EROSION ON LOGGING ROADS IN REDWOOD CREEK, NORTHWESTERN CALIFORNIA

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EROSION ON LOGGING ROADS IN REDWOOD CREEK, NORTHWESTERN CALIFORNIA[1]

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ABSTRACT: Road-related erosion was estimated by measuring 100 randomly located plots on a 180 km road network in the middle reach of Redwood Creek in northwestern California. The estimated erosion rate of 177 m^3 km^{-1} was contrasted with two earlier studies in nearby parts of the same watershed. A sizable proportion of the great reduction in erosion from that reported in the earlier studies is attributed to changes in forest practice rules. Those changes have resulted in better placement and sizing of culverts and, especially, to less reliance on culverts to handle runoff from logging roads.

(KEY TERMS: erosion; logging roads; forest practice rules; forest management; forest hydrology; social and political.)

INTRODUCTION

Road-related erosion has long been cited as a major source of sediment in streams draining logged areas (Anderson, 1954; Dyrness, 1967). In studies in Oregon (Swanson and Dyrness, 1975) and northwestern California (McCashion and Rice, 1983) roads were estimated to be responsible for about half of the erosion associated with timber management on terrain averaging about 43 percent slope. However, another study on the Six Rivers National Forest (the site of the McCashion and Rice study and just east of the site of this study) found that on terrain flatter than 58 percent, about 85 percent of the erosion was due to roads (Furbish, 1981). Several articles in a recent compendium of research in the Redwood Creek basin (Nolan *et al.*, 1995) identified roads and skid trails as a major cause of erosion in and upstream from the Redwood National Park. These studies, however, were mainly evaluating the consequences of road and logging practices that were in effect prior to the implementation of the Z'berg-Nejedly Forest Practice Act of 1973 (Arvola, 1976). Since the implementation of the Act forest practices related to environmental protection have, for the most part, significantly improved on private timberlands in California. It seems appropriate, therefore, to estimate the effects of current road maintenance and construction practices and contrast them with erosion associated with the earlier practices. The Redwood Creek watershed provides such an opportunity since one of the owners of timberland upstream of the Park undertook a study to estimate road-related erosion on his property since 1980. Erosion measured in that study will be contrasted with that reported in two of the earlier studies (Best *et al.*, 1995, Weaver *et al.*, 1995).

The mouth of Redwood Creek is located about 50 km (30 mi) north of Eureka California (Figure 1). The 725 km^2 (283 mi^2) watershed, which follows the Grogan Fault (Cashman *et al.*, 1995), extends 80 km (50 mi) in a south-southeasterly direction, usually not exceeding 10 km (6 mi) in width. The Grogan Fault divides the watershed into a relatively stable western side underlain mainly by the Redwood Creek Schist and a more erodible eastern side underlain by sandstones and mudstones (Cashman *et al.*, 1995). Annual precipitation ranges from about 1500 mm (60 in) at the creek's mouth near the town of Orick to about 2500 mm (100 in) in the headwaters (Harden, 1995). Descriptions of the basin typically divide it into thirds. The lower third, the Park, is dominated by redwood (*Sequoia sempervirens*). The middle third covers a transition to a Douglas-fir (*Pseudotsuga menziesii*) dominated forest with increasing amounts of oak-woodland and grasslands. That transition continues in the upper third of the basin. By 1954 about 28 percent of the middle third of the Redwood Creek watershed and 22 percent of the total watershed had

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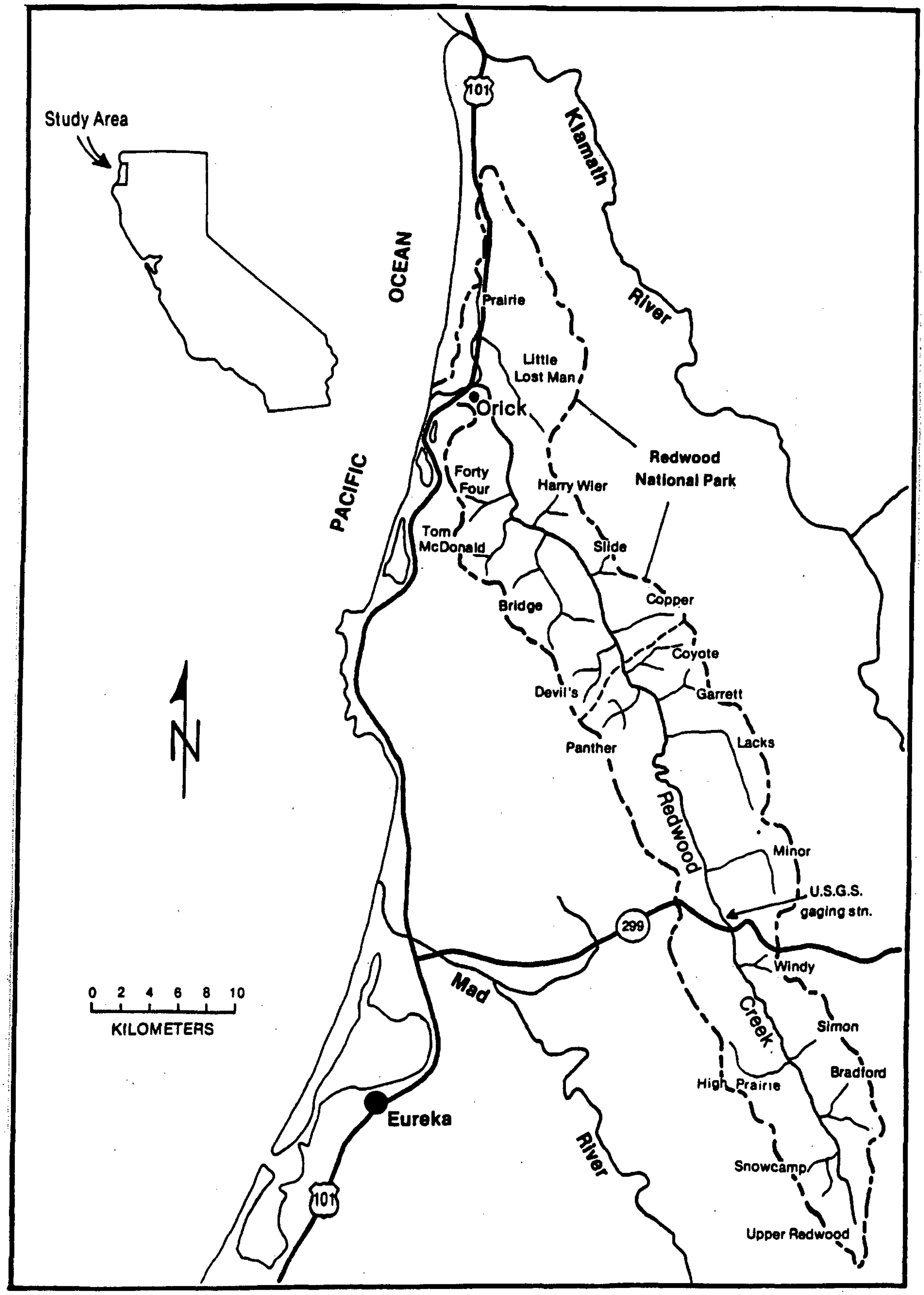

Figure 1. Redwood Creek Watershed.

been logged (Best, 1995). By 1978 those figures were 72 percent and 66 percent, respectively. By 1997 virtually all the coniferous forest outside the Park had been logged at least once.

Earlier forest practices were studied in Copper Creek (Weaver *et al.*, 1995) and Garret Creek (Best *et al.*, 1995). The current study area is north of Highway 299 mainly in the watersheds of Lacks Creek and Minor Creek (Figure 1).

The winters of 1995-1997 appear to have presented an opportunity to contrast the amount of road-related erosion before and after the implementation of the Forest Practice Act. The storms of those winters seemed severe enough that weaknesses in the present roads should have been revealed. Whatever their actual effect, the winters of 1995-1997 prompted the owner of the study area to undertake this investigation. The annual peak flows for those years ranked fourth, tenth, and sixth in the 86-year record of floods of the Eel River at Scotia, California [about 60 km (37 mi) south of the study area]. In the 44-year record of Redwood Creek at Orick the 1997 peak ranked fifth and the 1996 peak ranked eighth but 1995 only ranked 26th (Figure 2). In spite of its low ranking, it was the opinion of foresters working in the study area that 1995 was on a par with 1996 and 1997 with respect to road-related erosion. The nearest rain gage with a continuous record covering the time span of Figure 2 is in Eureka 35 km (22 mi) from the study area (Figure 1). Since there are no rainfall or runoff data from the study area it is not possible to know if these annual peaks reflect the risk of road-related erosion. Due to different locations and the vast differences in drainage areas between these two gaged watersheds and the typical area tributary to a road failure, these three winters may not have been very important with respect to road-related erosion in Redwood Creek. However, it seems more likely that within the longer, more widespread, rainfalls relevant to the Eel River and the entire Redwood Creek watershed there were localized intensities that could have caused accelerated road-related erosion in the study area. The low ranking of the 1995 Redwood Creek peak flow at Orick does cast a cloud over that assumption. 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.

FOREST PRACTICES: 1956-1997

It is not sufficient to merely compare erosion rates on earlier roads with those measured in this study. In order for those rates to be instructive, the construction and maintenance practices must be compared. Furthermore, it will be helpful to understand the political and legislative environments that, in part, motivated forest managers to adopt various practices. Although most of the studies in Nolan *et al.* (1995) cover a time span of 1956-1980, the major change in logging road standards and the associated forest practices actually occurred in 1976. It was then that the Forest Practice Act of 1973 began to be fully implemented and the Timber Yield Tax Law, AB-1258 (Martin, 1989) was enacted. Both had profound effects on how forest properties were managed.

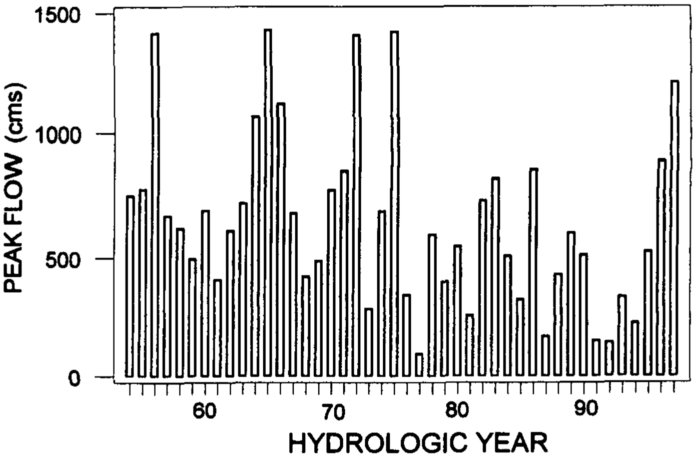

Figure 2. Redwood Creek at Orick HY-1954 to HY-1997.

Prior to the enactment of AB-1258, timber land was taxed at the value of the standing timber if the trees were more than 40 years old. With the increase in timber values that accompanied the post WW-II building boom, this tax treatment was a great incentive to logging of any timber older than 40 years. For example, in the study area during 1951-1958 practically the entire area was logged, leaving only seed trees. In the 1960s the seed trees were removed and any areas that had by then reached taxable age were cut. This practice continued into the 1970s. This history is fairly typical of the middle and upper reaches of the Redwood Creek watershed (Best, 1995). The Timber Yield Tax Law allowed for a nominal property tax but deferred tax on the value of the timber crop until it was harvested. This change permitted land owners to take a long-term view in the management of their properties. The cutting of timber that had reached maturity was based on economic and biological concerns, not on the stand having reached 40 years of age. With a more long-term view of forest management came an interest in permanent road systems to serve on-going forest management. Previously most roads were built on an ad-hoc basis to serve current logging.

The Forest Practice Act of 1973 marked a dramatic change in the level and focus of forest practice regulation by the State of California. Prior to it, although there had been forest practice legislation since 1945, regulations dealt mainly with regeneration and fire control (Arvola, 1976). The Forest Practice Act of 1973 addressed a broader range of environmental concerns which have been further enlarged in response to the California Environmental Quality Act (1970) and Section 208 of Public Law 92-500 (1972 amendments to the Federal Water Pollution Control Act). These laws, together with the Endangered Species Act, have become the vehicles by which the general public and various special interests attempt to affect forest practices. While sometimes burdensome, these laws have not been entirely at odds with the transition that has been occurring during the past half century. The timber industry has gone from utilizing virgin forests to sustained yield forestry.

The changes in practices within the study area between 1956 and 1997 are typical of most ownerships in the middle and upper reaches of Redwood Creek. Prior to 1976 practically all timber was tractor yarded downhill to roads and landings located near stream channels. This pattern of yarding timber tended to cause concentrated runoff and erosion resulting from yarding disturbances to feed into and exacerbate road-related erosion. The roads were two lane, about 8 m (25 ft) wide with occasional wider turnouts. Both alignments and grades were built to minimize road length and stress on logging trucks. Often mid-slope landings were approached with "beaver slides" (spur roads with grades as steep as 35 percent which empty trucks could scale and loaded trucks could descend under control). Most small streams were crossed using "Humboldt crossings" (i.e., cull logs laid in the channel and covered with earth). The failure of "Humboldt crossings" created most of the pre-1980 gullies encountered in this study. Roads were in-sloped and relief culverts, if used at all, were 20-30 cm (8-12 in) in diameter. After a particular road was no longer being used it was water-barred at about 100 m (300 ft) spacing and abandoned (if, in fact, any water-barring was done). All maintenance ceased with the conclusion of logging. Only one main-haul logging road in the study area was surfaced with rock. It was kept open year-round to serve a cattle operation. All other roads were reopened each spring with new fords and by rebuilding crossings that had washed out or plugged during the winter.

The most important difference in practices that has occurred since 1976 is the decreased reliance on tractors for yarding timber. Changes that have occurred in the study area are indicative of those throughout northwestern California. Currently about 35 percent of the timber harvested in the study area is skyline cable yarded. This has led to the relocation of much of the road network out of canyon bottoms to mid-slope and ridge locations. Cable yarding also creates less ground disturbance and the runoff and erosion from cable yarded areas is not so directly channeled into the road system as is the case with tractor yarding. Beginning in the mid-1980s roads in the study area were reduced in width to about 5 m (15 ft). Road grades have been reduced to less than 15 percent except for short pitches of 20 percent where necessary. Streams are crossed with bridges or culverts sized appropriately for a 50 yr. storm using empirical formulas and relief culverts are at least 46 cm (18 in) in diameter. Roads dip into and out of culverted crossings so that the fills over culverts will erode first should the culvert become blocked, preventing the stream from being diverted down the road. Culverts are installed to conform to the stream grade and entrances and outfalls are riprapped with large rock. Frequently, they are fitted with half-round down spouts. Furthermore, less than half of the road mileage in the study area is even drained by culverts. Outsloping, rolling dips, and water bars divert water off of 51 percent of the right-of-way. These changes have reduced the average drainage structure spacing in the study area to less than 37 m (120 ft). Nearly 20 percent of the present road system is surfaced for year-round use and perennially wet sections of seasonal roads are also rocked. Lastly, one man residing on the property inspects the roads throughout the rainy season and during large storms the entire field crew assists him in checking and correcting trouble spots. In addition, the entire road system was checked annually for places needing correction.

STUDY AREA

This investigation was conducted on a single 6,971 ha (17,110 ac) ownership in the middle reach of Redwood Creek, about 27 km (17 mi) inland from the Pacific Ocean. Ninety-six percent of the area lies on the east side of Redwood Creek between the mouth of Lacks Creek and Highway 299 (Figure 1). The watersheds are underlain by the Franciscan Assemblage of Cretaceous and Jurassic rocks (see descriptions in the Appendix) and range in elevation from 240 m (800 ft) to 1200 m (3,900 ft). They receive about 2000 mm (80 in) of precipitation annually, almost entirely as rain between October and April. At the time of the study about 80 percent of the ownership was in a secondgrowth coniferous forest – mainly Douglas-fir (*Pseudotsuga menziesii*). The addition of hardwoods – mainly Tan Oak (*Lithocarpus densiflora*) brings the total forested proportion of the study area to about 89 percent. Grasslands, brush and bare soil account for the remainder of the area.

Most of the road system evaluated in this study was originally built to support logging during 1950-1958. Consequently, roads still show evidence of erosion during the large storms in hydrologic years 1956, 1965, 1972, and 1975. Most of the system has been brought up to current standards during the past decade. The current 180 km (112 mi.) road system consists of 134 km (83 mi.) of seasonal roads, 24 km (15 mi.) of all-weather roads, 10 km (6 mi.) of jeep roads, and 11 km (7 mi.) of abandoned roads that have not brought up to current standards (see the Appendix for definition of standards). Apart from the use of the road system by logging and silvicultural crews, there is year-round use to manage cattle grazing on the property.

STUDY DESIGN

The sampling frame consisted of 1,117 road segments 0.16 km (0.1 mi.) long [the total length of logging roads in the ownership is 180 km (112 mi)]. One hundred randomly located sites were measured. The following procedure was used to eliminate observer bias in the location of plots in the field. The plots were identified as being a certain distance (to the nearest 0.1 mi) from an intersection. The field crew measured that distance using their vehicle's odometer. At that point a random distance from -80 m to +80 m (-264 ft to +264 ft) was selected. That distance was then measured from the vehicle to the near edge of the 1.5 m (5 ft) plot. The 0.16 km (0.1 mi) segment for tallying Major Events (described below) began at this point and continued in the direction from the vehicle to the plot. In theory this permitted every 30.48 cm (1.0 ft) road segment be included in our sample and therefore every drainage structure had a probability of being sampled in proportion to the length of road it drained.

Site descriptors were recorded at each location in addition to the erosion estimates (Appendix). Their purpose was to elucidate the proportion of erosion associated with various erosion mechanisms, locations, and times of occurrence. Erosion was assumed to equal the volume of the cavity left by the various mechanisms. The volume of each erosional feature was estimated by as many sets of average length, average width, and average depth as the field crew felt necessary to represent its shape. Sheet erosion was not recorded unless it left unmistakable indicators as described under Surface Sloughing in the Appendix. Only erosion deemed to have been caused by the road was recorded. Since the focus of this study was erosion and sediment sources no attempt was made to estimate delivery of sediment to a stream. The field data were collected during June and July 1997. The land owner refrained from any road maintenance on roads included in the random sample until the study data had been collected in order to avoid obliterating evidence of erosion.

Field measurements were taken in feet and converted to $yd^3 mi^{-1}$. English units were used in the field because the crew was more familiar with them and had equipment in those units. It was hoped that by doing so the likelihood of data recording errors was lessened. The equations listed below are the metric equivalents of those used in the study. Each sample site consisted of the following three components:

The Plot. A 1.5 m (5 ft) wide swath from the top of the cut bank to the toe of the fill slope running at right angle to the road centerline. Its primary purpose was to estimate minor erosion on the cut, fill, inside ditch, and running surface.

$$\textbf{Plot } m^3 \times 656 = m^3\,km^{-1}$$

The Drain. Erosion related to the drainage structure conveying runoff from the Plot to a natural surface or channel. Drains included outsloping, inside ditches, rolling dips, waterbars, and culverts. The distance to be measured is clear for the last three. For outsloped roads the distance was measured to where most of the water left the road surface. The designation 'inside ditch' was used when a ditch on an abandoned road drained directly into a stream. The distance (Dist) from the Plot to the Drain was measured as an estimate of half of the spacing between drains since the average distance between the Plot and Drain will be half the average distance between drainage structures.

$$\frac{\textbf{Drain } m^3}{\textbf{2 x Dist km}} = m^3 km^{-1}$$

Major Events. The sum of the volumes of all erosional features individually displacing more than 15.3 m^3 (20 yd^3) found within a 0.16 km (0.1 mi) road segment bordered by the Plot. The much longer road segment sampled for major events was dictated by their rarity and the fact that earlier studies had found that they were a major part of the measured erosion (Rice and Datzman 1981, McCashion and Rice 1983).

$$\textbf{Major Events } m^3 \times 6.21 = m^3 km^{-1}$$

The erosion for each sampled site was the sum of the estimated erosion of these three components.

RESULTS

Erosion Rate

The estimated erosion rate was 177 m^{3}km^{-1} (372 yd^{3}mi^{-1}) for the period 1980-1997 (Table 1). During that period the land owner only repaired existing or potential erosion sites. Routine regrading of roads was not done. The data are highly skewed (Figure 3) as is typical of erosion studies with which I am familiar (Dodge *et al.,* 1976; Furbish, 1981; McCashion and Rice, 1983; Rice and Datzman, 1981; Rice and Lewis, 1991). Twelve plots produced about half of the erosion measured. Therefore, any confidence limit based on normal theory would be unrealistic. Frequently erosion data are well fitted by a log-normal distribution. Unfortunately, the logarithms of these data have a strong left hand skew because of a number of small values (not considering nine zero erosion plots). However, the fact that similar patterns of erosion volumes have been frequently encountered (Dodge *et al.,* 1976; Furbish, 1981; McCashion and Rice, 1983; Rice and Datzman, 1981; Rice and Lewis, 1991) suggests that these results are not an anomaly and the average can be accepted with the assurance that it does represent the erosion on the road system. Although the data are based on simple random sampling they appear to give a good estimate of the erosion on the whole road network. An estimate using a stratified sample based on road standard differed from the above figure by less than one percent. Furthermore, the proportion of samples on each road standard agreed quite closely with the proportion of the network in each standard.

Thirteen plots were re-measured by a separate crew to gain some insight into possible 'bias' in the field measurements. The check plots were **chosen** (not at random), without knowledge of their erosion rates, to give a 'representative' sample of the different conditions on the road system. Although there was considerable plot-to-plot variability, the two crews' estimated average erosion rates for the 13 plots were quite close: 240 m^{3}km^{-1} (505) yd^{3}mi^{-1} and 228 m^{3}km^{-1} (479 yd^{3}mi^{-1}). Satisfaction with the relatively close agreement of these two mean erosion rates was considerably diminished when, in response to a question by a reviewer of an earlier draft of this paper, a detailed analysis was made of the source of each difference of each measurement on each of the 13 plots. The analysis revealed the considerable role that subjective measurements had in determining what was

TABLE 1. The Number of Plots Reporting Erosion Associated With Various Sites, Site Conditions, and Erosional Mechanisms (also the erosion rates and proportion of total erosion attributable to each).

	Number of Plots	Erosion m^{3}km^{-1}	Erosion (percent)
Erosion Site			
Five-Foot Plot	100	81	46
Major Events	100	67	38
Drainage Structure	100	28	16
Total	100	177	100
Place on Right-of-Way			
Cut Bank	64	110	63
Fill Slope)includes drain)	75	55	31
Road Surface	57	11	6
Erosional Mechanism			
Sloughing	23	53	30
Rills	24	19	11
Gullies	29	24	14
Slides	5	19	10
Slumps	11	62	35
Road Standard			
Seasonal	73	194	80
All Weather	19	146	16
Abandoned and Jeep	8	86	4
Time of Occurrence			
1997	34	6	4
1995-1997	81	92	52
1980-1997	60	78	44
No Erosion	9	0	0

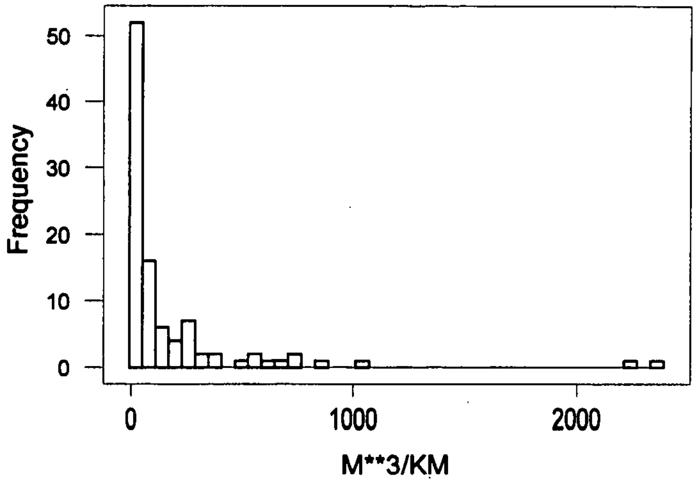

Figure 3. Number of Sites Yielding Various Amounts of Road-Related Erosion.

measured. Each of the three estimates (Plot, Drain, Major Events) had unique problems but all were affected by the determination of whether the erosion had occurred after 1979. Plot measurement differences were dominated by one plot having a high cut bank [4.42 m (14.5 ft)] on which the crews differed by 0.35 m^3 (12.2 ft^3). The next largest difference was 0.05m^3 (1.8 ft^3). The land owner's widespread use of outsloping and rolling dips was the source of much of the differences in Drain measurements. The crews had to determine whether all of the runoff on outsloped roads left the right-of-way before the dip and, if so, where (on average) did it leave? In one instance the check crew missed a culvert and consequently measured a more distant one. The crews agreed on the time of occurrence for only two of the five Major Events on the test plots. The crews volumes differed by about 8% for a large [about 153 m^3 (200 yd^3)] feature. A small slump was measured as 15.7 m^3 (20.5 yd^3) by one crew and 12.4 m^3 (16.3 yd^3) by the other causing it to be tallied by the first crew and rejected by the second.

The estimation difficulties just cited mean that the results reported here must be recognized as the product of the main crew's interpretation of the right-of-way and the volume and age of erosion features encountered. However, it is doubtful that any similar study is free of the same limitation.

Sources of Erosion

Most of the measured erosion took place on road cut banks (Table 1). Cut banks were also the site of most of the erosion by the two dominant mechanisms: sloughing and slumps. None of the site descriptors was a useful predictor of erosion. Slope had the highest correlation: 0.27. The data were plagued with over half of the sites being in one soil or geologic type or one of two types of dominant vegetation. The development of a prediction equation was not the purpose of this study but the low simple correlations suggest that such an attempt would meet with little success.

The last comparison in Table 1 deals with the estimated time of occurrence of the erosion. With some of the larger or more recent features the field crew could remember the time of occurrence. With most features, large or small, indirect evidence had to be relied upon. The sharpness of the scarps or margins was a clue to most features since weathering and animal traffic tends to break down the edges. Plants invading soil exposed by erosion are the other principal age key. Grasses and hydrophytes were usually the first invaders, appearing in the first and second post-disturbance years. Conifer seedlings, appearing in the second and later years, were the next most reliable indicators. Older erosion was usually dated by counting whorls of branches on coniferous reproduction. All of these indicators were subjectively weighted to arrive at an age determination. The three categories overlap in recognition of the uncertainty associated with such determinations. The 1997 value probably does not include all of the erosion occurring in that year. Some 1997 erosion features were likely mistaken for earlier erosion with which they were associated. The 1995-1997 category has a similar problem. Mistaking older erosion for more recent seems less likely to have been a problem. However, earlier erosion that had been corrected and obliterated by maintenance would also not be tallied. What is clear is that the most recent three years produced the majority of the road-related erosion **tallied** in this study. Coming on the heels of two (possibly three) years having high erosion potential (Figure 2) it is likely that the data are a fair representation of the erosion that **has** occurred since 1980. Whatever the truth of that assertion, the time-related errors in this study are shared with all similar investigations.

Erosion associated with drainage structures was estimated separately because earlier studies in lower Redwood Creek (Weaver *et al.*, 1995; Best *et al.*, 1995) had identified faulty stream crossings as a major source of road-related and gully erosion. Those studies estimated erosion occurring between 1956 and 1980. The roads in this study showed evidence of similar erosion having occurred prior to 1980. But, as can be seen in Table 1, the drainage structures measured in this study are associated with only 16 percent of the road-related erosion – a far cry from 80 percent as reported by Best *et al.* (1995) or about 71 percent estimated in South Copper Creek by Weaver *et al.* (1995). Nonetheless, culverts had the highest erosion rate of the drainage structures tallied in this study (Table 2).

Comparison With Other Studies

Direct comparison with the earlier Redwood Creek studies is not straightforward. Neither of the two which will be considered (Weaver *et al.*, 1995; Best *et al.*, 1995) had the same objective or experimental design as this study. All three reported erosion evident at the time of measurement with varying amounts of information about when the erosion had occurred. However, both of the other studies contained estimates of road-related erosion that occurred between 1956 and 1980. As such they provide the best available data with which to contrast erosion during that period with measurements made in this study. Both studies were part of a watershed rehabilitation program of the Redwood National Park. They aimed at estimating the magnitude and causes of erosion in

TABLE 2. Erosion Rates Associated With Various Types of Drainage Structures, Their Average Spacing, Their Contribution to Total Drain-Related Erosion, and the Proportion of Total Road Length Served.

Type	Plots (no.)	Erosion Rate (m^3km^{-1})	Spacing (m)	Erosion (percent)	Length (percent)
Out Slope	24	11	34	9	11
Rolling Dip	45	8	51	13	32
Water Bar	9	6	59	2	8
Culvert	17	96	146	59	35
Inside Ditch*	1	46	155	1	2
Other**	4	109	214	16	12

*An inside ditch that became a gully draining into a watercourse.
**Three low-water crossings and one "Humboldt crossing," all on abandoned roads.

the Park and in watersheds tributary to Redwood Creek above the Park boundary.

Weaver *et al.* (1995) were interested in gully erosion and chose nine study sites from preexisting high quality geomorphic maps to represent varying erosion rates. Detailed information was given about one of their study sites: the 246 ha (608 ac.) south side of Copper Creek about 17 km (10 mi) downstream of this study (Figure 1). Fortunately, it is the closest of their study sites to the area included in this study. It was classified as "High Yield" and was entirely underlain by the incoherent sandstone and mudstone unit of Coyote Creek (Cashman *et al.*, 1995), as were 81 percent of the plots in this study. About 73 percent of the Copper Creek site was steeper than 30 percent whereas only 56 percent of the plots in this study were steeper than 30 percent. That discrepancy may be partly due to slope measurements in this study being limited to road rights-of ways (which would tend to be on flatter terrain than the study area as a whole). Copper Creek underwent intermittent selective logging between 1959 and 1963. The remaining timber was clearcut during 1970-1971. Tractors were used for yarding during both periods. The roads were abandoned after 1971. Weaver *et al.* (1995) measured road-related erosion amounting to about 5,200 $m^3 km^{-1}$ (11,000 yd^3mi^{-1}). From the text it is clear that their estimate does not include sloughing or rills which amounted to almost 41 percent if the erosion measured in this study. Presumably, most of this erosion and that measured by Best *et al.* (1995) occurred during the large storms of hydrologic years 1972 and 1975 (Figure 2). It is likely that most of the evidence of erosion that occurred during the winter of 1965 (and also 1955 in the study by Best *et al.*) would have been obliterated by subsequent road repairs or the effects to the 1972 and 1975 storms. Neither study reports any attempt to date the erosion measured.

Best *et al.* (1995) estimated road-related erosion in the 1,080 ha (2,669 ac) Garrett Creek watershed
about om the center of
this st pper Creek, it is
entirel t sandstone and
mudst ; *et al.* (1995) do
not gi scribe a convex
watersl slopes and 65-70
percent . Garrett Creek
has thi was complete prior to
1954; one built between 1954 and 1965; and one built between 1954 and 1977. One major spur was also constructed between 1978 and 1982. They estimated 7,567 metric tons per kilometer. That rate is about 4,730 m^3km^{-1} (9,970 yd^3mi^{-1}) assuming a specific gravity of 1.6. The authors note that Copper Creek produced more erosion in a nine-year period (1971-1979) than Garret Creek did in 25 years. They attribute the difference to the fact that, unlike Copper Creek roads, Garrett Creek roads were used and sporadically maintained throughout the 25 years. They reported the average size of erosion features resulting from different causes. The smallest average size they reported was about 57 m^3 (63 yd^3) for erosion of inside ditches. From this figure it must be assumed that they too did not record any of the smaller features making up most of the erosion measured in this study.

$M^3/KM \rightarrow YD^3/MI$

MULT. BY 2.1

The estimated 17 years of road-related erosion of this study (1980-1997) can be contrasted with those earlier studies although this study probably did not include as severe storms as the earlier investigations (Figure 2). The contrast with Garrett Creek, which adjoins the study area on the north, is fairly straightforward. The two study areas share common soil, geology, and climate. The only appreciable difference between the two watersheds is the presence of a sizable fraction of redwood-dominated forest in Garrett Creek. The contrast with the south side of Copper Creek is almost as good. Although it is about 17 km (10 mi.) downstream from the site of this study it is still 19 km (12 mi.) inland from the coast. It is topographically similar and underlain by the same geologic formation (KJfc) as under 81 percent of the plots in this study. Like Garrett Creek, Copper Creek had a larger redwood component in its forested areas than found in the study area.

Although the above comparisons are made to support the contention that improved forest practices have greatly reduced road-related erosion, too much importance should not be attached to the exact ratios of the pre-1980 data and the estimate in this study. There is some ambiguity concerning the length of time represented by the erosion measured in the earlier studies. However, it is safe to say that the earlier roads yielded about 20 times as much erosion as measured in this study.

DISCUSSION

The fact that 56 percent of the measured erosion was identified as having occurred in the last three years suggests that the study was timely. However, the small proportion of erosion clearly identified as having occurred in 1997 and its low rate suggests that 1995 and 1996 were mainly responsible for currently active erosion. It may be, however, that recent erosion was just more obvious. The only erosion studies that avoid this ambiguity are those which are installed immediately after a disturbance and track its effects over time. Therefore, the data reported here are comparable to that reported by the majority of studies of road-related erosion in not having a chronology based on observations spanning the time covered by the study.

Since the 1.5 m (5 ft) plot erosion and major events occurred mainly on cut banks, the estimated erosion is likely to present a smaller environmental hazard than might be assumed from the estimated erosion rate. It has been my experience that the vast majority of this eroded sediment will come to rest on the road surface where it can be dealt with in a manner that minimizes its opportunity to enter a watercourse. Deposits blocking inside ditches are removed during routine maintenance or during storm patrols, if possible. Deposits on the 51 percent of the road system that does not depend on inside ditches (out slope, rolling dip, water bar; Table 2) are left in place if they do not impede traffic.

This study confirmed the pervasiveness of bank sloughing as an important part of road-related erosion. As reported by McCashion and Rice (1983), sloughing will have to be accepted as an unavoidable cost of having roads. Fortunately, most of it occurs on cut banks and is less likely to reach a stream channel. Gullies and, to a lesser extent, rills have much higher chance of delivering sediment to a stream since they are formed by flowing water. Slides, in this study, also had a higher sediment delivery potential because about 77 percent of the slide volume measured was eroded from fill slopes. Consequently, it was more likely to have unimpeded delivery of sediment to stream channels.

The erosion rates associated with different drainage structures displayed in Table 2 suggest that this topic might warrant further investigation. Contrary to expectation, rolling dips were associated with a lesser erosion rate than out-sloping, even though they permit a greater concentration of runoff. It may be that they were used in tandem with outsloping frequently enough that their average rate was decreased by those dips being robbed of erosion even though they were the principal drainage structure associated with those plots. Of greater importance is the high erosion rate associated with culverts. Unadjusted for spacing (that is m^3 as opposed to m^3km^{-1}), the average volume of erosion per culvert is nearly 40 times higher than that of water bars, out-sloping, or rolling dips. This may be due to the fact that culverts are often also conveying runoff from other areas in addition to that from roads. It may also stem from many culverts being located in still-erodible gullies created prior to 1980. It may also be due to the random sampling including one extreme event. One site yielded almost 80 percent of all the culvert erosion. However, even with that one extreme plot removed, erosion at culverts is still more than ten times larger than that associated with other drainage structures (excluding the one inside ditch drain and the 'Other' category). The very high erosion rate of the 'Other' sample sites suggests that abandoned roads should be inventoried and erosion problems corrected.

In spite of the likely differences in erosional stress between the time period covered by the earlier Redwood Creek studies and the time period covered by this one it is highly unlikely that the differences in erosion were solely due to that cause. The erosion rate measured in this study amounted to about 3 percent of that estimated in Garrett Creek (Best *et al.*, 1995) and in South Copper Creek (Weaver *et al.*, 1995). The annual sediment load of Redwood Creek was approximately the 1.9 power of the annual peak discharge ($r^2 = 0.83$) from 1971 to 1992. If that relationship applies to erosion in the watershed the 1980-1997 erosion should have been about 40 percent of the 1956-1979 erosion. Since it was much less than that percentage it seems likely that improved forest practices played a role in reducing road-related erosion. Furthermore, both the earlier studies focused on large features, neglecting about half the erosion measured in this study. The assumption that poor road construction and maintenance was a substantial contributor to the differences between them and this study is supported by a study of road-related erosion on the adjoining Six Rivers National Forest by McCashion and Rice (1983). That investigation spanned a similar time period as the early Redwood Creek studies but estimated that road-related erosion was 188 m^3km^{-1} (395 yd^3mi^{-1}) which is close to the 177 m^3km^{-1} (372 yd^3mi^{-1}) found in this study. Road maintenance and construction standards on the Six Rivers National Forest at that time were quite comparable to those currently being employed in the study area. Disparities in culvert erosion also support the contention that differences in road standards are responsible for much of the reduction in erosion measured in this study. Both of the earlier studies report stream diversions because of blocked culverts or other stream crossings were the major cause of erosion. There were no stream diversions or blocked culverts in this study.

CONCLUSIONS

The results of this investigation suggest that changes in forest practices have greatly reduced road-related erosion in the middle reach of Redwood Creek. The estimated erosion rate was more than an order of magnitude less than that estimated in the adjacent Garrett Creek watershed (Best *et al.*, 1995) and for the south slopes of Copper Creek (Weaver *et al.*, 1995) as the result of practices employed prior to 1976. The reduction in erosion is attributable to better sizing and placement of culverts and, especially, to less reliance on culverts to handle runoff from road prisms. It is also likely the result of less reliance on tractor yarding. Cable yarding tends to isolate yarding disturbances from road rights-of-way. Since nearly 63 percent of the measured erosion occurred on cut banks and, therefore, has less direct access to the stream network, it is likely that the road system's impact on water quality will be less than might be inferred from the gross erosion rate.

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APPENDIX
EROSION MEASUREMENTS

Each erosion measurement was first identified as to location: cut, fill, road surface, or drainage structure. Next its erosional mechanism and estimated time of occurrence (1997, 1995-1997, or 1980-1997) was recorded. Finally, its dimensions were transcribed.

MECHANISMS

Surface Sloughing

This is the gradual retreat of cut or fill surfaces. On cuts it is evidenced by exposed roots (the ends of which were at the cut surface when the road cut was made) or overhanging sod where the roots of the surface vegetation has held a thin layer of soil in place as the bank beneath it retreated. On fills sloughing may be evidenced by soil deposits at the toe of the fill or by the presence of rocks, sticks, or other more resistant material protruding from the general surface (indicating that the finer soil has eroded either by water flow or dry ravel).

Rill

A rill is a clearly defined channel that is at least 0.1 ft. deep and no more than 1.5 ft. across. It also can not have a cross sectional area greater than 1.0 $ft.^2$.

Gully

A gully is a clearly defined channel made by flowing water that has a cross sectional area greater than 1.0 $ft.^2$.

Slide

All rapid incoherent mass movements will be included in this category. They range from rock falls to debris torrents depending upon the amount of water involved. Typically they are sudden in initiation and move rapidly down steep slopes (almost always slopes > 55 percent). They usually triggered by high intensity one to two day rainfall amounts (once soil moisture deficits have been satisfied in autumn or winter).

Slump

This category will include all of the more or less coherent mass movements such as block glides, slumps, and soil creep. These features are typically more deep seated than slides and, with the possible exception of block glides, are slower moving. They are also usually larger than slides. Slumps normally have a curved failure surface with a steep scarp above a cavity at the head of the movement and a depositional mound at the toe. All involve a large amount of subsurface water and respond to long duration [weeks to seasonal] rainfall amounts.

FIELD MEASUREMENTS

Plot Description Variables

Slope – Percent
Dominant Vegetation – Coniferous forest, hardwood forest, brush, grass, bare
Cut Bank Height – Feet
Cut Bank Vegetation – Bare, grass, woody plants
Road Standard
  Seasonal – Usually unsurfaced single lane with turn-outs
  All-Weather Secondary – Usually most of the length is two lane; surfaced with gravel or crushed rock of moderate depth
  Abandoned – Roads that have not been maintained since 1980
  Jeep – Roads of such a standard that they are only passable to four-wheel drive vehicles or ATVs
Drainage Structure
  Type – Outslope, water bar, rolling dip, inside ditch, culvert
    For Culverts – Diameter, condition
  Erosion Site – Outfall, entrance, road surface

Office Measurements

Plot Description Variables
  Geology (from Cashman *et al.,* 1995)
    KJfc – Incoherent sandstone and mudstone unit of Coyote Creek
    KJfg – Transitional rocks of the Grogan Fault Zone
    KJfr – Redwood Creek Schist
    Qt – Terrace deposits
    Qls – Landslide deposits

Road Age – Years since construction or major maintenance. Major maintenance would include such activities as replacing culverts, outsloping or installing rolling dips on a road previously drained in some other fashion, repairing storm damage, adding new surfacing, etc.

Soil – Types by the California Cooperative Soil-Vegetation Survey (Colwell, 1979)