Erosion and Channel Adjustments Following Forest Road Decommissioning, Six Rivers National Forest

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Although watershed restoration through road decommissioning has become common in the last decade, few studies have attempted to investigate the success or failure of such projects. This study examines 117 km (73 miles) of decommissioned roads, including 262 stream crossings, on the Six Rivers National Forest, northwestern California, to quantify erosion and identify failure mechanisms and potential areas for improvement. Although most crossings had experienced some adjustment, erosion was generally minor. The average amount of erosion for stream crossings was 21 m^3 (28 yd^3), which represents 4.5% of the amount of fill excavated. Of this volume, 40% of the erosion was due to channel adjustment and 60% was due to bank failures. Erosion from the roadbed between crossings was very small and was observed only in areas of highly unstable geology. The amount of erosion appears well correlated with the timing and intensity of storm events. Large storm events occurring the first winter after decommissioning produced elevated erosion levels. After several dry winters, erosion was very minor, even from large storm events.

Keywords: *roads, decommissioning, obliteration, erosion*

Introduction

It has long been recognized that roads, particularly roads in steep, mountainous terrain, can have significant impacts on water quality and aquatic ecosystems by: accelerating erosion and sediment loading, altering channel morphology, and changing the runoff characteristics of watersheds (Furniss et al. 1991). Where forest roads are located in steep terrain, mass soil movement is a common mechanism of erosion and sediment delivery (Lyons and Beschta 1983). Also common are road-stream crossing failures that occur when culverts fail to pass wood, sediment or storm discharge. The plugging of culverts may result in the loss of the roadbed at the stream crossing or the diversion of the stream offsite, both of which may generate large erosional features and sedimentation of adjacent water bodies. Road cuts can also intercept groundwater and reroute subsurface water into streams. This increase in stream discharge may result in channel enlargement including downcutting and bank erosion.

On Six Rivers National Forest, northwestern California, roads are the leading source of management-related sediment inputs, predominantly associated with mass wasting features such as shallow debris slides and debris torrents. The majority of road-related erosion and sediment delivery are associated with large storm events that trigger culvert failures, stream diversions, and mass wasting such as debris slides and smaller slumps within the roadbed. With declining road maintenance funding, the risk of road failures and elevated sediment delivery is increasing, particularly in the event of large storms.

In an effort to reduce erosion and sediment delivery associated with forest roads, a road-decommissioning program was initiated in the early 1990s on Six Rivers National Forest. Over the past decade, the forest has decommissioned approximately 341 km (212 mi) of forest roads. Road decommissioning efforts target abandoned and low-use roads with high erosion and sedimentation risks. The focus of road decommissioning efforts has been on improving water quality and aquatic ecosystems through reducing sediment introduced to streams, and on reducing the risk of future sediment delivery from roads in the event of a large storm.

The primary road decommissioning treatments on the Six Rivers has been the removal of culverts and the associated fill in stream crossings, and recontouring the stream crossing to as close to the original channel morphology as possible or practical. Roads were not completely obliterated (i.e., fully recontoured) as is typically done in the Redwood National Park restoration program (Madej 2001), but rather were placed in a free-draining condition. Where areas of instability were evident, road fill between stream crossings was recontoured, but in areas where there were no signs of instability, the roadbed was

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left in place. Generally speaking, the upper to mid slope location of the majority of forest roads on Six Rivers National Forest and the geology in many of the areas was such that leaving the majority of the road prism intact was seen as a low risk and a means to cost-effectively decommission more miles of road. In addition to culvert removal and occasional outsloping of the roadbed, installation of water bars or rolling dips was also employed to make the road free-draining. In some cases, the roadbed was ripped or sub-soiled, or trees were planted to speed up revegetation. In all cases, the ultimate objective of the road decommissioning treatment was to make the road free-draining, maintenance-free, and hydrologically benign relative to future erosion and sedimentation risk.

Because of the relatively new emphasis on road decommissioning in recent years on national forest lands and on private timber lands, little attention has yet been given to understanding the extent of erosion and sedimentation that occurs after a road has been decommissioned. There is a general recognition that there will be short-term effects associated with road decommissioning. These short-term effects are considered small given the long-term gain in reducing the larger sedimentation risk if more roads were to fail during large storm events. However, few studies have quantified the sediment lost due to post-decommissioning erosion and channel adjustments. A recent post-treatment decommissioning study was conducted in Redwood National Park (Madej 2001). Madej found that on stream crossing sites, post-treatment sedimentation was small and the majority of the post-treatment erosion and sedimentation were attributable to treated roadbeds. Regardless of treatment, post-project erosion and sedimentation were low when compared to untreated sites. For the period 1980 to 1997, an average of 50 m^3 (66 yd^3) of sediment delivery per stream crossing occurred (Madej 2001). Klein (2003) conducted a post-treatment erosion and turbidity monitoring study on decommissioned roads in the Mattole River watershed in northern California. Klein reported an average of 11 m^3 (15 yd^3) of sediment delivery associated with restored stream crossings. During the first winter after treatment, erosion and elevated turbidity within the restored stream crossings was common but the erosional responses diminished considerably over the winter sampling period. Dunkley et al. (2004) assessed the effectiveness of road deactivation ('decommissioning') techniques in reducing the incidence of landslide initiations but did not assess the volumes of erosion and sedimentation associated with landslides. On the Clearwater National Forest in Idaho, a study was conducted to assess the short-term total suspended-solid concentrations resulting from stream crossing obliteration (Brown 2002). The Clearwater study determined that turbidity and suspended sediments increased during stream crossing restoration and that total sedimentation could be reduced if sediment traps were installed. No analysis was conducted to determine how long the turbidity and suspended solids lasted after the restoration work ceased.

Project Objectives

In light of the extensive road decommissioning that had occurred over the past ten years on the Six Rivers National Forest and the high likelihood that more roads will continue to be decommissioned in the near future, assessing road decommissioning projects was identified as a critical step that would quantify the extent of post-treatment road decommissioning erosion and sedimentation, and improve future road decommissioning projects through incorporating lessons learned. The objectives of the post-treatment road decommissioning assessment were to:

1. Quantify the amount of fill removed and the amount, types and locations of post-project erosion. Assess the effectiveness of treatments in reducing sediment inputs
2. Identify successful or unsuccessful treatment techniques (e.g., ripping, leaving road prism intact, and so on)
3. Identify criteria that would facilitate predicting when future projects may need special treatments (e.g., stream power, slope gradient, slope position)
4. Identify any limiting factors contributing to less than fully successful road decommissioning

These objectives are aimed at assessing the relative risk of implementing road-decommissioning projects and quantifying the nature of the short-term post-treatment erosion risk. This information is particularly relevant given the extent of threatened and endangered anadromous fisheries within the Six Rivers National Forest and the potential for road decommissioning projects to result in adverse effects on these fisheries and water quality.

Project Area Description

Six Rivers National Forest is located in northern California within the Klamath Mountains and California Coast Ranges Geomorphic Provinces. The Klamath Mountains Province has been uplifted relatively rapidly and is deeply dissected, contributing to the ruggedness of the terrain. Both rugged and gentle terrain is found in the Coast Ranges, and drainage systems are generally smaller in area. Topography throughout the Forest is typically steep (slopes ranging from 30 to 80 percent), well dissected, and forested, although there are extensive areas of grassland in

the south and barren areas of ultramafic rock in the north. The large number of older, deep-seated landslides and younger, shallow landslides is due to rapid downcutting by streams through weak bedrock and overlying surficial materials in response to the rapid uplift, as well as the active tectonic environment. Over 90 percent of the high and extreme landslide hazard areas occur adjacent to stream channels on slopes steeper than 65 percent which typically occur in inner gorges of stream channels, recently active landslides, toe zones of deep-seated landslides, and fault zones of weakened bedrock. In general, roads located on slopes steeper than 50% have a greater risk of failure and sediment delivery (USDA 1999, Appendix 2). Roads located within these areas pose a higher risk of erosion and sedimentation during large storm events.

The geology of Six Rivers National Forest is complex and can be categorized in four groups: (1) sedimentary and metasedimentary rocks; (2) metaigneous [or metavolcanic] rocks; (3) ultramafic intrusive rocks; and (4) igneous rocks. The sediments and metasediments include graywacke, shale, schist, and chert of the Franciscan Complex, slate, phyllite and sandstone of the Galice Formation, and pre-Cretaceous metavolcaniclastic rocks of the Rattlesnake Creek and Hayfork Terranes. The metavolcanic rocks are mainly associated with the Galice and Rogue formations or part of the pre-Cretaceous terranes, or occur as isolated blocks in the Franciscan Complex. The ultramafic rocks are predominantly serpentinite, dunite and serpentinized peridotite. The igneous rocks range from diorite and quartz diorite to gabbro, and most occur as relatively small intrusive bodies or inclusions in mélange.

Six Rivers National Forest is characterized by a Mediterranean climate with cool, moist winters and warm dry summers. Precipitation is moderately heavy over most of the forest. It ranges from around 1,270 mm (50 inches) on the middle to southern portion of the forest and up to 3,048 mm (120 inches) on the more northerly portions of the forest. Roughly 90 percent of the total precipitation falls in the six-month period between November and April. Stream runoff is mainly from rainfall, and snowmelt makes up only a minor part of total runoff. The largest storm runoff is usually associated with rain-on-snow events. The relatively high rainfall in combination with steep terrain poses challenges for maintaining forest roads, particularly during large storm events.

To examine the effect of rainfall on decommissioned roads, monthly rainfall from each ranger district was analyzed. Information about individual storm intensities would be more relevant, but this data is not available. Instead, the highest monthly rainfall of the year was used to create an annual maximum series. Rainfall with a return period of 5 years or greater was used to designate that year as a "wet" year. Rainfall return periods were similar to flood discharge return periods for the few stream gages that exist nearby.

Since the decommissioning program began, three large storm events have occurred. Intensity varied from district to district (Figure 1), but most decommissioning sites have experienced at least an 18-year storm. The largest event was the "1997 New Year's Day Flood" which had a return period between 22 and 52 years (Figure 1). Such heavy rainfall should reveal decommissioned sites that are erosion prone or inadequately restored.

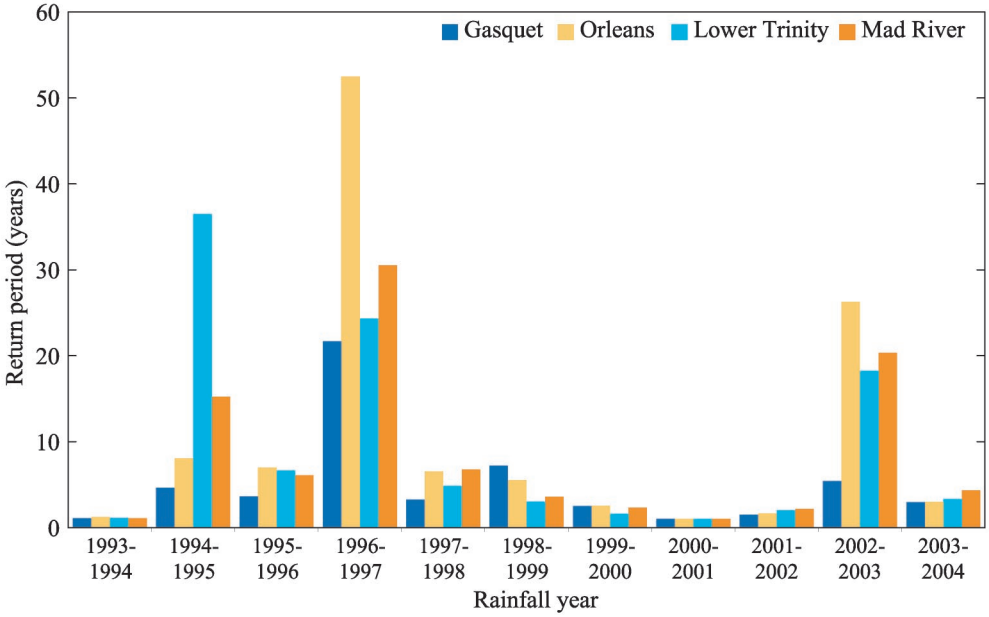


Figure 1: Recent monthly rainfall return periods for the Gasquet, Orleans, Lower Trinity, and Mad River Ranger Districts, coastal northern California ,from 1993 to 2004.

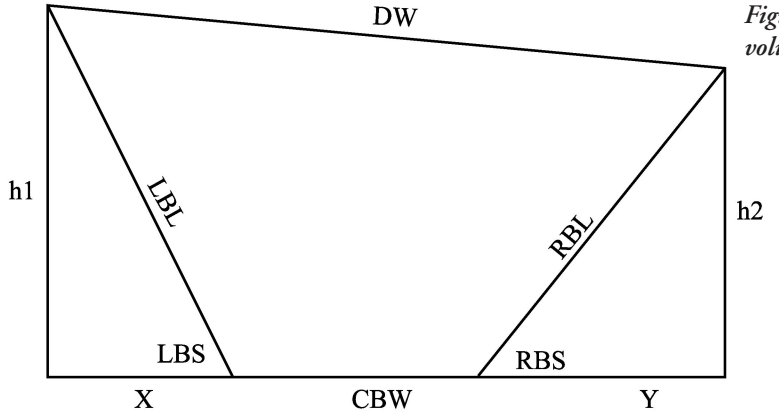


Figure 2. Method for estimating excavated volume: cross-sectional area.

DW = Draw Width
CBW = Channel Bottom Width
LBS = Left Bank Slope
RBS = Right Bank Slope
LBL = Left Bank Length
RBL = Right Bank Length

Total Area = Parallelogram area - both triangles
Parallelogram Area = (CBW + X + Y)((h1 + h2)/2)
Left side triangle area = 1/2 Xh1 Right side triangle area = 1/2 Yh2

X = (LBL)cos(LBS)
Y = (RBL)cos(RBS)
h1 = (LBL)sin(LBS)
h2 = (RBL)sin(RBS)

Methods

A total of 117 km (73 mi) of previously decommissioned roads were assessed, or 34% of the total miles of decommissioned road (341 km or 212 mi of road decommissioned). Decommissioned roads were haphazardly selected based on age since treatment; however, attempts were made to get a cross section of different geologic terrains as well as a variety of stream crossing treatment sizes (i.e., large fill volumes versus small fill volumes). The intent of the post-treatment road decommissioning monitoring was to sample as many roads as possible that had weathered large storm events and thereby had treatments that were "tested" by winter storms. Eighty-eight percent of the sampled decommissioned roads had experienced at least three winters of post-treatment adjustment, including storm events with at least an 18-year recurrence interval.

Decommissioned roads were assessed to determine the effectiveness of the treatments at stream crossings as well as the roadbed between the stream crossings. Methods and questions assessed are discussed below.

Estimating Excavated Stream Crossing Fill Volume

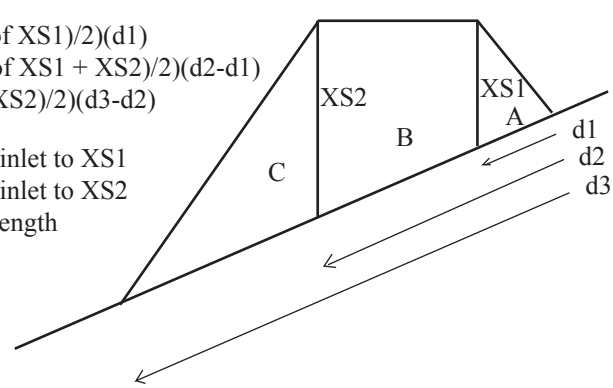
The post-treatment road decommissioning monitoring protocol required that the amount of material excavated from stream crossings be measured along with the volume of any post-treatment erosional features. A simplified model of the excavated crossings was used to facilitate rapid measurement of fill volume (see Figure 2 and Figure 3). In using the model, two cross-sections were measured (using a tape and clinometer), along with channel length and slope. The cross-sections were modeled as parallelograms. Total area of the cross-section was calculated by subtracting the area of the two triangles on the sides from the parallelogram area.

This method allowed estimating excavated fill volume for stream crossings that had a significant road gradient going through the channel, yet kept the measurements simple. When measuring the channel bottom width, due to post-treatment adjustments, estimates of the original channel bottom configuration were made to estimate the total fill volume excavated. Total volume for the excavated stream crossing was calculated by scaling the cross-sectional areas by the appropriate distance along the channel (Figure

Figure 3. Profile measurements for estimating fill volume.

Volume A = ((area of XS1)/2)(d1)
Volume B = ((area of XS1 + XS2)/2)(d2-d1)
Volume C = ((area XS2)/2)(d3-d2)

d1 = Distance from inlet to XS1
d2 = Distance from inlet to XS2
d3 = Total channel length



3). Cross-sectional area was assumed to be zero at the upstream and downstream end of the crossing.

Most crossings were adequately measured with two cross-sections. In the case of very small crossings, only one cross-section was needed. In such instances, the profile was viewed as a rectangle with sides equal to the cross-section and bottom equal to the total channel bottom length. The upstream cross-section was located where the inboard edge of the old road meets the excavated crossing. The downstream cross-section was placed at the widest point of the excavation. Where significant road curvature exists, excavated fill volume may be slightly over-estimated.

Measuring Post-Treatment Erosional Features

Post-treatment erosional features in both excavated stream crossings and on the roadbed between stream crossings were measured. All visible erosional features were measured using average width, average length and average depth, which yielded estimates of total volume of material eroded. The type of feature was also noted (e.g., channel incisement, slump, gully, rill, debris slide, and so on). Sheet erosion was not measured. When possible, the cause of the erosion was noted and discussed. An estimate of percent delivery of sediment to watercourses from all erosional features was made. For the purposes of this study, all reported erosion volumes within stream crossings were considered 100% delivered sediment.

In addition to measuring the excavated and eroded volume, post-treatment assessments were made to determine if the erosional features had stabilized or were still susceptible to chronic future adjustment and sedimentation. For sites with large post-treatment erosion, evidence as to whether or not poor contract design or implementation was a factor was also assessed.

Post-treatment erosion was compared to the following independent variables: hillslope position, hillslope gradient, stream power, storm return interval, and size of excavation. The intent of the analysis was to identify interactions that might serve to predict when the intensity of road decommissioning design needs to be elevated because the risk of post-treatment adjustments are high. In other words, under what circumstances are the risks of post-treatment erosion and sedimentation high and how can they be reduced?

Results and Discussion

Approximately 117 km (73 mi) of decommissioned roads (or 34% of the total length of decommissioned roads) were monitored for post-treatment erosion (stream channel and sideslope erosion at the crossings, and erosion of the roadbed between stream crossings). The majority of these roads and stream crossings had experienced large storms (18-year or greater return period) during the winters of 1995, 1997 and 2003. High intensity storms were considered a good test of the type and magnitude of post-treatment erosion that occurs on typical road decommissioning projects in the Six Rivers National Forest.

Stream Crossings

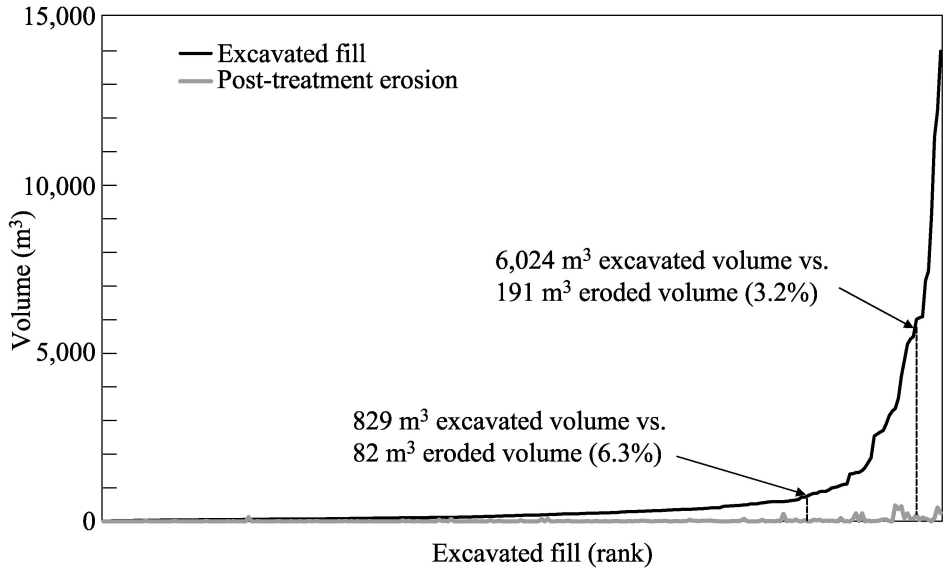
A total of 262 stream crossings were assessed for post-treatment channel erosion. These stream crossings were predominantly perennial streams but intermittent and ephemeral streams were also assessed. Post-treatment stream channel erosion was quite common, and was generally not large when compared to the amount of material excavated during the initial stream crossing restoration. On average, the amount of post-treatment erosion occurring within stream crossings was 4.5% of the total volume of fill excavated, or 21 m^3 (28 yd^3) (Table 1).

Post-treatment erosion on larger stream crossings (greater than 765 m^3 or 1000 yd^3 of fill) was more variable. The average post-treatment erosion on the larger stream crossings was approximately 3.2% of the total fill excavated but varied from 0 to 16%. Large post-treatment adjustments were rarely observed. In approximately 80% of these large sites, post-treatment erosion was less than 4.5% of the total fill excavated or under 111 m^3 (146 yd^3) (Table 1). The majority (64%) of the inventoried stream

Table 1: Stream crossing excavations and post-treatment erosion.

Excavated Stream Crossing Volume (yd^3)	Percent of Stream Crossings (%)	Volume Excavated (yd^3)	Average post-treatment erosion (yd^3)	Range of post-treatment erosion (yd^3)	80% of sites eroded less than # (yd^3)	Percent of excavated fill volume lost to post-treatment erosion (%)
0-400	64	153	6.7	0 to 156	5.7	5.1
400-1000	20	612	21	0 to 284	25.1	3.3
>1000	16	4692	124	0 to 621	146	3.2
All sites	100	967	28	0 to 621	20	4.5

Figure 4. Stream crossing excavation and erosion volumes.



crossings had excavated fill volumes under 305 m^3 (400 yd^3) and these stream crossings had very small amounts of post-treatment channel adjustments and erosion (average of 5 m^3 or 6.7 yd^3). Stream crossings larger than 305 m^3 (400 yd^3) experienced slightly more post-treatment erosion (average of 16 m^3 or 21 yd^3) but these quantities were small compared to the volume of material excavated from the stream crossings.

While the total volume of post-treatment erosion increased with the size of the excavation, the relative proportion of post-treatment erosion compared to fill volume excavated decreased from 5.1% for small stream crossings to 3.2% for large stream crossings (Table 1). Post-treatment channel erosion remained fairly constant regardless of stream crossing size (Figure 4). While occasional large stream crossing restoration sites have significant post-treatment channel erosion, on average the post-treatment channel erosion on these larger treatment sites is small considering the amount of fill removed.

Photo 1: Typical stream crossing erosion due to post-treatment channel incisement.

On Six Rivers National Forest, approximately 40% of measured post-treatment stream crossing erosion was attributable to channel downcutting or widening, and 60% was attributable to channel bank or sideslope failures. Post-treatment channel downcutting or widening was commonly found at most treatment sites (Photo 1) but excessive downcutting may indicate inadequate restoration design or contract implementation (Photo 2). Rills and gullies were only rarely observed on channel sideslopes and usually only associated with a nearby spring. The bulk of channel sideslope failures were attributable to oversteepened slopes and could be a result of inadequate restoration design or implementation (Photo 3). Depending on the size of the stream crossing restoration site, oversteepened slopes led to shallow slumps and small debris slides. Channel sideslope failures are an inherent risk in restoring stream channels, particularly in naturally steep and incised topography, regardless of the quality of contract design and implementation. Nevertheless, in some instances inadequate channel design, such as too narrow a stream channel configuration or too shallow a depth of excavation, resulted in channel incision, which led to oversteepened and unstable sideslopes (Photo 4). The data indicate that while the total post-treatment erosion was small, a greater emphasis on designing and excavating less steep channel sideslopes would likely reduce post-treatment erosion to

Photo 2: Atypical and excessive post-treatment channel incisement (note exposed root across channel indicative of depth of erosion).

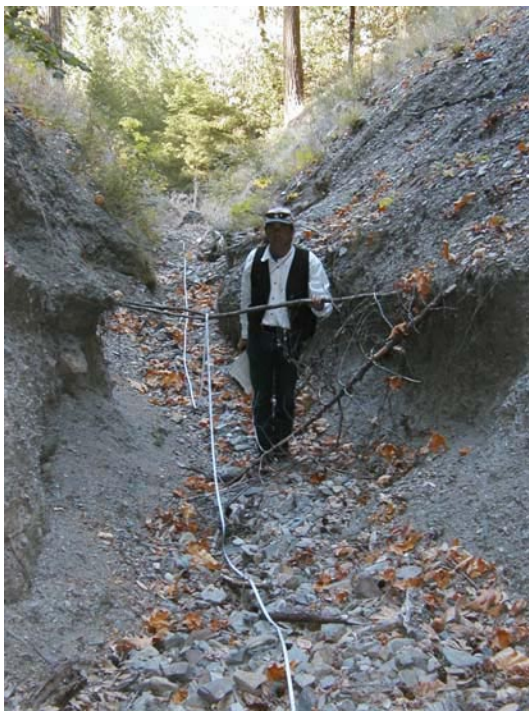


Photo 3: Incipient slope failure due to oversteepened channel side slope.

even smaller volumes, especially in stream crossings that are not topographically constrained by narrow, incised valleys.

Post-treatment erosion on excavated stream crossings is widely recognized as an inherent short-term effect that is offset by larger long-term gains in reducing the risk of major sedimentation resulting from culvert and fill

Photo 4: Channel bank failure due to oversteepened slope and inadequate channel width

failures. Fill failures and diversions of road stream crossings have been shown to be significant contributors of fluvial hillslope erosion (Best et al. 1995; Weaver et al. 1995). Furniss et al. (1998) assessed stream crossing failures on non-decommissioned forest roads in Washington, Oregon and Northern California and found that after the winter floods of 1995 and 1996, significant portions of road fill were lost due stream crossing failures. Figure 5 illustrates the proportion of stream crossing fill eroded where streamflow overtopped the road. The Furniss et al. data indicate that in approximately 35% of the culvert failures sampled, over 25% of the stream crossing fill eroded, and that 44% of the failures had between 1 and 25% of the stream crossing fill eroded. While the total percentage of storm-related stream crossing fill erosion on non-decommissioned roads varies, it is clear that the proportion lost due to post-treatment road decommissioning erosion is significantly smaller than the erosion that occurs during large storm events. Post-treatment road decommissioning erosion on the Six Rivers varied between 3.2 to 5.1% of the total stream crossing fill volume and was typically considerably less than the volume of erosion that occurs on untreated roads during large storm events.

A general assumption of stream crossing restoration is that the risk of post-treatment erosion and volume of sediment generated increased with size of the stream channel being restored. Data from this assessment indicate that while the total volume of erosion increased with larger stream crossings, the total volume of material was small compared to the total material excavated (typically 3 to 5%) (Figure 4). Photos 5 and 6 are examples of typical small and large stream restoration sites with very limited post-treatment channel erosion and sedimentation.

Figure 5. Proportion of road-stream crossing fill eroded where streamflow overtopped the road. From: Furniss et al. (1996).

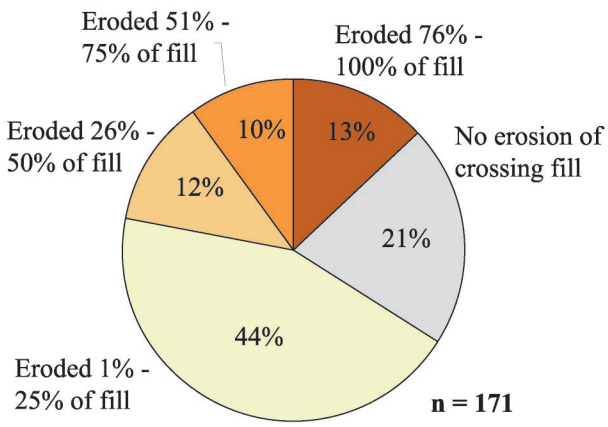


Photo 5: Typical large size restored stream crossing - 5N13B.

Photo 6: Typical small to moderate size stream crossing excavation - Road 2N14H.

Restoration of stream crossings must be carefully planned and executed, but even the best-designed projects have some post-treatment channel erosion. Some of these erosional features can be avoided while others are unpredictable and probably unavoidable. During site excavation, unforeseen conditions may occur and best guesses are made of original channel bottom depths and configurations, only to find out the next year that the channel has downcut, indicating that the original channel was clearly not reached during the initial excavation.

A relatively small proportion of the decommissioned roads (8%) were identified as warranting further monitoring for future channel adjustments and erosion pending the next large storm event. The majority of the decommissioned roads were determined to be in a stable condition and did not pose a significant future sedimentation risk. In others, the short-term impact had largely abated. Sites that warranted future monitoring were mostly associated with roads located in steep inner gorges and large perennial streams (typically 3rd-order or larger) where post-treatment channel erosion had varied between 1 to 15% of the total fill excavated. In these sites, roughly 229 to 459 m^3 (300 to 600 yd^3) of erosion occurred. In general, it is more difficult to minimize post-treatment erosion at decommissioned crossings with deeper channels and higher stream power within the inner gorge. A very small percentage of the sites warranted continued monitoring because of poor contract implementation.

Roadbed

Few surface erosional features attributable to road decommissioning were found on the remaining roadbed between stream crossings. The total volume of all erosional features associated with the 117 km (73 miles) of inventoried roadbed was 2,646 m^3 (3,460 yd^3) (total erosion and associated sediment from restored stream crossings was 9,213 m^3 (12,050 yd^3) or approximately 78% of total post treatment erosion). Roadbed fillslope failures occurred on two roads located in inherently unstable Franciscan mélange terrain (less than 1% of total miles of roads treated). Approximately 2,263 m^3 (2960 yd^3) of fill were associated with post-treatment fillslope failure on mélange terrain and 5% of this material was delivered to adjacent watercourses. The erosional features that produced the greatest erosion were associated with fillslope failures (2,523 m3 or 95%), followed by gullies (76 m^3 or 3%) and cutslope failures (42 m^3 or 1%).

The decision early on in the road-decommissioning program to minimize obliteration and recontouring of the road prism between stream crossings was validated by the relatively small proportion of sedimentation generated from post-treatment roadbed slumps and fillslope failures and by those few failures that occurred being limited to inherently unstable terrain. However, this conclusion should be re-evaluated after a major storm event, such as following a 50-year or greater recurrence interval storm.

Photo 7: Untreated roadbed on decommissioned road.

Photo 8: Outsloping associated with unstable roadbed.

Photo 7 shows a typical untreated roadbed left between restored stream crossings. Photo 8 is an example of road prism outsloping where slope stability was a concern.

Small gullies were the most common erosional feature on the roadbed between stream crossings, but did not account for a large amount of erosion (76 m^3 or 100 yd^3 total). Unlike fillslope failures however, gully erosion resulted in almost 100% sediment delivery to adjacent watercourses. Gully erosion was largely attributable to poor road drainage due to either faulty contract design or incomplete implementation of contract specifications.

Roadbeds between stream crossings were generally not ripped. Rolling dips and waterbars were installed between stream crossings to improve drainage of springs and seeps from road cutslopes. Limited post-treatment erosion was evident as a result of these practices.

Other Post-Treatment Variables

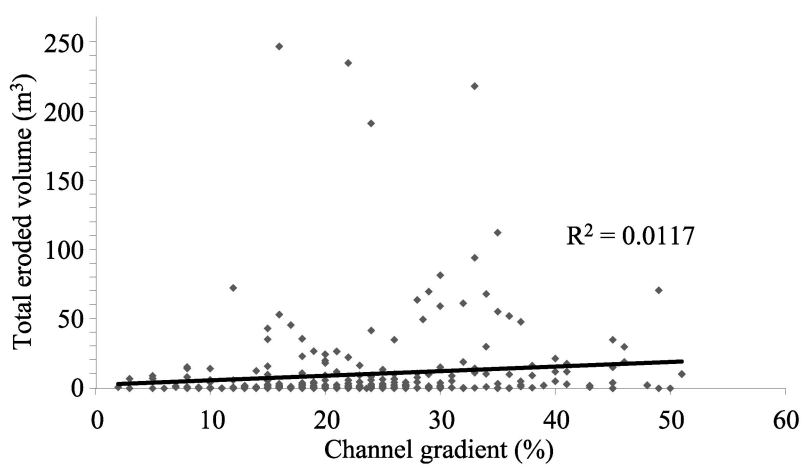
Independent variables such as geology, hillslope gradient, channel gradient, location in the inner gorge, storm history, drainage area, stream power, contract design and contract implementation were assessed to determine whether they influenced post-treatment erosion on decommissioned roads. Due to the high variability of post-treatment erosion within stream crossings, statistical relationships with the variables listed above were not significant. Storm history, geology, drainage area and location in the inner gorge appear to be useful predictors of increased erosion.

The influence of channel gradient on post-treatment adjustments was examined, but no statistical relationships were evident (Figures 6 and 7). We hypothesized that steeper channel gradients would result in more erosion, but this was not supported by the data.

Geology and post-treatment erosion were also evaluated, and some generalizations can be made. All treated sites were classified into five types of parent material: diorite rock, metasedimentary rock, mica schist, sedimentary and metasedimentary rock, and sheared metasedimentary rock. A means test was conducted and diorite and mica schist parent materials showed statistically significant lower post-treatment erosion rates than those sites located in sedimentary and metasedimentary rock (95% confidence interval) (Figure 8).

This finding is counter-intuitive because diorite parent material is generally non-cohesive and highly erodible. Further examination of the data reveals that all of the

Figure 6. Channel gradient regressed against total erosion.



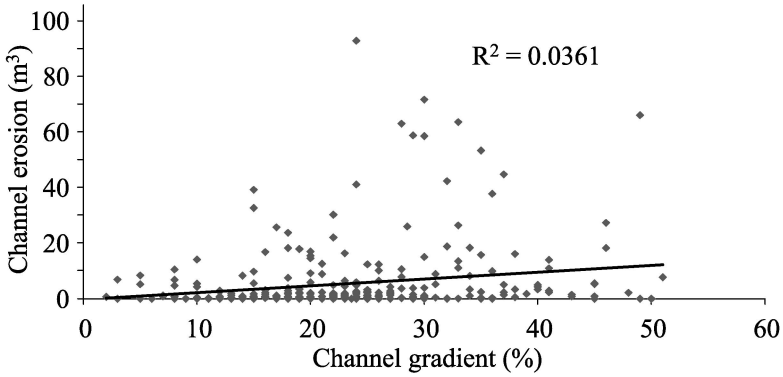
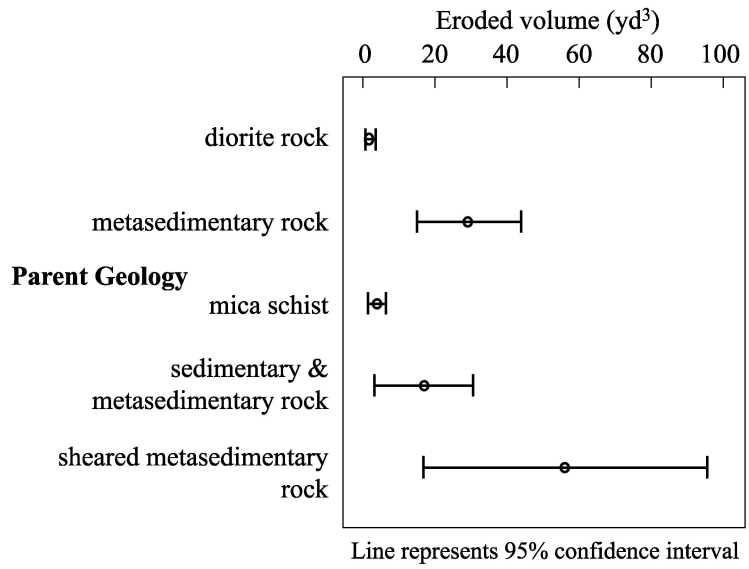


Figure 7. Channel gradient regressed against channel erosion.

Figure 8. Means test between eroded volume and parent material.



treated stream crossing sites within dioritic parent material are above 1,220 m (4,000 feet) in elevation and may be protected from winter storms due to presence of a seasonal snow pack. Treatment sites located in lower elevation diorite parent material are likely still highly susceptible to post-treatment erosion. (Qualitative observations of post-treatment erosion on low elevation sites in diorite parent material support this hypothesis; however, insufficient time was available to include these sites in this study).

Bedrock geology might also be an influence in post-treatment erosion associated with roadbed fillslope failures. Field data indicated however, that post treatment slope failures on roadbeds were extremely limited and located only in the Franciscan mélange terrain. The slope failures on these sites were not clearly attributable to the road decommissioning and could have resulted from the unstable geologic and geomorphic terrain. Overall, a relationship between post-treatment erosion and differing bedrock geology was not evident in the analysis.

The amount of in-channel erosion observed was compared to excavated volume, drainage area, and hillslope gradient as well as stream power. Hillslope gradient was defined as the average gradient of hillslope through which stream channel dissects and stream power was defined as drainage area times channel slope. No correlation was observed between either hillslope gradient (Figure 9) or stream power (Figure 10) and the amount of observed erosion. This was surprising, especially in the case of stream power which had been found to be a good predictor of erosion in the Franciscan terrain of Redwood Creek by Madej (2001). A multiple regression was conducted on post-treatment erosion, excavated volume, and drainage area on decommissioned stream crossings in Six Rivers. These variables were significantly related ($n = 52$, $r^2 = 0.55$, $p = 0.0001$)

Contract design appeared to influence the amount of erosion at some stream crossings, primarily where excavation did not reach the original channel grade, or where post-treatment channel sideslopes were overly steep. These were generally some of the earliest decommissioning project sites with inadequate pre-project surveys. Standard procedure currently is to survey all but the smallest crossings to ensure good contract design. Therefore, faulty contract design should not be a cause for significant erosion in the future.

Figure 9. Hillslope gradient regressed against eroded volume.

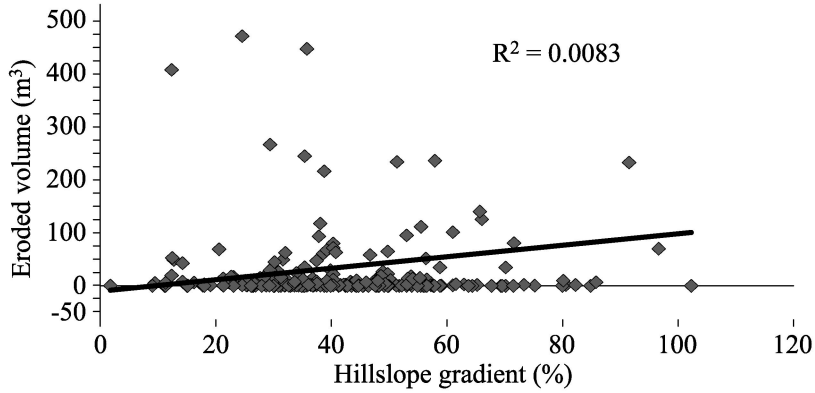


Figure 10. Stream power regressed against eroded volume.

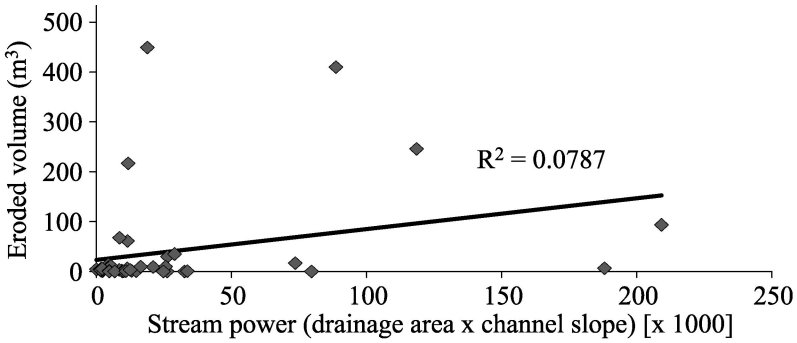
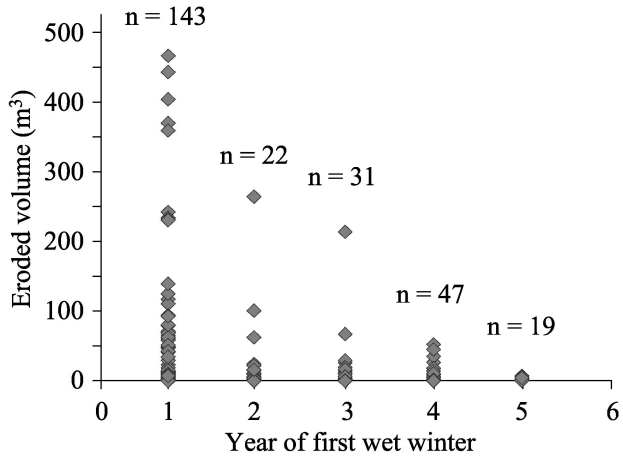


Figure 11. Erosion related to the year of the first wet winter after decommissioning.



Quality of contract implementation did not consistently relate to the amount of post-treatment erosion. In fact, some of the largest erosion was associated with the best-implemented contracts, as determined by the level of on-site inspection during treatments. The large amounts of post-treatment erosion primarily occurred at large or sensitive crossing sites that experienced an unusually wet first winter.

The amount of rainfall, particularly during the first winter, was found to be a good predictor of erosion. Each treatment site was classified into one of five categories reflecting the number of years since the site had experienced a wet winter. For purposes of this analysis, a wet winter was defined as the wettest monthly rainfall occurring with a recurrence interval of 5 or more years. In some cases (such as Bluff Creek), just weeks after completing the decommissioning, a 50-year storm event occurred. This storm produced some of the greatest observed post-treatment erosion, even though the project was well designed and implemented.

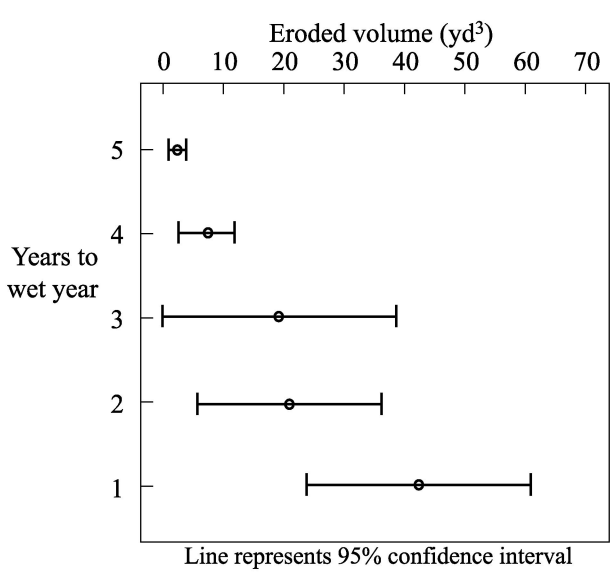
Relatively dry winters allow treated sites to revegetate and increase stability to the point where they can withstand a large storm with little erosion. Comparing the post-treatment erosion volumes in relation to time between storm events indicates that after four dry years, erosion from a wet year is minimal (Figure 11). There also appears to be a substantial reduction in erosion after only one dry winter (Figure 11).

While the relationship between time since storm events and post-treatment erosion is clearly visible in Figure 11, statistical analysis of the data show large variability. Comparing post-treatment erosion and years since first wet winter indicated that there was a high variability of erosion in sites that had a greater than 5-year storm event the first year following treatment ($r^2 = 0.35$, $p = 0.001$). This variability is due to lack of data on rainfall intensities of the storms, or knowing whether these storms were associated with rain-on-snow events, or the timing of the storms. Seasonal timing of large storms is important because if they occur in the late fall just after the completion of the decommissioning treatments, the recently treated channel

slopes are highly vulnerable due to the unconsolidated nature of the disturbed soils; these disturbed soils become progressively more consolidated as the winter progresses due to the settling and compaction associated with raindrop impact. Despite the weak statistical significance between post-treatment erosion and years between large storms (r^2 = 0.35), a means test revealed there was a significant difference in post-treatment erosion between the sites that experienced a greater than 5-year recurrence interval storm the first year after treatment when compared to sites that had not experienced a storm greater than 5-year recurrence interval four and five years after treatment (95% confidence interval) (Figure 12). Further examination of the sites that experienced a greater than 5-year storm recurrence interval the first year after treatment revealed a significant relationship between the amount of excavated volume and post-treatment erosion (r^2 = 0.59). Sites that are exposed to large storm events close to completion of the treatment have a greater likelihood of experiencing post-treatment erosion than sites that have had at least four to five years to stabilize under milder winter conditions.

The amount of erosion was also correlated to whether the stream crossing was located in the inner gorge or not. Inner gorge was defined as any slope greater than 65% and adjacent to a stream channel. Crossings in the inner gorge produced about 4.5 times as much erosion as crossings not in the inner gorge. The 34 sites located in the inner gorge averaged 89 yd^3 (68 m^3) of erosion per year, where as the 226 sites outside the inner gorge yielded an average of only 20 yd^3 (15.3 m^3) of erosion per year. A means test was conducted and the observed differences between post-treatment erosion within the inner gorge were statistically different (95% confidence interval, $p < 0.001$) from those outside the inner gorge and the observed differences were not a function of sample size. Greater post-treatment erosion within the inner gorge occurred because crossings in the inner gorge tend to be larger, on steeper slopes, and have more water. Faulty contract design or implementation at these inner gorge sites will generally have more severe consequences on post-treatment erosion than at sites with smaller stream crossings in more gentle terrain. In extremely incised and narrow inner gorge stream crossings, the natural topography can severely hamper the creation of stable channel side slopes. In these instances, it must be recognized that the ability to fully reconstruct the stream crossing close to its original morphology without risk of some sedimentation and post-treatment erosion is limited. However, the volume of material saved will likely be much larger than the amount lost due to post-treatment adjustments. Data indicate that in inner gorge areas, where the risk is highest, opportunities need to be explored to reduce the risk of post-treatment adjustment by minimizing overly steepened stream channel sideslopes where possible. While more costly, designing stream crossings so that the fill removal extends to and mimics the gradient of the surrounding valley walls will reduce the risk of post-treatment sideslope failure.

Figure 12: Means test between eroded volume and years to first wet year.



The duration of post-treatment erosion was not assessed in this study, however qualitative observations over many years indicate that the bulk of post-treatment erosion and channel adjustments occurs the first year after treatment and rapidly diminishes over subsequent winters. Klein (2003) conducted a post-treatment erosion and turbidity study on decommissioned stream crossings in the Mattole River watershed, coastal northern California, and found that peak turbidity levels downstream of treated sites occurred as a result of the first few winter storms during the first year but that, by and large, erosional response in the sampling sites diminished considerably over the winter sampling period.

Conclusions

Total erosion from decommissioned roads was found to be relatively minor and not likely to persist. Average post-treatment erosion on stream crossings was 21 m^3 (28 yd^3), which is 4.5% of the fill excavated. This amount is much smaller than the amount of erosion that could occur if the culverts failed during large storm events. Larger crossings produced greater amounts of erosion, but a smaller proportion of the excavated fill. Approximately 40% of erosion was from channel adjustment (primarily downcutting with some widening) and 60% was due to sideslope failures (usually from over-steepened slopes that resulted in shallow soil slumps). Over-steepened slopes in

many restored stream crossings were due to inadequate contract design or implementation, but in other sites the over-steepened slopes were due to natural topographic constraints. Leaving the roadbed between stream crossings intact and only outsloping visibly unstable portions of the roadbed was shown to be a viable option in designing road decommissioning projects with limited risk of post-treatment erosion. Erosion from the roadbed between stream crossings was very small and occurred only in unstable mélange terrain. Analysis of data indicated that hillslope gradient, channel gradient, channel sideslope gradient, and stream power were not good predictors of post-treatment erosion. The amount of post-treatment erosion was best predicted by the storm history following treatment. When large storm events occur during the first winter after decommissioning, post-treatment erosion is above average and the amount of post-treatment erosion is influenced by the volume of material excavated. The risk of post-treatment erosion will be considerably less if the site does not experience a large winter storm until 4 or 5 years after treatment.

Post-treatment road decommissioning monitoring indicates that while there is a short-term risk of increased erosion and sedimentation, the amount of erosion is minor when compared to the volume of material removed, and that road-decommissioning treatments are effective in reducing long-term sedimentation risks. Recommendations for future work include assessing the extent and duration of sedimentation effects from decommissioning treatments on local aquatic fauna (e.g., macro-invertebrates), as well as assessing the magnitude of changes to the local hydrology of affected streams.

References

Best, DW, HM Kelsey, DK Hagans, and M Alpert. 1995. Role of fluvial hillslope erosion and road construction in the sediment budget of Garret Creek, Humboldt County, California. In: KM Nolan, HM Kelsey, and DC Marron, eds. Geomorphic processes and aquatic habitat in the Redwood Creek basin, northwestern California. U.S. Geological Survey Professional Paper 1454: M1-M9.

Brown, TM. 2002. Short-term total suspended-solid concentrations resulting from stream crossing obliteration in the Clearwater National Forest, Idaho. Seattle, WA: University of Washington, Forest Engineering and Hydrology Graduate Program. 107 p. M.S. thesis.

Dunkely J, M Wise, M Leslie, and D Collins. 2004. Effectiveness evaluation of road deactivation techniques on the west coast of Vancouver Island. Forest Research Extension Note EN-020. Nanaimo, BC, Canada: Research Section, Coast Forest Region, B.C. Ministry of Forests. 11 p.

Furniss, MJ, TS Ledwith, MA Love, BC McFadin, and SA Flanagan. 1998. Response of road-stream crossings to large flood events in Washington, Oregon, and northern California. Report No. 9877-1806. San Dimas, CA: USDA Forest Service, San Dimas Technology and Development Center. 14 p.

Furniss, MJ, TD Roelofs, and CS Yee. 1991. Road construction and maintenance. In: WR Meehan, ed. Influences of forest and rangeland management. Special Pub. 19. Bethesda, MD: American Fisheries Society: 297-324. Chapter 8.

Klein, R. 2003. Erosion and turbidity monitoring report - Sanctuary Forest stream crossing excavations in the upper Mattole River basin, 2002-2003. Prepared for: Sanctuary Forest, Inc., P.O. Box 166, Whitethorn, CA 95589.

Lyons, JK and RL Beschta. 1983. Land use, floods, and channel changes: Upper Middle Fork Willamette River, Oregon. *Water Resources Research* 19(2): 463-471.

Madej, MA. 2001. Erosion and sediment delivery following removal of forest roads. *Earth Surface Processes and Landforms* 26: 175-190.

Switaliski, TA, JA Bissonette, TH DeLuca, CH Luce, and MA Madej. 2004. Benefits and impacts of road removal. *Frontiers in Ecology and the Environment* 2(1): 21-28.

Weaver, WE, DK Hagans, and JH Popenoe. 1995. Magnitude and causes of gully erosion in the lower Redwood Creek basin, Northwestern California. In: KM Nolan, HM Kelsey, and DC Marron, eds. Geomorphic processes and aquatic habitat in the Redwood Creek basin, Northwestern California. U.S. Geological Survey Professional Paper 1454. Chapter I.