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March 3, 1849

May 9, 2001

Mr. Matt St. John
5550 Skylane Boulevard, Suite A
Santa Rosa, California 95403

Dear Mr. St. John:

I am writing this letter in response to the North Coast Regional Water Quality Control Board's solicitation for new data on water quality conditions. Besides studies completed before 1997, the U.S. Geological Survey has collected and analyzed additional data for the Redwood Creek basin since 1997, which may not yet be in your data base. This information covers three areas of study: 1) landslide initiation during the January, 1997 storm, 2) erosion generated from both decommissioned and untreated roads, and 3) changes in pool depths and frequencies following the January, 1997 flood. The January, 1997 flood was a moderate flood in terms of the climatic record of the North Coast, including the Redwood Creek basin (recurrence interval of 12 years at Redwood Creek at Orick). Although such a flood could be expected to occur about once a decade, because the last few years have been fairly dry, it was the highest flood peak since 1975.

1. A student in the Department of Geology at Humboldt State University, Tera Curren, is working on a Master's thesis that involves the study of landslides in the Redwood Creek basin. Although her project is still in progress and results should be considered preliminary at this point, I am including summary results in Figure 1. Landslides were mapped from aerial photographs and were classified as being located in the Lower Basin (the area downstream of the boundary of Redwood National and State Parks), the Middle Basin (between State Highway 299 and the park boundary) or the Upper Basin (the area upstream of Highway 299). More than 100 landslides delivered sediment directly to the main channel of Redwood Creek (Figure 1-A). Most of these landslides were located in the Upper Basin, and most were older slides that were reactivated during the flood. In addition to mainstem landslides, about 300 landslides occurred higher on the hillslopes or contributed sediment to tributary streams (Figure 1-B). The west side of the basin in primarily underlain by schist bedrock, whereas the east side is dominated by sandstones. Figure 1 shows only the number of landslides, not the volume of sediment generated. Volume computations will be completed in the near future, but initial results show that the five largest sediment contributors during the storm were debris torrents that originated on logging roads. The analysis of the relationships among landslide occurrence and bedrock geology, hillslope gradient, presence of roads, and timber harvest is not yet completed. Nevertheless, it is clear that there are still many unstable areas within the Redwood Creek watershed, which were activated during a moderate-sized storm. Large volumes of sediment entered the Redwood Creek channel from landslides, and caused several discernible changes in channel morphology (see # 2).

2. Thalweg profiles have been surveyed in the downstream third of the Redwood Creek channel since 1977. These surveys of the channel bed are useful to detect changes in pool depths and frequencies through time. The attached publication, "Temporal and Spatial Variability in Thalweg Profiles of a Gravel-bed River" discusses the results of these surveys. Following large floods and high sediment input in Redwood Creek in 1975, the channel bed was relatively flat, with shallow water depths and few pools. Through time Redwood Creek began to recover from the poor habitat conditions of 1975. Average water depth increased, and the variability of water depths (indicative of channel complexity) also increased. The percentage of channel length in riffles decreased and pools increased. Then, following the 1997 flood, the trends of channel recovery reversed. The Redwood Creek channel reverted to conditions that were similar to those in 1983 (impaired, but not as severely as in 1975). All three monitored reaches in lower Redwood Creek showed the same reversal of channel recovery (no surveys are available from upper reaches of Redwood Creek). This indicates that the sediment supply in Redwood Creek was still high enough in 1997 to cause filling of pools, a decrease in water depth, and a decrease in channel complexity (variability of the channel bed).

3. Erosion from unpaved forest roads has been identified as a significant source of sediment to Redwood Creek (Nolan and others, 1995) Road decommissioning is designed to reduce erosion from abandoned or obsolete roads. Erosion from both decommissioned and untreated roads in the Redwood Creek basin was measured following the 1997 storm. The attached publication, "Erosion and Sediment Delivery Following Removal of Forest Roads," and Bloom (1998) report the results of these studies. One of the main points of these papers is that erosion from roads is highly dependent on the geomorphic setting of the road. Sediment delivery from treated roads varied from 10 m^3 of sediment per kilometer of treated road on gentle, upper hillslopes to 550 m^3 of sediment per kilometer of road on steep lower hillslopes. Untreated roads contributed significantly more sediment to streams (from 1500 to 4700 m^3 of sediment per kilometer of road length). Although road decommissioning does not completely eliminate erosion associated with forest roads, it does substantially reduce sediment yields from abandoned logging roads. Untreated roads, especially those in sensitive geomorphic locations, represent a future supply of sediment to the channel network of the Redwood Creek basin.

Another study of erosion from roads in the Redwood Creek basin was conducted by Rice (1999). In contrast to the above study, Rice's paper reported little erosion generated from roads during the 1997 storm. A rebuttal to his paper is attached. There are several reasons for the discrepancy between Rice's results and my own. First, although the storm of 1997 was the largest in several years, rainfall intensities were not unusual. Storm rainfall depths had a return period of only 2 to 7 years. The ground became saturated over the duration of the storm, resulting in many landslides (#1 above), but the relatively low intensity rainfall did not tax culvert capacities nor did it cause stream diversions at inadequate road-stream crossings. It is likely that under higher rainfall intensities, untreated roads would exhibit more erosional problems than occurred during the 1997 storm. In addition, as stated above, the erosion potential of a road strongly depends on its geomorphic setting. The Rice paper did not specify the setting of the roads in his study (hillslope gradient, hillslope position, drainage density, etc.). Historically, the most severe erosion in the basin has occurred during large (25-year or larger) storms. Rice's contention that improved forest practices resulted in low erosion rates from roads needs to be tested under more intense rainfall conditions.

In summary, although Redwood Creek conditions had improved from 1977 to 1996, conditions deteriorated following the flood of 1997. Landslide activity was evident throughout the basin. A widespread network of unimproved forest roads still presents a threat of erosion in future large storms. In the light of these studies, I support the continued listing of Redwood Creek as sediment impaired under the Federal Clean Water Act Section 303(d). Please feel free to contact me at the above address if you need any further clarification of these issues.

Sincerely,

Mary Ann Madej

Mary Ann Madej, Ph.D.
Research Geologist

Enc.

cc: Superintendent, Redwood National and State Parks
Chief, Resource Management and Science, Redwood National and State Parks

References:

Bloom, A. L. 1998. An assessment of road removal and erosion control treatment effectiveness: a comparison of 1997 storm erosion response between treated and untreated roads in Redwood Creek basin, Northwestern California. Master's Thesis. Humboldt State University. Arcata, CA. 150 p.

Nolan, K. M., H. M. Kelsey, and D. C. Marron. 1995. Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. U.S. Geological Survey Professional Paper 1454.

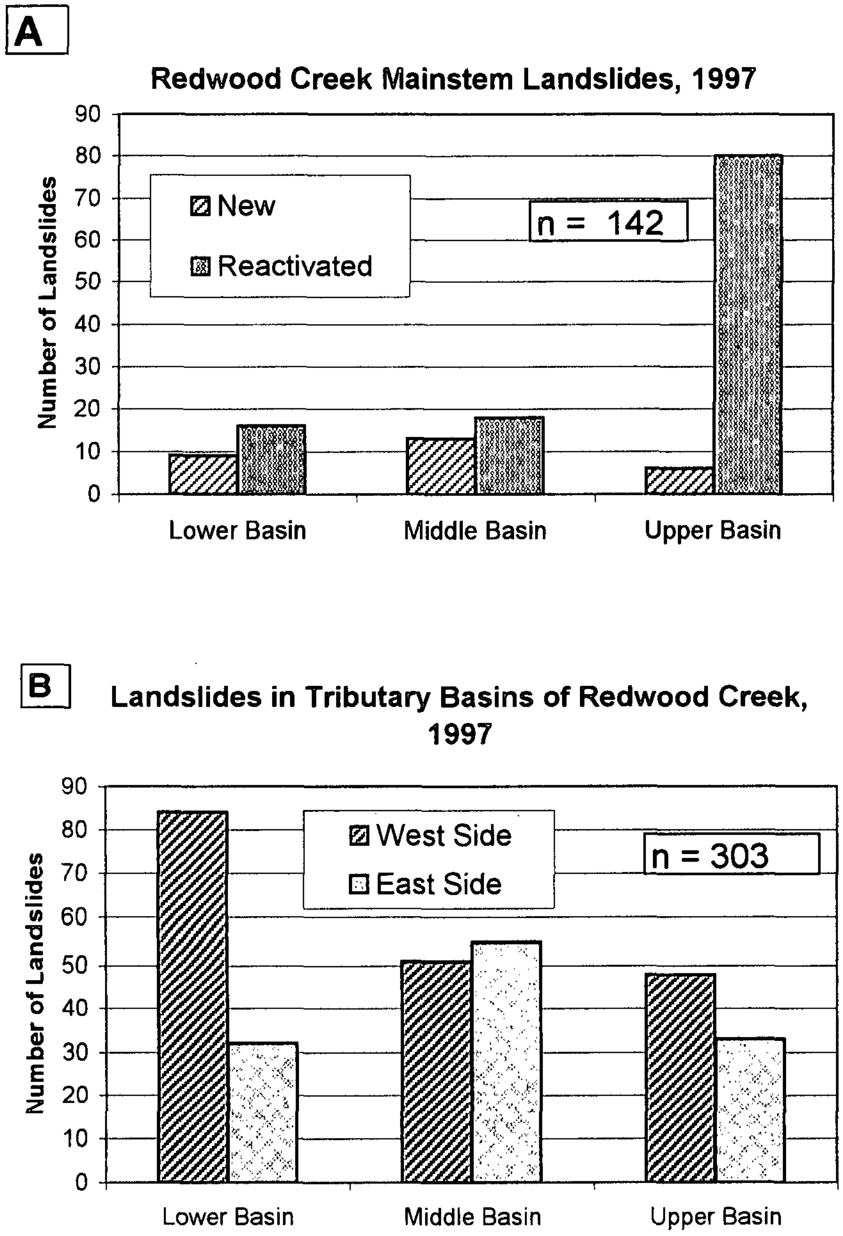

Figure 1. Frequency and distribution of landslides in the Redwood Cre basin following the flood of January, 1997.

Earth Surface Processes and Landforms
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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

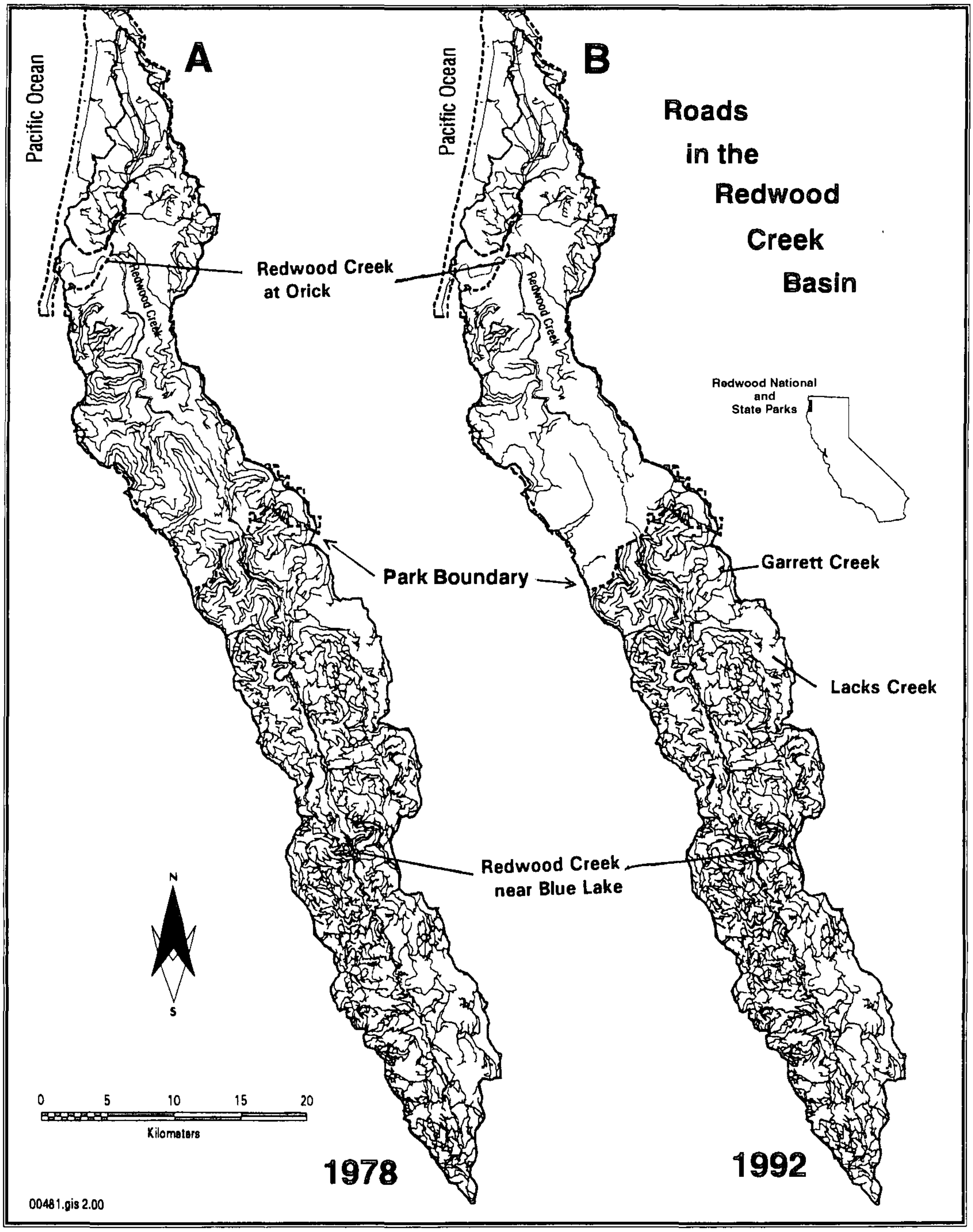

Figure 1. Location map of the Redwood Creek basin showing the distribution of roads in (A) 1978 and (B) 1992. Since 1978, about 300 km of road have been removed from the downstream third of the basin, which is managed by federal and state parks. The upstream two-thirds of the basin is privately owned 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 $5–7\ km\ km^{-2}$.

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

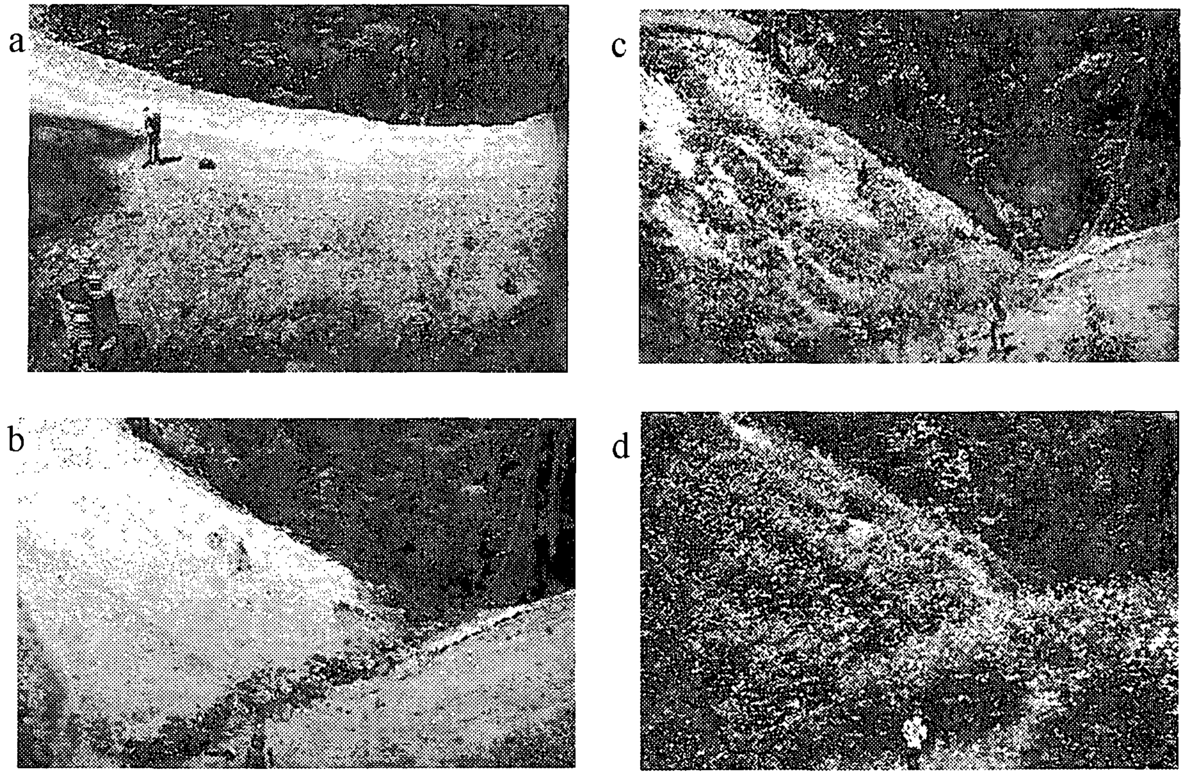

Figure 2. Typical stream channel excavation. (a) Abandoned logging road with intact culvert before treatment. (b) Immediately following stream crossing excavation. In this case, rock armour and check dams were installed on the channel bed to prevent downcutting. (c) Less than one year later, revegetation 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 $m^3 km^{-1}$ 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 $m^3 km^{-1}$ 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 (15000 to 20000 $m^3 km^{-1}$ 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

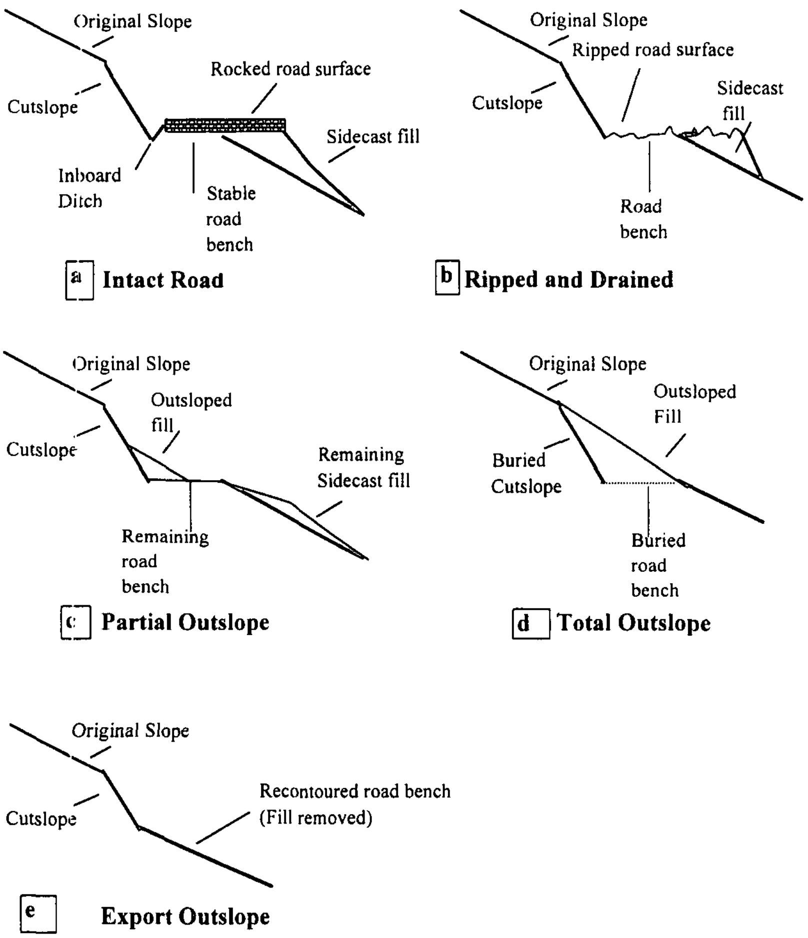

Figure 3. Schematic diagram showing the 'anatomy' of a road bench and various road treatment techniques. (a) Intact road bench with rocked surface and inboard ditch. (b) The road is ripped and drained, so the rocked surface is disaggregated and the function of the inboard ditch is eliminated. (c) Partial 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

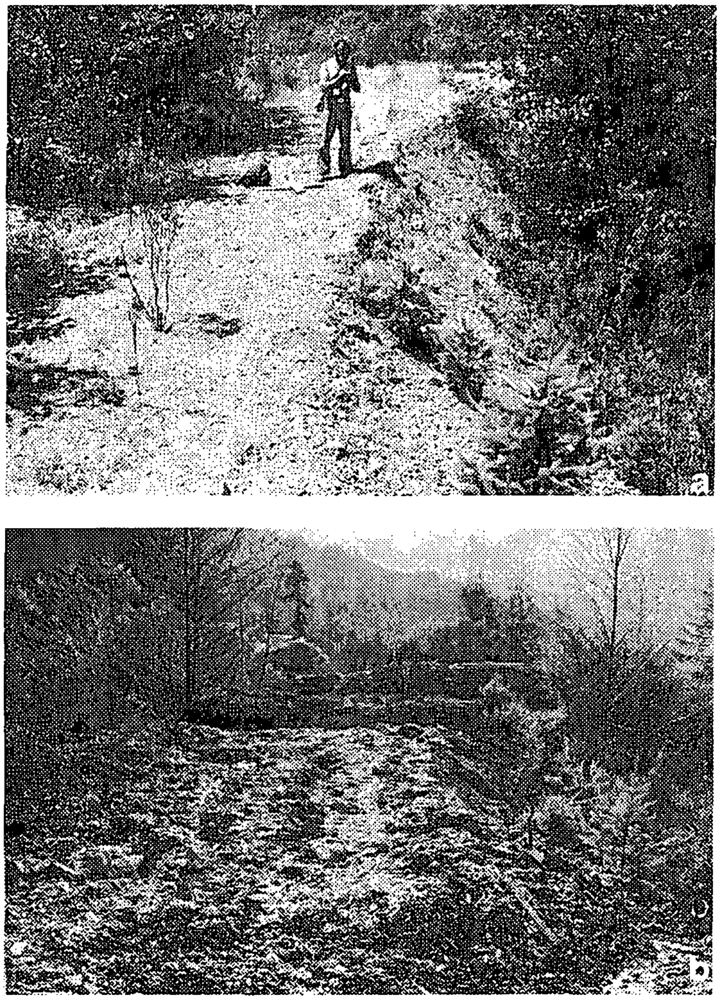

Figure 4. An example of the least intensive road rehabilitation technique. (a) Abandoned logging road before treatment. (b) The road surface is decompacted, and ditches are constructed perpendicular to the road alignment to drain the road. The road bench and road fill remain in place

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.

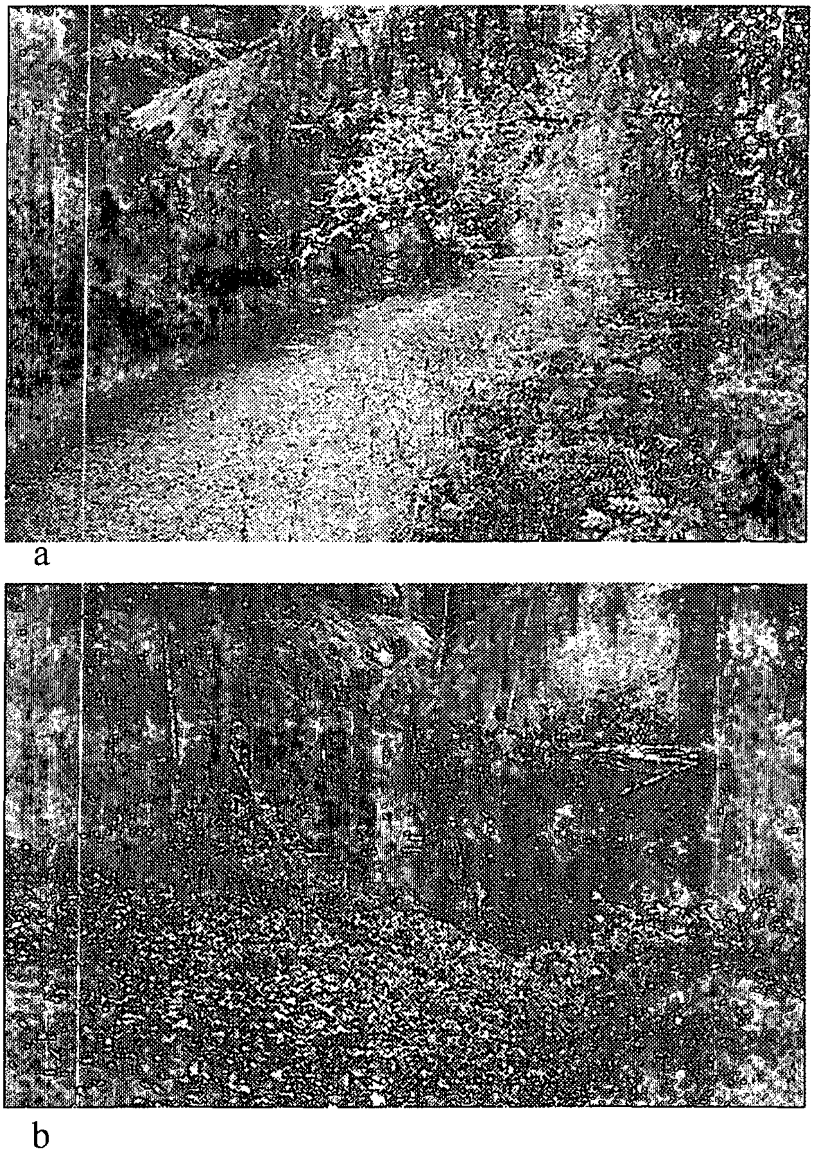

Figure 5. An example of the most intensive road rehabilitation technique. (a) Abandoned logging road before treatment. (b) The road bench is obliterated and the hillslope is recontoured (total outsloping of the road bench, and total excavation of the stream channel). Stumps uncovered during excavation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

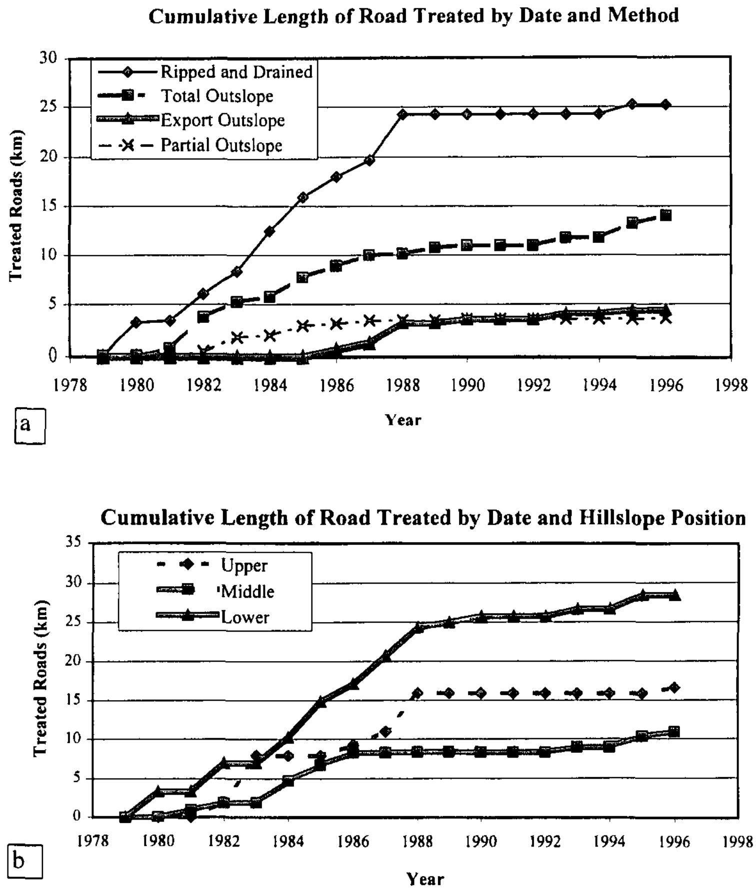

Figure 6. (a) Cumulative length of sampled roads by date and method of treatment. (b) Cumulative length of sampled roads by date and hillslope position

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 $2\,m^3$. 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

Hillslope position	Road rehabilitation technique: 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, 220000 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:

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

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

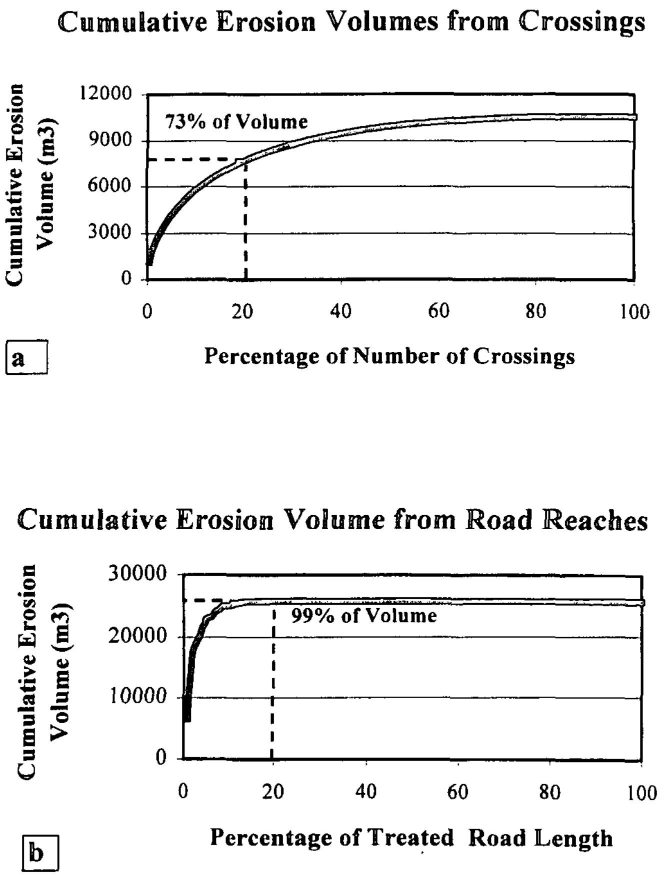

Figure 7. (a) Cumulative plot of total erosion from excavated stream crossings. Twenty per cent of the crossings accounted for 73 per cent of the total erosion. (b) Cumulative plot of total erosion from treated road reaches. Twenty per cent of the treated road length accounted for 99 per cent of the 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 600000 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, 144000 m^3 of sediment probably entered streams from treated roads. Consequently, sediment yield from treated roads represents a contribution of about 233000 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 $\mathrm{m}^3\,\mathrm{km}^{-1}$ of road, and future potential sediment delivery without road treatment to be an additional 820 $\mathrm{m}^3\,\mathrm{km}^{-1}$, for a total of 1540 $\mathrm{m}^3\,\mathrm{km}^{-1}$. 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 $\mathrm{m}^3\,\mathrm{km}^{-1}$. Untreated roads in the Garrett Creek catchment produced much more sediment (4670 $\mathrm{m}^3\,\mathrm{km}^{-1}$)), 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 $\mathrm{m}^3\,\mathrm{km}^{-1}$ 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 $m^3\ km^{-1}$ of treated road). In contrast, on more gentle, upper hillslope positions, all treatment styles worked well and sediment delivery rates were only about 10 $m^3\ km^{-1}$ 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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TEMPORAL AND SPATIAL VARIABILITY IN THALWEG PROFILES OF A GRAVEL-BED RIVER

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ABSTRACT

This study used successive longitudinal thalweg profiles in gravel-bed rivers to monitor changes in bed topography following floods and associated large sediment inputs. Variations in channel bed elevations, distributions of residual water depths, percentage of channel length occupied by riffles, and a spatial autocorrelation coefficient (Moran's I) were used to quantify changes in morphological diversity and spatial structure in Redwood Creek basin, northwestern California. Bed topography in Redwood Creek and its major tributaries consists primarily of a series of pools and riffles. The size, frequency and spatial distribution of the pools and riffles have changed significantly during the past 20 years. Following large floods and high sediment input in Redwood Creek and its tributaries in 1975, variation in channel bed elevations was low and the percentage of the channel length occupied by riffles was high. Over the next 20 years, variation in bed elevations increased while the length of channel occupied by riffles decreased. An index [(standard deviation of residual water depth/bankfull depth) × 100] was developed to compare variations in bed elevation over a range of stream sizes, with a higher index being indicative of greater morphological diversity. Spatial autocorrelation in the bed elevation data was apparent at both fine and coarse scales in many of the thalweg profiles and the observed spatial pattern of bed elevations was found to be related to the dominant channel material and the time since disturbance. River reaches in which forced pools dominated, and in which large woody debris and bed particles could not be easily mobilized, exhibited a random distribution of bed elevations. In contrast, in reaches where alternate bars dominated, and both wood and gravel were readily transported, regularly spaced bed topography developed at a spacing that increased with time since disturbance. This pattern of regularly spaced bed features was reversed following a 12-year flood when bed elevations became more randomly arranged. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: gravel-bed river; longitudinal profiles; pool–riffle morphology; Redwood Creek; residual water depth; spatial autocorrelation; thalweg

INTRODUCTION

Flow resistance in gravel-bed streams is influenced by the particle size present on the channel bed surface (skin friction) and form roughness caused by bed irregularities such as bed forms and pebble clusters. However, deformation of the velocity field associated with larger-scale features of bed topography, flow obstructions, large woody debris, channel bends and abrupt changes in channel geometry also contribute to flow resistance (Dingman, 1984). The flow resistance of the channel increases as the sum of all sources of channel roughness increases.

Disturbances such as major floods and large sediment inputs can modify bed topography, and so influence channel roughness. In gravel-bed rivers, low-gradient (<2 per cent) reaches commonly display pool–riffle morphology, and disturbances can reduce the size and frequency of deep pools. Consequently, channel roughness becomes smoother, and the changes in bed topography caused by disturbance will be reflected in changes in velocity and shear stress distributions as well. Following input of a pulse of sediment and debris, river channel processes and forms will adjust and evolve towards a new equilibrium state. The trajectories and timing of these adjustments involved in 'recovery' following disturbance are of interest to both

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geomorphologists and aquatic ecologists. Disturbance to a dynamically stable riffle–pool channel which results in aggradation leads to riffles becoming more extensive, pools becoming smaller and shallower, and bed material textures becoming finer (Lisle, 1982; Jackson and Beschta, 1984). The fluvial system may be interpreted as exhibiting non-linear system behaviour and, hence, system trajectories are dependent upon instantaneous system states (Lane and Richards, 1997). Thus, an understanding of the sequence of configurations (in this case, the sequence of development of longitudinal thalweg profiles) through which the system evolves is essential in order to explain system behaviour (Lane and Richards, 1997).

The thalweg profile is influenced by the distribution of pools and riffles. The distribution of the gravel bar units that constitute riffles, and their associated pools, can be 'free' or 'forced' (Seminara and Tubino, 1989). Freely formed pools result from the fluvial hydraulics of the stream and patterns of flow convergence and meander development. Several studies have shown that in alluvial, self-formed channels, pool spacing is between five and seven times the channel width (Leopold *et al.*, 1964; Keller and Melhorn, 1978). Pools can also be 'forced' (Lisle, 1986; Montgomery and Buffington, 1997) by scour around obstructions such as large woody debris, boulders and bedrock outcrops. Forced pools may be spaced closer than pools in self-formed channels (Montgomery *et al.*, 1995). The distribution of forcing elements (large woody debris, boulders and bedrock outcrops) in many catchments is random and, consequently, no regular spacing between forced pools would be expected. It follows that different patterns of pool distribution (random or regular) may be used to determine the relative importance of different formative mechanisms.

The conceptual model proposed in this paper is that spatial structure in a longitudinal profile may be attributed to the type of material dominating channel boundary characteristics (sediment, woody debris or bedrock) and the time elapsed since the last major disturbance (due to floods or landslides, for example). Spatial structure in a thalweg profile is defined by several elements, including the presence of regular oscillations in bed topography (primarily due to pools and riffles), the strength of spatial autocorrelation between points in the channel bed, and the length of channel bed exhibiting autocorrelation (such as the length of a riffle crest). Immediately following disturbance, a river that can readily reorganize the dominant channel-forming materials in the channel bed may exhibit low variation in bed elevations and no regular pattern in bed topography. This would be the case, for example, in rivers where the bed material size is much less than the bankfull depth, or the length of key elements of woody debris is less than the channel width. However, with increasing time since disturbance, variation in bed topography will increase and the arrangement of spatial structure in the bed profile will become more regular. In contrast, no regularly spaced features in the bed will evolve in rivers that cannot readily reorganize the dominant channel-forming materials. This would be the case, for example, in rivers where the bed particle size approaches bankfull depth, or length of large woody debris is greater than the channel width and forced pools dominate. A random pattern of bed topography would be expected in a stream with many forced pools, whereas a regular pattern would be expected if pools were freely formed by the hydraulics of converging flow in an alternate bar river.

REVIEW OF EXISTING APPROACHES

Several methods of quantifying longitudinal channel bed patterns, and especially the presence of pools, have been developed. A technique frequently used in the United States to determine the distribution of pools is 'habitat typing' in which an observer walks the channel and uses a tape to measures the length of pools, riffles and other features (US Forest Service, 1992). There are, however, problems with habitat typing including high operator variability, lack of replicability and discharge dependency.

O'Neill and Abrahams (1984) suggested an objective method of identifying pools, but their approach determines only numbers of pools and riffles and it is still based on a single threshold measure of the deepest part of the pool. Peterson *et al.* (1992) attempted to set target conditions for pool frequency, but they admitted that the criteria used to define pools varied considerably among studies that applied their analysis. Hogan and Church (1989) suggested that depth and velocity distributions across the entire channel area could be used to support more complete habitat assessment. In practice, these distributions are functions of river stage and they are, in any case, difficult to measure for high flows.

The problem with all these approaches is that they assume that the pool is the only feature of interest in channel spatial structure, and that a pool can be objectively defined and consistently identified. In addition to pools, the degree of variation of channel bed elevations is an important component of channel boundary conditions, which cannot be derived simply from an analysis of maximum pool depths. In practice, two pools with equal maximum depths may have very different bed morphologies and may have been formed by different fluvial processes.

To monitor pool depths independently of discharge, Lisle (1987) adapted the concept of residual water depth that was first introduced by Bathurst (1981). The residual pool depth (d_r) is the depth of water in the pool below the elevation of the downstream riffle crest. This can be thought of as the water depth that would be present in the river if stream flow were zero and the riffle were impermeable. The distribution of residual water depths along the entire longitudinal profile incorporates thalweg topography and provides more useful information than any analysis of the pools alone. For example, Lisle (1995) found comparison of the standard deviation of residual water depths useful in identifying and assessing morphological differences between two streams due to differences in their coarse woody debris loadings. However, this approach has not to date been applied to larger rivers with different disturbance histories.

Spatial statistics provide an objective technique to detect the presence of channel bed features, such as pools or riffles. Richards (1976) used spatial series analysis to quantify oscillations in channel width and in the longitudinal bed profile. Robert and Richards (1988) demonstrated the usefulness of semivariograms to model sand bedforms, and Robert (1988) used them to define micro-scale bed relief (5 mm spacing along a 6 m transect) in gravel-bed streams. However, two fundamental problems exist in the use of the semivariogram to define patterns in bed topography. First, there is no simple way of determining confidence limits analytically (Robert and Richards, 1988) and, second, they have limited utility in detecting areas of similar bed elevation, such as a riffle crest. While spectral analysis has been used to define patterns of bed elevation in sand-bed channels, it is difficult to place a physical interpretation on the results (Robert and Richards, 1988). Murray and Paola (1996) discuss the limitations of using spectral analysis and fractal methods to determine the downstream spatial structure of fluvial patterns. For example, similar power law spectral behaviour can be produced by systems that are very different in character. Robison and Beschta (1989) used correlograms to define the spatial autocorrelation of low flow depths in several small streams with high coarse woody debris loadings. The results showed no significant pattern in the distribution of low flow depths for their study reaches, which were located in pristine, forested streams with many forced pools. Also, although spatial statistics have been used to characterize channel morphology at a given time, their use in monitoring temporal trends of morphological change following channel disturbance is much more limited.

On the basis of this review of past research, it may be concluded that changes in longitudinal profiles over decadal time-scales have not to date been studied systematically. To address this gap in knowledge, this paper evaluates several potential approaches to quantifying changes in thalweg morphology following disturbances due to large sediment inputs. The paper examines the potential for using the distribution of residual water depths as a tool for monitoring the bed morphology of disturbed channels. It employs spatial autocorrelation analysis of the morphological data to depict temporal changes in the spatial structure of bed topography. Within the temporal framework, spatial statistics are used to characterize whether the longitudinal pattern of bed elevations is random or regular, and to estimate the maximum morphological variance or similarity in different parts of the channel.

FIELD AREA

The Redwood Creek catchment is located in the northern Coast Ranges of California, USA (Figure 1), and is underlain by rocks of the Franciscan Assemblage, mostly sandstones, mudstones and schist. The basin has an area of 720 km^2 and 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. Redwood Creek is a gravel-bed river with a length of 100 km and channel gradients ranging from 12 per cent in the headwaters to 0·0·1 per cent in the lower reaches. Channel gradient is less than 2 per cent in the lowest 80 km of Redwood Creek and the bed morphology is characterized by pools and riffles.

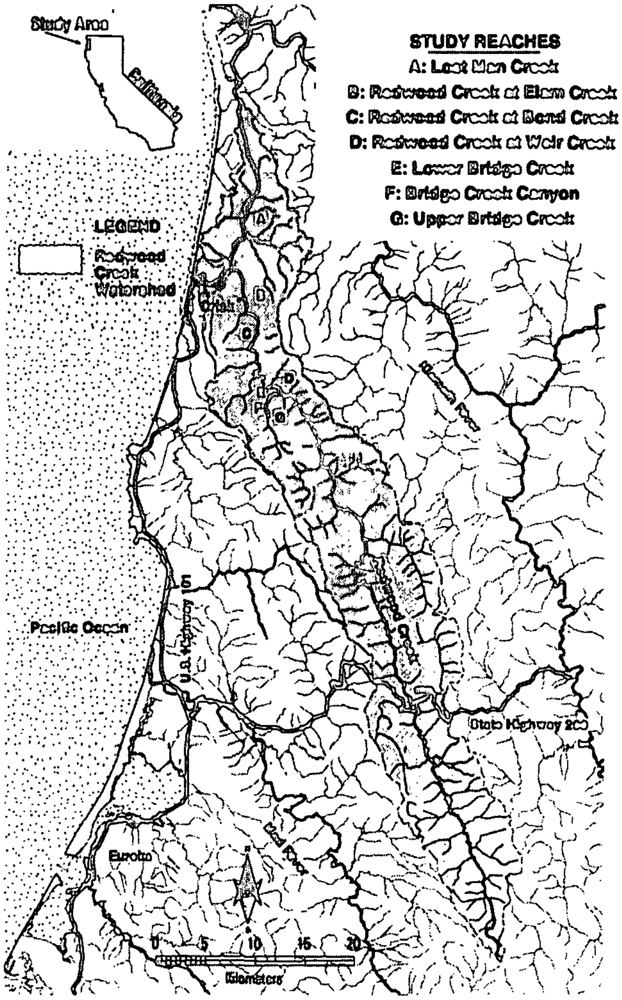


Figure 1. Location map of the Redwood Creek catchment showing the three study reaches on the mainstem of Redwood Creek, three in Bridge Creek and one in Lost Man Creek

Most tributaries are steep (>4 per cent), but the four largest tributaries include low-gradient reaches with well developed pool–riffle morphology like that in the main stream. Two of the larger tributaries, Bridge Creek and Lost Man Creek, are included in this study. There is no pristine, low-gradient 'control' reach with which to compare the disturbed reaches. However, Lost Man Creek has experienced no land-use disturbances since it underwent timber harvesting and road construction during the 1960s. Hence, this stream was used for comparison with the study reaches.

Prior to 1945, 85 per cent of the Redwood Creek basin was forested with stands of redwood (*Sequoia sempervirens*) and Douglas fir (*Pseudotsuga menziesii*) (Best, 1995). These trees can reach 100 m in height and 3 m in diameter, and the large woody debris contributed by fallen trees affects the morphology of many streams. During the last four decades, large floods and extensive logging have resulted in widespread channel aggradation and bank erosion (Madej and Ozaki, 1996). A 50-year flood in 1964 caused extensive streamside landsliding, but no surveys are available during that period to quantify channel changes.

Following a 25-year flood in 1975, the channel beds of Redwood Creek and its tributary Bridge Creek were almost flat and featureless in many reaches. Between 1977 and 1997, longitudinal thalweg profiles of several reaches of Redwood Creek and Bridge Creek were resurveyed on several occasions to monitor the changes in

Table I. Study reach characteristics

	Redwood at Weir Creek	Redwood at Bond Creek	Redwood at Elam Creek	Upper Bridge Creek	Bridge Creek Canyon	Lower Bridge Creek	Lost Man Creek
Drainage area (km^2)	523	585	605	25	27	30	20
Bankfull width (m)	60	70	110	23	12	15	14
Bankfull depth (m)	2·2	2·0	1·9	1·0	1·3	1·2	1·2
Channel gradient (%)	0·24	0·18	0·15	1·24	1·66	1·12	0·71
Profile length (m)	2500	2100	2530	550	670	400	810
D_{50} (mm)	22	18	15	30	60	32	45
Influence of large woody debris	Low	Low	Low	Moderate	High	Moderate	Moderate

pool distribution and depths as the morphology responded to the 1975 depositional event. The depth and frequency of pools in Redwood Creek increased between 1977 and 1995 (Madej, 1996; Madej and Ozaki, 1996) and pools are presently spaced about three channel widths apart in most of the study reaches. Channel cross-sectional changes were also monitored, and these have shown systematic spatial patterns of bank erosion, aggradation and subsequent degradation (Madej and Ozaki, 1996). Between 1977 and 1996, no flow exceeded a five-year recurrence interval. However, in 1997, a 12-year flood initiated many new debris flows that contributed large volumes of sediment to the rivers and triggered renewed aggradation in several reaches.

Seven study reaches, representing a range of channel morphologies and types, were established on Redwood Creek (three), Bridge Creek (three) and Lost Man Creek (one) (Figure 1). Reach characteristics are listed in Table I. Redwood Creek has low-sinuosity planform ($p = 1{\cdot}03$ to $1{\cdot}10$) displaying alternate bars. Typical bar lengths are 350 to 500 m. Mean particle size is small in comparison to depth, and the few pieces of in-channel large woody debris in the study reach are much shorter than the channel width. Upstream reaches of Redwood Creek aggraded following the 1975 flood, but have subsequently degraded (Madej, 1996). The study reach 'Redwood Creek at Weir Creek' is within this degrading segment of river. Farther downstream, Redwood Creek at Bond Creek and Redwood Creek at Elam Creek are two reaches that aggraded by an average of 0·6 m between 1975 and 1986, but subsequently degraded by about 0·3 m between 1986 and 1995 (Madej and Ozaki, 1996). The channel bed in these three study reaches aggraded slightly (0·1 m) after the 1997 flood (Ozaki and Jones, 1998).

Bridge Creek is a gravel-bed stream which presently exhibits an alternate bar planform, with typical bar lengths of 150 to 200 m. In 1954 and 1971, large woody debris was removed from the channel to salvage merchantable timber (Klein *et al.*, 1987). Since 1971 the input of new large woody debris has been limited and, due to the extensive harvesting of streamside trees, the present debris loading is lower than it would be under pristine conditions. Although longitudinal profile surveys did not commence until 1986, field observations and examination of available aerial photographs indicate that Upper Bridge Creek received high sediment inputs in 1975. Cross-sectional monitoring shows that a great deal of sediment was transported out of the upper reach prior to 1986, but that only 0·2 m of further degradation occurred between 1986 and 1995. In 1997 a debris flow delivered 13 000 m^3 of sediment and a great deal of large woody debris to the channel upstream of the upper surveyed reach and the channel aggraded locally as a result (Madej and Gibbs, 1998).

A narrow canyon, in which large woody debris, boulders and bedrock outcrops are common, separates the upper and lower reaches of Bridge Creek. In Lower Bridge Creek the channel degraded by 2 m between 1975 and 1986, but the rate of downcutting had decreased to 0·1 m/yr by 1996 (Madej and Gibbs, 1998). In 1986, woody debris loading was low in Lower Bridge Creek, but landslides generated by the 1997 storm event contributed many new pieces of large woody debris to this reach.

FIELD METHODS

Three to five resurveys of the study reaches were performed between 1977 and 1997 to document the development of bed morphology, and especially pools and riffles, following the 1975 flood. The US

Geological Survey in the summer of 1977 surveyed a longitudinal thalweg profile of the lowest 22 km of Redwood Creek. The author resurveyed selected reaches of this area in 1983, 1986, 1995 and 1997. Surveys of Bridge Creek, reported by Klein *et al.* (1987), were conducted in 1986, and by the author in 1995 and 1997. Surveyed long-profiles began and ended at riffle crests and survey distances were measured along the centreline of the high-flow channel. Elevations of the thalweg and water surface were established using either an automatic level and stadia rod, or an electronic distance meter and target. Survey readings were taken at all breaks in slope of the channel bed in order to characterize all major morphologic features (i.e. top, middle and base of riffles and pools) along the thalweg. The spacing of survey points averaged 15 m in Redwood Creek and 4 m in Bridge Creek. In Redwood Creek, surveyors used staff plates at three gauging stations and 20 permanent bench marks established for channel cross-sectional monitoring as controls on surveying accuracy. The total error in elevation between the surveys was less than 0·2 per cent (0·8 m). The length of each surveyed profile was 20 to 55 channel widths (400 to 2500 m, depending on the stream reach; Table I).

Channel planform patterns and bar lengths were mapped from aerial photographs at a scale of 1:6000, dating from 1978 and 1997. Unfortunately, bar lengths on the two dates could not be compared quantitatively because the discharge in the 1997 photographs is six times higher than that in the 1978 photographs. However, bar shape and location in the channel were compared qualitatively. Bar lengths measured on the 1978 photographs (taken during summer low flow) were used to calculate mean bar lengths in Redwood Creek.

ANALYTICAL TECHNIQUES

The distribution of residual water depths for each longitudinal survey was calculated using the method of Lisle (1987). First, bed elevations between survey points were linearly interpolated to create a common base from which to compare profiles for different years. A 5 m spacing was used for Redwood Creek, where channel widths vary from 60 to 110 m, in order to define all but the finest features of longitudinal bed topography. A 3 m spacing was employed for Bridge and Lost Man Creeks, where widths vary from 12 to 23 m. A computer program was written to plot the profiles, convert the surveys into standardized data sets, calculate the distribution, mean and standard deviation of residual water depths, and compute the percentage of channel length occupied by riffles. For this purpose, riffle points were defined as points where the residual depth was zero. Figure 2a shows an example of a surveyed thalweg profile and Figure 2b illustrates the profile data transformed into residual water depths. Variability in bed elevations was evaluated using the standard deviations of residual water depth for each study reach. The significance of differences in the means, medians and distributions of residual water depth distributions from successive surveys was examined using the Student's *t*, Mann–Whitney and Kolmogorov–Smirnov tests, respectively.

The spatial distribution of pools and riffles is also of geomorphological interest, but the residual depth distributions do not contain information on the spatial ordering of pools within the fluvial system. To analyse spatial patterns in the distributions of pools and bed elevations, residual water depths were analysed by the use of the Moran's I spatial autocorrelation coefficient (Legendre and Fortin, 1989). The formula for I at distance class d is:

$$I(d) = \frac{n\sum\sum w_{ij}(y_i - \bar{y})(y_j - \bar{y})}{W\sum(y_i - \bar{y})^2}$$

where y = residual water depth at points i and j in the channel, and $\bar{y}$ = mean residual depth. All summations are for i and j varying from 1 to n, the number of data points, but exclude the cases where $i = j$. The w_{ij}'s take the value of 1 when the pair (i,j) pertains to the distance class d, and 0 otherwise. W is the number of pairs of points used in computing the coefficients for the given distance class. Moran's I may be positive or negative, with values usually ranging between -1 and $+1$. Moran's I compares values for pairs of points (residual water depths) at different distance classes (lag distance). The distance classes used ranged from 5 m (3 m in Bridge and Lost Man Creeks) to one-third of the long-profile length, or about 800 m in Redwood Creek.

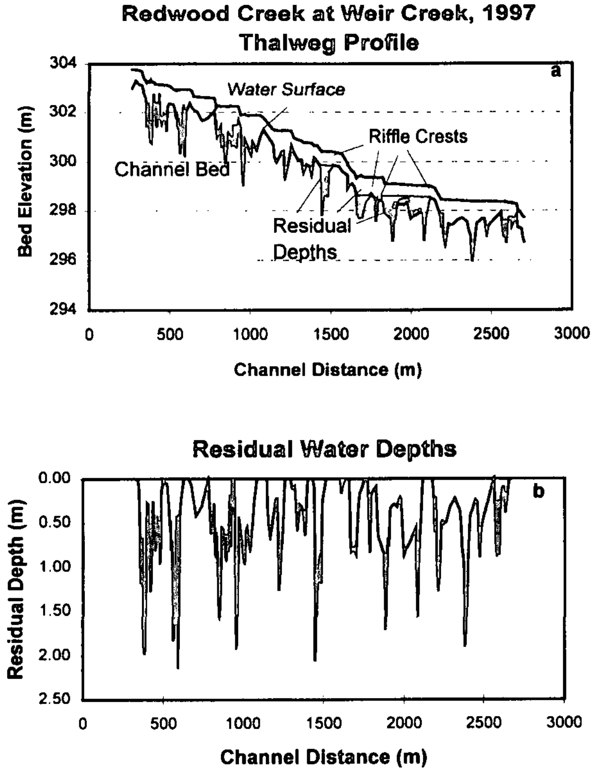


Figure 2. Examples of longitudinal thalweg profile plots showing (a) how residual water depths are calculated and (b) the corresponding residual water depth plot for Redwood Creek at Weir Creek

Surveys from 1977 were not used in this analysis because the spacing of survey points was larger than in the other surveys, which would limit the ability of the correlograms to detect small bed features.

The spatial structure of the channel bed profiles was examined using correlograms. Correlograms are plots of autocorrelation values (in this case, Moran's *I*) in the ordinate against distances between pairs of thalweg survey points (lag distances). The characteristics of the correlogram shape, such as the spacing between peaks and troughs and the width of a peak, are associated with particular spatial structures (Legendre and Fortin, 1989). Positive correlation (points plotted above the 95 per cent confidence interval line on the correlogram) show distances at which residual water depths are similar to each other (for example, pools and pools, or riffles and riffles), whereas negative correlation (points plotted below the 95 per cent confidence interval line on the correlogram) show distances at which residual water depths are significantly different from each other (for example, pools and riffles). It is common for the first few points in a correlogram to be positively correlated up to a short lag distance. This distance represents the length of channel in which neighbouring points have similar residual water depths, such as the length of a riffle crest.

Correlograms were used in two ways. First, correlograms from different years were compared to identify temporal trends, through detecting the presence and scale of significant spatial autocorrelation of bed elevations. Second, correlograms were used to test whether the pattern of bed elevations was random or non-random. To test for spatial patterns, each set of residual water depths was randomized, and then a new correlogram was calculated. A chi-squared test was then used to compare the expected number of significant (positive or negative) and non-significant coefficients in the observed-values correlogram against those in the random correlogram.

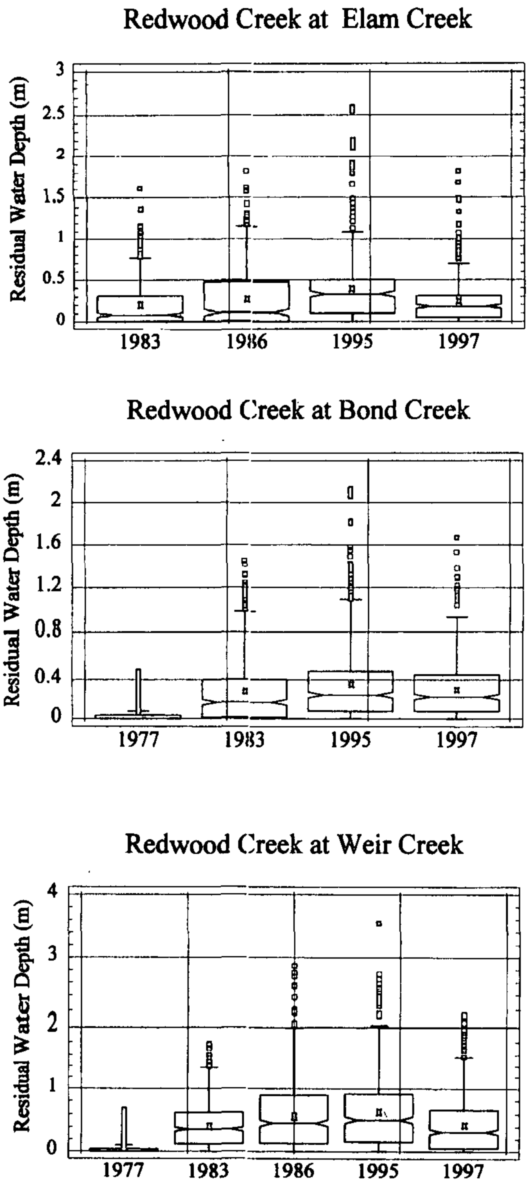


Figure 3. Box plots of residual water depths for Redwood Creek study reaches for the period 1977 to 1997. The upper and lower lines of the box are the 75 and 25 percentiles of the residual water depth distribution, the notches and centreline show the median values, and the × sign is the mean of the distribution. The lowermost horizontal line (whisker) is drawn from the lower quartile to the smallest point within 1·5 interquartile ranges from the lower quartile. The top whisker is drawn from the upper quartile to the largest point within 1·5 interquartile ranges from the upper quartile. Values that fall beyond the whiskers, but within three interquartile ranges are plotted as individual points (outliers)

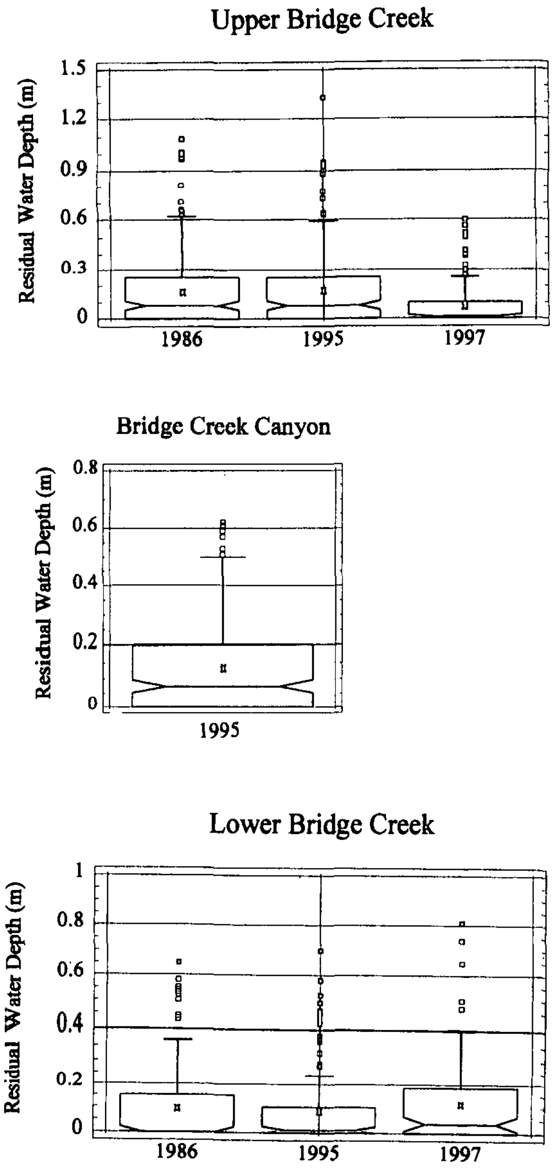


Figure 4. Box plots of residual water depths for Upper Bridge Creek, Bridge Creek Canyon and Lower Bridge Creek study reaches. See Figure 3 caption for explanation

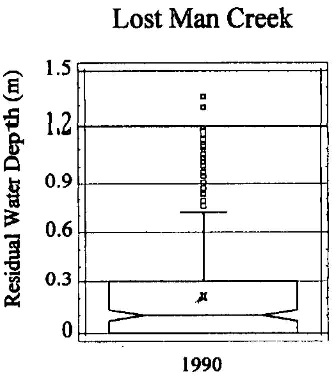


Figure 5. Box plot of residual water depths for Lost Man Creek study reach. See Figure 3 caption for explanation

RESULTS AND DISCUSSION

Distribution of residual water depths

Figures 3 to 5 present box plots of residual water depth in the study reaches on Redwood Creek, Bridge Creek and Lost Man Creek reach, respectively. In Redwood Creek, the mean residual water depths were very low in 1977, due to the impacts of the 1975 flood. The mean, median and maximum residual water depths then increased up until 1995, before decreasing, in response to the flood of 1997, to approximately their 1983 levels. Although the mean residual depths were not significantly different for some of the comparisons (for example, Redwood Creek at Bond Creek in 1983 and 1997; *t*-test with $\alpha = 0{\cdot}05$), the distributions for all reaches are significantly different from one another (Kolmogorov–Smirnov test, 95 per cent confidence levels). This finding demonstrates that consideration of the entire distribution of residual water depths can give a more complete picture of trends in the channel bed status than consideration of the means and maxima alone.

By the time of the initial profile survey in Bridge Creek, in 1986, Upper Bridge Creek had already recovered from the impacts of the 1975 flood, and only remnants of the flood deposits remained stored in the channel. Channel cross-sections reveal that about 0·2 m of bed lowering took place between 1986 and 1995, and show that a few pools increased in depth. Following the flood-associated debris flows of 1997, mean residual depth decreased in Upper Bridge Creek and was significantly lower than in previous years (Figure 4). The Bridge Creek Canyon reach displays a similar distribution of residual water depths to Upper Bridge Creek, although the mean residual depth is smaller. In Lower Bridge Creek, cross-section monitoring shows that the channel incised into the flood deposits by 2 m between 1975 and 1986, but little further bed degradation occurred after 1986. Mean residual water depths were not significantly different during this period, although maximum depths increased through time.

Figure 5 shows the distribution of residual water depths in Lost Man Creek, a stream unaffected by timber harvesting activities since the 1960s. The shape of the distribution is the same as in the other streams. However, it should be noted that the mean residual water depth in Lost Man Creek is greater than those in any of the Bridge Creek study reaches, even though Lost Man Creek drains a smaller catchment.

Figure 6 presents a plot of mean residual depths in the study reaches during the period 1977 to 1997. Mean depths increased between 1977 and 1995, although the rate of increase slowed after 1986. Mean residual depths in all study reaches decreased to values typical of the early 1980s following the 1997 flood, which had a recurrence interval of 12 years.

Figure 7 shows a graph of the percentage of channel length classified as riffle (residual depth = 0) in the study reaches as a function of time. Trends in percentage riffle are the inverse of those for residual depths. Hence, the percentage of channel length occupied by riffles decreased in the years following the 1975 flood,

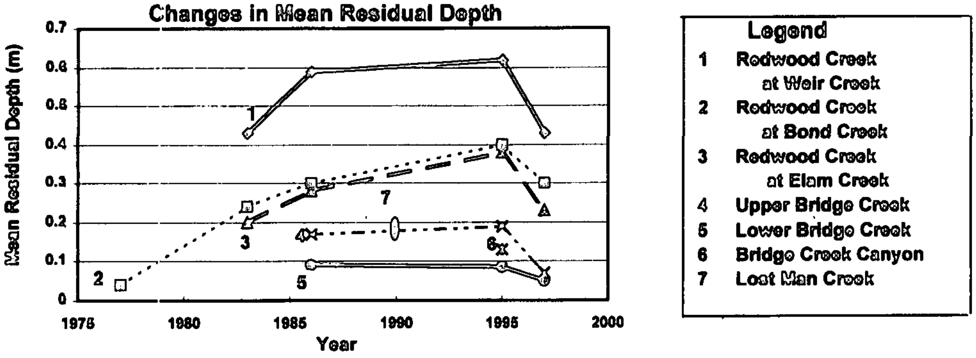


Figure 6. Mean residual water depth for each surveyed profile

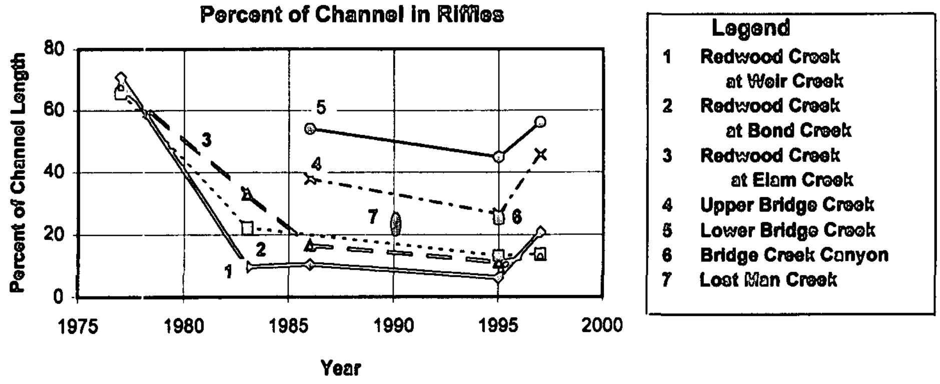


Figure 7. Percentage of channel length classified as 'riffle' in the thalweg profile surveys. Note: riffles are defined as points where the residual water depth equals zero

rapidly up until the mid-1980s, and then more slowly. The percentage of channel occupied by riffles increased to about mid-1980s levels following the 1997 flood.

The variance of bed elevations was evaluated using the standard deviation of the population of residual water depths (Figure 8). The underlying assumption is that increased variance in bed elevations reflects increased morphological diversity in the channel bed. In Redwood Creek, standard deviations increased rapidly for 10 years following the 1975 flood, but between the mid-1980s and 1995 standard deviations increased only slightly. This flattening of the curve may indicate that bed variability was approaching the upper limit of morphological diversity that can develop in this river under the present flow and sediment regimes. Standard deviations decreased in all reaches following the 1997 flood, although they remained higher than the levels observed in 1977 (immediately following the larger, 1975 flood).

In addition to these within-reach comparisons, it would be useful to compare the measurements made in all three creeks. However, to facilitate this the results must be standardized to remove scale effects. The statistic usually employed to allow scale-independent comparisons is the coefficient of variation [(standard deviation/mean) × 100]. However, plots of this statistic did not show any obvious pattern except that the magnitude of the standard deviation is frequently the same as the mean residual depth. Both mean residual depth and standard deviation change through time, but not necessarily at the same rate. As an alternative approach to removing scale effects, bankfull depth was used to normalize residual depths. Although bed topography was changing through time, the reach-averaged bankfull depth could be considered to be constant during the study period. Figure 9 shows a plot of the resulting variation index [(standard deviation of residual water depth/

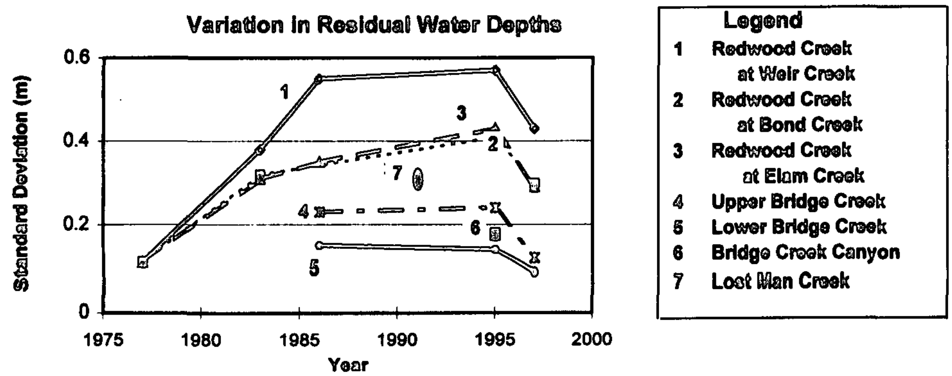


Figure 8. Variation in residual water depths in the thalweg profile surveys. The standard deviation of the population of residual water depths is plotted against time for the individual reaches

bankfull depth) × 100] as a function of time. The stream reaches with the smallest quantities of flood deposits remaining from the 1975 event (Upper Bridge Creek, Redwood Creek at Weir Creek, and Lost Man Creek) all plot above a value of 20, although the values for all the study reaches decrease following the 1997 flood. The general trend that emerges is that index values are higher at sites with better habitat conditions.

Spatial autocorrelation in thalweg profiles

Figures 10 to 15 display the correlograms for the repeat surveys of the study reaches. Most of the correlograms show significant positive correlations at short lag distances. This fine scale of correlation indicates similarity of neighbouring points, in other words, the length of channel bed with similar residual water depths (such as the length of a riffle). The length of this fine-scale correlation decreases through time in most study reaches. For example, in Redwood Creek at Weir Creek, the correlation distance decreases from 66 m in 1983, to 31 m in 1997 (Figure 10). Decreasing correlation distances may reflect reductions in the extent of riffles identified in the residual depth plot (Figure 7).

Significant positive or negative correlations in the correlograms at larger lag distances indicate the spacing of larger bed features. In 1983 in the Redwood Creek at Weir Creek reach, a positive correlation existed at 250 m, which is about four times the channel width (Figure 10a). This corresponds to the average bar length measured in the 1978 aerial photographs. In 1986 residual depths were greater and two positive correlations

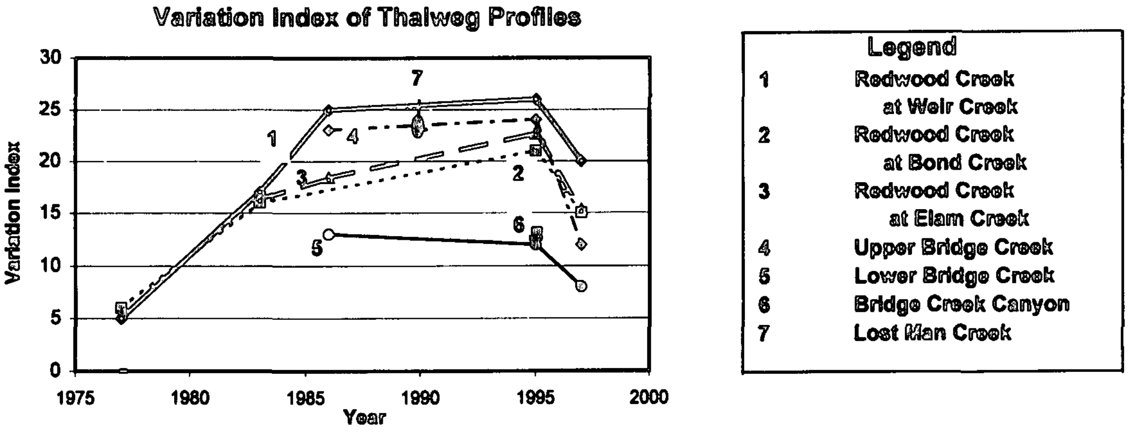
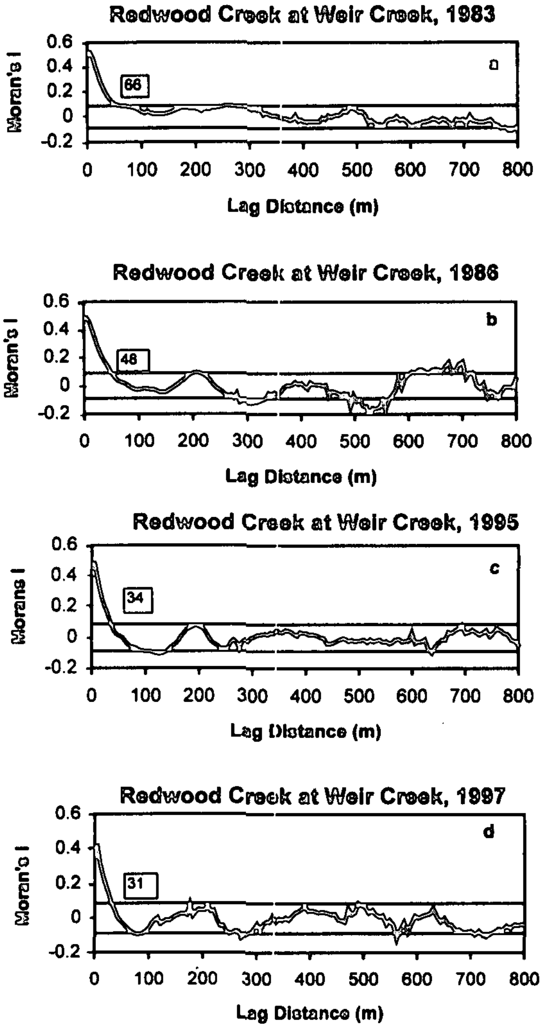


Figure 9. Variation index for study reaches plotted against time. The variation index is defined as [(standard deviation of residual water depths/bankfull depth) × 100]



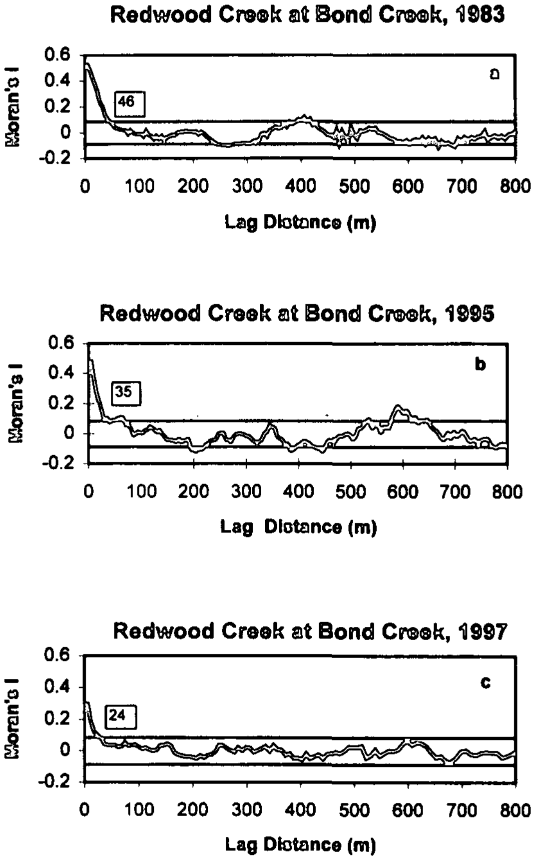
Redwood Creek at Weir Creek, 1983

Redwood Creek at Weir Creek, 1986

Redwood Creek at Weir Creek, 1995

Redwood Creek at Weir Creek, 1997

Figure 10. Correlogram based on Moran's *I* spatial autocorrelation coefficient for Redwood Creek at Weir Creek



Redwood Creek at Bond Creek, 1983

Redwood Creek at Bond Creek, 1995

Redwood Creek at Bond Creek, 1997

Figure 11. Correlogram based on Moran's *I* spatial autocorrelation coefficient for Redwood Creek at Bond Creek

occurred, at 200 m and 600–720 m (Figure 10b). Qualitative analysis of the aerial photographs revealed no obvious change in the planform of the river during this period, and it may be concluded that the second peak in the correlograms is probably an artifact due to the repetition of a 200-m long feature. The positive correlation at 200 m remained present through to 1997 (Figure 10c and d).

Further downstream, in the aggrading reach, the history of bedform development differs significantly. In 1983 in the Redwood Creek at Bond Creek study reach, there was positive correlation at 400 m, which is about five times the channel width (Figure 11a). This approximates to the average length of alternate bars in this reach measured on the 1978 aerial photographs. By 1995, the lag distance of the positive correlation had increased to 600 m, or about eight times the channel width (Figure 11b), but following the 1997 flood, the distribution of residual water depths became more random. Aerial photographs taken in 1997 show that the planform still featured alternate bars, but expression of these bar units in the 1997 thalweg profile is weak (Figure 11c).

In 1983 in the downstream-most reach, Redwood Creek at Elam Creek, positive correlations existed at 180 and 350 m, corresponding to 1·6 to three times the channel width, respectively (Figure 12a). The peak at 180 m had disappeared by 1986 (Figure 12b), but a significant correlation at 280–350 m was evident in all of

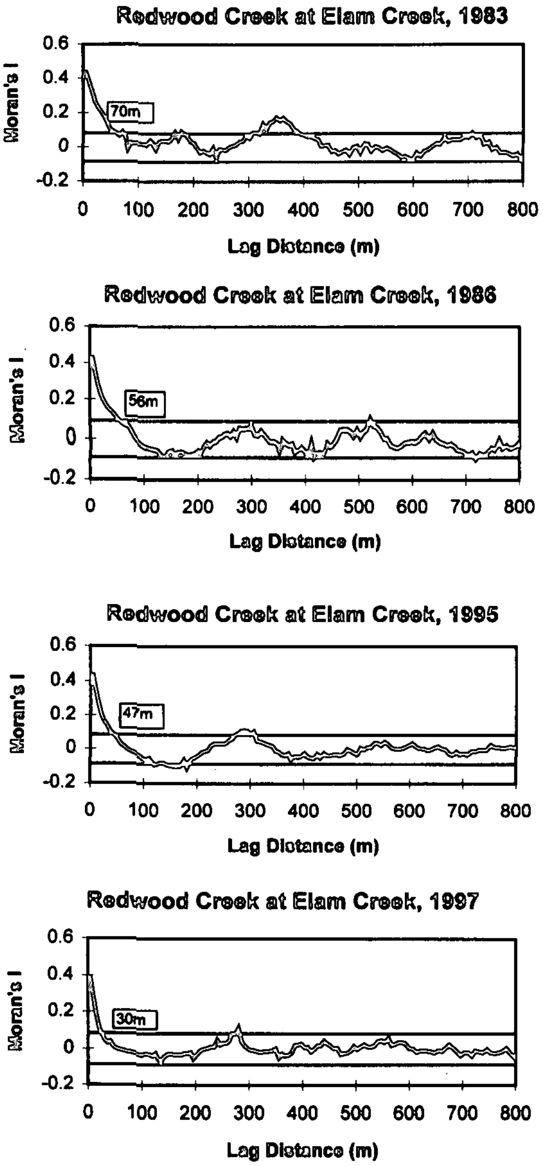


Figure 12. Correlogram based on Moran's *I* spatial autocorrelation coefficient for Redwood Creek at Elam Creek

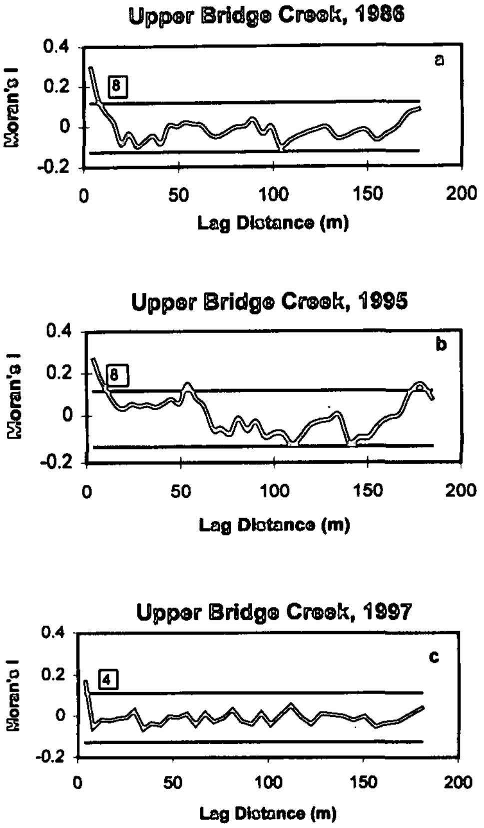


Figure 13. Correlogram based on Moran's *I* spatial autocorrelation coefficient for Upper Bridge Creek

the surveyed profiles. Examination of available aerial photographs indicates that the average bar length in this reach is 400–500 m. The finer scale of spatial autocorrelation in the thalweg profile actually corresponds to the pool spacing in this reach.

In Upper Bridge Creek the degree of organization of the channel bed (defined as detectable, regularly spaced features in the channel) increased between 1986, when no significant positive correlations were detected (Figure 13a), and 1995, when significant positive correlations appeared at 55 m and 180 m (Figure 13b). The correlation at 55 m corresponds to the most common spacing of riffle crests, while the correlation at 180 m corresponds to the length of alternate bar units in Upper Bridge Creek (150–200 m). The lack of regularly spaced alternate bars in this reach in 1986 is unsurprising because, historically, the high loading of large woody debris would have generated numerous, random irregularities in bed topography. Recently, inputs of woody debris have consisted of shorter, smaller pieces and the forced features produced by this type

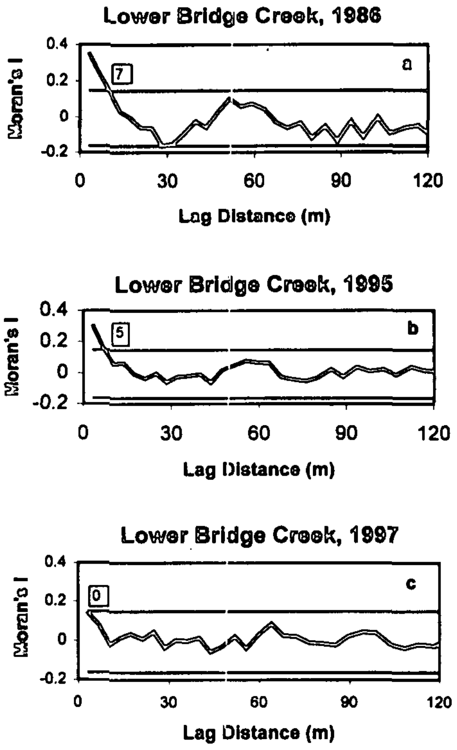


Figure 14. Correlogram based on Moran's I spatial autocorrelation coefficient for Lower Bridge Creek

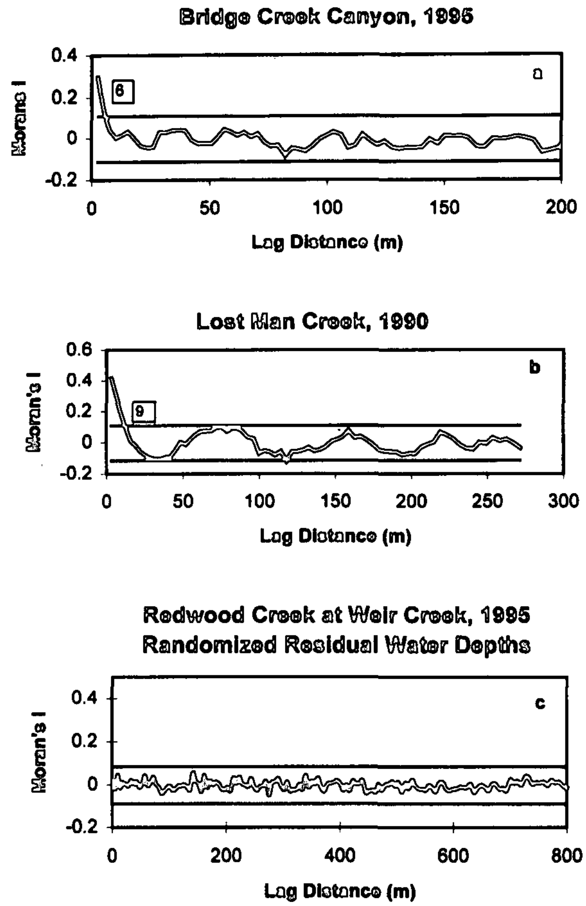


Figure 15. Correlogram based on Moran's I spatial autocorrelation coefficient for the Bridge Creek Canyon reach, Lost Man Creek, and a randomized set of residual water depths based on data from Redwood Creek at Weir Creek, 1995

of debris have not persisted. This is the case because moderate flows have been competent to entrain the wood, either reorganizing it into regularly spaced features or transporting it downstream. By 1995 the abundance of large woody debris compared to natural conditions was reduced to the point that forced pools and bars were no longer prevalent. However, the introduction of a great deal of sediment and large wood following the flood and debris flow of 1997, resulted in the distribution of residual water depths returning to a more random pattern in 1997 (Figure 13c). This residual depth distribution shows no significant correlation at lag distances greater than 4 m.

No strong bed features with lag distances greater than a few metres appeared in any of the correlograms for Lower Bridge Creek (Figure 14), which is consistent with the fact that its planform has never exhibited well developed bars. Following the 1997 flood, and its associated inputs of sediment and woody debris, even the fine-scale autocorrelation between neighbouring points that was present in 1986 and 1995 had disappeared and the thalweg profile was completely random (Figure 14c).

Three further correlograms were formulated to exemplify the patterns of autocorrelation associated with particular bed morphologies and to support statistical testing of the significance of autocorrelation patterns observed at the study reaches (Figure 15). The correlogram for canyon reach of Bridge Creek (Figure 15a) has no significant correlations beyond a lag distance of 6 m. This indicates a lack of regular features in the bed that is consistent with the actual configuration of the bed, which exhibits a few small, irregularly spaced bars and forced pools scoured around boulders, bedrock outcrops and large woody debris.

At Lost Man Creek, neighbouring points are significantly correlated up to a lag distance of 9 m and a regular structure is apparent in the correlogram at a spacing of about 80 m or six times the channel width (Figure 15b). These autocorrelations are representative of morphological features in the channel, which has only small pieces of woody debris and in which free riffle bars are well developed. It should be noted that under pristine, unlogged conditions large woody debris would probably be more abundant in this creek and this would influence channel morphology through generating more forced features and a more random pattern of bed topography.

Figure 15c shows the correlogram for a randomized set of residual water depths, based on the observed actual values plotted in Figure 10c. This is one example of the randomized sets that were created in the study for each surveyed profile. A chi-squared test, with a significance level $\alpha = 0{\cdot}05$, was used to establish whether the actual and randomized residual depth distributions were significantly different. The results confirmed that spatial organization in several profiles was not significantly different from a random pattern. This was the case at Redwood Creek at Weir Creek in 1983, Redwood Creek at Bond Creek in 1997 and all the Bridge Creek profiles.

Numerical modelling of alluvial channels suggests there should be substantial elongation of alternate bar wavelength during morphological evolution from initial instability to fully developed, stable bars (Nelson, 1990). The correlograms generated in this study demonstrate that the large flood and sedimentation event of 1975 initiated morphological instability in Redwood Creek and suggest that a regular bed topography was re-established during the subsequent decade. They do not, however, provide clear evidence that the wavelength of alternate bars elongated during the recovery period. The trend towards development of regularly spaced bar features was interrupted by a further flood in 1997. In fact, following this event, the degree of organization in the bed topography was reduced and positive correlations were only found at shorter lag distances. In most study reaches, positive autocorrelations were found at a spacing of about three channel widths, which corresponds to the average pool spacing, whereas alternate bar lengths were four to six times the channel width. It appears that, in this fluvial system, pools occur more frequently than the spacing of alternate bars would suggest. This is probably due to the presence of 'forcing' elements, such as large woody debris.

DISCUSSION AND CONCLUSIONS

This study used a statistical analysis of series of residual water depths to quantify changes in the pattern and variability of channel bed topography at a reach scale. During the 22 years following a large flood in 1975, the distributions of residual water depths changed significantly. Mean residual water depth and depth variability increased through time, while the length of channel occupied by riffles decreased, resulting in an increase in the degree of bed heterogeneity with the time since disturbance. Following the 1997 flood and associated sediment inputs, some of this heterogeneity was lost because variability in the thalweg profiles decreased markedly.

The use of spatial statistics to define morphological structure was found to be a promising technique for objective monitoring of changes in bed topography following disturbance. Study reaches represented a range of channel types, and the spatial analysis successfully identified the scales of autocorrelation associated with different bedforms and bed features. The length of fine-scale positive correlation decreased through time, perhaps corresponding to the decrease in the length of riffle crests that was documented in the surveyed profiles. Coarser-scale correlations were shown to correspond to the length of alternate bar units in the channels (four to six times the channel width) and to pool spacing (about times the three channel width). Pools are more frequent in Redwood Creek than might be expected in a free alternate bar system because of the presence of large woody debris and other obstructions that generate forced pools.

The results presented here provide a basis upon which to compare variability of longitudinal profile patterns in different sized streams and in response to disturbance by large floods and associated inputs of sediment and woody debris. Variation in both residual water depths and their spatial characteristics can be used to characterize the response of channel bed pattern to disturbance and the generation of significant spatial patterns during recovery from disturbance. The capability of the channel to remobilize inputs of woody debris and sediment determines the rate and degree of subsequent bed organization. The development of longitudinal patterns through time indicates the self-adjusting nature of river channels, by which fluvial processes order random inputs of sediment and debris from hillslope processes into spatially organized, fluvial bedforms and features. Stream reaches which could readily remobilize hillslope inputs (particle size was much less than bankfull depth, and length of large woody debris was less than channel width) increased both bed heterogeneity and spatial organization in the decades following disturbance. The analysis reported here only considered variation in the downstream direction. It would be useful in future to extend the analysis to consider changes in the cross-channel dimension, although, in the Redwood Creek basin, lateral channel changes are frequently constrained by narrow valley bottoms and bedrock outcrops and the planforms of the study reaches did not change markedly during the monitoring period. Despite this constraint, the longitudinal expression of alternate bar units became stronger with increasing time since disturbance.

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DISCUSSION[1]

"Erosion on Logging Roads in Redwood Creek, Northwestern California," by Raymond M. Rice[2]

Randy Klein, Vicky Ozaki, Greg Bundros, and Mary Ann Madej[3]

We are pleased to acknowledge Dr. Rice's effort to evaluate the effectiveness of the California Forest Practice Rules (FPRs) in preventing erosion on forest roads. He makes several valid points regarding improvements in California forest practices with passage of the Z'berg-Nejedly Forest Practice Act of 1973 and subsequent additions. However, we feel the author's conclusions regarding the efficacy of California's Forest Practice Rules are unfounded based on the data he presents.

A serious limitation in Dr. Rice's study is the fact that he bases much of his conclusions on the claim that the winters of 1995-1997 (just prior to his study period) were severe enough to adequately 'test' current road construction and maintenance practices. Previous road erosion studies cited by Dr. Rice (Best *et al.*, 1995; Weaver *et al.*, 1995) reported much higher erosion rates. These studies measured erosion from all roads over a period that included a 50-year flood (in 1964) and several 10- to 25-year floods (in 1972 and 1975) (Coghlan, 1984). In contrast, recurrence intervals for peak flows on Lacks Creek (within Dr. Rice's study area) during the period of his study (1995-1997) were only 1.2-, 3-, and 7-years respectively [based on gage records from Redwood National and State Parks (RNSP) and the U.S. Geological Survey (USGS)]. Storm rainfall depths recorded at Lacks Creek and the nearby USGS gage Redwood Creek near Blue Lake (No. 11481500) were of similarly low magnitude (2- to 7-year recurrence interval) (Goodridge, 1989) during Dr. Rice's hydrologic 'test' period. To attribute the lower erosion rates found by the author solely to improvements in forest practices ignores the large influence of storm severity on erosion rates. Higher rainfall intensities than those in the three years preceding Dr. Rice's study are needed to realistically evaluate the performance of current forest road standards in preventing erosion during severe storms.

It is also important to note that the previous studies cited by the author (Best *et al.*, 1995; Weaver *et al.*, 1995) measured the entire population of erosion sites along all roads within the basins and did not extrapolate erosion volumes from a sample. In contrast, the author randomly selected sites, covering only about 10 percent of the road network. Recent data from 100 percent sampling of road erosion (on file at RNSP, Arcata, California) show that: (1) only 5 percent of the erosion features contribute 84 percent of the total erosion volume, and (2) 10 simulations of simple random sampling of 10 percent of the full data set indicated that such sampling would have underestimated the true erosion volume by 27 to 86 percent in nine out of ten cases. McCashion and Rice (1983) also support this observation in their study of erosion from logging roads and noted that, "The overwhelming influence of a few large events (i.e., erosion sites) was evident . . . *and* . . . That a few large events are responsible for so much erosion seems to be typical in northwestern California." With such highly skewed distributions, random sampling is not efficient, and stratified sampling based on geomorphic variables would probably give a more realistic estimate of total erosion.

Through cooperative agreements, RNSP is assisting local landowners with inventories of their road

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[2] Paper No. 98043 of the *Journal of the American Water Resources Association* 35(5):1171-1182.

[3] Respectively, Hydrologist and Geologist, Redwood National and State Parks, 1655 Heindon Road, Arcata, California 95521; and Research Geologist, U.S. Geological Survey Western Ecological Research Center, 1655 Heindon Road, Arcata, California 95521.

systems to identify and prescribe treatments for erosion prevention and secure funding for corrective work. Such a program would not be necessary in Redwood Creek or other north coast basins were there not serious and recognized erosion threats left unaddressed by the FPRs. Although we are pleased to note the road system in Dr. Rice's study area did not produce much sediment during moderate storms, the true test of the revised FPRs awaits a large storm event.

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REPLY TO DISCUSSION

by Randy Klein, Vicky Ozaki, Greg Bundros, and Mary Ann Madej[1]

"Erosion on Logging Roads in Redwood Creek, Northwestern California"[2]

Raymond M. Rice[3]

I hope that the questions raised by Klein, Ozaki, Bundros, and Madej will serve to alert the unwary reader to the limitations of "outdoor research." I was apparently not completely successful in my paper. I will try again.

They seem to believe that I was attributing all of the difference in erosion estimated between the earlier studies (in Copper Creek and Garret Creek) and my study to improved forest practices. That is not the case. In the last sentence of my "Introduction," after outlining some of the confounding factors affecting my study, I stated: "The reader will have to decide how much of the differences that will be reported should be attributed to differences in weather and how much to differences in road maintenance and construction practices." In the "Conclusions" I begin by saying: "The results of this investigation suggest that changes in forest practices have greatly reduced road-related erosion. . .." The reader was free to accept or reject that suggestion.

The discussants claim that the storms of the 1980-1997 (and especially 1997) were inadequate to test the improved construction and maintenance practices. I find that peculiar, given that their own organizations funded a study of road-related erosion in Redwood National Park in response to the 1997 storm (Bloom, 1998) ". . . to see how rehabilitated roads behaved after being "tested" by a large flood." (Harris *et al.,* 1997). In my paper, I noted that the actual return periods of the 1995-1997 storms for the drainages tributary to each of the 100 plots are unknown. Also unknown is the erosional response of the plots to different size storms. Therefore, the question is not "how big was the storm" but is "was it big enough to reveal weaknesses in the road system?" I contend that it was big enough to give useful insights into the importance of erosional mechanisms and the effectiveness of various mitigation measures.

Lastly, Klein *et al.,* questioned my use of simple random sampling and noted ". . . that the previous studies . . . (to which I compared my results) . . . measured the ***entire population of erosion sites*** . . .." I doubt that this is strictly true. Every field study must, as a practical matter, set limitations on what is measured. For example, no attempt was made in my study to estimate sheet erosion and Bloom (1998) only tallied features greater than 2.3 m^3 (3 yd^3). Such restrictions affect a study's results. Having a random sample, I can estimate that there is about a 4 percent probability that there is a site in my study area that produced more erosion than the largest site in my data (~2,400 m^3 km^{-1}). However, the people working in the area do not believe such a site exists. On the other hand, had Bloom (1998) been measuring my study area, I predict she would have underestimated the total erosion by 37 percent because of not recording features displacing less than 2.3 m^3. The choice of sampling criteria depends on study objectives. In my case, one of the objectives was an estimate of the contribution of even "minor" erosional mechanisms. The careful author needs to inform the reader of the sampling methods used and the careful reader must take the limitations of those methods into consideration when interpreting study results.

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[2] Paper No. 98043 of the *Journal of the American Water Resources Association* 35(5):1171-1182.

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