LONG TERM ON-SITE AND OFF-SITE EFFECTS OF LOGGING AND EROSION IN THE REDWOOD CREEK BASIN, NORTHERN CALIFORNIA

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I INTRODUCTION

For nearly 15 years, the Redwood Creek watershed in north coastal California has been the focus of both U.S. Geological Survey (USGS) and National Park Service (NPS) studies designed to document and quantify the nature of erosion, sedimentation and sediment transport processes active in the basin. While none of these studies were specifically designed to assess possible cumulative effects resulting from land use, we can demonstrate, by synthesizing a number of study findings throughout the watershed, that some land use practices do result in long-term and persistent changes to hillslopes and stream channels.

For this discussion, "Cumulative Effects" are viewed as multiple, persistent impacts which are separated in either space or time from the original land use disturbance. Although each incremental disturbance may have an insignificant effect when viewed alone, the impacts may become cumulatively significant when seen in aggregate or when multiple erosion sources are triggered simultaneously by a large storm. For example, an undersized culvert which becomes plugged or whose capacity is exceeded by storm runoff can cause erosion at the site where it is installed as all or part of the fill crossing is washed out. In addition, streamflow can be diverted from the channel and cause considerable erosion in downslope areas where gullies will form, and in far removed fish-bearing streams where the sediment is finally deposited.

In addition to being spatially displaced from its source, the effect may also be delayed in time. The undersized culvert may not plug or its capacity be exceeded for many years, and the resultant erosion and sedimentation may not occur for decades after the original disturbance. An entire road network, which is not being permanently maintained or whose culverts have been underdesigned, may not reveal significant erosional impacts from road construction until a major storm causes widespread culvert failure, stream crossing erosion and stream diversions. The effects of land use are then additive, occur essentially instantaneously over large areas, and are displaced both spatially and temporally from their source and time of initiation.

The objective of this brief report is to describe how specific land use practices can cause multiple on-site and off-site geomorphic impacts which may become obvious only years following the land use disturbance. Additionally, we will briefly outline how a large percentage of these persistent effects can be avoided entirely by minor changes in road construction techniques.

II METHODS

The results presented here are a compilation of published and unpublished study findings by park researchers in the Redwood Creek watershed over the last eight years. All results were obtained from a National Park Service study initiated in 1978 to formulate a sediment budget for the Redwood Creek watershed. Of the published studies, we have drawn heavily from four publications (15, 9, 13, 10).

Weaver and others (15) discuss the magnitude and causes of hillslope gully erosion in the 197 km^2 lower Redwood Creek watershed for the study period 1954 to 1981. The publication details how various site factors have influenced gully yields. Kelsey and others (9) field mapped and measured the volumes of streamside landslides and volumes of stored sediment in the upper one-third of the Redwood Creek watershed, as well as in 15 tributary streams throughout the basin. Pitlick (13) presents detailed results from measurements in 16 tributary basins comparing sediment production and sediment storage. He documented the effects of high intensity storm events and timber harvest patterns on sediment production. Madej (10) mapped, measured, and categorized all sediment stored in the Redwood Creek channel. The volume of sediment stored in Redwood Creek, estimated from aerial photographic studies, historic records and survey data, was quantified for a time period spanning 35 years. Ages and residence times for stored sediment were also estimated

III STUDY AREA

The 720 km^2 Redwood Creek basin, located in coastal northern California about 480 kilometers north of San Francisco (Figure 1), is one of several circum-Pacific regions which display increases in both the amount and rate of landsliding and fluvial hillslope erosion over pre-disturbance (land use) conditions (8). Because of differences in climate, logging history and vegetation patterns, we have divided the Redwood Creek basin into three (3) distinct segments of approximately equal length. Each has a USGS gaging station at its downstream end. The upper section extends from the headwaters to State Highway 299, the middle reach or middle 1/3 of the basin is situated from Highway 299 down to the southern or upstream boundary of Redwood National Park, and the lower reach stretches from the upstream boundary of the park down to the town of Orick, located near the mouth of Redwood Creek (Figure 1).

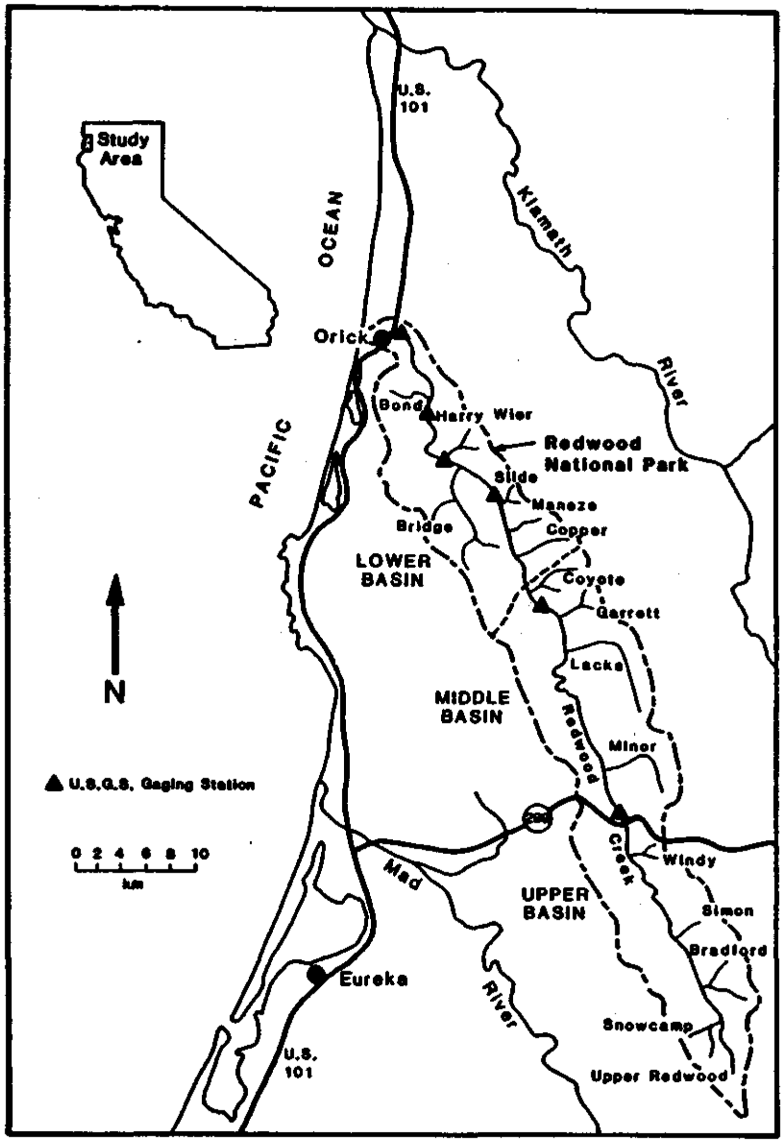

FIGURE 1

LOCATION MAP OF THE 720 KM^2 REDWOOD CREEK BASIN SHOWING TRIBUTARY WATERSHEDS DISCUSSED IN THIS PAPER AND THE LOCATION OF U.S.G.S. GAGING STATIONS

The Redwood Creek basin is underlain by rocks of the Franciscan Assemblage (1, 7), which is a Mesozoic to early Cenozoic accumulation of weakly indurated and pervasively sheared continental margin deposits. The Grogan Fault, expressed as a well defined, NNW-trending lineament, roughly bisects the basin and juxtaposes unmetamorphosed and slightly metamorphosed clastic sedimentary rocks to the east against metamorphosed schistose rocks to the west. Soils developed on these rock types are highly varied and have been extensively studied by Marron (11) and Popenoe (unpublished NFS reports). In general, soils are moderately coarse in texture and have high infiltration capacities but possess little cohesion and very low shear strength.

The course of Redwood Creek is structurally controlled by the Grogan Fault, resulting in an elongate basin geometry (elongation ratio = 0.34). As a result, there are 74 tributary basins drained by third order or higher streams which flow directly into Redwood Creek. The drainage basin is characterized by high relief (1500 meters), moderate to steep hillslopes and narrow valley bottoms. Janda and others (8) estimated the average hillslope gradient to be about 0.26 (14.4 degrees). Most hillslopes exhibit a distinct convexity with the steepest hillslope segments adjacent to stream channels and more moderate gradients at middle and upper slope positions.

For most study results presented in this summary paper, the period of record extends from 1947 to 1980. The time frame for this and a number of the other erosion and sedimentation investigations in the watershed was selected for three principle reasons: (a) it includes a period of widespread timber harvesting; roughly 72 percent of the coniferous forest was logged (Figure 2), resulting in the construction of approximately 2,000 km of roads and over 9,000 km of skid trails (2), (b) a series of five intense storms occurred with recurrence intervals of 10 to 50 years (6, 3), and (c) extensive data on watershed changes and erosion rates are available from aerial photographs, field mapping and stream gaging stations.

IV RESULTS

Cumulative effects in the fluvial system may be divided into several categories, including both hydrologic, and erosion and sedimentation. Other authors in this volume and elsewhere have dealt with possible hydrologic changes. Our emphasis will be on measurable erosion and sedimentation effects. These can be divided into four possible categories: increases in surface erosion, increases in the volume of mass erosion, increases in fluvial erosion (i.e. gullying, bank erosion, etc.), and increases in the volume of channel stored sediment.

In Redwood Creek, sediment production from surface erosion has been judged a minor constituent of total basin sediment yield and of comparatively lesser geomorphic importance than other sources. For example, in the 197 km^2 lower Redwood Creek basin, the total amount of sediment delivered to stream channels by surface erosion processes (raindrop, sheetwash and rill erosion) between 1954 and 1980 was estimated to be 124,400 m^3 compared to a total sediment yield, from all sources, of 3.1 x 10^6 m^3 for this time period (Hagans and Weaver, unpublished data, Table 1). The amount of surface erosion was determined by analyzing National Park Service sediment trough data and USGS erosion pin data (12), by determining the total surface area of bare soil present following logging which could deliver sediment to stream channels, and by estimating recovery times and revegetation rates. Results suggest surface erosion processes acting on bare soil areas, while directly linked to land use practices, account for a maximum of only four percent of the total lower basin sediment yield in the 27-year study period. We conclude that in the Redwood Creek basin, surface erosion processes are a minor contributor to downstream erosion and sedimentation impacts.

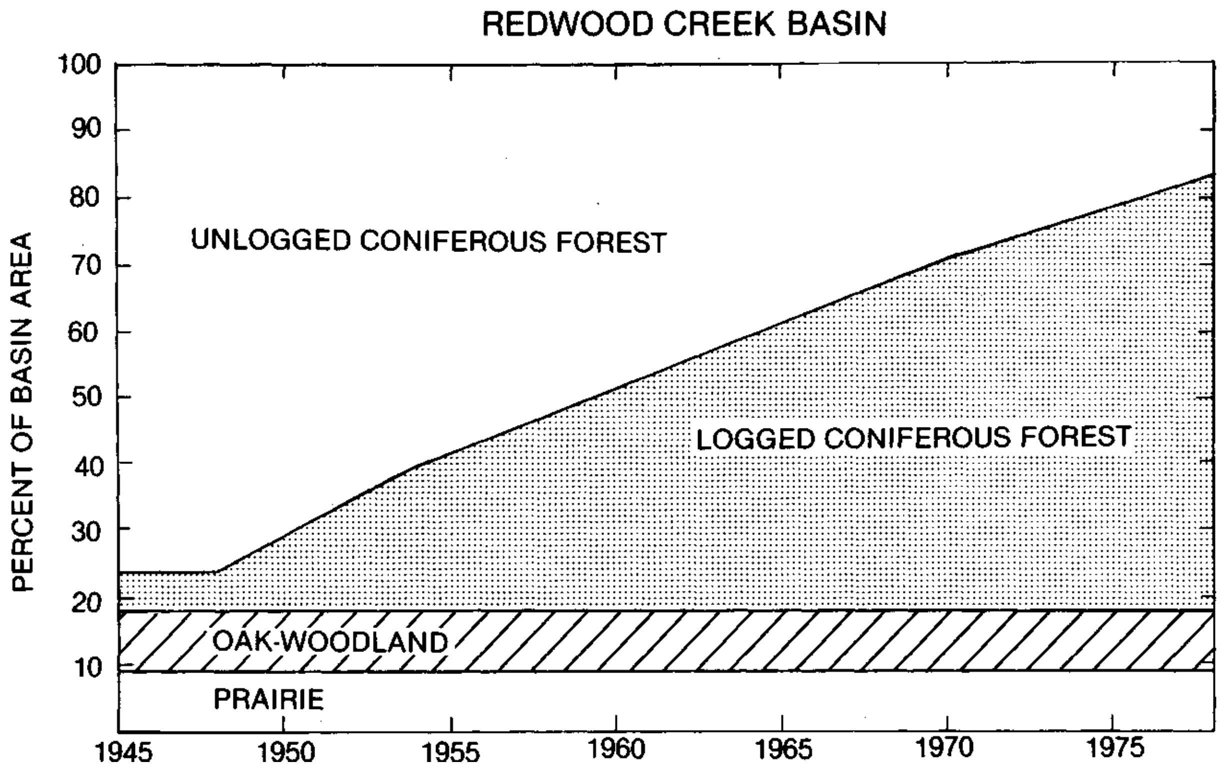

FIGURE 2

TIMBER HARVEST IN THE REDWOOD CREEK BASIN SHOWING CHANGES IN PERCENT OF BASIN LOGGED FROM 1945 TO 1978

TABLE 1 MEASURED SEDIMENT SOURCES IN THE LOWER REDWOOD CREEK BASIN (1954-1980)

Sediment Source	Volume (m^3)	Percent of Total Yield
Gullies	1,157,400	37
Eroded Stream Crossings	225,600	7
Surface Erosion	124,400	4
Streamside Landslides	1,600,000	52
Totals	3,107,400	100

Mass erosion, originating from a variety of landslide mechanisms, is of nearly equal importance to fluvial erosion in its total contribution to sediment production in Redwood Creek (Table 1). However, a clear cause and effect relationship between mass erosion and land use activity is far more difficult to establish than for fluvial sources. Analysis of sequential aerial photographs and field mapping show that the number of landslides occurring on unlogged slopes as opposed to logged slopes is nearly the same (Table 2). However, the slides associated with both roads and harvested slopes are substantially larger and account for nearly 80 percent of the total mass erosion (13, 9). Similarly, road-related landslides (i.e., road-fill or cut bank failures not necessarily associated with timber harvesting) have contributed nearly 40 percent of total sampled landslide volume in the Redwood Creek basin (Table 2).

TABLE 2 INVENTORY OF LANDSLIDES LARGER THAN 281 m^3 AND SITE CONDITIONS PRIOR TO FAILURE IN 16 REDWOOD CREEK TRIBUTARY BASINS (MODIFIED FROM PITLICK, 13)

	UNLOGGED[1]	LOGGED			
			CLEAR-CUT		
		ROAD-RELATED[2] FAILURES	TRACTOR-YARDED	CABLE-YARDED	SELECTION-CUT TRACTOR-YARDED
Number of slides larger than 281 m^3	222	109	47	46	37
Total volume of sediment delivered (m^3)	429,900 m^3	749,800 m^3	379,200 m^3	290,200 m^3	152,400 m^3
Average slide volume	1,900 m^3	6,900 m^3	8,100 m^3	6,300 m^3	4,100 m^3
Percent of total inventoried slide volume	21.5	37.5 m^3	18.9	14.5	7.6

[1]Slides occurring in unlogged areas may be related to upslope or upstream timber harvesting. However, in most cases, the association between the slide and timber harvesting is not direct or obvious.

[2]Road related failures are those types of slides associated with failure of the road fill and/or the cut-bank upslope and are not necessarily associated with timber harvesting.

While there is a strong association between sediment production caused by landsliding and the occurrence of road construction and timber harvesting, data needed to define a strict cause and effect relationship are difficult to obtain. This, in turn, makes it difficult to directly attribute measured, downstream impacts to specific land use activities, although data clearly suggest their potential importance. For this reason, rather than addressing their on-site impact or effects caused by their volumetric contribution to sediment storage in the main channel of Redwood Creek, this paper will emphasize the basin-wide sources of fluvial erosion and their contribution to sediment yield.

An ambiguity between cause and effect does not exist for sources of fluvial erosion throughout the watershed. We will demonstrate that in Redwood Creek, increases in fluvial erosion and changes in stored sediment can be unquestionably linked to specific land use practices. As will be discussed later in this report, the relative magnitude of these long term changes are often significant whether we inventory a small portion of a sub-watershed or the whole basin.

Fluvial erosion and sedimentation effects can be conveniently broken into three locations of occurrence: (a) on-site changes which affect the individual harvest units, (b) off-site downslope changes occurring on older cut blocks or in old growth areas below a given harvest unit, and (c) off-site downstream changes which occur either in higher order tributaries or in the main stem of Redwood Creek itself.

A. On-site Effects

The types of on-site long-term land use related changes which have been quantified in the Redwood Creek basin include: (a) increases in drainage density, (b) increases in stream channel dimensions, and (c)increases in fluvial erosion and consequent sediment yield.

Table 3 demonstrates changes in drainage density for seven study sites in the lower Redwood Creek basin. The sites ranged from 1.4 to 4.1 km^2 in area and had pre-roading and pre-logging "natural" drainage densities of 4.1 to 6.1 km/km^2 of hillslope. Clearcutting, tractor yarding and road construction on these sites occurred during the 1960's and 1970's, and most units have since experienced at least three ten-year return interval storms. Post-logging (c.1980) drainage densities (including gullies and natural stream channels) on the seven study sites ranged from 5.4 to 14.4 km/km^2. This amounts to increases in drainage density ranging from six percent to 136 percent. On average, drainage densities increased by 71 percent on the 16.4 km^2 sampled areas.

A map of the South Copper Creek site graphically shows the extent and length of gullies compared to original stream network (Figure 3). The gullies are widespread and complexly interconnected. They represent the dominant sediment source contributing to increased post-harvest sediment yield and changes in drainage density on this and all the study sites. Increased drainage densities were commonly caused by stream diversions and the resultant creation of lengthy and large hillslope gully systems (Figure 4). Stream flow was diverted onto adjacent bare hillslopes when culverts plugged or where logging roads and skid trails crossed ephemeral and intermittent streams which had not been fitted with culverts.

TABLE 3 CHANGES IN DRAINAGE DENSITY ON SEVEN STUDY SITES IN THE LOWER REDWOOD CREEK BASIN

Site Name	Area (km^2)	Pre-logging drainage density (km^{-1})	Post-logging drainage density (km^{-1})	Increase in drainage density (percent)
South Copper (79-4)	2.5	6.1	14.4	136
Maneze (80-2)	1.7	4.5	9.4	114
North Copper (81-1)	4.1	4.4	7.5	70
Upper Slide (81-3)	2.4	4.1	6.8	66
Lower Slide (81-2)	2.0	4.2	6.8	62
Dolason (80-5)	1.4	5.2	7.0	35
Bond (82-4)	2.3	5.1	5.4	6
TOTALS	16.4	4.8	8.2	71

On the seven sites, 70 percent of the total length of newly formed channels were attributable to three principle causes: (a) culvert plugging and subsequent stream diversions along logging roads (17 percent), (b) diversion of streams at skid trail stream crossings on logged hillslopes (37 percent), and (c) lack of culverts at logging-road stream crossings, with consequent diversion of streamflow into roadside ditches and eventually across overland areas or into nearby stream channels (16 percent). The newly formed gullies are now an integral part of the drainage network. Whether they are still actively evolving or are inactive, they intercept near surface storm flow and carry runoff to higher order channels downslope.

The second type of <u>on-site</u> effect is an increase in channel dimensions, primarily on lower order streams (first, second and some third order channels). As with increases in drainage density, the diversion of stream flow at road and skid trail stream crossings is primarily responsible for the enlargement of natural stream channels. The substantial and relatively rapid adjustments of channel morphology occur as a result of increased discharges and sediment loads. Because of the difficulty in graphically reconstructing original channel dimensions after gullying has already occurred, our approach has been to determine the length of natural stream channels which have been "significantly" enlarged or gullied, based on detailed field mapping and comparison with unimpacted reaches. Enlarged channels display near vertical and raw streambanks and are characterized by abundant young vegetation which is actively toppling from the sideslopes into the stream channel,(<u>Figure 5</u>).

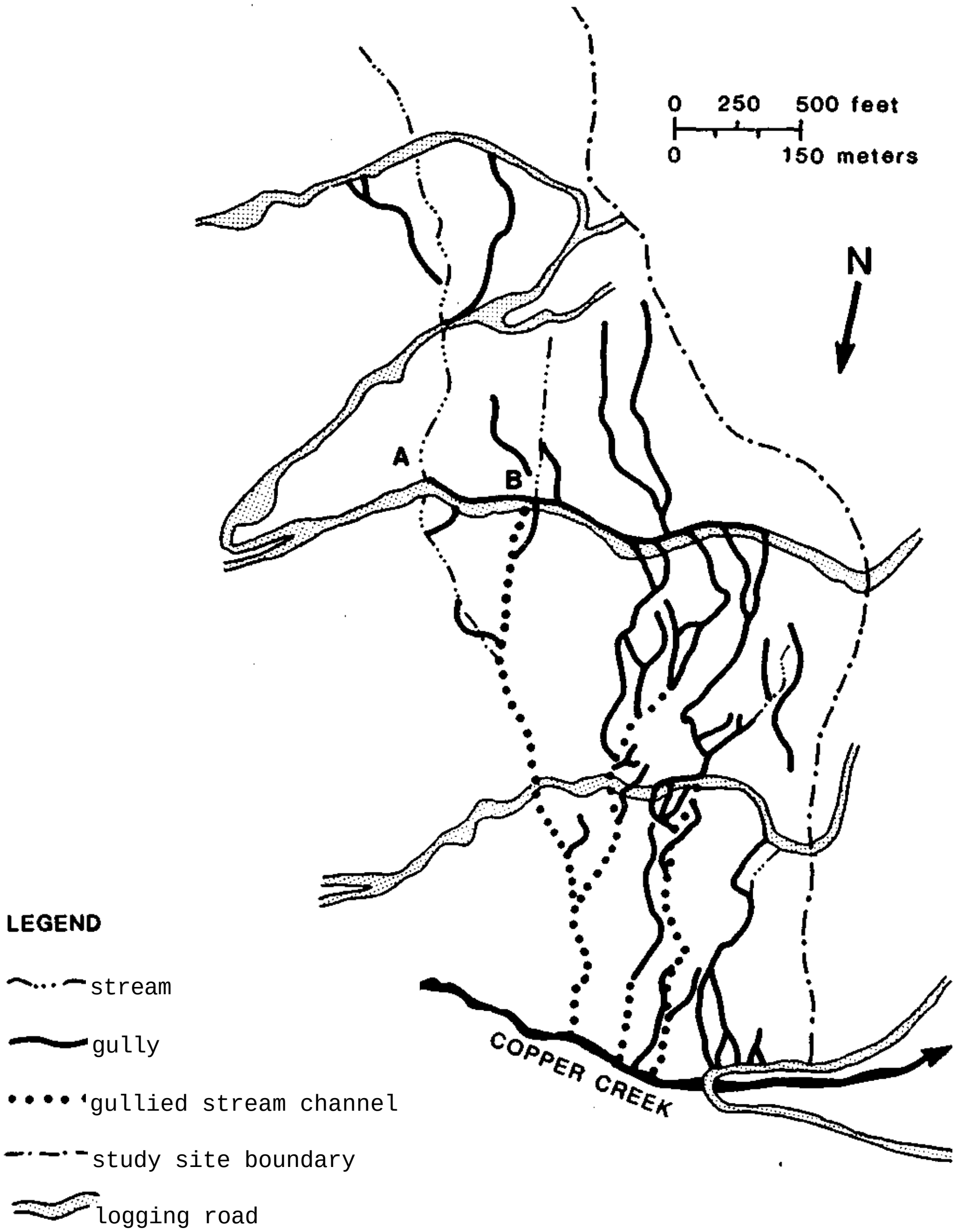

FIGURE 3

DETAILED MAP OF MEASURED GULLY NETWORK AND ENLARGED STREAM CHANNELS ON THE WESTERN SIDE OF THE SOUTH COPPER CREEK STUDY SITE. TOTAL MEASURED GULLY EROSION FOR THE MAPPED AREA IS 40,600 m^3. ROAD CROSSINGS AT LOCATIONS A AND B DRAIN 29- AND 8-HECTARE WATERSHEDS RESPECTIVELY. THE DIVERSION OF STREAM FLOW TO THE INBOARD DITCH AT THESE LOCATIONS RESULTED IN THE MAJORITY OF GULLY EROSION AND ENLARGED STREAM CHANNELS SHOWN ON THE MAP

By inventorying the same seven study sites used in the drainage density analysis, we found the total lengths of natural stream channel ranged from 7.5 to 17.9 km per site (Table 4). On these sites, 0.3 to 5.3 km of the natural stream channels had been enlarged or gullied; this represents 3 to 30 percent

FIGURE 4

GROUND PHOTOGRAPH OF TYPICAL GULLY IN REDWOOD CREEK BASIN. GULLY AVERAGES TWO TO THREE METERS WIDE BY TWO METERS DEEP. NOTE THE INCOMPETENT NATURE OF FRANCISCAN ASSEMBLAGE BEDROCK EXPOSED IN THE GULLY WALLS. DIVERTED STREAMFLOW AT ROAD CROSSINGS FREQUENTLY DEVELOPS LARGE GULLIES BEFORE A COARSE LAG DEPOSIT CAN ACCUMULATE AND ARREST FURTHER DOWNCUTTING AND ENLARGEMENT.

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of their original lengths. On average, 19 percent of the total length of natural stream channel has been enlarged on the 16.4 km^2 study area.

The third type of on-site effect is increased fluvial erosion and sediment yield. On nine study sites totalling 22.1 km^2, Weaver and others (15) measured 76 km of gullies with a total volume of sediment yield equalling 329,500 m^2 (Table 5). Based on inventories of several site variables, including degree of ground disturbance, soil and bedrock characteristics, slope gradient and hillslope position, we extended the gully volumes from mapped areas to unmapped areas and estimated the total fluvial sediment yield for the 197 km^2 lower Redwood Creek basin. The total gully erosion equaled 1.2×10^6 m^3 (Table 1). Other sources of fluvial erosion, including failed or eroded road and skid trail crossings, totaled 0.3×10^6 m^3 of erosion. For comparison purposes, the total measured landslide volume in the lower basin equaled 1.6×10^6 m^3, or roughly the same amount as that occurring by fluvial erosion processes (Table 1).

Our field studies have shown that the diversion of streamflow at logging road and skid trail crossings has caused 89 percent (1.0×10^6 m^3) of the total post-harvest gully erosion. By extension, this accounts for 33 percent of the total lower Redwood Creek sediment production from 1954 to 1980. Based on sampled plots from throughout the upper two-thirds (523 km^2) of the Redwood Creek basin (Figure 1), it appears that land use related and avoidable fluvial erosion accounts for at least 40 percent of the total basin-wide sediment production.

FIGURE 5

GROUND PHOTOGRAPH OF ENLARGED OR GULLIED NATURAL STREAM CHANNEL NOTE LARGE AMOUNT OF INTRODUCED LOGGING DEBRIS (BACKGROUND) WHICH DEFLECTS STREAMFLOW INTO SIDESLOPES AND CAUSES FURTHER BANK EROSION

B. Off-Site Downslope Effects

Off-site downslope effects are essentially of the same type and magnitude as the on-site effects, but the ultimate "cause" of the erosion always stems from upslope activities. For example, Figure 6 shows a portion of the existing logging road network in Copper Creek, a lower Redwood Creek tributary basin. It demonstrates how 89 percent of the lower basin gully erosion and, based on sample plots, a comparable or greater percentage in the upper and middle basin, has been caused by land use; how this erosion was preventable; and how it has resulted in long-term and persistent changes to the watershed. The region above the logging road may be thought of as the area experiencing on-site effects, and the area below the road as the off-site downslope area or area below the harvest unit. The figure shows a stream network with gullies originating from five different causes (labeled by italic print). All five causes of gullying were associated with disruption of the natural drainage pattern on the hillslope. Importantly, individual gullies resulting from most causes are generally small (less than one meter wide

TABLE 4 ENLARGEMENT OF NATURAL STREAM CHANNELS ON SEVEN SITES IN THE LOWER REDWOOD CREEK BASIN

Site Name	Area (Km^2)	Total Natural Channel (Km)	Enlarged Channel (Km)	Percent of Natural Channel Enlarged (percent)
North Copper (81-1)	4.1	17.9	5.3	30
South Copper (79-4)	2.5	14.9	3.5	23
Maneze (80-2)	1.7	7.6	1.6	21
Upper Slide (81-3)	2.4	9.9	2.0	20
Lower Slide (81-2)	2.0	8.4	1.1	13
Dolason (80-5)	1.4	7.5	0.7	9
Bond (82-4)	2.3	11.4	0.3	3
TOTAL	16.4	77.6	14.5	19

TABLE 5 GULLY EROSION ON NINE SITES IN THE LOWER REDWOOD CREEK BASIN

Site Name	Area (ha)	Gully length (km)	Number of cross sections measured	Total gully volume (m^3)	Gully Yield (m^3/ha)	Gully Density (m/ha)	Mean gully cross sectionl (m^2)
South Copper (79-2)	246	20.3	3,168	87,100	354	83	4.3
North Copper (81-1)	410	12.7	377	108,500	265	31	8.5
Maneze (80-2)	172	8.5	380	36,000	209	49	4.2
Lower Slide (81-3)	198	5.0	149	34,400	174	25	6.9
Bridge (80-6)	304	14.8	826	23,300	77	49	1.6
Upper Slide (81-3)	239	6.4	474	17,300	72	27	2.7
Dolason (80-5)	144	2.6	132	7,900	55	18	3.0
Bridge (80-3)	275	4.7	238	14,300	52	17	3.0
Bond (82-4)	226	0.8	37	700	3	4	0.9
TOTAL	2,214	75.8	5,781	329,500	149	34	4.3

[1] Mean gully cross sectional area - total gully volume divided by total gully length.

and deep). However, when these gullies merge, or if streamflow is diverted out of a channel as shown at locations A and B (Figure 6), exceptionally large gullies may develop off-site and downslope from the harvest area. Their off-site impact to stream systems is nearly immediate since measured delivery ratios for the developing gully systems exceed 90 percent. Likewise, the relatively rapid creation of these new "stream channels," usually during larger storms, can also cause the gullying or enlargement of natural stream channels downslope as large volumes of sediment are routed through the stream network (Figure 6).

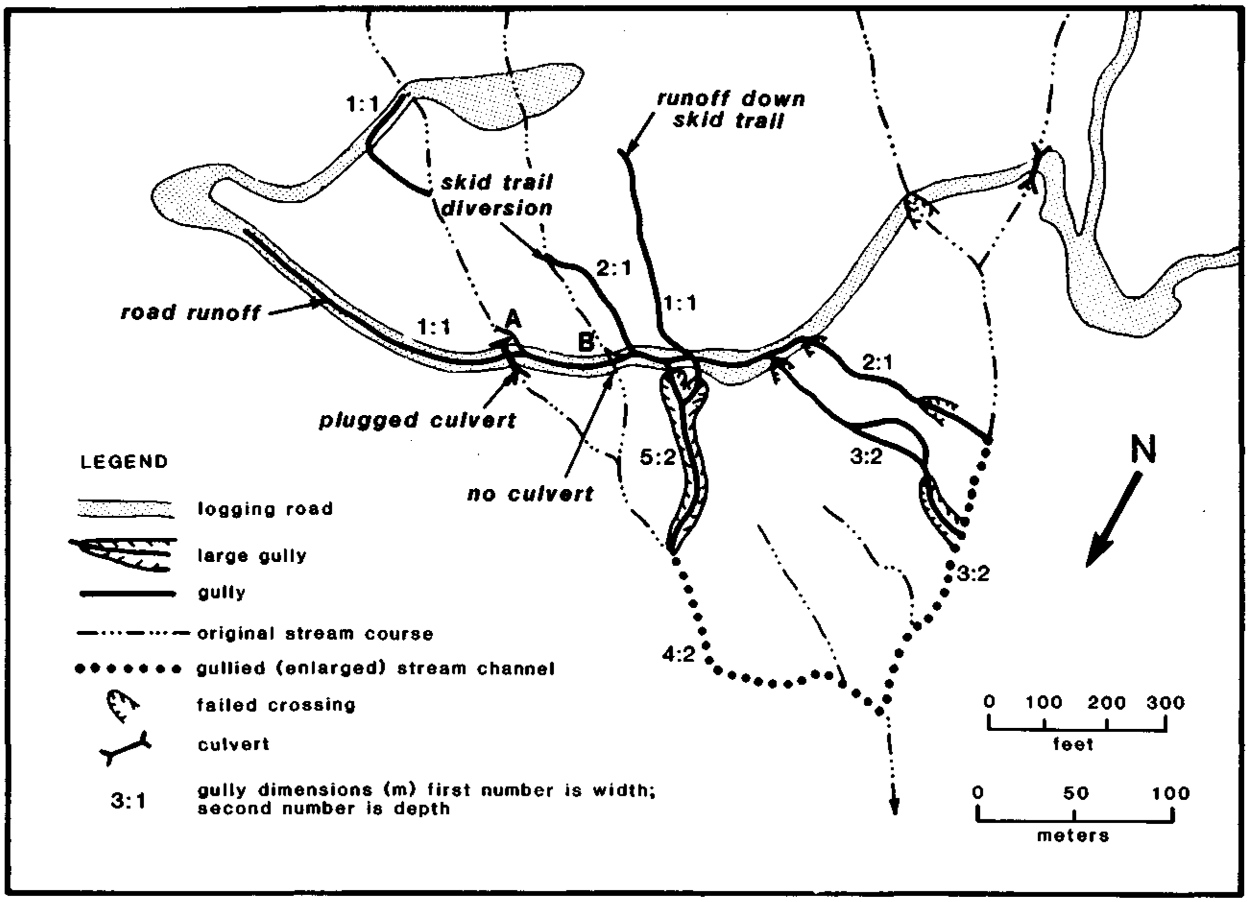

FIGURE 6

SIMPLIFIED MAP SHOWING CAUSES AND EXTENT OF GULLYING ON LOGGED LANDS IN THE REDWOOD CREEK BASIN. LOCATIONS A AND B ARE DESCRIBED IN THE TEXT

Thus, while sediment production may decrease to near background levels within one or two decades after reading and timber harvesting, some land use practices have resulted in long-term changes to hillslope morphology and sediment yield. These are most graphically demonstrated by increases in drainage density and changes in channel geometry caused by stream diversions.

C. Off-Site Downstream Effects

Our discussion of off-site downstream effects focuses on higher order streams, mainly the major tributary streams, as well as the main stem of Redwood Creek. The types of off site downstream effects of fluvial erosion that we have been able to quantitatively document include: (a) increases in the volume of stored sediment, including that deposited in "compartments" displaying relatively long residence times, (b) increased incidence of bank erosion, and (c) decreases in pool number.

Long term changes in channel geometry do not seem as widespread in steep third, fourth and fifth order tributaries when compared to the effects on the hillslopes and in small streams. Much of this lack of persistent changes or effects appears to be controlled by channel gradient which in turn affects residence times of introduced sediment. Most of these higher order tributaries have average gradients between 0.05 and 0.30 m/m and drain small watersheds ranging from 1.6 to 44 km^2. Their channels are, in general, deeply incised and have narrow, discontinuous floodplains (Figure 7).

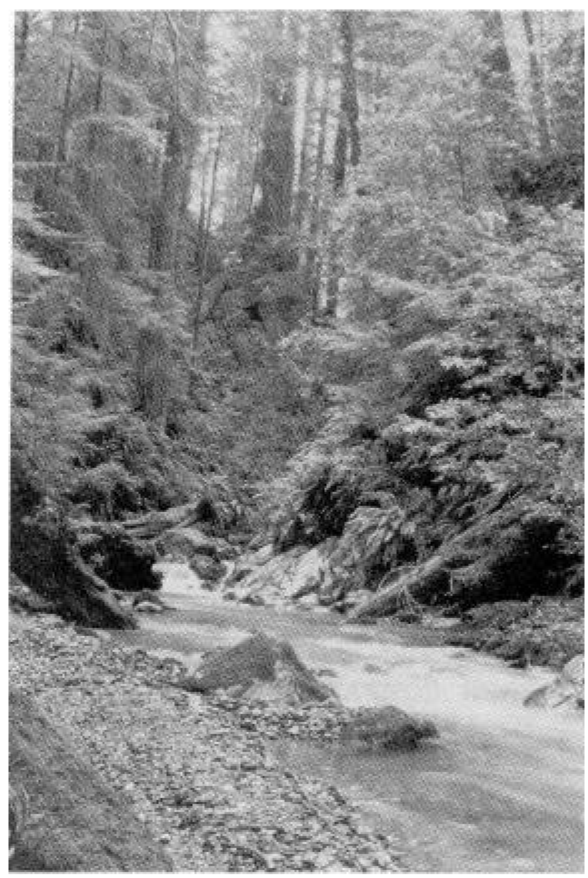

FIGURE 7

CHANNEL OF DEVILS CREEK (NEAR SOUTH PARK BOUNDARY) EXHIBITS COMMON CHARACTERISTICS OF REDWOOD CREEK TRIBUTARY STREAMS: STEEP SIDESLOPES, COARSE BED MATERIAL AND LITTLE FLOODPLAIN DEVELOPMENT

Pitlick (13) showed that for the most part, tributary streams are very efficient transporters of sediment. Using measured landslide volumes in these tributaries for comparison purposes, Figure 8 shows that while relatively large sediment volumes were introduced to these streams, very little of the introduced material was still in storage by 1981. On average, these tributaries have stored between 9 and 66 percent of the introduced material. If fluvial hillslope contributions (i.e. an additional 30 to 40 percent not shown in Figure 8) are considered together with landslide volumes, the tributaries actually store between 5 and 30 percent of the total introduced material. Thus, except where tributary gradients are naturally low, or locally reduced behind log jams, the off-site geomorphic effects of increased upstream erosion appears to be minimal. Instead, steep high order tributaries serve as corridors through which material introduced upstream and upslope is efficiently transported to lower gradient reaches in Redwood Creek.

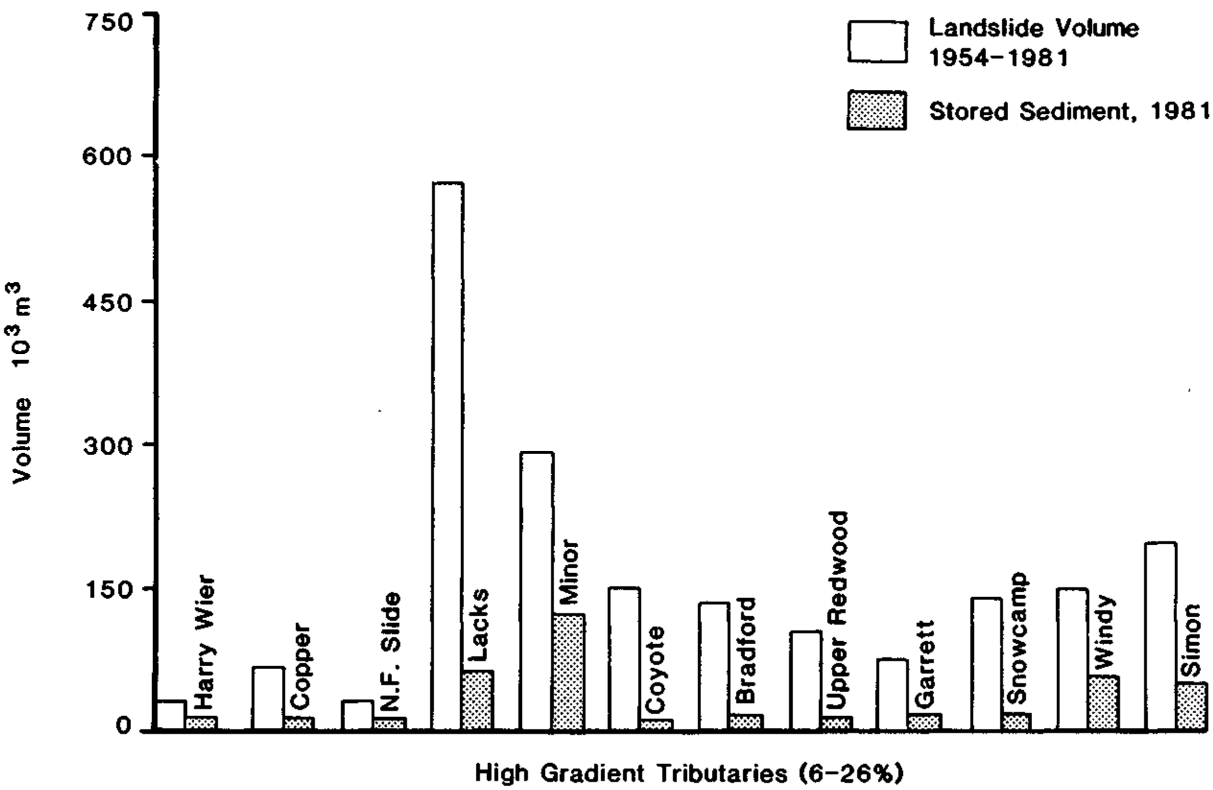

FIGURE 8

BAR GRAPH COMPARING MEASURED LANDSLIDE VOLUME FOR THE PERIOD 1954 TO 1981 TO THE AMOUNT OF SEDIMENT IN STORAGE AS OF 1981 ON 12 TRIBUTARY BASINS TO REDWOOD CREEK. TAKEN FROM PITLICK (13)

Tributary efficiency is exemplified in a series of cross-sections surveyed near the mouth of the 29.4 km^2 Bridge Creek watershed (Figure 9). It illustrates the exceptionally short residence time of stored sediment in many higher order tributary streams. One year after the March 1975 flood had deposited over two meters of sediment in the channel, well over one meter of degradation had occurred throughout the cross-section. Within just three years, the channel had flushed out virtually all the introduced sediment and returned to near its original configuration with little evidence of major secondary changes in channel geometry (e.g., bank erosion).

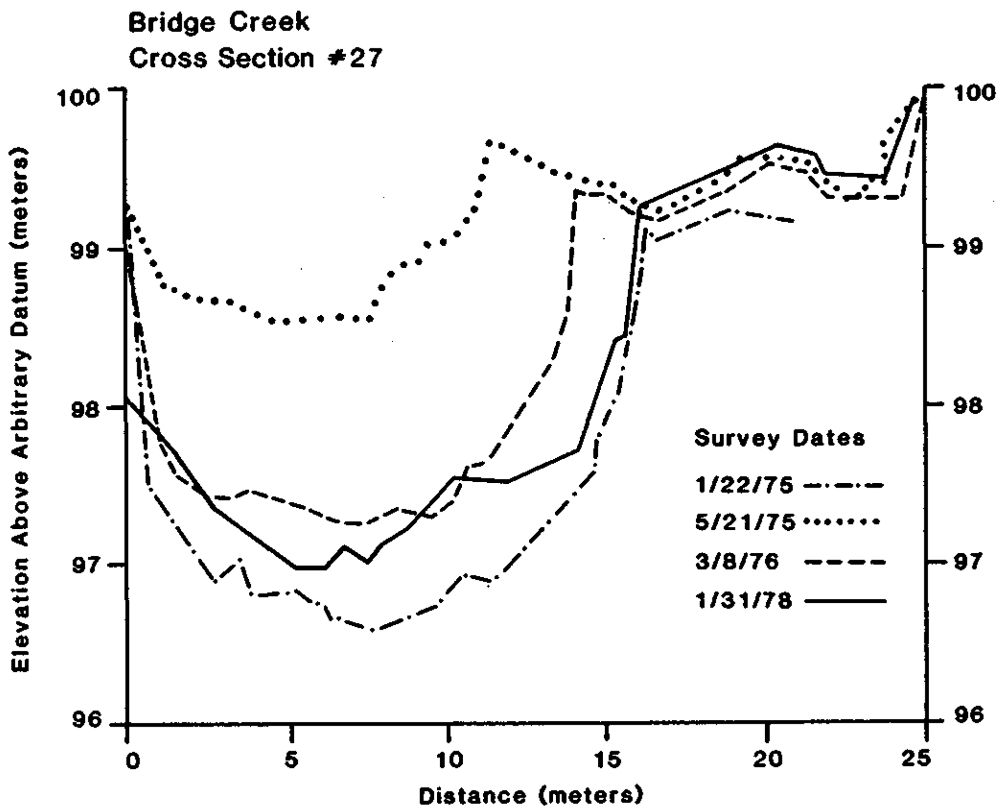

FIGURE 9

BRIDGE CREEK CHANNEL CROSS SECTIONS MEASURED OVER A THREE YEAR PERIOD ILLUSTRATE THE SHORT RESIDENCE TIME OF STORED SEDIMENT IN MANY HIGHER ORDER TRIBUTARY STREAMS OF REDWOOD CREEK

Even though major geomorphic effects are commonly absent in larger tributaries, our studies show they are persistent and widespread in the main stem of Redwood Creek. There, much of the sediment eroded from hillslopes is temporarily stored in the channel bed. Pools fill as the channel aggrades, and gravel bars become larger and more extensive to accommodate this influx of sediment (Figure 10).

Figure 11 shows the cumulative volume of stored sediment in the upper, middle and lower reaches of Redwood Creek plotted against the channel distance from the divide. Three distinct time markers are used to illustrate land use related effects. The 1947 line represents the amount of sediment in Redwood Creek under pre-disturbance conditions, prior to significant road construction and timber harvesting in the basin. Total sediment in the Redwood Creek channel in 1947 was about 11 x 10^6 m^3. By

1964 the amount of stored sediment had increased to over 16 x 10^6 m^3. The most severe aggradation occurred in the upper reach during the December 1964 flood, a flood with a local recurrence interval of about 50 years.

FIGURE 10

GROUND PHOTOGRAPH OF TYPICAL CHANNEL CONDITIONS IN THE LOWER 20 km OF REDWOOD CREEK. THE CHANNEL IS AGGRADED, BROAD, EXPERIENCES FREQUENT THALWEG SHIFTING, AND LOCALLY DISPLAYS MULTIPLE CHANNELS DURING SUMMER LOW-FLOW CONDITIONS

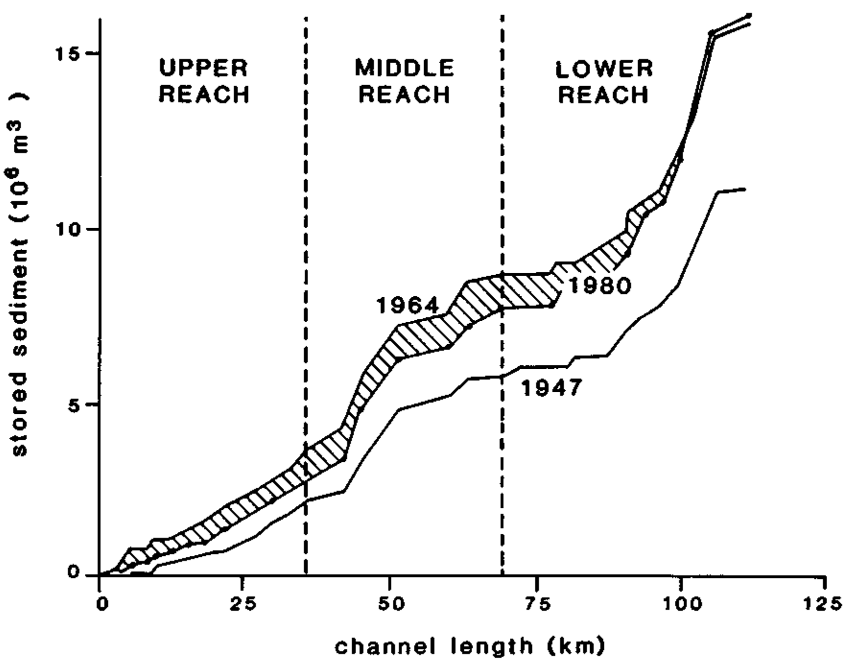

FIGURE 11

CUMULATIVE VOLUMES AND SPATIAL DISTRIBUTION OF STORED SEDIMENT IN REDWOOD CREEK AS OF 1947, 1964 AND 1980

By 1964 the amount of stored sediment almost doubled in the upper reach and increased by 37 percent in the lower reach. Moderate floods during the subsequent 20 years eroded roughly half of the sediment in the aggraded upper reach, where channel gradients (average 0.035) are gentler than major tributary channels, and transported it farther downstream. The 1980 line (Figure 11) shows that the amount of stored sediment had decreased in much of the river by 1980, although continued aggradation near the mouth resulted in a net amount of sediment still 5 x 10^6 m^3 greater than pre-disturbance levels. It is clear that widespread erosion and sedimentation, such as that which occurred in 1964, and of which we can demonstrate that 40 percent is associated with stream diversions at logging road and skid trail stream crossings, affect volumes of channel stored sediment for many years following disturbance.

Not only is there presently a large increase in the amount of sediment in the Redwood Creek channel, but it will persist for a long time. Residence times for sediment in Redwood Creek were estimated by dividing the volume of stored sediment per unit distance by the bedload discharge rate (measured at six USGS gaging stations in the Redwood Creek basin). Details of the procedure used, adapted from Dietrich and Dunne (5), are given in Madej (10). The persistence of recently deposited sediment in the upper reach ranges from 25 - 100 years, depending on how close to the active channel the sediment is stored and how well vegetated the deposit is. To flush post-1947 stored sediment out of Redwood Creek entirely would take up to 300 years. Likewise, in the lower reach residence times range from 10-100 years.

Thus, once a large influx of sediment is deposited in Redwood Creek, it will remain for decades to centuries. Major inputs of additional sediment from the hillslopes in the future would only lengthen recovery time. Documented effects associated with channel aggradation include a decrease in bed material size, channel widening and a decrease in the number of pools. Long sediment residence times imply that secondary effects will also persist.

To further illustrate the extent of <u>off-site downstream</u> effects, bank erosion was studied in detail using aerial photographs and survey data. For example, in a 30 km long middle reach of Redwood Creek, 51 locations of major bank erosion (greater than six meters of lateral scour) occurred between 1955 and 1978 (Figure 12). Channel widening was associated with severe channel bed aggradation of up to five meters at some locations. At 71 percent of the bank erosion locations, the channel remained wider for decades following initial erosion and has not recovered to its pre-disturbance channel configuration. Figure 13 dramatically illustrates the lack of recovery of original channel width during 12 years of record at a cross section in the lower reach of Redwood Creek, where major bank erosion is also occurring. Between 1973 and 1985, the right

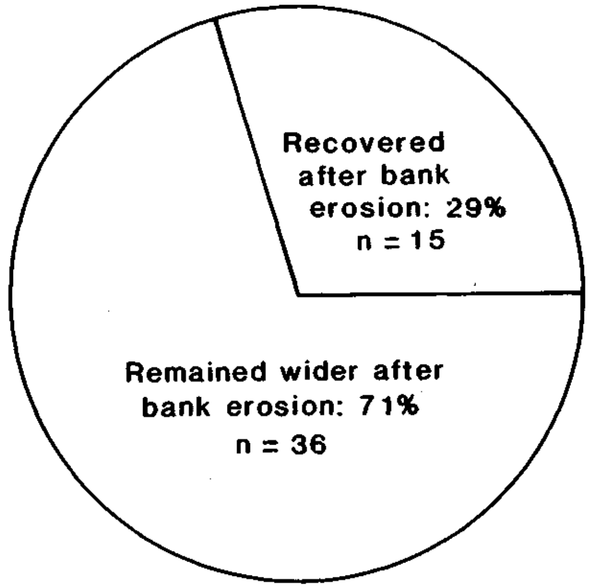

FIGURE 12

PIE DIAGRAM DEMONSTRATING PERSISTENT CHANGES IN CHANNEL WIDTH CAUSED BY MAJOR (GREATER THAN 6 METER) BANK EROSION ON A 30 km SAMPLE REACH OF REDWOOD CREEK BETWEEN 1955 AND 1978

Redwood Creek Near Orick
Cross Section #3

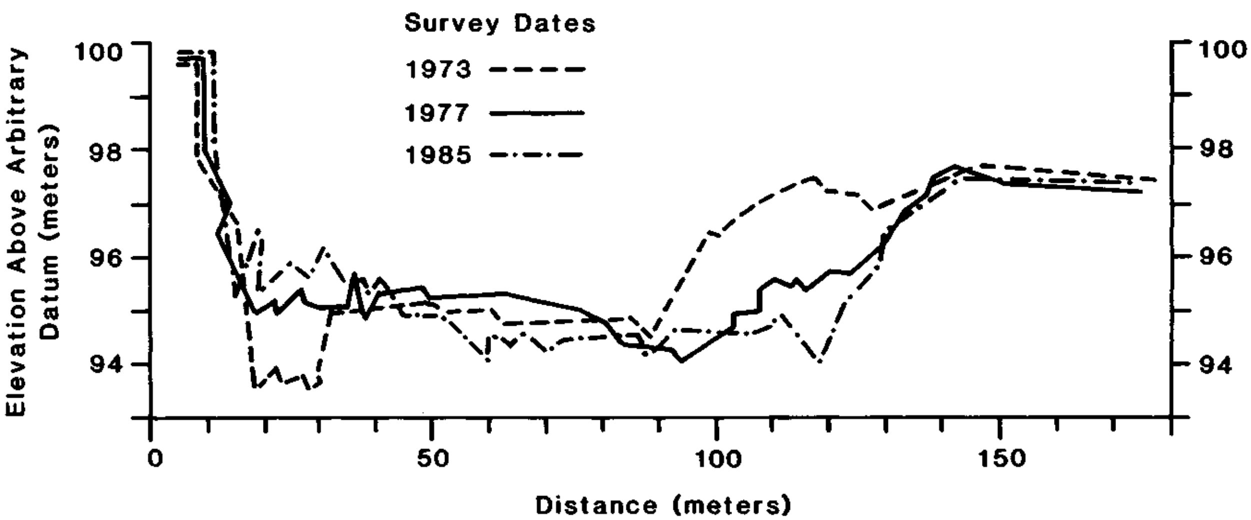

FIGURE 13

CROSS-SECTION #3, LOCATED ON REDWOOD CREEK NEAR THE MOUTH OF HAYES CREEK (NEAR ORICK), ILLUSTRATES LACK OF RECOVERY OF ORIGINAL CHANNEL WIDTH DURING 12 YEARS OF SURVEY RECORD. BANK EROSION CONTINUES AS A RESULT OF SEVERE BED AGGRADATION IN THIS REACH bank of the channel widened by more than 40 meters. The majority of this widening occurred between 1973 and 1977, with no recovery in the subsequent eight years to 1985.

Severe bank erosion changes the flow and sediment transport characteristics of a channel. It also reduces the amount of canopy cover for a stream, which can lead to increased water temperatures, at times a limiting factor for fish. All these changes are persistent effects on the channel system.

Pool frequency is also affected by aggradation. In north coastal California, an undisturbed gravel bed river has a profile of alternating pools and riffles at fairly regular spacing. Pools are commonly formed by scour around obstructions such as bedrock outcrops and large organic debris. Pools provide important habitat for anadromous and resident fish populations. A typical result of aggradation, however, is that the pool-riffle sequence is smoothed out; that is, the pools become filled in with fine bed material. In Redwood Creek, pool numbers and depths have decreased following aggradation. This conclusion is based on cross section surveys, aerial photographic interpretation and discussion with local residents.

Varnum and Ozaki (14) have shown that in reaches where stream recovery has occurred since aggradation, pool numbers have increased again. A comparison of two reaches, one where aggradation is actively occurring and one that is recovering, illustrates this fact. Longitudinal profiles were surveyed for two 1000-meter long reaches about 16 km apart, with similar channel gradients (Figure 14). The amount of large organic debris and exposed bedrock in the two reaches were essentially the same. Based on cross section surveys, the upper reach has been degrading over the last seven years and the thalweg has remained entrenched in the same location through runoff events for this time period. The lower reach is still actively aggrading. Over a six year period, the mean depth of degradation in the upper reach (based on profile surveys in 1977 and 1983) is 1.1 m; whereas the mean depth of aggradation for the lower reach is 0.4 m (14) .

Thalweg slopes were calculated by regression analysis of theodolite surveys and the associated coefficients of determination (r^2) were calculated for the reaches. The r^2 value associated with the upstream reach (0.62) is lower than that for the downstream reach (0.93). The lower r^2 value in the upstream channel segment reflects the increase in bed variation seen in recovering reaches, where the most well defined pool-riffle sequence occurs (Figure 14). Conversely, the higher values of r^2 are associated with aggrading reaches of Redwood Creek where pools are not as deep or frequent (14). Presently, there are 15 km of channel in lower Redwood Creek that are actively aggrading. Thus, in reaches where Redwood Creek stores increased amounts of sediment, and streambeds are aggraded to higher than pre-disturbance elevations, pool frequencies are reduced.

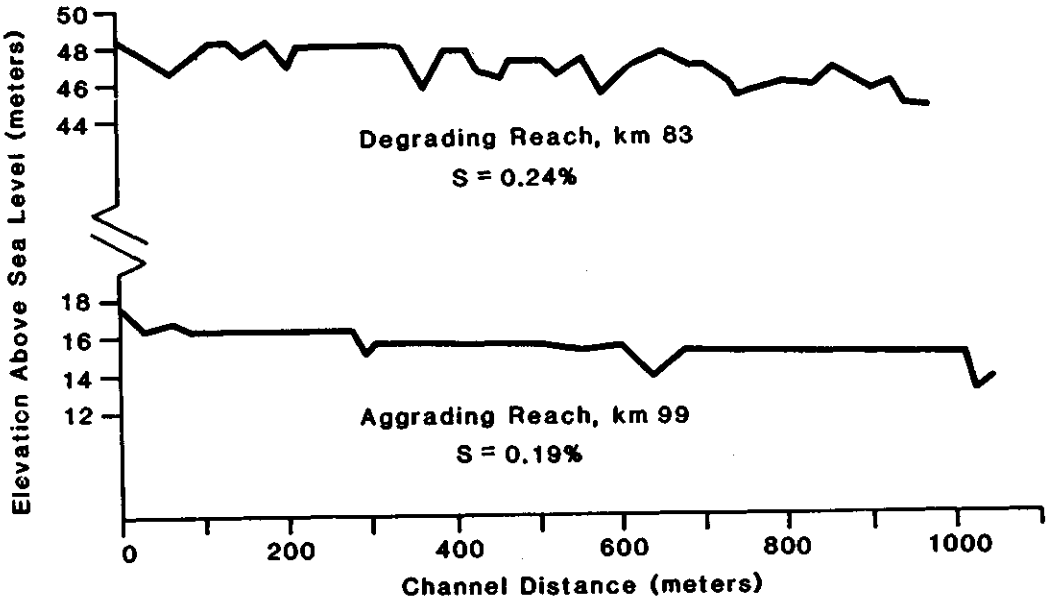

FIGURE 14

A COMPARISON OF LONGITUDINAL PROFILES FOR TWO SEPARATE 1000 METER REACHES WITH SIMILAR CHANNEL GRADIENTS IN THE LOWER REDWOOD CREEK BASIN. THEODOLITE AND ELECTRONIC DISTANCE METER SURVEYS WERE PERFORMED DURING THE SUMMERS OF 1977 AND 1983

V DISCUSSION

Dickert and Tuttle (4) suggest the existence of two broad methodologies for dealing with cumulative effects: (a) a comprehensive approach and (b) an incremental approach. In the comprehensive approach, an *a priori* determination of system threshold levels must be made. Future land use is then regulated to stay below this established threshold level so that cumulative effects never exceed the capacity of the system to buffer or absorb them. In steepland fluvial systems, background variability in erosion and sediment yield is high. A multiplicity of variables and processes interact to produce observed morphologic and biologic responses to change. Therefore, the identification of natural thresholds is extremely difficult.

For this reason, regulators and managers have largely chosen the incremental approach. In this scheme, projects are reviewed on a case-by-case basis without reference to other proposed or completed projects, and without knowledge of any biologic or geomorphic system thresholds. Project-by-project analyses and mitigations are continued until impacts are recognized, usually following a major storm, at which time further projects may be deferred or modified.

The incremental approach also has severe limitations. Cumulative effects theoretically become evident only when the accumulation of individually insignificant effects exceeds some system threshold or otherwise becomes unacceptable. Without long term monitoring of biologic and geomorphic conditions, system change may go unnoticed for years until unacceptably obvious symptoms appear.

Thus, by the time cumulative effects can be assessed, as in Redwood Creek, incipient watershed thresholds may have already been irreversibly exceeded or the resultant environmental damage may be uncorrectable. Often, hillslope processes are set in motion simultaneously throughout an entire watershed, usually in response to a large scale, low frequency storm event. If system "stress" (severe aggradation) is already evident lower in the watershed, existing and continued impacts may be irreversible and system recovery through land use mitigation on future projects is no longer possible.

Likewise, in the natural system, thresholds may be exceeded with no immediate visible morphologic expression on the land-scape. This occurs because climatic stress, the driving force for watershed erosion and sedimentation processes, is applied in a non-linear, episodic fashion with events of variable magnitude, Change is triggered only at discrete points in time during the occurrence of geomorphically significant storms. Because of this, land use activities may exceed the system's buffering capacity well before any measurable on-site or off-site impact occurs.

An important aspect of our cumulative effects definition is that many measurable effects are separated both in time and space from the original land use disturbance. The ideas presen-ted here suggest it is easy to overlook or not recognize land use practices which have high probabilities of resulting in far removed effects which, once initiated, will result in persistent geomorphic changes. However, the recognition of future causes of erosion and downstream effects can be predicted through knowledge of the relative importance of various erosional processes operative in a watershed or sub-watershed. This knowledge can be quantified by field mapping of erosional features, successive surveys, aerial photograph interpretation and utilizing stream discharge and sediment transport data.

Most of the measured fluvial erosion on study sites throughout the Redwood Creek basin occurred during relatively shortlived, large magnitude storms. However, the storms merely triggered the accelerated erosion. Detailed erosion inventories have clearly revealed certain land management practices to be the actual cause of at least 80 percent of the increased fluvial erosion (15).

Stream diversions at logging road and skid trail stream crossings were the leading cause of sediment production. Diverted waters often created large, complex gully systems which were responsible for documented increases in hillslope drainage density, sediment production and yield, and enlarged stream channels. These hillslope processes, in turn, led to further off-site impacts associated with stream channel aggradation.

Triggering mechanisms for stream diversions are frequently traceable to either culvert plugging, undersized culverts whose capacity is exceeded during storms, or the absence of a culvert at the crossing of an intermittent or ephemeral stream. However, diversions can only occur if the stream crossing itself was constructed with a high diversion potential; that is, at locations where the road and ditch system slope away from the crossing in at least one direction. This allows streamflow to be diverted down the road.

To describe this situation, a diversion potential rating system, based solely on the gradient of the road as it crosses a stream channel, was developed. In the example diagram of a road system in the lower Redwood Creek basin (Figure 6), each crossing was examined in the field and assigned one of two potentials (Figure 15). For the three crossings with no diversion potential, the road gradient on both approaches dips into the stream

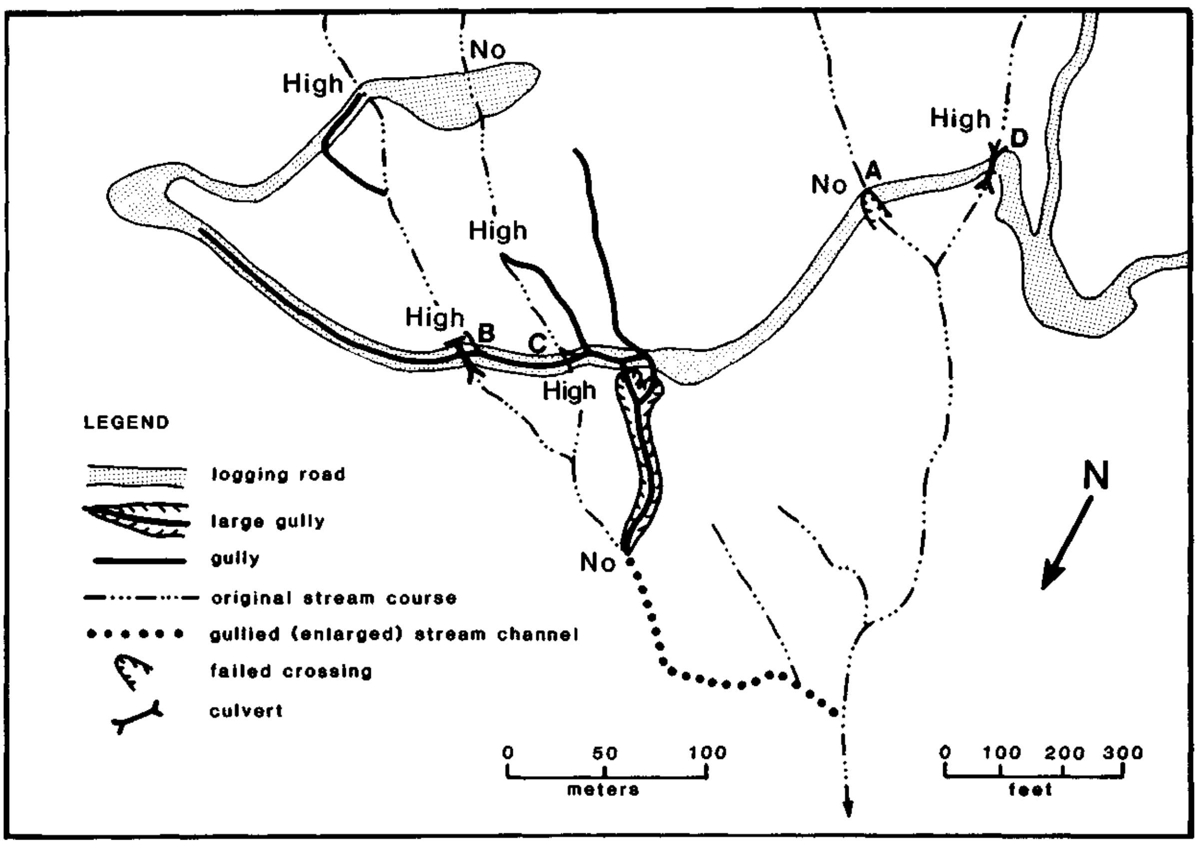

FIGURE 15

DIVERSION POTENTIAL RATINGS APPLIED TO ROAD AND SKID TRAIL CROSSINGS IN A PORTION OF THE COPPER CREEK DRAINAGE BASIN. THE RATING IS BASED SOLELY ON THE GRADIENT OF THE ROAD AS IT CROSSES THE STREAM. "HIGH" RATINGS INDICATE DIVERSIONS OF STREAMFLOW COULD OCCUR, "NO" RATINGS INDICATE STREAMFLOW WILL ALWAYS BE CONFINED TO THE CROSSING, EVEN IF THE CULVERT PLUGS. LOCATIONS A, B, C AND D ARE DESCRIBED IN THE TEXT

FIGURE 16

ABANDONED LOGGING ROAD STREAM CROSSING CONSTRUCTED WITH NO DIVERSION POTENTIAL. THE ROAD RISES AT THREE DEGREES IN BOTH DIRECTIONS FROM THE STREAM CHANNEL. SINCE STREAM DIVERSIONS AT THIS TYPE OF CROSSING CANNOT OCCUR, EROSIONAL PROBLEMS ARE CONFINED TO FAILED ("WASHED OUT") STREAM CROSSINGS. VOLUME OF ERODED STREAM CROSSING IS 600 m^3

channel at the crossing (Figure 16). Even if the culvert plugs, flow cannot escape the drainage system. For the five crossings with high diversion potentials, the road surface was found to slope away (down) from the stream crossing in at least one direction (Figure 17).

Uncontrolled streamflow at crossings constructed with no diversion potential can, at worst, only erode the volume of the fill crossing and no extensive gully networks can develop from diverted water (Location A, Figure 15). However, crossings constructed with a high diversion potential have been inadvertently designed to create extensive gully systems on adjacent hillslopes when stream flow exceeds the capacity of the culvert, for whatever reason, and is diverted out of its natural channel (Locations B and C, Figure 15). The links between the specific land use practice (i.e. road crossing construction), stream diversions, and consequent gully erosion is quite clear.

There are many stream crossings throughout the Redwood Creek watershed which exhibit high diversion potentials but whose culverts have not yet plugged (Location D, Figure 15). Many other crossings have already experienced stream diversions at least once. For example, seventy percent of the logging road stream crossings surveyed in the lower Redwood Creek basin were constructed with a high diversion potential (Table 6). Of these, 56 percent have experienced diversions at least once, only to be reconstructed again with a high diversion potential.

Based on the sample percentages, we estimate there are over 5,200 stream crossings in the Redwood Creek basin which have been constructed with a high stream diversion potential. Were major storms to occur or if the stream bed is very mobile at these sites, the mechanism still exists to once again significantly accelerate fluvial sediment yield.

FIGURE 17

LOGGING ROAD STREAM CROSSING CONSTRUCTED WITH A HIGH DIVERSION POTENTIAL. CULVERTS SHOW ORIGINAL ORIENTATION OF STREAM CHANNEL IN RELATION TO ROAD. NOTE GULLIED INBOARD DITCH DOWN ROAD FROM POINT OF STREAM DIVERSION (CULVERT INLET). STREAM DIVERSIONS IN THE REDWOOD CREEK BASIN FREQUENTLY CREATE GULLY NETWORKS ON ADJACENT HILLSLOPES WHICH MAY YIELD 2,000 TO 4,000 m^3 OF ERODED SEDIMENT

TABLE 6 STREAM CROSSING DIVERSION POTENTIAL AND GULLY YIELD FROM STREAM DIVERSIONS ON FIVE SITES TOTALLING 2,131 ha IN THE REDWOOD CREEK BASIN

Site name	Total No. of Xings	Km of road	Diversion Potential			Crossing That Diverted		Pct. That Diverted		Gully Yield From Stream Diversions (m^3)
			No	High	Un-known	No	High	No	High	
South Copper (79-2)	36	10.8	8	28	0	0	20	0	71	50,800
Bridge (80-3)	17	5.0	3	14	0	0	10	0	71	10,900
Bond (82-4)	19	2.7	1	18	0	0	5	0	28	600
Bridge (80-6)	32	11.8	12	20	0	0	13	0	65	12,100
Garrett Creek	57	12.7	21	32	4	0	14	0	44	39,900
Totals	161	43.0	45	112	4	0	62	0	56	114,300

VI CONCLUSIONS

A determination of cumulative watershed impacts requires the system of cause and effect linkages be well established (4). In Redwood Creek, linkages between land use, resultant fluvial erosion and its basin-wide effects are well documented. Although not detailed here, similar analyses suggest a significant but unquantified proportion of the sediment contributed by land-sliding is also causally connected to land use activities. These land use related sources of sediment have resulted in measurable, persistent impacts to both on-site and off-site physical and biologic resources.

The concepts, techniques and data described here are useful for determining the existence, source and magnitude of cumulative effects related to fluvial erosion. Park research indicates gullying is a major land use related source of sediment in the Redwood Creek watershed. Since the watershed is primarily underlain by rocks of the Franciscan Assemblage, a suite of rocks subject to high fluvial erosion rates, gullying should be considered a major potential source of sediment yield throughout the Pacific Northwest where similar rock types occur.

The quantification of sediment sources, and the causes and effects of increased erosion provide a basis to assess whether cumulative effects occur and whether these effects are additive and persistent. For example, by first inventorying and quanti-fying watershed changes, we nave established the relationships between certain land use practices, consequent erosion processes and basin-wide impacts in Redwood Creek. This has allowed us to separate human-induced from naturally occurring impacts. As a result, a clear basis has been established to modify current land use practices and successfully diminish fluvial erosion as one important contributor to documented cumulative impacts.

Bedrock, soil, and hillslope characteristics, as well as land management practices and climatic variability, presently determine the magnitude, extent and frequency of fluvial erosion in the Redwood Creek basin. On mountainous slopes managed for timber production, land use practices must address and anticipate the occurrence of extreme storms which frequently trigger widespread erosion and sedimentation. This can be effectively accomplished by employing preventive land management techniques.

For example, measures which prevent stream diversions would largely eliminate fluvial gully erosion and its long term effects. Simple land management measures to accomplish this include: (a) constructing road and skid trail stream crossings with no diversion potential (i.e., both approaches dip into the crossing), (b) performing regular and storm maintenance of roads and drainage structures throughout the life of the roads, (c) putting unused roads "to bed" by removing culverts and excavating fill crossings, (d) installing adequately sized culverts, with debris filters, and (e) excavating skid trail stream crossings following harvest operations. Recent changes in California's Forest Practice Rules have begun to address the latter two issues, but only with respect to future harvest operations.

Although the persistent cumulative effects measured in Redwood Creek are a direct result of land use practices conducted during a period of little land use regulation, current timber harvest and road construction regulations still largely ignore the potential for stream diversions - the principle cause of most gully erosion in the Redwood Creek basin. The results of both earlier and ongoing practices continue to significantly affect fluvial erosion rates, lower order and main stem channel geometry, drainage densities, stream bed structure and the volume and residence time of stored sediment.

VII SUMMARY

Erosion and sedimentation studies conducted in the 720 km^2 Redwood Creek basin show that some land use practices have caused persistent geomorphic effects at the logging site, on downslope areas and in far removed stream channels. These effects include on-site increases in drainage density and channel dimensions; off-site, downslope increases in fluvial erosion rates, drainage density and stream channel dimensions; and off-site, downstream increases in the volume of stored sediment and incidence of bank erosion, as well as decreases in pool number.

Sediment budget studies and detailed mapping on 1.4 to 197 km^2 study sites reveal that fluvial erosion, mostly gullying, accounts for 30 percent to 85 percent of the yield from all sources since 1947. Up to 85 percent, or more, result from logging-caused stream diversions that create complex channel networks and increase downslope drainage density. Multiple networks may develop from one diversion and more are expected where high diversion potentials remain uncorrected. Eighty percent of all gully erosion was avoidable.

Long-term changes in channel geometry do not seem as widespread in higher (third and fourth) order tributaries due to the short residence time of introduced sediment. Except where tributary gradients are naturally low, or locally reduced behind log jams, the off-site geomorphic effects of upstream increased erosion are minimal.

Volumes of stored sediment in Redwood Creek have risen from 11×10^6 m^3 in 1947 to over 16×10^6 m^3 in 1980. Much of this increase can be accounted for by logging-caused fluvial erosion. Landslides also add sediment, but the portion caused by land use is not easily determined. Contrary to one model, aggradation in Redwood Creek has not itself triggered substantial stream side landsliding primarily because storage areas are wide and flanked by gently hillslopes. However, as degradation has occurred over the last 20 years, long term off-site changes in channel morphology are persisting. Residence times of most stored sediment ranges from decades to centuries.

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