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EROSION AND SEDIMENT DELIVERY FOLLOWING REMOVAL OF FOREST ROADS

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ABSTRACT

Erosion control treatments were applied to abandoned logging roads in California, with the goal of reducing road-related sediment input to streams and restoring natural hydrologic patterns on the landscape. Treatment of stream crossings involved excavating culverts and associated road fill and reshaping streambanks. A variety of techniques were applied to road benches, which included decompacting the road surface, placing unstable road fill in more stable locations, and re-establishing natural surface drainage patterns. Following treatment and a 12-year recurrence-interval storm, some road reaches and excavated stream crossings showed evidence of mass movement failures, gullying, bank erosion and channel incision. Post-treatment erosion from excavated stream crossings was related to two variables: a surrogate for stream power (drainage area × channel gradient) and the volume of fill excavated from the channel. Post-treatment erosion on road reaches was related to four explanatory variables: method of treatment, hillslope position (upper, mid-slope or lower), date of treatment, and an interaction term (hillslope position × method of treatment). Sediment delivery from treated roads in upper, middle and lower hillslope positions was 10, 135 and 550 m^3 of sediment per kilometre of treated roads, respectively. In contrast, inventories of almost 500 km of forest roads in adjacent catchments indicate that untreated roads produced 1500 to 4700 m^3 of sediment per kilometre of road length. Erosion from 300 km of treated roads contributed less than 2 per cent of the total sediment load of Redwood Creek during the period 1978 to 1998. Although road removal treatments do not completely eliminate erosion associated with forest roads, they do substantially reduce sediment yields from abandoned logging roads. Published in 2001 by John Wiley & Sons, Ltd.

KEY WORDS: erosion control; forest road removal; road decommissioning; water shed restoration; sediment yield monitoring

INTRODUCTION

Forest roads are significant sources of sediment (Megahan and Kidd, 1972; Janda *et al.*, 1975; Best *et al.* 1995). Abandoned and unmaintained roads once used for timber harvest are common across the steep, forested landscape of southwest Canada and the Pacific Northwest of the United States. Haul roads constructed across steep slopes frequently result in massive landslides and extensive gullying that contribute sediment directly into stream channels. Sidecast material from road construction can be mobilized when it becomes saturated, or gullies can form if road runoff is diverted onto previously unchannelled slopes.

Road cuts and drainage structures, such as culverts, can disrupt natural drainage patterns. Stream crossings fail when culverts plug with sediment or wood, or are too small to convey storm discharge. In these cases, the road fill at the stream crossing may be removed by erosion. Drainage structures can divert streams out of their natural course onto unchannelled hillslopes when the structures fail to function properly. For example, if a culvert plugs and the road slopes away from the culvert inlet, runoff is diverted from the channel and may flow down the road onto an unprotected hillslope. These diversions frequently result in further gullying or road fill failures (Weaver *et al.*, 1995). Road cuts can intercept groundwater and increase the amount of surface runoff (Wemple, 1998). As a result of this hydrologic rerouting, some streams receive an increase in discharge, and the channels enlarge through downcutting and bank erosion. In addition, widespread surface

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runoff from the road bench and cutbanks flows into inboard ditches, which commonly deliver fine sediment to channels.

In response to the erosional threat posed by abandoned forest roads, the United States USDI National Park Service and USDA Forest Service fund programmes to upgrade existing roads and to remove roads that are no longer needed for the transportation network. In 1978, the National Park Service initiated one of the earliest and most extensive restoration programmes focused on roads at Redwood National Park in north coastal California. At that time, Redwood National Park was expanded to include 15 000 ha of recently logged lands. Most of the redwood forest on this land had been tractor logged, which resulted in an extensive network of unpaved haul roads and tractor trails (skid roads). The newly acquired park lands included more than 650 km of abandoned haul roads and 4800 km of smaller skid trails. Due to a concern regarding downstream impacts of roads on streamside redwood forests and salmon-bearing rivers, the USDI National Park Service initiated an erosion control programme to reduce sediment production from these abandoned roads. The purpose of the programme, as stated in Public Law 95–250, was to reduce human-induced erosion within Redwood National Park and encourage the return of natural patterns of vegetation.

The main focus of the restoration programme has been to reduce sediment delivery from abandoned logging roads and restore natural drainage patterns. Typical treatments include decompacting the road surface, removing drainage structures (primarily culverts), excavating road fill from stream channels and exhuming the original streambed and streambanks, excavating unstable sidecast fill from the downslope side of road benches or landings, filling in or draining the inboard ditch, and mulching and replanting the sites. An evolution of road rehabilitation techniques, beginning in 1978, will be discussed in more detail below. About 300 km of abandoned logging roads were treated between 1978 and 1996 (Figure 1).

The restoration programme at Redwood National Park operated for many years under benign weather conditions, and between 1978 and 1996 Redwood Creek had no floods of greater than a five-year recurrence interval. In 1997, the treated roads received their first ‘test’ in the form of a 12-year recurrence interval storm. Although storm damage reports documented many landslides and culvert failures on untreated roads (Redwood National and State Parks, unpublished reports), the effect of the storm on treated roads was not known. An evaluation of treated roads was initiated to assess the success of the park’s rehabilitation programme in meeting its goal of sediment reduction from treated roads following a large storm.

The purpose of this paper is to evaluate the erosion and sediment delivery from treated roads based on measurements after the 1997 storm. The format of the study is retrospective rather than experimental because the road treatments from 1978 to 1996 were not applied in an experimental design. Several questions are posed in the present assessment: Are post-treatment erosion rates from removed roads related to hillslope position, hillslope gradient or hillslope curvature? Did the type of underlying bedrock influence post-treatment erosion rates? Did the effectiveness of different road treatment methods vary significantly in terms of reducing sediment yields? Because revegetation of treated sites increases with time, was post-treatment erosion related to time since rehabilitation? Was post-treatment stream channel adjustment related to stream power? From a basin-wide perspective, have road removal treatments significantly reduced sediment delivery from forest roads into streams?

PREVIOUS STUDIES

Many researchers have documented the effects of timber harvest and associated road construction in the Redwood Creek catchment. Janda *et al.* (1975) described hillslope and channel conditions in the Redwood Creek catchment, including the extent of timber harvest and some of its effects on the landscape. Their initial work spawned a series of more detailed studies of specific erosional processes. Marron *et al.* (1995) found that surface erosion from overland flow on forested and logged slopes in sandstone terrain in the Redwood Creek basin was minor, but sheetwash on tractor-logged slopes in schist terrain can be a significant sediment source. Gullying was a major erosion process on roaded prairies and logged lands in the Redwood Creek basin, and most of the gullies originated on unpaved logging roads (Weaver *et al.*, 1995). A sediment budget for Garrett Creek, a tributary to Redwood Creek, showed that road construction and logging accounted for

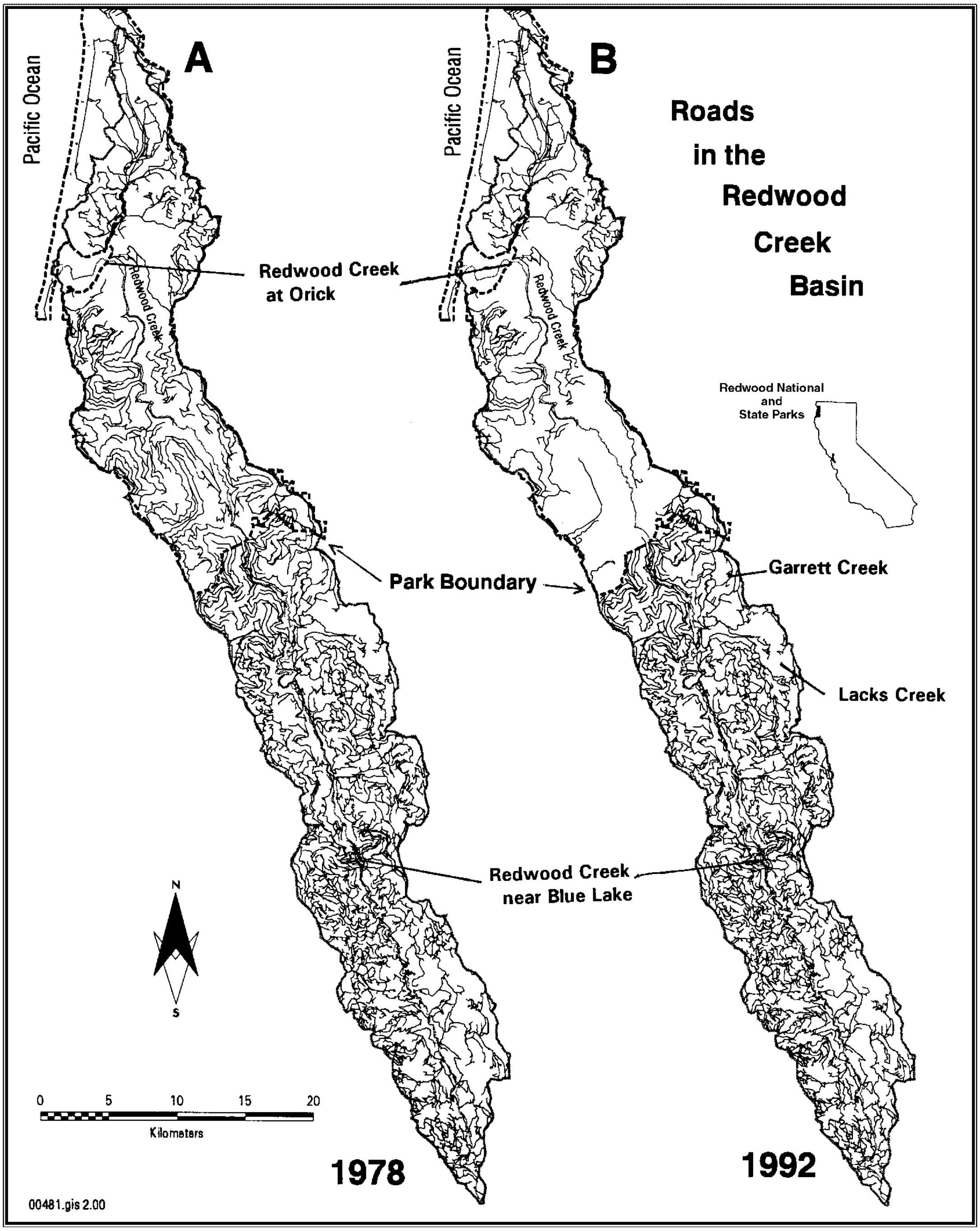


Figure 1. Location map of the Redwood Creek basin showing the distribution of roads in (A) 1978 and (B) 1992. Since 1978, about 300 km of road have been removed from the downstream third of the basin, which is managed by federal and state parks. The upstream two-thirds of the basin is privately owned and timber harvest is the primary land use

almost all significant sources of hillslope erosion (Best *et al.*, 1995). Landslides associated with roads and recently logged hillslopes accounted for nearly 80 per cent of total landslide erosion measured in the Redwood Creek catchment (Pitlick, 1995). Finally, Nolan and Janda (1995) reported that synoptically measured values of suspended-sediment discharge were roughly ten times greater from harvested terrain than from unharvested areas.

Although increased erosion rates and sediment yields following road construction and logging have been well documented in the Redwood Creek catchment, few studies address the change in erosion rates following road removal. Klein (1987) measured channel adjustments during the first year following excavations of 24 stream crossings in Redwood National Park. Following a five-year return interval flood, crossings eroded an average of $0{\cdot}8\,m^3\,m^{-1}$ of length of stream in the excavated crossing. Post-treatment erosion was most strongly related to stream power and inversely related to the percentage of coarse material in stream banks and large wood in the channel. Luce (1997) found that road ripping (decompacting the road bench) was effective in increasing the hydraulic conductivities of road surfaces, but did not restore the conductivities to those of a forested slope. Bloom (1998) contrasted the erosion derived from treated and untreated road segments in Redwood National Park following the 1997 storm, and reported that storm-related erosion on untreated roads was four times greater than on treated roads, and that erosion was related to hillslope position and proximity to fault zones.

FIELD AREA

The Redwood Creek catchment, located in the northern Coast Ranges of California, USA, is underlain by rocks of the Franciscan Assemblage, mostly sandstones, mudstones and schist. Redwood Creek drains an area of $720\,km^2$ and the basin receives an average of 2000 mm of precipitation annually, most of which falls as rain between October and March. Total basin relief is 1615 m and the average hillslope gradient is 26 per cent. Typical hillslope profiles consist of broad, convex ridges with steeper streamside slopes, where streamside landslides are common. Locally, a break in slope separates the more gentle upper hillslopes and steeper (>65 per cent) streamside hillslopes, which is called an inner gorge (Kelsey, 1988). Floodplain development is limited in the Redwood Creek catchment, and the streams considered in this study are highly constrained (valley width is less than two channel widths). None of the roads included in this study was located on a floodplain or terrace.

Prior to timber harvest, a conifer forest dominated by Coastal Redwood (*Sequoia sempervirens*) and Douglas Fir (*Pseudostuga menziesii*) covered most of the catchment, although scattered grasslands and oak-woodlands lined the eastern ridgetops. By 1997, 80 per cent of the original coniferous forest had been logged, and parklands encompass the remaining old-growth forests. The primary silvicultural method was clearcut logging with tractor yarding, which resulted in extensive ground disturbance and large areas of bare soil. Widespread construction of haul roads and smaller skid roads accompanied the timber harvest activities. The density of logging haul roads is $5\text{–}7\,km\,km^{-2}$.

DESCRIPTION OF ROAD TREATMENTS

The first step in treating forest roads was to map the geomorphic and hydrologic features of the road and adjacent hillslopes. Erosion features, drainage structures, the stream network, and the location of all roads, skid trails, seeps and springs were identified on enlarged aerial photographs at a scale of 1:1200. Following the mapping phase, road removal treatments were designed and implemented. In the early 1980s, road treatment work focused on removing culverts and pulling back road fill from streambanks (Figure 2a–d). In some cases, newly excavated stream channels were protected with check dams or large rocks (Figure 2b). The crossing excavations surveyed in this study varied from 100 to $7500\,m^3$ in volume, and averaged about $1000\,m^3$. Stream gradients of excavated stream crossings ranged from 1 to 50 per cent.

On road reaches between stream crossings, a variety of techniques were used, which varied in the amount of earth-moving involved (Figure 3a–e). Treatments in the early 1980s decompacted the road surface and constructed drains perpendicular to the road alignment to dewater the inboard ditch (a technique referred to as ‘ripped and drained’). Typically, 200 to $500\,m^3$ of road fill were moved for every kilometre of road treated

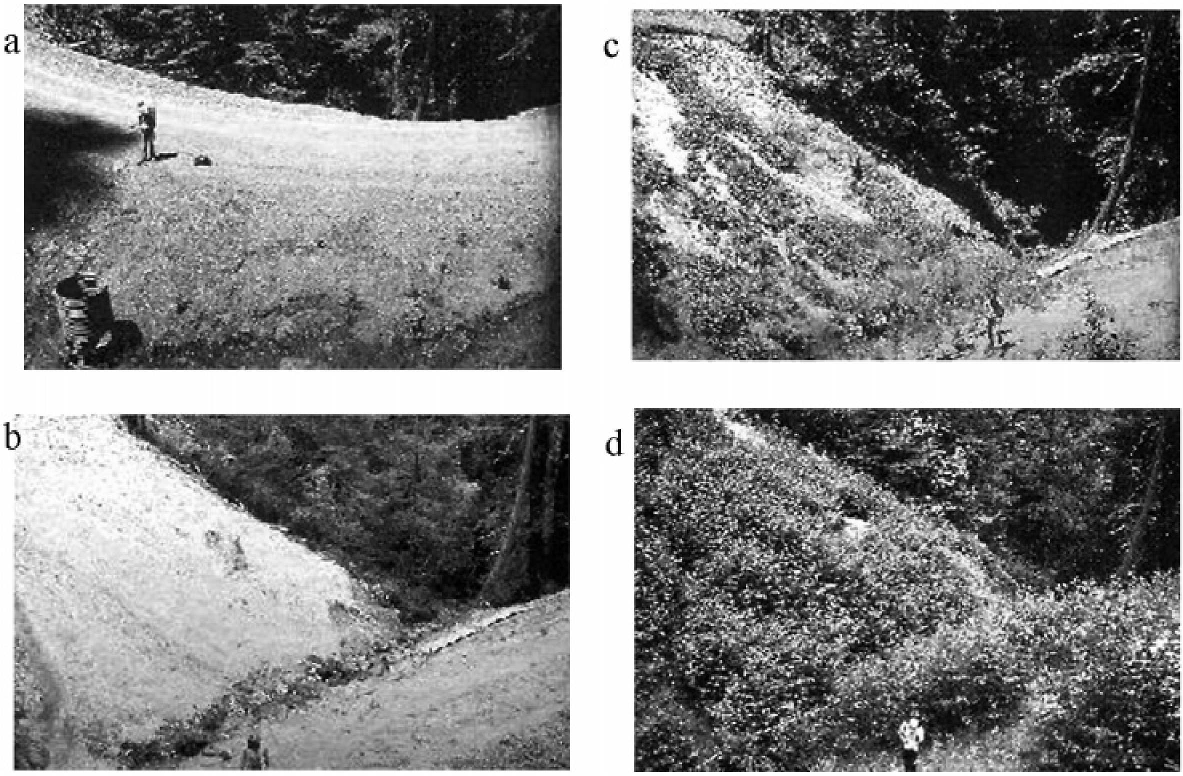


Figure 2. Typical stream channel excavation. (a) Abandoned logging road with intact culvert before treatment. (b) Immediately following stream crossing excavation. In this case, rock armour and check dams were installed on the channel bed to prevent downcutting. (c) Less than one year later, revegetation of the streambanks is well underway. (d) Three years after treatment, alders have revegetated most of the ground disturbed during treatment

with this method. This approach is the least intensive treatment (Figure 3b). Following this treatment, the roads were mulched with straw and seeded and replanted with native vegetation (Figure 4a and b).

As the programme progressed, park geologists began to use more intensive treatment methods, which included 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 (Figure 3c). This technique required more earth-moving (1000 to 2000 $\mathrm{m^3\,km^{-1}}$ of treated road). By the 1990s, geologists commonly prescribed complete recontouring of the road bench (total outslope), in which the cutbank was covered by excavated fill, original topsoil from the outboard edge of the road was replaced on the road bench where possible, stream channels were excavated to the original channel bed elevation, streambanks were extensively reshaped and the road bench was fully recontoured (Figures 3d, 5a and b). Total outsloping involved moving an average of 6000 $\mathrm{m^3\,km^{-1}}$ of treated road. Channel armouring was seldom used in this phase, but trees felled during road treatment were later placed in the stream channels and on the treated road surface. On some road segments, excavated road fill was removed from the road bench and transported to a more stable location; this technique is termed export outslope (Figure 3e). The locations where the road spoils were placed are called fill sites. Export outsloping involved the greatest amount of earth-moving (15 000 to 20 000 $\mathrm{m^3\,km^{-1}}$ of treated road). Because surface erosion is not considered to be a major sediment source (Kveton *et al.*, 1983), and natural revegetation is rapid in this region, little mulching or replanting has been done in recent years.

The cumulative length of road treated by the different methods is shown in Figure 6a. Most roads that were ripped and drained were treated prior to 1988, and most export outsloping occurred after 1988. This means that most minimally treated roads were subject to more storms than roads which had more intense levels of

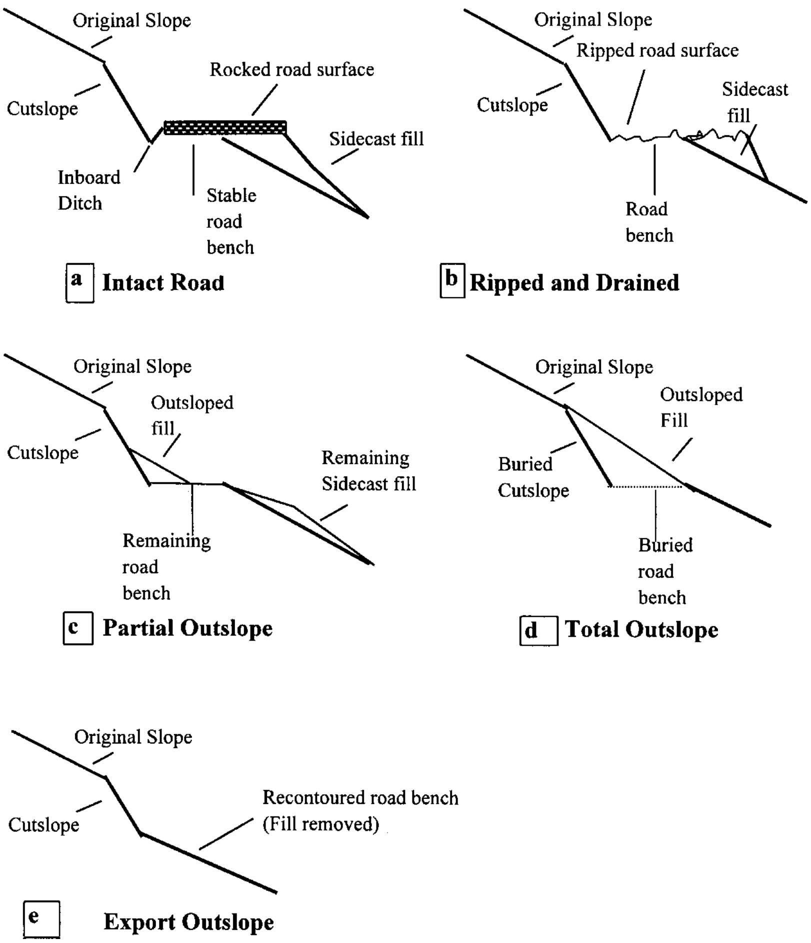


Figure 3. Schematic diagram showing the ‘anatomy’ of a road bench and various road treatment techniques. (a) Intact road bench with rocked surface and inboard ditch. (b) The road is ripped and drained, so the rocked surface is disaggregated and the function of the inboard ditch is eliminated. (c) Partial outslope, in which the steepest sidecast fill is placed at the toe of the cutbank. (d) Total outslope, in which all sidecast fill is placed at the toe of the cutbank. (e) Export outslope, where all the sidecast fill is removed from the road bench entirely

treatment. A greater length of road was treated in early years, when treatments were still being refined. Due to budget constraints and more intensive treatment in later years, fewer road segments were treated in more recent years. Figure 6b shows the cumulative length of road treated by hillslope position. More lower hillslope roads were treated in the first few years of the restoration programme than roads in upper and middle hillslope positions, and overall more lower hillslope roads were treated. The implications of these interactions among date of treatment, treatment method and hillslope position will be discussed more fully later.

METHODS

All treated roads within Redwood National and State Parks were subdivided into 1·6 km road segments. Because Bloom (1998) found that hillslope position was an important variable in evaluating erosion, road segments were stratified into three hillslope positions (upper, mid-slope and lower). The classification was based on the distance of the road from the adjacent ridgetop to the nearest high-order stream channel. In this catchment, hillslope position is related to slope gradient, with upper, middle and lower hillslopes averaging

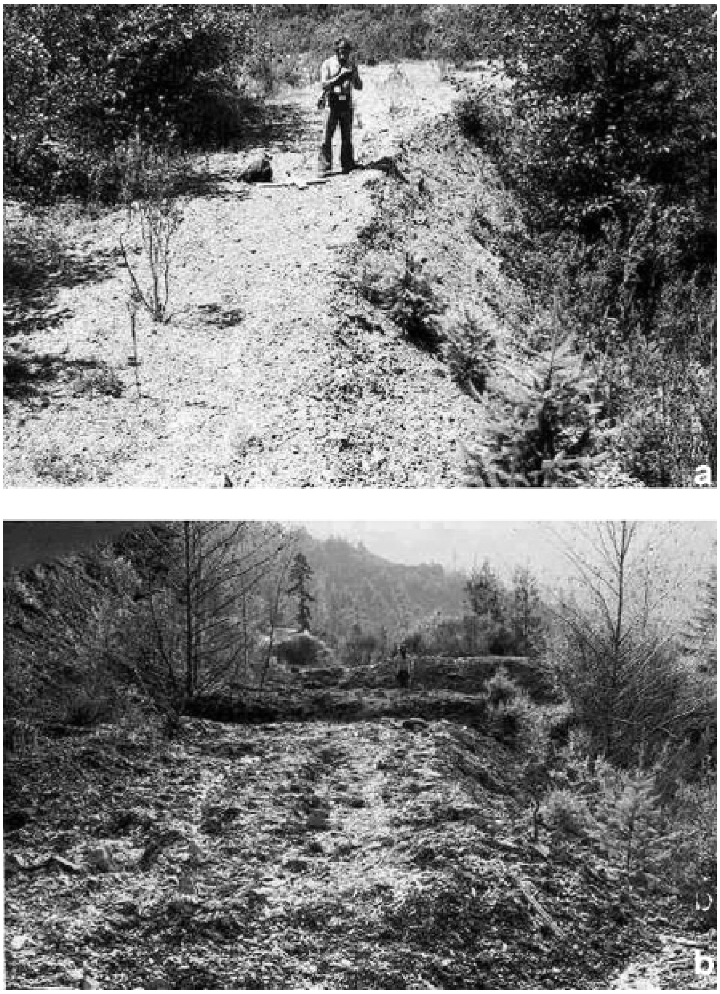


Figure 4. An example of the least intensive road rehabilitation technique. (a) Abandoned logging road before treatment. (b) The road surface is decompacted, and ditches are constructed perpendicular to the road alignment to drain the road. The road bench and road fill remain in place

25, 35 and 40 per cent, respectively. It was difficult to measure hillslope gradient accurately at treatment sites, because thick vegetation and large road prisms obscured the original topography. For this reason, hillslope position is used as a surrogate for hillslope gradient. Because the streams in this study are highly constrained within steep, V-shaped valleys, 'lower hillslope roads' do not include any roads on floodplains or terraces, but are typically in the steepest topography.

Forty road segments were selected randomly for field mapping, but two segments, later deemed inaccessible, were not surveyed. During the field mapping phase each road segment was further subdivided into 'stream crossings' where a culvert had been removed, and intervening 'road reaches' that were treated by a variety of methods. Geomorphic maps that were constructed when the roads were first treated were used to supplement field observations to reconstruct site conditions at the time of treatment. Each sampled road segment comprised several treatment sites, representing both stream crossings and road reaches. Consequently, the inventory of 38 segments of treated roads (61 km) resulted in a data set consisting of 207 crossings and 301 road reaches. Each excavated stream crossing and treated road reach had a separate inventory form with pertinent site information, map and erosion measurements.

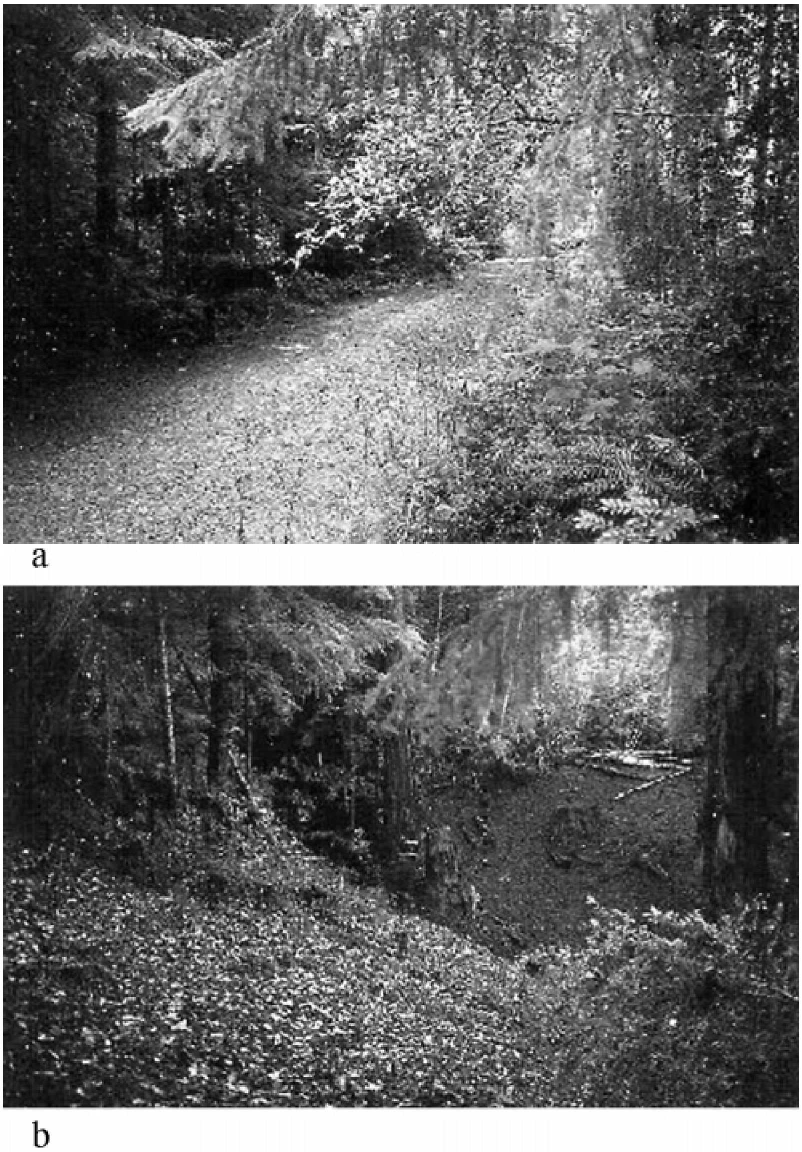
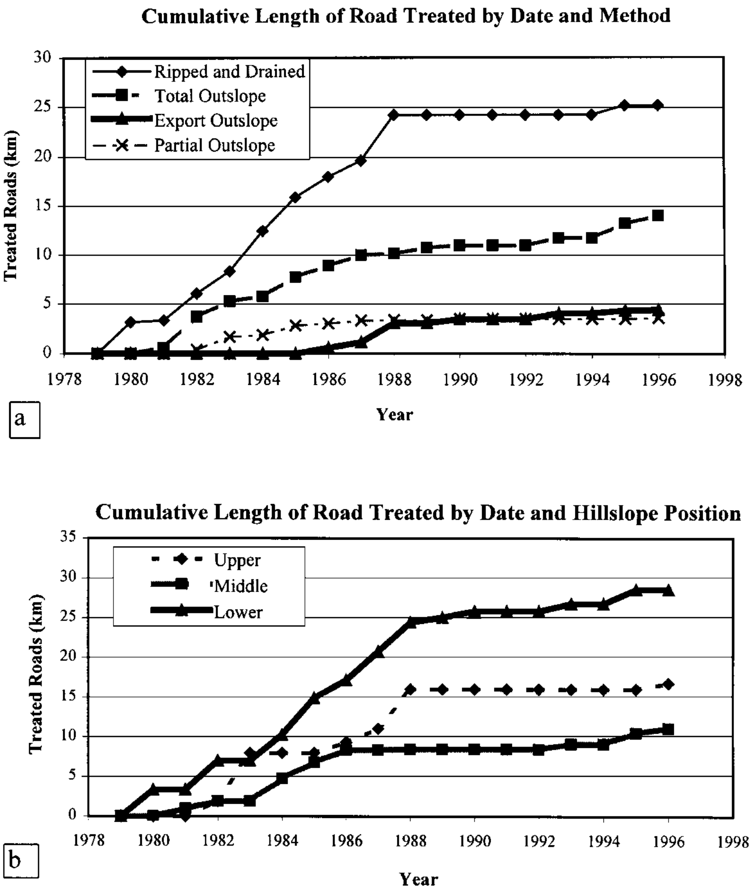


Figure 5. An example of the most intensive road rehabilitation technique. (a) Abandoned logging road before treatment. (b) The road bench is obliterated and the hillslope is recontoured (total outsloping of the road bench, and total excavation of the stream channel). Stumps uncovered during excavation indicate the location and elevation of the original hillslopes

Volumes from several types of post-road removal erosion were measured: mass movement, bank erosion and channel incision, and gullying. Because previous studies had shown that surface erosion from treated roads delivered a small proportion of the total sediment in this catchment (Kveton *et al.*, 1983) surface erosion on the treated road bench or crossing was not measured. Sediment delivery was estimated by measuring the void left by bank erosion or mass movement features and measuring the dimensions of the downslope deposit, if present. The estimated error of measuring the volume of voids and deposits was ±25 per cent. Commonly, the toe of the landslide entered a stream channel, and the eroded material had been transported from the site by the time of field mapping. Type and density of trees and percentage ground cover



Cumulative Length of Road Treated by Date and Method

Cumulative Length of Road Treated by Date and Hillslope Position

Figure 6. (a) Cumulative length of sampled roads by date and method of treatment. (b) Cumulative length of sampled roads by date and hillslope position

of herbaceous vegetation on the site were also recorded. Many road reaches were thickly vegetated, which obscured small post-treatment erosion scars.

Regression analyses were used to evaluate which site factors were important in explaining post-treatment erosion. Factors used in the analysis of erosion and sediment delivery from treated road reaches were: hillslope position (upper, mid-slope or lower); bedrock (schist, sandstone or other); treatment type (ripped and drained, partial outslope, total outslope, export outslope or fill site); time period of restoration activity (1980–1983, 1984–1987, 1988–1991 and 1992–1996); and hillslope curvature (convex, planar or concave). For stream crossings, the factors used were: bedrock type, date of treatment, drainage area, channel gradient, volume excavated from channels, step frequency and elevation drop due to steps. Because road reach boundaries were based on the spacing between stream crossings, road reaches were of unequal length. Consequently, erosion from road reaches was normalized by the length of road reach ($m^3\,m^{-1}$ of road). In contrast, crossing erosion was expressed as 'm^3 eroded per excavation'. It might also be preferable to express channel erosion volumes as a normalized value ($m^3\,m^{-1}$ of channel), but in the field it was difficult to determine accurately the length of the excavated channel. Post-treatment channel adjustment upstream and downstream of the excavated channels blurred the boundaries of the excavated channel, and in many sites post-treatment erosion extended beyond the limits of the crossing excavation itself.

The treatment method for stream crossings (removal of culverts and reshaping streambanks) differed from that for road reaches (decompacting, draining or recontouring the road bench). Also, fluvial erosion (channel incision and bank erosion) caused most post-treatment erosion in excavated stream crossings, whereas mass movements accounted for three-quarters of the erosion from road reaches. For these reasons, the analysis considered data for stream crossings separately from road reaches.

The results of the erosion measurements are reported as two values: (1) ‘total erosion since treatment’ in cubic metres (a measure of the volume of voids from mass movement, channel erosion or gullying on the treatment site); and (2) ‘sediment delivery to streams’, in cubic metres (the volume of the voids minus the volume of downslope deposits). Although the measure of voids on the treatment site was fairly straightforward, the determination of how much of the eroded material actually reached a stream was more subjective. Consequently, the estimates of sediment delivery from some sites are not as accurate as those of total erosion.

The date of treatment of the inventoried sites ranged from 1980 to 1996, and by 1997 when the sites were mapped, most road reaches and crossings were heavily revegetated with shrubs, hardwoods and some conifers. Thick revegetation (for example, Figure 2d) on most of the treated road reaches hindered a close inspection of the ground surface, and the minimum volume of erosion measured was $2\,\mathrm{m}^3$. This was considered the detection limit for erosion on road reaches, and by this definition only 20 per cent of the road reach sites had detectable erosion. Helsel and Hirsch (1997) consider data to be severely censored when data sets have >50 per cent of the values categorized as below the detection limit. In this situation, they recommend logistic regression as the appropriate analytical tool, and a response variable of ‘erosion’ or ‘no erosion’ on road reaches was used.

The explanatory variables are not necessarily independent. For example, the treatment technique of ripping and draining was more commonly used in the early time period of 1980 to 1983 than in later periods (Figure 6a). Another confounding factor is that the roads considered the most unstable were treated early in the programme (Figure 6b). Contingency tables were used to check for independence among the variables, and several interaction terms were tested for significance in the regression analyses. Step-wise logistic regression with forward selection, including interaction variables, was used to determine which variables to include in the most reasonable regression model.

In contrast to road reaches, 96 per cent of treated stream crossings exhibited detectable levels of erosion (although most channel adjustment was minor). The entire length and width of the excavated channel were surveyed, so detection of erosion was not a problem. In this case, standard multiple regression techniques were applied. An interaction term included in the regression analysis was (drainage area × channel gradient), a surrogate for stream power. Stepwise regression with forward selection, using an F-to-enter of 4 ($p = 0{\cdot}05$) determined which variables to include in the final regression model.

RESULTS AND DISCUSSION

Distribution of treated roads across sampling strata

Due to the history of the restoration programme at Redwood National Park, not all road types and road treatment techniques are equally distributed across time and space. Contingency table tests showed that, at a 99 per cent confidence level, several variables were not independent of one another: year of treatment, method of treatment and hillslope position. This fact is illustrated in Tables I and II, which show the percentages of road length sampled in different categories. For example, 50 per cent of the sampled road length was on lower hillslope positions. This does not mean there was originally greater road length on lower hillslopes, but that the restoration programme targeted such roads for early treatment, leaving more upper hillslope roads untreated. Export outsloping was more commonly prescribed on lower hillslope roads, so few of the randomly selected road reaches in upper and mid-slope positions had this treatment technique applied. Early in the programme, more roads were minimally treated, and total outsloping was more common in later years. Because of budget constraints and the use of more expensive techniques, fewer roads were treated in the period 1992–1996, so the length of treated road in this category is less than for other time periods.

Table I. Percentage of sampled road length according to hillslope and treatment types

	Road rehabilitation technique					
Hillslope position	Ripped and drained	Partial outslope	Total outslope	Export outslope	Fill site	Total
Upper	13	5	9	<1	3	30
Mid-slope	8	2	9	<1	1	20
Lower	21	6	7	12	4	50
Total	42	13	25	12	8	100

Consequently, any extrapolation of the results of this study must consider the constraints placed by the distribution of sampled road reaches across the various strata.

Stream crossings

From 1980 to 1997, the total amount of material eroded from 207 crossings following treatment was 10500 m^3, or about 50 m^3 per crossing. Although this represents a direct contribution of sediment to perennial streams, it is likely that, if these crossings had not been treated, much more sediment would have eventually been eroded and delivered into streams. For example, 220 000 m^3 of road fill was excavated from the crossings during treatment (1060 m^3 per crossing) which represents the maximum volume of erodible material if those crossings had remained intact. In reality, not all the road fill actually erodes when a crossing fails. In the Garrett Creek catchment (a basin adjacent to the study area), Best *et al.* (1995) determined that the average erosion from 75 failed crossings that had not been treated was 235 m^3. On the other hand, by excavating crossings and restoring natural drainage patterns, diversion of flow from the natural channel is prevented. Best *et al.* (1995) showed that at locations where roads did cause streams to divert (at one-quarter of the crossings sampled), the average erosion was 2650 m^3. These lines of evidence suggest that the likely volume of erosion from the excavated crossings would have been at least four times greater, and probably more, if they had not been treated.

Most excavated stream crossings produced very little sediment. (Crossings which had debris torrents originating upslope and off-site of the crossing excavation were not included in this analysis because the purpose was to look at the effectiveness of the road treatment itself.) Twenty per cent of the excavated stream crossings produced 73 per cent of the total volume eroded from stream crossings (Figure 7a) Klein (1987) and Bloom (1998) suggest that most channel erosion occurs in the first few floods following treatment, and later adjustments of the channel form are smaller in magnitude. Virtually all the road fill eroded from the treated channels was transported off site by the time the crossings were inventoried.

Channel incision and bank erosion were the most common forms of post-treatment erosion in crossings. Only two explanatory variables were significant in the best-fit regression model:

$$\begin{aligned}\text{Volume eroded from crossing } (\mathrm{m}^3) = {} & 20{\cdot}8 + 0{\cdot}041 \text{ (drainage area} \times \text{channel gradient)} \\ & + 0{\cdot}009 \text{ (volume excavated, } \mathrm{m}^3)\end{aligned}$$

Table II. Percentage of sampled road length according to bedrock, hillslope curvature and date of treatment

Bedrock type %		Hillslope curvature %		Date of treatment %	
Schist	72	Concave	25	1980–1983	30
Sandstone	22	Planar	19	1984–1986	32
Other	6	Convex	56	1987–1991	27
				1992–1996	11

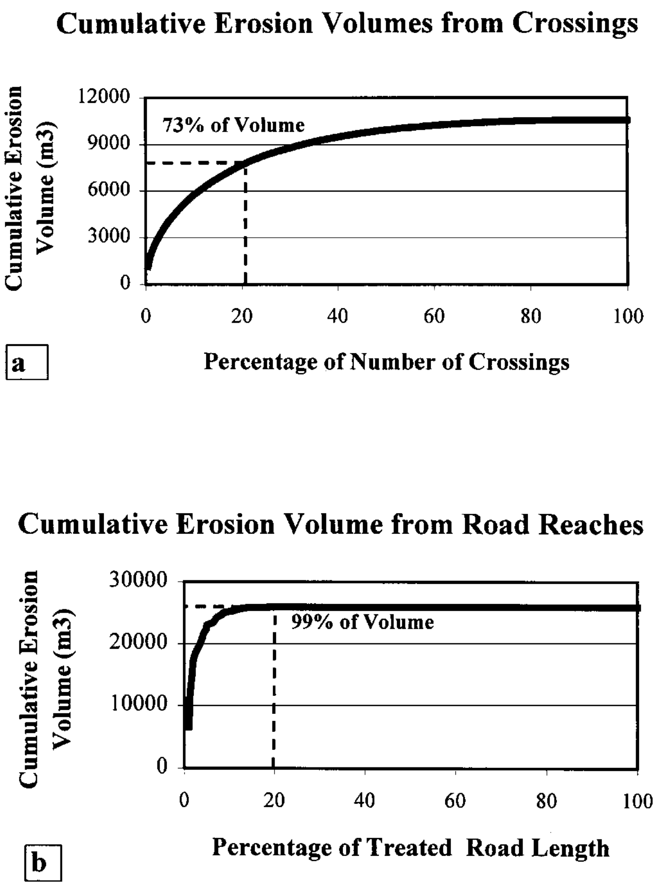


Figure 7. (a) Cumulative plot of total erosion from excavated stream crossings. Twenty per cent of the crossings accounted for 73 per cent of the total erosion. (b) Cumulative plot of total erosion from treated road reaches. Twenty per cent of the treated road length accounted for 99 per cent of the total erosion

The surrogate for stream power (drainage area × channel gradient) ($p < 0{\cdot}001$) and the volume of material excavated from a channel during treatment ($p = 0{\cdot}0085$) were significant variables in explaining the volume of post-erosion in excavated stream channels. The greater the stream power and the larger the excavation, the more the channel eroded following treatment. Deeply incised channels that required more fill to be excavated were more vulnerable to post-treatment erosion than shallow crossings with less road fill because the reshaped streambanks were steeper, more extensive and more likely to fail. The regression model was statistically significant at the 99 per cent confidence level; however, the fitted model explains only 18 per cent of the variability in post-treatment erosion. Erosion following treatment is highly variable, and many site-specific conditions (such as the presence of bedrock, springs or poorly drained soils or incomplete excavations) can influence post-treatment erosion as well.

Road reaches

The total amount of material eroded from treated road reaches was 25 900 m^3. Most (77 per cent) of this erosion was attributed to mass movement processes, primarily road fill failures. Of the total erosion from road reaches, 74 per cent of the eroded material was delivered to a stream channel. Most treated road reaches performed well and produced very little sediment. The cumulative distribution of erosion from road reaches is

Table III. Volume of sediment delivered to channels from treated road reaches ($m^3 km^{-1}$ of road length)

Hillslope position	Road rehabilitation technique: Ripped and drained	Partial outslope	Total outslope	Export outslope	Fill site
Upper	10	10	10	N/A*	0
Mid-slope	310	0	20	N/A*	80
Lower	640	550	630	920	40

* Less than five samples in this category

even more highly skewed than that for road crossings (Figure 7b). Twenty per cent of the treated road reach length produced 99 per cent of the total erosion from treated road reaches. Total post-treatment erosion from 61 km of road, including both fill failures and stream crossing erosion, was 36 400 m^3 (600 $m^3 km^{-1}$ of road); total sediment delivery was 29 500 m^3 (480 $m^3 km^{-1}$ of road).

A logistic regression model, based on 'erosion' or 'no erosion' of the treated road sites, resulted in four significant explanatory variables: hillslope position, date of treatment, treatment type and an interaction term (hillslope position × treatment type). The results of the logistic regression can be expressed by the odds of failure (that is, erosion occurred on the road reach). For example, the odds of failure of roads treated in the early part of the programme (1980–1983) were 6·7 times greater than the odds of failure for roads treated later (1992–1996). An approximate 95% confidence interval for this odds ratio is 5.4 to 8.1. Similarly, the odds of failure for roads in lower hillslope positions were five times those of upper hillslope roads (95% CI: 4.5 to 6.3 times), and the odds of failure for mid-slope roads were 3 times those of upper slope roads (95% CI: 2.2 to 4.4 times). The logistic regression was rerun, redefining 'failure' to be erosion >50 m^3 rather than only >2 m^3. The odds ratios were similar, in that lower slope roads treated early in the restoration programme were the most likely to have failed (Madej, 2000).

Although the model was significant at the 99 per cent confidence level, the percentage of deviance explained by the model is only 16 per cent. Erosion on treated road reaches was highly variable, as it was for treated stream crossings. Besides the geomorphic variables considered in this analysis, road reach erosion is also influenced by site-specific conditions, such as the presence of seeps, depth to bedrock, or history of past mass movement activity. Even though bedrock type was not a significant variable in this regression model, a finer distinction of bedrock based on the degree of fracturing, shearing and erodibility in individual units may be worth exploring in the future.

The interaction of hillslope position and treatment type was significant in the logistic regression model, and this interaction is described more fully in Table III. The 'odds of failure' result defined by the logistic regression does not give information on the size of failure. Accordingly, Table III pertains to the magnitude of the failure, and contrasts sediment delivery under different treatment and hillslope conditions. On upper hillslopes, sediment delivery from all treatment types is low. Even minimal treatment seemed to be sufficient to prevent erosion on these sites. This suggests that, except for sensitive geomorphic locations such as headwater swales, a low intensity (and concomitantly, less expensive) treatment is adequate for upper hillslope roads. Sediment delivery from mid-slope roads was also low, except for those that had minimal treatment. For effective sediment reduction, more intensive treatment, such as partial or total outsloping, is warranted on mid-slope roads. Lower hillslope roads, which were built on the steepest topography in the catchment, exhibited the highest erosion rates, no matter which treatment was used. It is interesting to note that the most intensive treatment method (export outsloping) was associated with the highest sediment delivery to streams from road reaches in lower hillslope positions.

The expectation of the road rehabilitation programme had been that the more intensive the treatment, the less post-treatment erosion would occur. Nevertheless, this result of high erosion rates should not be automatically interpreted as a general failure of the technique. Professional judgement is used when restoration treatments are formulated for a given road reach. Park staff who prescribed the high intensity treatment of export outsloping recognized some inherent instability of the road reach, based on evidence of past mass movement, the presence of seeps in the cutbanks, incipient failure of the road bench, etc. Consequently, these road reaches were among the most unstable even before road treatments were applied, and so might be expected to erode more following any type of treatment. On the other hand, because more land area is disturbed using this treatment method, and the capacity of the road bench to store material from cutbank failures is eliminated, it may be that the treatment allows for greater sediment delivery than other treatments. A closer examination of the conditions under which export outsloped road reaches fail and deliver sediment is necessary to distinguish the causal mechanism.

Road rehabilitation efforts following road construction in steep, lower slope positions have a high failure rate and contribute much sediment to streams, no matter what type of treatment is used (Table III). If sediment reduction from roads is the objective in a catchment, these observations suggest the need to avoid road construction (or improve road construction techniques) in these steep, streamside areas. Not only are these likely spots for erosion while the road is in place, but also subsequent treatment of the road may not be effective in eliminating road-related sediment production.

BASIN-WIDE PERSPECTIVE OF SEDIMENT PRODUCTION

No direct measurements of sediment yield from treated roads during the 1997 storm are available. The numbers from this inventory can be roughly compared with measurements made at the gauging station at the mouth of Redwood Creek (drainage area = 720 km^2). The total sediment load for water-years 1978 to 1998 was about 13 600 000 Mg. The inventory of 61 km of treated roads showed a contribution of 29 500 m^3 of sediment to streams (480 m^3 per km of treated road) during this same period. If the randomly sampled roads are representative of all treated roads, and this rate is applied to the entire 300 km of treated roads in Redwood National Park, 144 000 m^3 of sediment probably entered streams from treated roads. Consequently, sediment yield from treated roads represents a contribution of about 233 000 Mg to the basin's sediment load (assuming a bulk density of 1·62 g cm^{-3}), which constitutes less than 2 per cent of the total load of Redwood Creek at Orick during this period. Of the sediment contributed from treated roads, some of the coarse particles eroded from the road fill were transported as bedload, some broke to suspended size particles during transport, and some sediment was temporarily stored in small stream channels, but little is known about the specifics of sediment routing through these steep, low-order channels.

Without treatment, roads have some potential to eventually fail and contribute sediment to streams. Based on an inventory of 330 km of untreated roads in nearby basins, Weaver and Hagans (1999) estimated past road-related sediment delivery to be 720 m^3 km^{-1} of road, and future potential sediment delivery without road treatment to be an additional 820 m^3 km^{-1}, for a total of 1540 m^3 km^{-1}. In a similar study based on 140 km of untreated roads in the Redwood Creek catchment (G. J. Bundros and B. R Hill, unpublished data, 1997) past and potential sediment delivery from roads was reported to be 1450 m^3 km^{-1}. Untreated roads in the Garrett Creek catchment produced much more sediment (4670 m^3 km^{-1})), most of which originated from debris torrents caused by stream diversions (Best *et al.*, 1995). By removing culverts and restoring natural drainage patterns, park staff have removed the risk of stream diversions that would cause such debris torrents. None of the 207 excavated crossings examined in this study had diversions or debris torrents related to road treatment. These different lines of evidence suggest that, although road restoration in Redwood National Park did not completely prevent sediment production from removed roads, it does substantially reduce the long-term sediment risk from abandoned roads.

In contrast to the road inventories described above, a recent study by Rice (1999); also conducted in the Redwood Creek basin, reports an erosion rate of only 176 m^3 km^{-1} of untreated logging road during the period 1995 to 1997. The hillslope position of these sampled road plots was not reported. The roads in Rice's study area were only subjected to a rainfall event of less than five-year return interval, based on rain gauge records at Redwood Creek near Blue Lake and at Lacks Creek. Under these relatively low rainfall intensity storms, few culverts failed, as might be expected. Most road-related erosion in the past has been linked to culvert failures, diversions and landslides that occurred during high intensity rainfall events. It is likely that the erosion rate reported by Rice (1999) does not represent the full erosion potential from untreated roads if these roads underwent a high intensity rainfall event.

CONCLUSIONS

Post-treatment erosion of both stream crossings and road reaches following removal of forest roads was highly variable. On average, treated roads contributed 480 m^3 of sediment to streams per kilometre of road, which was about one-quarter the sediment produced from untreated roads. Only 20 per cent of the excavated stream crossings accounted for 73 per cent of the post-treatment erosion from crossings. In stream crossings, two variables (a surrogate for stream power [drainage area × channel gradient] and the amount of road fill excavated from the stream crossing during treatment) were significant in the best fit model for post-treatment erosion.

Almost 80 per cent of the treated road reaches had no detectable erosion following a 12-year recurrence interval storm. Even though most treatment sites were heavily vegetated within a few years of treatment, road fill failures still occurred on 20 per cent of the road reaches. Hillslope position was an important variable in explaining post-treatment erosion of road reaches. Road reaches that exhibited erosional problems were most commonly found on steep, lower hillslopes and both minimal (ripping and draining) and more intensive (export outsloping) road treatments on lower hillslope roads resulted in high sediment yields to streams ($660\,\mathrm{m}^3\,\mathrm{km}^{-1}$ of treated road). In contrast, on more gentle, upper hillslope positions, all treatment styles worked well and sediment delivery rates were only about $10\,\mathrm{m}^3\,\mathrm{km}^{-1}$ of treated road. By eliminating the risk of stream diversions and culvert failures, road treatments significantly reduce the long-term sediment risk from abandoned roads.

Adaptive land management involves monitoring the effects of management activities, and modifying land management approaches and techniques based on what is found to be effective. The results of this study can be used in an adaptive management strategy to guide future road removal work in the most cost-effective manner. The assessment presented here can also serve as a framework for evaluating the success of other restoration programmes. Although erosion rates measured in this study are specific to the site conditions of the Redwood Creek catchment, this approach can be adapted to other regions. Accelerated erosion rates are a widespread problem in many regions of the world, and road treatments can be effective in significantly reducing sediment yields from abandoned roads.

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