A Methodology for Implementing Best Management Practices using WEPP:Road Erosion Modeling and a Simulated Annealing Algorithm

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Abstract

Forest road erosion causes problems for downstream water bodies, with these problems being readily evident in the Lake Tahoe Basin. 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 and issues. We present a methodology for addressing this challenge through combining WEPP: Road erosion modeling and Simulated Annealing Optimization. Field surveys provided inputs for WEPP: Road and subsequent identification of erosion risk potential. Appropriate BMPs were identified for segments posing an erosion risk. These BMPs, along with their associated costs and maintenance frequencies, were input into a Simulated Annealing algorithm. 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 spatial adjacency were accounted for within the algorithm framework. In the solution presented here, of the 37 segments where applicable BMPs could be installed, 30 were installed in period zero. Sediment leaving the buffer over the course of the planning horizon was reduced by 40%. We note that this methodology can be applied to any watershed, but relies heavily on the perceived accuracy of WEPP: Road.

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, or the world, for that matter, are as aware of the consequences of downstream impacts from upstream management actions as the Lake Tahoe Basin (LTB). 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- thereby entering a stream- 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 stem 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, we present a solution to this problem through combining WEPP: Road-derived erosion data with a Simulated Annealing algorithm to spatially optimize BMP placement across the road network. In doing so, we have produced a methodology for minimizing 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.

Study Site:

Lake Tahoe, on the California-Nevada border, is nestled between the Sierra Nevada Range to the west and the Carson Range to the east. The Lake Tahoe Basin receives hundreds of inches of annual snowfall but receives little precipitation during the summer months. Because weather tends to track west to east across the basin, the east side of the basin is much drier.

The Glenbrook Creek Watershed encompassed the majority of the study area (Figure 1). Glenbrook Creek, on the east side of the LTB, 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 (1899 m) to 8800 feet (2686 m) at its furthest upslope extent. Soils are both volcanic and granitic in origin (Grismer and Hogan 2004).

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 also 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 only is used for administrative access.
Figure 1. Map of study area.

Data acquisition and processing

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 LTB), 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.

Data acquisition/processing using GIS:

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.

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. 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. Following suit with a 2006 application of WEPP: Road in the basin by the LTBMU (Briebart et al. 2006), road traffic level was held constant at “low” for all 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 sediment, delivery points for these segments were designated at the middle of the segment. Buffer length and slope for each segment were then calculated from these delivery points to the nearest point on streams. 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 1 foot were used.

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 (J. Rhee 2008 personal communication). Climate was derived using the PRISM climate generator in WEPP: Road Batch. “TAHOE CA” was chosen for the climate, being the closest available climate base station and was modified using coordinates from a central location in the watershed.

“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 (entering LTB streams). Natural breaks in a
histogram were used to determine “hot spots”, or those segments that were contributing disparate 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 2008, personal communication). The breakdown is shown in Table 1.

We conducted field verification of the high risk road segments within the Glenbrook Watershed in September 2008. A LTBMU roads engineer accompanied us during the field verification. During this process, we assessed the legitimacy of the hot spot by identifying the overriding characteristic causing the segment to be high risk. These 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 1. Classification of road segments with greater than 0 T/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 for class (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>134</td>
<td>1292</td>
<td>0.94</td>
<td>12</td>
</tr>
<tr>
<td>Moderate risk</td>
<td>30</td>
<td>12</td>
<td>134</td>
<td>1.45</td>
<td>19</td>
</tr>
<tr>
<td>Low risk</td>
<td>35</td>
<td>0</td>
<td>11</td>
<td>1.58</td>
<td>21</td>
</tr>
</tbody>
</table>

Selection of applicable BMPs for problem road segments:

Due to time constraints, we were unable visit every road segment on the network generating sediment; accordingly, we couldn’t identify the most appropriate BMP for each segment in the field. We were, however, able to identify patterns in treatment of problem BMPs. From these patterns, we constructed a simple hierarchy of appropriate BMPs used to treat problem road segments in the Glenbrook watershed (Table 2). WEPP: Road outputs confirmed the benefits of applying a given BMP on a road segment and the applicability of our decision hierarchy in the Glenbrook watershed.

Using those site-specific BMP options identified in the field and expanding on them, all segments within the Glenbrook Watershed producing greater than 0 T/yr sediment leaving buffer were assigned potential BMPs.
Table 2. Hierarchy used to assign BMPs to problem road segments.

<table>
<thead>
<tr>
<th>Problem</th>
<th>BMP</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffer slope &gt; fill slope</td>
<td>Outslope</td>
<td></td>
</tr>
<tr>
<td>Road slope &gt; 17%</td>
<td>Pave</td>
<td></td>
</tr>
<tr>
<td>Road length &gt; 300 feet</td>
<td>Drain dip</td>
<td>Segment length reduced by one third</td>
</tr>
</tbody>
</table>

Simulated Annealing algorithm problem formulation:

Those designated BMPs became one of several inputs into a Simulated Annealing algorithm. This algorithm, originally developed by Metropolis et al. (1953), uses a modified Monte Carlo simulation that loosely resembles metal cooling after leaving a forge. A flowchart explaining the adaptation of Simulated Annealing algorithm framework to this planning problem is in Figure 2.

An initial budget per period was specified, as was the length of the planning horizon (in this case, 20 years), the number of total segments, and the number of segments on which BMPs can be installed. The algorithm first calculated the cost of maintaining pre-existing BMPs over the course of a planning horizon. This cost per period of existing BMP maintenance was subtracted from the initial budget for each period. Costs of new BMP installation, maintenance and associated frequencies presented in Table 3 were compiled through a combination of personal communication with Lake Tahoe Basin Management Unit personnel and the Region 4 Cost Estimating Guide for Road Construction (USDA 2008).

Table 3. BMPs applied to forest road network for Glenbrook Creek watershed using Simulated Annealing algorithm.

<table>
<thead>
<tr>
<th>Category/treatment</th>
<th>Low-end cost($)</th>
<th>High-end cost($)</th>
<th>Necessary equipment</th>
<th>Maintenance cost</th>
<th>Frequency (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drain dips</td>
<td>95/each</td>
<td>130/each</td>
<td>Cat D7</td>
<td>150/each</td>
<td>5</td>
</tr>
<tr>
<td>Outsloping</td>
<td>820/mile</td>
<td>1220/mile</td>
<td>Cat D7</td>
<td>same as</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>installation</td>
<td></td>
</tr>
<tr>
<td>Asphalt paving</td>
<td>200000/mile</td>
<td>290000/mile</td>
<td>contracted</td>
<td>15000/mile</td>
<td>7</td>
</tr>
<tr>
<td>Graded aggregate</td>
<td>150000/mile</td>
<td>220000/mile</td>
<td>contracted</td>
<td>4400/mile</td>
<td>3</td>
</tr>
<tr>
<td>base</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*in Lake Tahoe Basin, aggregate base is always used under paved segments.
*Asphalt paving costs are for a project less than 1 mile that does not include aggregate base.
Figure 2. Flowchart describing adapted Simulated Annealing algorithm.

1. **Input initial budget per period, length of planning horizon**
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**
5. **Compute proximity between segments; discount solution cost if treatments are < 1000 feet apart**
6. **Compute sediment leaving buffer over course of planning horizon for each solution**
7. **Does the current solution save more sediment than the new solution?**
   - Yes: Go to next iteration; update current solution
   - No: Compute acceptance probability; “degree of worseness”
8. **Accept solution?**
   - Yes: Go to next iteration; update current solution
   - No: **Time to change temperature?**
9. **Lower temperature**
10. **Have stopping criteria been reached?**
    - Yes: Stop, report best solution
    - No: **Stop, report best solution**
The algorithm generated a scenario where, starting with planning period zero, one BMP option (including “no treatment”) was installed on an individual road segment and maintained through the course of the planning horizon. Individual BMP treatments were installed on individual road segments until the budget for period zero was exceeded or until every segment had one BMP installed on it. As another component of this initial solution formulation, any BMP treatments installed less than 1000 feet from one another in the same period were discounted by 10% to reflect savings on equipment move-in costs. From this initial solution, a new solution was formulated such that either the BMP installed on a given road segment was changed or the period in which the BMP was installed was randomly changed. The maintenance regimen for the new solution was then formulated and the solution was checked for feasibility. BMPs installed in close proximity (less than 1000 feet) were discounted, just as with the initial solution.

The algorithm next calculated sediment leaving the road buffer (entering a stream) for the initial and new solutions using the following formula:

\[
Total\ sediment = \sum_{i=1}^{n} [H \times Sed_i + (H - q) \times Sed\_Saved_i]
\]

Where \( n \) is the total number of segments in the study area, \( Sed_i \) is annual sediment leaving the road buffer produced by road segment \( i \) without a new BMP, \( Sed\_Saved_i \) is the difference between annual sediment leaving the buffer from a single road segment with and without the applied BMP treatment, \( H \) is the length of the planning horizon (\( H = 20 \) years in this study), \( q \) equals the time period (year) in which a BMP is installed on a given road segment. When no new BMP is selected for a segment, the \( Sed\_Saved \) term becomes zero.

This total amount of sediment leaving the road buffer was compared for the two solutions. If the new solution produced less sediment over the course of the planning horizon, it replaced the existing solution and a new solution was formulated according to those criteria outlined above. If the new solution was worse than the existing solution, an acceptance probability \( p(\text{new}) \) was calculated and compared to a random number to decide solution acceptance:

\[
p(\text{new}) = e^{\frac{\text{new-current}}{\text{temp}}}
\]

The algorithm repeated the solution procedures described above until the stopping criterion (final temperature) was met. For this modeling exercise, initial temperature was set at 10 degrees and final temperature was set at .0005 degrees with a cooling rate of 1%. Number of iterations performed at a given temperature level was 15, making for a total of approximately 18,000 iterations before reaching the final temperature. Initial budget per period was 30,000 dollars.

**Results and Discussion:**

*WEPP: Road Analysis:*

Of the 173 segments analyzed in the study area, 99 of them (accounting for 3.6 miles of the study area) produced zero erosion over the 30-year modeling period. WEPP: Road found a total of 54.96 tons per year of sediment leaving the road and 2.95 tons of sediment leaving the buffer -
theoretically entering a waterway—per year (Table 4). Rates of erosion were lower within Glenbrook than across the entire study area.

Overall, our WEPP: Road Batch results fall within the range of empirical results found in other studies. Megahan and Kidd (1972) measured .09 ton/yr of background erosion in granitics of the Idaho Batholith, which are less erodible than the volcanic substrates frequently found in the Lake Tahoe Basin (Grismer and Hogan, 2004). In terms of erosion rates from forest roads, active logging operations can produce 15 ton/ha/yr, including erosion from the associated roads (Brooks et al. 2003). In a 2003 study, Simon and others found 8.90 tons/yr of fine sediment leaving Glenbrook Creek. Evaluated against WEPP: Road outputs, forest roads in this watershed are responsible for approximately 17% of all sediment in Glenbrook Creek.

Table 4. Sediment leaving road and sediment leaving buffer in t/yr and t/ha/yr. Average road width across the entire study area was used to calculate t/ha/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/ha/yr</td>
</tr>
<tr>
<td>Entire Study Area</td>
<td>54.96</td>
<td>14.99</td>
</tr>
<tr>
<td>Glenbrook Watershed</td>
<td>22.66</td>
<td>8.40</td>
</tr>
</tbody>
</table>

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

Simulated Annealing Algorithm results:

Of the 37 segments where BMPs were assigned, 30 were installed in period zero (Figure 3). Since sediment leaving the road network over the course of the planning horizon would be minimized if every possible BMP was installed in period zero, these results are appropriate. Six segments had no BMPs assigned because of budget limitations in later planning periods. 35 preexisting BMPs had to be maintained in period 12, making this period the most limiting in terms of available initial budget (Figure 4). Pavement was never chosen as an applicable BMP because of its high implementation cost as well as the fact that pavement, in several cases, increased sediment leaving the road buffer.

As the result of new BMP installation, sediment was reduced from the maximum possible output of 59.0 tons over the course of the planning horizon (should no new BMPs be installed) to 35.5 tons, creating a 40% reduction in sediment.
Figure 3. Simulated Annealing result for BMP installation in Glenbrook Creek. No new BMPs were installed later than the second year.

Figure 4. Number of BMPs maintained in each planning period over the course of the planning horizon.

Conclusion:

We have presented a method for increasing efficiency of BMP implementation on a forest road network. Road-related sediment leaving the forest buffer is minimized over the course of a planning horizon while accounting for budget constraints as well as spatial adjacency considerations. The solution presented here used modeled road erosion data from a high-density
road survey as well as a hierarchy for establishing which BMPs are appropriate for a given road segment. While the data used here is from the Lake Tahoe Basin, this methodology can be applied to any watershed.

A critical assumption of this modeling exercise is that BMPs must be maintained at appropriate intervals in perpetuity, otherwise money spent installing BMPs is not worthwhile. Currently, this algorithm does not account for adjacent BMPs with identical maintenance frequencies. A logical continuation of this research would be to incorporate this important planning consideration into the optimization process, such as through cost discounting of nearby BMPs with identical maintenance frequencies.

Also of note is the fact that this modeling process relies on the accuracy of WEPP: Road to determine problematic road segments. Validation of WEPP: Road through any means beyond our on-the-ground verification was out of the scope of this project. While on-the-ground verification is not unwarranted, we have left that task to other researchers.

References:


Rhee, J., Rocky Mountain Research Station- Moscow Forest Sciences Laboratory research engineer. Email communication, September 3, 2008.


