Original scientific paper

Planning Best Management Practices to Reduce Sediment Delivery from Forest Roads Using WEPP:Road Erosion Modeling and Simulated Annealing Optimization

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Abstract

Planning and implementation of road BMPs on a watershed scale can be a difficult task because of the need to prioritize locations while accounting for multiple constraints, such as the available budget, continuous maintenance, and equipment scheduling. Using simulated annealing (SA) as its heuristic optimizer, BMP-SA accounts for sediment being delivered to the stream network through incorporation of modeled road erosion predictions and alternative BMP options and scheduling for problematic road segments. BMP-SA was applied to the Glenbrook Creek watershed in the Lake Tahoe Basin in Nevada, US. WEPP:Road predictions were used to identify road segments posing an erosion risk and appropriate BMPs were identified for problematic segments. Using BMP-SA, modeled road-related sediment leaving the forest buffer, thus entering streams, was minimized over the course of the planning horizon while considering budget constraints and equipment scheduling concerns. BMP-SA can be applied to any watershed but relies heavily on the perceived accuracy of road erosion predictions.

Keywords: forest roads, BMPs, simulated annealing, WEPP:Road, erosion modeling, road management, budget planning

1. Introduction

To minimize sediment-related impacts of forest roads, Best Management Practices (BMPs) are frequently implemented on forest road networks. While BMPs may consist of a planning practice or mitigation strategy (e.g. maintaining a set buffer distance from a stream channel), the term is also broadly used in reference to specific structures or road network attributes that address sedimentation issues. Examples include, but are not limited to: sediment traps; drain dips; vegetated or rock-lined ditches, and/or road surfacing. Field research supports the effectiveness of specific BMPs and the physics behind them (e.g., Clinton and Vose 2003, Foltz and Truebe 2003, Luce and Black 2001, Megahan and Ketcheson 1996).

In practice, physical BMPs are generally prescribed using expert judgment in the field, inevitably under limited budget conditions. Regardless of whether erosion risk is evaluated, not all potential BMP options may be explored at a given site, for reasons ranging from inexperience of the prescriber to budget limitations. While a BMP or set of BMPs may be ideal for a given site, selection of BMPs at the one- to few-segment scale may not effectively minimize erosion and sedimentation at the watershed scale.

Optimization strategies have been employed since the 1970s to address multiple management goals and environmental constraints in forest planning (Rönnqvist 2003, Weintraub et al. 1995, Weintraub 2006). Application of heuristic optimization specifically to environmental concerns, including sedimentation associated with roads, has only occurred more recently due to the complexity of such spatially-explicit planning problems (Coulter et al. 2006, Contreras and Chung 2009, Weintraub et al. 2000). Multiple projects have incorporated BMPs and/or associated erosion potential into cost-benefit analyses using heuristics for road management planning (e.g., Aruga et al. 2005, Madej et al. 2006, Rackley and Chung 2008). Of these projects, however, none has directly addressed BMP implementation and maintenance on an existing road network.

The research presented here fills this need with a decision support tool designed to assist managers in formulating watershed-scale road BMP installation and maintenance plans. The decision support tool-called BMP-SA uses simulated annealing (SA) as its heuristic solver to minimize sediment contribution to downstream water bodies by prioritizing road BMP installations while accounting for budget constraints, maintenance requirements, and equipment scheduling concerns.

2. Study area

The study area for this project is located in the Lake Tahoe Basin. Losing its famed clarity at a rate of approximately one-quarter meter per year for the past 25 years, the lake is currently designated as an impaired water body under Section 303(d) of the Clean Water Act (Roberts and Reuter 2007). Sediment from the basin road network has been identified as a negative contributor to the lake water clarity (Murphy and Knopp 2000).

The Glenbrook Creek watershed encompassed the majority of the study area (Fig. 1). Glenbrook Creek lies approximately 24 km west of Carson City, NV and 32 km north of South Lake Tahoe, CA on the east side of the Lake Tahoe Basin. Elevations in the Glenbrook Creek watershed range from approximately 1900 m to 2,700 m. Soils are volcanic and granitic in origin (Grismer and Hogan 2004). Average annual precipitation at the Marlette Lake SNOTEL weather station site, which lies at 2,400 m 5.6 km north of the Glenbrook watershed boundary, is approximately 84 cm. Most precipitation in the Glenbrook watershed falls as snow (Rowe et al. 2002). Monthly average maximum temperature at the Marlette Lake SNOTEL site between 1989 and 2008 was 11° C and monthly average minimum temperature was –1° C.

3. Materials and methods

3.1 Problem formulation

Simulated annealing, developed by Kirkpatrick and others (1983), uses a modified Monte Carlo simulation that is analogous to a metal cooling, or annealing, after leaving a forge. Initial temperature and cooling rate are variables which control the number of iterations and range of acceptable solution values. This optimization technique is well suited to this problem type for multiple reasons: 1) It can readily be scaled to large and

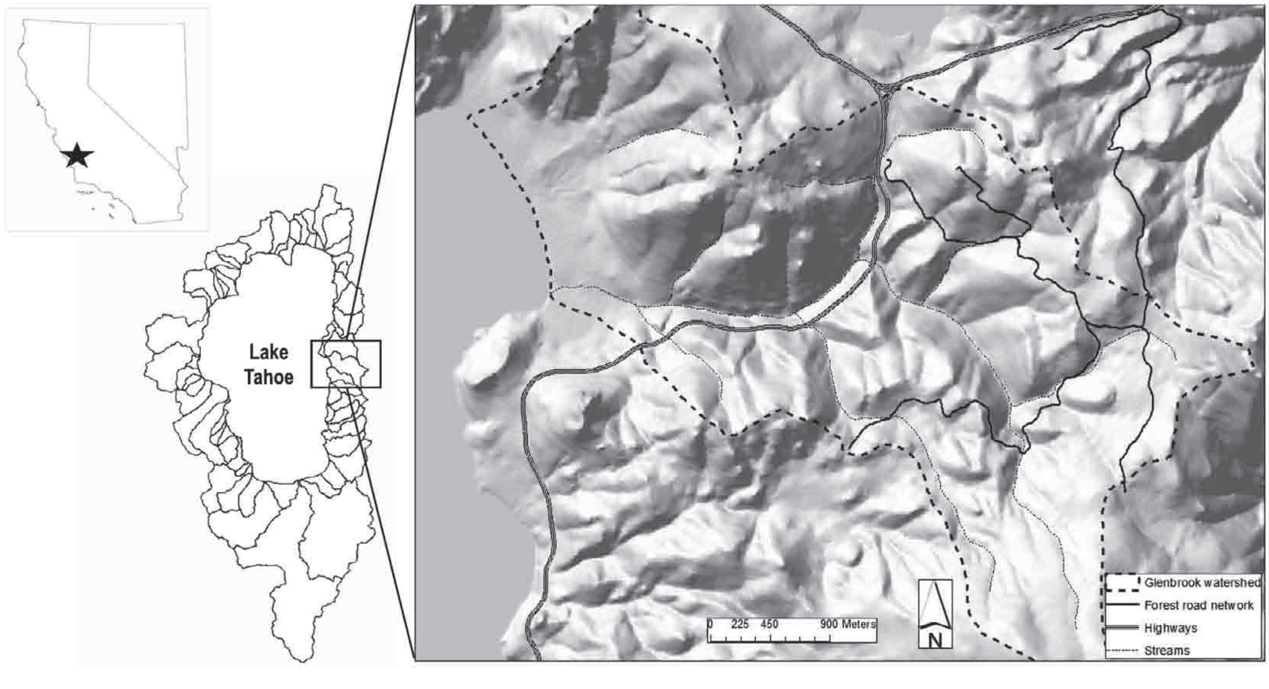

Fig. 1 Map of Glenbrook Creek watershed vicinity, Nevada USA

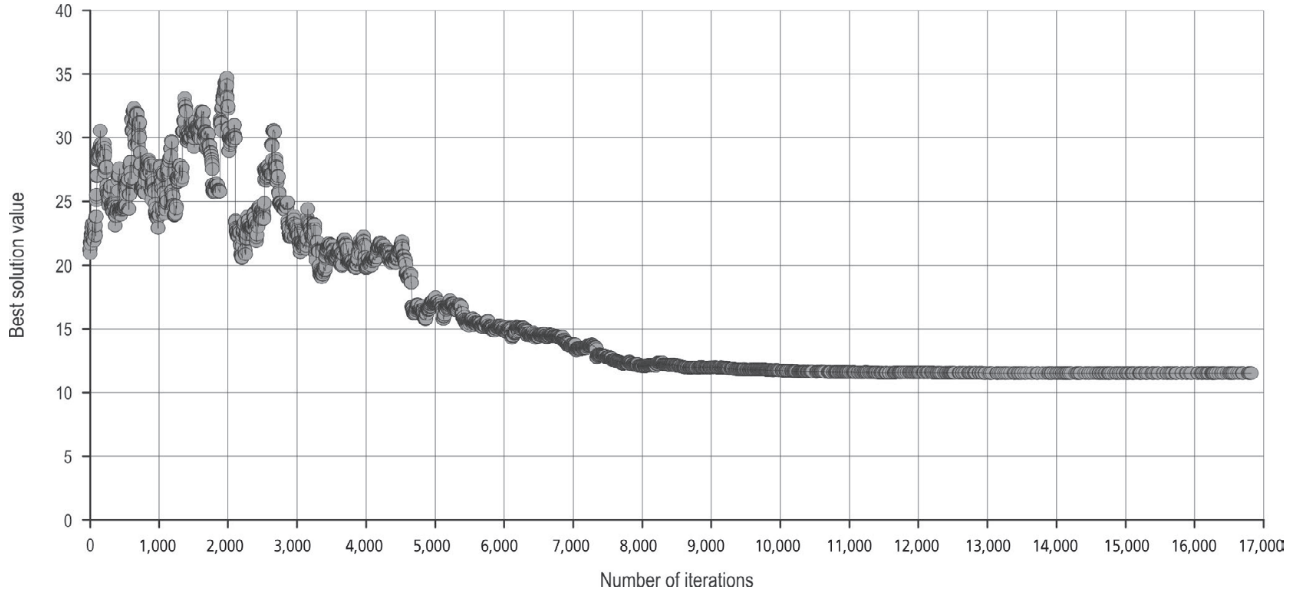

Fig. 2 Changes in objective function value of the current solution during the simulated annealing optimization process

small datasets; and 2) it is a relatively simple yet efficient heuristic solution technique for combinatorial optimization problems (Kirkpatric et al. 1983, Tarp and Helles 1997). During comparison of neighbourhood solutions, if the current solution is superior to the alternative, an acceptance probability is calculated in order to determine whether the alternative should be accepted despite its inferiority. This unique heuristic component is linked to the temperature variable:

$$p(new) = e^{\frac{|current-new|}{temp}} \qquad (1)$$

Where p(new) is the probability of accepting the new solution, current is the objective function value of the current solution, new is the objective function value of the new solution, and temp is the value of the temperature variable at the time of comparison. When compared against a randomly generated value, the solution may be accepted as the »new« current solution, from which a subsequent neighborhood solution will be formulated. In doing so, a near-optimal solution may be reached faster than if solutions were formulated randomly, since the »worse« solution may provide a bridge to a superior solution more quickly. As temperature decreases (more iterations are run), so too will the probability of acceptance of an inferior solution, thereby reducing solution variability (Fig. 2).

To apply this heuristic framework to the issue at hand, the planning problem can be formulated as a minimization problem with the amount of sediment entering streams as the objective function (Equations 2 and 3, Fig. 3). The formulation below assumes that sediment is discounted over time in order to promote early BMP installation and subsequent sediment reduction. A discount rate of four percent was used as it is standard practice in natural resource economic analysis involving U.S. Forest Service investments (Row et al. 1981).

Minimize

$$Z = \sum_{j=1}^{H} \sum_{i=1}^{N} \frac{sediment_{\mathrm{i,j}}}{1.04^{(\mathrm{j}-1)}} \qquad (2)$$

Subject to

$$\sum_{i=1}^{N} cost_{\mathrm{i,j}} \le budget_{\mathrm{j}} \qquad j \in H \qquad (3)$$

Where

Z	Total sediment leaving the buffer through the course of the planning horizon
j	Planning period
H	Total number of planning periods
i	Segment number
N	Total number of segments on the road network
$sediment_{\mathrm{i,j}}$	Sediment entering the nearest waterway from segment *i* during planning period *j*
$cost_{\mathrm{i,j}}$	Cost of BMP treatment or maintenance scheduled for segment *i* in planning period *j*.
$budget_{\mathrm{j}}$	Budget for planning period *j*
$1.04^{(\mathrm{j}-1)}$	Discount term

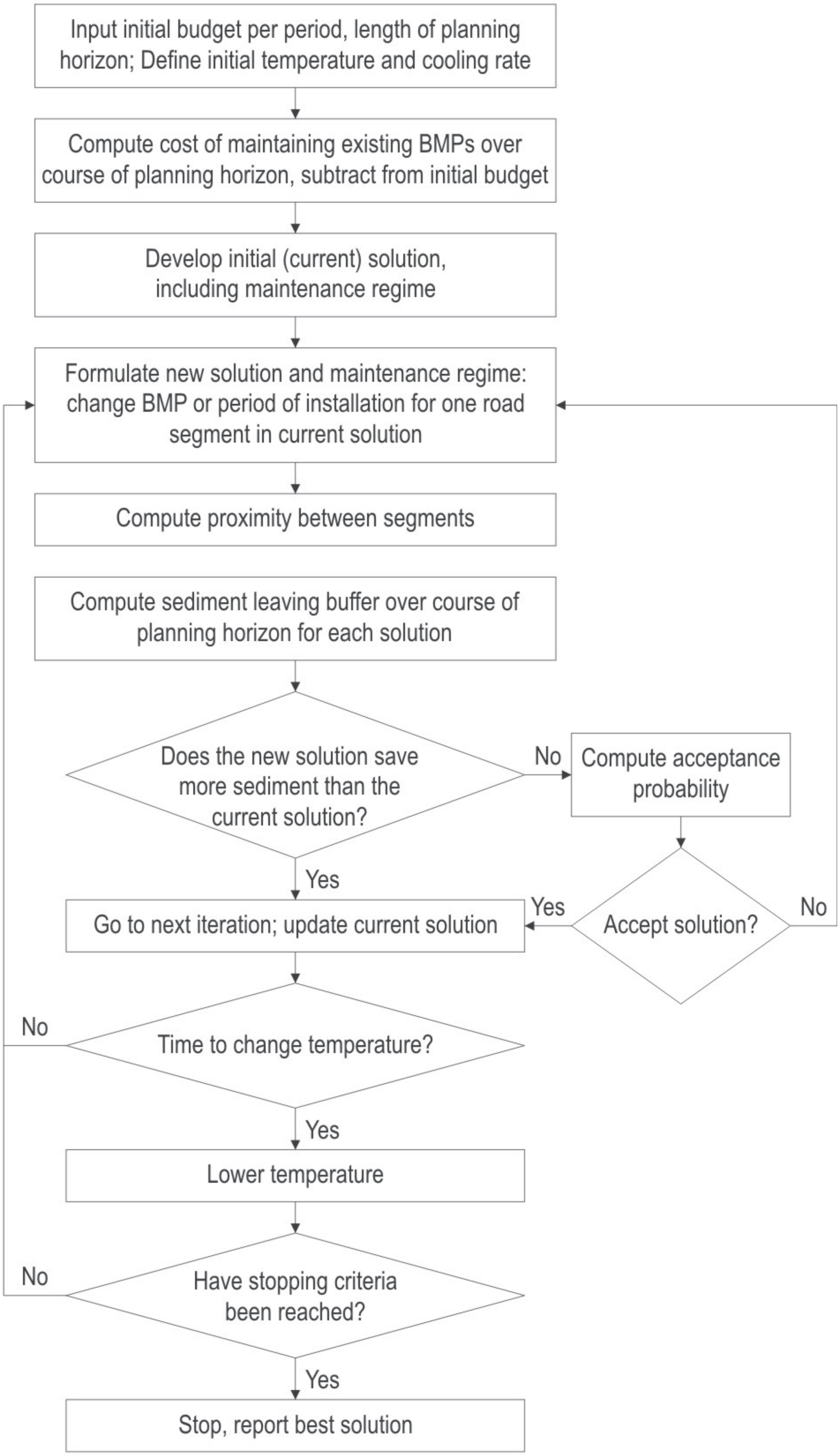

Fig. 3 Flowchart describing adapted simulated annealing optimization

Estimates of sediment entering the stream network from each road segment of interest must be established prior to execution of the heuristic. Currently, there are a suite of empirically-based and process-based erosion models being used for estimating road erosion, each with varying degrees of user accessibility (Fu et al. 2010). Among these, WEPP:Road has gained traction among US land management agencies including the Lake Tahoe Basin Management Unit (LTBMU) and continues to gain widespread use among academic and nonprofit organizations (e.g. Briebart et al. 2007, Contreras et al. 2008, Inlander et al. 2007). WEPP:Road, a user-friendly interface to the Water Erosion Prediction Project (WEPP) Model (Flanagan and Nearing 1995), provides a web browser-based interface that requires few input parameters.

Table 1 WEPP:Road input parameters and possible values or parameter ranges

WEPP:Road input parameter	Possible values/ allowable range
Climate	N/A
Soil type	Silt loam
	Sandy loam
	Clay loam
	Loam
Road design	Insloped, bare ditch
	Insloped, vegetated or rocked ditch
	Outsloped, unrutted
	Outsloped, rutted
Surface type	Native
	Graveled
	Paved
Traffic level	None
	Low
	High
Road width	1 ft – 300 ft
Road length	1 ft – 999 ft
Road gradient	3% – 99%
Fill slope length	1 ft – 999 ft
Fill slope gradient	3% – 99%
Buffer length	1 ft – 999 ft
Buffer gradient	3% – 99%
Coarse rock content	0% – 100%
Years of simulation time	1 yr – 200 yrs

In this study, we used WEPP:Road to assess potential erosion risk and threat of sedimentation from each road segment in a watershed as well as appropriate BMPs to address the erosion risk factor(s) for that segment. WEPP:Road estimates runoff and soil loss on three overland flow elements: the roadbed itself, a fill slope, and the 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, along with four road designs, three road surface types, and three traffic levels (Table 1). A variety of other parameters are also required by the model, some of which are best gathered in the field and some of which are best collected using a GIS or other data sources.

3.2 WEPP:Road data preparation

A total of 173 road segments were identified on 12.5 km of road. 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. WEPP:Road input parameters were determined or measured through a combination of field data collection and geoprocessing using datasets acquired from the Lake Tahoe GIS Data Clearinghouse (http://tahoe.usgs.gov/). »From« nodes comprised the entrance or beginning segment locations for runoff and sediment entrainment. »To« nodes were delivery points, or the perceived segment outlet for runoff and sediment. Analysis of coarse rock content and soil texturing were performed on soil adjacent to the road grade itself. As WEPP:Road only accepts one of four soil textures (Table 1), soil textures evaluated in the field were matched as closely as possible to one of those four textures available in the standard WEPP:Road interface.

The Tahoe CA SNOTEL site, the closest available long-term climate station was used as the climate input for WEPP:Road. While the model is running, WEPP:Road uses the CLIGEN weather generator to stochastically generate daily climate data for the desired simulation time (Elliot et al. 1999). Thirty years of daily climate data were generated for these simulations. Per WEPP:Road Documentation, thirty years of simulation is generally adequate for obtaining reasonable erosion estimates (Elliot et al. 1999). Road traffic level was held constant at »low« for all segments (Briebart et al. 2007).

Table 2 Priority of BMP assignment for a given road segment

Condition	Priority 1	Priority 2	Priority 3
Buffer slope > fill slope	Outslope*	Drain dips†	Pave‡
Road slope > 17%	Pave‡	Drain dips†	Outslope*

Notes: *Delivery point reassigned to center of road segment. Not applicable on paved or graveled segments. †Drain dips applicable on any segment greater than 46 meters (150 feet) in length. Segment length iteratively divided in half until segment length is less than 46 meters or sediment leaving buffer is zero. Not applicable on outsloped segments. ‡ If paving is already installed on a segment, no further BMPs can be installed

Table 3 Installation costs, maintenance costs, and maintenance frequencies associated with assigned BMPs

BMP	Installation cost	Equipment move-in costs	Maintenance cost	Equipment move-in costs for maintenance	Maintenance frequency
	$	$	$	$	yrs
Outsloping	1,865/km	1,000	622/km	500	3
Drain dips	100/each	500	100/each	500	5
Pavement	15,2269/km	1,500	9,323/km	500	7

Each road segment was modeled multiple times using WEPP:Road, first to simulate erosion under existing conditions then under the range of possible BMPs that were then incorporated into BMP-SA model inputs.

3.3 BMP-SA model input formulation

During a field visit with a Lake Tahoe Basin road engineer, site-specific BMP options were prescribed for those segments predicted to yield the most sediment. From this visit, along with personal communication with other engineers, guidelines were established for installing BMPs on those sites not visited in the field (Table 2) (Catherine Schoen and Paul Potts, pers. comm., USFS Lake Tahoe Basin Management Unit, July 2008). BMP installation costs, maintenance costs, and maintenance frequencies associated with a given BMP were also obtained through personal communication (Paul Potts, pers. comm., USFS Lake Tahoe Basin Management Unit, July 2008) along with the Region Four Cost Estimating Guide for Road Construction (Table 3; USDA FS 2009). For each potential BMP scenario on a given segment, WEPP:Road was used to predict the effectiveness of each potential BMP installation. Up to four BMP options were assigned to each segment, including no treatment.

To account for equipment scheduling costs (in doing so favoring solutions where BMPs are installed in close proximity in the same time period), a clustering subroutine was developed as a part of the model. For testing purposes, cluster diameter was fixed at 305 meters. If the same type of treatments were scheduled on road segments that are located within the cluster diameter, equipment move-in cost was counted only once for those treatments.

Planning horizon was assumed to be 20 years with a planning period of one year. Three budget expenditure scenarios for BMP implementation and maintenance were modeled: a given annual budget is used for 1) new BMP installation only, 2) new BMP installation and maintenance, and 3) existing BMP maintenance along with new BMP installation and maintenance. In all modeling scenarios, BMPs were assumed to be maintained in perpetuity at their assigned frequencies (Table 3). When included, existing BMPs were assumed to start their maintenance cycle in period one. Each scenario was modeled at multiple initial budgets to assess model behavior under different budget levels. At each level, it was assumed that the annual budget was constant throughout the planning horizon and unspent budget was not carried over into future years.

4. Results and Discussion

4.1 WEPP:Road results

Of the 173 segments analyzed in the study area, 74 of them (accounting for 6.7 km, or 53 percent, of roads in the study area) were predicted to produce sediment leaving the buffer over the 30-year modeling period.

Table 4 Predicted sediment leaving road and sediment leaving buffer in Mg yr^{-1} and Mg ha^{-1} yr^{-1} across the study area, Glenbrook Creek, NV. Average road width across each area of interest was used to calculate Mg ha^{-1} yr^{-1} values

Study area	Sediment leaving road		Sediment leaving buffer	
	Mg yr^{-1}	Mg ha^{-1} yr^{-1}	Mg yr^{-1}	Mg ha^{-1} yr^{-1}
Entire study area	49.9	13.6	2.7	0.7
Glenbrook watershed	19.0	7.0	1.4	0.5

Per-segment sediment outputs ranged from 0 Mg yr^{-1} to 0.6 Mg yr^{-1} with a mean of less than 0.1 Mg yr^{-1}. WEPP:Road predicted a total of 49.9 Mg yr^{-1} of sediment leaving the road and 2.7 Mg yr^{-1} sediment leaving the buffer from the study area (Table 4).

The well-maintained existing BMP infrastructure on Glenbrook Creek forest roads, as well as the watershed dry climate, partially explains the minimal amount of sediment predicted to be leaving the buffer.

Predicted average erosion rate from native surface roads in sandy loam soils - the predominant soil texture found within the Glenbrook Creek watershed - was 8.1 Mg ha^{-1} yr^{-1}. In comparison to regional empirical values, on the west slope of the Sierra Nevada range Coe (2006) observed an erosion rate of 8.1 Mg ha^{-1} yr^{-1} on native surface roads during one wet season (October through June) of data collection. Annual precipitation during this wet season was near the long-term average of 1,300 mm. Coe's study segments were in primarily loam soils. Average road gradients, segment lengths, and parent materials were comparable for both studies.

4.2 Alternative BMP assignment

Of the 74 road segments producing greater than zero sediment leaving the buffer per year, 38 were assigned treatments. Thirty-six 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.

The effectiveness of BMPs, defined in this study as predicted reduction in sediment delivery, varied depending on the characteristics of the road segment to which a BMP was assigned. Drain dips showed an exponential increase in effectiveness as segments were divided into two (one drain dip), four (three drain dips), and eight (seven drain dips), respectively (Table 5). Outsloping was modeled as being three times more effective at reducing sediment than one drain dip, but an order of magnitude less effective than three drain dips and two orders of magnitude less effective than seven drain dips. 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 potentially due to increased runoff exacerbating ditch and buffer erosion (Table 5). Other researchers have had similar results when applying WEPP:Road to paved road segments in the Lake Tahoe Basin (Briebart et al. 2007).

4.3 New BMP installation only

In this modeling scenario, it was assumed that the annual budget can be used for new BMP installation only. The results show that sediment leaving the buffer produced a negative exponential trend with increasing annual budget (Fig. 4). The minimum sediment delivery solution was achieved when the annual budget reached $20,000. In this solution, all 38 segments had BMPs applied to them in period one (Fig. 5). Discounted sediment was reduced from 37.8 Mg when no treatment was applied over the 20 year planning horizon to 10.4 Mg. Increasing budget beyond this level yielded no reduction in sediment leaving the buffer.

Proportion of segments with outsloping, chosen as an appropriate BMP, also increased with the budget. In several instances, solutions with two different budgets yielded decreases in sediment leaving the buffer while having the same number or fewer BMPs installed in period one. In all of these instances, the 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 single drain dips (Luce and Black 2001, Elliot et al. 2009, USDA FS 2009). In addition, there are limitations for where and when outsloping may be an applicable BMP. Fig. 6 shows the number of segments where BMPs were installed in each period for all three mod-

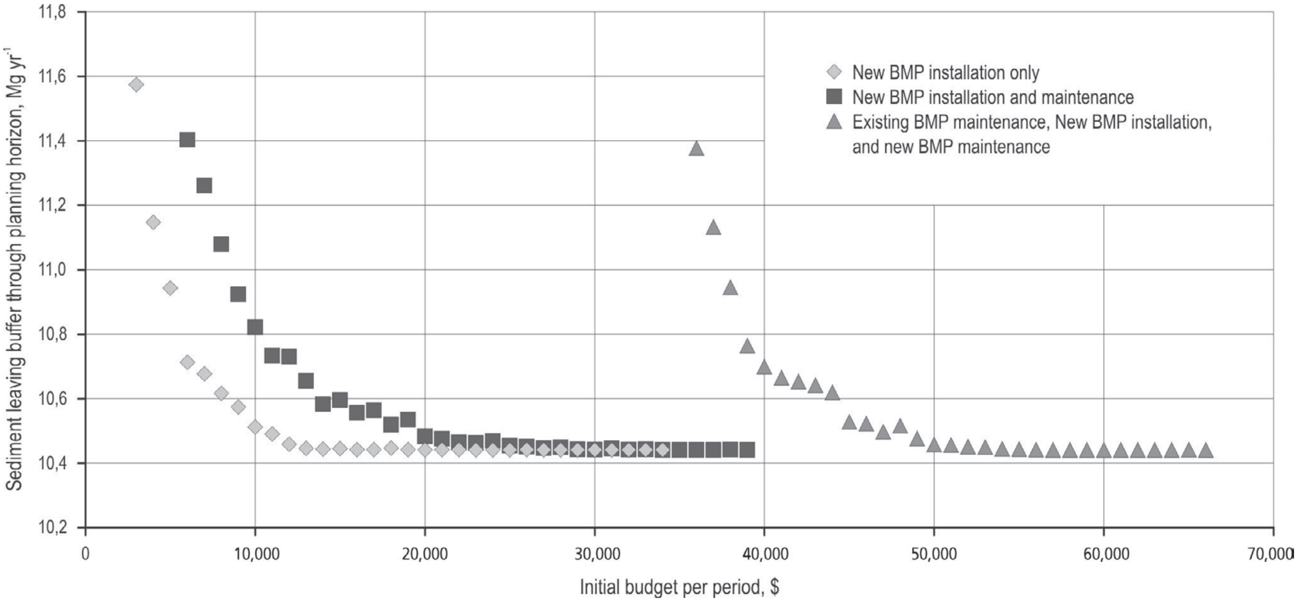

Fig. 4 Sediment leaving buffer through the 20 year planning horizon at various budgets under three modeling scenarios

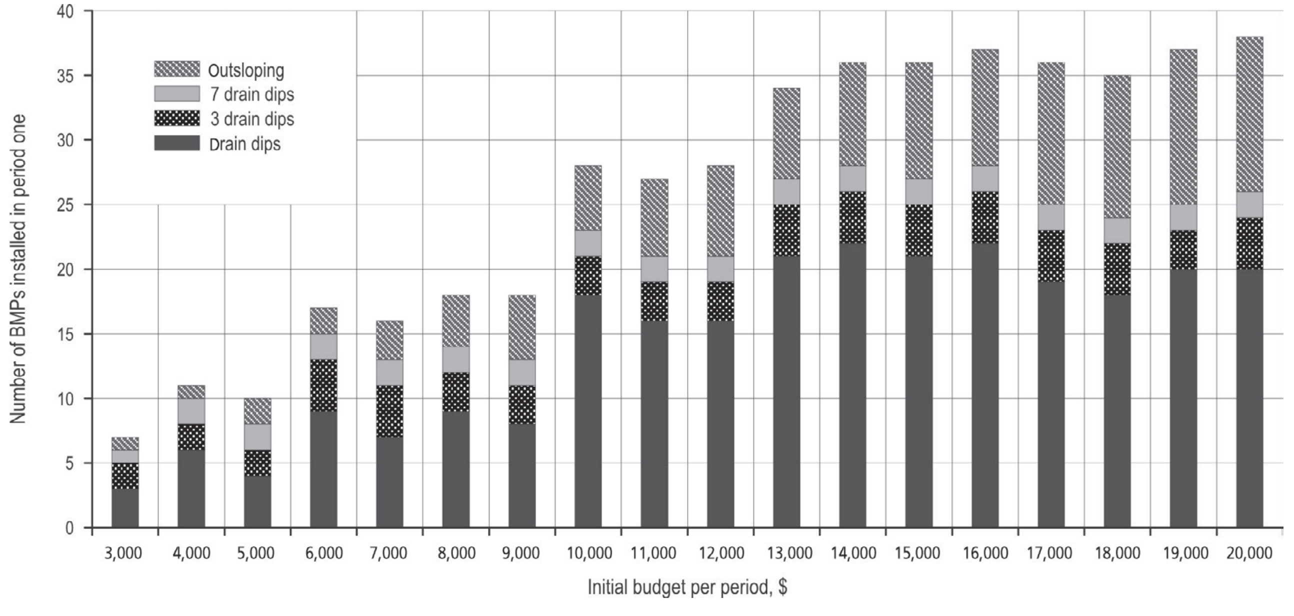

Fig. 5 Number and type of BMP installed in period one at varying initial budget per period resulting from the new BMP installation only scenario

eling scenarios. At $3,000, all BMPs were installed in the first seven periods under the new BMP installation only scenario.

4.4 New BMP installation and maintenance

With maintenance costs incorporated into the model, a greater initial budget was required to achieve the same reduction in sediment as that found under the new BMP installation only scenario. At a budget level of $6,000, the model failed to produce feasible solutions because no possible combination of BMPs existed below this budget threshold.

Minimum sediment leaving the buffer through the course of the planning horizon was 10.4 Mg, the same solution as that found in the previously modeled scenario. At $6,000 annual budget, two segments had no

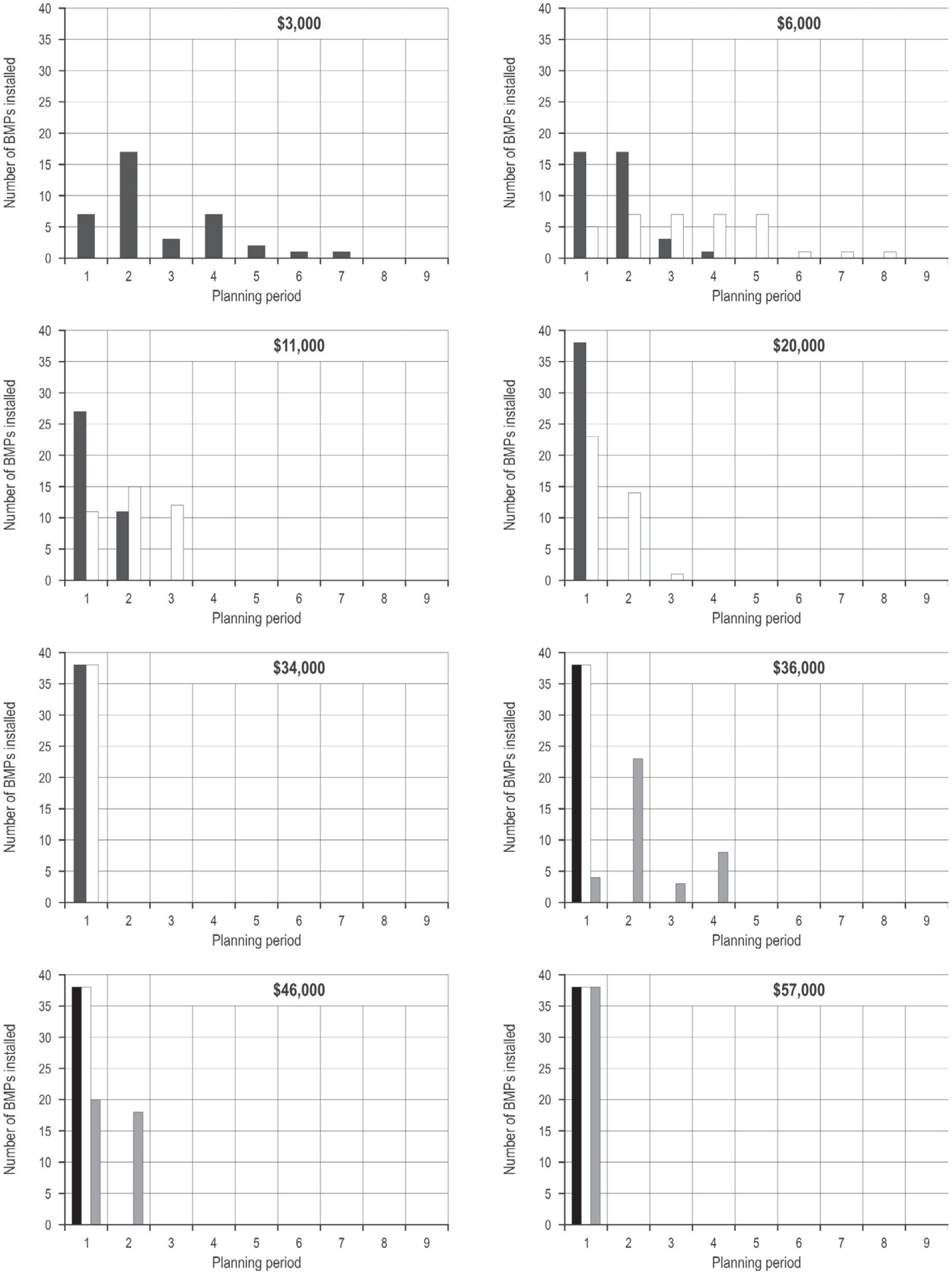

Fig. 6 With varying initial budget, number of periods required by BMP-SA to install all new BMPs. Black bars represent the new BMP installation only scenario, white bars represent the new BMP installation and maintenance scenario, and gray bars represent the existing BMP maintenance, new BMP installation, and new BMP maintenance scenario

Table 5 Predicted effectiveness of BMPs (in terms of sediment savings) assigned to problematic road segments. Average road width across all segments with the same BMP assignment was used to calculate erosion rates

BMP	Number assigned	Minimum effectiveness	Maximum effectiveness	Mean effectiveness
		Mg ha^{-1} yr^{-1}	Mg ha^{-1} yr^{-1}	Mg ha^{-1} yr^{-1}
One drain dip	33	0.00	0.11	0.02
Three drain dips	7	0.02	1.51	0.53
Seven drain dips	3	0.77	2.56	1.65
Outslope segment	20	0.00	0.59	0.06
Pave segment	5	-1.37	-0.01	-0.52

treatment chosen as the best possible option. This result indicates that the budget was so limited that neither BMP installation nor maintenance was feasible for these two segments. The number and types of BMPs installed in period one at varying budgets for the new BMP installation and maintenance scenario was very similar to that seen with the new BMP installation only scenario.

4.5 Existing BMP maintenance and new BMP installation and maintenance

The lowest sediment delivery solution was achieved with a higher annual budget than the previous two modeled scenarios (Fig. 4). Maintenance of existing BMPs required approximately $35,000 minimum annual budget. Period 13 required the greatest annual budget as a result of numerous preexisting BMPs having maintenance frequencies of two, three, or four years. As a result, any new BMPs with a three-year maintenance frequency (such as outsloping) could not be installed in period one until the budget was increased beyond this minimum level.

A budget of $57,000 was necessary for all BMPs to be installed in period one. As a result of accounting for maintenance costs, the solution became more constrained, making this BMP installation scenario less variable than the previous scenario. In general, the number of periods required to install BMPs on all segments decreased with the increase in the budget (Fig. 6).

4.6 Discussion of BMP-SA modeling results

Optimized solutions by BMP-SA for different budgets show that the model was able to produce cost-efficient BMP locations, types and implementation periods in reducing sediment delivery under limited budgets. High cost efficiency of BMPs was realized at low budget levels, but increases in the budget yielded diminishing returns in sediment reduction (Fig. 4).

When solutions are constrained (as in these types of scenarios), BMP-SA has the potential to provide the most benefit. A BMP may be chosen that is not necessarily the best for a given location due to the budget constraint but serves to maximize sediment savings across the area of interest. This highlights the importance of the clustering subroutine in BMP-SA. While a sensitivity analysis of cluster size is beyond the scope of this study, it provides one future avenue of research using this tool.

Discount rate plays a role in dictating the budget at which BMPs can be most cost-effectively implemented (indicated by an inflection point in budget-sediment reduction plots for the three model scenarios in Fig. 4). If discount rate were increased, an inflection point would also be reached more quickly but would require a greater initial budget. Conversely, a lower discount rate would result in a less rapid reduction in sediment leaving the buffer.

The maximum possible sediment reduction was achieved with all three modeling scenarios, albeit at higher budget levels when maintenance of new and existing BMPs was accounted for within the given budget. Under the best possible solution, sediment leaving the buffer was reduced by 72% if compared to buffer sediment outputs should no treatments be installed through the course of the planning horizon. With respect to the 38 treated segments, sediment was reduced by nearly 93% if compared to buffer sediment outputs with no treatment. Estimated sediment savings with new BMP installation was considerable, in part because little sediment was predicted to leave the buffer from the Glenbrook Creek watershed. If predicted sediment leaving the 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 be more potential for a tool like BMP-SA that can assist field managers in prescribing effective BMPs to minimize sediment leaving the buffer, especially when the budget is constrained.

5. Conclusions

This research developed a decision support tool designed to increase the efficiency of BMP planning on a forest road network. Modeled 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 estimates as well as guidelines for prioritizing appropriate BMPs for a given road segment. To minimize sediment leaving the buffer, these data were input into a model using an adapted simulated annealing optimization algorithm. Under limited budgets, the model was able to prioritize BMP placements and types through a tradeoff analysis between costs and effectiveness of BMPs.

While the data used here is from the Lake Tahoe Basin, BMP-SA can be applied to any watershed. The model is also applicable at a scale greater than a single watershed and can be easily modified to accommodate non-linear spatial constraints, such as scheduling of equipment and BMP maintenance, though problem complexity may substantially increase if more BMP locations and options exist.

There are two critical assumptions implicit in BMP-SA. 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. BMP implementation is often site-specific in nature. For that reason, some road segments 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.

Acknowledgements

We would like to thank Bill Elliot, Randy Foltz, and Jun Rhee at the Rocky Mountain Research Station in Moscow, ID, for their cooperation and insight through the course of this collaboration. Paul Potts, Catherine Schoen, and Jim Harris of the USFS Lake Tahoe Basin Management Unit also have our thanks for their time on the phone, in meetings, and in person through the duration of this project. This study was funded by the Tahoe Science Program and administered by the USDA Forest Service Pacific Southwest Research Station in cooperation with the Rocky Mountain Research Station (Project No. P010) along with significant cost match and in-kind contribution from The University of Montana.

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Received: March 4, 2014
Accepted: July 11, 2014

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