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

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Mass Movement in the Redwood Creek Basin, Northwestern California

By DEBORAH R. HARDEN, STEVEN M. COLMAN, *and* K. MICHAEL NOLAN

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MASS MOVEMENT IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

By DEBORAH R. HARDEN, STEVEN M. COLMAN, and K. MICHAEL NOLAN

ABSTRACT

Mass movement has played a dominant role in the geomorphic history of the Redwood Creek basin. Areas of active mass movement presently occupy approximately 16 percent of the total area of the watershed, and sites of inactive mass-movement features occupy an additional 15 percent. Most of these features are earthflows. Although debris slides and avalanches occupy less than 2 percent of the basin area, these landslides, particularly those adjacent to stream channels, are important sediment sources. Since the late 1950's, the amount of sediment derived from landslides adjacent to tributaries of Redwood Creek has been similar to the amount derived from landslides adjacent to the main channel.

Photointerpretive studies of landslide history document dramatic increases in the number of streamside landslides since 1947. Debris slides and avalanches have shown the greatest increase in activity; earthflow activity has not increased significantly since 1947. Most of the increased landsliding occurred between 1962 and 1966. The causes for the increase were the 1964 flood, destabilization of hillslopes by earlier storms, and intensive timber harvesting and road construction in the late 1950's and early 1960's. Since 1970, landslide activity in the basin has apparently decreased, but the lesser impact of the 1972 and 1975 floods on slope stability may partly be explained by the failure of most unstable slopes in the earlier 1964 flood.

INTRODUCTION

Mass movement has been a dominant geomorphic agent shaping the Redwood Creek basin (fig. 1), and both active and inactive landslides are common on most of the landscape. In addition, bowl-shaped basins, convex-upward hillslopes, and benched slopes throughout the basin suggest that mass movement has been responsible for much of the morphology of hillslopes, even in areas where discrete landslide features are absent. The presence of well-developed relict soils on many of these latter slopes suggests that they have not experienced landslides for thousands or even tens of thousands of years. However, these slopes are probably affected by active creep (Harden and others, 1978). The extent of active landslides (Nolan and others, 1976) attests to the continuing importance of mass movement as an erosional agent in the basin. Mass movement is also a significant contributor to the high fluvial sediment loads of Redwood Creek and its tributaries.

The number of streamside landslides increased by a factor of four between 1947 and 1976 (Colman, 1973; Nolan and others, 1976). This increase was a major concern to those responsible for protecting the resources of Redwood National Park (Janda, 1978). The degree to which the increase in streamside landslides resulted from the intensive clearcut timber harvesting that occurred between 1955 and 1975, rather than from the destabilizing influence of major floods of the same period, was a subject of considerable public debate during the course of our studies (Janda, 1978). Our photointerpretive studies of landslide history and landslide monitoring within the basin were begun as a result of this controversy. Results of these studies also have provided insights into the evolution of the drainage basin, as well as an understanding of the interactions between hillslope and channel processes in the basin.

ACKNOWLEDGMENTS

As project chief of the Forest Geomorphology Project, Richard Janda began and directed the U.S. Geological Survey's studies of landsliding in the Redwood Creek basin. We are grateful to him for his advice and creative suggestions throughout the course of our studies. James Duls, Sam Morrison, Tom Stephens, Jackie Miller, and many others aided in field mapping and surveying. David Keefer and S.D. Ellen reviewed the manuscript and provided many helpful suggestions.

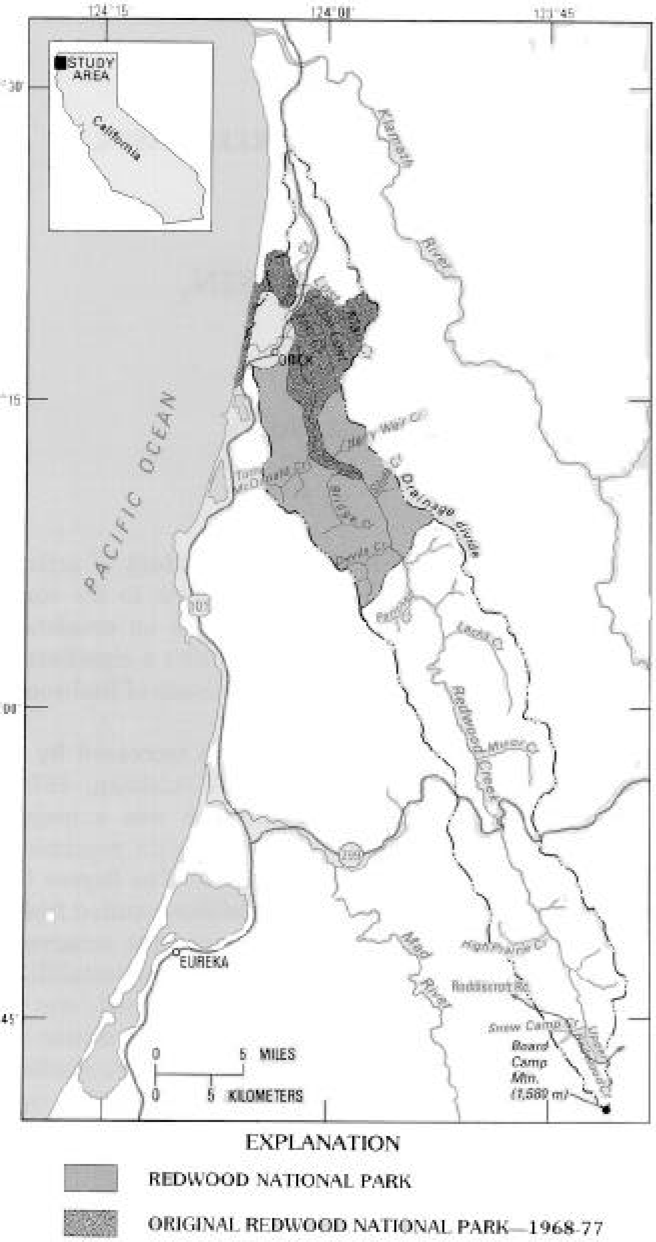


FIGURE 1.—Redwood Creek basin.

PREVIOUS WORK

Much of the U.S. Geological Survey's effort in the Redwood Creek basin from 1973 to 1976 was devoted to the characterization of mass movement on the basin's hillslopes. Study of recent streamside landslides was begun by Colman (1973) and expanded by Nolan and others (1976) and Harden and others (1978). This report draws heavily on the results of those studies, and the reader is referred to those reports for complete presentations of data. More recent unpublished studies by the U.S. Geological Survey and studies by the National Park Service (chap. J, this volume) have provided additional descriptions of mass movement in the basin. Finally, the general report by Janda and others (1975) provided considerable background information for this paper.

SETTING

The strongly elongate Redwood Creek basin, in the Coast Ranges of northwestern California (fig. 1), has an area of 725 km^2 in steep terrain. Redwood Creek flows approximately 102 km northwestward from its headwaters at Board Camp Mountain to the Pacific Ocean near the town of Orick (fig. 1). The total basin relief is approximately 1,615 m, and the relief normal to the basin axis is between 610 and 915 m (Janda and others, 1975). The average hillslope gradient is 26 percent; hillslopes in the basin are commonly steepest along their lower segments adjacent to steam channels.

Redwood Creek has a gravelly inner flood plain that is inundated during periods of high discharge. Along reaches in lower Redwood Valley and within Redwood National Park (fig. 1), a higher outer flood plain is underlain by 2 to 5 m of sandy loam and silt loam. Channel gradients range from 0.15 m/m (meters per meter) in the headwaters to 0.003 m/m in lower Redwood Creek, and the average gradient above Orick is 0.014 m/m (Janda and others, 1975). Tributaries are generally steep and lack flood plains.

Sheared and fractured bedrock of the Franciscan assemblage of Late Jurassic and Cretaceous age underlies most of the basin (Harden and others, 1981). Unmetamorphosed sandstone and shale, together with associated small bodies of greenstone, crop out in the eastern half of the basin. The western half and the southwestern corner of the basin are underlain by fine-grained quartz-mica schist. Rocks transitional in texture and degree of metamorphism crop out between these two units in portions of the basin. Weakly consolidated sedimentary rocks of probable Pliocene and Pleistocene age crop out in the northern part of the basin (chap. B, this volume).

The Redwood Creek basin receives about 2,000 mm of rain annually, and average precipitation ranges from about 1,525 mm near Orick to over 2,540 mm in the basin headwaters. Most of the rain falls between October and April during moderately intense regional storms that commonly produce as much as 500 mm of precipitation in 72 hours. During the last 30 years, the basin has had six floods that had instantaneous peak discharges of about 1,400 m^3/s (cubic meters per second) at Orick. Redwood Creek transports one of the highest sediment loads in the conterminous United States (Janda and Nolan, 1979). The long-term average annual total sediment load is about 2,350 Mg/km^2.

TYPES OF MASS MOVEMENT

Discrete erosional landforms occupy approximately 30 percent of the Redwood Creek landscape (Nolan and others, 1976; Harden and others, 1978) (table 1). Tilted trees, midslope depressions, and ground cracking in many of the remaining areas attest to the activity of less clearly defined landslides even in more stable portions of the basin. In addition, creep processes are active on almost all basin hillslopes. The types and rates of mass movement operating on hillslopes in the basin appear to be influenced by the underlying bedrock, slope aspect, vegetation, and land use (Harden and others, 1978). The type of mass movement operating on a given hillslope influences the rate of sediment supply to adjacent stream channels (chap. J, this volume). Our landslide classification scheme (Nolan and others, 1976) closely follows that of Varnes (1978).

DEBRIS SLIDES

Debris slides produce well-defined, nearly planar failure surfaces as a result of discrete, episodic failures. Movement is dominantly translational and generally involves the upper 2 to 4 m of colluvium and fractured bedrock (Marron, 1982) (fig. 2). Debris slides in the Redwood Creek basin are concentrated on streamside hillslopes (Colman, 1973; Nolan and others, 1976) and adjacent to roads and log-loading decks. Examination of time-sequential aerial photographs indicates that most slides are initiated during major winter storms, sometimes in conjunction with human disturbance. Although partial stabilization of streamside debris slides may occur within several years, activity on portions of many failures persists for decades.

DEBRIS AVALANCHES

Debris avalanches produce long, narrow scars that are straight to slightly sinuous and generally shallow (<4 m) (fig. 3). Movement is rapid and produces a chaotic mixture of disrupted vegetation, soil, and colluvium. Debris avalanche chutes are common on the steepest upper hillslopes in the basin and are also a common result of road failure. Like debris slides, debris avalanches occur in response to a single disruptive influence such as a major storm. Once initiated, these shallow scars may remain unvegetated for years but do not tend to enlarge significantly. Debris avalanche chutes at the heads of stream channels may carry debris flows during extremely wet periods; through geologic time, the chutes may evolve to form parts of stable drainage networks on steep upper slopes.

TABLE 1. — *Abundance of mass-movement landforms in the Redwood Creek basin as of 1974*

[Sources: Nolan and others (1976) and Harden and others (1978)]

Category	Percent of basin area above Prairie Creek
Active features:	
Debris slides………………………….	1
Debris avalanches…………………….	.2
Earthflows…………………………….	23
Unstable streambanks…………………	3
Total……………………….	16.2
Inactive features:	
Old and questionable landslides………	10
Amphitheater-shaped basins………….	5
Total………………………..	15

[1] Very active earthflows, which display unvegetated areas, open cracks, and bulbous toe slopes, occupy 2 percent of the basin area.

FIGURE 2.— Streamside debris slide, about 20 m in height, along the main channel of Redwood Creek about 6 km upstream from State Highway 299.

EARTHFLOWS

Earthflows occupy more area within the Redwood Creek basin than all other types of mass failure combined (Nolan and others, 1976) (table 1). Movement by both translational and rotational sliding, as well as by flowing, produces characteristic hummocky and lobate topography (fig. 4). Measured depth of one earthflow, near the mouth of Minor Creek (fig. 1), ranges from 4.5 to 7.7 m (Richard Iverson, U.S. Geological Survey, written commun., 1983). Earthflows typically bear grassland prairie vegetation and associated oak and madrone. They are commonly dissected by discontinuous gullies, which are important sediment sources in the basin (chap. F, this volume).

Movement of earthflows is variable but tends to be continuous rather than episodic. Active earthflows generally move during every rainy season, and the amount of seasonal movement varies with both rainfall amount

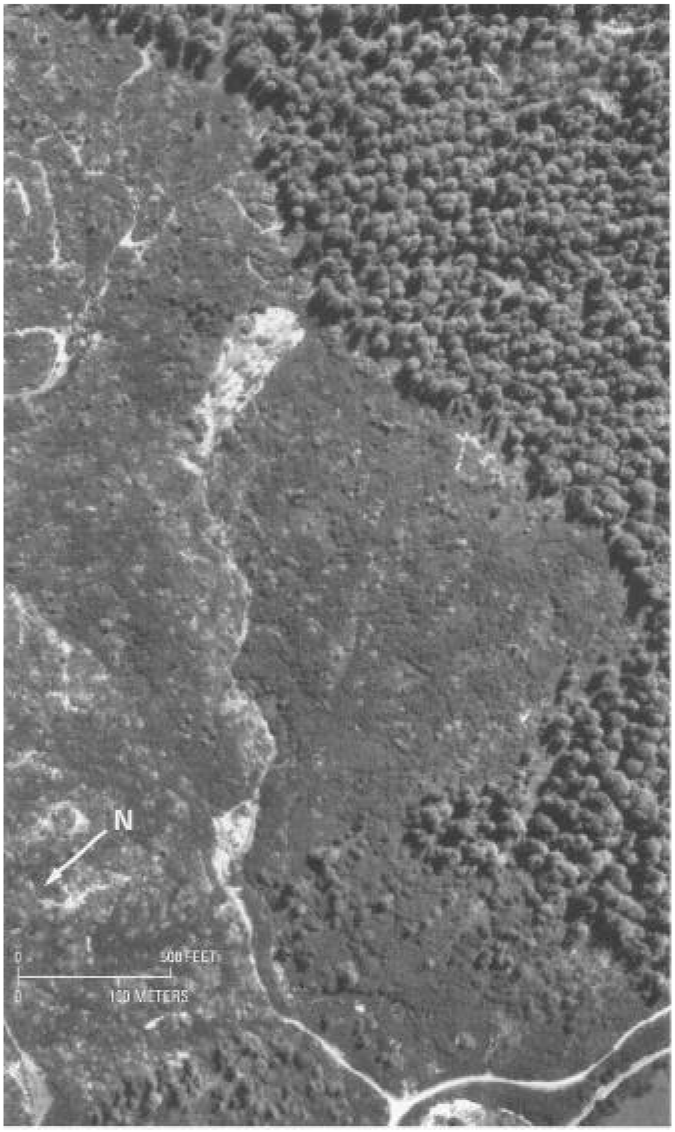


FIGURE 3. — Debris avalanche in the Prairie Creek basin approximately 2 km from the town of Orick.

and distribution (Harden and others, 1978). Movement rates also depend on the distribution of mass within the earthflow (chap. F, this volume). Repetitive surveys of stake lines indicate that a period of prolonged rainfall that saturates earthflows at depth is required before earthflows begin to move. High annual movement rates have occurred during winters such as that of 1973-74, when persistent heavy rains fell during November (Harden and others, 1978). Brief intense storms do not necessarily trigger deep-seated earthflow movement, but they can result in gullying and other surface erosion from earthflows. Average movement rates on four monitored earthflows in the basin ranged from 0 to 2.5 m/yr (meters per year) between 1974 and 1982 (Harden and others, 1978).

FIGURE 4. —Typical earthflow in the Redwood Creek basin adjacent to the downstream end of Minor Creek. View is toward north; local relief is about 200 m.

Large areas of bowl-shaped basins having characteristic earthflow topography indicate that earthflow movement has been a major geomorphic process in the basin during recent geologic time. Many of these features bear stands of trees that indicate stability for at least the past 50 to 100 years. Prairies lacking earthflow topography and recently forested areas adjacent to earthflows suggest that active earthflows may presently be less widespread in the basin than at some time in the past. However, the relationship between prairie vegetation and inactive earthflows is not clearly established.

SLUMPS

Slumps are uncommon in the Redwood Creek basin except as components of complex earthflows (Nolan and others, 1976). Slumps involve rotational movement of intact colluvial masses and produce concave-upward failure surfaces. Movement rates are probably similar to, or less than, those of debris slides. Slumping in the basin is generally confined to streamside hillslopes and along roads.

SOIL CREEP

Soil creep is probably active on most slopes in the basin but produces no discrete erosional landforms. Creep is probably a continuous mass-movement process. Rates vary from site to site within the basin and with fluctuations in rainfall. Swanston and others (chap. E, this volume) discuss soil creep in the basin.

INFLUENCE OF BEDROCK TYPE ON MASS-MOVEMENT PROCESSES

The underlying bedrock exerts a strong influence on both the type and rate of mass movement processes operating in the basin. A comparison of landslide distribution (Nolan and others, 1976) within different lithologic units (Harden and others, 1981) shows that most discrete, active mass failures are located on hillslopes underlain by unmetamorphosed and partially metamorphosed rocks of the Franciscan assemblage. Fewer mapped landslides lie within the schist terrain, although the existence of unmapped forested earthflows and other probable landslides in areas underlain by schist would weaken the observed relationship between landsliding and bedrock type.

Earthflow distribution shows strong correlation with lithologic type. Large, deep-seated earthflows are almost entirely restricted to areas underlain by unmetamorphosed argillaceous deposits of the Franciscan assemblage. Furthermore, the bedrock observed in active earthflow areas is apparently finer grained and more intensely sheared than that in surrounding areas. Earthflows bearing prairie vegetation are generally restricted to south- and west-facing hillslopes; this condition indicates that slope aspect, as well as lithology, influences earthflow distribution.

The terrain formed by shallow debris avalanches contrasts sharply with earthflow terrain in the basin (fig. 5). Debris avalanches are restricted to steep slopes underlain by massive, resistant sandstone units within the unmetamorphosed Franciscan assemblage (Harden and others, 1981). The upper portions of Lost Man and Little Lost Man Creeks and the northwest-trending part of the Lacks Creek basin are two prominent examples of debris-avalanche terrain in the basin.

The location of large debris slides also appears to be partly controlled by bedrock lithology. Streamside debris slides, particularly those adjacent to upper Redwood Creek, seem to be preferentially developed in unmetamorphosed rocks. Streamside debris slides are also concentrated along the linear zones of sheared rocks parallel to the Grogan fault in the lower basin (Harden and others, 1981). Northwest-trending linear zones of slope instability also mark other shear zones along Bridge and Devils Creeks.

The concentration of mappable landslides in areas underlain by unmetamorphosed rocks of the Franciscan assemblage (Nolan and others, 1976) suggests that these terranes contribute more sediment to Redwood Creek than do areas underlain by schist. However, hillslopes are steeper in areas underlain by unmetamorphosed and partially metamorphosed Franciscan assemblage rocks (Janda and others, 1975); thus, hillslopes shaped by rapid creep or less well defined landslides may be eroding more rapidly over geologic time to produce the gentler slopes of the schist terrane. Alternatively, the schist slopes may indeed represent a more mature and thus more stable landscape; more gentle slopes created by reduced relief are less susceptible to active mass movement. We do not have conclusive evidence to support either hypothesis, but the presence of deep ultisols on early Pleistocene(?) gravels that cap the schist on divides in the lower Redwood Creek basin (Harden and others, 1981) suggests that at least the upper parts of the schist landscape are relatively old. In addition, the predominance of unmetamorphosed clasts in the gravel bed of Redwood Creek (chap. N, this volume) may indicate that the schist terrain is eroding less rapidly; however, the fine-grained schist cobbles are less resistant to abrasion than the sandstone clasts.

FIGURE 5.—Contrast between earthflow terrain (foreground) and steeper debris-avalanche terrain (background). Area shown is in the Lacks Creek basin. Local relief is about 300 m.

RELATION OF PHYSIOGRAPHY TO MASS MOVEMENT

Approximately 80 percent of the 551 mapped active landslides in the basin (Nolan and others, 1976) occur on hillslopes having average gradients between 30 and 70 percent (table 2). Earthflows generally occur on gentler slopes than do debris slides and avalanches. Slopes having debris slides and debris avalanches show similar average gradients (table 2).

The incidence of mass failure other than earthflows on slopes less than 30 percent (table 2) is relatively low. The low incidence of landslides on slopes having dominant

TABLE 2.— *Selected data for sites of active mass movement related to dominant hillslope gradient*

[Number of features is given outside parentheses; percentages of total are shown in parentheses. Modified from Harden and others (1978). Hillslope gradients were measured from a photomechanically generated slope map of the basin, scale 1:62,500]

		Type of mass movement feature					
Slope class (gradient in percent)	Total percent of basin area in slope class	Debris slides and small mass failures	Debris avalanches	Slumps	Active earthflows	Total	Percent features in slope class weighted by basin area in slope class
0-15	8.6	2 (0.5)	2 (2.3)	0 (0)	0 (0)	4 (0.7)	0.9
15-30	35.3	48 (13.2)	11 (12.4)	2 (28.6)	41 (45.6)	102 (18.5)	5.5
30-50	50.2	222 (60.8)	56 (62.9)	4 (57.1)	48 (53.3)	330 (59.9)	13.0
50-70	5.5	85 (23.3)	19 (21.3)	1 (14.3)	1 (l.D	106 (19.3)	37.3
>70	.4	8 (2.2)	1 (1.1)	0 (0)	0 (0)	9 (1.6)	43.3
Total	100	365 (100.0)	89 (100.0)	7 (100.0)	90 (100.0)	551 (100.0)	100.0

TABLE 3. — *Selected data for sites of active mass movement related to steepest hillslope gradient*

[Number of features is given outside parentheses; percentages of total are shown in parentheses. Modified from Harden and others (1978). Hillslope gradients were measured from a photomechanically generated slope map of the basin, scale 1:62,500]

		Type of mass movement feature					
Slope class (gradient in percent)	Total percent of basin area in slope class	Debris slides and small mass failures	Debris avalanches	Slumps	Active earthflows	Total	Percent features in slope class weighted by basin area in slope class
0-15	8.6	2 (0.5)	1 (1.1)	0 (0)	0 (0)	3 (0.5)	0.1
15-30	35.3	13 (3.6)	3 (3.4)	0 (0)	3 (3.3)	19 (3.5)	.2
30-50	50.2	151 (41.4)	43 (48.3)	4 (57.1)	72 (80.0)	270 (49.0)	1.8
50-70	5.5	120 (32.9)	26 (29.2)	3 (42.9)	8 (8.9)	157 (28.5)	9.5
>70	.4	79 (21.6)	16 (18.0)	0 (0)	7 (7.8)	102 (18.5)	88 4
Total	100	365 (100.0)	89 (100.0)	7 (100.0)	90 (100.0)	551 (100.0)	100.0

gradients steeper than 70 percent reflects the fact that these slopes occupy only 0.4 percent of the total basin area. That these steep slopes are highly susceptible to mass failure is demonstrated by the incidence of landslides on hillslopes where the steepest gradient exceeds 70 percent (table 3).

Slope aspect also apparently exerts a controlling influence on earthflow distribution. Earthflows bearing prairie vegetation are confined to south- and west-facing slopes in the basin. Greater insolation on these slopes apparently affects at least the vegetation type. However, the number of unmapped forested earthflows in the basin is unknown, and the influence of slope aspect on earthflow distribution may be less than is apparent.

Flood plains play an important role in controlling streamside landslides in the basin (Janda and others, 1975). The wide alluvial flats in lower Redwood Creek and in Redwood Valley (Harden and others, 1981) (fig. 6) protect the toes of streamside hillslopes from undercutting. Slopes along these reaches of Redwood Creek are therefore less susceptible to the destabilizing effects of flood-induced aggradation (chap. N, this volume).

RECENT INCREASES IN STREAMSIDE LANDSLIDES

The number of active streamside landslides in the basin increased dramatically between 1947 and 1975 (Colman, 1973; Nolan and others, 1976; Harden and others, 1978). About 100 unvegetated landslides, mainly debris slides, can be seen along the Redwood Creek channel on 1947 aerial photographs, whereas 415 active landslides appear on the 1976 photographs. The erosional landform map of Nolan and others (1976) documents a similar dramatic increase for many tributaries in the basin.

Widespread landsliding along many north coast rivers is often attributed to the flood of December 1964 (Dwyer and others, 1971; Kelsey, 1977; Harden and others, 1978). The degree to which intensive timber harvesting exacerbated these landslides has been a subject of controversy (U.S. House of Representatives, 1976). The disturbances caused by the 1964 storm were probably increased by the destabilizing effects of earlier major storms in the basin, as well as by timber harvesting. As Colman (1973) and Harden and others (1978) have pointed out, the combined impact of timber harvesting and the floods between 1953 and 1975 probably was greater than if either disturbance had occurred alone. The impact of the 1964 storm on north coast hillslopes appears to have been unusually severe relative to that of other similar storms of the past 120 years (chap. D, this volume).

By using sequential sets of aerial photographs of the Redwood Creek channel (table 4), Colman (1973) and Harden and others (1978) have documented the history of basinwide landslide activity since 1947. Colman (1973) supplemented landslide inventories made from aerial photographs with field mapping and descriptions. Because of the variable scale of the photographs (table 4), we estimate that the smallest discernible landslides

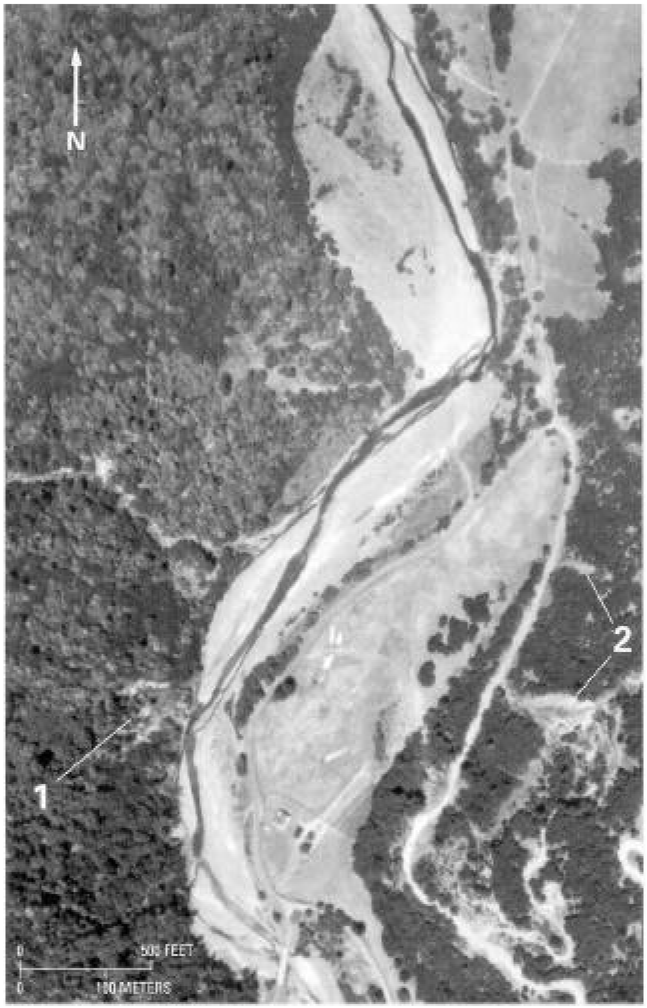


FIGURE 6.—Protective influence of flood plains on streamside hillslopes. Streamside landslides are numerous where Redwood Creek abuts hillslopes directly (1). On opposite bank, landslides (2) are separated from the active channel by a low flood plain. The photograph depicts the main channel of Redwood Creek immediately below the mouth of Minor Creek.

discussed in the following paragraphs are about 30 m in width. We have inventoried landslides primarily by number of features, although volumes were crudely estimated by Colman (1973). However, we include brief discussion of National Park Service volumetric measurements of landslides where appropriate.

Not surprisingly, periods having major flood-producing storms showed the greatest increases in streamside landslides (fig. 7). During the interval from 1947 to 1958, the two major storms of 1953 and 1955 apparently triggered numerous streamside slides. However, the impacts of these storms on hillslopes were much less severe than the impacts of the 1964 and 1972 storms, even though storm intensity and flood runoff were similar to those of the 1953 and 1955 storms (chap. D, this volume). The lesser impact of the earlier storms may reflect the fact that they occurred before extensive streamside logging took place (fig. 8). However, streamside slopes may have also been more susceptible to landsliding during the later storms because of channel aggradation and small-scale destabilization during the 1953 and 1955 events.

The period of maximum streamside landsliding (1962-66) includes the December 1964 flood (fig. 7). The concentration of new and increased landslide activity from 1962 to 1966 would be even more pronounced if volumes rather than numbers of landslides were compared (Colman, 1973). Pitlick (chap. K, this volume) has estimated that more than half of the volume of landslide debris delivered to tributary channels between 1947 and 1978 was supplied during this interval, specifically during the 1964 flood. Streamside timber harvesting was most intense from 1958 to 1966, especially in the upper watershed where precipitation was also greatest during the 1964 storm.

The impact of the 1972 and 1975 floods on streamside hillslopes was significantly less dramatic than that of the 1964 storm (fig. 7). Rainfall intensities were probably lower for the 1972 storms (chap. D, this volume), and streamside logging lessened from 1970 to 1974 (fig. 8).

TABLE 4.—*Aerial photograph coverage of the main channel of Redwood Creek*

Date	Scale	Area of main channel covered[7]	Source
1936……………	1:30,000	Prairie Creek to Lupton Creek	T. Hatzimanolis, Redwood National Park.
1947 ……….……	1:45,000	About 0.8 km below Copper Creek to Roddiscroft Road.	U.S. Geological Survey.
1958……….……	1:12,000	Prairie Creek to Roddiscroft Road	Humboldt County.
1962……………	....do....	....do....	Do.
1966……………	… do....	....do....	Do.
1970 – 71………	… do....	....do....	Do.
1972……………	1:36,000	....do....	National Park Service.
1973 ……….……	1:10,000	Prairie Creek to 0.8 km below Snow Camp Creep	U.S. Geological Survey.
1974 ……….……	.....do....	Prairie Creek to Roddiscroft Road	Do.
1974……………	1:12,000	Prairie Creek to Roddiscroft Road	Humboldt County.
1975 ……….……	.1:10,000	Prairie Creek to about 1.6 km above Pardee Creek	National Park Service.
1976 ……….……	.....do....	Prairie Creek to Roddiscroft Road	Do.

Localities are shown on figure 1.

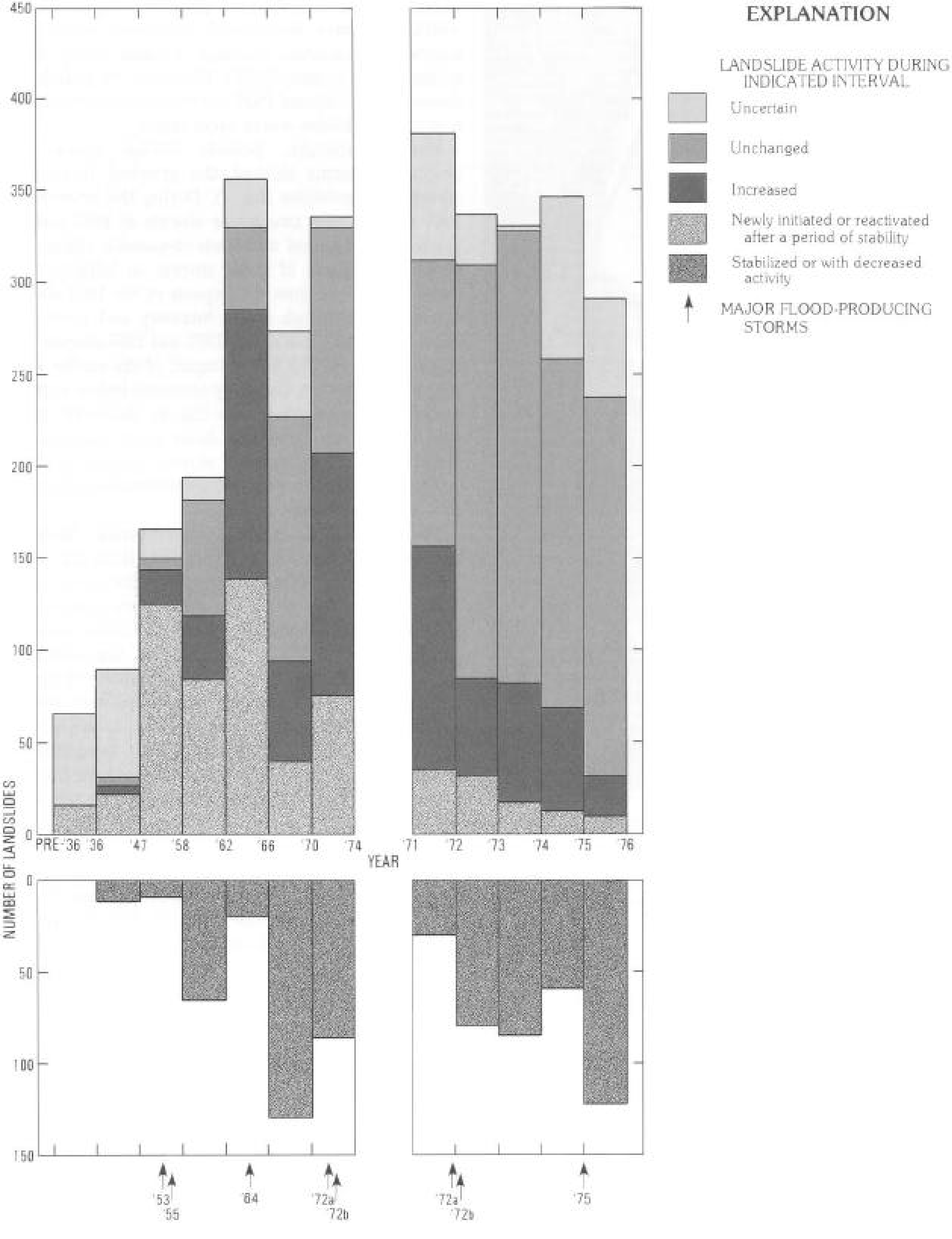


FIGURE 7. —Activity of streamside landslides adjacent to Redwood Creek between Roddiscroft Road and Prairie Creek, 1936-76. Data are based on interpretation of aerial photographs (from Harden and others, 1978). Note that time periods are not even. They represent times of available aerial photography.

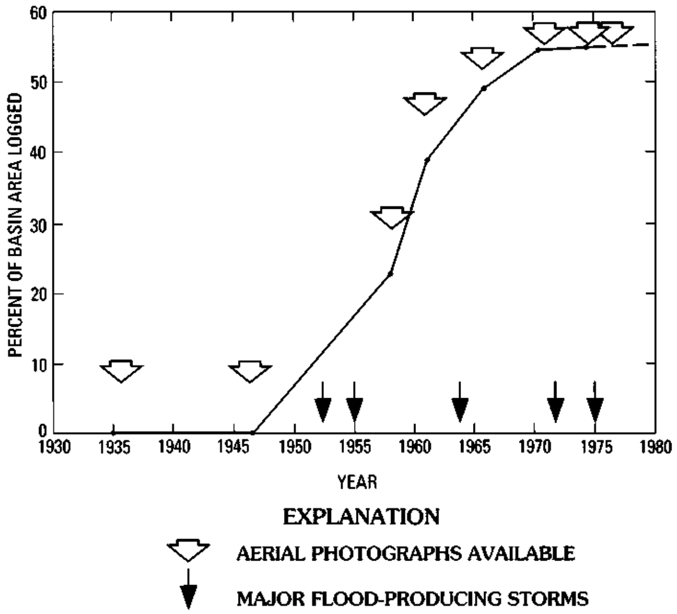
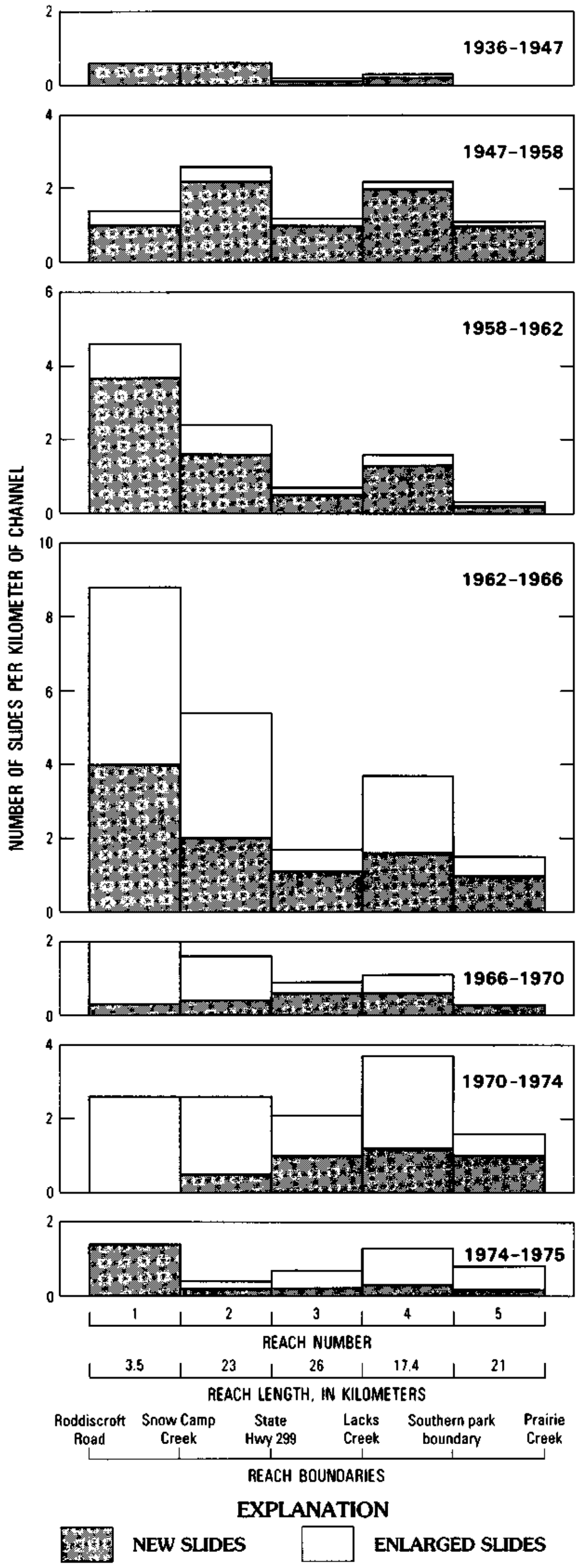


FIGURE 8.—Cumulative percent of Redwood Creek streamside hillslopes logged between 1936 and 1976.

FIGURE 9.—Distribution and occurrence of landslides adjacent to selected reaches of Redwood Creek. Boundaries between reaches are shown at bottom and on figure 1. Note that time periods are not even. They represent times of available aerial photography. >>



New timber harvest practices involving less ground surface disruption were also in force from 1974 to 1975 (Janda, 1978), and these new practices may have lessened the impacts of timber harvest on streamside hillslopes. Nevertheless, the number of new or enlarged slides below State Highway 299 (fig. 9, reaches 3-5) for both 1970-74 and 1974-75 was almost as great or greater than for the 1962-66 interval, although these slides were generally much smaller than the massive slides triggered during 1962-66 along the upper channel.

The flood-free periods of 1958-62 and 1966-70 were characterized by only minor increases in streamside mass movement in most reaches. Many features stabilized or decreased in activity, and few new slides were initiated. The lesser amount of slide activity between 1958 and 1962 indicates that the absence of major storms was the main reason for the decreased number of landslides, because streamside timber harvest was most intense during this period (fig. 8). However, those increases in slide activity that did occur from 1958 to 1962 were concentrated in areas where timber harvest was active (fig. 9, reaches 2 and 4). The additional harvesting combined with the lingering effects of pre-1958 logging, including root decay and poorly maintained roads, were probably responsible for many of the additional landslides.

Between 1966 and 1970, many slides along the Redwood Creek channel healed to some extent, and very few new slides were initiated (fig. 7). Most preexisting features remained active to some extent, however, particularly in the upper basin. Many of the massive debris slides initiated in 1964 along reaches 1 and 2 showed little if any vegetation by 1970.

The locus of maximum landslide activity along the channel has migrated downstream since 1947 (fig. 9). New and increased slide activity was generally concentrated above State Highway 299 (reaches 1 and 2) prior to 1966. After 1966, the number of new and enlarged slides per kilometer of channel increased in the lower reaches and generally decreased proportionately upstream from State Highway 299 (fig. 1). Several factors may have contributed to this shift. First, most unstable slopes in upper reaches already may have failed by 1966, presumably during the intense rainfall of 1964. Second, streamside timber harvesting was concentrated in the lower Redwood Creek basin after 1966. Finally, sediment deposited in the upper reaches during the 1964 flood has migrated to the lower channel since that time (chap. N, this volume). The increased sliding in lower reaches since 1966 may be partly a response to the channel widening and undercutting of slopes that resulted from the massive influx of sediment related to the 1964 flood.

The damage to streamside hillslopes by the 1964 flood persisted for at least 15 years, and many of the massive debris slides in the upper basin showed only minor revegetation by 1976. However, these slides are presently contributing much less sediment to Redwood Creek than they did during the 1960's (chap. J, this volume); as a result, major channel aggradation has presently ceased in upper Redwood Creek (chap. N, this volume). Nevertheless, these massive, unvegetated debris slides in the upper basin may be remobilized during major storms comparable to the storm of December 1964. Continuing slope failures triggered by aggradation in downstream areas are in part another legacy of the 1964 flood-induced landslides in the upper basin.

CONTRIBUTION OF TIMBER HARVEST TO STREAMSIDE LANDSLIDES

The series of flood-producing storms during the period 1953 to 1975 (chap. D, this volume) was undoubtedly a major cause of the observed increases in streamside landslides. The 1964 storm was the most damaging of the series and resulted in massive landslides and channel aggradation that can still be observed along most north coast rivers. The magnitude of this storm, its concentration in the upper watershed where streamside slopes are highly susceptible to failure, and the destabilizing effects of the 1955 flood probably all contributed to the severity of the 1964 flood impact. However, the intensive streamside timber harvest in those reaches where the storm was most intense was also an important factor in triggering slope failures. The tendency, during any given interval, for streamside reaches having active logging to show concurrent landslides during flood years (Harden and others, 1978) reflects the destabilizing effects of logging.

One of the most conclusive lines of evidence that points to timber harvest as a factor for the increased streamside landslides since the 1950's is the dramatically smaller impact of the floods of the late 1800's compared to those between 1953 and 1975. Despite the apparent similarity between the two storm series (chap. D, this volume), streamside landslides were much less widespread during the earlier events time period.

Evidence of streamside landslides during floods of the late 1800's is preserved in the form of landslide-shaped, streamside areas of young, even-aged vegetation visible on 1936 and 1947 aerial photographs. These young stands are interpreted as revegetated landslide scars, and they occur to a limited extent along all major north coast streams. Scars of large landslides initiated by the 1890 flood would bear vegetation not more than 57 years old in 1947; scars of slides initiated by the 1861-62 floods would bear vegetation not more than 85 years old in 1947. Arboreal vegetation populating the scars of late-19th-century landslides in 1947 can clearly be distinguished from old-growth forest on aerial photographs, but only a limited number of streamside landslide scars can be identified on 1936 and 1947 aerial photographs. Conclusive evidence of landsliding during the late 1800's was provided by coring of trees on two landslides along Redwood Creek near the former southern boundary of Redwood National Park (fig. 1). The tree-ring records revealed that nearly all of the trees were established immediately after the 1861-62 floods (S. Veirs, Jr., U.S. National Park Service, written commun., 1977). One slide showed evidence of continued movement until after the 1890 flood.

Evidence of aggradation that was presumably triggered by landslides during the 19th-century floods is also visible in parts of the Redwood Creek basin and other areas, but evidence for aggradation before 1960 appears localized and inconsistent from valley to valley. Even-aged stands of conifers on some gravel bars near Redwood Valley were about 100 years old in 1974 (Janda and others, 1975). Other sites having evidence of major aggradation during the late 19th century include Blue

Creek (Kelley and LaMarche, 1973) and Bald Mountain Creek (Kelsey, 1977). Evidence also exists for older major episodes of aggradation (Kelley and LaMarche, 1973; Kelsey, 1977). Along the upper reaches of the Redwood Creek channel, the age of riparian trees buried and killed by the 1964 flood was estimated at 200 to 300 years. Many streamside redwoods that have been toppled by recent bank erosion or buried by recent gravel deposits along parkland reaches of Redwood Creek are more than 1.8 m in diameter and probably more than 150 years old.

SUMMARY

Studies of mass movement in the Redwood Creek basin document the importance of landslides both as long-term landscape-forming processes and as major factors in the ongoing denudation of the area. The fourfold increase in streamside debris slides adjacent to the Redwood Creek channel between 1947 and 1975 can be attributed to the combined impacts of major floods, particularly the flood of 1964, and to intensive timber harvesting. Over geologic time, persistently active earthflows and creep processes, which have not been significantly affected by recent storms and timber harvesting, have been at least as important as episodic mass failures in the sculpting of basin of hillslopes.

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