP: Road erosion estimates to incorporate environmental concerns into NETWORK2000, a forest transportation planning tool. Since environmental constraints had to be assigned a dollar amount within their modeling framework, Rackley and Chung’s research provided an indirect assessment of these constraints.

In another application of WEPP: Road to a forest transportation planning problem, Contreras and others (2008) used WEPP: Road sediment predictions to incorporate road sediment as a side constraint into an Ant Colony Optimization (ACO) metaheuristic. While modeled sediment was directly assessed (not assigned a dollar value), it was not the objective function of the planning problem.

No studies to date have exclusively emphasized sediment concerns associated with BMP implementation on existing forest road networks. While process-based models have been used to estimate erosion, they have only been used to assess side constraints in forest transportation planning problems. The logical evolution of watershed-scale road network planning problems is to formulate sedimentation concerns as objective functions.
within the planning problem. Furthermore, process-based road erosion predictions, being the current state-of-the-art, could be used in the place of empirical equations.

Though multiple heuristics could be used to solve similar planning problems, simulated annealing (Kirkpatrick et al. 1983) is a primary candidate for addressing forest road BMP planning. For uncomplicated planning problems not concerned with transportation network planning, the use of more complex heuristics is unwarranted. Simulated annealing is simple compared with other heuristics, yet effective, and can be applied to a variety of optimization problems (Kirkpatrick et al. 1983, Tarp and Helles 1997).

Description of Simulated Annealing: Simulated annealing loosely resembles cooling metal leaving a forge. Beginning and ending temperatures are specified before starting the search, as is cooling rate. When the search starts, two solutions are generated. The second of these solutions is a neighborhood solution to the initial (current) solution, where one element of the initial solution has been altered. The objective function values for these two solutions are then compared.

If the alternative (new) solution value is indeed better than the initial solution, the new solution is stored as the current solution. The next iteration of the algorithm generates a new solution by again altering one element of the current solution. In the case that the alternative solution is not better than the initial solution, an acceptance probability is generated using the following equation:

\[ p(\text{new}) = e^{\frac{\text{new-current}}{\text{temp}}} \]
Depending on whether the objective function is to minimize or maximize a value, the relationship between the acceptance probability and a randomly generated number will dictate whether the worse new solution will be accepted and used as the current solution in the next algorithm iteration. In accepting a worse solution, simulated annealing provides for the possibility that the worse solution may serve as a link to a better solution that would not be found as quickly using a random search.

After a set number of iterations, temperature is cooled at the set cooling rate. As temperature becomes smaller, the interval of difference between the new and current temperature must be smaller in order for a worse solution to be accepted. This creates a solution space that becomes less variable as algorithm iterations increase and temperature decreases. Upon reaching stopping criteria (often defined as maximum number of iterations or minimum temperature), the algorithm stops and a best solution is reported.

Figure 1. Example of solution value change with iteration number in a minimization problem using simulated annealing optimization.
Simulated annealing has been used to solve complicated natural resource planning problems that include both spatial adjacency and temporal constraints. Example applications include forest harvest scheduling (e.g. Lockwood and Moore 1993, Liu et al. 2000) and land-use allocation associated with mine reclamation (Aerts and Heuvelink 2002). In terms of road-related applications, simulated annealing has been used to optimize forest road vertical alignment within forest road construction decision support tools (Akay and Sessions 2005). Additionally, Coulter et al. (2005) used simulated annealing to optimize forest road maintenance and upgrade projects on Oregon State University research forests. To date, no projects have addressed spatially-explicit BMP installation and maintenance scheduling with the exclusive intention of minimizing water quality degradation using simulated annealing.

1.3 Literature Review Summary

Surface hydrology associated with road networks is fairly well-understood. To address negative impacts associated with roads, BMPs have been implemented on road networks. Examples of BMPs used on forest roads in the Lake Tahoe Basin include outsloping, paving, and drain dips. Road erosion models come in multiple different forms, ranging from empirical to process-based. Researchers have begun bridging the gap between identification of problematic road segments and planning of BMP implementation. There is a lack of planning tools available for directly addressing road sedimentation and planning applicable BMPs on existing road networks. Combining process-based road erosion modeling with heuristic optimization, specifically simulated annealing, provides a possible framework for this needed tool.
1.4 References


2. AN ANALYSIS OF WEPP: ROAD PARAMETER SENSITIVITY

2.1 Abstract

WEPP: Road is a user-friendly interface to a process-based road erosion model that is applicable virtually anywhere in the U.S. The sensitivity analysis presented here provides a perspective for identifying those parameters that are most important to collect accurately during road surveys. In addition, the analysis provides insight into the central physical concepts that drive WEPP: Road predictions. Forty road segments were generated where one parameter was altered in each segment from its control value. Quantitative parameters were altered to plus and minus 10% and 30% of their control value. All 40 segments were input into WEPP: Road under all soil options using the same climate.

WEPP: Road erosion rate estimates were substantially different between soil types. These differences could be explained through a combination of soil cohesive strength and particle size. WEPP: Road predicted an increase in sediment leaving the road and sediment leaving the buffer with a change in road surface from native to paved. Any change in rock content above 50% in WEPP: Road yielded no change in erosion rate predictions. Road length and width were the most sensitive quantitative parameter inputs for estimates of both sediment leaving the road and sediment leaving the buffer. Generally, WEPP: Road estimates matched published data.
2.2 Introduction

Forest roads fulfill a critical service through providing access to remote public and private lands, often in rugged terrain (Forman and Alexander 1998, Switalski et al. 2003). While providing important functions, forest roads have numerous negative consequences. These effects include biological impacts (e.g. FPAC 2000, Switalski et al. 2004, Forman and Deblinger 2000), changes to hillslope hydrology (e.g. Jones and Grant 1996, Maholland 2002, Luce 2002), and geomorphic consequences (e.g. Wemple et al. 1996, Montgomery 1994, Jones et al., 2000).

Runoff and erosion prediction (hydrologic) models are one method by which consequences of watershed erosion can be mitigated. With hydrologic models, future events can be forecast and previous hydrologic events can be analyzed. Managers and planners can minimize environmental damage resulting from management decisions (Singh and Woolhiser 2002). Through prediction of sediment loss, thousands of dollars in economic loss may be prevented as a result of property damage, incorrect placement of a road or drainage structure, or restoration of an area following an ill-conceived management decision.

For years, empirical models such as the Universal Soil Loss Equation (Wischmeier and Smith 1978), and Revised Universal Soil Loss Equation (Renard et al. 1997) were widely used to make erosion estimates. Empirical models, while simple, do not make full use of our understanding of hydrologic system dynamics (Renschler 2003). Process- and physics-based models, in contrast, incorporate knowledge about the physics of a system to derive more detailed yet generalizable predictions of runoff and sediment (Renschler 2003). The Water Erosion Prediction Project (WEPP) (Flanagan and Nearing
1995) is one of many process-based hydrologic models currently in use. Originally designed for agriculture, it has been adapted for use in forest conditions (Elliot et al. 2006) and has been applied to a variety of watersheds with success at multiple scales (Amore et al. 2004).

To address the need for a relatively simple, user-friendly road erosion model, WEPP: Road was developed by the Rocky Mountain Research Station in Moscow, ID (Elliot 2004). WEPP: Road provides a web-based graphic user interface requiring few input parameters, many of which can be acquired without field surveys. The interface allows users from a variety of technical backgrounds to effectively predict impacts associated with road-related management decisions. By providing a range of climates (and the option to alter climates to represent site-specific conditions), surface types, traffic levels, and road designs, WEPP: Road is applicable virtually anywhere in the U.S.

Understanding how a given parameter will affect road erosion estimates is important for model users. Given limited resources, WEPP: Road users may be unable to measure all necessary input parameters in the field at every site of interest. Knowing which parameters are essential to accurately measure gives users a better idea of where to best allocate resources. In addition, it is important to understand sources of prediction variability in assessing model outputs when trying to achieve the best possible erosion predictions.

The sensitivity analysis presented here fills this need. From this sensitivity analysis, identified sources of prediction variability can inform users of the general concepts that drive the WEPP model. Additionally, WEPP: Road’s predictive capability can be validated by analyzing whether predictions agree with current literature.
2.3 Description of WEPP: Road Interface:

WEPP: Road is an interface to the WEPP model specifically catering to road hydrology and sediment production estimation. Numerous climate base station records are available in the climate library. To accommodate local climate variation, base station data can be altered using the Parameter-elevation Regression based on Independent Slopes (PRISM) model, which modifies precipitation based on linearly regressed relationships with elevation (Daly et al. 2004). WEPP: Road estimates runoff and soil loss on three overland flow elements: the roadbed itself, a fill slope, and the road buffer (hill slope area between the base of the fill slope and the nearest water source) (Elliot et al. 1999). Four soil types can be modeled by WEPP: Road: clay loam, silt loam, sandy loam, and loam. Four road designs (insloped, bare ditch, insloped, vegetated ditch, outsloped, unrutted, and outsloped, rutted), three road surface types (native, graveled, or paved), and three traffic levels (none, low, and high) are provided as options in the WEPP: Road interface. Other input parameters include road gradient, road length, road width, fill slope gradient, fill slope length, buffer gradient, buffer length, and percent rock content (defined as the percent volume of rock fragments greater than 2 mm in diameter in the soil substrate (H. Rhee personal communication)). While the default simulation time is 30 years, the user can specify longer time periods if desired (Table 1).

WEPP: Road outputs include a summary of input values as well as predicted runoff from rain events, predicted runoff from winter storm events, sediment leaving the road prism (road), and sediment leaving the buffer.
Table 1. WEPP: Road input parameters and possible values or parameter ranges.

<table>
<thead>
<tr>
<th>WEPP: Road input parameter</th>
<th>Possible values/allowable range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>N/A</td>
</tr>
<tr>
<td>Soil type</td>
<td>Silt loam</td>
</tr>
<tr>
<td></td>
<td>Sandy loam</td>
</tr>
<tr>
<td></td>
<td>Clay loam</td>
</tr>
<tr>
<td></td>
<td>Loam</td>
</tr>
<tr>
<td>Road design</td>
<td>Insloped, bare ditch</td>
</tr>
<tr>
<td></td>
<td>Insloped, vegetated or rocky ditch</td>
</tr>
<tr>
<td></td>
<td>Outsloped, unrudded</td>
</tr>
<tr>
<td></td>
<td>Outsloped, rutted</td>
</tr>
<tr>
<td>Surface type</td>
<td>Native</td>
</tr>
<tr>
<td></td>
<td>Gravelled</td>
</tr>
<tr>
<td></td>
<td>Paved</td>
</tr>
<tr>
<td>Traffic level</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Road width</td>
<td>1 ft - 300 ft</td>
</tr>
<tr>
<td>Road length</td>
<td>1 ft - 999 ft</td>
</tr>
<tr>
<td>Road gradient</td>
<td>.3% - 99%</td>
</tr>
<tr>
<td>Fill slope length</td>
<td>1 ft - 999 ft</td>
</tr>
<tr>
<td>Fill slope gradient</td>
<td>.3% - 99%</td>
</tr>
<tr>
<td>Buffer length</td>
<td>1 ft - 999 ft</td>
</tr>
<tr>
<td>Buffer gradient</td>
<td>.3% - 99%</td>
</tr>
<tr>
<td>Coarse rock content</td>
<td>0% - 100%</td>
</tr>
<tr>
<td>Years of simulation time</td>
<td>1 yr - 200 yrs</td>
</tr>
</tbody>
</table>

2.4 Methods

WEPP: Road inputs for this analysis were chosen based on average values frequently seen on forest roads in the western United States. The control segment can be found in Table 2.
Table 2. Control road segment used for WEPP: Road sensitivity analysis.

<table>
<thead>
<tr>
<th>Design</th>
<th>Surface, traffic</th>
<th>Road grad (%)</th>
<th>Road length (ft)</th>
<th>Road width (ft)</th>
<th>Fill grad (%)</th>
<th>Fill length (ft)</th>
<th>Buff grad (%)</th>
<th>Buff length (ft)</th>
<th>Rock cont (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insloped, bare ditch</td>
<td>native low</td>
<td>7</td>
<td>300</td>
<td>12</td>
<td>50</td>
<td>10</td>
<td>20</td>
<td>300</td>
<td>50</td>
</tr>
</tbody>
</table>

After establishing a control segment, new road segments were created, each with one input parameter altered from the control. Qualitative parameters (road design, surface, and traffic level) were altered such that every possible parameter value was represented in a segment. Each quantitative parameter was altered to plus and minus 10% and 30% of the control parameter value. In doing so, a wide range of forest road conditions commonly seen on the ground could be evaluated. Using these criteria, a total of 40 test segments were developed. Interaction between input parameters was not tested.

The 40 segments were run in WEPP: Road Batch, an alternative WEPP: Road interface which allows the user to estimate sediment leaving the road and buffer for up to 200 segments simultaneously. All 40 segments were run with each of the four soil texture options. “TAHOE CA” base station climate data (available in the WEPP: Road Batch climate library) was used for the simulation. Monthly average precipitation values from this base station data were increased using PRISM based on elevation at a central location within the Glenbrook Creek watershed, NV. (For justification of study site, see Chapter 3.3.)
2.5 Results/Discussion

A comparison of control segment erosion predictions for each soil type is shown in Table 3. Loam soils were predicted to produce greater than double the sediment leaving the road in sandy loam soils. Clay loam and silt loam soils were predicted to produce 1.5 and 1.9 times more sediment leaving the road than sandy loam soils, respectively. WEPP: Road estimated 2.4 times more sediment leaving the buffer in clay loam than in sandy loam soils and approximately 1.5 times more sediment leaving the buffer in silt loam and loam soils than in sandy loam soils. Research suggests that forest soils with higher silt contents are more readily erodible (Luce and Black 2001a), indicating that WEPP: Road estimates match empirical studies.

<table>
<thead>
<tr>
<th>Table 3. WEPP: Road control segment predictions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay loam</td>
</tr>
<tr>
<td>Sediment leaving road (lbs)</td>
</tr>
<tr>
<td>Sediment leaving buffer (lbs)</td>
</tr>
</tbody>
</table>

2.5a Qualitative parameters:

Figure 2 shows WEPP: Road predictions of sediment leaving the road for the four different road design templates available in the model. The insloped, bare ditch road design was predicted to produce more sediment leaving the road per year than any other road design. The difference in sediment prediction between outsloped, unrutted and outsloped, rutted road profiles reflects the importance of proper maintenance (Swift 1984, Grigal 2000).
Modeled behavior of the different soil types across the four road designs was consistent except for sandy loam on the outsloped, unrutted road segment. Greater sediment leaving the road in sandy loam soils relative to other soil types could be attributed to the lower cohesive strength of sandy loam compared to the other soil types (Brady 1990). As a result, sandy loam can be more easily entrained than the other soil types over short distances. Continuous flow path length on the road bed is shortest on the outsloped, unrutted road design. Assuming that short flow paths favor greater coarse soil sediment transport, since coarser (sandier) soils are deposited after traveling shorter distances relative to other soil types, WEPP: Road predictions are appropriate.

Predictions of sediment leaving the buffer (Figure 3) demonstrate the utility of outsloping road segments as a Best Management Practice that minimizes road sediment. This modeled result is backed by published literature (Megahan and Ketcheson 1996, Luce and Black 2001a, Elliot et al. 2009). With the exception of clay loam, predicted sediment leaving the buffer was similar or nearly identical between insloped, vegetated ditch profiles and outsloped, rutted profiles. Clay loam, with a smaller particle size distribution relative to the other soil types, can be entrained over longer distances given the same amount of runoff.
WEPP: Road predictions of sediment leaving the road under four road designs are shown in Figure 4. Predictions indicated that graveled road surfaces are more effective at reducing sediment leaving the road than pavement. Since the road design in the control segment was insloped with a bare ditch, all sediment leaving the road on paved segments must be attributed to ditch erosion. In all cases, pavement increased
sediment leaving the road, with the greatest increase being in sandy loam soils. Pavement, being essentially impervious to infiltration, generates more and flashier runoff than graveled or native surface roads. Despite having less available source sediment, WEPP: Road predictions indicate that paved segment runoff can be substantial enough to produce greater sediment leaving the road from ditch erosion alone than total sediment leaving the road from a native surface segment. Sandy loam, being more readily entrained, will produce more sediment leaving paved road segments than other soil types.

WEPP: Road predicted sediment leaving the buffer in loam soils on paved segments to be less than that on native surface segments; the same holds true for silt loam soils (Figure 5). Sandy loam and clay loam do not follow this trend. The greater predicted runoff leaving paved road segments can easily entrain clay loam for longer distances prior to deposition, thereby explaining the increase in sediment leaving the buffer on clay loam segments relative to silt loam and loam soils. As for sandy loam, the combination of increased runoff and more entrained sediment leaving the road relative to other soil types could explain the disparate amount of sediment leaving the buffer in this soil type.

Reid and Dunne observed paved segments producing less than 1% of sediment generated on a heavily used gravel segment (1984). In another study conducted in Georgia and South Carolina, paved road segments were found to produce less than 5% of the Total Suspended Solids (TSS) leaving unimproved gravel road segments (Clinton and Vose 2003). These results were found on slopes greater than 20% in unknown soil types with riprap on drainage surfaces. For both of these studies, ditch roughness and maintenance regime assumptions were not clearly conveyed.
WEPP: Road is not capable of modeling effects of BMPs on downslope drainage surfaces, which may explain buffer erosion predictions being greater than those predicted below other surface types. To clarify whether the bare ditch component of the road design was responsible for elevated WEPP: Road erosion predictions from the road surface, the paved segment road design was changed to “insloped, vegetated or rocked ditch” and again modeled for erosion using WEPP: Road. Traffic level on the graveled surface segment was altered to “high” and modeled again using WEPP: Road. Figure 4 also includes these model predictions. WEPP: Road predicted less sediment leaving the road from the paved segment than the high traffic graveled segment, but predictions ranged from 54-85% of that found on high traffic graveled segments.

While no conclusion can be made regarding WEPP: Road’s prediction of sediment leaving paved segment road buffers, WEPP: Road may be overestimating sediment leaving the ditches of paved road segments. Not all parameters associated with field tested segments, however, are known. More information about the condition of paved segments used in field studies, especially regarding their ditches, must be compared to WEPP: Road model assumptions to detect whether sediment leaving the road is truly being overestimated.
Figure 4. WEPP: Road predictions of sediment leaving road under different road surface types. All road designs are insloped, bare ditch except for the paved segment with an insloped and vegetated or rocked ditch. All segments were modeled using low traffic assumptions except for one graveled segment.

Figure 5. WEPP: Road predictions of sediment leaving the buffer under three road surface types.

Effects of traffic level on WEPP: Road predictions can be found in Figures 6 and 7. WEPP: Road predicted an exponential increase in sediment leaving the road and sediment leaving the buffer with increases in traffic. WEPP: Road assumes high traffic to be equivalent to sediment available on a newly constructed road or during an active logging operation. Low traffic, in contrast, is assumed to generate one quarter of the sediment generated during an active logging operation (B. Elliot personal...
communication). With such assumptions, WEPP: Road predictions related to traffic follow closely with literature-supported findings (e.g. Reid and Dunne 1984, Foltz 1996, Bilby et al. 1989).

Figure 6. WEPP: Road predictions of sediment leaving the road under no traffic, low traffic, and high traffic scenarios.

Figure 7. WEPP: Road predictions of sediment leaving the buffer under no traffic, low traffic, and high traffic scenarios.
2.5b Quantitative parameters:

In all three soil types, sensitivity trends between parameters are identical. Accordingly, only WEPP: Road predictions in silt loam soil are shown below.

Road length was the most sensitive of the six parameters in terms of change in predicted sediment leaving the road, followed by road gradient and road width (Figure 8). These results suggest that BMPs which reduce segment length stand to reduce sediment leaving the road more than BMPs that alter other quantitative road parameters. Fill slope gradient and length were predicted to have minimal effect on sediment leaving the road. Rock content, if greater than 50%, has no effect on predicted sediment leaving the road.

Free rocks on the soil surface have been shown to dissipate the kinetic energy of runoff (Descroix et al. 2001). Research has found forest soils with rock fragment cover greater than 50% to take longer to generate runoff and to protect finer subsurface soils from being entrained by runoff (Cerda´ 2001). Martínez-Zavala and Jordán report an increase in infiltration rate and exponential decrease in soil loss rate with increase in rock fragment cover (2008). While the research cited above would suggest that WEPP: Road predictions disagree with published literature, Kidwell and others (1997) report, as per Poesen et al.’s findings (1990), that degree of embeddedness acts as a control on infiltration rate; rock fragments embedded under the soil surface restrict infiltration rate and also therefore time to production of overland flow. This physical control appears to be the driver behind WEPP: Road predictions of sediment production at percent rock contents less than 50%. WEPP: Road uses default values when modeling roads containing 50% rock content or greater (H. Rhee personal communication), explaining the lack of change in predicted erosion at rock contents greater than 50%.
Figure 8. WEPP: Road predictions of sediment leaving the road in silt loam soil under multiple quantitative parameter scenarios. Multiplier represents control value of a given parameter (1) as well as +/- 10% (1.1 and .9) and +/-30% (1.3 and .7) that value.

Figure 9. WEPP: Road predictions of sediment leaving the buffer in silt loam soil under multiple quantitative parameter scenarios. Multiplier represents control value of a given parameter (1) as well as +/- 10% (1.1 and .9) and +/-30% (1.3 and .7) that value.

Since all parameters controlling sediment leaving the road influence sediment volume available for downslope transport, all eight quantitative parameters could
potentially affect WEPP: Road predictions for sediment leaving the buffer (Megahan and Ketcheson 1996). For that reason, all quantitative parameters have been included in Figure 9. As with sediment leaving the road, road length was the most sensitive parameter. Buffer gradient and road width both had a positive relationship with sediment leaving the buffer. Buffer length, in contrast, had a negative relationship with sediment leaving the buffer. Buffer length was more sensitive than both buffer gradient and road width. As with predictions for sediment leaving the road, fill slope length and fill slope gradient had little bearing on sediment leaving the buffer. Rock content had the same effect on sediment leaving the buffer as it did with sediment leaving the road; there was no change in sediment leaving the buffer with change in rock content above 50% due to WEPP: Road model assumptions.

Multiple studies highlight the importance of road segment length and also interactivity with slope on the road bed and buffer in explaining sediment transport from forest roads (e.g. Luce and Black 1999, Luce and Black 2001a, Elliot et al. 2009). In addition, Coe (2006) found segment surface area, and thereby segment length, to be a significant explanatory variable for sediment production from forest roads in the Western Sierras. With these studies considered, WEPP: Road predictions match empirical research.

2.6 Conclusions

Generally, differences in WEPP: Road erosion predictions between soil types appear to be governed by relations between soil cohesive strength and particle size. Soils with lower cohesive strengths can more easily entrained by runoff, but are prone to earlier deposition due to their more massive particle size.
WEPP: Road erosion predictions for paved road segments were not intuitive. Further investigation of field condition of paved road segment ditches in published literature and WEPP: Road model assumptions are necessary to resolve this potential discrepancy. In addition, WEPP: Road is limited in its capacity to model roads in soils with greater than 50% rock content.

WEPP: Road predictions may deviate as much as +/- 50% from measured values in the field (Elliot et al. 1999). With this fact in mind, the often-used slogan “garbage in, garbage out” becomes highly pertinent for managers wishing to achieve accurate predictions with this model. It is critical that managers collect accurate input data for use in WEPP: Road. Averaging values over large areas could substantially alter WEPP: Road results, rendering predictions invalid. In doing so, valuable resources—economic, environmental, or otherwise—may be wasted.

This sensitivity analysis is not a validation of WEPP: Road. Rather, it is meant to give further insight into parameter behavior under multiple conditions. Reasons for model predictions from these test road segments were hypothesized here but, to date, have not all been confirmed by model developers.

The sensitivity analysis presented here provides further background from which users can evaluate WEPP: Road erosion and predictions. With this analysis, users can also channel limited resources into collecting parameters which stand to most affect the erosion prediction of interest (sediment leaving the road versus sediment leaving the buffer). Finally, erosion prediction deviation from direct observation can be evaluated through this sensitivity analysis and critical interpretation of model performance.


2.7 References


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Rhee, H., Rocky Mountain Research Station- Moscow Forest Sciences Laboratory Research Engineer. Email communication 15 March 2008 and 10 August 2009.


3. A METHODOLOGY FOR PLANNING ROAD BEST MANAGEMENT PRACTICES COMBINING WEPP: ROAD EROSION MODELING AND SIMULATED ANNEALING OPTIMIZATION

3.1 Abstract

To minimize erosion from roads, managers install and maintain physical Best Management Practices (BMPs). BMP installation on a watershed scale is a difficult task because of the need to account for multiple constraints, such as available budget, BMP maintenance, and equipment scheduling. A methodology for addressing this challenge is presented here that combines WEPP: Road erosion modeling and simulated annealing optimization. Field surveys of forest roads at Glenbrook Creek, NV provided inputs for WEPP: Road and subsequent identification of erosion risk potential. Appropriate BMPs were identified for segments posing an erosion risk. These BMPs, associated sediment, costs, and maintenance frequencies were input into a model using simulated annealing as a heuristic search backbone. The algorithm minimized sediment leaving the road buffer over the course of the planning horizon by comparing potential BMP installation and maintenance scenarios. Preexisting BMP maintenance costs, new BMP installation costs and maintenance regimens, and equipment scheduling considerations were accounted for within the algorithm. Three scenarios at multiple initial budget levels were modeled to demonstrate the utility of this methodology.

Of the 173 surveyed segments, 38 segments were available to have BMPs installed. The best possible solution yielded a reduction in sediment leaving the buffer over the course of the planning horizon by 70%. This methodology can be applied to any watershed, but relies heavily on the perceived accuracy of road erosion predictions.
3.2 Introduction

Forest roads, when imposed on the landscape, often become the most prominent source of erosion in mountainous watersheds (Burroughs 1990). Roads can magnify erosion rates by multiple orders of magnitude (e.g. Megahan and Ketcheson 1996, Megahan and Kidd 1972). Frequently, roads increase sediment delivery to streams in a given watershed and alter geomorphic processes both in and out of the stream channel (e.g. Montgomery 1994, Jones et al. 2000, Wemple et al. 1996). Impacts of road-generated fine sediment entering streams include increased turbidity (Forman and Alexander 1998) and impairment of fish habitat (FPAC 2000). Roads become a chronic source of fine sediment to downstream water bodies (Luce 2002).

It could be argued that few places in the western United States are as aware of the downstream consequences of upstream management actions as the Lake Tahoe Basin. Lake Tahoe has been declared an Outstanding Natural Resource Water by the U.S. Environmental Protection Agency. As a result of precipitous losses in water clarity over the past 25 years, Lake Tahoe is currently designated as an impaired water body under Section 303(d) of the Clean Water Act (Roberts and Reuter 2007). In order to stem this decline in water clarity, it is imperative that innovative solutions for mitigating fine sediment inputs to Lake Tahoe be conceived.

To minimize road erosion, managers frequently implement Best Management Practices (BMPs). In practice, physical BMPs (e.g. drain dips, cross-draining culverts, rip rap) are installed based on professional judgment in the field. Often, no data on sediment leaving the road surface or sediment leaving the buffer (that portion of the hill slope lying between the fill slope and the nearest waterway) is used to guide judgment. One way to
mitigate this issue is to apply a road erosion model such as WEPP: Road (Elliot et al. 1999). WEPP: Road provides a user-friendly process-based model via web interface for managers to evaluate erosion from forest roads.

While WEPP: Road provides a highly cost-effective means of evaluating road erosion using relatively few measurements made in the field, new BMP implementation on a watershed scale is a daunting task. Given budget constraints, managers must evaluate which sites stand to benefit most from BMP implementation right now as well as planning future BMP implementation. In addition, existing BMPs must be maintained to ensure continued effectiveness, along with any new BMPs. Further complications arise from the logistics associated with project planning for BMP installation because it would be cheaper to install and maintain BMPs in near proximity in the same time period.

Here, a solution to this problem is presented that combines WEPP: Road-derived erosion data with simulated annealing optimization to spatially optimize BMP placement across the road network. In doing so, this methodology minimizes road-related sediment entering streams in a given watershed while taking into account budget constraints and spatial adjacency considerations over the course of a planning horizon.

3.3 Study Site

Lake Tahoe, on the California-Nevada border, lies between the Sierra Nevada Range to the west and the Carson Range to the east. Elevations range from approximately 6900 feet to nearly 11,000 feet. Average maximum air temperature from 1915-1998 was 56 degrees F and average minimum temperature was 30 degrees F. Precipitation in the
basin ranges from 70 to 90 inches per year on the west side of the basin to 30 to 40 inches on the east side, with most precipitation falling as snow (Rowe et al. 2002).

Figure 10. Map of study area.

The Glenbrook Creek watershed encompassed the majority of the study area (Figure 10). Glenbrook Creek is close to Carson City, NV, making it an important recreation access point for the Lake Tahoe Basin. In addition, the Rocky Mountain Research Station is parameterizing WEPP: Road using rainfall simulation data from Glenbrook Creek. With these factors in mind, Glenbrook Creek was deemed an appropriate watershed for this study.
Glenbrook Creek, on the east side of the Lake Tahoe Basin, lies approximately 15 miles west of Carson City, NV and 20 miles north of South Lake Tahoe, CA. The watershed ranges in elevation from approximately 6200 feet to 8800 feet at its furthest upslope extent. Soils are primarily granitic in origin (Grismer and Hogan 2004). Average annual precipitation at the TAHOE CA SNOTEL site, which lies at lake elevation 12 miles northwest of and across the lake from Glenbrook Creek, is approximately 31 inches.

A gated housing development near the mouth of Glenbrook Creek was excluded from the study area. The portion of Forest Road 14N32 connecting with Highway 50 at Spooner Summit was included in the study area since it served as a major access point to the watershed. The gated road segment to the west of Highway 50, known as the “Old Lincoln Highway,” was initially surveyed using GPS but never modeled for road erosion since it was only used for administrative access.

3.4 Methods

3.4a Field data collection:

Field data collection was conducted in July 2008. Of the 7.6 miles of road surveyed (5.6 miles of those roads being in the Lake Tahoe Basin), 173 hydraulically contiguous road segments were identified. WEPP: Road input parameters determined or measured in the field for each of these segments included:

- Identification of road segment “from” nodes and “to” nodes
- GPS coordinates for “from” and “to” nodes
- Road gradient
- Road surface type
- Coarse rock content
- Fillslope gradient
- Fillslope length
- Soil texture
- Road width
- Road design (insloped or outsloped, rutted or unrutted, bare or vegetated ditch)

“From” nodes and “to” nodes were identified for each road segment. “To” nodes were always delivery points, or the perceived segment outlet for runoff and sediment. “From” nodes comprised the entrance or beginning segment locations for runoff and sediment entrainment. Segments were delineated between two existing drainage structures, from a slope break or high point to a drainage structure, from a high point to a low point, or between a drainage structure and a low point.

GPS points were taken using a GPS flash card adapter for a Dell Axim Personal Digital Assistant. Road gradient and fillslope gradient were both manually measured with a clinometer. Widths and lengths were all taken using a logger’s tape delineated in tenths of feet. When necessary, slope and length/width measurements were averaged over the length of the segment. Coarse rock content and soil texture were both performed on soil adjacent to the road grade itself. Coarse rock content was established using a 2 mm sieve by taking a ratio between total soil volume and rock volume greater than 2 mm diameter. Soil texture was evaluated using the hand-texturing procedure developed by Thein (1979).
3.4b Data acquisition using GIS/preparation for model input:

For GIS-derived input parameters, vector data was provided by the Tahoe Regional Planning Agency (TRPA) and the 10 m Digital Elevation Model (DEM) was obtained from the Lake Tahoe GIS Data Clearinghouse (http://tahoe.usgs.gov/).

WEPP: Road parameters derived from GIS data or from Lake Tahoe Basin Management Unit (LTBMU) data included segment length, buffer slope, buffer length, and road traffic level. Segment length was found by first reprocessing the GPS-derived road layer into segments based on hydraulic connectivity observed on the ground, then using a GIS to calculate the length of those segments.

Delivery points for insloped segments were always assumed to be “to” nodes. Since sediment delivery from outsloped segments occurs along the entire length of the segment, delivery points for these segments were designated at the middle of the segment. Buffer length and slope for each segment were calculated from these delivery points. Since WEPP: Road will not accept slopes exceeding 100% and road lengths exceeding 1000 feet, values exceeding these thresholds were replaced with 99 and 999, respectively. In locations where there was no fill slope, WEPP defaults of .3% slope and one foot were used.

Buffer slope and buffer length were found using a software program developed by the Forest Operations Research and Management Sciences Group at The University of Montana. Using road network delivery points, a raster stream layer, and a flow path raster derived from a DEM, this program calculated buffer length as total flow path distance to the nearest stream. Buffer slope was calculated for each road segment using this flow path distance.
Road segments were processed in WEPP: Road Batch according to soil texture. Sandy clay loam and silty clay loam were grouped together and processed as being “clay loam” soil type (H. Rhee personal communication). “TAHOE CA” was chosen for the climate, being the closest available climate base station within the WEPP: Road climate library. Based on elevation at a central location in the watershed, monthly precipitation values were increased based on the PRISM model (accessible through the WEPP: Road interface). Since climate data stored for use with the FS WEPP interfaces include only monthly values, WEPP: Road uses the CLIGEN weather generator to produce daily climate data for the desired simulation time (Elliot et al. 1999). Thirty years of daily climate data were generated for these simulations. Road traffic level was held constant at “low” for all segments (Briebart et al. 2006).

A sensitivity analysis of WEPP: Road (Chapter 2) and current literature suggest that road length and width, road gradient, soil type, and surface type all serve as important controls on sediment leaving the road. Those same factors, coupled with buffer gradient and length, control sediment leaving the buffer. To explore the linkage between these factors and WEPP: Road predictions in Glenbrook Creek, relationships between erosion rate (which normalizes erosion values across segments of all lengths and widths) and these parameters were evaluated along with absolute prediction values for Glenbrook Creek. Where necessary, erosion rates were calculated using average surface areas; total road length within a surface or soil type was multiplied by average road width for that soil or surface type.
3.4c “Hot spot” identification and verification:

Following WEPP: Road Batch processing, results were reviewed to identify which segments had the greatest amount of sediment leaving the buffer. Natural breaks in a histogram were used to determine “hot spots”, or those segments that were contributing large amounts of sediment to Glenbrook’s streams. Those segments that were not classified as high risk segments were classified as moderate or low risk segments. The LTBMU supported our risk rating criteria (C. Shoen personal communication). The breakdown is shown in Table 4.

Field verification of the high risk road segments within the Glenbrook Watershed was conducted in September 2008. A LTBMU roads engineer accompanied us during field verification. During this process, we assessed the legitimacy of each hot spot by identifying the overriding characteristic causing the segment to be an erosion risk. Segments were deemed legitimate hot spots for reasons ranging from steepness of the segment to length of segment to lack of surface durability. In addition to validating erosion risk from modeled road segments, applicable treatments were assigned to the road segments visited.

Table 4. Classification of road segments with greater than 0 lbs/yr sediment leaving buffer into risk rating classes.

<table>
<thead>
<tr>
<th>Risk rating</th>
<th>Number of segments in class</th>
<th>Low bound (lbs/yr sediment leaving buffer)</th>
<th>High bound (lbs/yr sediment leaving buffer)</th>
<th>Miles of road in risk class</th>
<th>Percent of total road mileage surveyed</th>
</tr>
</thead>
<tbody>
<tr>
<td>High risk</td>
<td>9</td>
<td>130</td>
<td>1300</td>
<td>0.9</td>
<td>12</td>
</tr>
<tr>
<td>Moderate risk</td>
<td>30</td>
<td>12</td>
<td>130</td>
<td>1.5</td>
<td>19</td>
</tr>
<tr>
<td>Low risk</td>
<td>35</td>
<td>1</td>
<td>11</td>
<td>1.8</td>
<td>21</td>
</tr>
</tbody>
</table>
3.4d Simulated annealing modeling framework:

Simulated annealing, developed by Kirkpatrick and others (1983), uses a modified Monte Carlo simulation that loosely resembles metal cooling after leaving a forge. This optimization technique solves problems through comparison of neighborhood solutions. An integral component of the algorithm is its linkage to temperature; initial and final temperatures, along with a cooling rate, are defined within the algorithm. Acceptance probabilities, also linked to temperature, provide for the possibility of accepting worse solutions during iterative solution comparison. A flowchart explaining the adapted simulated annealing algorithm framework to this planning problem is in Appendix B.

The objective function of this optimization problem was to minimize sediment leaving the buffer through the course of the planning horizon [Eq. 1] while accounting for budget as a constraint [Eq. 2].

Minimize

\[ Z = \sum_{j=1}^{H} \sum_{i=1}^{N} \frac{\text{sediment}_{i,j}}{1.04^{(j-1)}} \]  

[Eq. 1]

Subject to

\[ \sum_{i=1}^{N} \text{cost}_{i,j} \leq \text{budget}_j, \quad j \in H \]  

[Eq. 2]

where

- \( Z \): total sediment leaving the buffer through the course of the planning horizon
- \( j \): planning period
- \( H \): length of planning horizon
- \( i \): segment number
- \( N \): total number of segments on the road network
- \( \text{sediment}_{i,j} \): sediment leaving the buffer from segment \( i \) during planning period \( j \)
Sediment was minimized by applying appropriate BMPs to treatable road segments. Appropriate BMPs were prioritized based on existing condition of the road network (Table 5). These priorities were established through a field visit with LTBMU roads engineers as well as personal communication with other USFS roads engineers. Of the 74 road segments producing greater than zero sediment leaving the buffer per year, 38 could be assigned treatments. 36 segments could not be assigned BMPs because they were either paved (assumed to be an “end-point” BMP) or had some combination of conditions which prevented assignment of BMP treatments. For example, outsloping was not considered an appropriate BMP for graveled segments and drain dips were not applied to segments already outsloped.

Within the algorithm, an initial budget per period was specified. This initial budget was the maximum that could be spent on BMP installation and maintenance in a given planning period. Planning horizon was specified as 20 years, with planning period being one year.

Each segment had four possible BMP treatment options available, with one option being “none”, or no BMP assigned to the segment. Only one option per segment could be selected for implementation by the algorithm. If greater than four options were possible on a given road segment, the three options (besides none) that produced the greatest reduction in sediment leaving the road buffer were used. Further criteria used to assign BMPs on the road network are shown in Table 6.
Table 5. Priority of BMP assignment for a given road segment

<table>
<thead>
<tr>
<th>Condition</th>
<th>Priority 1</th>
<th>Priority 2</th>
<th>Priority 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffer slope &gt; fill</td>
<td>Outslope</td>
<td>Drain dips</td>
<td>Pave</td>
</tr>
<tr>
<td>slope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road Slope &gt; 17%</td>
<td>Pave</td>
<td>Drain dips</td>
<td>Outslope</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Drain dips applicable on any segment greater than 150 feet in length.

Table 6. Further criteria used when assigning BMPs to problematic road segments.

<table>
<thead>
<tr>
<th>BMP</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outslope</td>
<td>Delivery point reassigned to center of road segment. Not applicable on paved or graveled segments.</td>
</tr>
<tr>
<td>Pave</td>
<td>If paving is already installed on a segment, no further BMPs can be installed.</td>
</tr>
<tr>
<td>Drain dips</td>
<td>Segment length iteratively divided in half until segment length is less than 150 feet or sediment leaving buffer is zero. Drain dips not applicable on outsloped segments.</td>
</tr>
</tbody>
</table>

In the case of drain dips, multiple options could be assigned. On segments longer than 150 feet, segments were divided in half to represent a hydrologic break between the two segments. These segments were iteratively divided in half until segment length was less than 150 feet or sediment leaving the buffer equaled zero.

Installation costs, maintenance costs, and maintenance frequencies associated with a given BMP assignment can be found in Table 7. For each potential BMP scenario on a given segment, WEPP: Road was used to predict sediment leaving the buffer. These predictions, along with the costs and maintenance frequencies associated with each BMP scenario, were formatted into an input table for the BMP-SA algorithm. See Appendix C for an example BMP-SA input table.
Table 7. Installation costs, maintenance costs, and maintenance frequencies associated with assigned BMPs. These costs were compiled through a combination of personal communication with USFS personnel and the USFS Region 4 Cost Estimating Guide for Road Construction (USDA 2008).

<table>
<thead>
<tr>
<th>BMP</th>
<th>Installation cost ($)</th>
<th>Equipment move-in costs ($)</th>
<th>Maintenance cost ($)</th>
<th>Equipment move-in costs for maintenance ($)</th>
<th>Maintenance frequency (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outsloping</td>
<td>3000/mile</td>
<td>1000</td>
<td>1000/mile</td>
<td>500</td>
<td>3</td>
</tr>
<tr>
<td>Drain dips</td>
<td>100/each</td>
<td>500</td>
<td>100/each</td>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>Pavement</td>
<td>245000/mile</td>
<td>1500</td>
<td>15000/mile</td>
<td>500</td>
<td>7</td>
</tr>
</tbody>
</table>

Applicable BMP installation and maintenance scenarios were created from this list of BMP options. BMP-SA first randomly assembled an initial, or current, solution where one treatment option was selected for every segment. A neighborhood solution was then formulated where one element of the current solution was altered (Figures 11-13). Sediment generated from these alternative solutions was compared within the algorithm as temperature was cooled. If the neighborhood solution was better than the current solution, the current solution was always accepted and used to formulate the next neighborhood solution for comparison. If a neighborhood solution was worse than the current solution, an acceptance probability was calculated that was linked to the temperature at the time of comparison using the following equation:

\[ p(\text{new}) = e^{\frac{\text{new-current}}{\text{temp}}} \]
Depending on the acceptance probability, the neighborhood solution could be accepted as the current solution despite producing more sediment than the previous solution over the course of the planning horizon. With this iterative comparison of solutions, a near-optimum BMP installation and maintenance scenario was formulated upon reaching the stopping conditions dictated within the algorithm.

To account for equipment scheduling on adjacent road segments, clusters of segments were created. Road segments with delivery points within 1000 feet of each other were grouped into a single cluster both manually and using a subroutine within the BMP-SA algorithm. For road work conducted in the Lake Tahoe Basin, it costs $500 for each piece of equipment that must be moved into the basin (P. Potts personal communication). It was assumed that the same piece of equipment could be used for maintenance and installation of all BMPs of the same type within a cluster. Thus, equipment move-in costs were incurred only once within each cluster. In accounting for these costs, assumptions were made as to how many pieces of equipment were required to install each BMP.

While computing the objective function, BMP-SA discounted sediment leaving the buffer by four percent per year. Discounting by four percent is standard practice in natural resources economic analysis involving U.S. Forest Service investments (Row et al. 1981).
<table>
<thead>
<tr>
<th>BMP</th>
<th>Segment</th>
<th>Period</th>
<th>Sediment leaving buffer (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outslope</td>
<td>10</td>
<td>2</td>
<td>0.010</td>
</tr>
<tr>
<td>Drain dip</td>
<td>27</td>
<td>4</td>
<td>0.002</td>
</tr>
<tr>
<td>Pavement</td>
<td>13</td>
<td>8</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Figure 11. Example initial solution formulated from a list of alternative BMPs on a road segment. Initial solutions are randomly formulated within BMP-SA.

<table>
<thead>
<tr>
<th>BMP</th>
<th>Segment</th>
<th>Period</th>
<th>Sediment leaving buffer (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outslope</td>
<td>10</td>
<td>2</td>
<td>0.010</td>
</tr>
<tr>
<td>Drain dip</td>
<td>27</td>
<td>4</td>
<td>0.032</td>
</tr>
<tr>
<td><strong>None</strong></td>
<td>27</td>
<td>4</td>
<td>0.032</td>
</tr>
<tr>
<td>Pavement</td>
<td>13</td>
<td>8</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Figures 12 and 13. Examples of neighborhood solutions formulated from the initial (current) solution. Neighborhood solutions are formulated by changing one element of the initial (current) solution, either period of installation (Figure 12) or BMP installed (Figure 13). In this case, the BMP that was installed or the type of BMP installed can be changed. With BMP-SA, current and neighborhood BMP solutions are iteratively compared. The algorithm compares two solutions, and if a neighborhood solution is worse than the current solution, an acceptance probability is calculated such that, based on temperature, the neighborhood solution may be accepted as the current solution. In doing so, BMP-SA can arrive at a consistent near-optimum BMP implementation and management scenario more quickly than if purely random search techniques were employed.
Three BMP implementation and maintenance scenarios were modeled: New BMP installation only, new BMP installation and maintenance, and existing BMP maintenance along with new BMP installation and maintenance. In those modeling scenarios accounting for BMP maintenance, BMPs were assumed to be maintained in perpetuity at their assigned frequencies. When included, existing BMPs were assumed to start their maintenance cycle in period one. Each scenario was modeled using multiple budget levels to assess model behavior under different budget conditions.

3.5 Results

3.5a WEPP: Road erosion modeling results:

Of the 173 segments analyzed in the study area, 99 of them (accounting for 3.6 miles of the study area) were predicted to produce zero sediment leaving the buffer over the 30-year modeling period. Per-segment sediment outputs ranged from .7 tons per year to 0 tons per year, with a mean of less than .1 tons per year. WEPP: Road predicted a total of 55.0 tons per year of sediment leaving the road and 3.0 tons of sediment leaving the buffer per year (Table 8). Rates of sediment loss were lower within Glenbrook than across the entire study area. Erosion risk did not seem to follow any spatial pattern (Figure 14).

In terms of general trends related to specific road segment parameters, no relationship could be established between road width and erosion rate. Segment length and road gradient, in contrast, showed weak positive relationships ($R^2 = .26$ and .14, respectively) with erosion rate for sediment leaving the road (Figures 15 and 16).
Table 8. Predicted sediment leaving road and sediment leaving buffer in ton/yr and ton/acre/yr in Glenbrook Creek, NV. Average road width across the entire study area was used to calculate ton/acre/yr values.

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Sediment Leaving Road</th>
<th>Sediment Leaving Buffer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ton/yr</td>
<td>ton/acre/yr</td>
</tr>
<tr>
<td>Entire Study Area</td>
<td>55.0</td>
<td>6.1</td>
</tr>
<tr>
<td>Glenbrook Watershed</td>
<td>22.7</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Note: tons are English short tons (1 short ton = 2000 pounds).

Figure 14. Map of erosion risk by road segment, Glenbrook Creek forest road network.
Although there was no correlation between buffer gradient and sediment leaving the buffer, a negative logarithmic trend was evident between sediment leaving the buffer and buffer length (R² = .21) (Figure 17).

![Graph showing erosion rates vs. segment length](image1.png)

Figure 15. Erosion rates for sediment leaving native surface road segments at various segment lengths, Glenbrook Creek, NV. Erosion rates were calculated using WEPP: Road erosion estimates.

![Graph showing erosion rates vs. road gradient](image2.png)

Figure 16. Erosion rates for sediment leaving native surface roads at various road gradients, Glenbrook Creek, NV. Erosion rates were calculated using WEPP: Road erosion estimates.
Average erosion rates on three road surface types are presented in Figure 18. Native surface roads had an average erosion rate of 7.4 ton/acre/yr, which was higher than that estimated by WEPP: Road for graveled and paved segments. Paved segments erosion rates were estimated at 5.1 ton/acre/yr for sediment leaving the road. Erosion rate for sediment leaving the buffer adjacent to paved segments was higher than in the other two surface types, at .6 ton/acre/yr.
WEPP: Road estimated segments in loam soils to have an average erosion rate of 18.3 ton/acre/yr for sediment leaving the road, three and a half times that of segments in clay loam and sandy loam soils (Figure 19). Segments in clay loam were predicted to have the next greatest erosion rate for sediment leaving the road at 4.9 ton/acre/yr, followed by sandy loam with 3.8 ton/acre/yr. Segments in loam soils were also projected to have the greatest erosion rates for sediment leaving the buffer, at .5 ton/acre/yr, followed by sandy loam (.3 ton/acre/yr) and clay loam (.1 ton/acre/yr), respectively.
Figure 19. Average erosion rates for native surface roads in three soil types, Glenbrook Creek, NV. Erosion rates were calculated using WEPP: Road erosion estimates.

3.5b BMP-SA modeling results:

**New BMP installation only:** Trend in sediment leaving the buffer with increasing initial budget per period (hereafter referred to as “budget”) is shown in Figure 20. Sediment leaving the buffer produced a negative exponential trend with increasing budget. Note that the theoretical minimum number of BMPs installed is zero. Below $3,000, the model failed to find a feasible solution within one hour.

The best solution was achieved when all 38 segments had BMPs applied to them in period one. Sediment was reduced from 41.7 tons over the course of the planning horizon to 11.5 tons through the course of the planning horizon. With this modeled scenario, all 38 BMPs were installed in period one when budget equaled $20,000 (Figure 21). Increasing budget beyond this level yielded no reduction in sediment leaving the buffer.
Number of BMPs installed in period one increased with initial budget per period. Proportion of segments with outsloping chosen as an appropriate BMP also increased with budget. In several instances, solutions at two different budgets yielded decreases in sediment leaving the buffer while having the same number of BMPs installed in period one. In all of these instances, number of segments where outsloping was installed as a BMP was greater in the solution producing less sediment leaving the buffer. Outsloping
is a highly effective BMP for reducing sediment leaving the road and buffer, but also tends to be more expensive than drain dips (Luce and Black 2001a, Elliot et al. 2009, USDA 2008).

Figure 22 shows the number of segments where BMPs were installed in each period. At $3,000, all BMPs were installed in the first seven periods. As budget increased, the number of periods required for all BMPs to be installed was reduced.

![Figure 22. Number of BMPs installed in each period at varying initial budgets per period, new BMP installation only model scenario.](image)

**New BMP installation and maintenance:** The new BMP installation and maintenance modeling scenario displayed a negative exponential trend similar to the trend displayed with previous modeled scenario (Figure 23). Below $6,000, the model failed to produce feasible solutions in one hour.
As with the previous modeling scenario, minimum sediment leaving the buffer through the course of the planning horizon was 11.5 tons. The less-than-perfect negative exponential trend seen in Figure 23 served as evidence of the solution quality-computation time tradeoff that occurs with heuristic optimization. Had the model been run for longer periods of time at each budget level, the curve would likely be completely smooth. With this scenario, all 38 BMPs can be installed in period one at a $34,000 budget.

Figure 24 shows the distribution of types of BMPs installed at varying budgets. While no distinct pattern was evident, at $6,000 budget two segments had no treatment chosen as the best possible option. This result indicates that budget was so limited that neither BMP installation nor maintenance was feasible for these two segments. Had there been sufficient budget available for installation, the model would have installed BMPs on these segments late in the planning horizon so as to avoid maintenance costs.
Figure 24. Number and type of BMPs installed on treatable road segments at varying initial budgets per period for new BMP installation and maintenance model scenario.

Figure 25 presents the number and types of BMPs installed in period one at varying budgets for the new BMP installation and maintenance scenario. Again, number of outsloped segments installed in period one relative to drain dips increased with budget. Cost-benefit tradeoffs similar to those seen in the previously modeled scenario could also be found here.

Figure 25. Number and types of BMPs installed in period one at varying initial budgets per period for new BMP installation and maintenance model scenario.
The number of segments treated during a given planning period at varying budgets is presented in Figure 26. As with the previously modeled scenario, the number of BMPs installed in period one increased with budget.

![Figure 26. Number of BMPs installed in each period at varying initial budgets per period for new BMP installation and maintenance model scenario. Note that no treatment is applied to two segments at $6,000 initial budget per period.](image)

**Existing BMP maintenance and new BMP installation and maintenance:** The best solution achieved with this scenario was the same as with the previous two modeled scenarios- 11.5 tons of sediment leaving the buffer over the course of the planning horizon (Figure 27). Maintenance of existing BMPs required approximately $35,000 minimum initial budget. Period 13, with numerous preexisting BMPs having maintenance frequencies of 2, 3, or 4 years (installed in period one), required the greatest initial budget. As a result, any new BMPs with a three-year maintenance frequency (such as outsloping) could not be installed in period one until budget was increased beyond this minimum level.
Figure 27. Sediment leaving buffer through course of planning horizon at varying initial budgets per period for existing BMP maintenance, new BMP installation, and new BMP maintenance model scenario.

Again, sediment leaving the buffer decreased exponentially with increase in budget. With this scenario, a budget of $57,000 was necessary for all BMPs to be installed in period one.

Figure 28. Number and type of BMPs installed in period one at varying initial budgets per period for existing BMP maintenance, new BMP installation, and new BMP maintenance model scenario.

When installation of new BMPs and maintenance of all BMPs was accounted for, the number of BMPs installed in period one increased linearly as budget increased.
(Figure 28). As a result of accounting for maintenance costs, the solution became more constrained, making the BMP installation scenario less variable than with the previous scenario. Outsloped segments increased with budget as with the two previously modeled scenarios.

![Figure 29. Number of BMPs installed per period at varying initial budgets per period for existing BMP maintenance, new BMP installation, and new BMP maintenance model scenario.](image)

In general, number of periods required to install BMPs on all segments decreased with increase in budget (Figure 29).

### 3.6 Discussion

#### 3.6a Discussion of WEPP: Road modeling results:

The outstanding BMP infrastructure on Glenbrook Creek’s forest roads partially explains the lack of spatial trend in erosion risk prediction. The LTBMU’s BMP installation and maintenance regimen, coupled with the dry climate found in this watershed, explains the minimal amount of sediment predicted to be leaving the road and buffer.
Though correlations between sediment leaving the road and buffer for segment length, road gradient, and buffer length were not strong, the trends do suggest agreement between WEPP: Road predictions and empirical research (Luce and Black 1999, Luce and Black 2001a). Note that regressions were not fitted with the intention of predicting parameter response within WEPP: Road; rather, regressions were used to evaluate whether parameter response within WEPP: Road matched empirical research.

Modeled differences in sediment leaving the road and buffer for the three surface types were not anticipated. While the reduction in sediment leaving the road and buffer in graveled segments compared to native segments was expected, pavement, having an impervious surface, should produce even less sediment leaving the road than graveled segments. This was not the case with WEPP: Road predictions for Glenbrook Creek. Numerous paved segments in Glenbrook Creek had unvegetated ditches, which could partially explain why the erosion rate for sediment leaving the road was greater than double that found on graveled segments. Due to more and flashier runoff leaving paved segments, buffer sediment can be more readily entrained than on road segments with other surface types. In some cases, paved segments in Glenbrook Creek had armored drainage surfaces below the road, but these BMPs cannot be modeled in WEPP: Road. As a result, road segments with this surface type were generally predicted to have higher average erosion rates for sediment leaving the buffer than the other two surface types. No conclusions can be drawn regarding accuracy of predictions for sediment leaving the buffer. Published field research coupled with a sensitivity analysis of WEPP: Road suggest that the model may be overestimating sediment leaving paved road segments.
Further investigation is necessary, however, to determine whether sediment leaving paved segments is truly being overpredicted.

Particle size relationships and soil cohesive strengths govern WEPP: Road’s erosion predictions across different soil types (Chapter 2). Forest soils highest in silt content have been found to be most erodible, having less cohesive strength than clay-rich soils and smaller particle sizes than sandy soils (Luce and Black 2001a). With loam soils having the greatest silt content of these three soil types, WEPP: Road’s estimate of sediment leaving the road in this soil type is appropriate though quite large. In contrast, estimates for sediment leaving the buffer were suspect. Segments in clay loam, having less massive particle sizes, could be expected to post the greatest losses from the buffer. This discrepancy, coupled with the high erosion rate estimate for sediment leaving the road, is likely due to the high slopes, long contiguous segment lengths, and few BMPs found on segments in loam soils. Similar confounding factors may be influencing erosion rate in other soil types. Field validation using stratified sampling would be necessary to discern the true effect of all three soil types on sediment leaving the road and buffer.

Segment length, road gradient, buffer length, and surface type appear to be the primary drivers for predicted erosion in the Glenbrook watershed. The weak, nonexistent, or confounded signals from specific parameters affecting severity of erosion impact highlight the interplay of multiple factors in dictating sediment losses from a given road segment. These results also reflect the complexity of process-based road erosion prediction.
Comparison of predictions with empirical studies: WEPP: Road Batch results fall within the range of empirical results found in other studies. Megahan and Kidd (1972) measured less than .1 ton/acre/yr of background erosion in granitics of the Idaho Batholith, which are less erodible than the volcanic substrates found in the Lake Tahoe Basin (Grismer and Hogan, 2004) but similar to the much of the parent material found in Glenbrook Creek. In contrast, erosion rates greater than 40 ton/acre/yr are routinely observed on forest roads (Grace 2008). Table 9 contains some published erosion rates for reference. (For more published reference values, see Elliot and Foltz 2001).

Table 9. Forest road erosion rates from multiple published studies. Note that these rates come from a variety of climates, soil types, road designs, traffic levels, study designs, and sample sizes. Rates from either native or graveled surface roads. Reported numbers are averages unless specified otherwise. Values are included here as a general reference against predicted WEPP: Road values.

<table>
<thead>
<tr>
<th>Authors/source</th>
<th>Erosion rate (ton/acre/yr)</th>
<th>Traffic</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Megahan and Kidd 1972</td>
<td>32.0</td>
<td>Logging/Truck</td>
<td>Idaho Batholith, newly constructed roads</td>
</tr>
<tr>
<td>Foltz 1996</td>
<td>1.4</td>
<td>Logging</td>
<td>western Oregon, good aggregate (graveled road)</td>
</tr>
<tr>
<td>Luce and Black 2001b</td>
<td>4.4</td>
<td>Logging/Truck</td>
<td>western Oregon, not graded, less than one year study</td>
</tr>
<tr>
<td>Fransen et al. 2001</td>
<td>4.0</td>
<td>Unknown</td>
<td>New Zealand, granitic, included cutslope contribution</td>
</tr>
<tr>
<td>Sugden and Woods 2007</td>
<td>2.4</td>
<td>Logging/Truck</td>
<td>Belt Supergroup, western Montana</td>
</tr>
<tr>
<td>Sugden and Woods 2007</td>
<td>2.3</td>
<td>Logging/Truck</td>
<td>Glacial till, western Montana</td>
</tr>
</tbody>
</table>

These general numbers can be compared with empirical results specific to the Lake Tahoe area. On the west slope of the Sierra Nevada range, Coe (2006) found a mean erosion rate of 1.4 ton/acre/yr on native surface roads over three wet seasons (approximately October through June). During the first wet season of data collection, where average annual precipitation was near the long-term average of 1300 mm, 3.6
ton/acre of sediment were measured leaving the road. In comparison, WEPP: Road erosion predictions yielded an average rate of 7.4 ton/acre/yr across all native surface segments in the study area. Precipitation in Coe’s study site was approximately one and a half times the average annual precipitation generated by PRISM for WEPP: Road erosion estimates in Glenbrook Creek (33.2 inches, or approximately 843 mm). Average road gradients, segment lengths, and parent materials were comparable for both studies, but road designs and traffic levels for segments in Coe’s study are unknown. Coe’s study segments were in primarily loam soils.

Graveled segments in the Coe study also yielded a lower average erosion rate of .5 ton/acre/yr, compared to 1.8 ton/acre/yr predicted over 30 years in Glenbrook Creek. For both native surface and graveled segments, WEPP: Road estimates for sediment leaving the road in Glenbrook Creek are higher than regional empirical values.

No empirical values for sediment leaving road segment buffers in the Lake Tahoe Basin could be found. To give some perspective to estimates for sediment leaving the buffer, Simon and others found 9.7 ton/yr of fine sediment entering Lake Tahoe from Glenbrook Creek in 2003. Evaluated against WEPP: Road outputs, forest roads in this watershed are responsible for approximately 16% of Glenbrook Creek’s yearly sediment load.

WEPP: Road is in the process of being parameterized specifically for the Lake Tahoe Basin by the Rocky Mountain Research Station in Moscow. This parameterized model version may mitigate some of the differences between empirical research and modeled predictions. Currently, the TAHOE CA SNOTEL site is the closest base station
available within the WEPP: Road climate library. Site-specific climate data may also reduce prediction disagreement with field-derived data.

3.6b Discussion of BMP-SA modeling results:

Despite the potential deviation of some erosion predictions from reality, BMP-SA and its associated methodology are applicable no matter whether predictions agree with absolute values found in the field. BMP-SA uses predicted relative differences between two treatments to identify the most appropriate BMP implementation and maintenance scenario. Assumptions within the model never change, so though absolute values may be incorrect, relative predicted differences between segments (and associated BMPs) will be consistent.

The best possible BMP installation scenario was achieved with all three modeling scenarios, albeit at higher budget levels when maintenance of new and existing BMPs was accounted for. Under the best possible solution, sediment leaving the buffer was reduced by greater than 72% if compared to buffer sediment outputs should no treatments be installed through the course of the planning horizon (Table 10). With respect to the 38 treated segments, sediment was reduced by nearly 93% if compared to buffer sediment outputs should no treatments be installed through the course of the planning horizon. This savings is substantial considering that the Glenbrook watershed is in a dry climate and already has numerous well-maintained BMPs. Assuming that managers are aware of hot spots on the road network, installing and maintaining BMPs without using this model could yield significant sediment savings. Budget, maintenance, and equipment scheduling
constraints, however, would not be accounted for. Also, sediment may not be minimized
to the greatest degree possible.

Using the best available cost estimates for road BMP installation and maintenance, sediment leaving the buffer can be minimized at $57,000 budget per period through the course of a twenty-year planning horizon. This result assumes that existing BMPs and new BMPs are regularly maintained during the horizon. All BMPs must be installed during period one to maximize sediment savings.

Table 10. Reduction in predicted sediment leaving the buffer using BMP-SA model.

<table>
<thead>
<tr>
<th>Portion of study area</th>
<th>Sediment leaving buffer with no new BMPs installed (tons through planning horizon)</th>
<th>Sediment leaving buffer with best possible BMP installation scenario (tons through planning horizon)</th>
<th>Percent reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire study area</td>
<td>41.7</td>
<td>11.5</td>
<td>72.4%</td>
</tr>
<tr>
<td>38 treatable segments</td>
<td>32.5</td>
<td>2.3</td>
<td>92.9%</td>
</tr>
</tbody>
</table>

Note: sediment has been discounted using 4% discount rate.

There were no instances where paving was chosen as an applicable new BMP. In every instance where pavement was a potential BMP option, WEPP: Road model outputs indicated that pavement increased sediment leaving the buffer above existing levels. Other researchers have had similar results in applying WEPP: Road to paved road segments in the Lake Tahoe Basin (Briebart et al. 2006).

3.7 Conclusions

When forest road BMP planning issues are approached from the one- or few-segment perspective, watershed-scale sedimentation, maintenance, and equipment
planning concerns cannot be addressed. At the watershed scale, however, accounting for all of these issues and concerns for every road segment becomes highly complicated and, in some cases, may be simply too complex to address using conventional methods. The methodology presented here makes watershed-scale forest road BMP planning feasible. Multiple constraints can be accounted for consistently for every segment across the entire road network.

This research tested a methodology for increasing efficiency of BMP planning on a forest road network. Road-related sediment leaving the forest buffer was minimized over the course of a planning horizon while accounting for budget constraints as well as equipment scheduling considerations. The solutions presented here used modeled WEPP: Road erosion data from a high-density road survey as well as guidelines for prioritizing appropriate BMPs for a given road segment. To minimize sediment leaving the road buffer, this data was input into an adapted simulated annealing optimization algorithm. Under the best BMP implementation scenario, predicted sediment leaving the road buffer was reduced by greater than 70% over the course of a planning horizon. From these tests, it can be concluded that WEPP: Road erosion modeling combined with simulated annealing optimization provides a viable approach to water quality issues associated with sedimentation from forest roads. While the data used here is from the Lake Tahoe Basin, this methodology can be applied to any watershed. This methodology is also applicable at a scale greater than a single watershed, though problem complexity may substantially increase.

Sediment savings with BMP-SA was considerable, in part because little sediment was predicted to leave the road buffer from the Glenbrook Creek watershed. If predicted
sediment leaving the road buffer was greater, percent decrease in sediment leaving the buffer as a result of BMP installation could be lower. In a watershed without a well-developed BMP infrastructure, however, there would more potential for a tool like BMP-SA to minimize sediment leaving the buffer.

There are two critical assumptions of this modeling exercise. One is that BMPs must be maintained at appropriate intervals in perpetuity, otherwise money spent installing BMPs is not worthwhile. In addition, this modeling process relies on the accuracy of road sedimentation prediction for determining problematic road segments and the effects of BMP installation on sediment savings. WEPP: Road is an easy-to-use, process-based model interface for estimating road sediment losses and has gained widespread use among researchers and managers. It is important to note that WEPP: Road estimates have been shown to deviate from field measurements by +/- 50% (Elliot et al. 1999). Accordingly, the importance of having accurate model inputs cannot be understated.

BMP implementation is often site-specific in nature. For that reason, some hot spots may not be able to be treated using one of only a handful of generic BMPs; only professional judgment in the field may provide the ideal option in such situations. With this point in mind, coupled with all of the above assumptions and limitations, the results of BMP-SA are not meant to replace professional judgment in the field. Rather, this tool is meant to assist in the decision-making process associated with forest road management and planning. By implementing a methodology and/or tools like those used here, managers can identify where to focus limited resources to achieve the greatest economic and environmental benefit across multiple spatial and temporal scales.
References


Coe, D. 2006. Sediment production and delivery from forest roads in the Sierra Nevada, California. MSc Thesis, Colorado State University, Fort Collins, CO.


Rhee, H., Rocky Mountain Research Station- Moscow Forest Sciences Laboratory Research Engineer. Email communication, September 3, 2008.


Appendixes

A. Example Solution from BMP-SA Algorithm

Notes about solution:
This is a raw solution output. The fact that the solution starts at Period 0 and ends at Period 19 is an artifact of algorithm programming, since arrays store values starting at 0. Results are correct despite this discrepancy; simply add 1 to each period value.
Nonzero values for periods where there is no installation or maintenance activity is due to addition and subtraction of floating point values. Note that, in all instances where this occurs, values are zero to at least the second decimal place.

Pre-existing BMP codes:
- rld: rock-lined ditch
- nd: native ditch
- god: gravel on drain dip

________________________________________________________________________

BMP SIMULATED ANNEALING ALGORITHM RESULTS

The best solution has a sediment output over the course of the planning horizon of:
11.512097 tons
Cost of the best solution over the course of the planning horizon: 127083.781250 dollars

Initial budget: 57000.000000 dollars per period

THE SOLUTION:

PERIOD 0

install BMP 3draindips on segment 6 at install cost 300.000000
install BMP outslope on segment 7 at install cost 89.520454
install BMP draindip on segment 31 at install cost 100.000000
install BMP draindip on segment 33 at install cost 100.000000
install BMP outslope on segment 38 at install cost 72.805679
install BMP outslope on segment 41 at install cost 50.951530
install BMP draindip on segment 49 at install cost 100.000000
install BMP draindip on segment 52 at install cost 100.000000
install BMP 3draindips on segment 59 at install cost 300.000000
install BMP draindip on segment 60 at install cost 100.000000
install BMP draindip on segment 62 at install cost 100.000000
install BMP draindip on segment 65 at install cost 100.000000
install BMP draindip on segment 66 at install cost 100.000000
install BMP 3draindips on segment 67 at install cost 300.000000
install BMP draindip on segment 69 at install cost 100.000000
install BMP draindip on segment 71 at install cost 100.000000
install BMP draindip on segment 79 at install cost 100.000000
install BMP draindip on segment 80 at install cost 100.000000
install BMP draindip on segment 93 at install cost 100.000000
install BMP outslope on segment 95 at install cost 133.189194
install BMP outslope on segment 96 at install cost 122.434662
install BMP outslope on segment 108 at install cost 143.797150
install BMP outslope on segment 112 at install cost 123.576141
install BMP 3draindips on segment 113 at install cost 300.000000
install BMP draindip on segment 115 at install cost 100.000000
install BMP outslope on segment 116 at install cost 486.000000
install BMP draindip on segment 117 at install cost 100.000000
install BMP 7draindips on segment 119 at install cost 700.000000
install BMP draindip on segment 120 at install cost 100.000000
install BMP draindip on segment 121 at install cost 100.000000
install BMP outslope on segment 127 at install cost 1143.000000
install BMP draindip on segment 133 at install cost 100.000000
install BMP draindip on segment 134 at install cost 100.000000
install BMP outslope on segment 136 at install cost 91.398865
install BMP outslope on segment 141 at install cost 47.919949
install BMP outslope on segment 142 at install cost 390.000000
install BMP 7draindips on segment 146 at install cost 700.000000
install BMP draindip on segment 174 at install cost 100.000000

Treatment cost for period 0: 32494.597656 dollars
NOTE: preexisting BMP cost already accounted for, so it won’t show up in treatment cost

PERIOD 1

Treatment cost for period 1: 0.000000 dollars
NOTE: preexisting BMP cost already accounted for, so it won’t show up in treatment cost

PERIOD 2

maintain preexisting BMP rld on segment 66 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 67 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 68 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 70 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 72 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 109 at maintenance cost 94.500000

Treatment cost for period 2: -0.000977 dollars
NOTE: preexisting BMP cost already accounted for, so it won’t show up in treatment cost

PERIOD 3
maintain BMP outslope on segment 7 at maintenance cost 29.840151
maintain preexisting BMP outsloping on segment 8 at maintenance cost 43.489964
maintain preexisting BMP gravel on segment 32 at maintenance cost 154.104172
maintain preexisting BMP outsloping on segment 32 at maintenance cost 35.023674
maintain preexisting BMP gravel on segment 34 at maintenance cost 34.347500
maintain BMP outslope on segment 38 at maintenance cost 24.268560
maintain BMP outslope on segment 41 at maintenance cost 16.983845
maintain preexisting BMP gravel on segment 42 at maintenance cost 161.444168
maintain preexisting BMP outsloping on segment 50 at maintenance cost 25.320456
maintain preexisting BMP gravel on segment 66 at maintenance cost 175.522491
maintain preexisting BMP gravel on segment 67 at maintenance cost 351.648315
maintain preexisting BMP gravel on segment 68 at maintenance cost 76.655334
maintain preexisting BMP gravel on segment 70 at maintenance cost 112.001663
maintain preexisting BMP gravel on segment 72 at maintenance cost 115.975838
maintain preexisting BMP gravel on segment 80 at maintenance cost 175.290009
maintain preexisting BMP outsloping on segment 81 at maintenance cost 57.188446
maintain preexisting BMP outsloping on segment 94 at maintenance cost 19.917046
maintain BMP outslope on segment 95 at maintenance cost 44.396400
maintain BMP outslope on segment 96 at maintenance cost 40.811554
maintain BMP outslope on segment 108 at maintenance cost 47.932384
maintain preexisting BMP gravel on segment 109 at maintenance cost 49.375500
maintain BMP outslope on segment 112 at maintenance cost 41.192047
maintain preexisting BMP gravel on segment 114 at maintenance cost 80.570831
maintain BMP outslope on segment 116 at maintenance cost 162.000000
maintain BMP outslope on segment 127 at maintenance cost 381.000000
maintain preexisting BMP outsloping on segment 135 at maintenance cost 185.059280
maintain BMP outslope on segment 136 at maintenance cost 30.466288
maintain preexisting BMP outsloping on segment 138 at maintenance cost 60.063633
maintain BMP outslope on segment 141 at maintenance cost 15.973315
maintain preexisting BMP outsloping on segment 143 at maintenance cost 20.971781
maintain BMP outslope on segment 142 at maintenance cost 130.000000
maintain preexisting BMP outsloping on segment 148 at maintenance cost 48.701519

Treatment cost for period 3: 6964.864258 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 4

maintain preexisting BMP nd on segment 34 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 42 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 50 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 53 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 63 at maintenance cost 400.000000
maintain preexisting BMP rld on segment 66 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 67 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 68 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 70 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 72 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 109 at maintenance cost 94.500000
maintain preexisting BMP nd on segment 114 at maintenance cost 400.000000

Treatment cost for period 4: 0.000549 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 5

maintain BMP 3draindips on segment 6 at maintenance cost 300.000000
maintain preexisting BMP dd on segment 8 at maintenance cost 150.000000
maintain BMP draindip on segment 31 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 32 at maintenance cost 150.000000
maintain BMP draindip on segment 33 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 34 at maintenance cost 150.000000
maintain preexisting BMP dd on segment 35 at maintenance cost 150.000000
maintain BMP draindip on segment 49 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 50 at maintenance cost 150.000000
maintain BMP draindip on segment 52 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 53 at maintenance cost 150.000000
maintain BMP 3draindips on segment 59 at maintenance cost 300.000000
maintain BMP draindip on segment 60 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 61 at maintenance cost 150.000000
maintain BMP draindip on segment 62 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 63 at maintenance cost 150.000000
maintain BMP draindip on segment 65 at maintenance cost 100.000000
maintain BMP draindip on segment 66 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 67 at maintenance cost 150.000000
maintain BMP 3draindips on segment 67 at maintenance cost 300.000000
maintain preexisting BMP dd on segment 68 at maintenance cost 150.000000
maintain BMP draindip on segment 69 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 70 at maintenance cost 150.000000
maintain BMP draindip on segment 71 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 72 at maintenance cost 150.000000
maintain BMP draindip on segment 79 at maintenance cost 100.000000
maintain BMP draindip on segment 80 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 81 at maintenance cost 150.000000
maintain BMP draindip on segment 93 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 94 at maintenance cost 150.000000
maintain BMP 3draindips on segment 113 at maintenance cost 300.000000
maintain preexisting BMP dd on segment 114 at maintenance cost 150.000000
maintain BMP draindip on segment 115 at maintenance cost 100.000000
maintain BMP draindip on segment 117 at maintenance cost 100.000000
maintain BMP 7draindips on segment 119 at maintenance cost 700.000000
maintain BMP draindip on segment 120 at maintenance cost 100.000000
maintain BMP draindip on segment 121 at maintenance cost 100.000000
maintain BMP draindip on segment 133 at maintenance cost 100.000000
maintain BMP draindip on segment 134 at maintenance cost 100.000000
maintain BMP 7draindips on segment 146 at maintenance cost 700.000000
maintain BMP draindip on segment 174 at maintenance cost 100.000000
Treatmen[]
t cost for period 5: 17599.998047 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 6

maintain BMP outslope on segment 7 at maintenance cost 29.840151
maintain preexisting BMP outsloping on segment 8 at maintenance cost 43.489964
maintain preexisting BMP gravel on segment 32 at maintenance cost 154.104172
maintain preexisting BMP outsloping on segment 32 at maintenance cost 35.023674
maintain preexisting BMP gravel on segment 34 at maintenance cost 34.347500
maintain BMP outslope on segment 38 at maintenance cost 24.268560
maintain BMP outslope on segment 41 at maintenance cost 16.983845
maintain preexisting BMP gravel on segment 42 at maintenance cost 161.444168
maintain preexisting BMP outsloping on segment 50 at maintenance cost 25.320456
maintain preexisting BMP gravel on segment 66 at maintenance cost 175.522491
maintain preexisting BMP rld on segment 66 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 67 at maintenance cost 351.648315
maintain preexisting BMP rld on segment 67 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 68 at maintenance cost 76.655334
maintain preexisting BMP rld on segment 68 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 70 at maintenance cost 112.001663
maintain preexisting BMP rld on segment 70 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 72 at maintenance cost 115.975838
maintain preexisting BMP rld on segment 72 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 80 at maintenance cost 175.290009
maintain preexisting BMP outsloping on segment 81 at maintenance cost 57.188446
maintain preexisting BMP outsloping on segment 94 at maintenance cost 19.917046
maintain BMP outslope on segment 95 at maintenance cost 44.396400
maintain BMP outslope on segment 96 at maintenance cost 40.811554
maintain BMP outslope on segment 108 at maintenance cost 47.932384
maintain preexisting BMP gravel on segment 109 at maintenance cost 49.375500
maintain preexisting BMP rld on segment 109 at maintenance cost 94.500000
maintain BMP outslope on segment 112 at maintenance cost 41.192047
maintain preexisting BMP gravel on segment 114 at maintenance cost 80.570831
maintain BMP outslope on segment 116 at maintenance cost 162.000000
maintain BMP outslope on segment 127 at maintenance cost 381.000000
maintain preexisting BMP outsloping on segment 135 at maintenance cost 185.059280
maintain BMP outslope on segment 136 at maintenance cost 30.466288
maintain preexisting BMP outsloping on segment 138 at maintenance cost 60.063633
maintain BMP outslope on segment 141 at maintenance cost 15.973315
maintain preexisting BMP outsloping on segment 143 at maintenance cost 20.971781
maintain BMP outslope on segment 142 at maintenance cost 130.000000
maintain preexisting BMP outsloping on segment 148 at maintenance cost 48.701519

Treatment cost for period 6: 6964.864746 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 7

Treatment cost for period 7: -0.000366 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 8

maintain preexisting BMP nd on segment 34 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 42 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 50 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 53 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 63 at maintenance cost 400.000000
maintain preexisting BMP rld on segment 66 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 67 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 68 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 70 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 72 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 109 at maintenance cost 94.500000
maintain preexisting BMP nd on segment 114 at maintenance cost 400.000000

Treatment cost for period 8: 0.000000 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 9

maintain BMP outslope on segment 7 at maintenance cost 29.840151
maintain preexisting BMP outsloping on segment 8 at maintenance cost 43.489964
maintain preexisting BMP gravel on segment 32 at maintenance cost 154.104172
maintain preexisting BMP outsloping on segment 32 at maintenance cost 35.023674
maintain preexisting BMP gravel on segment 34 at maintenance cost 34.347500
maintain BMP outslope on segment 38 at maintenance cost 24.268560
maintain BMP outslope on segment 41 at maintenance cost 16.983845
maintain preexisting BMP gravel on segment 42 at maintenance cost 161.444168
maintain preexisting BMP outsloping on segment 50 at maintenance cost 25.320456
maintain preexisting BMP gravel on segment 66 at maintenance cost 175.522491
maintain preexisting BMP gravel on segment 67 at maintenance cost 351.648315
maintain preexisting BMP gravel on segment 68 at maintenance cost 76.655334
maintain preexisting BMP gravel on segment 70 at maintenance cost 112.001663
maintain preexisting BMP gravel on segment 72 at maintenance cost 115.975838
maintain preexisting BMP gravel on segment 80 at maintenance cost 175.290009
maintain preexisting BMP outsloping on segment 81 at maintenance cost 57.188446
maintain preexisting BMP outsloping on segment 94 at maintenance cost 19.917046
maintain BMP outslope on segment 95 at maintenance cost 44.396400
maintain BMP outslope on segment 96 at maintenance cost 40.811554
maintain BMP outslope on segment 108 at maintenance cost 47.932384
maintain preexisting BMP gravel on segment 109 at maintenance cost 49.375500
maintain BMP outslope on segment 112 at maintenance cost 41.192047
maintain preexisting BMP gravel on segment 114 at maintenance cost 80.570831
maintain BMP outslope on segment 116 at maintenance cost 162.000000
maintain BMP outslope on segment 127 at maintenance cost 381.000000
maintain preexisting BMP outsloping on segment 135 at maintenance cost 185.059280
maintain BMP outslope on segment 136 at maintenance cost 30.466288
maintain preexisting BMP outsloping on segment 138 at maintenance cost 60.063633
maintain BMP outslope on segment 141 at maintenance cost 15.973315
maintain preexisting BMP outsloping on segment 143 at maintenance cost 20.971781
maintain BMP outslope on segment 142 at maintenance cost 130.000000
maintain preexisting BMP outsloping on segment 148 at maintenance cost 48.701519

Treatment cost for period 9: 6964.864746 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 10

maintain BMP 3draindips on segment 6 at maintenance cost 300.000000
maintain preexisting BMP dd on segment 8 at maintenance cost 150.000000
maintain BMP draindip on segment 31 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 32 at maintenance cost 150.000000
maintain BMP draindip on segment 33 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 34 at maintenance cost 150.000000
maintain preexisting BMP dd on segment 42 at maintenance cost 150.000000
maintain BMP draindip on segment 49 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 50 at maintenance cost 150.000000
maintain BMP draindip on segment 52 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 53 at maintenance cost 150.000000
maintain BMP 3draindips on segment 59 at maintenance cost 300.000000
maintain BMP draindip on segment 60 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 61 at maintenance cost 150.000000
maintain BMP draindip on segment 62 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 63 at maintenance cost 150.000000
maintain BMP draindip on segment 65 at maintenance cost 100.000000
maintain preexisting BMP rld on segment 66 at maintenance cost 94.500000
maintain BMP draindip on segment 66 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 67 at maintenance cost 150.000000
maintain preexisting BMP rld on segment 67 at maintenance cost 94.500000
maintain BMP 3draindips on segment 67 at maintenance cost 300.000000
maintain preexisting BMP dd on segment 68 at maintenance cost 150.000000
maintain preexisting BMP rld on segment 68 at maintenance cost 94.500000
maintain BMP draindip on segment 69 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 70 at maintenance cost 150.000000
maintain preexisting BMP rld on segment 70 at maintenance cost 94.500000
maintain BMP draindip on segment 71 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 72 at maintenance cost 150.000000
maintain preexisting BMP rld on segment 72 at maintenance cost 94.500000
maintain BMP draindip on segment 79 at maintenance cost 100.000000
maintain BMP draindip on segment 80 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 81 at maintenance cost 150.000000
maintain BMP draindip on segment 93 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 94 at maintenance cost 150.000000
maintain preexisting BMP rld on segment 109 at maintenance cost 94.500000
maintain BMP 3draindips on segment 113 at maintenance cost 300.000000
maintain preexisting BMP dd on segment 114 at maintenance cost 150.000000
maintain preexisting BMP rld on segment 114 at maintenance cost 94.500000
maintain BMP draindip on segment 115 at maintenance cost 100.000000
maintain BMP draindip on segment 117 at maintenance cost 100.000000
maintain BMP 7draindips on segment 119 at maintenance cost 700.000000
maintain BMP draindip on segment 120 at maintenance cost 100.000000
maintain BMP draindip on segment 121 at maintenance cost 100.000000
maintain BMP draindip on segment 133 at maintenance cost 100.000000
maintain BMP draindip on segment 134 at maintenance cost 100.000000
maintain BMP 7draindips on segment 146 at maintenance cost 700.000000
maintain BMP draindip on segment 174 at maintenance cost 100.000000

Treatment cost for period 10: 17600.000000 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 11

Treatment cost for period 11: -0.000244 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 12

maintain BMP outslope on segment 7 at maintenance cost 29.840151
maintain preexisting BMP outsloping on segment 8 at maintenance cost 43.489964
maintain preexisting BMP gravel on segment 32 at maintenance cost 154.104172
maintain preexisting BMP outsloping on segment 32 at maintenance cost 35.023674
maintain preexisting BMP gravel on segment 34 at maintenance cost 34.347500
maintain preexisting BMP nd on segment 34 at maintenance cost 400.000000
maintain BMP outslope on segment 38 at maintenance cost 24.268560
maintain BMP outslope on segment 41 at maintenance cost 16.983845
maintain preexisting BMP gravel on segment 42 at maintenance cost 161.444168
maintain preexisting BMP nd on segment 42 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 50 at maintenance cost 400.000000
maintain preexisting BMP outsloping on segment 50 at maintenance cost 25.320456
maintain preexisting BMP nd on segment 53 at maintenance cost 400.000000
maintain preexisting BMP gravel on segment 63 at maintenance cost 400.000000
maintain preexisting BMP gravel on segment 66 at maintenance cost 175.522491
maintain preexisting BMP rld on segment 66 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 67 at maintenance cost 351.648315
maintain preexisting BMP rld on segment 67 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 68 at maintenance cost 76.655334
maintain preexisting BMP rld on segment 68 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 70 at maintenance cost 112.001663
maintain preexisting BMP rld on segment 70 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 72 at maintenance cost 115.975838
maintain preexisting BMP rld on segment 72 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 80 at maintenance cost 175.290009
maintain preexisting BMP outsloping on segment 81 at maintenance cost 57.188446
maintain preexisting BMP outsloping on segment 94 at maintenance cost 19.917046
maintain BMP outslope on segment 95 at maintenance cost 44.396400
maintain BMP outslope on segment 96 at maintenance cost 40.811554
maintain BMP outslope on segment 108 at maintenance cost 47.932384
maintain preexisting BMP gravel on segment 109 at maintenance cost 49.375500
maintain preexisting BMP rld on segment 109 at maintenance cost 94.500000
maintain BMP outslope on segment 112 at maintenance cost 41.192047
maintain preexisting BMP gravel on segment 114 at maintenance cost 80.570831
maintain preexisting BMP nd on segment 114 at maintenance cost 400.000000
maintain BMP outslope on segment 116 at maintenance cost 162.000000
maintain BMP outslope on segment 127 at maintenance cost 381.000000
maintain preexisting BMP outsloping on segment 135 at maintenance cost 185.059280
maintain BMP outslope on segment 136 at maintenance cost 30.466288
maintain preexisting BMP outsloping on segment 138 at maintenance cost 60.063633
maintain BMP outslope on segment 141 at maintenance cost 15.973315
maintain preexisting BMP outsloping on segment 143 at maintenance cost 20.971781
maintain BMP outslope on segment 142 at maintenance cost 130.000000
maintain preexisting BMP outsloping on segment 148 at maintenance cost 48.701519

Treatment cost for period 12: 6964.864258 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 13

Treatment cost for period 13: -0.001923 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost
PERIOD 14

maintain preexisting BMP rld on segment 66 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 67 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 68 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 70 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 72 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 109 at maintenance cost 94.500000

Treatment cost for period 14: -0.002686 dollars
NOTE: preexisting BMP cost already accounted for, so it won’t show up in treatment cost

PERIOD 15

maintain BMP 3draindips on segment 6 at maintenance cost 300.000000
maintain BMP outslope on segment 7 at maintenance cost 29.840151
maintain preexisting BMP dd on segment 8 at maintenance cost 150.000000
maintain preexisting BMP outsloping on segment 8 at maintenance cost 43.489964
maintain BMP drain dip on segment 31 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 32 at maintenance cost 150.000000
maintain preexisting BMP gravel on segment 32 at maintenance cost 154.104172
maintain preexisting BMP outsloping on segment 32 at maintenance cost 35.023674
maintain BMP drain dip on segment 33 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 34 at maintenance cost 150.000000
maintain preexisting BMP gravel on segment 34 at maintenance cost 34.347500
maintain BMP outslope on segment 38 at maintenance cost 24.268560
maintain BMP outslope on segment 41 at maintenance cost 16.983845
maintain preexisting BMP dd on segment 42 at maintenance cost 150.000000
maintain preexisting BMP gravel on segment 42 at maintenance cost 161.444168
maintain BMP drain dip on segment 49 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 50 at maintenance cost 150.000000
maintain preexisting BMP outsloping on segment 50 at maintenance cost 25.320456
maintain BMP drain dip on segment 52 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 53 at maintenance cost 150.000000
maintain BMP 3draindips on segment 59 at maintenance cost 300.000000
maintain BMP drain dip on segment 60 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 61 at maintenance cost 150.000000
maintain BMP drain dip on segment 62 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 63 at maintenance cost 150.000000
maintain BMP drain dip on segment 65 at maintenance cost 100.000000
maintain preexisting BMP gravel on segment 66 at maintenance cost 175.522491
maintain BMP drain dip on segment 66 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 67 at maintenance cost 150.000000
maintain preexisting BMP gravel on segment 67 at maintenance cost 351.648315
maintain BMP 3draindips on segment 67 at maintenance cost 300.000000
maintain preexisting BMP dd on segment 68 at maintenance cost 150.000000
maintain preexisting BMP gravel on segment 68 at maintenance cost 76.655334
maintain BMP draindip on segment 69 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 70 at maintenance cost 150.000000
maintain preexisting BMP gravel on segment 70 at maintenance cost 112.001663
maintain BMP draindip on segment 71 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 72 at maintenance cost 150.000000
maintain preexisting BMP gravel on segment 72 at maintenance cost 115.975838
maintain BMP draindip on segment 79 at maintenance cost 100.000000
maintain preexisting BMP gravel on segment 80 at maintenance cost 175.290009
maintain BMP draindip on segment 80 at maintenance cost 100.000000
maintain preexisting BMP dd on segment 81 at maintenance cost 150.000000
maintain preexisting BMP outsloping on segment 81 at maintenance cost 57.188446
maintain BMP draindip on segment 93 at maintenance cost 100.000000
maintain preexisting BMP outsloping on segment 94 at maintenance cost 19.917046
maintain preexisting BMP dd on segment 94 at maintenance cost 150.000000
maintain BMP outslope on segment 95 at maintenance cost 44.396400
maintain BMP outslope on segment 96 at maintenance cost 40.811554
maintain BMP outslope on segment 108 at maintenance cost 47.932384
maintain preexisting BMP gravel on segment 109 at maintenance cost 49.375500
maintain BMP outslope on segment 112 at maintenance cost 41.192047
maintain BMP 3draindips on segment 113 at maintenance cost 300.000000
maintain preexisting BMP dd on segment 114 at maintenance cost 150.000000
maintain preexisting BMP gravel on segment 114 at maintenance cost 80.570831
maintain BMP draindip on segment 115 at maintenance cost 100.000000
maintain BMP outslope on segment 116 at maintenance cost 162.000000
maintain BMP draindip on segment 117 at maintenance cost 100.000000
maintain BMP 7draindips on segment 119 at maintenance cost 700.000000
maintain BMP draindip on segment 120 at maintenance cost 100.000000
maintain BMP draindip on segment 121 at maintenance cost 100.000000
maintain BMP outslope on segment 127 at maintenance cost 381.000000
maintain BMP draindip on segment 133 at maintenance cost 100.000000
maintain preexisting BMP outsloping on segment 135 at maintenance cost 185.059280
maintain BMP draindip on segment 134 at maintenance cost 100.000000
maintain BMP outslope on segment 136 at maintenance cost 30.466288
maintain preexisting BMP outsloping on segment 138 at maintenance cost 60.063633
maintain BMP outslope on segment 141 at maintenance cost 15.973315
maintain preexisting BMP outsloping on segment 143 at maintenance cost 20.971781
maintain BMP outslope on segment 142 at maintenance cost 130.000000
maintain BMP 7draindips on segment 146 at maintenance cost 700.000000
maintain preexisting BMP outsloping on segment 148 at maintenance cost 48.701519
maintain BMP draindip on segment 174 at maintenance cost 100.000000

Treatment cost for period 15: 24564.867188 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 16

K
maintain preexisting BMP nd on segment 34 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 42 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 50 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 53 at maintenance cost 400.000000
maintain preexisting BMP nd on segment 63 at maintenance cost 400.000000
maintain preexisting BMP rld on segment 66 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 67 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 68 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 70 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 72 at maintenance cost 94.500000
maintain preexisting BMP rld on segment 109 at maintenance cost 94.500000
maintain preexisting BMP nd on segment 114 at maintenance cost 400.000000

Treatment cost for period 16: -0.001190 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 17

Treatment cost for period 17: -0.000977 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 18

maintain BMP outslope on segment 7 at maintenance cost 29.840151
maintain preexisting BMP outsloping on segment 8 at maintenance cost 43.489964
maintain preexisting BMP gravel on segment 32 at maintenance cost 154.104172
maintain preexisting BMP outsloping on segment 32 at maintenance cost 35.023674
maintain preexisting BMP gravel on segment 34 at maintenance cost 34.347500
maintain BMP outslope on segment 38 at maintenance cost 24.268560
maintain BMP outslope on segment 41 at maintenance cost 16.983845
maintain preexisting BMP gravel on segment 42 at maintenance cost 161.444168
maintain preexisting BMP outsloping on segment 50 at maintenance cost 25.320456
maintain preexisting BMP gravel on segment 66 at maintenance cost 175.522491
maintain preexisting BMP rld on segment 66 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 67 at maintenance cost 351.648315
maintain preexisting BMP rld on segment 67 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 68 at maintenance cost 76.655334
maintain preexisting BMP rld on segment 68 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 70 at maintenance cost 112.001663
maintain preexisting BMP rld on segment 70 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 72 at maintenance cost 115.975838
maintain preexisting BMP rld on segment 72 at maintenance cost 94.500000
maintain preexisting BMP gravel on segment 80 at maintenance cost 175.290009
maintain preexisting BMP outsloping on segment 81 at maintenance cost 57.188446
maintain preexisting BMP outsloping on segment 94 at maintenance cost 19.917046
maintain BMP outslope on segment 95 at maintenance cost 44.396400
maintain BMP outslope on segment 96 at maintenance cost 40.811554
maintain BMP outslope on segment 108 at maintenance cost 47.932384
maintain preexisting BMP gravel on segment 109 at maintenance cost 49.375500
maintain preexisting BMP rld on segment 109 at maintenance cost 94.500000
maintain BMP outslope on segment 112 at maintenance cost 41.192047
maintain preexisting BMP gravel on segment 114 at maintenance cost 80.570831
maintain BMP outslope on segment 116 at maintenance cost 162.000000
maintain BMP outslope on segment 127 at maintenance cost 381.000000
maintain preexisting BMP outsloping on segment 135 at maintenance cost 185.059280
maintain BMP outslope on segment 136 at maintenance cost 30.466288
maintain preexisting BMP outsloping on segment 138 at maintenance cost 60.063633
maintain BMP outslope on segment 141 at maintenance cost 15.973315
maintain preexisting BMP outsloping on segment 143 at maintenance cost 20.971781
maintain BMP outslope on segment 142 at maintenance cost 130.000000
maintain preexisting BMP outsloping on segment 148 at maintenance cost 48.701519

Treatment cost for period 18: 6964.863281 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost

PERIOD 19

Treatment cost for period 19: 0.001938 dollars
NOTE: preexisting BMP cost already accounted for, so it won't show up in treatment cost
B. Flowchart Describing Adapted Simulated Annealing Algorithm

1. Input initial budget per period, length of planning horizon, Define initial temperature

2. Compute cost of maintaining existing BMPs over course of planning horizon, subtract from initial budget

3. Develop initial (current) solution, including maintenance regime

4. Formulate new solution and maintenance regime: change BMP or period of installation for one road segment in current solution

5. Compute proximity between segments

6. Compute sediment leaving buffer over course of planning horizon for each solution

7. Does the new solution save more sediment than the current solution?
   - Yes: Accept solution?
     - Yes: Stop, report best solution
     - No: Go to next iteration; update current solution
   - No: Time to change temperature?
     - Yes: Lower temperature
     - No: Have stopping criteria been reached?
       - Yes: Stop, report best solution
       - No: Go to next iteration; update current solution

8. Compute acceptance probability

9. Accept solution?
### C. Example Input Table for BMP-SA Algorithm

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