Decision Support for Road Decommissioning and Restoration by Using Genetic Algorithms and Dynamic Programming[1]

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Abstract

Sediment contributions from unpaved forest roads have contributed to the degradation of anadromous fisheries streams in the Pacific Northwest. Efforts to reduce this degradation have included road decommissioning and road upgrading. These expensive activities have usually been implemented on a site specific basis without considering the sediment contributions from all roads within a watershed.

This paper describes results from optimization models developed for determining road removal management plans within a watershed. These models consider the tradeoffs between the cost and effectiveness of different treatment strategies to determine a treatment policy that minimizes the predicted sediment erosion from all forest roads within a watershed, while meeting a specified budget constraint.

Two optimization models are developed using dynamic programming and genetic algorithms. Each model accepts road survey data from the Redwood National Park's (RNSP) GIS layers for a watershed with approximately 700 road segments and stream crossings. The models also require treatment effectiveness data, which are derived from previous published studies for the same area. The output from the model is the treatment level for each road segment and crossing and the total cost of the road removal management plan. The output is then exported to the GIS.

The models currently consider only road removal, but could be expanded to include additional road modifications or watershed restoration projects. Our approach is portable to other watersheds.

Key words: optimal watershed management, road removal, sediment

Introduction

Abandoned and unmaintained logging roads are common across the steep, forested landscapes of western North America and present concerns as a major sediment source (Best and others 1995, Janda and others 1975, Megahan and Kidd 1972). Few studies have evaluated long-term and watershed-scale changes to sediment yields as the roads are abandoned, removed or restored. Madej (2001) reported on the post-treatment erosion in Redwood National Park after a 12-year

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recurrence-interval storm, and provides a measure of the effectiveness of different road and crossing treatment methods.

Figure 1 summarizes the road treatments evaluated in Madej (2001) that are used in this study. Road segments and stream crossings receive different types of treatments. For road segments (lengths of road between stream crossings) four road treatment alternatives (including no treatment) were assessed which varied in the amount of earth-moving involved *(fig. 1a–d)*. The least intensive treatment decompacts the road surface and constructs drains perpendicular to the road alignment to dewater the inboard ditch—a technique referred to as 'ripped and drained' *(fig. 1b)*. This treatment moves 200 to 500 m^3 of road fill for every kilometer of road treated. More intensive treatment methods include partially outsloping the road surface by excavating fill from the outboard edge of the road and placing the material in the inboard ditch at the base of the cutbank *(fig. 1c)*. This technique requires more earth-moving (1000 to 2000 m^3/km of treated road). Complete recontouring of the road bench is called "total outslope" *(fig. 1d)*. The cutbank is covered by excavated fill, and the original topsoil from the outboard edge of the road is replaced on the road bench where possible. Total outsloping involves moving an average of 6000 m^3/km of treated road.

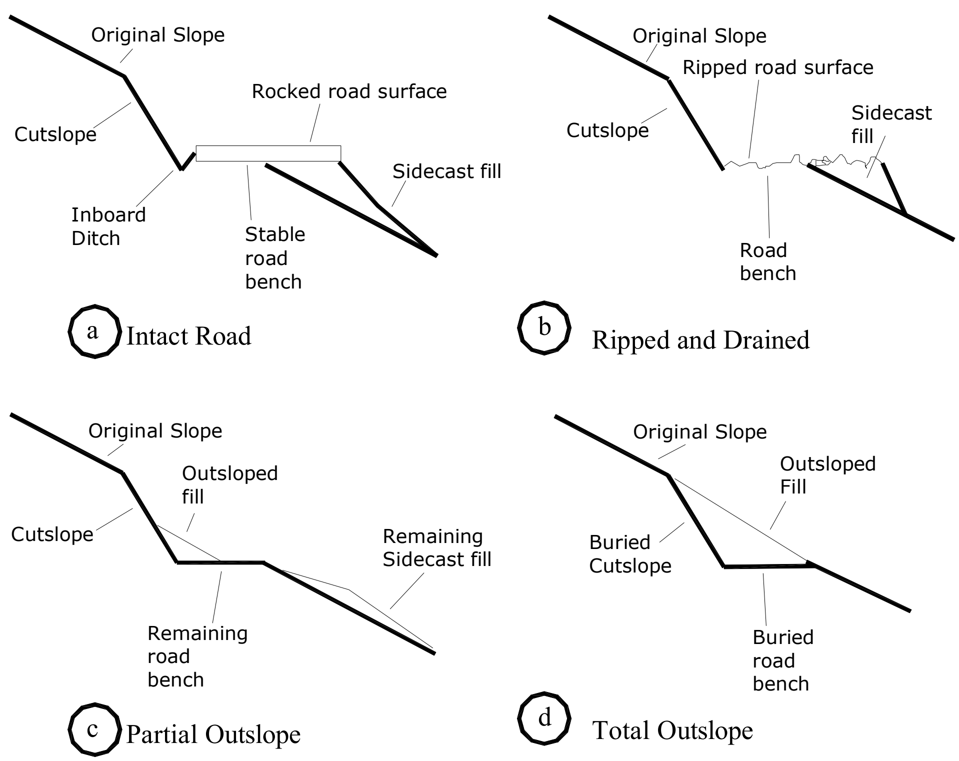

Figure 1—Road treatment methods described in Madej (2001).

Stream crossings are treated by excavating road fill overlying a culvert, removing the culvert and grading a new channel form. "Basic excavation" removes the culvert and establishes a channel in the previous culvert location. "Total excavation" removes more road fill, creates a channel at the elevation of the original stream channel, and excavates sediment deposited upstream of the crossing, if present.

Up to now, few watershed level policies for managing sediment contributions from logging roads have been developed as there has been a lack of information about the effectiveness of different road and crossing treatment methods. Given the effectiveness measures provided by Madej (2001), optimization methods can be implemented to consider trade-offs between cost and sediment savings over an entire watershed. One of the few uses of applied optimization to develop road removal policy was by Tomberlin and others (2002). They report using Stochastic Dynamic Programming to determine if a road in the Casper Creek watershed should be left alone, upgraded or removed based on its erosion potential.

This paper describes the development of two optimization models that are used to determine the level of treatment for removing roads within a watershed, using a strategy that maximizes the sediment saved from critical habitat, while maintaining a specified budget. These two models consider tradeoffs in effectiveness and cost across a watershed.

Methods

Dynamic programming and genetic algorithms are used to determine the best combination of road removal strategies that minimize sediment erosion to a stream (or maximize the sediment saved from entering a stream channel). The problem is formulated with the objective: *Maximize the sediment saved from entering a stream channel as a function of road and crossing treatment levels*. The optimization problem is constrained by the budget and by the existing treatment methods. The problems is stated mathematically as follows

$$\max_{\forall x_r, x_c} z = \{\sum_{\forall r} W_r L_r S_r(x_r) + \sum_{\forall c} W_c V_c S_c(x_c)\} \quad \textit{Equation} \quad 1$$

subject to

$$TC = \sum_{\forall r} L_r C_r(x_r) + \sum_{\forall c} V_c C_c(x_c) \leq B \quad \textit{Equation} \quad 2$$

$$x_r = 0,1,2,3 \quad x_c = 01,2 \quad \textit{Equation} \quad 3$$

Where

S_r = sediment saved / mile on road segment r

S_c = sediment saved / cubic yard on crossing c

x_r = treatment level for road r

x_c = treatment level for crossing c

L_r = length of road segment r in miles

V_c = volume of crossing c in cubic yards

W_r = critical habitat weighting factor for road *r*

W_c = critical habitat weighting factor for crossing *c*

TC = total cost of all road and crossing treatments in $

C_r = cost in dollars / mile to treat road segment *r*

C_c = cost in dollars / cubic yard to treat crossing *c*

B = budget in dollars

x_r = 4 road treatment methods *(fig. 1)*

x_c = 3 road crossing treatment methods *(table 3)*

The formulation above allows for the weighting of sediment depending on its location or importance to habitat within the watershed via the weighting factors for roads and crossings: W_r. and W_c

Genetic Algorithms (GA) are based on the mechanics of natural selection and genetics, where the most "fit" of randomly generated solutions are allowed to "mate" with the hope of creating more "fit" solutions (Holland 1992). Each solution is a "chromosome" that is made up of a string of "genes" where each gene carries an integer value that represents the level of treatment applied to a road or crossing. The "fitness" of each chromosome (solution) is measured by the objective function. Mating occurs via Selection, Crossover, and Mutation to combine the more fit solutions into a new generation of solutions. In Selection, chromosomes with higher fitness have a higher probability of mating. In Crossover, each member's chromosome is sliced in two locations and the center pieces are swapped with each other *(fig. 2)*. Mutation is the random alteration of genes in randomly selected chromosomes to diversify the population. Generations of chromosome populations are generated iteratively until a near global optimum is achieved.

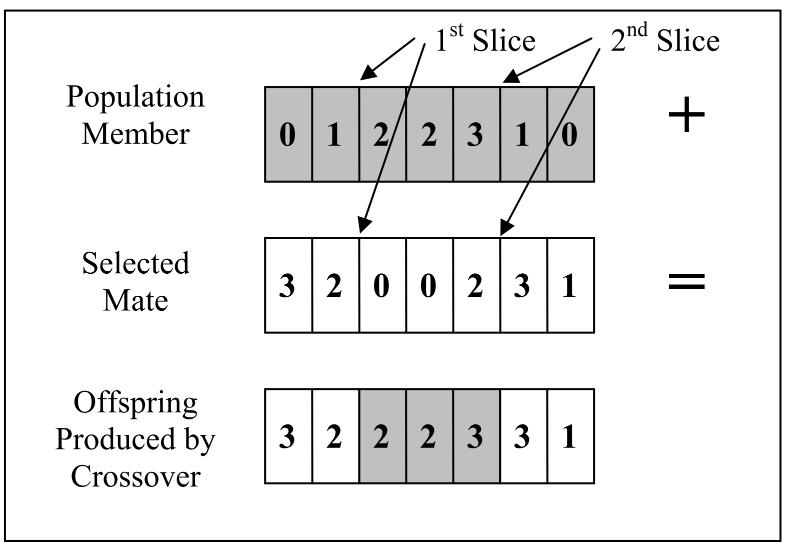

Figure 2—Example of crossover methodology used in genetic algorithms.

One of the strengths of genetic algorithms is they can solve large complex problems that are not solvable with traditional optimization methods that require a differentiable description of the problem. A drawback of GAs is that it is a heuristic method and one cannot prove the optimal solution has been obtained (Goldberg 1989).

We use the Generator™ to build and run the GA. This software is easy to use and runs through an Excel interface. The problem is formulated with a penalty function as provided in Equation 4 in order to meet the requirements of the software. All variables have been defined above, except for P, the penalty.

$$\max_{\forall x_r, x_c} z = \left[\sum_{\forall r} \{W_r L_r S_r(x_r)\} + \sum_{\forall c} \{W_c V_c S_c(x_c)\} \right] - P * |B - TC| \quad \textit{Equation} \quad 4$$

The penalty term is used for numerical stability for the GA. The penalty term pushes the solution toward those solutions that use all the budget B for the total cost *TC* of the solution, i.e. in order to maximize the entire quantity, the penalty term, (the difference between *B* and *TC*) should be small.

The dynamic programming (DP) approach (Bellman 1957) separates the problem into a series of subproblems using stages and states. Each stage has a number of states. The stages are each of the roads and crossings. The states are the amount of remaining budget available to spend to treat that road or crossing. Once each subproblem is solved, one can forward simulate through all the solutions to determine the optimal treatment for each road and crossing that meets the specified budget.

The dynamic program has the following formulation which is a resource allocation DP. Given the End Condition, where $N = N_c + N_r$

$$f_N(R_N) = \max_{x_N} \{W_N V_N S_N(x_N)\} \quad \textit{Equation} \quad 5$$

The recursive equation is solved for $n = N_c + N_r - 1, \ldots, 1$

For $n = N_c + N_r, \ldots, N_{r+1}$, the recursive equation for crossings is

$$f_n(R_n) = \max_{x_n} \left\{ W_n V_n S_n(x_n) + f_{n+1}(R_n - V_n C_n(x_n)) \right\} \quad \textit{Equation} \quad 6$$

For $n = N_r, \ldots, 1$, the recursive equation for roads is

$$f_n(R_n) = \max_{x_n} \left\{ W_n L_n S_n(x_n) + f_{n+1}(R_n - L_n C_n(x_n)) \right\} \quad \textit{Equation} \quad 7$$

Where

$N = N_c + N_r =$ the total number of roads and total number of crossings

$R_n =$ the amount of remaining budget for treatment of road or crossing *n*

$C_m(x_n) =$the cost to treat road or crossing n at treatment level x_n

$f_{n+1}(R_n - L_n C_n(x_n)) =$the maximum amount of sediment saved using the budget remaining after treating road or crossing n at treatment level x_n at cost C_n. Other variables are previously defined.

The dynamic program is subject to the following constraint:

$$TC = \sum_{n=N_r+1}^{N_r+N_c} V_n C_n(x_n) + \sum_{n=1}^{N_r} L_n C_n(x_n) \leq B \quad Equation \quad 9$$

A strength of the DP approach is that a global optimum is guaranteed. A drawback of DP is the "curse of dimensionality," where the computation requirements grows exponentially as the problem size increases. However, using a resource allocation formulation, the computational requirements grow linearly in the number of roads and crossings considered.

The optimization algorithms are applied to a sample watershed—the Lost Man Creek Basin in RNSP that has approximately 32 miles of roads and 73 crossings. A field-based road inventory was used to generate a GIS data base with 618 different road segments. *Table 1* provides a summary of the distribution of roads and crossings through the basin. Given four possible road treatments and three possible crossing treatments, the total possible policies for this basin is $(4^{618}) \times (3^{73})$. This number of policies is much too large to examine individually. Optimization algorithms provide a rational method to consider such a large number of policies.

Table 1—*Number of Crossing and Roads for Each Hillslope Position in the Lost Man Creek Basin.*

Hillslope position	**Number of crossings**	**Number of road segments**
Lower	49	196
Middle	19	257
Upper	5	165

Tables 2 and *3* show the sediment saved and associated costs for both roads and crossing treatments. These data are based on Madej (2001) and decommissioning work conducted in RNSP from 1978-1996. Both the potential sediment saved and the cost for treatment increase for roads in the lower slopes of the watershed, i.e. steep slopes closest to the stream Each table provides a cost-benefit ratio, denoting the ratio of money spent to save a cubic yard of sediment. As one might expect, crossing treatments *(table 3)*, in general, have the best cost-benefit ratios. The road treatments with the best cost-benefit ratio occur in the lower slopes *(table 2)*.

Table 2—*Potential sediment savings and associated costs for 4 road treatments.*

Hillslope location and level of treatment	Sediment saved (yd^3/mi)	Cost/mile of road ($/mi)[1]	Cost-benefit ratio ($/$yd^3$)
Upper slopes			
No treatment	0	$0	0.0
Ripped & drained	250	$5,280	21.1
Partial outslope	400	$7,920	19.8
Total outslope	490	$15,840	32.3
Middle slopes			
No treatment	0	$0	0.0
Ripped & drained	300	$5,280	17.6
Partial outslope	650	$7,920	12.2
Total outslope	950	$21,120	22.2
Lower slopes			
No treatment	0	$0	0.0
Ripped & drained	1000	$6,600	6.6
Partial outslope	2000	$7,920	4.0
Total outslope	2500	$26,400	10.6

[1]Costs are based on decommissioning work conducted in RNSP from 1978-1996

Table 3—*Potential sediment savings and associated costs for 3 crossing treatments.*

Crossings - Hillslope location & level of treatment	Sediment saved (yd^3)	Cost/ crossing ($)	Cost-benefit ratio ($/$yd^3$)
Upper slopes			
No treatment	0	$0	0.0
Basic excavation	300	$1,200	4.0
Total excavation	400	$2,100	5.3
Middle slopes			
No treatment	0	$0	0.0
Basic excavation	600	$2,400	4.0
Total excavation	800	$3,500	4.4
Lower slopes			
No treatment	0	$0	0.0
Basic excavation	1000	$3,600	3.6
Total excavation	1200	$5,250	4.4

Results

Table 4 provides a summary of the costs, sediment saved and overall cost-benefit ratio for the Dynamic Program model and a uniform policy of the minimal treatment, where both crossings and roads have the lowest level of treatment of basic excavation *(table 3)* and rip and drain *(fig. 1)* respectively. The uniform policy represents a non-optimized approach to allocate treatments throughout the basin.

Table 4—*Comparison of dynamic program and uniform policy results.*

Policy	Cost ($)			Sediment saved (yd3)			Cost/benefit ratio ($/yd3)
	Roads	Crossings	**Total**	Roads	Crossings	**Total**	
DP	152,451	97,250	**249,701**	24,755	15,062	**39,817**	6.3
Uniform Minimum	178,230	164,960	**343,190**	15,183	14,892	**30,075**	11.4

Table 5 summarizes the policies generated by the dynamic program and the genetic algorithm for two budgets of $250,000 and $500,000 by reporting costs, sediment saved and an overall cost/benefit ratio.

Table 5—*Comparison of dynamic program and genetic algorithm policies for $250K and $500K budgets.*

Budget constraint ($)	Optimization method	Cost ($)			Sediment saved (yd^3)			Cost/ benefit ratio ($/$yd^3$)
		Roads	Crossings	**Total**	Roads	Crossings	**Total**	
250,000	DP	152,451	97,250	**249,701**	24,755	15,062	**39,817**	6.3
	GA	153,783	96,200	**249,983**	23,600	14,476	**38,076**	6.6
500,000	DP	347,036	153,010	**500,046**	32,293	17,352	**49,645**	10.1
	GA	346,789	153,200	**499,989**	32,123	17,029	**49,152**	10.2

Figures 3 and *4* summarize the treatment policies developed by the dynamic program model for 4 budget scenarios: $250K, $500K, $750K and 1 million dollars for crossings and road segments.

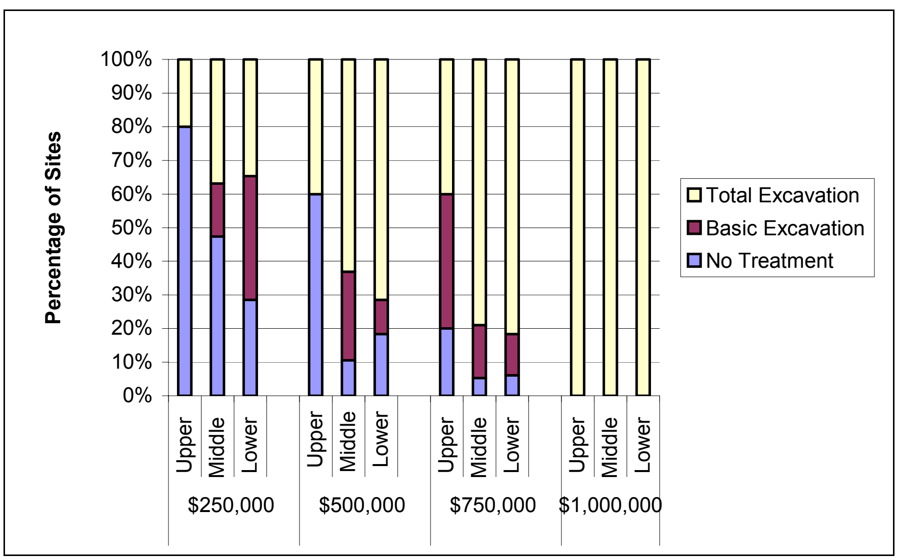

Figure 3—Comparison of dynamic programming crossing treatment policies developed with budgets of $250,000, $500,000, $750,000 and $1,000,000.

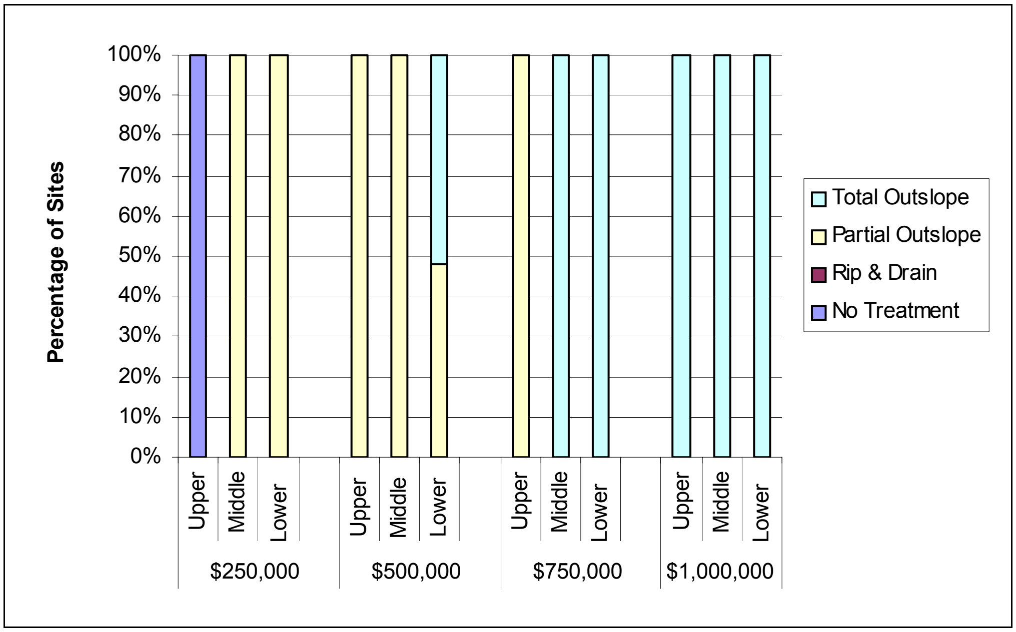

Figure 4—Comparison of dynamic programming road treatment policies with budgets of $250,000, $500,000, $750,000 and $1,000,000.

Figures 5 and *6* compare the treatment polices developed by the GA and the DP models given a $500K budget for crossings and roads respectively.

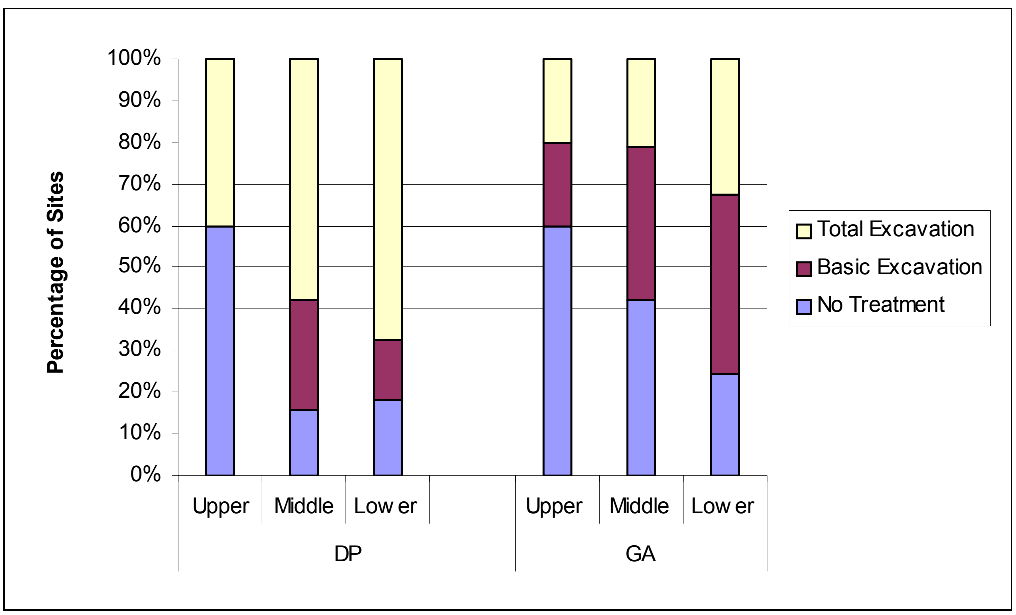

Figure 5—Comparison of DP to GA treatment policies for crossings with a $500,000 budget.

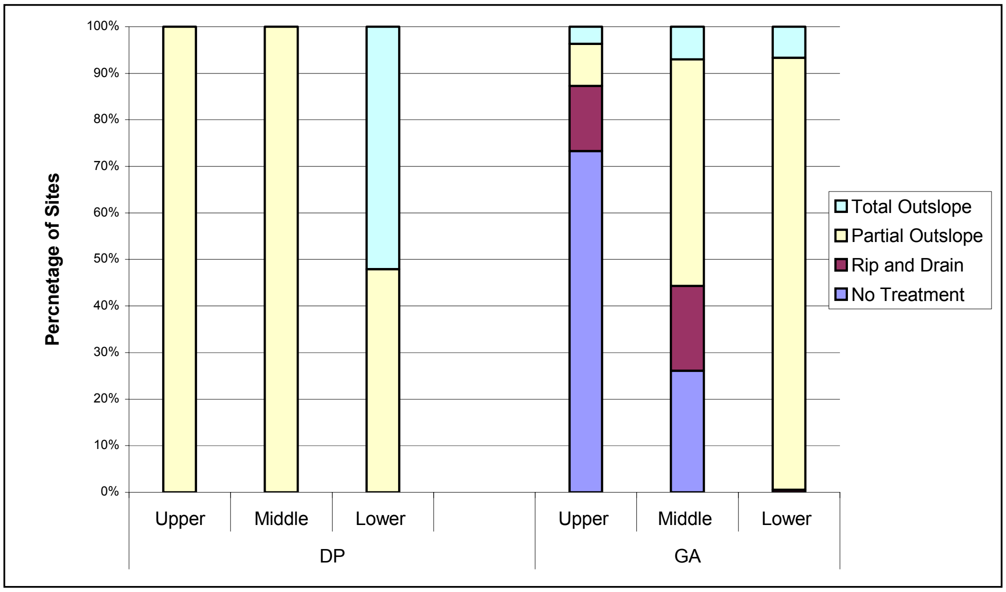

Figure 6—Comparison of DP to GA treatment policies roads with a $500,000 budget.

Discussion

Table 4 results demonstrate that the dynamic program policy allocates financial resources much more effectively than a minimum uniform policy in Lost Man Creek Basin. The DP policy spends almost $100,000 less while saving almost 10,000 yd^3 more sediment than the Uniform Minimum policy. Another measure of the effectiveness of these policies is via the reported cost/benefit ratio.

Table 5 results demonstrate that the GA is obtaining a result that is close to optimal. The summaries of the DP and GA polices are similar *(table 4)*. (As described earlier, no global optimum is guaranteed with GAs while DP results reflect a global optimum.)

Figures 3 and *4* demonstrate that the DP optimization results are rational. As the budget increases, the DP policies include more expensive treatments. In general, the more expensive treatments are used first in the lower basin roads and crossings, as these areas have the best cost/benefit ratio as presented in *tables 2* and *3*.

Figures 5 and *6* compare the GA and DP generated policies for a $500K budget and indicate that the DP policies may be easier to implement as they have less variation. While the total cost and sediment saved for these two policies are similar *(table 5)*, the distribution of the actual treatment types is different for DP and GA policies *(figs. 5* and *6)*. The DP policies have less variation. For example, in *figure 6*, the DP policy only indicates two types of treatments for roads, while the GA indicates four treatment types. This larger variation in treatment types reflects the randomly generated solutions in the GA approach.

Conclusions

Unpaved forest roads can cause erosion and downstream sedimentation in anadromous fish-bearing streams. Although road decommissioning and road upgrading activities have been conducted on many of these roads, these activities have usually been implemented and evaluated on a site-specific basis without the benefit of a watershed perspective. Land managers still struggle with designing the most effective road treatment plan to minimize erosion while keeping costs reasonable across a large land base. We suggest an approach to develop the most cost-effective strategy to treat roads based on field road inventories of erosion potential from roads. The approach can be adapted as more data on erosion and restoration effectiveness become available. In the redwood region, more land managers are using a watershed assessment approach which includes detailed road inventories. Future efforts will also consider the impacts of short-term erosion which occurs immediately following restoration work.

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