Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California

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Sediment Routing in Tributaries of the Redwood Creek Basin, Northwestern California

By JOHN PITLICK

GEOMORPHIC PROCESSES AND AQUATIC HABITAT IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

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SEDIMENT ROUTING IN TRIBUTARIES OF THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

BY JOHN PITLICK[1]

ABSTRACT

Detailed studies of 16 streams draining diverse terrain in the drainage basin of Redwood Creek indicate that tributaries have been major sediment sources since the early 1950's. Low-frequency, high-intensity storm events and timber harvesting resulted in sediment production by landslides along tributary channels comparable in magnitude to production along the channel of Redwood Creek, a much larger stream. In the majority of tributaries, the amount of sediment in storage is low relative to sediment supply; hence, the residence time of sediment in tributary channels is necessarily short. Over short periods of time, sediment yield from these small steepland watersheds is largely dependent on sediment supply rather than on water discharge.

INTRODUCTION

Traditionally, studies of sediment yield from small steepland drainage basins have relied heavily on data obtained from a gaging station located at the outlet of the basin. The significance of such studies is commonly limited by the lack of reliable data collected over a long period of time. Furthermore, such an approach tells very little about the complex interaction between the processes that mobilize and those that transport sediment. Several workers (Mosley, 1978; Dietrich and Dunne, 1978; Kelsey, 1980; Lehre, 1981; Trimble, 1981) have recently presented detailed analyses of changes in sediment source areas and of sediment transport through both natural and disturbed drainage basins. A point highlighted in much of this work is the disparity between the measured rates of erosion by selected geomorphic processes and the downstream sediment discharge.

In many watersheds, sediment storage on hillslopes and in channels has been identified as an important link between the mobilization and transport processes. Given this knowledge, a thorough understanding of the spatial and temporal changes in sediment mobilization and storage is necessary to put information on sediment yield in proper perspective.

In focusing on channel and hillslope processes centered along the main stem of Redwood Creek, previous studies (Colman, 1973; Harden and others, 1978; Janda, 1978) were fundamental in documenting the recent acceleration in erosion rates within the 725-km^2 Redwood Creek basin (fig. 1). Much of this effort was directed to the collection of water and sediment discharge data along the main stem of Redwood Creek and at selected tributary localities. In summarizing this work, Janda (1978) concluded that "at discharges that are likely to occur several times in any given decade*** tributaries may indeed be major contributors of suspended sediment to Redwood Creek***." In a contrasting view, Winzler and Kelly Engineers Water Laboratory (1975) specified massive landslides along the main-stem channel as the primary source of sediment for Redwood Creek and concluded that "the contribution of sediment from the individual tributary streams***is insignificant compared to the load carried by Redwood Creek." The data presented in this paper were collected as part of more recent studies on sediment source areas and sediment transport in the Redwood Creek basin (Kelsey and others, 1981). Through detailed studies of 16 diverse tributary basins within the Redwood Creek basin, I have attempted to quantify the amount of sediment delivered from streamside landslides, to determine the extent to which major storm events and changes in land use have generated landslides, and to assess the role of sediment storage and large organic debris in tributary channels.

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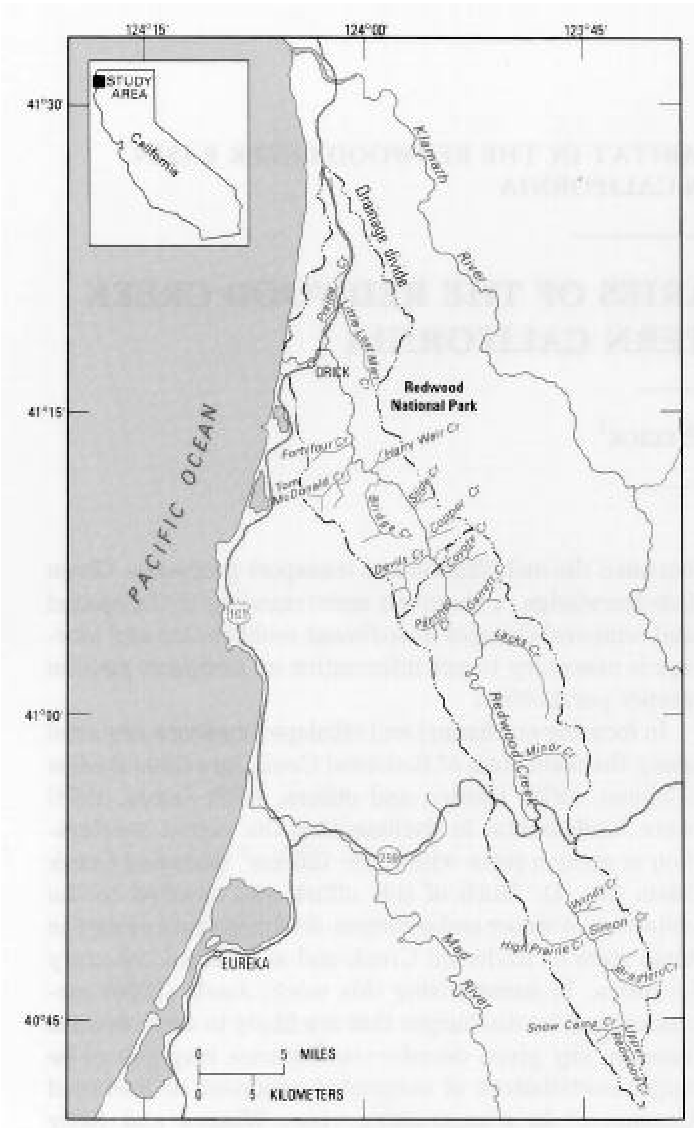

FIGURE 1.—Redwood Creek basin, showing Redwood National Park and tributary basins.

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STUDY AREA

The physical setting of the Redwood Creek basin has been described in detail by previous authors (Janda and others, 1975). While the Redwood Creek basin offers an opportunity to study a large number of low-order streams within a physiographically similar region, the basin is not without variability. Differences in geology, climate, vegetative cover, and land use within the basin play important roles in the mobilization and storage of sediment in tributaries.

GEOLOGY AND PHYSIOGRAPHY

The Redwood Creek basin is underlain by rocks of the Franciscan assemblage (Bailey and others, 1964; Harden and others, 1982), which consists of weakly indurated and pervasively sheared continental margin deposits of Late Jurassic and Cretaceous age; these deposits are highly susceptible to fluvial erosion and mass wasting. The Grogan fault, expressed as a well-defined north-northwest-trending lineament, roughly bisects the basin and juxtaposes unmetamorphosed and slightly metamorphosed clastic sedimentary rocks to the east against metamorphic schistose rocks to the west.

Tributary streams are nearly equally divided between those draining sedimentary rocks and those draining metamorphic rocks. The soils developed on these rock types are moderately coarse in texture. They 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, and the unusually elongate shape of the watershed is a strong reflection of this structural control (fig. 1). As a result, there are no major tributary forks to Redwood Creek, and the frequency distribution of tributary drainage areas is strongly skewed (fig. 2). In all there are 74 tributary basins drained by second-order (as ordered according to Strahler, 1957) or higher order streams flowing directly into Redwood Creek. Most tributaries are characteristically low-order, high-gradient streams draining small drainage basins (fig. 3). Their channels are, in general, deeply incised, and their flood plains are narrow and discontinuous. Average stream gradients range from 0.05 to 0.30 m/m (meters per meter). Average hillslope gradients within these basins range from 0.25 to 0.35.

Topographic relief and average stream gradient are greater in those tributary basins draining the eastern portion of the watershed. Many tributary basins have steep hillslope segments adjacent to channels and more moderate gradients at middle and upper slope positions. This incised inner valley is particularly susceptible to

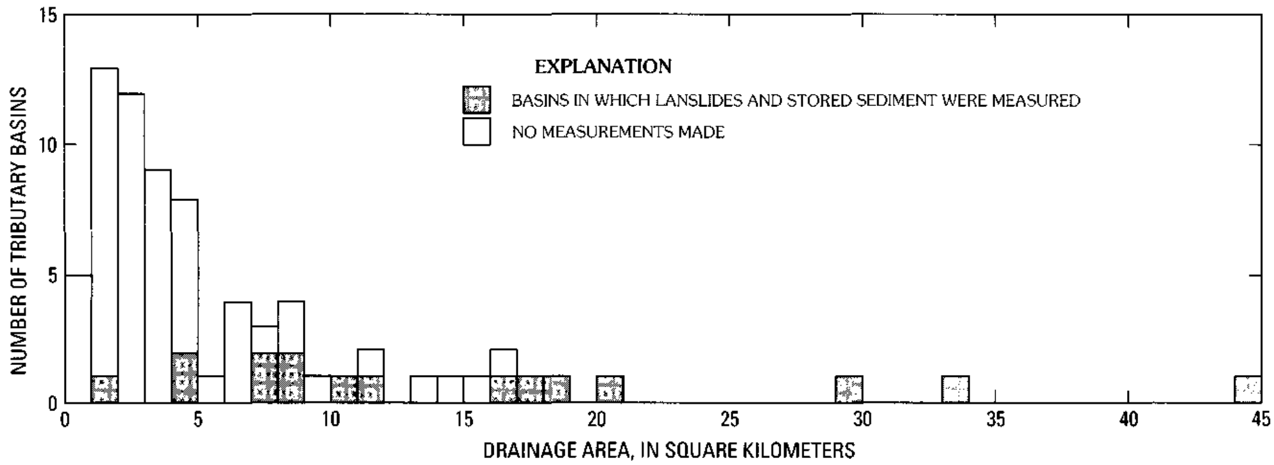

FIGURE 2.—Frequency distribution of tributary basins by drainage area. Drainage areas were measured on 1:24,000-scale topographic maps by using a polar planimeter. The data include only those tributaries upstream of Prairie Creek. Shaded areas indicate the 16 basins in which streamside landslides and channel-stored sediment were measured.

FIGURE 3.—Lacks Creek channel. The steep sideslopes, coarse bed material, and narrow flood plain are typical of Redwood Creek tributaries. Average channel width is approximately 10 m.

mass wasting by shallow debris slides and debris avalanches.

VEGETATION AND LAND USE HISTORY

Tributary watersheds are distinguished by predominant forest type and degree of timber harvesting. Eighty-five percent of the Redwood Creek basin was forested prior to the initiation of logging in 1936 (Janda and others, 1975). Under natural conditions, the northern third of the basin, which is near the coast, supported mixed stands of mature old-growth redwood and Douglas-fir (here called "redwood-dominated" forests), while the southern two-thirds, which is inland, supported primarily mixed Douglas-fir and hardwood forests (here called "Douglas-fir-dominated" forests) (fig. 1). The distribution of forest types is a reflection of the variation in microclimate throughout the basin. Redwood is less tolerant of summer drought and winter cold than Douglas-fir and hence is found in the more temperate areas near the coast. Today, over 65 percent of the basin has been logged, and most of this logging occurred over the last 25 years. Most units have been clearcut and tractor-yarded. Twenty percent of the basin, nearly all of which is within the Redwood Creek unit of Redwood National Park, remains as uncut virgin forest, and the remaining 15 percent consists of prairie and oak woodland (Janda and others, 1975).

CLIMATE

The climate of the Redwood Creek basin is characterized by a strong seasonal variation. The basin receives an estimated mean annual precipitation of 2,000 mm (Harden and others, 1978), most occurring between October and April. Rainfall during the summer months is very infrequent.

Major flood-producing storms occurred throughout northern California in 1953, 1955, 1964, 1972, and 1975. Peak discharges of greater than 1,275 m^3/s (cubic meters per second) were recorded near the mouth of Redwood Creek for each of these floods (Harden and others, 1978). The storm of December 1964 resulted in widespread

TABLE 1.-*Properties of 16 tributary basins within the Redwood Creek basin*

Tributary	Drainage area (km²)	Average gradient (m/m)	Predominant rock type[1]	Predominant forest type[2]
Lacks Creek	44.0	0.06	SS	DF
Minor Creek	33.6	.08	SS	DF
Bridge Creek	29.4	.06	SH	RW
Coyote Creek	20.4	.13	SS	DF/RW
Devils Creek.	18.0	.08	SH	RW
Tom McDonald Creek	18.0	.07	SH	RW
Bradford Creek	16.5	.18	SS	DF-O-P
Upper Redwood Creek	11.1	.11	SS	DF-O-P
Garrett Creek	10.8	.18	SS	DF
Snow Camp Creek	8.2	.17	SS/SH	DF
Fortyfour Creek ..	8.1	.10	SH	RW
Harry Weir Creek ...	7.8	.16	SS/SH	RW
Copper Creek.	7.4	.18	SS	RW/DF
Windy Creek	4.5	.19	SS	DF-O-P
Simon Creek.	4.5	.23	SS	DF-O-P
N. Fork Slide Creek. .	1.6	.26	SS	RW

[1] SS, Unmetamorphosed and slightly metamorphosed sedimentary rocks of the Franciscan assemblage; SH, quartz-mica schist of the Franciscan assemblage.

[2] RW, predominantly redwood forest with minor amounts of hardwood and Douglas-fir; RW/DF, predominantly redwood forests with significant amounts of Douglas-fir; DF/RW, predominantly Douglas-fir forests with significant amounts of redwood; DF, predominantly Douglas-fir with associated hardwoods; DF-O-P, nearly equal amounts of Douglas-fir forests, oak woodland, and prairie.

TABLE 2.— *Erosional landforms in the Redwood Creek basin*

[Modified from Harden and others, 1978]

Features active in 1974	Percent of basin area
Debris slides	1.0
Debris avalanches	.2
Earthflows	12.0
Unstable streambanks	3.0
Total, active features	16.2

landslides and changes in channel morphology. Other storms occurring since the early 1950's, although similar in magnitude, did not have the erosional effects of the 1964 storm.

STUDY METHODS

As a first step in determining the magnitude and timing of sediment contribution from tributaries, streamside landslides and channel-stored sediment were measured conjunctively in 16 of the 74 tributary basins within the Redwood Creek basin (table 1). These basins include a wide range of drainage areas and terrain types. The amount of sediment delivered from streamside landslides was determined by detailed field measurements of hillslope scars. The surface area of the landslide scar was measured by using a tape and rangefinder. Depth of the scar was determined from measurements or estimates of side- or head-scarp heights. More than 1,000 landslides were measured along a total channel length of 70 km. A review of the landslide scars visible on aerial photographs indicates that an estimated 80 to 98 percent of the total sediment production from streamside landslides was measured by the field surveys along individual tributaries.

Sediment stored in fill terraces and in association with large organic debris was measured along a total of 67 km of tributary channel. The volume of material stored in terraces was determined by measuring terrace surface area and average height above the present thalweg. The amount of sediment stored upstream of a debris jam was determined by treating the trapped sediment as a wedge. The surface area of the deposits associated with the debris was measured, and the depth of stored sediment taken as one-half the height of the debris jam. Buried tree stumps, root wads, boulders, and other objects that are now partially exhumed were used to determine the depth of recent aggradation.

Temporal changes in landslide activity were documented by reviewing sequential aerial photographs taken in 1954, 1958, 1962, 1966, 1970, 1974, and 1978 at scales ranging from 1:20,000 to 1:6,000. For each landslide measured in the field and visible on aerial photographs, I noted the period during which the slide was initiated and any increase in the size of the slide. On sites that had been logged, I noted the timber harvesting methods and amount of roads at time of failure. Aerial photographs were of little use in documenting changes in stream morphology because a dense vegetative cover usually obscured tributary channels.

STREAMSIDE LANDSLIDES ALONG TRIBUTARIES

The natural instability of Franciscan terrane, a clustering of major storm events, and timber harvesting have been cited (Janda, 1978; Kelsey, 1980) as the main contributors to the acceleration in erosion rates of the northern California Coast Ranges over the last 30 years. Streamside landslides have been identified (Janda, 1978; Kelsey, 1980, chap. G, this volume) as major sources of sediment for northern California streams and rivers. In the Redwood Creek basin, debris slides, debris avalanches, and complex earthflows are the most common types of mass movement. Although they occupy a small percentage of the basin area (table 2), these types of sediment sources can contribute a significant amount of the total sediment load in northern California rivers (Kelsey, 1980).

Debris slides and debris avalanches are episodic types of failures that are characteristically shallow (less than 3 m deep) and move predominantly by translation, resulting in relatively rapid and direct sediment contributions to stream channels. Earthflows are large-scale, deep-seated features that characteristically exhibit both rotational and translational movement. Earthflows are slower but more persistent in delivering sediment to channels.

Streamside landslides in tributary watersheds are as large and as complex as similar landslides along the main channel of Redwood Creek. The 20 largest landslides in the tributary basins of this study have contributed a total of 1,470,000 Mg (megagrams) of sediment to stream channels. By comparison, of the 566 landslides measured along the main stem of Redwood Creek upstream of State Highway 299 (fig. 1), the largest 20 debris slides have produced 1,353,000 Mg of sediment. In individual tributaries, sediment production from streamside landslides is highly variable, but in terms of mass per drainage area, tributary landslide contribution does not differ substantially from the contribution due to landslides along the main stem of Redwood Creek upstream of Highway 299 (table 3).

TIMING OF STREAMSIDE LANDSLIDES

The data from the landslide surveys along tributaries emphasize two important points (table 4). First, slightly more than half of the total measured mass of landslide material was delivered during the 1964 storm, and the tributary basins south of Highway 299 were particularly affected during this storm. Second, the total amount of landslide material delivered to each tributary during the other intervals varies significantly from one tributary to another; that is, the standard deviation is nearly equal to or higher than the mean percentage of material delivered in all cases except for the period from 1962 to 1966.

The marked differences between the number of landslides initiated during the 1964 storm and during storms of similar magnitude may be due to several factors. The exceptional amount of erosion that occurred in the upper 175 km^2 of the Redwood Creek basin suggests that the 1964 storm was more intense at higher elevations in the upper basin. Storms and land use practices of the 1950's were important in "conditioning" the basin for an event such as the 1964 storm (Harden and others, 1978). These authors reported that an exceptionally large number of landslides that were visible on 1958 aerial photographs

TABLE 3.—*Mass of debris slides along 16 tributaries to Redwood Creek, 1954 to 1981*

Tributary	Drainage area (km)	Landslide mass[1] delivered between 1954 and 1981 (Mg)	Landslide mass per unit drainage area (Mg/km^2)
Lacks Creek	44.0	917,700	20,900
Minor Creek	33.6	465,500	13,900
Bridge Creek	29.5	311,000	10,600
Coyote Creek	20.4	231,800	11,400
Devils Creek	18.0	53,900	3,000
Tom McDonald Creek	18.0	50,000	2,800
Bradford Creek	16.5	213,100	12,900
Upper Redwood Creek	11.1	169,800	15,300
Garrett Creek	10.8	108,300	10,000
Snow Camp Creek	8.2	215,500	26,300
Fortyfour Creek	8.1	29,900	3,700
Harry Weir Creek	7.8	47,500	6,100
Copper Creek	7.4	92,000	12,400
Windy Creek	4.6	241,600	52,500
Simon Creek	4.5	323,200	71,800
N. Fork Slide Creek	1.6	36,700	23,000
Mean			18,600
Standard deviation			18,800
Main stem of Redwood Creek upstream of State Highway 299	175.3	3,736,800	21,400

[1] Landslide mass computed by taking the product of the measured volume and assumed soil density of 1.6 g/cm^3 (100 lb/ft^3) (James Popenoe, National Park Service, oral commun., 1981). The reported values represent data from only those landslides measured during the tributary landslide surveys. Survey coverage accounted for between 80 and 98 percent of the total sediment production from landslides in individual basins.

TABLE 4.— *Distribution through time of sediment produced from landslides in 16 tributary basins in the Redwood Creek basin*

Tributary	Total measured mass of failure (Mg)	Percentage of total landslide material delivered to individual tributaries during specific time periods						
		1978-74	1974-70	1970-66	1966-62	1962-58	1958-54	Pre-1954
Lacks Creek	967,000	10.5	10.6	1.8	44.0	9.4	18.6	5.1
Minor Creek	490,400	8.1	1.0	2.2	59.4	0	24.3	5.0
Bridge Creek[1]	372,000	1.3	16.8	0	55.4	0	10.1	16.4
Coyote Creek	233,200	9.6	7.3	6.0	65.2	10.8	.5	.6
Devils Creek[1]	146,800	3.1	16.4	5.8	10.9	0	.5	63.3
Tom McDonald Creek[1]	82,500	0	26.0	4.6	27.3	0	2.6	39.5
Bradford Creek.	214,400	0	11.1	7.6	56.9	20.5	3.3	.6
Upper Redwood Creek	171,300	1.7	11.6	7.3	71.4	1.9	5.2	.9
Garrett Creek	123,100	0	43.4	7.3	19.2	0	18.1	12.0
Snow Camp Creek	264,800	3.2	5.3	0	67.0	5.3	.6	18.6
Fortyfour Creek[1]	41,400	4.2	4.2	0	38.3	0	25.4	27.9
Harry Weir Creek	56,400	12.7	31.5	8.2	29.6	2.3	0	15.7
Copper Creek	98,100	29.9	43.6	1.0	19.3	0	0	6.2
Windy Creek	241,600	0	5.7	0	68.9	11.4	14.0	0
Simon Creek	337,400	0	3.8	3.7	85.2	3.1	0	4.2
N. Fork Slide Creek[1]	36,700	26.0	15.6	16.6	9.3	0	32.5	0
Mean		6.9	15.9	4.5	45.5	4.0	9.7	13.5
Standard deviation		9.2	13.5	4.4	23.9	6.0	10.9	17.4

[1] Basins in which the forest canopy obscured more than 20 percent of the landslides. The accuracy of this analysis depends greatly on landslide visibility on aerial photographs.

TABLE 5.—*Inventory of debris slides larger than 450 Mg in 16 study basins and site conditions prior to failure*

	Unlogged[1] slopes	Logged slopes			
		Road-related failures[2]	Clearcut		Selectively cut
			Tractor-yarded	Cable-yarded	Tractor-yarded
Number of slides measured larger than 450 Mg	222	109	47	46	37
Total mass of sediment produced (Mg)	687,900	1,199,700	606,800	464,300	243,800
Average slide mass (Mg)	3,099	11006	12,910	10,094	6,590
Percent of total inventoried slide mass	21.5	37.5	18.9	14.5	7.6

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

[2] Road-related failures are those types of landslides associated with failure of the road fill and (or) the cutbank upslope and are not necessarily associated with timber harvesting.

increased in size during the 1964 storm. The most extensive logging in the basin was conducted during the 1950's, in which nearly half the streamside area along Redwood Creek was at least partially logged. Finally, storms of the 1970's did not initiate as many slides, or slides of such large size as in 1964, simply because the slopes most susceptible to sliding had already failed.

LANDSLIDES AND LAND USE

Numerous studies (Brown and Krygier, 1971; Rice and others, 1972; Harr, 1976; Beschta, 1978) have shown that the hydrologic and erosional consequences of logging are highly variable and dependent on physical factors such as soils, geology, climate, and degree of ground disturbance. The importance of road construction and timber harvesting is illustrated in table 5. The number of landslides occurring on unlogged slopes as opposed to logged slopes is nearly the same. However, slides associated with roads and those initiated on cut slopes are substantially larger and account for nearly 80 percent of the total landslide-related erosion. Failures associated with roads (and not necessarily timber harvesting) are the most frequent and produce the largest total amount of sediment from landslides in logged areas. There is little difference between the frequency and total mass of slides generated on tractor-yarded, clearcut slopes and cable-yarded, clearcut slopes. Cable-yarding is a commonly used procedure in the timber harvesting of steeper slopes. Slides initiated on this type of site illustrate the importance of slope as a factor in hillslope failure. Landslides initiated in selectively cut, tractor-yarded areas are the least important in terms of sediment production. Tractor-yarding is usually restricted to more moderate slopes, and selective cutting generally results in less ground disturbance.

SEDIMENT STORAGE AND SEDIMENT TRANSPORT IN TRIBUTARIES

Quantifying the amount of sediment stored in stream channels is a basic component in any study of sediment routing. Storage elements attenuate the effects of rapid inputs of sediment to a channel from adjacent hillslopes by providing a compartment that slowly releases sediment to downstream reaches. In the Redwood Creek basin, large organic debris and local variations in bedrock lithology exert strong control on the morphology of tributary channels. Unlike the main-stem channel of Redwood Creek, tributary streams do not show a uniform downstream increase in the amount of stored alluvium because of the variability in sediment supply, the stream gradient, and the loading of organic debris in any particular reach. Sediment storage in tributaries is restricted to lower gradient reaches or behind accumulations of large organic debris.

The effects of large organic debris on channel morphology have been studied in detail by other investigators (Swanson and Lienkaemper, 1978; Mosley, 1981; chap. P and U, this volume). First- and second-order streams lack enough power to move most large organic debris; hence, the debris tends to remain where it entered the channel. Logs and other woody debris are found within and adjacent to the channel in many configurations. In third- and fourth-order streams, logs are mobilized more frequently, and there is a tendency for debris to accumulate in jams composed of several to hundreds of logs. Higher order streams, such as the main stem of Redwood Creek, have enough power under high-flow conditions to move even the largest debris; hence, the accumulation of large organic debris tends to be negligible and often is confined to channel margins.

Organic debris and, especially, log jams alter the hydraulics of a reach by impeding flow; this change reduces the available stream power and results in deposition of sediment behind the jam. The changes in channel morphology commonly include an abrupt step in the longitudinal profile at the jam with an associated decrease in gradient upstream of the jam, an increase in channel width upstream of the jam, and a decrease in particle size behind the jam.

Channel processes and channel morphology in Redwood Creek tributaries are strongly influenced by organic debris. In their studies of old-growth redwood

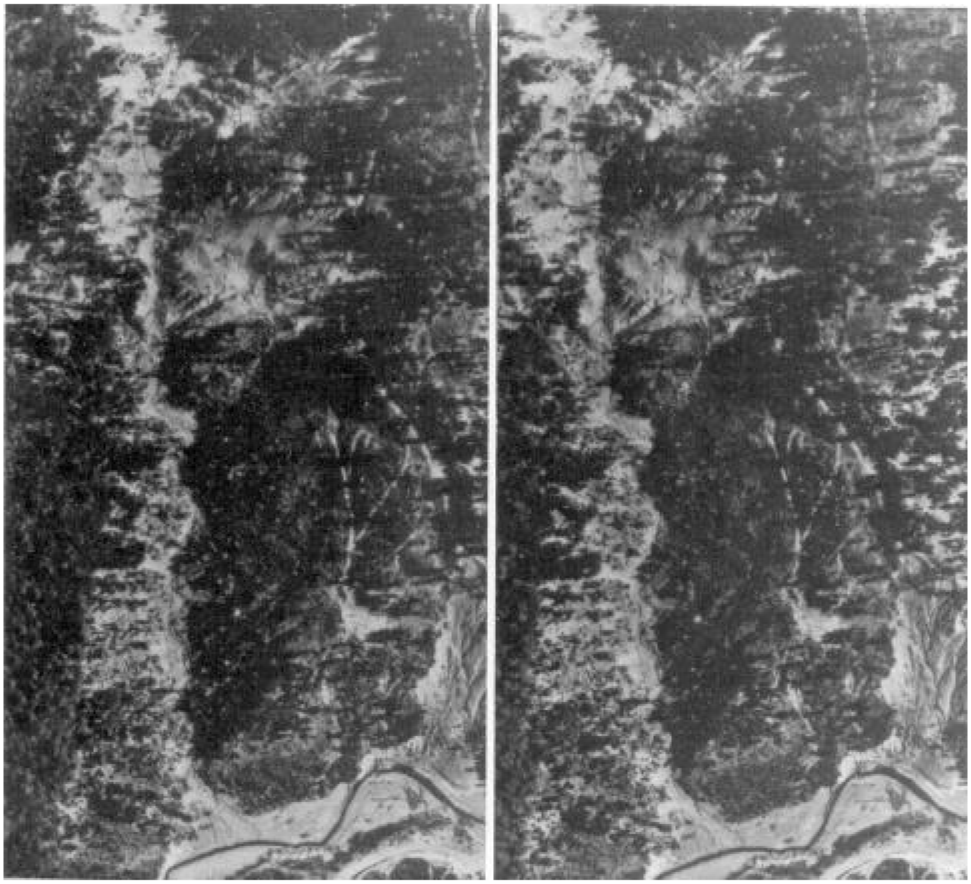

FIGURE 4.—Stereoscopic pair of aerial photographs (acquired 1966; scale 1:12,000) showing the confluence of Simon Creek and Redwood Creek. Note that the landslides along both the tributary and main-stem channels are of similar size, but the amount of sediment stored in the narrow, deeply incised tributary (left in photograph) is negligible compared to the amount stored along Redwood Creek (at bottom of photograph).

streams, Keller and others (chap. P, this volume) found that variables such as pool-and-riffle spacing, elevation drop, and channel area were, in large measure, controlled by the presence of large organic debris. The relative size of organic debris determines the degree to which the debris influences channel form and processes. Old-growth redwood trees are renowned for their girth and resistance to decay. Even the largest tributary streams do not carry enough runoff under any conditions to move massive redwood logs. Consequently, debris jams tend to be stable and may remain in place for hundreds of years influencing channel morphology for periods of time on the order of 1,000 years (Keller and Talley, 1979).

Although sediment source areas along tributaries are as large and as complex as those along Redwood Creek, sediment storage along Redwood Creek is much greater (fig. 4). Comparison of the amount of sediment stored in tributary channels and that stored in the main stem of Redwood Creek illustrates the relative transport capability of these streams. To estimate the total amount of sediment stored in all tributary channels, I have combined the sediment storage data from the 16 measured tributaries with the distribution of all 74 tributary basins by drainage area (fig. 2). The amount of stored sediment for individual drainage area classes was computed by taking the product of the average amount of stored sediment for basins of a class and the number of basins in the class. My estimate of the total amount of sediment stored in the 74 tributary channels is 1,050,000 m^3, or approximately 2,000,000 Mg. This value is only 6 percent of the total amount stored in the main stem of Redwood Creek (chap. 0, this volume). On the average, 95 percent of the sediment stored in tributaries is found in the lower half of their drainage lengths (table 6). In contrast, 95 percent of the sediment stored in Redwood Creek is distributed over 75 percent of its length (chap. 0, this volume).

A comparison of the amount of landslide material delivered to the 16 measured tributary streams from

1954 to 1981 and the amount of sediment in storage as of 1981 serves as another measure of tributary sediment transport or storage efficiency (table 7). Tributary basins characterized by high relief and dominated by Douglas-fir forests store a significantly smaller proportion of sediment supplied by streamside landslides than do redwood-dominated tributary basins, even though average sediment production from streamside landslides is much higher in Douglas-fir basins. Of the 74 tributary channels within the Redwood Creek basin, only a few would be characterized as low-relief and redwood-dominated basins. The more typical tributary basins, characterized by high relief and dominated by Douglas-fir and redwood, contain streams in which sediment yield is limited only by sediment supply. The data from table 7 also imply that the residence time of sediment along the higher gradient tributary channels is necessarily short. Changes in stored sediment provide an incomplete measure or record of sediment transport through a drainage basin. Continuous or periodic measurement of water discharge, suspended sediment concentration, and bedload discharge generate data on sediment yield more directly. Nolan and Janda (1981) used water discharge and suspended sediment discharge records to assess the

TABLE 6. —*Comparison of total tributary length to length of channel where most sediment is stored*

[DL, drainage length; DL_{95}, length where 95 percent of sediment is stored; TDL, total drainage length]

Tributary	Length of longest channel (DL, meters)	Length of channel, measured from mouth, along which 95 percent of total sediment is stored	
		(DL_{95}, meters)	DL_{95}/DL
Bridge Creek	12,859	6,645	0.52
Tom McDonald Creek	7,451	3,901	.52
Fortyfour Creek	5,053	3,597	.71
Harry Weir Creek	4,426	2,256	.51
Lacks Creek	13,600	9,656	.71
Windy Creek	3,300	1,433	.43
Devils Creek	7,966	5,000	.63
Karen Creek[1]	4,120	1,555	.38
Upper Redwood Creek . . .	8,030	3,475	.43
Simon Creek	4,635	1,676	.36
Bradford Creek	6,389	3,780	.58
Coyote Creek	6,518	2,134	.33
Garrett Creek	4,538	2,804	.62
Copper Creek	4,748	2,377	.50
Mean DL_{95}/TDL. . . .			.52
Standard deviation .			.12

[1] Basin in which DL_{95} was determined from qualitative field observations and measured reaches in this basin.

TABLE 7.—*Data on channel-stored sediment for three groups of study basins* [N/A, not applicable]

Tributary	Drainage area (km²)	Total stored sediment as of 1981[1] (metric tons)	Stored sediment per unit drainage area as of 1981 (metric tons/km²)	Total landslide mass delivered to tributary channels, 1954 to 1981[2] (metric tons)	Landslide mass per unit drainage area delivered 1954 to 1981 (metric tons/km²)	Percentage of 1981 stored sediment mass with regard to post-1954 landslide mass	Percentage of sediment stored upstream of large organic debris
Redwood-dominated, low-relief basins							
Bridge Creek[3]	29.5	381,000	13,000	311,000	12,700	123	N/A
Devils Creek	18.0	50,400	2,800	53,900	3,000	94	91
Tom McDonald Creek	18.0	80,000	4,400	50,000	2,800	160	56
Fortyfour Creek	8.1	81,800	10,100	29,900	3,700	274	83
Mean			7,575		5,600	163	77
Standard deviation			4,785		4,782	79	18
Redwood-dominated, high-relief basins							
Harry Weir Creek	7.8	29,200	3,700	47,500	6,100	61	76
Copper Creek	7.4	18,700	2,500	92,000	12,400	20	82
N. Slide Fork Creek	1.6	24,300	15,200	36,700	23,000	66	57
Mean			7,130		13,800	49	72
Standard deviation			7,010		8,500	25	13
Douglas-fir-dominated, high-relief basins							
Lacks Creek	44.0	120,000	2,700	917,700	20,900	13	49
Minor Creek[4]	33.6	219,300	6,500	465,500	13,900	47	13
Coyote Creek	20.4	22,000	1,100	231,800	11,400	9	52
Bradford Creek	16.5	27,000	1,600	213,100	12,900	13	16
Upper Redwood Creek	11.1	32,700	2,900	169,800	15,300	19	27
Garrett Creek	10.8	18,800	1,700	108,300	10,000	17	70
Snow Camp Creek	8.2	28,200	3,400	215,500	26,300	13	94
Windy Creek	4.6	116,200	25,800	241,600	52,500	48	19
Simon Creek	4.5	74,700	16,600	323,200	71,800	23	29
Mean			6,920		26,100	22	41
Standard deviation			8,560		21,586	15	27

[1] Stored sediment mass was computed by taking the product of the measured volume and an assumed density of 1.9 g/cm³ (120 lb/ft³) (James Popenoe, National Park Service, oral commun., 1981)

[2] Landslide mass was computed by talcing the product of measured volume and an assumed soil density of 1.6 g/cm³ (100 lb/ft³) (James Popenoe, National Park Service, oral commun., 1981).

[3] Data on sediment storage in Bridge Creek provided by David Leslie, Department of Earth Sciences, University of California, Santa Cruz, Calif.

[4] Data on sediment delivery from Minor Creek earthflow provided by Mike Nolan, U.S. Geological Survey, Menlo Park, Calif. An additional 169,000 metric tons of sediment were delivered to Minor Creek by large gullies.

impacts of timber harvesting on sediment transport in Redwood Creek tributary basins characterized by both diverse terrain and land use history. They found that suspended sediment concentrations for tributaries exceeded those for Redwood Creek at discharges having a recurrence interval of approximately 5 years or greater. In other words, at higher discharges, tributaries become major sediment source areas and transport more sediment per unit drainage area than does the main stem of Redwood Creek.

CONCLUSIONS

The Redwood Creek basin provides an opportunity to study hillslope and channel processes operating in a large number of small, steepland drainage basins. Data from 16 tributaries draining diverse terrain suggests that these basins are major sediment source areas for the main stem of Redwood Creek. Streamside landslides in tributary basins are as large and as complex as similar landslides along the much larger channel of Redwood Creek. In individual tributary basins, the rate of sediment production from streamside landslides is highly variable in space and time but, on the whole, does not differ substantially from the rate along the upper 34 km of the main channel of Redwood Creek. Landslides initiated or enlarged during the 1964 storm delivered as much sediment to tributary channels as all other slides initiated over the 27-year period of this study. Other storms occurring during the study period, although of similar magnitude, did not have the erosional impact of the 1964 storm.

The frequency of landslides is nearly the same for unlogged as for logged slopes, but slides occurring in cutover areas are substantially larger and account for nearly 80 percent of the total landslide-related erosion measured in this study. Failures associated with roads are the most frequent and are responsible for the most sediment production of all logging-related landslides. Slide frequency and landslide sediment production on clearcut, tractor-yarded slopes and on clearcut, cable-yarded slopes are nearly the same. This finding illustrates the importance of both the degree of ground disturbance and hillslope gradient as factors in contributing to slope failure. Landslides on tractor-yarded, selectively cut slopes are the least important in producing sediment.

Tributary streams are capable of transporting a high percentage of the material supplied to them. The total amount of sediment stored in tributary channels is estimated to be only 6 percent of the total amount stored along the main channel of Redwood Creek. Most tributary-stored sediment is found in the lower half of main tributary channels and is associated with large organic debris and low-gradient reaches. In a comparison of the mass of landslide material delivered to the tributary streams from 1954 to 1981 with the mass of sediment presently in storage, tributaries characterized by Douglas-fir forest and high relief transported to the main stem, over a period of less than three decades, an average of 78 percent of the sediment supplied by streamside landslides. These tributaries represent streams in which sediment transport is limited by sediment supply and along which the residence time of sediment is necessarily short. This conclusion is supported by earlier studies (chap. L, this volume) that contrast the sediment transport characteristics of Redwood Creek with those of its tributaries.

Large organic debris can be an important determinant of channel form and process in the old-growth redwood forests. On the average, tributaries draining redwood forests have a higher proportion of debris-stored sediment than tributaries draining Douglas-fir forests or prairie-woodland terrain. The accumulation of organic debris in the redwood forest is greater because large redwood logs are mobilized less frequently, are highly resistant to decay, and may remain in the channel for hundreds of years.

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