MASS MOVEMENT AND STORMS IN THE DRAINAGE BASIN OF REDWOOD CREEK, HUMBOLDT COUNTY, CALIFORNIA--A PROGRESS REPORT

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ABSTRACT

Numerous active landslides are clearly significant contributors to high sediment loads in the Redwood Creek basin. Field and aerial-photograph inspections indicate that large mass-movement features, such as earthflows and massive streamside debris slides, occur primarily in terrain underlain by unmetamorphosed or slightly metamorphosed sedimentary rocks. These features cannot account for stream sediment derived from schist. Observed lithologic heterogeneity of stream sediment therefore suggests that large-scale mass movement is only one part of a complex suite of processes supplying sediment to streams in this basin. Other significant sediment contributors include various forms of fluvial erosion and small-scale discrete mass failures, particularly on oversteepened hillslopes adjacent to perennial streams.

Photo-interpretive studies of landslide and timber-harvest history adjacent to Redwood Creek, together with analysis of regional precipitation

and runoff records for six flood-producing storms between 1953 and 1975, indicate that loci and times of significant streamside landsliding are influenced by both local storm intensity and streamside logging. Analysis of rainfall records and historic accounts indicates that the individual storms comprising a late-19th-century series of storms in northwestern California were similar in magnitude and spacing to those of the past 25 years. The recent storms apparently initiated more streamside landslides than comparable earlier storms, which occurred prior to extensive road construction and timber harvest.

Field observations and repeated surveys of stake arrays at 10 sites in the basin indicate that earthflows are especially active during prolonged periods of moderate rainfall; but that during brief intense storms, fluvial processes are the dominant erosion mechanism. Stake movement occurs mostly during wet winter months. Spring and summer movement was detected at some moist streamside sites. Surveys of stake arrays in two recently logged areas did not indicate exceptionally rapid rates of movement in three years following timber harvest.

INTRODUCTION

Deep-seated slump-earthflow and shallow debris-slide types of mass failure have played key roles in forming the morphology of the Redwood Creek basin. More than 30 percent of the basin is underlain by distinct erosional landforms indicative of past or present mass movement (Nolan, Harden and Colman, 1976). Field inspection of forested hillslopes in many remaining areas indicates that they commonly display topography and (or) colluvium suggestive of episodic debris slides or persistent soil creep and slow sliding, even though these processes have not resulted in clearly bounded landforms discernible on aerial photographs.

The continuing importance of mass movement as a geomorphic process is apparent to most observers of the Redwood Creek basin. However, the relative significance of mass movement in contributing to present-day high stream sediment loads is less clear. Mass movement can contribute to sediment loads carried by Redwood Creek and its tributaries in three general ways. First, material may slide or flow directly into stream channels. Second, sediment deposited in valley bottoms during past episodes of widespread mass movement may be eroded as a result of recent increases in stream-channel widths (Janda and others, 1975). Third, mass movement may disrupt vegetation and ground surfaces to expose soil and make it susceptible to fluvial erosion.

Types and rates of mass movement in the basin have changed over the last 25 years. The occurrence of six major flood-producing storms together with widespread changes in land management, most importantly intensification of timber harvest, has produced these changes. The relative importance of these two factors is a source of controversy. Additional controversy exists regarding the degree to which recent mass movement contributes directly to the high stream-sediment loads in Redwood Creek (California State Board of Forestry, 1975; U.S. House of Representatives, Committee on Government Operations, 1976, 1977). Resolution of these controversies would aid in development of an effective long-term management plan for the Redwood Creek unit of Redwood National Park, which was established in 1968 at the downstream end of this rapidly eroding drainage basin (fig. 1). The location and configuration of the park, particularly its southern appendage, make it susceptible to impacts of upslope and upstream erosion, both natural and man-induced.

Purpose

This paper is a progress report of on-going research on hillslope-erosion processes in the Redwood Creek basin and represents part of a cooperative U.S. Geological Survey-National Park Service effort to understand better the geomorphic processes that may adversely affect the resources of Redwood National Park. The goals of hillslope-erosion studies in the basin are (1) to determine the spatial and temporal distribution of different types of landslides, (2) to evaluate effects of bedrock type, hillslope steepness, flood-producing storms, variations in seasonal precipitation, and recent human activities on landslide distribution and movement rates, and (3) to assess the relative importance of mass movement in supplying sediment to Redwood Creek and its tributaries.

Attainment of these goals would aid in resolving controversies concerning protection and management of Redwood National Park. Closely-related investigations are being performed by a number of State and Federal agencies; much of that work is being carried out under legally or legislatively-imposed deadlines. This report is intended to keep our colleagues informed of our progress. We plan to continue some of our hillslope research for several years and to prepare more definitive papers on specific topics.

Precipitation and runoff patterns for major flood-producing storms of 1953, 1955, 1964, 1972, and 1975 were analyzed in an attempt to evaluate possible causes of the varying impacts of these floods on landslide activity in the Redwood Creek basin. Precipitation and historical information for floods of the late 19th century have also been examined in order to compare that series of storms and floods with those of the past 25 years. The purpose in this comparison was to determine whether human activities can be cited as a significant cause of the more damaging impacts of the recent floods on channels and hillslopes throughout northwestern California, or whether the recent storms were more widespread and (or) intense than events of the late 19th century.

Information about recent streamside sliding adjacent to Redwood Creek which has been gained since Colman's (1973) description of the history of mass movement is also included in this paper. Additional data from interpretation of aerial photographs, field inspections, and repeated surveys of monumented stake lines on selected landslides are presented to document times and rates of movement. This report generally emphasizes large-scale streamside landslides and large compound earthflows relative to other mass-movement features.

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BASIN DESCRIPTION

The Redwood Creek basin encompasses about 280 square miles (725 sq km) of steep hillslopes that are naturally susceptible to erosion by both mass-movement and fluvial processes. The 63-mile long (102 km-long) channel of Redwood Creek is generally straight to slightly sinuous and roughly bisects its 4-to-5 mile wide drainage basin (fig. 1). The average gradient of Redwood Creek above Orick is 71 feet per mile (13.5 m/km) and the drainage density is about 7.7 miles per square mile (4.8 km/sq km) (Iwatsubo and others, 1975). Total basin relief is 5300 feet (1615 m) and the average hillslope gradient is 26 percent; only about seven percent of the basin is steeper than 50 percent.

The basin receives an annual average of about 80 inches (200 mm) of rain, most of which falls during the winter months. Rain is predominantly the result of orographic and frontal lifting of storms of regional extent. Localized intense showers from convective lifting are uncommon. About 66 percent of the annual rainfall appears as surface runoff (Rantz, 1969). During the last 24 years the basin has experienced six floods with instantaneous peak discharges of 50,000 $\pm$ 500 cubic feet per second (1400 $\pm$ 14 m^3/sec.).

Sheared and fractured upper Mesozoic Franciscan assemblage of rocks underlie most of the basin (Strand, 1962, 1963). Unmetamorphosed sedimentary rocks, together with occasional small greenstone bodies, crop out in most of the eastern half of the basin. Quartz-mica schist, which is commonly sheared and fractured, underlies most of the western

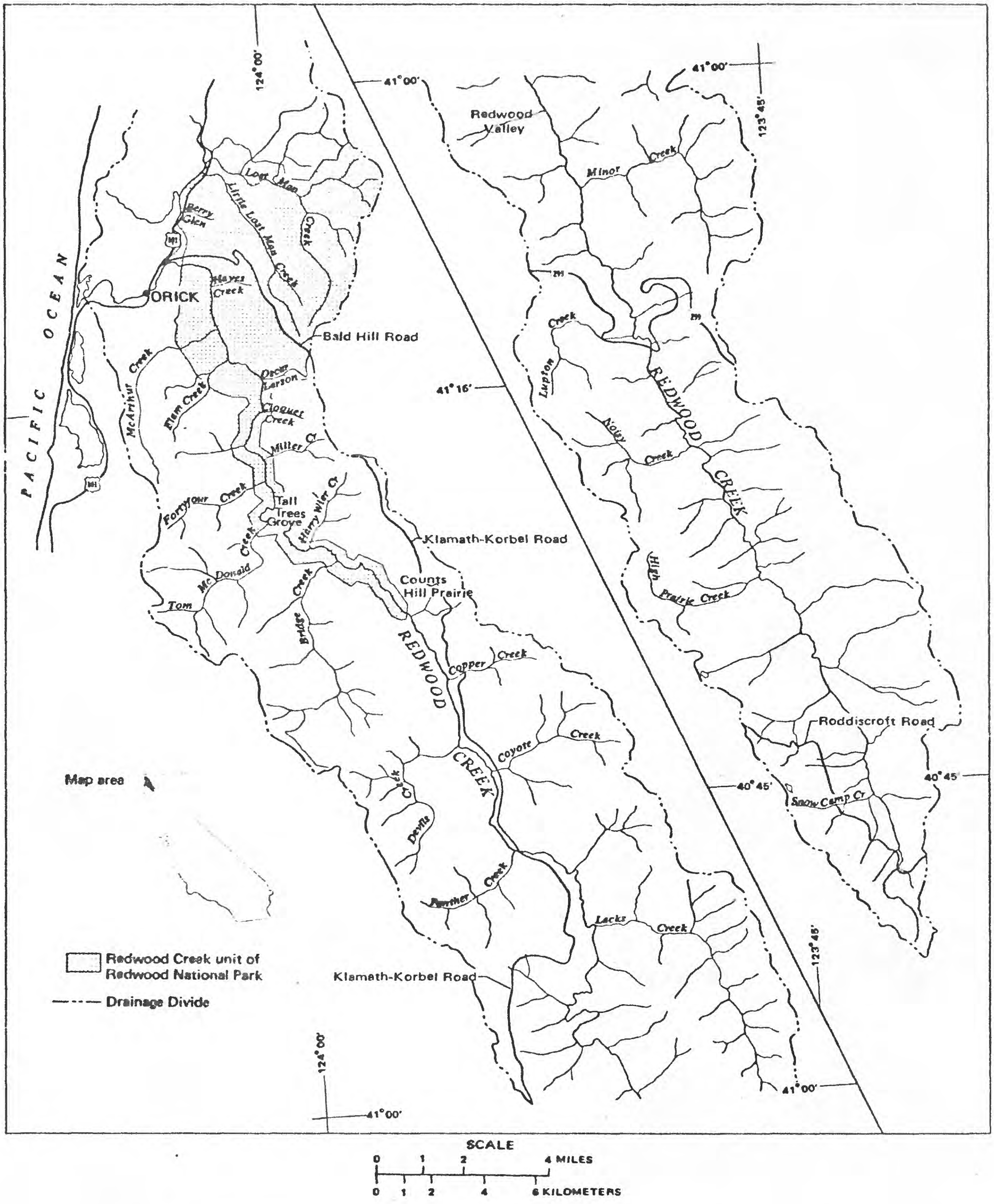

FIGURE 1. Location map of the Redwood Creek basin.

half as well as the southeastern corner of the basin. Relatively massive greenstone is prominently associated with the schist in some areas. Minor amounts of quartz-graphite schist and talc schist are also present in this unit. Field mapping by the authors indicates that rocks which are transitional in texture and mineralogy between the sedimentary rocks and the schist commonly occur along the contact between the two dominant units. Extensive shearing is observed along the contact, and locally unmetamorphosed sedimentary rocks are in direct contact with schist. This complex contact, which has been mapped as the Grogan Fault, roughly follows the course of Redwood Creek. Similar relationships between unmetamorphosed Franciscan rocks and schist units have been described by Blake and others (1967) along the South Fork Mountain Fault, which forms the contact between the metamorphosed and unmetamorphosed Franciscan rocks in the southeastern corner of the basin. The Bald Mountain Fault, which forms another contact between metamorphosed and unmetamorphosed Franciscan rocks near the western divide of the Redwood Creek basin, is apparently a simple high-angle structure lacking associated transition rocks and extensive shearing.

Residual soils and colluvium derived from the Franciscan rocks of the Redwood Creek basin are principally of two contrasting types. The prevalent type possesses little cohesion and shear strength and is highly susceptible to erosion by running water and shallow debris slides; the other common soil type consists of clayey soils derived from argillaceous and (or) intensely sheared rocks, and is highly susceptible to slump-earthflow movement (Winzler and Kelly, 1975, pp. 41-43; Janda and others, 1975, pp. 13-14, 17). Stable, intensely oxidized clayey soils are generally restricted to broad, gently sloping ridge tops in the northern portions of the basin.

In the maritime northern third of the basin, the prevalent vegetation is redwood and redwood-Douglas fir forest. In the southern parts of the basin, which are higher and further inland, Douglas fir predominates and other coniferous species appear (Alexander and others, 1959-62; Kuchler, 1964). Grass and grass-bracken fern prairies, brush, and grass-oak woodlands occur throughout the basin, but are most common on south- and west-facing hillslopes in inland parts of the basin. Stands of hardwoods and (or) young Douglas fir often surround prairie areas. The natural vegetation pattern in the basin has been greatly modified by the harvesting of large tracts of timber. More than 65 percent of the basin has been logged, mostly within the last 25 years (Harden, 1977).

The combination of factors described in the preceding paragraphs has resulted in unusually high stream-sediment loads in Redwood Creek. Average annual suspended sediment discharge measured at Redwood Creek at Orick for water years 1971 through 1976 is about 2,082,000 tons (1,889,000 tonnes) or 7500 tons per square mile (2600 tonnes/sq km) (U.S. Geological Survey, 1971-76). Annual suspended-sediment discharge during this interval ranged from about 753,000 tons (683,000 tonnes) in the 1976 water year to about 3,800,000 tons (3,447,000 tonnes) in the 1972 water year. Data collected during the 1973-76 water years suggest that bedload discharge at Orick is about 10 percent of the total load (James M. Knott, U.S. Geological Survey, written commun., 1975). Thus, the average annual total sediment load at Orick can be estimated at about 8300 tons per square mile (2900 tonnes/sq km). This average includes sediment moved by the notable floods of 1972 and 1975.

Exceptional floods on streams comparable to Redwood Creek have increased average rates of sediment transport for a given discharge, relative to pre-flood transport rates (Janda and others, 1975, p. 171-171a, and references therein). On the basis of a 1954-75 flow-duration curve and of sediment data collected during the 1973-75 water years James M. Knott (U.S. Geological Survey, written commun., 1975) has estimated the long-term annual total sediment discharge for Redwood Creek at Orick to be about 1,860,000 tons (1,687,355 tonnes), or 6700 tons per square mile (2347 tonnes/sq km). This procedure was used so as not to give undue emphasis to the high sediment yield generated by the floods in 1972.

MASS MOVEMENT AND FLUVIAL EROSION

Hillslope erosion processes can be conveniently grouped into two categories on the basis of the relative importance of running water in the process.

Mass-movement processes move soil, colluvium, rock, vegetation, and organic debris downslope under the dominant influence of gravity. Times, styles, and rates of mass movement are strongly influenced by soil moisture and ground water, but surface water has less effect. Fluvial processes move surficial soil, colluvium, rock, and organic debris downslope and downchannel under the dominant influence of running water.

The most common hillslope erosion processes in the Redwood Creek basin are described briefly below. More complete descriptions of most of these processes and their resulting landforms are given in Nolan, Harden, and Colman (1976).

Mass-Movement Processes

Soil creep: Slow, continuous downslope movement of soil, colluvium, and generally intact vegetation over large, poorly defined areas which lack well-defined basal shear planes or zones. Creep may be either episodic, in response to wet-dry or freeze-thaw cycles or soil stirring by burrowing animals, or uniform, solely in response to gravity.

Debris sliding: Dominantly translational downslope movement of soil, colluvium, fractured bedrock, disrupted vegetation, and organic debris along well-defined, nearly planar failure surfaces or zones. In the Redwood Creek basin, debris sliding occurs most commonly on streamside hillslopes and on fill slopes associated with roads and log-loading areas.

Debris avalanching: Rapid, chaotic, downslope movement of soil, colluvium, organic debris, disrupted vegetation, and artificial fill along narrow, well-defined tracks. Failure surfaces are irregular and usually long and narrow. When nearly saturated, materials in debris-avalanche chutes may fail by flowing rather than avalanching (Swanston, 1971). Debris avalanching is most common on steep upper hillslopes and at road failures.

Slumping: The downslope movement of intact masses of soil, rock, vegetation and colluvium accompanied by backward rotation along clearly defined, concave-upward failure surfaces or zones. Slumping in the Redwood Creek basin occurs mostly on streamside slopes or along mid-slope roads.

Earthflow: A combination of downslope slumping, flowing, and translational sliding which produces a characteristic hummocky and lobate topography. Earthflows typically bear prairie vegetation and are often gullied. They are most common on south- and west-facing hillslopes on the eastern side of the Redwood Creek basin.

Streamside sliding: Sliding, avalanching, slumping, or flowing of earthen materials in the zone of direct interaction between hillslope processes and stream-channel processes. Times and rates of movement are potentially influenced by streambank erosion, and significant quantities of colluvium are deposited directly in adjoining stream channels. In the Redwood Creek basin, most streamside landslides involve debris sliding, debris avalanching, earthflow, or combinations of these forms of movement.

Hillslope Fluvial-Erosion Processes

Rilling: Erosion of small channels whose cross-sectional area is less than 1 square foot (930 sq cm) in soil or colluvium. Rilling is generally confined to the upper B or higher soil horizons unless those horizons have been removed by prior erosion.

Gullying: Erosion of channels with cross-sectional areas greater than 1 square foot (930 sq cm) which results in exposed banks of bare mineral soil, colluvium, or rock. Gullying may involve the B and C soil horizons as well as poorly consolidated bedrock.

Other small-scale fluvial processes which operate on hillslopes, including rain splash and sheet erosion, are not discussed in this report.

Persistence of Erosional Processes

On the basis of the relative persistence of movement, mass-movement and fluvial-erosion processes can be generally placed into two groups. Under present climatic and geomorphic conditions, persistent processes are continuously or repeatedly active during every wet season, although the rates of activity may vary with seasonal rainfall amounts, rainfall distribution, and land use. Creep-sculptured slopes, earthflows, and some deep-seated slides are examples of erosional landforms produced by persistent processes. Episodic processes operate during brief, widely-separated periods of time. Activity is usually in direct response to major disruption of hillslope stability by major storms or earthquakes, possibly in combination with man-induced hillslope disturbances. Movement of slides initiated by an episodic mass-movement process may then persist for many years; thus the distinction between episodic and persistent processes is not always well defined. In general, debris slides, debris avalanches, slumps, and gullies are erosional landforms sculptured by episodic erosion processes. Those earthflows, gullies, and streamside translational slides whose activity apparently persists throughout the period of study are best classified as persistent features, although they may have been initiated over a period of minutes or hours.

Distribution and Age of Mass-Movement Features

The basin-wide distribution of erosional landforms is shown by Nolan, Harden, and Colman (1976). The proportion of the basin underlain by active and inactive erosional landforms discernible on aerial photographs is shown in Table 1. As was pointed out earlier, many hillslope segments which are not shown as erosional landforms by Nolan, Harden, and Colman (1976) display evidence of repeated mass movement and (or) present instability. For example, the forested western slope adjacent to Redwood Creek between Bridge Creek and Copper Creek has a smooth, convex-upward profile characteristic of hillslopes sculpted by persistent creep. In the field the lower third of this slope displays ground-surface disruption in the form of lateral cracks, small scarps, and midslope depressions; numerous tilted redwoods and Douglas firs are also discernible on aerial photographs and in the field. Likewise, the extremely steep west-facing

Table 1. Abundance of erosional landforms in the Redwood Creek basin, as shown by Nolan, Harden, and Colman (1976)

Map Category	Proportion of basin area upstream from mouth of Prairie Creek (percent)
Features active in 1974:	
Debris slides	1
Debris avalanches	0.2
Earthflows	10
Very active earthflows	2
Unstable streambanks	3
Total, active features	16
Inactive features:	
Old or questionable slides	10
Amphitheater-shaped basins	5
Total, inactive features	15

slopes of the Minor Creek and Lacks Creek basins appear to have been affected by episodic shallow debris slides and avalanches which are not shown on the map.

The types and spatial distribution of vegetation and soils in the basin (Alexander and others, 1959-62) and observations by the present authors suggest that not all the erosional landforms shown on the map of Nolan, Harden, and Colman (1976) now show the same degree of activity, nor have they undergone the same history of movement. Many unvegetated exposures of colluvium and unweathered rock attest to recent episodes of landslide activity. However, many active streambank slides and slumps shown by Nolan, Harden, and Colman (1976) show rates and styles of movement that permit forest growth, although many of the trees are tilted. Most of the active earthflows in this basin bear prairie or oak-grass-woodland vegetation which is disrupted only locally by differential or exceptionally rapid movement. Many hillslopes, including a large proportion of those classified on the map (Nolan, Harden, and Colman, 1976) as "deeply-incised amphitheater-shaped drainage basins" and "questionable or inactive landslides", bear old-growth forests or stands of young growth that are more than 50 years old. Most of these forests are thought not to be riding on deep-seated failure surfaces, because the trees are generally untilted and because downslope areas do not show extensive ground disruption.

The soil mantle developed on the deeply incised amphitheater-shaped basins and on some questionable or old slides is further evidence of their relative stability over a considerable period. Many of these features, especially in the maritime northern half of the basin, display moderately to strongly developed hapludults and haplohumults[1/] of the Melbourne, Orick, and Sites soil series (Alexander and others, 1959-62). Such strongly developed soil profiles are found only on landscapes that have been stable for many tens of thousand of years (Janda and others, 1975, pp. 18, 22, 25-26). The weakly developed xerumbrepts and dystrochrepts[1/] assigned to the Masterson and Hugo soil series are the most abundant soils in the basin and occur on both prominent erosional landforms and on more stable hillslopes. Even these soils display a degree of profile differentiation comparable to that developed on late Pleistocene till and outwash deposits in nearby areas (Davis, 1958, Sharp, 1960). The widespread occurrence within active earthflows of moderately-developed haploxerolls and argixerolls[1/] of the Yorkville,

[1/]Hapludults and haplohumults are ultisols, which are characterized by well-developed profiles and are common to the temperate forest. Xerumbrepts and dystrochrepts are inceptisols, characterized by weakly-developed profiles. They occur on steep topography or young surfaces. Haploxerolls and argixerolls are mollisols. They are common in grassland areas and display moderately differentiated profiles. Xerolls are mollisols which are dry for more than 60 consecutive days during most years.

Wilder, and Hulls soil series indicates that even many of these areas move with little churning of the soil (Alexander and others, 1959-62). Additionally the fact that the original morphology of many apparently old, large erosional landforms has been modified but not obliterated by subsequent erosion provides further indication that large areas well away from the deeply-incised channels of Redwood Creek and its major tributaries have experienced long periods of relative stability.

Creep

Two different types of creep mechanisms operate on hillslopes in the Redwood Creek basin: (1) episodic creep resulting from freeze-thaw cycles, wet-dry cycles, and differential stirring of the soil by burrowing animals and wind-toppled trees, and (2) uniform or true creep resulting solely from the downslope vector component of gravity. Episodic creep related to freeze-thaw and wet-dry cycles is probably not important in the Redwood Creek basin because the mild maritime climate and the marked wet and dry seasons limit the number of such cycles. Although blow-down mounds are clearly discernible on many hillslopes, the longevity of individual trees argues that this is not a major creep process (S. Veirs, oral commun., 1976). The minimal amount of erosional modification of these mounds in many otherwise undisturbed places indicates that other processes such as slope wash and true creep are also not operating rapidly.

The role of uniform creep in providing sediment to streams within the basin, although possibly significant, is incompletely understood. Kojan (1968) reported exceptionally rapid creep rates for nearby areas underlain by comparable rocks; these rates include surficial downslope displacements of as much as two inches (5 cm) per year and stream sediment contributions of about 750 tons per square mile per year. These rates are far in excess of others reported from temperate climates where surficial creep rates generally do not exceed 1.5 centimeters per year (Carson and Kirkby, 1972, p. 286-290; Swanston and Swanson, 1976, p. 205; Gray, 1977, p. 121). The creep rates reported by Kojan may in part reflect an unusually mobile regolith, but these rates may be an artifact of the manner in which values were obtained (Zeimer, 1977). In this regard, it is interesting to note that reported creep rates under natural conditions in the Pacific Northwest generally lie within the range of 0 to 15 mm/yr, with values of less than one millimeter per year being quite common (Swanston and Swanson, 1976; Gray, 1977).

In order to assess better the role of creep in the erosional development of hillslopes in the Redwood Creek basin, we installed 15 cased bore holes during the summers of 1974 and 1975, in cooperation with the Pacific Southwest Forest and Range Experiment Station of the U.S. Forest Service, and have repeatedly surveyed them with a pendulum-activated Wheatstone-bridge inclinometer. Preliminary observations in these holes indicate that creep rates are closer to those reported by Carson and Kirby (1972), Barr and Swanston (1970), Gray (1973,1977), and Swanston and Swanson (1976) than to those reported by Kojan (1968). Moreover, creep movement in the Redwood Creek basin appears to extend to depths of more than 10 feet (3 m), and in that regard is similar to the creep profiles reported by Kojan (1968), Swanston and Swanson (1976), and Gray (1977). Patterns of casing deformation are quite variable and often complex (R. Zeimer, written communication, 1978). Some holes show more abrupt changes in amount of downslope displacement than typical creep profiles discussed by Kirkby (1967). This mode of deformation may reflect a form of movement transitional between true creep and typical shallow sliding. The initial Redwood Creek observations, in conjunction with the recent literature (Swanston and Swanson, 1976; Gray, 1977), suggest that creep may significantly modify hillslope stress patterns and thereby lead to more discrete mass failure. However, creep appears incapable of supplying large amounts of sediment directly to Redwood Creek and its tributaries.

Landslide Occurrence Related to Hillslope Steepness

Hillslope steepness is generally recognized as a major factor controlling landslide occurrence. The dominant hillslope gradient at sites of active mass movement is shown in Table 2, and the steepest gradient within landslide sites is shown in Table 3. Data in Tables 2 and 3 were compiled by superimposing the erosional landform map of the basin (Nolan, Harden and Colman, 1976) over a photomechanically generated slope map of the basin (Scale 1:62,500). Because small localized areas of steep hillslopes may not appear on the slope map, and because many small landslides adjacent to stream channels are included within unstable streambanks as mapped on the erosional-landform map, some uncertainties are associated with the data shown in these tables.

TABLE 2. *Dominant category of hillslope gradient at sites of active mass movement.*

[Numbers outside parentheses are numbers of features within each category. Numbers inside parentheses are percentages of total numbers of features within each category]

Hillslope gradient category	Type of Mass Movement Feature: Slides and Small Mass Movements	Debris Avalanches	Slumps	Active Earthflows	Total	Total Percent of Basin Area in Slope Class	Total Percent Features in Slope Class ÷ Percent of Basin Area in Slope Class	Percent Features in Slope Class Weighted by Basin Area in Slope Class
0-15%	2(0.5)	2(2.3)	0(0)	0(0)	4(0.7)	8.6	.08	0.9
15-30%	48(13.2)	11(12.4)	2(28.6)	41(45.6)	102(18.5)	35.3	.51	5.5
30-50%	222(60.8)	56(62,9)	4(57.1)	48(53.3)	330(59.9)	50.2	1.20	13.0
50-70%	85(23.3)	19(21.3)	1(14.3)	1(1.1)	106(19.3)	5.5	3.45	37.3
>70%	8(2.2)	1(1.1)	0(0)	0(0)	9(1.6)	0.4	4.00	43.3
Total	365(100.0)	89(100.0)	7(100.0)	90(100.0)	551(100.0)	100	9.24	100.0

TABLE 3. *Steepest category of hillslope gradient at sites of active mass movement.*

[Numbers outside parentheses are numbers of features within each category. Numbers inside parentheses are percentages of total numbers of features within each category]

Hillslope gradient category	Type of Mass Movement Feature: Slides and Small Mass Movements	Debris Avalanches	Slumps	Active Earthflows	Total	Total Percent of Basin Area in Slope Class	Total Percent Features in Slope Class ÷ Percent of Basin Area in Slope Class	Percent Features in Slope Class Weighted by Basin Area in Slope Class
0-15%	2(0.5)	1(1.1)	0(0)	0(0)	3(0.5)	8.6	.06	0.1
15-30%	13(3.6)	3(3.4)	0(0)	3(3.3)	19(3.5)	35.3	.10	0.2
30-50%	151(41.4)	43(48.3)	4(57.1)	72(80.0)	270(49.0)	50.2	.98	1.8
50-70%	120(32.9)	26(29.2)	3(42.9)	8(8.9)	157(28.5)	5.5	5.09	9.5
>70%	79(21.6)	16(18.0)	0(0)	7(7.8)	102(18.5)	0.4	47.50	88.4
Total	365(100.0)	89(100.0)	7(100.0)	90(100.0)	551(100.0)	100	53.73	100.0

About 80 percent of the 551 active mass-movement features in the Redwood Creek basin (Nolan, Harden, and Colman, 1976) occur on hillslopes with dominant gradients of between 30 and 70 percent (Table 2). Earthflows and, to a lesser extent, slumps tend to occur on hillslopes with somewhat lower gradients than hillslopes where slides and debris avalanches are most prevalent (Table 2). The generally low incidence of mass failure other than earthflows on hillslopes of less than 30 percent (Table 3) reflects the stability of these slopes due to the relatively small downslope-directed component of the regolith weight. On the other hand, the low incidence of mass failure on hillslopes with gradients steeper than 70 percent primarily reflects the fact that these hillslopes comprise only about 0.4 percent of the total basin area. When the occurrence of mass failure is weighted by the percent of the total area within a given slope class (Table 3), steep hillslopes appear clearly to be far more susceptible to mass failure than gentle hillslopes. Even mass-movement features on gentle hillslopes almost always contain some areas where the hillslope gradient is greater than 30 percent (Table 3).

Geologic Controls of the Distribution of Mass Movement

The heterogeneous rocks of the Redwood Creek basin possess a wide range of physical properties that control the distribution and type of mass-movement activity. A comparison of landslide occurrence (Nolan, Harden, and Colman, 1976) with the distribution of different geologic units as determined by published geologic maps (Strand 1962, 1963) and recent field mapping by the authors (unpublished U.S.G.S. data) shows that more areas of active mass movement are underlain by unmetamorphosed and transitional rocks of the Franciscan assemblage than by schist. (The transitional rocks were not shown by Strand). Although the areas of the basin underlain by unmetamorphosed rocks and schist are roughly the same (Iwatsubo and others, 1975), almost three times as many mass-movement features occur partly or wholly within the unmetamorphosed terrain as within the schist. In addition, almost as many landslides occur partly or wholly within terrain underlain by transitional rocks as occur within the much larger area underlain by schist.

It is important to note that field observations suggest that many areas which appear by field inspection to be forested earthflows or slowly moving debris slides lacking distinct boundaries and supporting intact forest vegetation are not shown as discrete erosional landforms by Nolan, Harden, and Colman (1976). Some of these areas are within the unstable-streambank map unit, but others are completely unmapped. Our observations suggest that many unmapped landslide areas lie within the schist terrain, and that the apparent association of landslides with unmetamorphosed and transitional Franciscan rocks may therefore be less strong than is suggested by a comparison based solely on the use of the erosional landform map.

Geology exerts strong influence on the types as well as the loci of mass movement within the Redwood Creek basin. Field and aerial-photograph inspections indicate that abundant large-scale debris slides adjacent to Redwood Creek, upstream from State Highway 299, occur most commonly in unmetamorphosed and transitional Franciscan rocks. There debris slides supply coarse sedimentary-rock fragments and colluvium directly to the stream channels. Large earthflows are also most completely restricted to areas underlain by unmetamorphosed and (or) transitional rocks, but in that case the rocks tend to be more argillaceous and (or) more pervasively sheared than rocks in debris slide areas. Sediment supplied to stream channels by earthflows generally consists of incoherent masses of sheared and fractured sedimentary rocks and colluvium together with a few large coherent blocks of resistant rocks which become concentrated in the channels at the base of the earthflow because the blocks are too large for stream transport.

Particularly prominent streamside slides along the channels of Oscar Larson, Cloquet, and Miller creeks, and a rockfall along the south fork of Harry Wier Creek, are aligned roughly along a trend that is parallel to the Grogan Fault. These slides occur in different lithologic units and are apparently somewhat east of the actual contact. Some unrecognized zone of structural weakness probably exists in this area.

Numerous areas of instability exist adjacent to Redwood Creek between Copper Creek and Panther Creek and also along the topographic lineament defined by aligned segments of Bridge Creek, Devils Creek, and tributaries to Panther Creek. The streamside slides and unstable streambanks which occur in these areas apparently reflect linear zones of extensively sheared rocks.

Some geologic control of small debris slides in downstream tributaries is also apparent. The occurrence of streamside slides in downstream reaches of McArthur Creek and Elam Creek appears to coincide with that of recrystallized greenstone pods within the schist terrain (Harden and others, unpub. U.S.G.S. data).

Although some sediment is supplied to stream channels by small mass-movement features in schist terrain, much larger quantities of sediment appear to be supplied by larger, more abundant features in terrain underlain by unmetamorphosed and transitional rocks. Despite this fact, the coarse bed material in Redwood Creek does contain a significant percentage of clasts derived from schist (Harden and others, unpub. U.S.G.S. data). Additional evidence suggests that much of the suspended sediment carried by Redwood Creek is derived from soils developed on schist (Winzler and Kelly, 1975). These two observations indicate that significant quantities of sediment are being supplied to Redwood Creek from schist terrain by mass-movements which are too small to be distinguished on aerial photographs and (or) by fluvial erosional processes.

Other Basin Parameters Influencing Landslide Distribution

In addition to hillslope steepness and bedrock type several other factors apparently influence the occurrence of landslides in the Redwood Creek basin. Slides adjacent to streams can trigger additional streamside slides in adjacent areas. Debris slides also commonly occur along streamside roads or skid trails. Control of microclimate and vegetation hillslope aspect appears at least partly responsible for the almost exclusive occurrence of earthflows on south- and west-facing slopes. Less dense vegetative cover on these dry slopes may influence the location of earthflows.

Abundant streamside slides along tributaries of Redwood Creek are shown on the erosional-landform map (Nolan, Harden, and Colman, 1976). Field inspection indicates that these slides and similar features too small to show on the map can strongly influence the character of streambanks and channel at the site of sliding and in adjacent reaches. Streambank slides may expand by progressive lateral or headward failure. Stream deflection or aggradation caused by slide debris in the channel may also trigger new sliding on the bank opposite the initial failure and in downstream areas. Particularly massive slides may even block the channel completely and cause upstream aggradation and further instability. Thus, streamside instability can spread to upstream or downstream sites well away from the initial failure (fig. 2).

Improperly designed and maintained forest roads are widely recognized as major potential causes of erosion related to timber harvest (Environmental Protection Agency, 1975; Burroughs and others, 1976). The changes in hillslope stress patterns, the interception of shallow subsurface flow, and the increases in and concentration of surface runoff caused by forest roads and deeply incised skid trails are often considered to have more severe and persistent erosional impacts than other features related to timber harvesting.

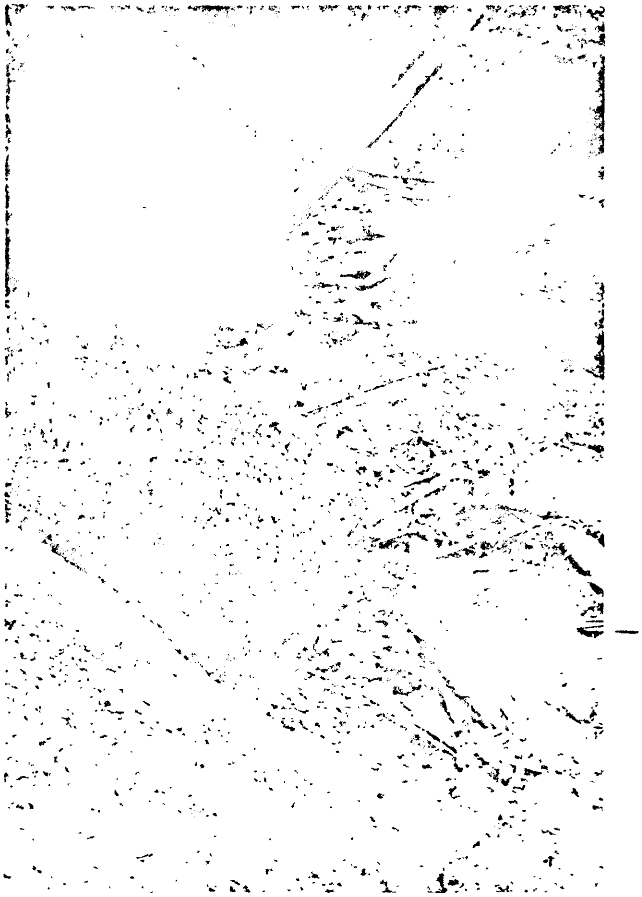

FIGURE 2. Photograph showing the interactions between streamside landslides and the stream channel in upper Lacks Creek. Channel is approximately 90 feet (27 m) wide.

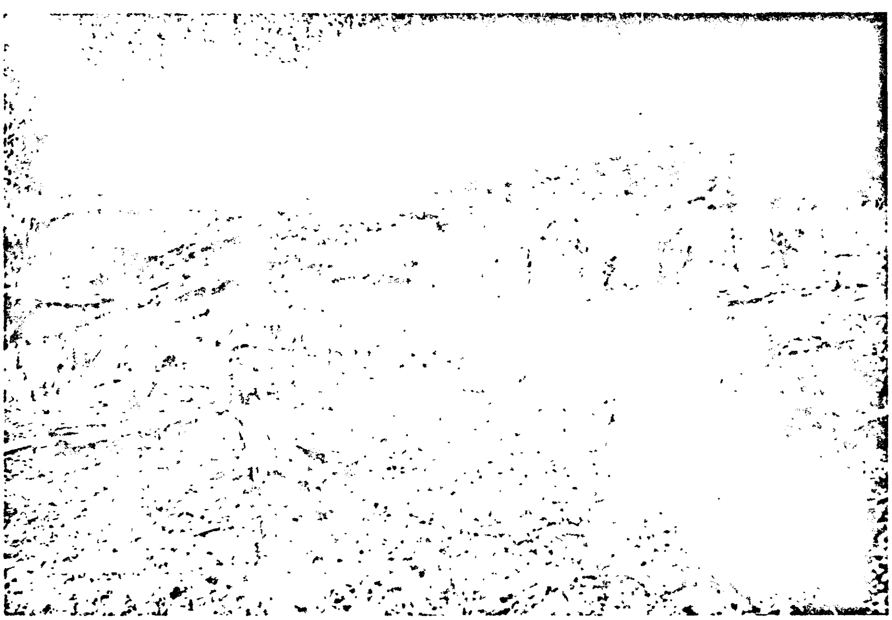

FIGURE 3. Photograph showing failure of old logging road adjacent to Redwood Creek along the present Bridge Creek Trail in Redwood National Park. The pull-away scarp is about 2-3 feet (60-90 cm) high. A photograph of this slide from Redwood Creek is shown in Figure 30.

More than 1100 miles of roads and 3000 miles of skid trails exist within the Redwood Creek basin (California Resources Agency, 1975, p. 8 and 10). Many of these have contributed to recent increases in debris avalanches and streamside sliding (Colman, 1973; Janda and others, 1975). Some former streamside road systems, particularly those along Redwood Creek in areas upstream from State Highway 299, have been virtually obliterated by sliding, and much of the former road prism has been deposited in the creek.

Inspection of aerial photographs shows that active debris slides adjacent to Redwood Creek tributaries are most common near roads or in cutover areas. Field inspections in the lower basin revealed that roads adjacent to streams have caused some failures whose effects have extended downstream into the Park. Such a slide occurred where an old roadfill failed, along Forty-Four Creek just above the Park boundary, probably during a major storm in March 1975. This slide apparently dammed the creek temporarily and backed up sediment and debris behind the dam. The breaking of this dam led to rapid introduction of large quantities of poorly-sorted, coarse sediment and organic debris into parkland reaches of Forty-Four Creek. Deposition of the sediment and debris altered the habitat and appearance of the creek. A second example of the impact of roads on streamside instability in the Park is provided by the numerous failures along the old M-line which now serves as the Park trail from Tall Trees to Bridge Creek (fig. 3). Considering the large number of unmaintained roads through the basin, including those in and adjacent to the Park, these small road failures may, in total, significantly alter Park resources.

Control of the microclimate and vegetation by hillslope aspect appears partly responsible for a general asymetry of hillslopes in the basin and for the prominence of earthflows on south- and west-facing slopes (Janda and others, 1975, pp. 42-43). These slopes receive more insolation during the warm part of the day, have a lower average vegetation density, and are generally less steep than their north- and east-facing counterparts.

RECENT INCREASES IN EROSION

Dramatic increases in the number of streamside slides and of debris avalanches since 1947 (Colman, 1973; Janda and others, 1975) are clearly seen on the erosional-landform map (Nolan, Harden, and Colman, 1976). Earthflow activity has not increased significantly since 1947 except at a few locations where road construction has caused gullying and increased disruption of the ground. Increased fluvial erosion is also indicated by the greater abundance of active gullies in 1974 relative to 1947 (Nolan, Harden, and Colman, 1976). The increase in gully activity has been greater than that shown on the map because many active gullies discerned on aerial photographs were too small to be portrayed on the map. The causes of the recent increase in landslide activity in the Redwood Creek basin have been a major source of controversy. The following two sections of this paper attempt to evaluate the impacts of flood-producing storms and increased timber harvest activity on landslide activity in the basin.

FLOOD-PRODUCING STORMS IN NORTHWESTERN CALIFORNIA

One controversy regarding the recent geomorphic history of the Redwood Creek basin concerns the relative importance of flood-producing storms and human activities during the past 25 years in accounting for recent extensive streamside landsliding and channel aggradation. Storm magnitude and destabilizing impacts of timber harvest have both been cited as the primary reason for the fact that the 1964 storm produced the most damaging floods of the century in northwestern California (U.S. House of Representatives, 1976). In order to evaluate whether differences in aerial distribution and amount of rainfall can explain contrasting amounts and locations of erosion associated with the six major floods of the past 25 years in the Redwood Creek basin, we have prepared maps showing the distribution of rainfall amounts and runoff associated with these flood-producing storms. In addition, climatological records and historical accounts of late-19th-century floods in northwestern California were examined in order to compare that series of floods with those floods during the past 25 years. The purpose of this comparison was to investigate the possibility that the apparently lesser erosional damage resulting from early floods was due to the lesser intensity and magnitude of the early storms relative to the more recent storms, rather than to the <u>recent</u> adverse impact of human activities on the stability of the landscape.

Recent Flood-Producing Storms

Six major flood-producing storms occurred in the Redwood Creek basin -- in January 1953, December 1955, December 1964, January 1972, March 1972, and March 1975. The instantaneous peak discharges of Redwood Creek at Orick for all of these floods were remarkably similar (Table 4), but the storms differed significantly from one another in terms of other hydrologic characteristics and in the amounts and loci of flood-associated erosion. The 1964 storm resulted in the greatest damage to streamside hillslopes and stream channels, particularly in upstream portions of the basin. The 1972 and 1975 storms also caused considerable damage, but these events were more destructive in the downstream half of the basin. Although data are sparse for the 1953 and 1955 storms, considerably less damage to the stream channels and hillslopes appears to have resulted from these storms than from the later ones.

In order to help assess the reasons for these different amounts and locations of flood damage in the Redwood Creek basin we compared regional rainfall and runoff patterns for the six major flood-producing storm periods. In addition, we investigated temperature and precipitation records at key stations prior to each storm, and temperature data collected during the storms, to determine antecedent conditions and possible snow-melt and frozen-ground effects on runoff. The following descriptions of these storms compare their intensities and distributions in northwestern California. We have also attempted to evaluate the probable magnitude of each storm in different parts of the Redwood

TABLE 4. *Instantaneous peak discharges on Redwood Creek near Blue Lake and at Orick during recent major floods. Discharges are in cubic feet per second (CFS) and cubic feet per second per square mile (CFS/mi^2).*

Date	Redwood Creek near Blue Lake		Redwood Creek at Orick	
	CFS	CFS/mi^2	CFS	CFS/mi^2
January 18, 1953	1/	1/	50,000	180
December 22, 1955	12,100	179	50,000	180
December 22, 1964	16,400	243 2/	50,500	182
January 22, 1972	6,900	102 3/	45,300	163
March 3, 1972	13,700	203 3/	49,700	179
March 18, 1975	12,200	180	50,200	181

1/ Flood marks for this event were at a stage of 15.3 feet, whereas flood marks for the 1955 event were at a stage of 13.7 feet. No discharge value has been assigned to the 1953 event.

2/ Discharge estimated from flood marks and stage discharge relations in effect when operation of station was discontinued in 1958. If any channel aggradation occurred in the interval between 1958 and 1964, as seems to be the case, the estimated peak discharge for the 1964 flood would be too high.

3/ At the time of these floods this station was being operated only as a flood-warning station. Peak discharges were estimated from peak stages and a periodically revised stage-discharge relation.

Creek basin. Individual storm precipitation and runoff totals are frequently compared with the 1964 totals because the 1964 storm appears from a regional perspective to have been the most intense and voluminous recent storm.

The location, elevation, and history of precipitation gages and runoff monitoring stations in the area are shown in figure 4 and Tables 5 and 6. Data compiled by the National Weather Service (formerly U.S. Weather Bureau-USWB) are published by the U.S. National Oceanic and Atmospheric Administration. Unpublished daily rainfall totals compiled by the California Department of Water Resources (DWR) are available in Red Bluff, California. Data compiled by the U.S. Geological Survey are published in Iwatsubo and others (1976). Data compiled by Winzler and Kelly (W&K) are unpublished but may be consulted at the offices of the authors.

The rainfall distribution and runoff values at operating stations during each event are presented in figures 5 through 11. Where possible, the beginning and end of each storm period were defined on the basis of precipitation values. However, in some cases two or more storm periods overlapped, or a storm was concentrated in different portions of the region at different times. In these instances an attempt was made to include only that rainfall which contributed to the major flood peak and the recession immediately following the peak discharge. We compiled flood hydrographs based on mean daily discharge values published by the United States Geological Survey (1964; annual publications for 1972 and 1975; and Waananen and others, 1971). Due to

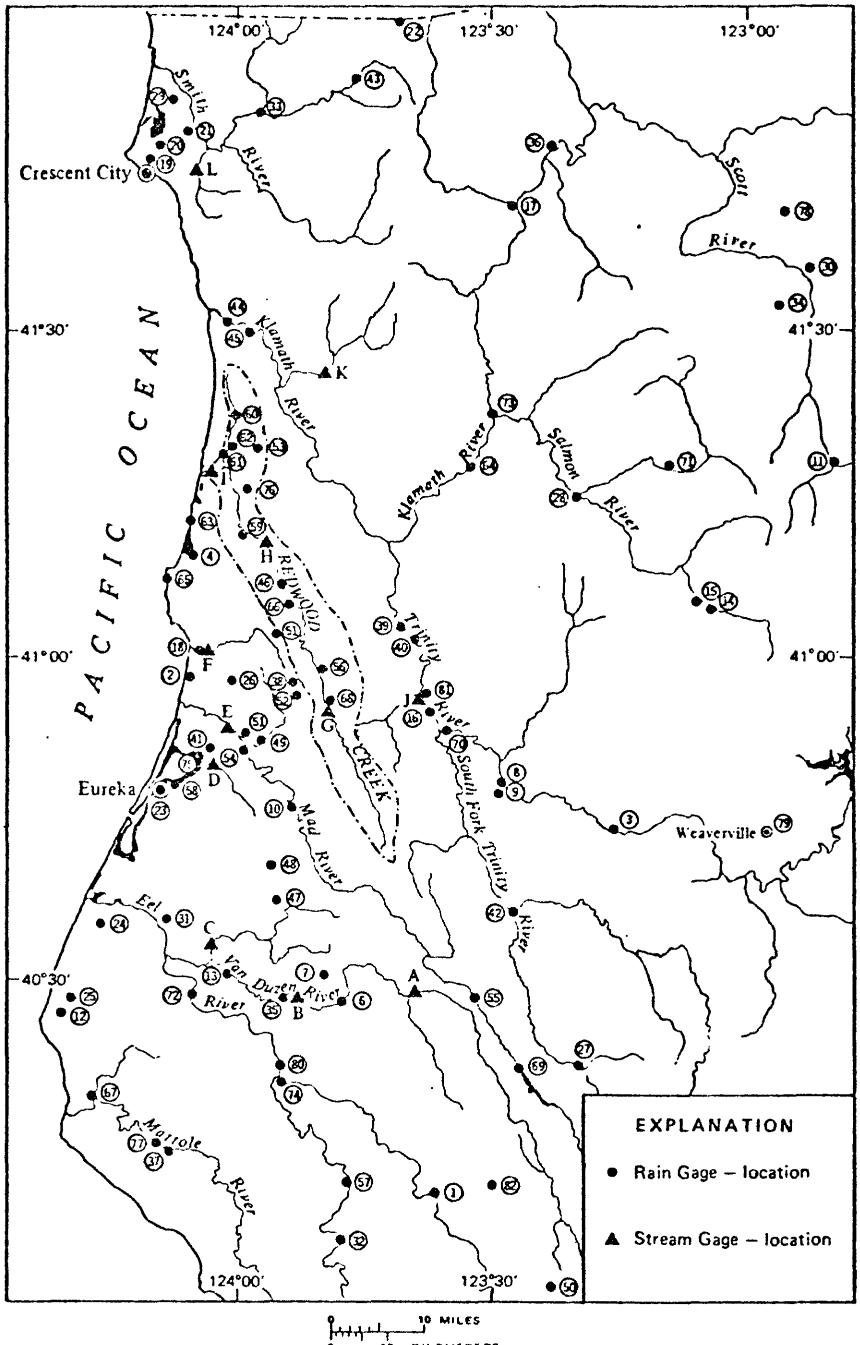

FIGURE 4. *Location map showing rain gages and stream gaging stations used in data compilation for storm maps. Station descriptions and histories are given in Tables* 5 *and* 6.

TABLE 5. *Precipitation gages used in data compilation for storm maps.*

[Abbreviations used to identify data compilers are explained in text (p. 34)]

Station Number on Location Map	Location	County	Data Compiled By.	Elevation (feet)	Storm Events For Which Data Used (X=us						
					1890	1953	1955	1964	1972a	1972b	197
1	Alderpoint	Humboldt	USWB	435	0	X	X	X	X	X	0
2	Arcata AP	Humboldt	DWR	217	0	0	0	X	X	X	X
3	Big Bar RS	Trinity	USWB	1270	0	X	X	X	X	X	X
4	Big Lagoon	Humboldt	DWR	100	0	0	0	X	X	X	X
5	Blue Lake	Humboldt	DWR	105	0	0	0	X	0	0	0
6	Bridgeville	Humboldt	DWR	650	0	0	0	X	0	0	0
7	Bridgeville 4NNW	Humboldt	USWB	2050	0	0	X	X	X	X	X
8	Burnt Ranch Honor Camp 36	Trinity	DWR ?	1540	0	0	X	X	0	0	0
9	Burnt Ranch 1S	Trinity	USWB	2150	0	0	X	0	X	X	X
10	Butler Valley Ranch	Humboldt	USWB	420	0	0	0	0	X	X	X
11	Callahan RS	Siskiyou	USWB	3136	0	X	X	X	X	X	X
12	Capetown 2S (Cape Ranch)	Humboldt	DWR	710	0	0	0	X	0	0	0
13	Carlotta-Cummings Cr	Humboldt	?	175	0	0	X	0	0	0	0
14	Cecilville-Sawyer Ranch	Siskiyou	USWB	3000	0	X	X	0	0	0	0
15	Cecilville 5SE	Siskiyou	USWB	2980	0	0	0	0	X	X	X
16	China Flat	Trinity	USWB	600	0	X	0	0	0	0	0
17	Clear Creek	Siskiyou	USWB	975	0	0	0	X	X	X	X
18	Crannell (Little R.)	Humboldt	DWR	150	0	0	X	X	0	0	0
19	Crescent City 1N	Del Norte	USWB	40	X	0	0	X	X	X	X
20	Cres City 5NNE (Thompson)	Del Norte	DWR	55	0	0	X	0	0	0	0
21	Cres City 7ENE	Del Norte	USWB	120	0	X	X	X	X	X	X
22	Elk Valley	Del Norte	USWB	1711	0	X	X	X	X	X	X
23	Eureka W.B.	Humboldt	USWB	43	X	X	X	X	X	X	X
24	Ferndale 2NW	Humboldt	USWB	10	0	0	0	0	X	X	0
25	Ferndale 8SSW	Humboldt	USWB	1445	0	0	0	X	0	0	0
26	Fieldbrook 4D Ranch	Humboldt	DWR	285	0	0	0	X	X	X	X
27	Forest Glen	Trinity	USWB	2340	0	X	0	X	X	X	X
28	Fork of Salmon	Siskiyou	USWB	1270	0	0	0	X	X	X	0
29	Fort Dick	Del Norte	USWB	46	0	X	X	0	X	X	X
30	Fort Jones RS	Siskiyou	USWB	2720	0	X	X	X	X	X	X
31	Fortuna	Humboldt	DWR	60	0	0	0	X	0	0	0
32	Garberville	Humboldt	USWB	340	0	X	0	X	X	X	X
33	Gasquet RS	Del Norte	USWB	384	0	X	X	X	X	X	X
34	Greenview	Siskiyou	USWB	2818	0	X	X	X	X	X	X
35	Grizzly Cr Redwoods SP	Humboldt	DWR	500	0	0	0	X	X	X	0
36	Happy Camp RS	Siskiyou	USWB	1090	0	X	X	X	0	X	X
37	Honeydew 2WSW	Humboldt	USWB	380	0	0	0	X	X	X	0
38	Honor Camp 42	Humboldt	DWR	1875	0	0	0	X	0	0	0
39	Hoopa	Humboldt	USWB	350	0	0	0	X	0	0	X
40	Hoopa 2SE	Humboldt	USWB	315	0	0	X	X	X	X	0
41	Humboldt State Univ	Humboldt	DWR	?	0	0	0	X	0	0	0
42	Hyampom	Trinity	USWB	1260	0	X	X	X	X	0	X

Table 5. Precipitation Gages used in Data Compilation for Storm Maps (continued)--

Station Number on Location Map	Location	County	Data Compiled By:	Elevation (feet)	1890	1953	1955	1964	1972a	1972b	1975
					Storm Events For Which Data Used						
43	Idlewild Hwy. MS	Del Norte	USWB	1250	-	0	0	X	X	X	X
44	Klamath	Del Norte	USWB	25	-	X	X	0	X	X	X
45	Klamath Glen	Del Norte	DWR	70	-	0	0	X	0	0	0
46	Klamath & Korbel Rd	Humboldt	USGS	850	-	0	0	0	0	0	X
47	Kneeland 10 SSE	Humboldt	USWB	2356	-	0	0	0	X	X	X
48	Kneeland 7 SSE	Humboldt	USWB	2130	-	X	X	0	0	0	0
49	Korbel	Humboldt	USWB	150	-	X	X	X	X	X	X
50	Lake Mtn	Trinity	USWB	?	-	X	X	X	0	0	0
51	Little River Divide(Simpson)	Humboldt	W & K	?	-	0	0	0	0	0	X
52	Long Prairie Rch (Preston Ranch)	Humboldt	DWR	1875	-	X	X	0	0	0	0
53	Lost Man Creek 18.5	Humboldt	USGS	950	-	0	0	0	0	0	X
54	Mad River Fish Hatchery	Humboldt	DWR	?	-	0	0	0	X	X	0
55	Mad River RS	Trinity	USWB	2775	-	X	X	X	X	X	X
56	Minor Creek	Humboldt	USGS	1200	-	0	0	0	0	0	X
57	Miranda-Spengler Ranch	Humboldt	USWB	400	-	X	X	X	0	0	0
58	Mitchell Heights	Humboldt	?	240	-	0	0	X	0	0	0
59	M & G Line Junction	Humboldt	USGS	700	-	0	0	0	0	0	X
60	Orick-Prairie Creek SP	Humboldt	USWB	161	-	X	X	X	X	X	X
61	Orick 3NNE (Davison)	Humboldt	DWR	50	-	0	0	X	0	0	X
62	Orick-Arcata Redwood	Humboldt	DWR	75	-	0	0	X	X	X	X
63	Orick 5SSW	Humboldt	DWR	475	-	X	X	0	0	0	0
64	Orleans	Humboldt	USWB	403	-	X	X	X	X	X	X
65	Patricks Pt SP (Trinidad 5N)	Humboldt	DWR	250	-	0	0	X	X	X	0
66	Panther Creek Crossing	Humboldt	W & K	450	-	0	0	0	0	0	X
67	Petrolia	Humboldt	DWR	175	-	0	0	X	0	0	0
68	Redwood Creek Okane(Blue Lake)	Humboldt	USWB	850	-	0	X	0	0	0	X
69	Ruth Reservoir	Humboldt	DWR	2550	-	0	0	0	X	X	0
70	Salyer RS	Trinity	USWB	623	-	X	X	X	0	0	0
71	Sawyers Bar RS	Siskiyou	USWB	2169	-	X	X	X	X	X	X
72	Scotia	Humboldt	USWB	139	-	X	X	X	X	X	X
73	Somesbar 1W	Humboldt	USWB	520	-	0	X	0	0	0	0
74	South Fork NW Pacific RR Depot	Humboldt	DWR	155	-	0	X	0	0	0	0
75	Sunny Brae (Arcata)	Humboldt	DWR	70	X	0	0	0	X	X	X
76	Upper Little Lost Man Creek	Humboldt	USGS	1525	-	0	0	0	0	0	X
77	Upper Mattole	Humboldt	USWB	255	X	X	X	X	X	X	X
78	Walls-Walla Cr (Ft Jones 8 NW)	Siskiyou	US Dept Army	2570	X	0	0	0	0	0	0
79	Weaverville RS	Trinity	USWB	2050	X	X	X	X	X	X	X
80	Weott 4 W	Humboldt	?	900	-	0	0	X	0	0	0
81	Willow Creek 1 NW	Humboldt	USWB	461	-	0	0	0	X	X	X
82	Zenia 1 SSE	Trinity	DWR	2880	-	0	0	X	0	0	0

Table 6. Stream Gaging Stations of the U.S. Geological Survey used in Data Compilation for Storm Maps

Station Letter on Location Map	Location	USGS Identification Number	Elevation (feet)	Drainage Area (mi^2)	Storm Events For Which Data Were Used					
					1953	1955	1964	1972a	1972b	1975
A	Van Duzen River near Dinsmores	11477500	1997	85.1		X	X	X	X	
B	Van Duzen River near Bridgeville	11478500	358	222	X	X	X		X	X
C	Yager Creek near Carlotta	11479000	200	127				X	X	
D	Jacoby Creek near Freshwater	11480000		6.05		X				
E	Mad River near Arcata	11481000	13	485	X	X				
F	Little River near Trinidad	11481200	18	44.4		X	X	X	X	X
G	Redwood Creek near Blue Lake	11481500	860	67.6		X				X
H	Redwood Creek at Southern Park Boundary	11482200	240	183				X	X	
I	Redwood Creek at Orick	11482500	5	278		X	X	X	X	X
J	Willow Creek near Willow Creek	11529800	586	41.0			X	X	X	
K	Blue Creek near Klamath	11530300	141	120				X	X	X
L	Mill Creek near Crescent City	11532620	190	28.6						X

the time lag between storm rainfall and runoff the dates of the runoff included in a storm period commonly extend beyond the dates of the rainfall period. Even using precipitation and runoff data together to define major storm periods, it was not possible to distinguish clearly the main flood-producing precipitation from the complex stormy periods during December 1964 and March 1975. Although the delineation of these storm events is discussed further in later sections of this report, it should be noted here that most comparisons with the 1964 storm were based on the shorter seven-day period for that event.

Three-day precipitation values for the days preceding, including, and following the flood peak are shown in parentheses at each rainfall station. In the case of storms that produced flood peaks on different days on different streams, the date of the peak at Redwood Creek at Orick was used to define the three-day period for all stations. Unfortunately, daily rain-gage readings are not taken at the same time at all rainfall stations; this variability produces some misleading differences in three-day totals at different stations. However, three-day values do provide a reasonable measure of storm intensity. They comprise almost the entire storm precipitation amount for brief, intense storms, whereas storms with less intense but more prolonged rainfall show proportionately lower three-day totals. The antecedent precipitation index (API) for the 60-day period preceding each storm was determined for Orick-Prairie Creek State Park and for at least one inland station. These API values are shown on the storm maps (figs. 5-12).

At least two contrasting types of regional precipitation patterns are discernible. One pattern, exemplified by the 1953 and January 1972 storms, is associated with storms that pass somewhat to the north of the study area; these storms have maximum rainfall in coastal areas. The second pattern, exemplified by the 1964 and 1975 storms, is associated with storms that pass directly over the study area or slightly to the south of it; these latter storms are characterized by relatively uniform rainfall or by maximum rainfall at higher inland sites.

Storm of January 16-20, 1953

The storm of January, 1953 was a brief, intense one which was concentrated along the coast (fig. 5). Precipitation totals for coastal stations from Eureka north to Crescent City were greater during the 1953 storm than in any succeeding flood-producing events. Lower parts of the Redwood Creek basin may have received more rain during the 1953 period than during any of the more recent storms.

Flooding was probably augmented by high antecedent-moisture conditions (fig. 5). API values for the 1953 storm at Orick and at Big Bar were higher than for any other storm. Snow influence on runoff would have been minimal, as only small amounts of snow fell late in December 1952, and the beginning of the storm period was warm. Inspection of total amounts of storm rainfall (fig. 5) indicates that totals at inland stations in the Klamath and Trinity basins were less during the 1953 storm than during the 1955, 1964, and 1975 storms but greater than during the 1972 storms. Totals at Korbel and Long Prairie

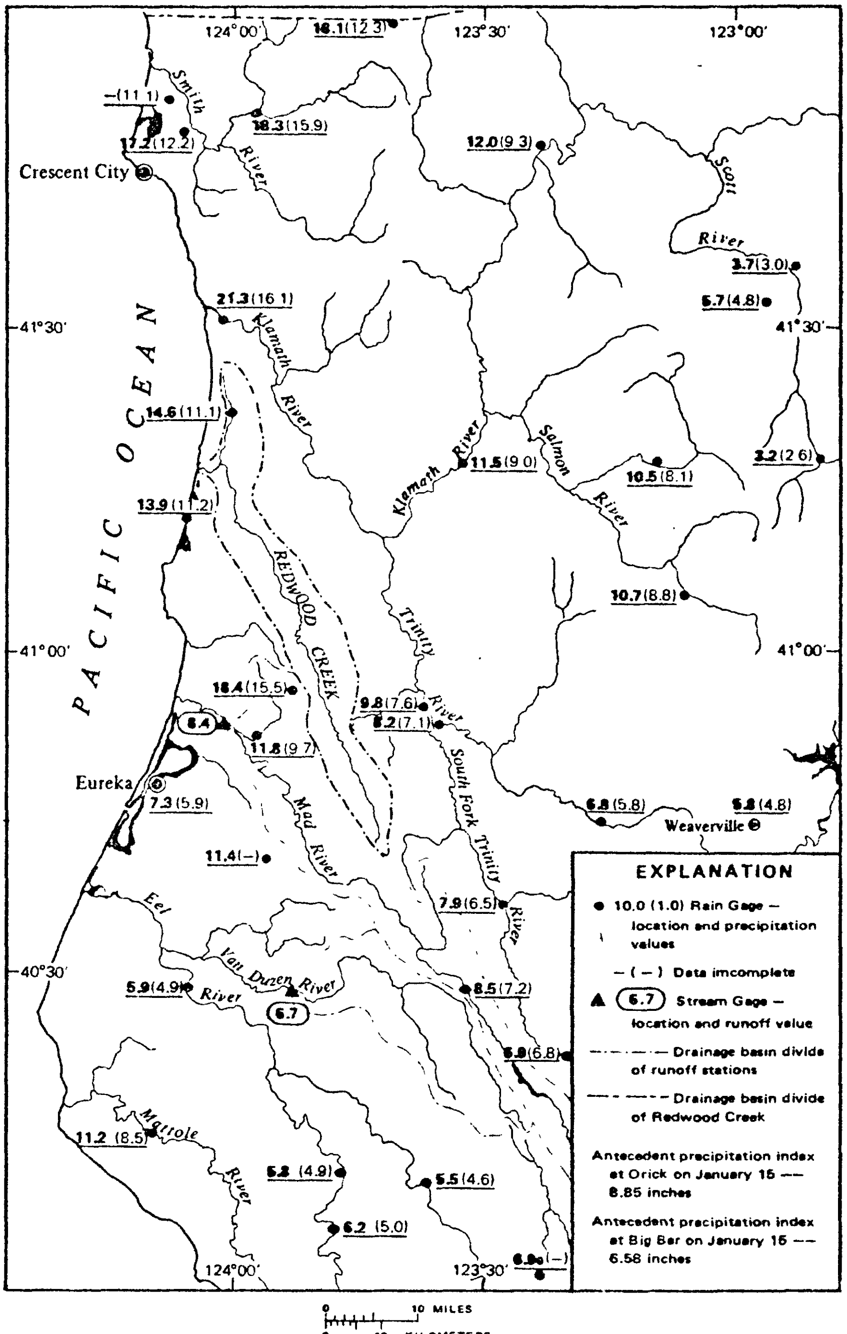

FIGURE 5. Precipitation and runoff, in inches, during the flood-producing storm of January 16-20, 1953 in northwestern California. Numbers outside parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period, January 17-19, 1953.

Ranch, the only operating stations in the vicinity of the inland portions of the Redwood Creek basin, were close to the 1955 and 1964 totals for the same area.

Three-day rainfall totals generally make the 1953 flood-producing storm appear particularly intense relative to the more recent storms. Three-day rainfall totals during the 1953 storm were greater than during the 1955 storm in the coastal area north of Eureka, and they were comparable to 1955 values in the Trinity and Klamath basins. Values for 1953 were also greater than 1964 totals in the area north of Eureka and west of the Trinity and Klamath stations. Three-day totals were generally greater during the 1953 storm than during the 1972 and 1975 storms at all stations; exceptions are noted in the discussions of these later periods.

Total runoff and peak discharges on the Mad River near Arcata and the Van Duzen River at Bridgeville were less during the 1953 storm than in 1955. In addition, the 1953 storm caused less severe flood damage than the 1955 event (Hofmann and Rantz, 1963; Rantz, 1959).

Storm of December 15-23, 1955

The December 1955 flood was considered to be the greatest flood of the century in the region at the time of its occurrence (Hofmann and Rantz, 1963). This storm appears to have been concentrated in the southern and inland parts of the mapped area and to have been more severe than any other recorded storm except that in 1964 (fig. 6). The magnitude of the regional flooding in 1955, relative to that in 1953,

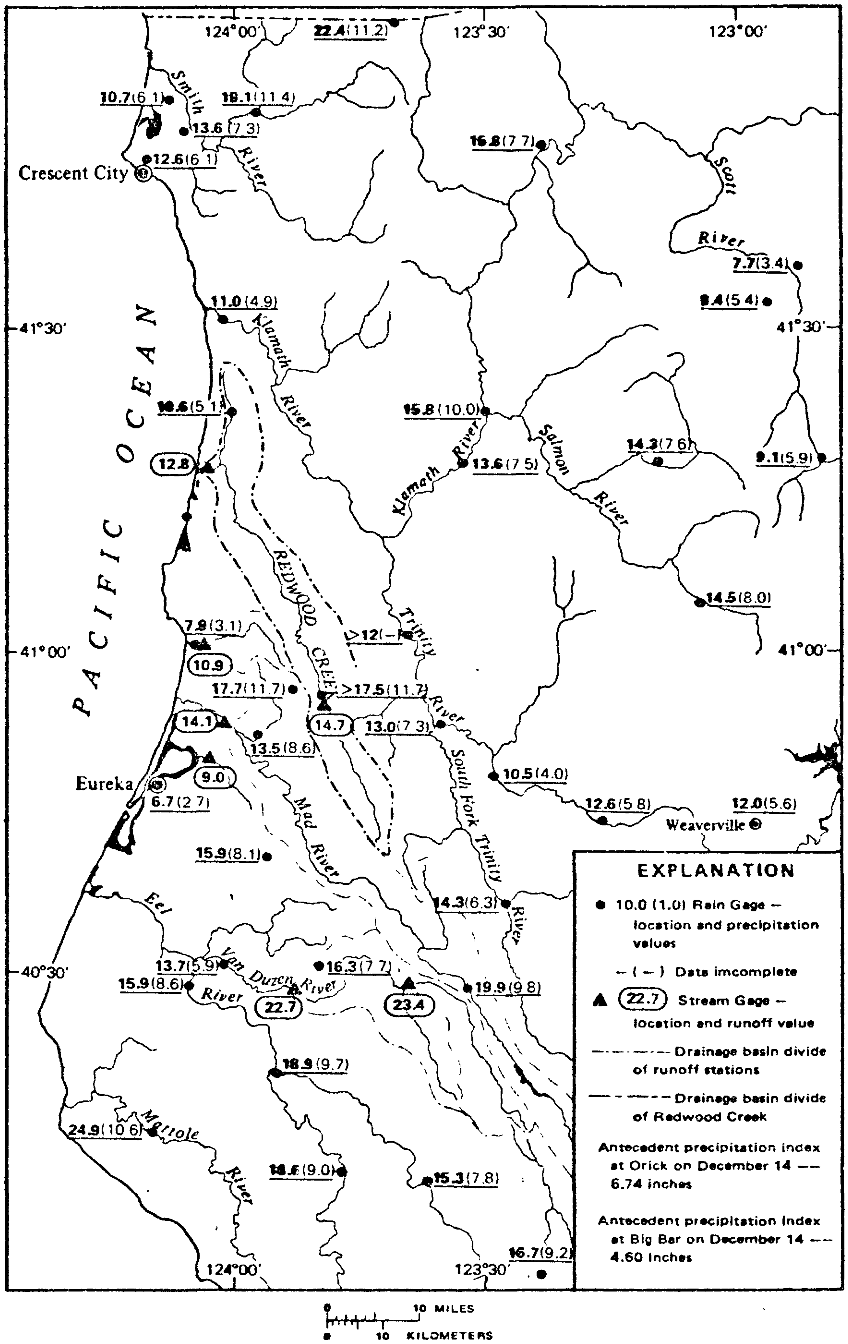

FIGURE 6. Precipitation and runoff, in inches, during the flood-producing storm of December 15-23, 1955 in northwestern California. Numbers outside parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period, December 21-23, 1955.

appears to reflect high total rainfall during a prolonged storm period rather than high three-day rainfall totals or antecedent-moisture conditions. In the Redwood Creek basin the 1955 and 1964 storms may have been comparable in magnitude except in the eastern side of the upper basin, which apparently received more rain in 1964.

The API at Orick was slightly less for the 1955 storm than for 1964; the opposite was true at Big Bar. Snow may have been present at high elevations during the weeks prior to the storm but minimum daily temperatures at the relatively high inland station at Big Bar were well above freezing for six days prior to the event. Southern portions of the map area received more rain than the Crescent City area, indicating that this storm was concentrated south of the 1953 center. Total precipitation amounts for the 1955 flood were comparable to the 1964 storm totals along the coast, but were generally somewhat less at inland areas such as the Klamath, Trinity and Van Duzen River basins. At some sites such as Fort Jones and Weaverville, 1955 total storm-rainfall values were greater than 1964 totals. Inspection of total rainfall at coastal stations and at Korbel indicates that the 1955 storm rainfall in coastal and western portions of the Redwood Creek basin probably was as great as, or greater than, that in the 1964 storm. Rainfall totals at Long Prairie Ranch and Honor Camp which are in close proximity to each other and at the same altitude, as well as at inland stations to the south and east of Redwood Creek, suggest that less rain fell in the southeastern portions of the Redwood Creek basin during the 1955 storm than in 1964.

Three-day rainfall totals in the vicinity of Redwood Creek for the 1955 storm are not particularly impressive relative to those associated with the 1953, 1964, 1972, and 1975 storms. Total storm runoff at the two stations in the Van Duzen basin was greater during the 1955 flood than during the 1964 flood. However, total storm runoff during the 1964 flood was greater than that during the 1955 flood at Little River and at Redwood Creek near Orick.

Storm of December 18-24, 1964

The 1964 flood was the most damaging flood of the century in the North Coast region as a whole, and produced record or near-record stages and discharges at most stream-gaging stations (Rantz, 1965; Waananen and others, 1971). Total storm-precipitation amounts from December 18 to 24, 1964 were greater than those for the comparable 1955 storm period in most inland areas. Additionally, the initial 1964 storm was immediately followed on December 25 by a second one which continued until December 30 and produced an additional 4 to 8 inches of precipitation. In coastal areas the precipitation was in the form of rain. This additional rain fell while hillslopes were saturated and river stages were high, and may therefore have been a significant factor in contributing to the particularly large erosional impact of the 1964 flood. However, the December 25-30 phase of the 1964 storm was associated with a cold air mass, so the bulk of its precipitation at inland sites fell as snow and had little erosional impact. The complexity of the prolonged storm period makes it difficult to define the actual flood-producing storm, and two separate maps have been prepared. Figure 7 depicts the totals for the December 18-24 period, and figure 8 depicts the totals for the longer period of December 18-30. The shorter storm period of December 18-24 was used as a basis of comparison with other storm events because it was responsible for producing the actual flood peak on December 22 and because it compares most closely in duration with other recent storms except the 1975 storm. Precipitation in the Redwood Creek basin from the 1964 storm (December 18-24) was roughly the same as that from the 1955 storm in coastal and southwestern areas, but was somewhat higher in 1964 than in 1955 in southern and southeastern areas of the basin. The center of the 1964 storm appears to have been north and inland of the 1955 center (figs. 6 and 7) and has been shown by Waananen and others (1971) to have extended northward into Oregon and Washington and eastward into Idaho.

API values at Orick were less for the 1964 storm than for the 1953 storm and about the same as for the 1955 storm. The 1964 API value at Big Bar was less than those for 1953 and 1955. Precipitation at the start of the 1964 storm may have fallen partly as snow which melted near the time of the peak and thereby augmented the extremely high peak discharges on some streams (Rantz, 1965). In addition to the rainfall comparisons discussed with the 1955 storm, it should be noted that total storm-rainfall amounts were lower at some Eel and Mattole River stations and in the Eureka area for the 1964 storm than for the 1955 storm, indicating a more northernly center for the 1964 storm. The fact that three-day rainfall totals in 1964 were in almost

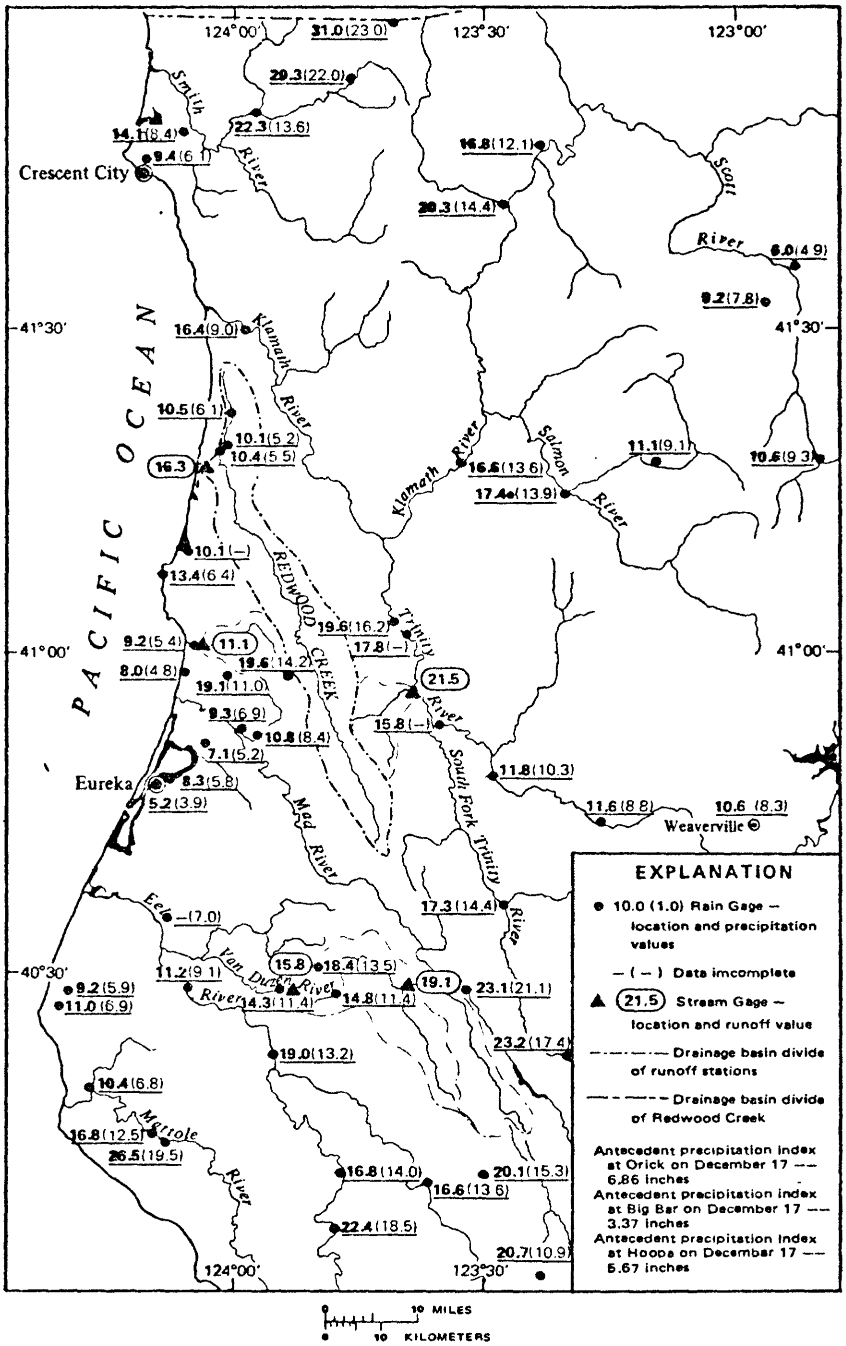

FIGURE 7. Precipitation and runoff, in inches, for the flood-producing storm of December 18-24, 1964 in northwestern California. Numbers outside parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period, December 21-23, 1964.

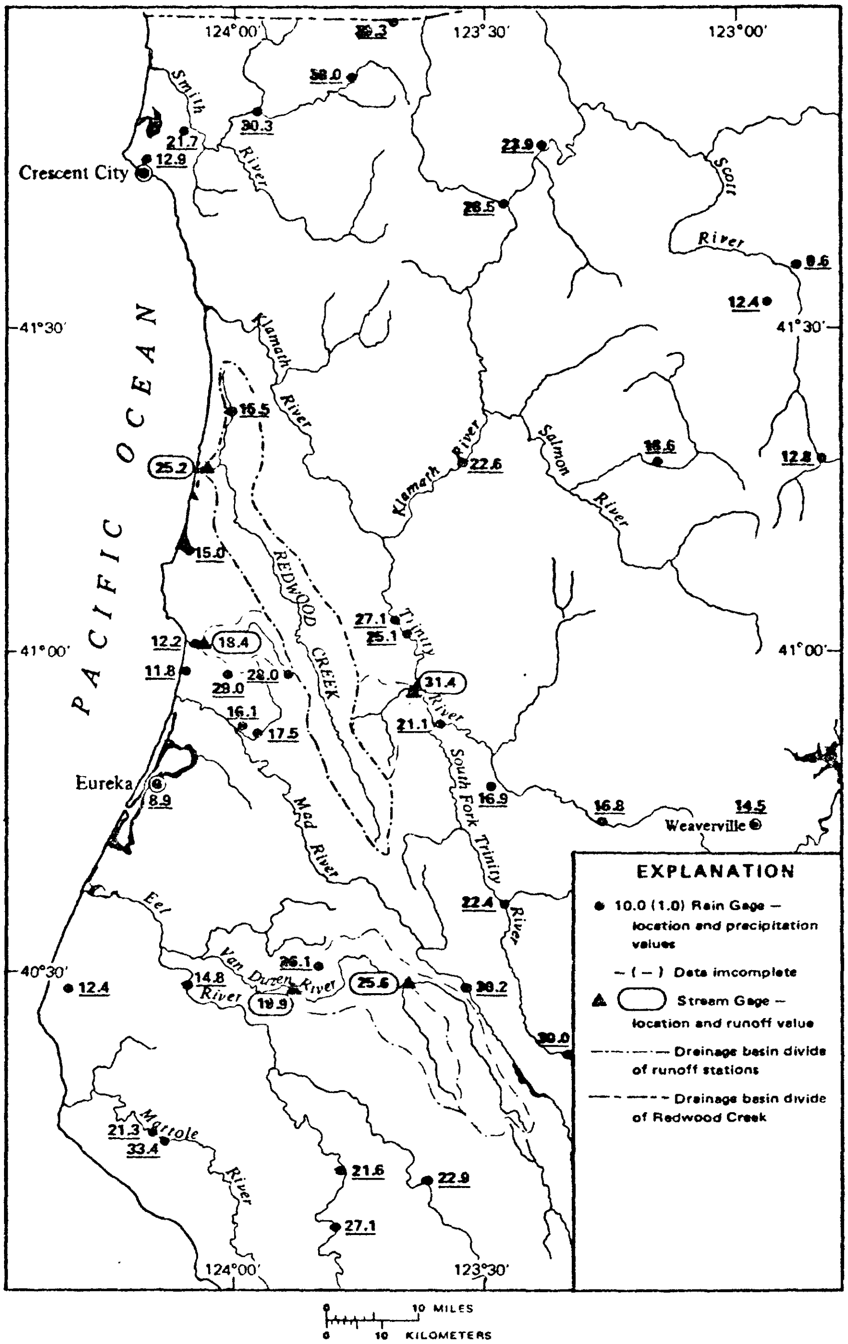

FIGURE 8. Precipitation and runoff, in inches, for the flood-producing storm period of December 18-30, 1964.

all cases greater than those in 1955 indicates that the 1964 storm produced especially intense, as well as prolonged and geographically widespread, precipitation.

Total runoff values were exceptionally high for the 1964 storm. Values up to 21.5 inches were recorded for the period December 18-24, and up to 31.4 inches for the longer period December 18-30. Runoff values, like precipitation values, were highest in northern inland areas.

Storm of January 19-24, 1972

The storm of January 1972, like that of 1953, was most intense in northern and coastal portions of the map area (fig. 9), but it produced less rainfall than the 1953 storm at all stations. The storm was apparently not significant in the Van Duzen, Eel, Mattole, and Upper Mad River basins south of Eureka. Rainfall totals at coastal stations were generally about the same as in 1964, but rainfall and runoff in the lower Redwood Creek basin may have been greater than in 1955 or 1964.

API values at both Orick and Big Bar were lower than those associated with earlier storms. Cold weather preceded the January 1972 storm, but little precipitation fell during this time. Therefore, the potential for snowmelt runoff was limited, but runoff may still have been augmented by large areas of frozen ground. Total rainfall amounts for the January 1972 storm in coastal areas from Klamath to

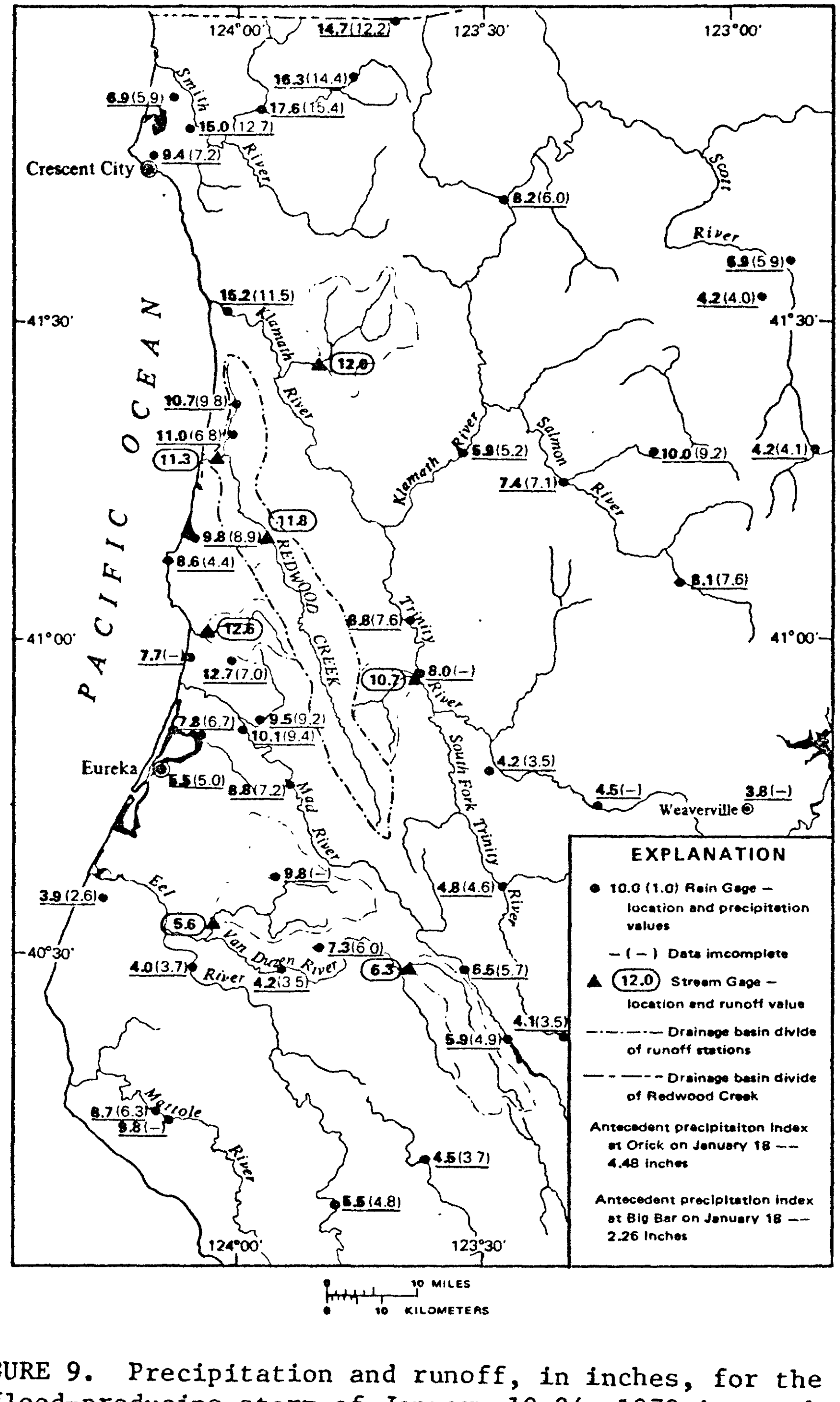

FIGURE 9. Precipitation and runoff, in inches, for the flood-producing storm of January 19-24, 1972 in northwestern California. Numbers outside parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period January 21-23, 1972.

Big Lagoon were comparable to or even greater than the 1955 and 1964 storms, while inland values were somewhat less for January 1972 than for the earlier storms. Three-day rainfall values for the January 1972 storm were generally much greater than for 1955. Compared to the 1964 storm, three-day rainfall totals were higher in the Crescent City, Orick, lower Mad River, and Eureka areas, but less in coastal areas from Patricks Point to Arcata and in southeastern portions of the map area.

The fact that runoff in the Little River basin was greater during the January 1972 storm than during the 1964 storm suggests that rainfall and runoff in the lower Redwood Creek basin, especially in the western tributaries, may have also been greater during January 1972. Runoff at Redwood Creek at Orick and in Willow Creek was less in January 1972 than in 1955 or 1964, reflecting the concentration of the 1972 storm in the coastal portions of the area. However, temperatures at the end of the storm were low and could have caused rapid recessions, thus lessening total runoff volumes.

Storm of March 1-4, 1972

The storm of March 1972 was a brief, intense one which produced a peak discharge on Redwood Creek at Orick that exceeded that of January 1972 (Table 4). Total rainfall amounts for the March 1972 storm were generally less than for the other recent storms (fig. 10). Even though total runoff was probably augmented by snowmelt from

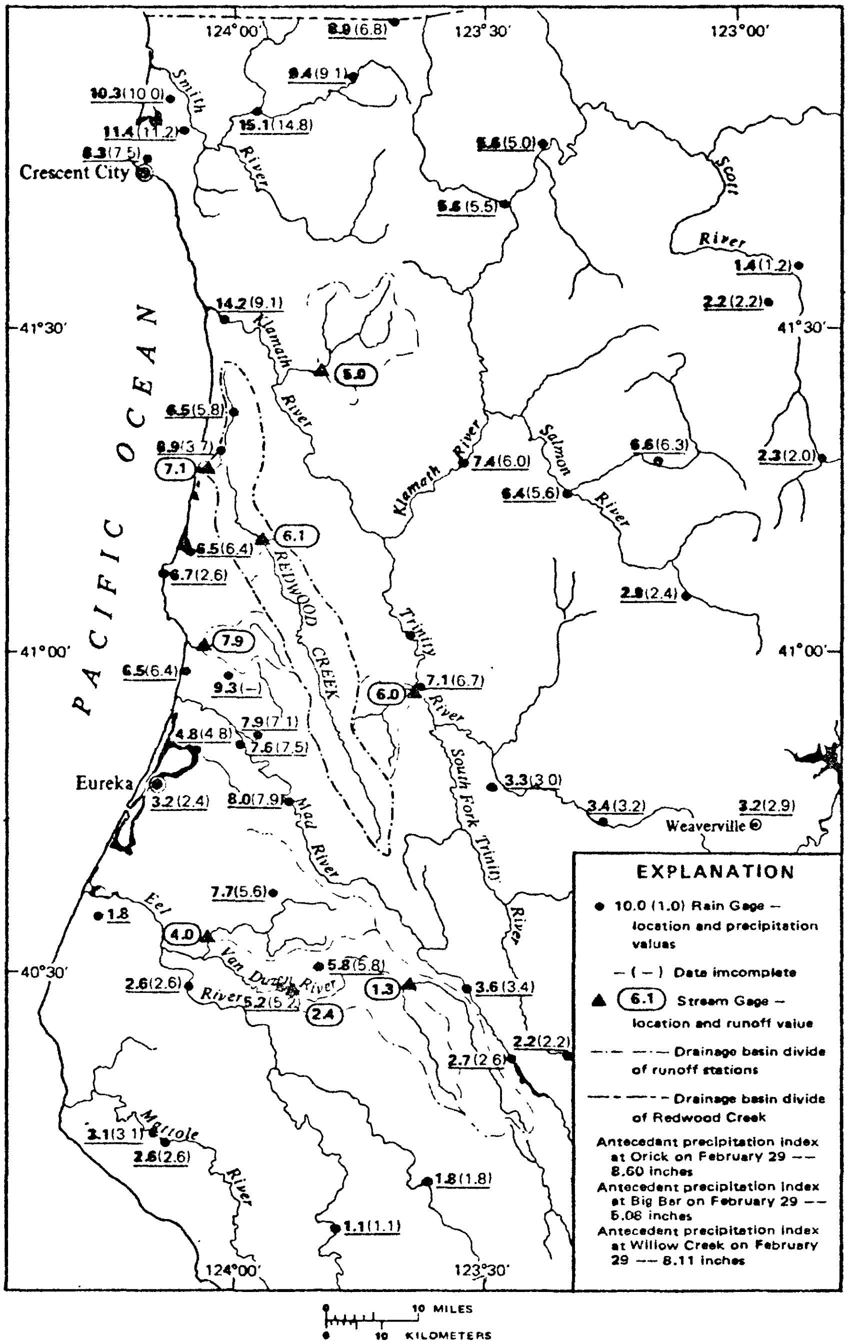

FIGURE 10. Precipitation and runoff, in inches, during the flood-producing storm of March 1-4, 1972 in northwestern California. Numbers outside parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period March 2-4, 1972.

higher elevations and by high API values, it still was generally less than for other recent floods. Much of the rainfall from the March 1972 storm fell in a three-day period and was centered in a relatively narrow area along the coast between Crescent City and Orick and inland to the Trinity river area.

API values at the start of the March 1972 storm were high. The value at Orick was almost as high as that for the 1953 storm. Similarly, the March 1972 API at Big Bar was greater than those for the 1955, 1964, or January 1972 storms. These high values partly reflect the occurrence of the January storm. In addition, the effective antecedent moisture conditions were probably considerably higher than API values indicate because much of the precipitation which occurred at higher altitudes during late January and late February fell as snow. The melting of this snow at the start of the March 1972 storm undoubtedly augmented total storm runoff. Both total rainfall and three-day rainfall amounts were generally less for the March 1972 storm than for all other recent flood-producing storms. Much of the rain fell within a three-day period, so that three-day totals are nearly as great as the storm totals.

The brief, intense flood in March 1972 generally produced less total storm runoff than the January 1972 flood, but the instantaneous peak discharges for the March 1972 flood equaled or exceeded those of the January 1972 storm. The occurrence of two major flood events in one winter probably caused a combined impact which was greater than the impact either storm would have had individually.

Storm of March 15-24, 1975

The storm of March 1975 was complex; it produced a hydrograph with an exceptionally rapid initial rise and fall during March 17-20. This was the most damaging hydrologic event to occur since we initiated intensive geomorphic studies in the Redwood Creek basin. Peak discharge recorded on March 18 on Redwood Creek at Orick was only slightly less than that recorded for the 1964 flood. The initial phase of the storm was followed by a prolonged period of less intense rain starting on March 20 and continuing until March 24. The area of heaviest rainfall from this storm appeared to have centered over the middle portions of the Redwood Creek basin (fig. 11).

The low API values for the March 1975 storm probably diminished its erosional impact. The values at Orick, Big Bar, and Hoopa were lower than for previously discussed storms with the exception of that of January 1972. Snow melt may have augmented runoff from the March 1975 storm since some snow was present at higher elevation prior to the storm. The period of March 15-24, 1975 was selected as the storm period for this event because the initial intense, peak-producing rainfall was followed by less intense rainfall which undoubtedly contributed greatly to recessional runoff. The 1975 storm is similar to the 1964 storm in this manner, and it therefore might be more reasonable to compare three-day 1975 totals with the totals of December 18-24, 1964 and to compare March 15-24, 1975 totals with totals for December 18-31, 1964. Total storm-rainfall amounts were generally less for the 1975 storm than for the 1964 storm, and greater

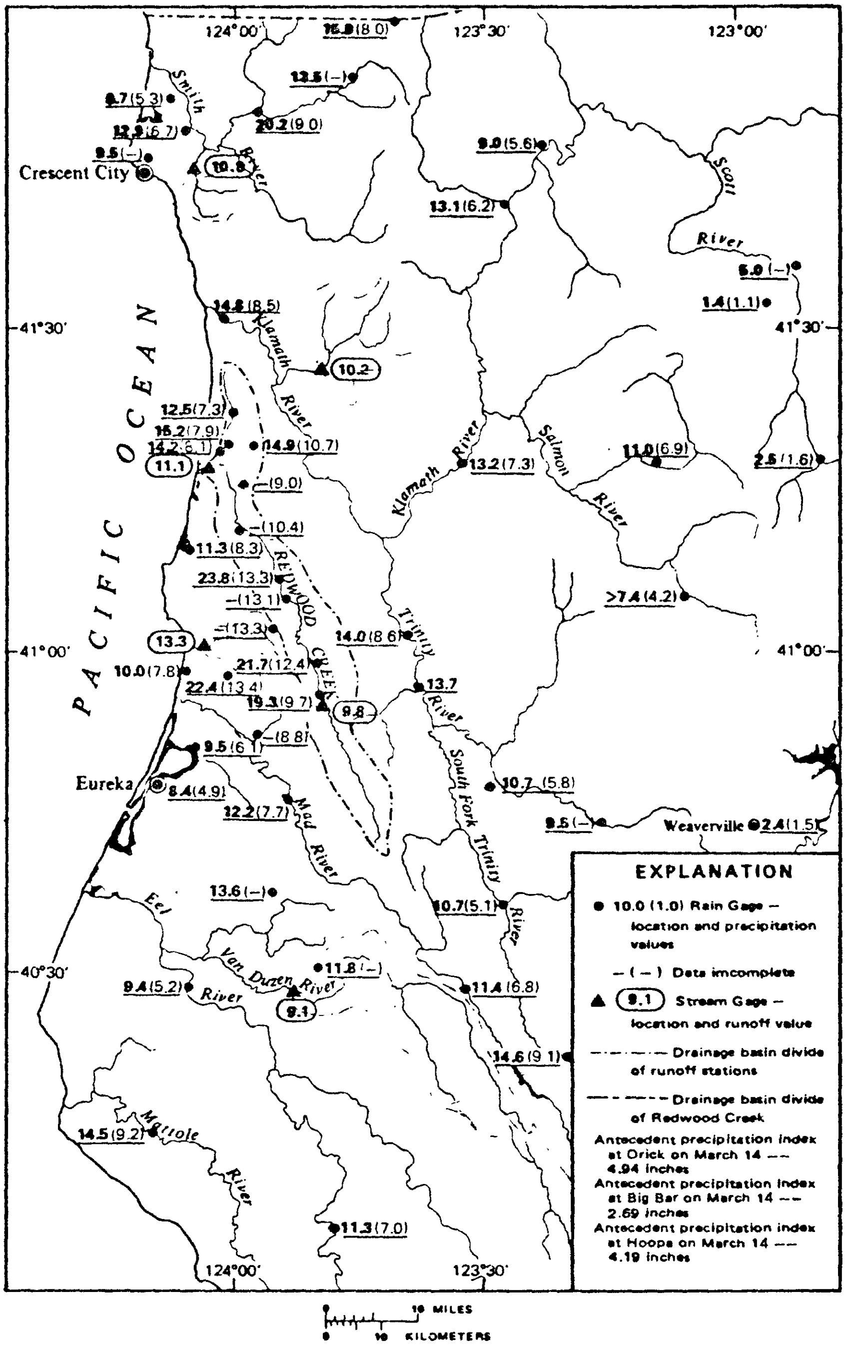

FIGURE 11. Precipitation and runoff, in inches, for the flood-producing storm of March 15-24, 1975 in northwestern California. Numbers outside parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period March 17-19, 1975.

than for the 1972 storms. Except in southern areas, such as the Eel, Mattole, and Van Duzen river basins, rainfall totals for the 1975 storm were similar to those for 1955. The 1975 storm was apparently equally intense along the coast and in the inland valleys and was concentrated in the area from Klamath to Arcata. Rainfall in the middle portions of the Redwood Creek basin appears to have been especially intense; however, the presence of gages at some high elevation sites in the basin since 1973 as a result of the U.S.G.S.-N.P.S. cooperative study probably may account for the observation that some March 1975 storm-rainfall totals appear unusually high relative to those of other storms. That is to say, precipitation at high-elevation sites, which generally receive more precipitation than low-lying coastal or valley stations, was sampled more adequately in 1975 than during earlier storms. Three-day rainfall totals were generally greater in 1975 than in January 1972 at inland stations, and at coastal stations from the Arcata airport to Orick. In contrast, three-day rainfall totals were less than for the January 1972 storm inland of Crescent City, at coastal stations north of Orick, and in the Eureka area.

The greatest runoff in the mapped area during the 1975 flood was from the Little River basin. Runoff from Blue Creek was less than during the January 1972 storm. Runoff from the Van Duzen River was greater than during the January 1972 storm but less than in 1955 and 1964. Runoff at Redwood Creek at Orick was about the same as during January 1972 and was, on a per-unit-area basis, greater than runoff at

Redwood Creek near Blue Lake, adding additional evidence to the conclusion that the 1975 storm was concentrated in the middle and lower portions of the Redwood Creek basin. Runoff values from the lower portions of Redwood Creek and from Little River, coupled with rainfall recorded at recently installed gages in the Redwood Creek basin suggest that the middle and lower portions of the Redwood Creek basin may have received more rainfall during the March 1975 storm than during all but the 1964 and possibly the 1953 storms.

Inconsistent Relation Between Storm Intensity and Erosion

The amount of precipitation during December 18-24, 1964 does not alone account for the extensive regional damage to hillslopes and stream channels caused by the 1964 flood. Neither can changes in land use alone account for the extensive erosion during the 1964 flood because severe erosion occurred in some densely forested areas such as the headwaters of the Middle Fork of the Eel River (J. C. Fraser, written commun., 1975), the upper Van Duzen River (Kelsey, 1977), and Coffee Creek (Stewart and LaMarche, 1967), as well as in areas of recent road construction and timber harvest. Several factors acting in combination with one another may have contributed to the disproportionately large impact of this flood in the Redwood Creek basin relative to the other floods of the past 25 years. Perhaps specific factors and combinations of factors contributing to erosion differed significantly in relative importance from place to place.

A second storm immediately following the peak 1964 flood discharges sustained near-bank-full stages in many coastal streams. However, even if this late December 1964 precipitation is added to the December 18-24 totals, the precipitation values are still comparable to 1955 totals at some stations. Moreover, in the intensively damaged, densely forested areas discussed above the second phase of the 1964 storm occurred as snow.

Some weakening or small-scale destabilization of hillslopes and stream channels may have occurred during the 1953 and especially the 1955 storms. However, destabilization by early floods alone cannot account for the disproportionately large erosional impact of the 1964 flood in the upper Redwood Creek basin because the rainfall patterns of the 1953 and 1955 storms suggest that hillslopes in the lower basin would presumably have received at least as much preconditioning by earlier storms as the upper basin. Moreover, if preconditioning was a major factor, the succeeding 1972 and 1975 storms should have been even more damaging than the 1964 storm, especially in the lower basin.

Differences in storm distribution and intensity can account for some differences in erosional impacts of floods. For example, rainfall amounts during the 1964 storm do appear to have been greater in the upper basin than in the lower basin, but the distribution and severity of flood damage in the Redwood Creek basin in 1964 can be more fully understood by also recognizing (1) that differences in physiography and native vegetation make streamside areas in the upper basin more inherently unstable than streamside areas in the lower basin (Janda and others, 1975), and (2) that major road construction and timber harvest were carried out in the upper basin between 1955 and 1964 (Janda and others, 1975; later parts of this report). Similarly, part of the explanation for the contrasting erosional impacts of the 1953 and 1972 storms in coastal areas seems to be changes in land use. Interpretation of aerial photographs and interviews with representatives of the local forest-products industry suggest that the January 1972 storm severely damaged Blue Creek near Klamath and several downstream tributaries of Redwood Creek, whereas the 1953 storm caused relatively little erosion. The contrasting amounts of erosional damage seems anomalous in light of the precipitation patterns associated with these two storms. Inspection of aerial photographs indicates that many of the erosional features initiated by the January 1972 storm are directly associated with roads and recently clearcut, tractor-yarded timber-harvest units. The patterns of erosion within the Redwood Creek basin discussed above are supported by analyses of streamside landslide history and distribution from aerial-photograph interpretations in a later section of this report.

Floods of the Late 19th Century

The series of flood-producing storms which occurred in the North Coast region since 1950 was preceded by more than 60 years during which only moderate or localized storm events occurred. Storms with widely distributed, heavy precipitation occurred in 1907, 1915, 1927, and 1937 (McGlashan and Briggs, 1939; Paulsen, 1953). Peak discharges associated with these storms, however, were generally much lower than those associated with the more recent major events of the 20th century or with some late 19th century floods, particularly those of 1861 and 1890. Many of the land-use patterns of the North Coast region developed during this long, relatively flood-free interval.

During the second half of the 19th century a series of major regional storms occurred in northwestern California. In an attempt to compare these storms and the magnitudes of the resulting floods with their more recent counterparts, a search was made of newspapers from northwestern California and other published information about the floods of this period. The storms of the 19th century with the widest rainfall distribution occurred in December 1861-January 1862 and in February 1890. Other major storms which produced floods in many North Coast basins occurred in 1852, 1879, 1881, and 1888 (McGlashan and Briggs, 1939). Information about the 1861 and earlier events is scanty and mainly of a qualitative nature. However, at the time of the 1890 flood, daily precipitation records were kept at several locations in northwestern California. Information gained about the two most widespread floods and brief descriptions of the intervening events are presented below.

Major sources of published information were Brewer (1930), and McGlashan and Briggs (1939). Issues of the Arcata Union (1890), Humbodt Weekly Times (1861-62), Humboldt Times (1890) and Weaverville Trinity Journal (1861-62, 1890) were available for viewing on microfilm at the Bancroft Library of the University of California, Berkeley.

Microfilm copies of daily rainfall and temperature records were available at the documents section of the State Library in Sacramento under the title "Climatological Records for California 1851-1892". Unfortunately, the original collection of records, which was kept at the U.S. Weather Bureau in San Francisco, was badly damaged by smoke and water during the 1906 fire, and records from many stations at which daily data had been collected were destroyed.

Storms of 1861-1862

The only locality in northwestern California for which daily precipitation values for the 1861-1862 storm periods are available is Fort Gaston, a former military post in the Hoopa Valley a few miles from the present U.S. Weather Service rain gage at Hoopa. Both precipitation and temperature records were kept by Army Medical Service personnel under the direction of the Surgeon General. Our interpretation of this data[1/] indicates that the three-month period from November 1861 through January 1862 was by far the wettest ever recorded for much of northern California. Four distinct flood peaks occurred in this interval, three of them in close succession. Between November 24 and 27, about 15 inches of rain fell at Fort Gaston, and the observer noted "high water" on November 27. The second period, from November 29 until December 2, produced almost 23 inches of rain; the resulting flood was "52 feet from low water" near Fort Gaston and

1/ [see p. 61]

1/ Rainfall amounts at Fort Gaston for November 1861-January 1862 were apparently listed in the form of Roman numerals representing whole inches of precipitation, followed by a decimal representation of the fractions of an inch. Amounts less than an inch were listed in decimal form. It appears that an individual other than the observer and recorder of the data compiled the monthly totals, perhaps at a substantially later date and perhaps at a different location. The published monthly totals counted only the decimal fractions for rainfall amounts so that monthly totals for this period are unreasonably low considering that several major floods occurred during the period. For instance, it seems highly unlikely that 0.90 inches of rain would cause a 52-foot rise in the river, as is noted by the observer in one instance. We assumed that the Roman numerals represented whole inches of rain for several reasons, even though this assumption results in higher rainfall totals than for any other flood period. First, in the Army Meteorological Register of the Surgeon General's Office (1855) description of the standardized procedures for rainfall measurements, it is stated that rainfall amounts are measured and recorded "in inches, or their decimals". Furthermore, it is unlikely that any denomination for units of rainfall other than inches would have been used at this date. Second, rainfall for Fort Jones, Sacramento, San Francisco, and Sonora was extremely high for this period. Ratios comparing December 1861-January 1862 values at each of these stations with values at Fort Gaston were not much different than ratios obtained by comparing mean yearly precipitation values obtained from Rantz's (1969) mean annual precipitation maps. Precipitation values for other stations are given in Brewer (1930) and in the U.S. Weather Bureau Monthly Climatological Data by sections. Third, ratios of the November 1861-January 1862 period compared to the mean annual rainfall amounts (Rantz, 1969) at each station were comparable for all of the stations except Sonora, where the 1861-62 period was 3.4 times the normal seasonal rainfall. Ratios at the other four stations ranged from about 1.6 to about 2.1. Fourth, monthly precipitation values greater than 20 inches were not uncommon at Hoopa-Fort Gaston in the 1861 to 1890 and 1952 to 1975 intervals, and values greater than 30 inches have occurred in March 1866 and December 1964.

at the time was cited as the "greatest flood since the white men came" (Trinity Journal, December 7). Less than a week later, between December 5 and December 8, another 15 inches of rain fell at Fort Gaston, causing more high water and the "greatest flood known even by Indians for 50 years" (Trinity Journal, December 14). This third peak occurred on December 9, 1861.

Issues of the Trinity Journal for December 14, 21, and 28, 1861 described extensive damage caused by the flood of December 9 and listed several high-water stages. Most bridges on the Trinity River were washed out. The flood waters were 70 feet above low water level at Weaverville and Burnt Ranch; at Weitchpec, the confluence of the Trinity and Klamath Rivers, the water level was reportedly raised 140 feet.

The Humboldt Weekly Times described the extent of the December floods in coastal basins, including that of Redwood Creek. The Mad River apparently reached flood stage three times during late November and early December. The first flood peak, which occurred on November 27, was reported as being 18 inches higher than any previous event. The second peak, on December 2, exceeded the first and was reported to be five feet above previous flood stages at one point along the lower river. The December 7 peak was reported as being slightly lower than the second peak, and residents along the river reported that little additional flood damage resulted because everything had already been washed away from susceptible low-lying areas during the December 2 flood.

The December 1861 floods on the Eel River were apparently less severe than in other areas and less severe than the January 1862 flood on that stream. Although the precise locations and reference altitudes for these stages are not known, they are substantially higher than any of those recorded for the 20th-century floods at nearby sites. However, the December 2 storm washed out bridges between Eureka and the Eel River, and the Van Duzen River was observed at higher stages than ever before. The Humboldt Weekly Times also reported severe damage in the Mattole area. The December 1861 flood on the Smith River apparently destroyed many farms, and the beach in Crescent City was strewn with miles of flood debris, including mining equipment, from the Klamath River (Brewer, 1930). The Klamath reservation, presumably at the mouth of the Klamath River, was reportedly destroyed. On December 10, 1861 the Sacramento River at Shasta was 10 feet higher than ever known (Humboldt Times).

Reports of flood extent and damage on Redwood Creek during the December 1861 flood were given in the Humboldt Weekly Times of December 21. "The freshet on Redwood Creek was quite severe and destructive of property". The water was reported as being much higher than any previous evidence of floods. The report also describes farm buildings carried away, fencing lost, and houses filled with water. We assume that the areas described were in the vicinity of Redwood Valley, as this area was settled at the time and was also on the traveled route to the Hoopa area.

Following the December 7-10, 1861 floods, the rivers apparently rose again around the 22nd of December. Later storms in January 1862 in the San Francisco and Sacramento areas produced far more rain than did the December storms. The resulting floods reportedly destroyed over a quarter of all the taxable property of the State, and the Sacramento and San Joaquin rivers flooded 5000-6000 square miles (Brewer, 1930). The January storms produced the highest flood peak on January 10, at which time the flood waters on the upper Sacramento River were 20 inches above those of December 9 (Humboldt Weekly Times). The lower Eel River was reportedly 18 inches higher than in December.

The Humboldt Weekly Times gave little mention to the floods in the North Coast during January 1862 except in the Eel River. No mention was made of new flooding on the Trinity River in January 1862. However, rainfall for January 8-11, 1862 at Fort Gaston was 11.70 inches and the Trinity River near Fort Gaston was reported as being "45 feet above low water". Therefore, although the January floods were probably less severe than those during December in the vicinity of Redwood Creek, some additional flooding probably did occur at that time.

Although the 1861-62 storms and resulting floods were apparently among the greatest in the history of the North Coast, no mention is made of landslides in the newspaper accounts of the floods. The toll road between Redding and Weaverville was impassable for several weeks, but all the reports of damage are of bridges washed out. However, it is possible that landslides did occur but were not mentioned in the newspapers. Evidence of old slide scars discernible on 1936 and 1947 aerial photographs suggests that some of these slides were probably active during the 1861-62 storms, but that massive streamside landsliding was not nearly as extensive as following the 1964 flood. Yreka Creek reportedly widened its channel from less than 20 feet to 100 to 300 feet as a result of the flood, but no other mention of flood-caused channel widening was found in newspaper accounts. Massive gravel deposition occurred locally along some streams (Helley and LaMarche, 1973), but no evidence of regional stream-channel aggradation, such as accompanied the 1964 flood, has been found.

Storms of 1867, 1879, 1881, and 1888

Significant floods in the interval between the 1861-62 and 1890 events occurred in 1867, 1879, 1881, and 1888. A flood along Redwood Creek in January 1867 destroyed a bridge near the Tall Trees Grove; the bridge deck was reported to have been constructed 10 feet higher than the flood peak of 1861-62 (Eureka Times-Standard, January 29, 1976). The March 1879 storm caused floods reported to be almost as high as earlier known events on the lower Eel River. The upper Eel basin, the Van Duzen River, and the Mad River also experienced major floods (McGlashan and Briggs, 1939). Floods were not reported on the Klamath River in 1879.

Floods during January 12-15, 1881 were apparently widespread throughout northwestern California. The lower Eel, Van Duzen and Mad Rivers were reportedly higher than 1879. The Klamath River also experienced heavy rains and flooding during this period and again in early February. In February, the lower Klamath and Trinity Rivers were reported to be at their highest stages since 1861. The 1881 flood stage was the highest ever recorded on the upper Sacramento River at Red Bluff. The Smith River was also exceptionally high in February 1881.

The January-February 1888 storm and resulting flood were apparently concentrated in the Mattole and lower Eel basins. At Upper Mattole, over 31 inches of rain fell between January 27 and January 31, 1888 (Humboldt Times).

Storm of 1890

The final major flood-producing storm of the late 19th century in northwestern California occurred in early February, 1890. Rainfall totals for January 31-February 4, 1890 are shown in figure 12. Values for Arcata and Weaverville were obtained from the Arcata Union and Trinity Journal, respectively. The remaining data were obtained from "Climatological records for California, 1851-1892". Additional information concerning the storm and flood was obtained from newspaper accounts.

Prior to the February floods, the winter of 1889-1890 was characterized by unusually heavy snowfall. According to newspaper accounts, January snowfall was the heaviest since European settlement of the area. The high areas between Kneeland and Yager Creek were

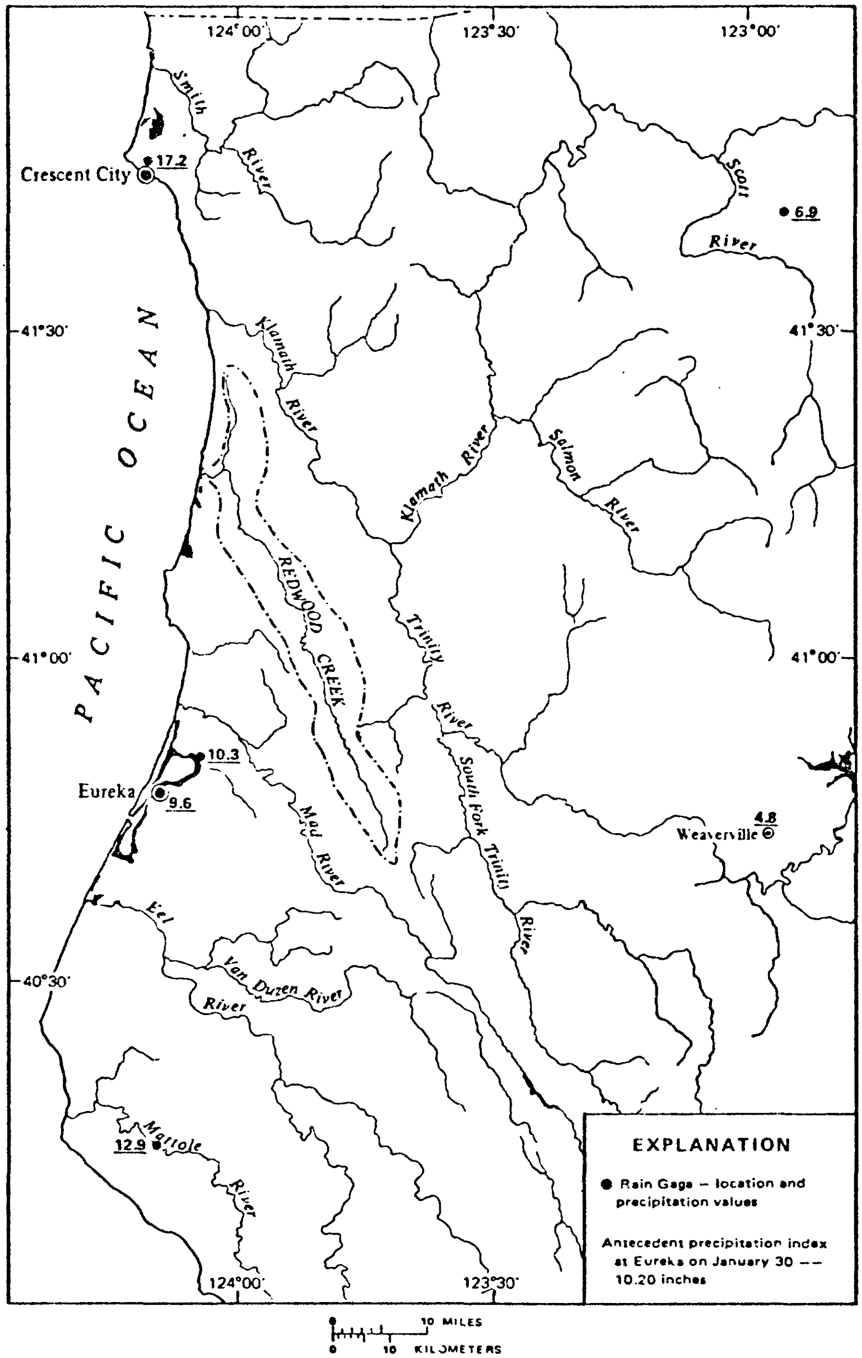

FIGURE 12. *Precipitation, in inches, for the flood-producing storm of January 31-February 4, 1890 in northwestern California.*

covered with 4 to 6 feet of snow before the flood. The trail from Arcata to Hoopa, which traversed the Redwood Creek basin near Minor Creek, was passable only with snowshoes in late January. On the Hyampom trail from the main Trinity River and at Hyampom, 8 and 2 feet of snow were on the ground, respectively. The New River area, in the vicinity of Burnt Ranch, reported 19 feet of snow at the beginning of February.

At the start of the 1890 floods, warm rains melted the snow at lower elevations in the Mad River basin. Newspaper accounts and the marked rise in temperature at Eureka at the end of January suggest that significant snowmelt probably occurred early in the storm throughout the region. In fact, snowmelt from high areas was cited as the cause of the 1890 flood stage on the Mattole being equal to that of 1881, because the 1881 storm produced far more rain than did the 1890 storm. It therefore seems likely that the 1890 flood peaks were augmented by snowmelt from at least some of the high areas.

Precipitation totals for the 1890 storm were greater than for any of the 1953 and more recent flood-producing storms at Crescent City, Eureka, and probably at Arcata. At Upper Mattole and Weaverville, rainfall totals were much less than the 1955 and 1964 totals; at Fort Jones, the 1890 rainfall totals were also slightly less than the 1955 totals. Thus, the southern portion of the North Coast region and the Upper Trinity River area were apparently much less affected by the 1890 storm than were northern and coastal areas. Since no data were collected in the immediate vicinity of Redwood Creek or in the lower Trinity or upper Mad Rivers, it is necessary to rely on newspaper accounts to try to determine the effect of the storm in the Redwood Creek basin.

According to the Trinity Journal and the Humboldt Times, the 1890 storm produced the greatest flood damage since 1861-62 in much of Oregon, notably at Ashland, Eugene, Portland, Roseburg, and Salem. The 1890 storm also produced floods on the upper Sacramento River, but stages were lower than in 1881. At Weaverville, the flood caused much damage and almost isolated the town. On the Trinity River below Weaverville and on the South Fork, the 1890 flood washed out almost all of the bridges and caused river stages almost as high as in 1861; however, stages on the South Fork of the Trinity River were apparently not as high as in 1881. A landslide across the Trinity River about 50 miles downstream of Weaverville dammed the river for 7 hours. Several other large landslides destroyed mining ditch lines and roads along the Trinity River. All homes and flumes at Fort Gaston were also washed away.

The Mad River was apparently higher during the 1890 flood than during the 1861-62 floods. On the Eel River, flood stages in 1890 were above those during 1888 except in the lowermost reaches, and at Blocksburg, streams were reported to be higher than previously observed on February 5. The Van Duzen River and Yager Creek were reported to be higher than "in years" on February 3, 1890. The Mattole River at Upper Mattole was as high as it had been in 1888 on February 2. Numerous landslides were reported along railroads and highways on the lower Eel River and the Mattole River.

North of the Mad River, reports of the 1890 flood are scanty. A road between Trinidad and Little River was washed away by the flood. Redwood Creek near the mouth was flowing over its banks during the flood, and the mail carrier reported a house being washed away. Water two feet deep was also reported in a dairy barn in lower Redwood Creek. No report was found of the Redwood Valley reaches of Redwood Creek.

At Crescent City the beach was littered with flood drift from the Klamath River comparable in extent to that of 1861-62. The debris included mining equipment and sawed logs. The sawed logs probably originated from Orleans or from sawmills at Forks of Salmon and Sawyers Bar, both of which were washed away during the flood.

In summary, the February 1890 flood probably had several things in common with the 1964 flood in the North Coast. First, at least two major floods occurred during the 12 years preceding both events. Second, flood peaks from both storms were probably augmented by snowmelt. Third, both storms were apparently less severe in the area south of Eureka than in northern areas. Finally, landslides that were initiated or enlarged during both storms had adverse consequences for the affairs of humans.

Rainfall data suggest that coastal parts of the Redwood Creek basin probably received more rain in 1890 than in 1964. It also seems possible that inland portions of Redwood Creek received at least as much rainfall in 1890 as in 1964, in view of newspaper descriptions of the Mad River and lower Trinity areas in 1890. It therefore seems reasonable to expect that the two storms should have had comparable geomorphic impacts on the basin as a whole, if other factors controlling erosional stability remained constant during the intervening period.

Comparison of Erosional Impacts of the 19th and 20th Century Floods

The late-19th-century floods, as well as their recent counterparts, apparently triggered landsliding throughout northwestern California. More widespread landsliding was reported for the 1890 storm than for any earlier storm. Most newspaper accounts of landslides which failed during the 1890 storm referred to slides connected with roads, railroads, or mine ditches. This may reflect the fact that only those slides that disrupted human affairs and were accessible to established settlements, roads, and mines were considered newsworthy. On the other hand, it may indicate that a large proportion of the slides which occurred in 1890 was related to human activity.

Additional evidence for streamside landsliding during the late-19th-century floods in the Redwood Creek basin and the North Coast region is provided by landslide-shaped, streamside stands of young vegetation that can be observed most effectively on aerial photographs taken prior to the floods and massive land-use changes that occurred starting in the 1950's. These young stands are interpreted as revegetated landslide scars and they occur to a limited extent along all major North Coast streams.

Large landslide scars initiated by the 1890 flood would bear vegetation not more than 57 years old in 1947. Even scars initiated by the 1861-1862 floods would bear vegetation not more than 85 years old in 1947. In fact, vegetation on such scars could have been substantially younger because landslide surfaces appear to become revegetated slowly. Numerous large scars initiated by the 1964 flood remained virtually unvegetated in 1976. In any case, arboreal vegetation of the age class populating the late-19th-century scars in 1947 can clearly be distinguished from old-growth forest on aerial photographs. However, only a limited number of unvegetated and recently vegetated streamside landslide scars can be identified on 1936 and 1947 aerial photographs relative to the number of slides that were initiated by the more recent floods, particularly that of 1964 (Nolan, Harden, and Colman, 1976).

Coring of trees on two apparently revegetated landslide scars along Redwood Creek near the southern boundary of Redwood National Park revealed that nearly all of the trees were apparently established after the 1862 water year (S. Veirs, Jr., written commun., 1977). One of these slides showed evidence of repeated movement with final stabilization and revegetation not occurring until after 1890.

Evidence of aggradation during the 19-century floods is also visible in parts of the Redwood Creek basin. 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 with evidence of major aggradation during the late 19th century include Blue Creek (Helley and LaMarche, 1967) and Bald Mountain Creek (Kelsey, 1977). Evidence also exists for older major episodes of aggradation

(Helley and LaMarche, 1967; Kelsey, 1977). Kelsey (1977) suggests that such events were probably the result of streamside debris slides and debris torrents. However, evidence for pre-1964 aggradation appears localized and inconsistent from valley to valley.

Evidence of landsliding and aggradation resulting from the late-19th-century floods in the Redwood Creek basin and surrounding region is much less extensive than evidence of the geomorphic impact of the 1964 flood. Undoubtedly, some evidence of the geomorphic effects of the 19th-century storms has been obscured and destroyed by subsequent events. However, the generally large size and great age of riparian trees outside of active landslides argues that channel aggradation and streamside landsliding were not as extensive following the 19th century storms as following the 1964 storm. For example, along the upper reaches of the Redwood Creek channel, riparian trees buried and killed by the 1964 flood appeared during field inspection to be 200-300 years old at the time of their death. Many of these trees were logged in salvage operations immediately following the flood, enabling annual rings to be counted on stumps. Similarly, many streamside redwoods that have been toppled by recent bank erosion or buried by recent gravel deposition along parkland reaches of Redwood Creek are more than 6 feet in diameter and probably more than 150 years old.

The flood-producing storms of the late 19th century were probably comparable to those from 1953 to 1975 in amounts of rainfall and in the occurrence of a succession of events which could have pre-conditioned unstable hillslopes and stream channels to augment the impacts of floods late in each series. In fact, considering the apparently unprecedented magnitude of the 1861-1862 floods, the recurrence of major flooding in 1867, 1879, 1881, and 1888, and the intense precipitation along the coast during the 1890 storm, it appears that the late-19th-century series of floods had the potential to have been at least as damaging as the more recent floods. The fact that the 19th-century floods had a dramatically smaller erosional impact in the Redwood Creek basin than did the floods of the past 25 years is logically attributable to changes in runoff regimes, hillslope stability, and stream-sediment loads caused by human activities, primarily road construction and timber harvest, in the second half of this century. No other major changes in drainage basin conditions have occurred.

RECENT HISTORY OF LANDSLIDING ALONG THE CHANNEL OF REDWOOD CREEK

The 1964 flood is often cited as a cause of widespread landsliding along northern California rivers (Kelsey, 1977; Dwyer and others, 1971). This streamside landsliding is commonly ascribed to removal of support from the bases of unstable hillslopes by lateral erosion during major floods. Colman (1973) suggested that the combined impact of timber harvest and floods may have been greater than the 1964 flood impact alone. In order to evaluate the applicability of these hypotheses to the Redwood Creek basin and in order to add information present on 1962, 1974, 1975, and 1976 aerial photographs to Colman's analysis (1973) of recent landslide history along Redwood Creek, we updated and revised his Appendix II. Because Colman identified streamside slides in the field in 1973 and then examined their history on the photographs, many slides which were active at an earlier time but not readily discernible in 1973 were not included on his 1973 strip map. In addition, many slides seem to have undergone periods of stabilization and reactivation. Many small features not included in Colman's table and strip map were identified during re-examination of the photographs. Differences in interpretation have also caused some discrepancies between Colman's figure 25 and figure 13 of this report. Table 7 shows the scale, area of coverage, and ownership of the aerial photographs which were used in this analysis. In discussing the recent history of streamside sliding frequent reference is made to events that occurred during the 1962-1966 interval because that interval included the exceptionally damaging 1964 flood.

Landslides were recognized on the photographs by the hummocky topography characteristic of disrupted ground, lateral and (or) crown scarps marking boundaries of landslides, bowl-shaped depressions surrounded by headwall scarps, and bulbous, gently sloping topography at the toes of slopes. In many areas, disrupted or absent vegetation or failures of roads or log-loading decks aided recognition of unstable areas. Because of dense forest cover in much of the basin, recognition of slowly moving features that do not disrupt vegetation on a large scale is often difficult. However, tilted trees and uniformly-aged stands of young trees are useful indicators of recent mass movement.

TABLE 7. *Available aerial photograph coverage of the main channel of Redwood Creek.*

Date	Scale	Area of Main Channel Covered	Ownership
1936	1:30,000	Prairie Creek to Lupton Creek	T. Hatzimanolis, Redwood National Park
1947	1:45,000	About 1/2-mile below Copper Creek to Roddiscroft Road	U.S. Geological Survey, Topographic Division
1958	1:12,000	Prairie Creek to Roddiscroft Road	Humboldt County
1962	1:12,000	Prairie Creek to Roddiscroft Road	Humboldt County
1966	1:12,000	Prairie Creek to Roddiscroft Road	Humboldt County
1970-71	1:12,000	Prairie Creek to Roddiscroft Road	Humboldt County
1972	1:36,000	Prairie Creek to Roddiscroft Road	National Park Service
1973	1:10,000	Prairie Creek to 1/2-mile below Snow Camp Creek	U.S. Geological Survey, Water Resources Div.
1974	1:10,000	Prairie Creek to Roddiscroft Road	U.S. Geological Survey, Water Resources Div.
1974	1:12,000	Prairie Creek to Roddiscroft Road	Humboldt County
1975	1:10,000	Prairie Creek to about 1 mile above Pardee Creek	National Park Service
1976	1:10,000	Prairie Creek to Roddiscroft Road	National Park Service

The history of active landslides adjacent to Redwood Creek that are large enough to be seen by stereoscopic observation of 1:12,000-scale vertical aerial photographs is presented in figure 13. The estimated smallest size of consistently discernible landslides is about 100 feet (30 m) across. In the case of long narrow features, slides and avalanches only a few tens of feet wide can be discerned. Figures 14 through 19 show the history of these slides along six separate reaches of Redwood Creek. Uncertainties caused by missing photograph coverage, poor-quality photographs, and scale limitations are also presented in these figures. The reaches are the 2.2 miles (3.5 km) between roddiscroft Road and Snow Camp Creek, the 14.5 miles (23 km) between Snow Camp Creek and State Highway 299, the 16 miles (26 km) between State Highway 299 and Lacks Creek, the 4 miles (6.4 km) between Lacks Creek and Panther Creek, the 6.8 miles (11 km) from Panther Creek to the Southern Park Boundary, and the 13 miles (21 km) from the Southern Park Boundary to Prairie Creek. The landmarks used to identify these reaches are shown in figure 1.

Before describing the recent streamside landsliding along Redwood Creek, we would like to list some of the limitations inherent in our approach that restrict the conclusions that can be drawn. First, and probably most important, all landslides were counted without regard to size of failure. The depth and aerial extent of landslides cannot always be accurately measured on available aerial photographs. For that reason the graphs presented in figures 13-19 display changes in numbers of features. Numbers of landslides are a reasonable index for

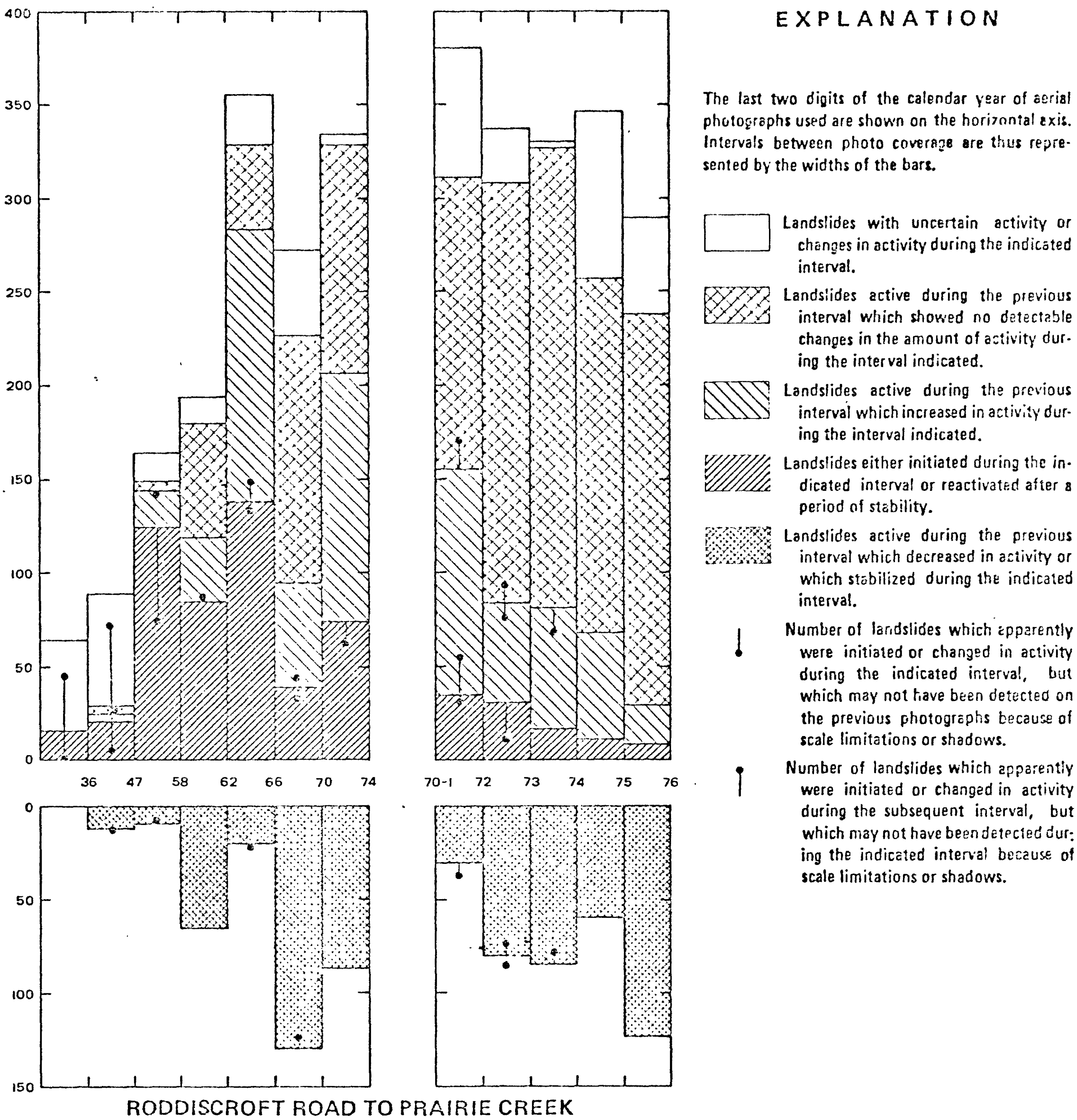

Figure 13.— History of streamside landsliding adjacent to Redwood Creek based on interpretation of aerial photographs.

comparing times and locations of maximum landslide activity, but they provide only a crude index of volumes of material eroded in a given time interval. Misleading interpretations regarding the significance of specific areas or time periods as sediment contributors to the stream system could be made if the numbers were interpreted as volumetric changes. A second drawback is that landslide history was tabulated for reaches of greatly differing length because emphasis was placed upon compiling landslide history for reaches of relatively consistent physiography and land-management history. The numbers of landslides in different stream reaches, therefore, reflect the varying lengths of the reaches as well as differences in slope stability. Third, in counting whether a slide was logged or unlogged at the time of failure, no consideration was given to the presence of upslope logging or road construction. Hicks and Collins (1971) and our own field observations indicate that increased or concentrated runoff from roads and clearcut timber-harvest areas can cause hillslope failures downslope from the actual management disturbance. We ignored this factor because of limited availability of aerial photographs and because of uncertainties as to the extent of the area in which management activity could indirectly affect streamside hillslope stability. This third limitation means that the analysis only suggests the minimum degree to which timber harvest has increased the potential for streamside landsliding along Redwood Creek.

1936-1947

The 1936-to-1947 period was generally characterized by near-average annual precipitation in northwestern California (Janda and others, 1975, fig. 28). At Prairie Creek State Park, where records are available beginning with the 1938 water year, only the 1938 and 1943 water years had substantially greater than average precipitation; 1937-38 (1938 water year) was an exceptionally wet winter. Rainfall at Eureka and Crescent City was less than average in the 1936 and 1937 winters. Although several significant floods occurred during this period, particularly in 1937 (Paulsen, 1953; Janda and others, 1975, fig. 28), none were noted as particularly damaging. As of 1947, less than 5 percent of the basin had been logged (Janda and others, 1975), and no logging other than clearing for pasture had taken place adjacent to the Redwood Creek channel. Therefore, neither storms nor land use would have triggered widespread landsliding.

Large uncertainties are associated with slide activity during the 1936-to-1947 interval due to incomplete photo coverage and the small scale of the 1936 and 1947 photographs. Overlapping coverage by both sets of photographs is available only from the mouth of Lupton Creek downstream to about 1/2-mile below the mouth of Copper Creek. Landslide activity throughout the reach of overlapping coverage appears to have remained constant during the interval, although several slides appeared to have decreased in activity (figs. 13-19). As of 1947, only 47 slides were definitely active along the entire Redwood Creek channel. This includes 6 active slides visible on 1936 photographs and not covered by 1947 photographs.

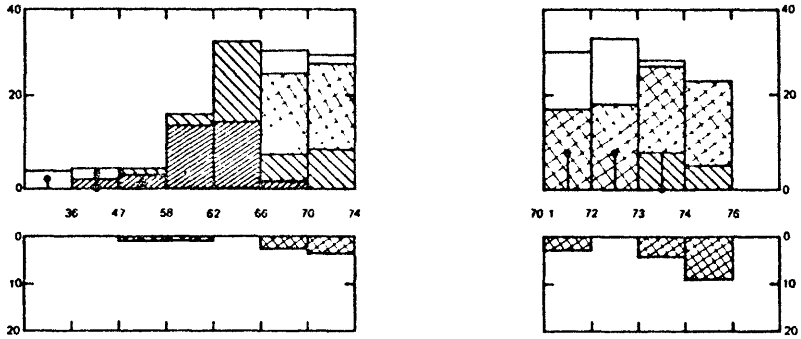

Figure 14. Landslide history adjacent to Redwood Creek between Roddiscroft Road and Snow Camp Creek. Explanation of symbols is shown in Figure 13.

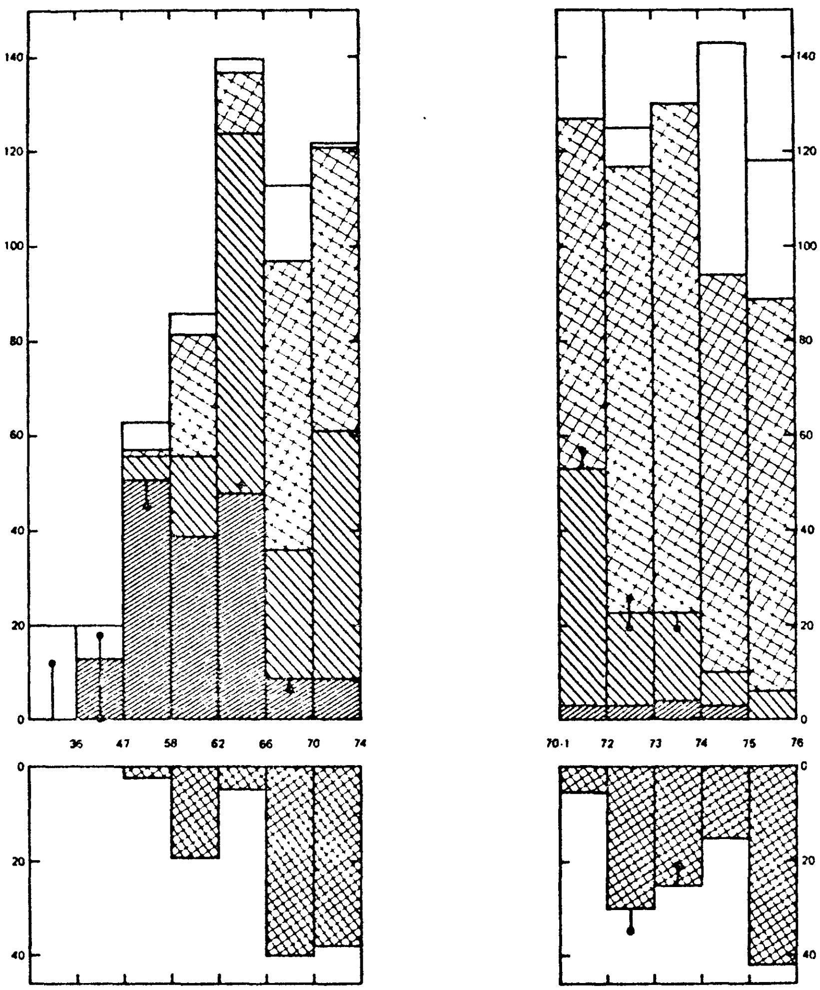

Figure 15. Landslide history adjacent to Redwood Creek between Snow Camp Creek and State Highway 299. Explanation of symbols is shown in Figure 13.

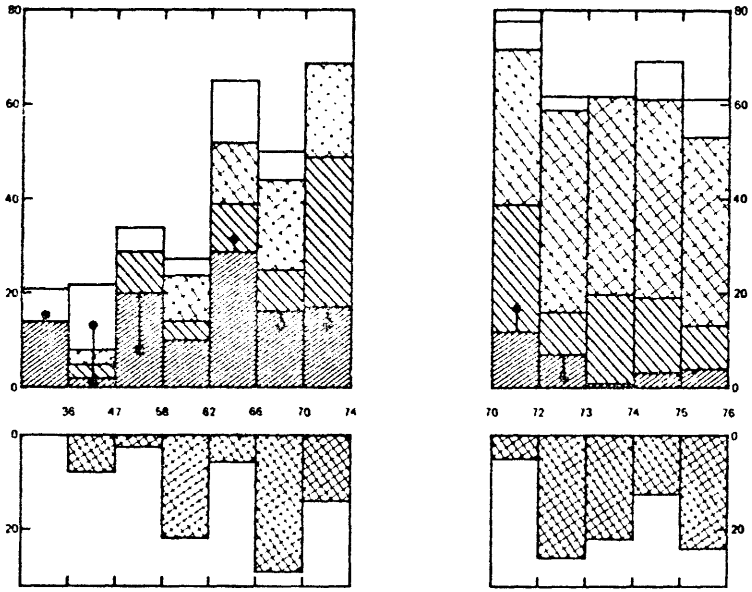

Figure 16. Landslide history adjacent to Redwood Creek between State Highway 299 and Lacks Creek. Explanation of symbols is shown in Figure 13.

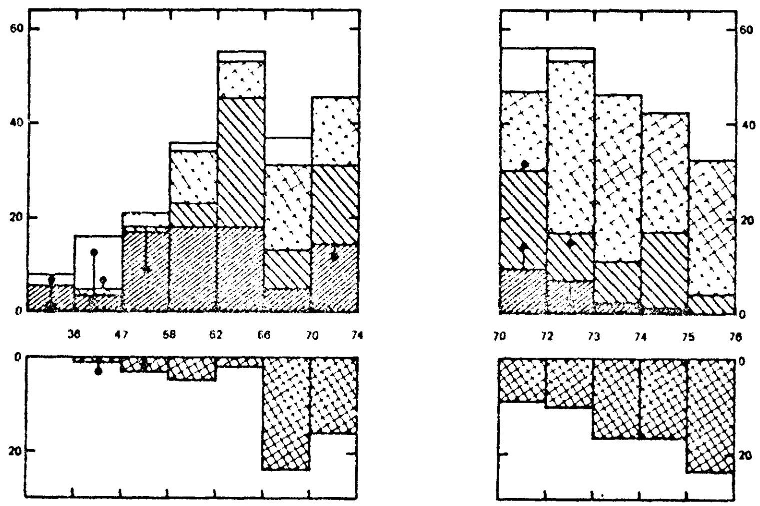

Figure 18. Landslide history adjacent to Redwood Creek between Panther Creek and the Southern Park Boundary. Explanation of symbols is shown in Figure 13.

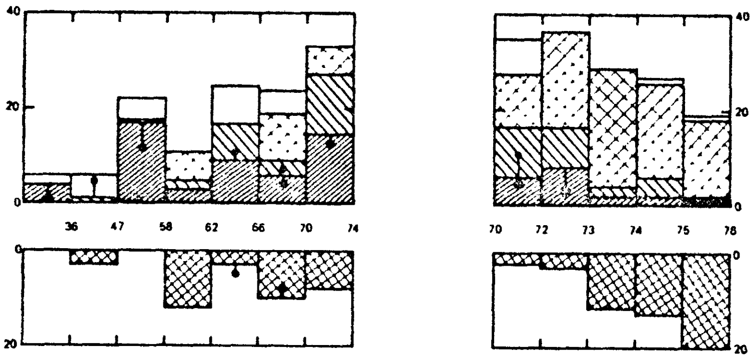

Figure 17. Landslide history adjacent to Redwood Creek between Lacks Creek and Panther Creek. Explanation of symbols is shown in Figure 13.

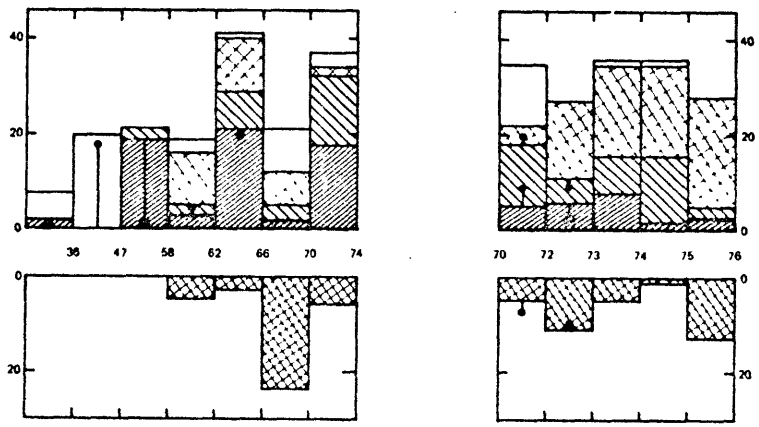

Figure 19. Landslide history adjacent to Redwood Creek between the Southern Park Boundary and Prairie Creek. Explanation of symbols is shown in Figure 13.

1947-1958

From 1947 to 1958, two floods which were probably larger than any floods that had occurred since 1890 occurred in the Redwood Creek basin, in January 1953 and December 1955 (figs. 5, 6). In addition, an intense storm which did not produce basin-wide flooding occurred in October, 1950 (Janda and others, 1975, p. 147). Precipitation during the winters of 1950-51, 1953-54, and 1957-58 was more than ten inches (254 mm) above the average at Orick-Prairie Creek State Park. Rainfall during the remaining six winters was within ten inches of the long-term average, except for 1948-49, which was 13 inches below the 1937-1976 average. Rainfall and runoff conditions during the 1947 to 1958 interval would, therefore, have been more conducive to triggering streamside slide activity than conditions during the 1936 to 1947 period.

Intensive timber harvest adjacent to Redwood Creek also began in the 1947-1958 interval. More logging took place immediately adjacent to Redwood Creek in this interval than in any subsequent interval between airphoto flights. All reaches except for the reach above Snow Camp Creek experienced some streamside logging in this period. Although not much streamside timber harvest was carried out in the reach between Panther Creek and the Southern Park Boundary, the Klamath and Korbel Road (fig. 1) was constructed along the east bank of Redwood Creek during this period. About 23 percent of the total miles of streambanks along Redwood Creek was logged between 1947 and 1958. This represents about 40 percent of all streambank logging that occurred along Redwood Creek prior to 1975.

Major increases in landslide activity took place during the period 1947 to 1958 in all but the uppermost reach along Redwood Creek (fig. 13-19). The small increase in landsliding above Snow Camp Creek (fig. 14) during this interval probably partly reflects a lack of streamside logging activity and limited changes in upstream and upslope landuse. In addition, rainfall during the 1953 storm may have been somewhat less in the headwaters of the basin than in lower Redwood Creek (fig. 5).

In the reach between Lacks Creek and Panther Creek (fig. 17), more new landslides could be seen on the 1958 photographs than on any other photographs used. This major increase in slide activity probably partly reflects the fact that in this reach as much streamside timber harvest and road construction occurred as during any other interval.

The two lowermost stream reaches (figs. 18, 19) also showed as many new slides as during the 1962 to 1966 interval. This partly, or perhaps even mainly, reflects uncertainties due to the lack of 1947 photographs in the lower basin. However, the potential for flood-induced damage during this interval may have been greater in the lower basin than in upstream areas (figs. 5, 6) because of the concentration of rainfall associated with 1950, 1953, and 1955 storms (Janda and others, 1975; fig. 5, 6).

Despite the fact that much of the streamside logging between State Highway 299 and Lacks Creek took place before 1958, slide activity in this reach between 1947 and 1958 was much less than during the 1962 to 1966 interval (fig. 16). Many landslides in the area between State

Highway 299 and Minor Creek are earthflows which may be less influenced by road construction and timber harvest than are sites of potential debris slides. Therefore, the greater slide activity during the 1962 to 1966 interval, relative to that during the 1947 to 1958 interval, may dominantly reflect the exceptionally heavy rainfall and runoff in this area during the 1964 flood (figs. 7, 8).

In the reach between Snow Camp Creek and State Highway 299 (fig. 15), as many new slides were initiated between 1947 and 1958 as during the 1962 to 1966 interval. Most slides initiated between 1947 and 1958 appeared on the 1958 photographs as small streambank failures individually involving only 1 or 2 acres (less than 1 hectare) (fig. 20). About 60 percent of these failures were associated with streamside roads or logging.

1958-1962

Annual rainfall during the interval from 1958 to 1962 was generally less than the long-term average rainfall. Only the 1960-61 winter had slightly greater than normal rainfall at Orick-Prairie Creek State Park (Janda and others, 1975, fig. 28). No major regional floods occurred during this interval. The only notable storm of the period occurred in February 1960; this storm apparently did not produce major flooding in the Redwood Creek basin (Janda and others, 1975, p. 150).

Between 1958 and 1962 an additional 14 percent of the total streamside miles adjacent to Redwood Creek was logged. Timber-harvest activity was concentrated in the reaches between Snow Camp Creek and State Highway 299 and from Lacks Creek to the Southern Park Boundary.

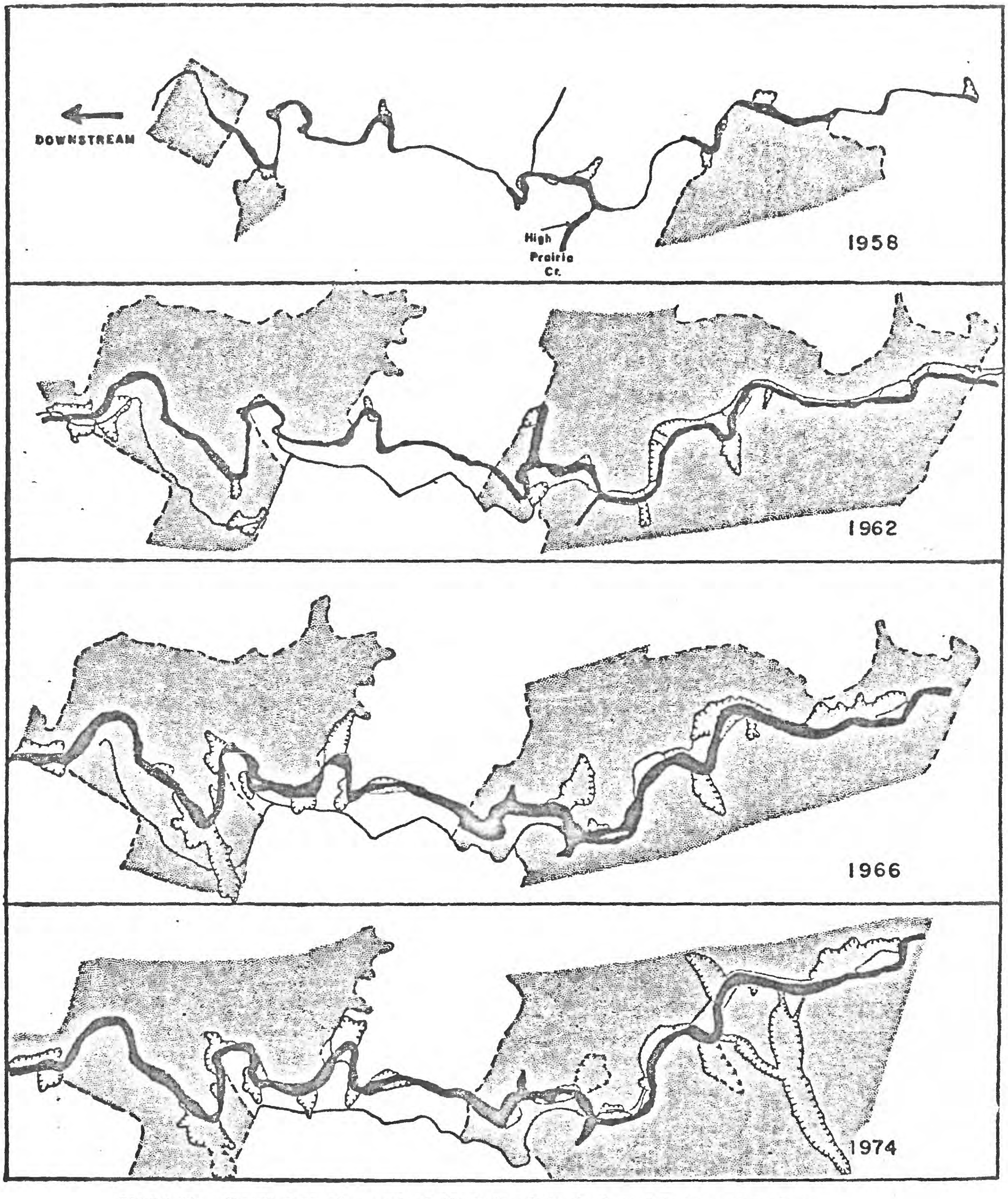

FIGURE 20. *Sketch maps of a part of the Redwood Creek channel between Snow Camp Creek and State Highway 299 traced from aerial photographs. Approximate scale 1:12,000. Stream channels are shown in black, streamside logging by shaded areas, roads by thin black lines, active landslides by hachured lines, healing landslides by dashed hachured lines, and flat-topped berms bearing live or upright dead vegetation by open circle patterns.*

Many slides showed decreased activity during the 1958-to-1962 interval, as would be expected in an interval with no floods following a period with two major floods. However, the number of new or reactivated slides is surprisingly large considering the lack of floods. In the reaches above Snow Camp Creek, between State Highway 299 and Snow Camp Creek, and between Panther Creek and Southern Park Boundary, almost as many or more new slides occurred as during the flood intervals of 1947 to 1958 and 1962 to 1966 (figs. 14, 15, 18, 20). Apparently, instability initiated by storms during the preceding interval increased even during this relatively dry period.

Between Panther Creek and the Southern Park Boundary the 1958-to-1962 interval was the period of most intensive streamside timber harvest. The Klamath and Korbel Road was also completed during this interval. The large number of new slides and the small number of slides which decreased in activity in this reach are probably largely due to streamside logging during this interval (fig. 18). However, the February 1960 storm, which was a significant flood event in the nearby Little River basin, may have been damaging in this reach.

During the 1958 to 1962 period, less streamside timber harvest took place in the reach between Snow Camp Creek and State Highway 299 than during the previous interval. Nevertheless, the fact that 30 of 39 new slides in this reach occurred in roaded or logged areas suggests that timber harvest had a continuing impact on streamside slope instability. The new and increased slide activity may reflect the influence of progressive channel widening. The increases in channel width in the upper basin, which may reflect increases in water and sediment discharge following the earlier logging activity and storm damage, can be seen by comparing the 1958 and 1962 aerial photographs (fig. 20). A second factor contributing to the occurrence of new slides during this interval may have been a time lag involved in the decay of stabilizing Douglas-fir root systems following earlier logging (O'Loughlin, 1974). This loss of root strength would not have been as significant in the redwood-dominated forests below Lacks Creek because of sprouting and slow decay of redwood roots (Robert Zeimer, oral commun., 1976). Still a third factor may be inadequate maintenance of timber haul roads following harvest. Nonetheless, many streamside slides in this reach decreased in activity during the 1958-to-1962 interval. The reasons for the occurrence of more new slides in the reach above Snow Camp Creek during this relatively storm-free period than during the 1947-to-1958 interval are not immediately clear (fig. 14) because only a third of the new slides was directly related to streamside roads or logging.

The remaining reaches of Redwood Creek showed significantly fewer newly initiated or enlarged landslides than during the 1947-to-1958 or 1962-to-1966 intervals. In addition, the number of slides which decreased in activity in these reaches was greater than the number of slides with newly initiated or increased activity. Only the reach from Lacks Creek to Panther Creek showed significant streamside timber harvest, and in much of that area, road construction had been carried out during the previous interval.

1962-1966

The major storm event of the 1962-to-1966 interval occurred in December 1964 and produced the most voluminous flood in the basin in this century (figs. 7, 8). Other significant storms, in January of 1964 and January 1966 (Janda and others, 1975, p. 150), did not produce major regional flooding. Annual rainfall for all four years was slightly below the long-term average at Orick-Prairie Creek State Park (Janda and others, 1975, fig. 28).

By 1966 about 47 percent of the total streamside area along Redwood Creek (about 82 percent of the total logged streamside area as of 1975) had been at least partially harvested. Thus, more than twice as much streamside logging had occurred by 1966 as had occurred by the end of the earlier 1947-to-1958 storm period. New timber harvest in the 1962-to-1966 interval took place above Snow Camp Creek, in the vicinity of Noisy Creek along the reach between Snow Camp Creek and State Highway 299, just upstream from Lacks Creek, and in the vicinity of Cloquet Creek. No new streamside timber harvest took place in the two reaches between Lacks Creek and the Southern Park Boundary. Some relogging of residual stands and salvage operations occurred along some downstream areas of Redwood Creek following a particularly severe windstorm in October 1962 which broke and toppled many trees.

The most dramatic increase in mass movement activity during the entire period of photographic documentation occurred during the 1962-to-1966 interval (fig. 13). Newly initiated and increased landslide activity provided enormous quantities of sediment directly to the stream channel and led to widespread channel aggradation (fig. 20). The number of slides initiated along most reaches of the channel during the 1962-to-1966 interval was either about equal to, or significantly greater than, the number initiated during the 1947-to-1958 interval. Even more striking is the fact that an exceptionally large number of slides increased in activity during the 1962-to-1966 interval. Many small slides first detected on the 1958 photos increased to more than 5 acres (more than 2 hectares) in area (fig. 20). The number of newly initiated and enlarged slides between 1962 and 1966 was particularly striking in the reaches between Snow Camp and Highway 299 (fig. 15) and between Panther Creek and the Southern Park Boundary (fig. 18). The short reach between Lacks Creek and Panther Creek (fig. 17) was somewhat anomalous in that the combined number of newly initiated and enlarged slides during the 1962-to-1966 interval was less than during the 1947-to-1958 interval.

Conversations with residents and workmen of northwestern California indicate that most of the increased landsliding during this interval probably occurred during or shortly after the 1964 flood. That the erosional impact of this flood was so much greater than that of the earlier major floods is somewhat problematical because as previously indicated the peak discharge and other hydrologic characteristics of this flood within the Redwood Creek basin were not significantly different from those of the other major floods (figs. 7 and 8). Perhaps the great increase in overall landslide activity partly reflects prior destabilization of streamside hillslopes where instability had been initiated by earlier floods and streamside timber harvest. Of course, many other factors, such as short-term rainfall intensities, which cannot be adequately addressed with available data, may also have been involved.

1966-1970

Between 1966 and 1970 annual rainfall totals were below the long-term average (Janda and others, 1975, fig. 28). Gaging-station records from Little River suggest that coastal portions of the Redwood Creek basin may have experienced significant flooding in 1970 (Janda and others, 1975, p. 150), but no major regional flooding occurred during this period. An additional 5 percent of the streamside hillslopes adjacent to Redwood Creek was logged during this interval. Most new logging took place adjacent to the Redwood Creek meanders upstream from Lacks Creek. Thus, neither storms nor land use would be expected to increase slide activity greatly during this period.

The 1966-to-1970 interval was a healing period for streamside landslides in basin as a whole. The 1970 photographs indicated that many slides decreased in activity, and that the number of new slides was less than in any period since 1947 (fig. 13). Nonetheless, the total number of active features still increased over 1966.

The proportion of slides with decreased activity along different reaches of the channel generally increased in a downstream direction (figs. 14-19). The only exception to this trend was that the reach from

Lacks Creek to Panther Creek showed less decrease than the reach from State Highway 299 to Lacks Creek (figs. 16, 17). The massive streamside slides that were presumably initiated by the 1964 storm along reaches upstream from State Highway 299 were apparently slower to heal than generally smaller slides adjacent to downstream reaches. The persistent activity of the massive slides upstream from State Highway 299 may reflect low soil moisture during the summer, steep streamside hillslopes, and the massiveness of the exposed areas, all of which lead to persistent dry ravelling and small scale sloughing that hinders revegetation.

1970-1974

The interval from 1970 to 1974 was generally wet compared to the long-term annual average. The 1973-1974 winter was the wettest ever recorded at Orick-Prairie Creek State Park. Only the 1972-1973 winter had less seasonal precipitation than average. In addition, two major floods occurred during the 1971-1972 winter (water year 1972). Rainfall and runoff conditions were therefore conducive to increased slide activity.

Major timber harvest activity during this interval occurred only in the two reaches between Lacks Creek and the Southern Park Boundary. Between Lacks Creek and Panther Creek, most of this activity was relogging of residual stands of timber which were initially logged prior to 1962.

Along Redwood Creek as a whole, fewer slides were initiated and more slides decreased in activity during the 1970-to-1974 interval than during the 1947-to-1958 and 1962-to-1966 intervals (fig. 13). This suggests that the events of the 1970-to-1974 interval had less of a destabilizing influence on streamside landsliding than the major floods and land-use changes that occurred during earlier intervals. However, most of the previously active slides remained active to some degree, so that no reduction in total number of active slides occurred. Moreover, landslide activity along reaches downstream from State Highway 299 (figs. 16 to 19) was strikingly greater than along upstream reaches (figs. 14 and 15).

The reach above Snow Camp Creek showed about the same number of active landslides as during the previous interval (fig. 14). The reach from Snow Camp Creek to State Highway 299 showed a greater number of slides with increased activity than in 1970, but, on the other hand, it also showed almost as many healing slides on the 1974 photographs as in the 1970 photographs (fig. 15). The number of new slides in this reach was about the same as during the preceding storm-free interval. Therefore, the 1972 storms probably did not greatly affect the upper two reaches, which were starting to recover from the erosional impacts of the 1964 flood.

In the reach between State Highway 299 and Lacks Creek, more slides increased in activity between 1970 and 1974 than during any previous interval (fig. 16). Additionally, the number of healing slides along this reach in this period was much less than during the preceding interval. Reaches downstream from Lacks Creek generally showed about as many new slides on the 1974 photographs as on the 1966 photographs (figs. 17, 18, and 19). In fact more new slides occurred in the Lacks Creek to Panther Creek reach than during the 1962-to-1966 interval (fig. 17).

Along all reaches downstream from State Highway 299 the number of slides showing new or increased activity was generally as large or larger during the 1970-to-1974 interval as during the 1962-to-1966 interval. This observation suggests that in downstream parts of the Redwood Creek basin the erosional impact of the 1972 floods may have been equal to or even greater than that of the 1964 flood. However, most newly-initiated and enlarged slides along the lower reaches of Redwood Creek are considerably smaller than the massive slides upstream from State Highway 299 (Nolan, Harden, and Colman, 1976).

The apparent downstream migration of the locus of maximum landslide activity may have resulted from the centers of maximum rainfall for the 1972 storms (figs. 9 and 10) being located farther downstream than those for the 1955 and 1964 storms (figs. 6, 7 and 8). However, intensification of timber harvest in downstream parts of the Redwood Creek basin concomitantly with recovery from earlier logging and flood-induced landsliding in the upper basin may also have contributed. Another factor that may have contributed to a downstream migration of the locus of maximum landsliding is downstream transport of sediment from earlier erosion in upstream areas. Channel aggradation resulting from deposition of this material could accelerate bank erosion and undercut the toes of marginally stable streamside hillslopes (Janda and others, 1975).

Landslides associated with the 1972 storms seem to have introduced far less sediment into Redwood Creek than landslides associated with the 1964 storm; probably the landslides initiated or enlarged by the 1972 events were substantially smaller than those associated with the 1964 flood. This reduced impact must reflect a great many factors, including the lesser runoff volumes of the 1972 floods (figs. 9 and 10) relative to the 1964 flood (figs. 7 and 8) and a general decrease in the amount of new streamside logging prior to 1972. Much of the logging that was carried out in the Redwood Creek basin in the few years immediately preceding the 1972 floods severely disrupted the land surface, but most of this disruption occurred in areas well away from the main channel of Redwood Creek. Additionally, the climatic conditions in the years preceding the 1972 storms were more conducive to restabilization than those preceding the 1964 flood, so that antecedent weakening of hillslopes may have been less a factor in 1972 than in 1964. A fact of possibly greater significance is that the area of maximum rainfall and runoff during the 1972 floods was not as susceptible to streamside landsliding as the area of maximum rainfall and runoff during the 1964 flood. The generally smaller size of streamside landslides in the lower basin, relative to the massive streamside landslides upstream from State Highway 299, probably reflects gentler streamside hillslope gradients, more protection of the bases of hillslopes by narrow floodplains, and more massive riparian vegetation in the lower basin (Janda and others, 1975). An alternative explanation, which would have particularly dire consequences for the streamside vegetation of Redwood National Park, is that these small landslides mark the initial phase of a major episode of streamside landsliding similar to that which occurred in the upper basin; further monitoring would be needed in order to test this alternative explanation.

Yearly Trends, 1970-1976

Aerial photographs of the Redwood Creek channel were obtained at least once a year from 1972 through 1976. Most of the photographs were taken during dry early-summer months when the mid-day sun angle was high. Special flights were also obtained following some major storms. The frequent aerial-photo coverage permits precise observation with regard to the timing of landslides relative to specific climatic events and land management activities.

1970-1972

Comparison of 1970 photographs (or 1971 photographs in a few areas where 1970 photographs are not available) with those from 1972 shows that landslide activity between Snow Camp Creek and State Highway 299 (fig. 15), between State Highway 299 and Lacks Creek (fig. 16), and between Panther Creek and the Southern Park Boundary (fig. 18) was much greater in the two-year interval that included the 1972 floods than in the rest of the 1970-1976 period. Uncertainties due to lack of coverage in the reach above Snow Camp Creek make comparison of photograph intervals in this reach difficult. Even in the upper basin, which was less affected by the 1972 floods than the lower basin, the 1970-1972 period showed more landslide activity than the following four years. Little timber harvest or road construction has taken place in the upper basin since 1970; thus the 1972 flood was probably the dominant destabilizing impact on upper reaches of the channel during the past eight years.

1972-1973

Although 1972-1973 was an unusually dry year, reaches of Redwood Creek between Lacks Creek and the Southern Park Boundary (figs. 17, 18) and between Snow Camp Creek and State Highway 299 (fig. 15) showed more new slides and more slides with increased activity than they showed during the following exceptionally wet year. These slides may partly represent a delayed or continuing response to the 1972 floods. However, the large number of new or increased slides seen on 1973 photographs of the channel between Lacks Creek and the Southern Park Boundary partly reflects uncertainties in interpretation of the smaller-scale 1972 photographs (table 7). Relogging operations along Redwood Creek above Panther Creek may also have destabilized hillslopes in that reach.

1973-1974

Periods of prolonged rainfall of moderate intensity during the 1973-1974 winter resulted in exceptionally high total rainfall but no major floods. Although no major landslide activity seems to have been initiated, and significant numbers of slides decreased in activity, the combined total of landslides showing new, increased, or constant activity was nonetheless greater than at any time during the 1970-to-1976 interval (fig. 13). The two reaches with the greatest number of slides having new or increased activity were between State Highway 299 and Lacks Creek (fig. 16) and between the Southern Park Boundary and Prairie Creek (fig. 19). However, the fact that these increases are not striking is somewhat surprising because the reach between State Highway 299 and Lacks Creek has the greatest concentration of active streamside earthflows in the basin (Nolan, Harden, and Colman, 1976). Earthflows are the type of mass movement most likely to respond to prolonged heavy rainfall (see p. 139).

Most new slides within the Park since 1973 have occurred in aggraded reaches (Nolan, Harden, Janda, 1976). Downstream migration of sediment previously deposited along the channel of Redwood Creek, as well as sediment resulting from recent intensive timber harvest in tributaries adjacent to the Park, may have contributed to aggradation and channel widening along parkland reaches of the main channel and thereby indirectly contributed to hillslope failures.

1974-1975

The March 1975 storm appears to have been concentrated in the lower two-thirds of the basin (fig. 11). Landslide activity during 1974-1975 was likewise concentrated along the lower reaches of the channel. The reach between Snow Camp Creek and State Highway 299 (fig. 15) showed fewer new slides and slides with increased activity than during any of the previous four years. In contrast to the slightly reduced level of landslide activity exhibited by the upper two reaches of Redwood Creek, all reaches downstream from State Highway 299 showed newly initiated and increased landslide activity either equal to or slightly greater than the amount associated with the preceding year. The newly initiated slides were all small.

The observation that the 1975 flood appears to have initiated fewer and smaller streamside landslides than other 20th-century flooding of comparable peak discharge may reflect the fact that the 1975 flood-producing storm was of relatively short duration and was centered over a part of the basin that is less prone to streamside landsliding than the areas of most intense flooding during the 1955 and 1964 storms. A contributing factor may have been the fact that the recently completed timber-harvest units in the area of maximum storm intensity involved less disruptive practices than those prevailing at the time of earlier flood-producing storms. Yet another factor accounting for the low number of newly initiated slides may have been the fact that most of the inherently unstable streamside hillslopes had previously failed during earlier storms.

1975-1976

Rainfall at Orick-Prairie Creek State Park during the 1975-1976 winter was only 57.02 inches (1448 mm), about 13 inches (33 mm) below the long-term average, and no major floods occurred in the basin. However, rainfall was sufficient to recharge soil moisture to a level that could sustain tree seedlings and newly established ground cover. This year was apparently a healing period for all reaches on the Redwood Creek channel, similar to the flood-free 1966-to-1970 period. The reaches between Snow Camp Creek and State Highway 299 (fig. 15) and the two reaches between Lacks Creek and the Southern Park Boundary (figs. 17, 18) showed as many healing slides on 1976 photographs as in 1970. The reaches between State Highway 299 and Lacks Creek (fig. 16) and between the Southern Park Boundary and Prairie Creek (fig. 19) showed the lowest number of healing slides. The lower degree of landslide activity during 1975-1976, relative to the 1972-1973 winter, which was also an unusually dry year, may partly reflect uncertainties associated with the small scale of the 1972 photographs.

Summary Of Recent Streamside Landsliding

The total number of evident, active streamside landslides adjacent to Redwood Creek has continuously increased from about 100 in 1947 to about 415 in 1976. Not all of these landslides are large enough to be shown by Nolan, Harden, and Colman (1976). The rate of increase has fluctuated greatly, with periods including major storms generally showing greater landslide increases than storm-free periods. Along much of the channel, and throughout most of northwestern California, a particularly large number of landslides showed increased activity or were newly initiated during the 1962 through 1966 period. Most of this increase, which would be even more pronounced if landslide volumes were included in the analysis, was caused by the major storm of December 1964. The impact of the 1964 storm on streamside landslides appears to have been disproportionately large in relation to other storms of comparable intensities (figs. 5-12).

The combined impact of the January 1953 and December 1955 storms appears, in general, to have been less severe than the impacts associated with the December 1964 or January and March 1972 floods. The increased level of impact suggests that streamside areas were less resilient during the later storms. Reduced stability may partly reflect erosion initiated by the earlier storms, continuing timber harvest, and progressive channel widening. Although the March 1975 storm caused much gullying in landslide areas and recently logged timberland, it apparently had substantially less impact on streamside landsliding than did earlier storms which produced comparable flood peak discharges. The impact of the 1972 and 1975 storms on streamside landslides was partly moderated by the fact that the maximum storm intensities for these storms occurred in areas that are inherently less susceptible to streamside landslides than the areas of most intense flooding during the 1964 storm.

Three reaches along Redwood Creek showed a peak increase in landslide activity in the 1970-to-1974 period rather than in the 1962-to-1966 interval. Additionally, the reach from Lacks Creek to Panther

Creek showed an increase in activity between 1947 and 1958 that was comparable to the increase during the 1962-to-1966 period. The prominent increase in activity during the 1970-to-1974 period probably is associated with the major storms of January and March 1972 and with the exceptionally wet winter of 1973-74. Relogging operations in streamside areas along the reach from Lacks Creek to Panther Creek, and continuing channel aggradation along the parkland reaches upstream from Oscar Larson Creek, may also have aggravated streamside instability. The noteworthy increase in landslide activity adjacent to Redwood Creek between Lacks Creek and Panther Creek following the 1947-to-1958 intervals probably was associated with the major storms of January 1953 and December 1955; seed-tree-leave logging and road construction may also have adversely affected streamside hillslope stability during the 1947-to-1958 interval.

The 1958-to-1962 and 1966-to-1970 intervals were characterized by relatively minor increases in streamside landslide activity. Although the total number of active streamside landslides increased during those periods, many of those landslides showed decreased activity, and relatively few showed newly initiated or increased activity. The trend toward stability was generally less pronounced in the earlier of these periods than in the later period, even though both periods were apparently comparably dry and flood-free. Indeed, significant numbers of streamside landslides were initiated or enlarged between Roddiscroft Road and State Highway 299 and between Panther Creek and the Southern

Park Boundary between 1958 and 1962. Most of this increased streamside landsliding, except in the area between Roddiscroft Road and Snow Camp Creek, was associated with streamside timber harvest, road construction, or previous small landslides.

Streamside landslides may be starting to contribute less to stream sedimentation in the area upstream from State Highway 299. The number of landslides showing newly initiated or increased activity has decreased progressively, and the number of landslides showing lessened activity has significantly increased since 1970. A comparable trend has not been found along the lower reaches of Redwood Creek.

STAKE LINE SURVEYS

In order to document the times and rates of surficial movement associated with different types of mass movement features, as well as to help assess the role of those features in supplying sediment to Redwood Creek and its tributaries, surficial movement rates were measured by repetitive surveys of stake lines transecting erosional landforms at ten sites (fig. 21). Although volumes of sediment transported to streams by landslides cannot be accurately measured without knowledge of slide depths, surficial movement rates in conjunction with reasonable depth estimates do aid in estimating volumetric sediment yields from mass movement. Such stake line surveys also provide estimates of the variability of movement rates between similar types of features. Sites which were accessible during the storm season were selected to represent features which are characteristic of different processes that appeared active during field and aerial photograph reconnaissance of the Redwood Creek basin. An attempt was made to sample the full spectrum of degrees of ground-surface disruption. Generalized descriptions of the types of erosional landforms available for study are given in Nolan, Harden, and Colman (1976). Precipitation data from three recording rain gages and from one storage gage with daily readings (fig. 21) were analyzed to aid in assessing the potential role of precipitation in accounting for observed stake line movements.

Five landforms studied are active earthflows--Poison Oak Prairie[3/] (Site 1), Minor Creek earthflow (Site 2), Rain Gage earthflow (Site 3), Devil's Creek earthflow (Site 4), and Counts Hill Prairie (Site 7). Three monitoring sites are translational slides--Bridge Creek Trail slide (Site 8), Elbow slide (Site 9), and Berry Glen slide (Site 10). The stake lines at the Quarter Section (Site 5) monitor several types of complex activity on a generally unstable hillslope segment. The stake lines located near the M-7-5 road (Site 6) were established both in uncut timber and in two different management units in order to assess the impact of changed land use in differential surficial soil movement. Sites 1, 2, 5, 6, 7, and 8 were established in November and December of 1973; additional stake lines at these sites and at Sites 3, 4, 9, and 10 were established in July, 1974.

3/ The names applied to Sites 1, 3, 5, 6, 8, and 9 are informal and do not appear on published topographic maps.

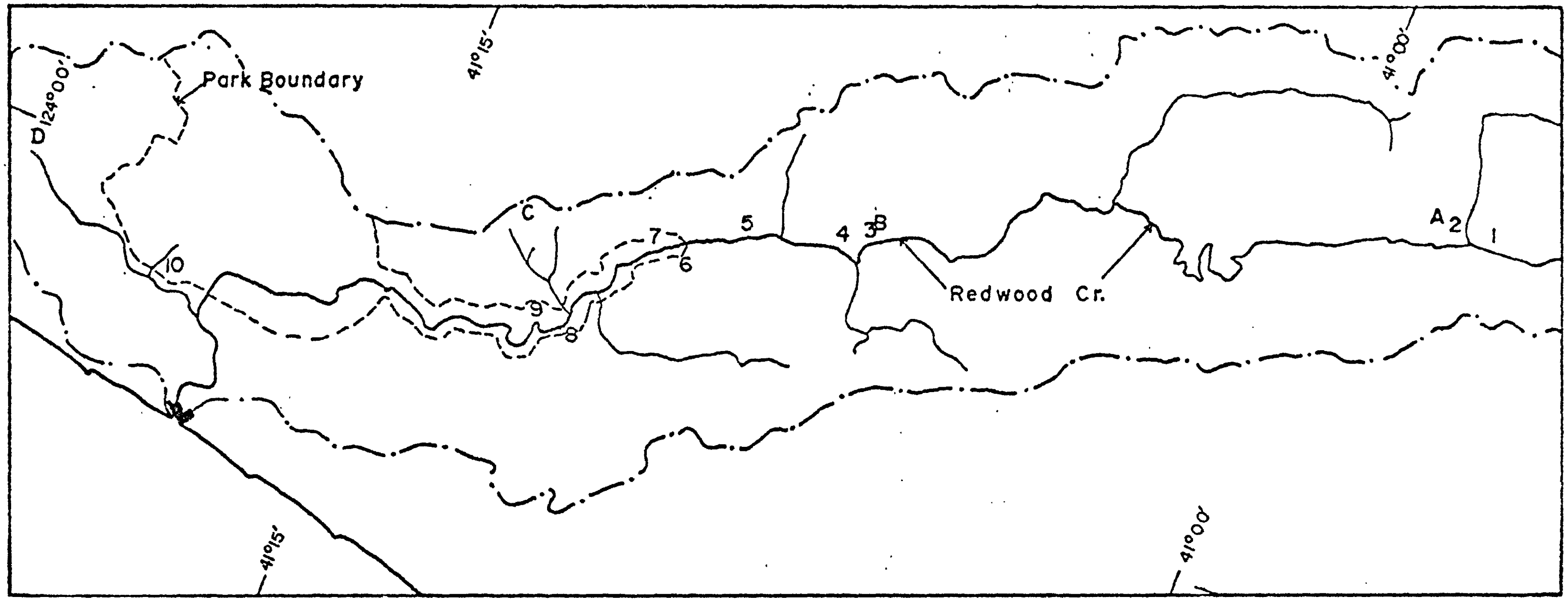

Figure 21. Mass-movement monitoring sites and selected rain gages in the Redwood Creek basin. Sites are designated by numbers. Rain gages are designated by letters as follows: A-Minor Creek (recording); B-Klamath-Korbel Road (recording); C-Elk Camp (recording); D-Prairie Creek State Park (daily readings).

Description of Monitoring Sites

Site 1

Site 1, Poison Oak Prairie, is an active earthflow in a prairie adjacent to Redwood Creek between the mouth of Minor Creek and State Highway 299 (figs. 1, 21, 22) and is underlain by closely fractured and sheared transition-zone rocks. The length of the active earthflow is about 800 feet (240 m), the average width about 400 feet (120 m), and the relief about 400 feet (120 m). Movement on the upper parts of the flow is dominantly slumping and flowing with some translational sliding on the steep slope between stake lines 1 and 2. Movement at the toe is dominantly translational sliding and sloughing of incoherent blocks of soil and highly fractured sedimentary rocks into the creek. Upper portions of the flow bear grass and brush vegetation, with stands of oak and Douglas fir on portions of the active slope. Many trees have been tilted or toppled since late 1973. Others have moved downslope while remaining upright. Bare soil is exposed on the steep slope below stake line 1, on the north end of the flow near stake line 2, and at the toe of the earthflow. The upper half of the earthflow is dry except during the winter storm season. Soil in the flat area near stake line 2 retains some moisture throughout the summer. The bare soil at the streamside toe is nearly saturated, highly viscous, and structurally weak throughout the storm season, but becomes hard and dry by the end of summer.

The top stake line (line 1) transects the flow just below its crown scarp. The end stakes extend into the oak and Douglas-fir woodland.

The bottom stake line (line 3) transects the active, unvegetated streamside toe of the earthflow. On 1962 aerial photographs taken for the Humboldt County timber assessor's office, a logging road can be seen transecting this lower part of the flow; this road has been completely removed by sliding.

FIGURE 22. Aerial photograph showing mass movement monitoring Site 1, Poison Oak Prairie. Approximate scale 1:3,300. Photo taken September 1975.

The south part of the middle stake line (line 2) is located in a relatively flat break in slope exhibiting ponded drainage and backward rotation of slump blocks. The north end is a steep, bare gully bounded by a steep lateral scarp. The end points of line 2 also extend into a forest with relatively few tilted trees.

Site 2

Site 2, Minor Creek earthflow, is an active earthflow adjacent to the channel of Minor Creek (figs. 1, 21, 23) and underlain by unmetamorphosed sedimentary rocks that are generally less fractured and sheared than those underlying Site 1. This site displays detailed morphological features that are typical of many earthflows in Franciscan terrain (fig. 24). However, Minor Creek earthflow is reasonably uniform in width and lacks the pronounced teardrop or hourglass shape typical of more highly disrupted earthflows like those at sites 3 and 4 (figs. 25, 26). The presently active part of the flow is about 2500 feet (760 m) long and 500 feet (150 m) wide. Relief is about 750 feet (230 m). The upper third of the flow appears to move dominantly by slumping and flowing, with compressional movement occurring at the lower portion of the upper flow. The lower flow moves by translational sliding, slumping, and flowing. The streamside toe of this earthflow moves by translational sliding. Several gullies, which probably formed along longitudinal tension cracks, transport soil and angular sedimentary rock fragments and soil to the creek.

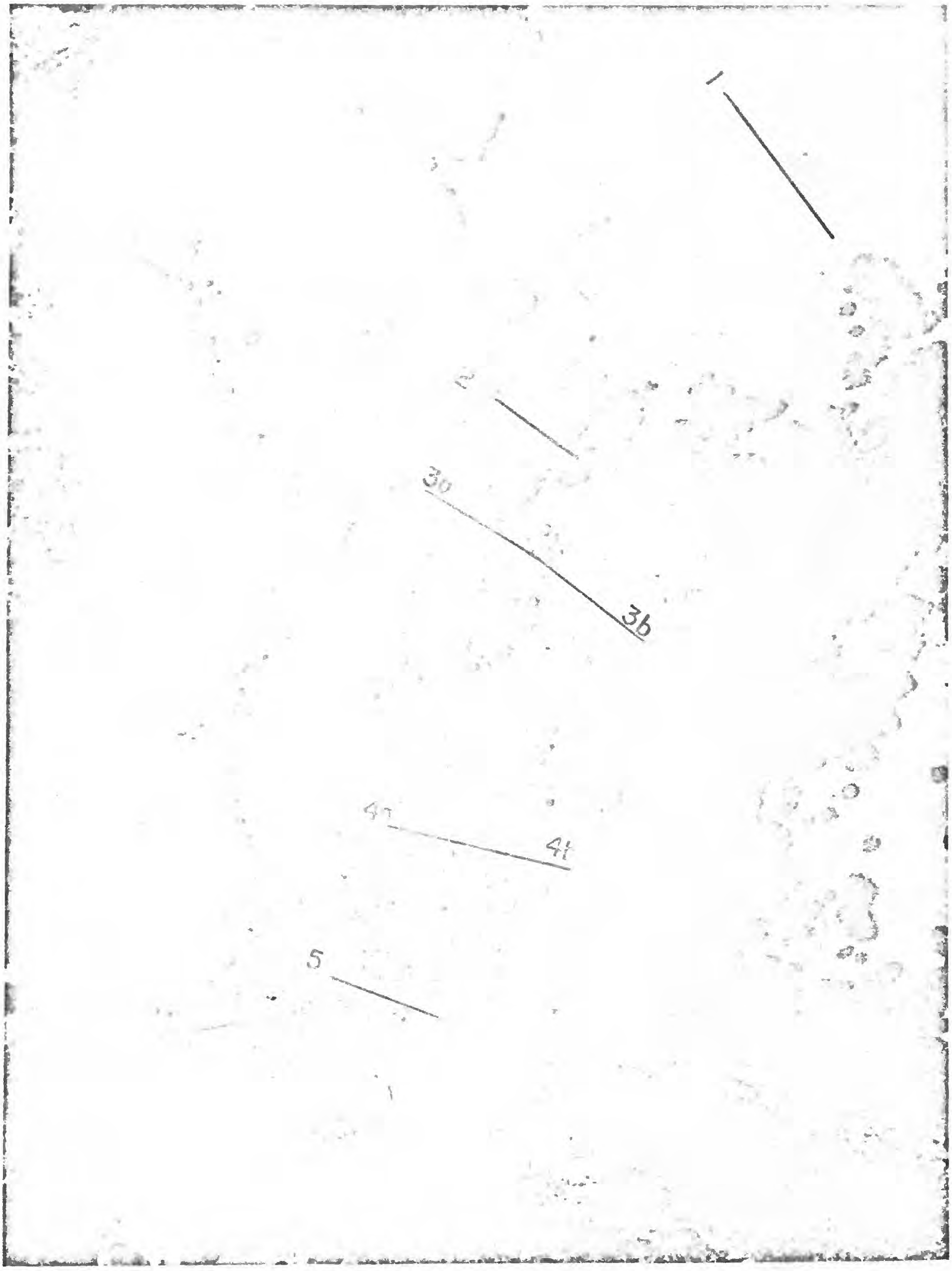

FIGURE 23. Aerial photograph showing mass-movement monitoring Site 2, Minor Creek earthflow. Approximate scale 1:5,000. Photo taken September 1975.

EXPLANATION

Boundary of landslide mass; sawtooth pattern indicates pronounced slope break or scarp.

Lobate landslide mass; arrow shows direction of movement.

Longitudinal gully.

Compressional ridge.

Hummocky ground.

FIGURE 24. *Sketch map of features on Minor Creek earthflow. Approximate scale 1:5000. Original data modified from J. Miller (unpub. senior thesis, Univ. of Calif., Santa Cruz, 1976).*

These gullies are most prominent downslope of stake line 3. Vegetation on the earthflow is grass with some brush and scattered small oaks. Bare soil is exposed only in gully walls, at the toe of the earthflow, and where a road crosses the flow between stake lines 1 and 2. The ground is dry during the late spring and summer, except in an area of ponded drainage near the west end of stake line 2. The Minor Creek earthflow has been described in detail by Jacquelyn Miller (unpub. senior thesis, University of California, Santa Cruz, 1976).

Stake line 1 transects the earthflow directly below its crown scarp and uphill from an area of compressional ridges. Line 2 is located at the narrowest part of the flow, where the edges of the lateral scarps are 10 to 20 feet (3 to 6 m) higher than the flow surface. Stake lines 3a and 3b cross the flow where a less active, tributary earthflow enters the main flow. Line 3b transects the main flow, and line 3a is located on the tributary flow. At stake line 4, the earthflow is wider and less steep than at the upper portions. Stake line 5 transects the flow about 100 feet (30 m) upslope from the streamside edge. At the lowermost line, deep, raw, longitudinal gullies are prominent, but most of the remaining ground surface is vegetated.

Sites 3 and 4

Sites 3 and 4, Rain Gage earthflow and Devils Creek earthflow, are active earthflows adjacent to the east bank of Redwood Creek between the mouths of Coyote Creek and Copper Creek (figs. 1, 21, 25, 26).

FIGURE 25. (left). Aerial photograph showing mass-movement monitoring Site 3, Rain Gage earthflow. Approximate scale 1:3,300.

FIGURE 26. (right). Aerial photograph showing mass-movement monitoring Site 4, Devils Creek earthflow. Approximate scale 1:5,000. Photos taken September 1975.

These areas are underlain by relatively unmetamorphosed sedimentary rocks that are closely fractured and sheared near the earthflow toes but relatively massive in their crown areas. These features differ from Sites 1 and 2 in that they appear to move almost completely by flowing in their midslope parts. They also display more typical earthflow morphology, with midslope portions being considerably narrower than the crown areas. The downslope part of Site 3 is bulbous and relatively flat in profile, with a steep translational slide at the streamside toe. The downslope part of Site 4 appears to move dominantly by translational sliding with some evidence of flow as well. At both earthflows, sediment is also transported by several deep gullies. Sediment from these areas consists mostly of sheared mudstone and sandstone fragments, clay-rich colluvium, and poorly sorted alluvium. Both earthflows show mostly grass and bracken fern vegetation, with some brush and small oaks. Bare soil is exposed in gully walls and at the toes of both sites. Stands of tilted oaks and coniferous trees at the lateral edges of both flows indicate that adjacent slopes are also unstable.

The active earthflow at Site 3 is about 1100 feet (340 m) long, 450 feet (140 m) wide at the crown area, and 350 feet (110 m) in relief. The upper stake line (line 1) transects the narrow section of the flow which during field reconnaissance appeared to be its most active portion. The lower line (line 2) at Site 3 crosses the flow at the hummocky, gentle slope of the toe above the streamside translational slide.

Site 4 is about 2200 feet (670 m) long and 800 feet (240 m) in relief. At the crown area, it is about 650 feet (200 m) wide; in the midslope area, the flow narrows to about 250 feet (80 m). Stake line 1 is located at the wide portion of the earthflow below the crown scarp. Because the flow appears to consist of two converging units at this point, the stake line bends midway across the flow in order to remain normal to the direction of movement. Stake line 2 is located at a narrow section of the flow, comparable to line 1 at Site 3, except that a deep gully defines the north edge of the flow at this site. Line 3 transects the flow about 300 feet (90 m) upslope from Redwood Creek. The gully at the north edge of the flow is about 30 feet (10 m) deep at this point. The south end of line 3 is similar to line 2 at Site 3, displaying gentle slopes and hummocky microtopography.

Site 5

Site 5, Quarter Section slide, is located on an unstable hillslope adjacent to Redwood Creek downstream from the mouth of Copper Creek (figs. 1, 21, 27). This site is underlain by unmetamorphosed sedimentary rocks that locally are intensively sheared. The southern portion of the slope, which includes stake lines 1, 2, and 5, appeared on 1972 aerial photographs to be an active landslide displaying considerable bare ground and some smaller trees on its midslope portions. Stake lines 1 and 2 transect the upper portion of this slide. The area including line 1 and the ends of line 2 was logged immediately prior to the installation of the lines. Vegetation on the area near line 2 includes many tilted and toppled conifers. Stake line 5 transects the raw translational slide at the base of the slope. This line was established in August 1974; at the time of resurveying in August 1975, only 5 of the original 24 stakes remained. Because the end stakes had moved, the line could not be reestablished, but the position of the remaining stakes suggests that much of the line probably moved about 20 feet (6 m).

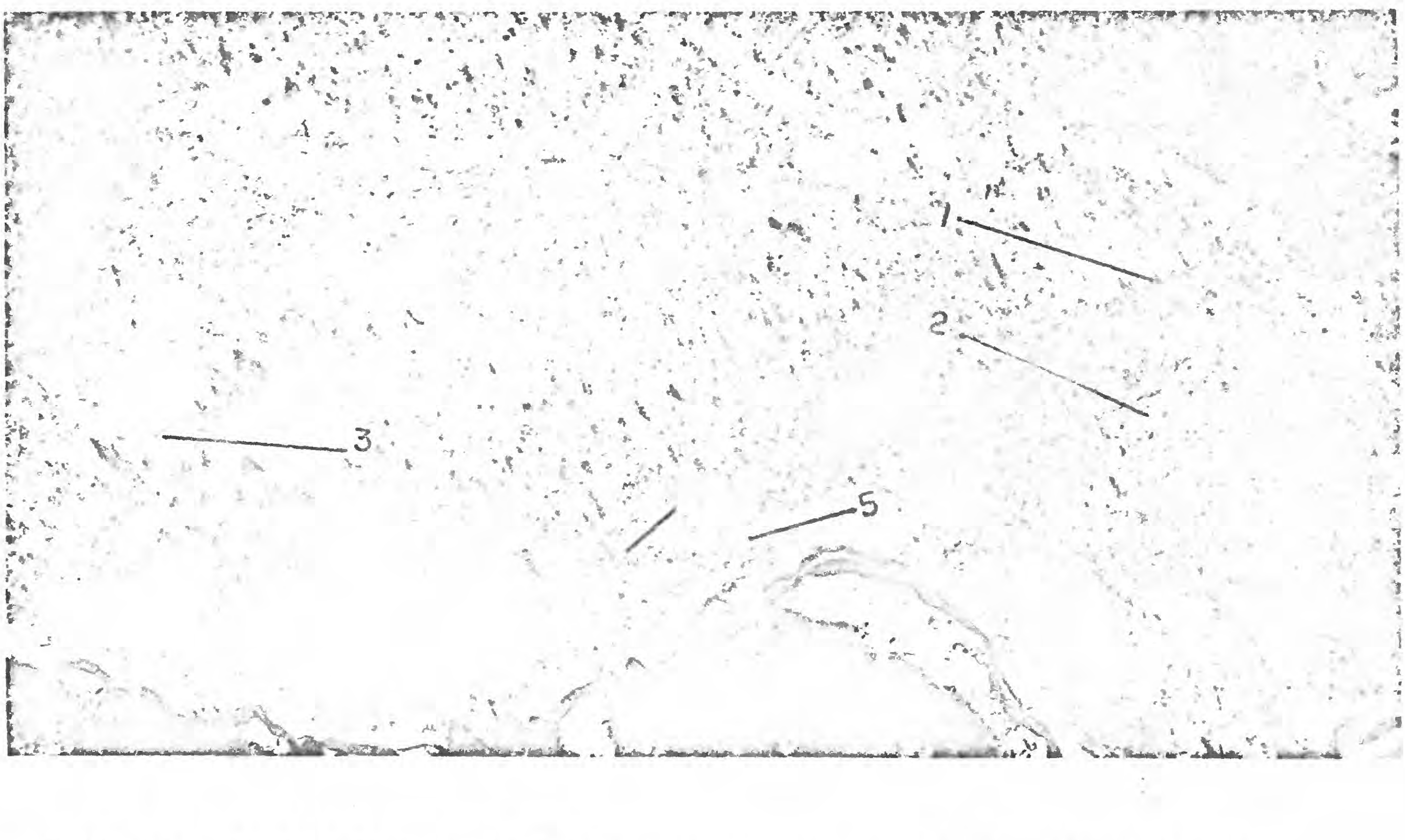

FIGURE 27. Aerial photograph showing mass-movement monitoring Site 5, Quarter Section slide. Approximate scale 1:5,000. Photo taken September 1975.

Stake line 4 transects the upper part of a small streamside translational slide adjacent to Redwood Creek north of line 5. The slide is about 300 feet (90 m) long, 200 feet (60 m) wide, and 80 feet (25 m) in relief. The slide has steep lateral scarps and a clearly defined crown scarp. Stake line 3 is located on a grass-bracken fern prairie north of the other lines and immediately downslope from a steep, recently cable-logged slope. This part of the site is marked by slightly hummocky ground and small-scale natural disruption of the natural ground cover; these features suggest that active creep or flow may occur but that differential movement is less than at the more highly disrupted active earthflow sites. This stake line is about 550 feet (170 m) upslope and 150 feet (45 m) in elevation above Redwood Creek. This hillslope is underlain by schist. Inclinometer readings from boreholes at this site (Swanston and Swanson, 1976, table 2), convex-upward topography, and numerous tilted trees suggest active surface creep, but discrete landslides occur mostly in areas downslope from the stake lines. The only well defined erosional landforms intersected by the stake lines are rills and gullies. Stake line 1 transects a tractor-yarded clearcut on the upper portions of the slope. The lower lines, lines 2 and 3, extend from the cable-yarded patchcut at the south end of the M-7-5 road into the uncut forest adjacent to the cut. Stake line 3 is about 1500 feet (460 m) upslope and 700 feet (210 m) in elevation from Redwood Creek.

Site 6

Stake lines were established at Site 6, M-7-5 slope, to detect differential soil creep in different management units on a smooth, convex-upward slope adjacent to Redwood Creek upstream from the mouth of Bridge Creek (figs. 1, 21, 28).

FIGURE 28. Aerial photograph showing mass-movement monitoring Site 6, M-7-5 Slope. Approximate scale 1:5,000. Photo taken September 1975.

Site 7

Site 7, Counts Hill Prairie, includes the largest active landslide adjacent to the Redwood Creek corridor of the Park (figs. 1, 21, and 29). It is a large complex earthflow, the margins of which have apparently stabilized. The entire earthflow is underlain by unmetamorphosed sedimentary rocks. Although features with this morphology are traditionally classified as earthflows, activity on this landslide is mainly slumping and translational sliding. The presently active part of the earthflow is marked by a clearly defined crown scarp. Eight stake lines have been established at Site 7, six of them downslope from the crown scarp. The dominant forms of movement on the upper third of the earthflow are apparently slumping and translational sliding. The style of movement on the less steep, hummocky middle portion of the earthflow is not clearly discernible on aerial photographs or in the field; stake line surveys suggest that little differential movement is occurring in this portion of the slope. The toe of the earthflow moves dominantly by translational sliding. Most of the prairie bears grass and bracken fern vegetation. Stands of redwood and Douglas fir occur at the margins, in the major longitudinal gully in the middle of the earthflow, and on the lower portion of the slope above the streamside translational slides. Bare soil is exposed in gully walls, on the steep slope near stake line 4, and at the toe of the flow. Clayey colluvium and sedimentary rock fragments are transported to the creek by translational sliding and gullying. A concentration of large angular blocks, tens of feet in median diameter

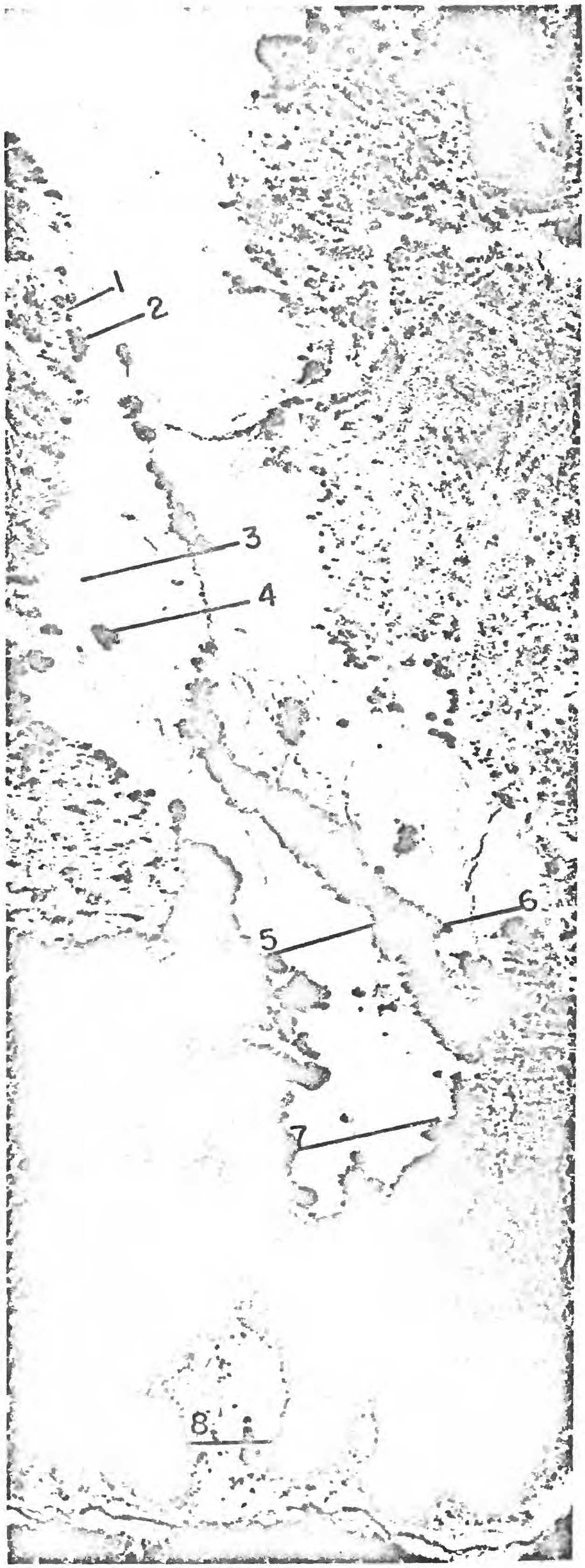

FIGURE 29. Aerial photograph showing mass movement monitoring Site 7, Counts Hill Prairie. Approximate scale 1:10,000. Photo taken September 1975.

in the creek, at the base of the earthflow, indicates that the earthflow has transported debris too large for stream transport through this reach. A transverse ridge of large coherent blocks of sandstone, chert, and conglomerate occurs immediately above the streamside translational slides. The apparently active part of the prairie downslope from the crown scarp is about 5000 feet (1520 m) long, 1100 feet (340 m) wide, and shows about 1500 feet (460 m) of relief.

Stake lines 1 and 2 transect the prairie above the prominent scarp at the head of the active earthflow; line 2 crosses an actively enlarging gully headwall. Line 3 is located just below the crown scarp in a gently sloping portion of the earthflow displaying little internal ground disruption. Stake line 4 transects the earthflow along the steepest portion of the slope in an area showing considerable ground disruption and exposed soil. Lines 5 and 6 are located on a gentle slope on the north and south (respectively) sections of the prairie, which are separated by a large forested gully. Line 7 crosses the prairie on a gentle slope just above the stand of redwood and Douglas fir that separates the prominent streamside slide from the main part of the earthflow. Line 8 is located on the active translational slide at the toe of the earthflow.

Site 8

Site 8, Bridge Creek Trail, is a small, dominantly translational slide adjacent to the west bank of Redwood Creek, about 1/2 mile (0.3 km) downstream from the mouth of Harry Wier Creek (figs. 1 and 21). This slide is underlain by schist, but its crown area involves considerable roadfill.

The slide is too small to be clearly seen on aerial photographs; a ground photo of the slide is shown in figure 30. Its length is about 200 feet (60 m), its width about 100 feet (30 m), and its relief about 70 feet (20 m). Uphill tilting of some trees at the margins of the slide suggests that some rotational movement has occurred in surrounding areas. Considerable bare soil is exposed in the scarps, where trees have been toppled, and at the toe of the slide. About half of the slide surface is vegetated with a mixture of grass, alders, and young conifers.

Site 9

Site 9, Elbow slide, is an old translational slide adjacent to the outside of a prominent bend along Redwood Creek shortly upstream from the Tall Trees Grove. This slide, which was discernible as a distinct, young, even-aged stand of trees in 1936 (figs. 1, 21, 30), has become increasingly active since 1972. The presently disrupted area is about 550 feet (170 m) in length, 300 feet (90 m) wide, and 300 feet (90 m) in relief. Movement in the vicinity of our stake lines appears to be dominantly translational, and the area of instability is apparently extending upslope. The upper portions of the slide show considerable ground disruption in the form of open cracks, depressions, and backward-rotated blocks, but the forest vegetation is intact except at the lateral edges of the slide, where trees are tilted downhill. The streamside edge of the slide is a bare, steep bank. Stake line 1 crosses the disrupted forested portion of the slide, and line 2 is located on the unvegetated streamside toe.

Two stake lines transect the slide. Line 1 is located at the top of the slide immediately below the scarp and line 2 is near the bare streamside toe.

FIGURE 30. Mass-movement monitoring Site 8, Bridge Creek Trail slide. Approximate width of slide is 100 feet (30 m) wide. Ground photograph taken September 1972.

FIGURE 31. Aerial photograph showing mass-movement monitoring Site 9, Elbow Slide. Approximate scale 1:5,000. Photo taken September 1975.

Site 10

Site 10, Berry Glen slide, is a translational slide in the headwaters of Berry Glen Creek which initially failed between July 1971 and March 1972, probably in response to the major storms of January and March 1972 (figs. 1, 21, 32). The slide is about 500 feet (150 m) long, 200 feet (60 m) wide and shows about 250 feet (80 m) of relief. The slide occurs along the Grogan Fault and is underlain by a sheared mixture of unmetamorphosed sedimentary rocks, transitional rocks, and schist. Sediment from the slide has caused considerable aggradation at the downstream end of the creek. The slide scar is vegetated at a few places by young alders, but most of the ground surface is bare. Both stake lines transect the middle third of the slide. The upper line (line 1) crosses a less steep portion of the feature than does line 2.

Installation of Stake Lines and Surveying Procedures

Stake-line sites were selected on the basis of aerial-photograph inspection and field reconnaissance. Multiple lines were installed at each site in order to monitor different types and rates of movement suggested by the detailed morphology of the site. Where possible, end stakes were located on stable ridges adjacent to the mass movement features. At several sites, where the adjacent hillslopes are themselves unstable, fixed end points could not be installed. Repeated surveys of these stake lines therefore detect only differential rates of surficial movement. At stake lines where the end stakes have moved considerably, stakes in more stable areas within the same line show apparent uphill displacements.

FIGURE 32. Aerial photograph showing mass-movement monitoring Site 10, Berry Glen slide. Approximate scale 1:5,000. Photo taken September, 1975.

Stakes were placed at regular intervals of 5, 10, or 15 feet (1.5, 3, or 5 m), depending on the length of the line. Stakes were occasionally omitted where brush or deep gullies occurred. The wooden stakes used are 3/4" x 1-1/2" (2 cm x 4 cm) across and approximately 22 inches (56 cm) long, with sharpened ends. Stakes were pounded approximately 15 inches (40 cm) into the ground, with the 1-1/2-inch (4-cm) side parallel to the stake line, and the long edge approximately vertical. The hardness of the ground at some lines established in August 1974 prevented penetration of more than 8 to 10 inches (25 cm). The hardness and rockiness of the ground also occasionally prevented stakes from being emplaced vertically; any tilted stakes were noted during installation and subsequent surveying. At Sites 5 and 6, angle iron was pounded into the ground around the uphill side of each stake to prevent loss of the stake lines during slash-burning operations.

At the Minor Creek earthflow (Site 2), a 6-inch (15-cm) stake was emplaced next to each 22-inch (55-cm) stake at stake line 2. This was done to measure any differential movement with depth. No differential movement or tilting of long and short stakes was observed, suggesting that at this stake line, translational movement is the dominant form of near-surface displacement. In addition, columns were excavated to a depth of 3 to 4 feet (0.9 to 1.3 m) with a post-hole digger at the ends and in the middle of stake lines 2 and 3. The columns were then filled with light-colored beach sand. Similar sand columns were also installed at stake lines 3 and 4 at Counts Hill Prairie (Site 7). Re-excavation of two columns was carried out in spring of 1976 in order to determine the differential movement rates at different depths. No internal deformation of the columns was detected although the surfaces of the excavated columns were displaced downhill; this further suggests that translational movement was dominant.

The original 1973 stake-line surveys were made with a transit, with which horizontal and vertical angles could be read to the nearest minute. After the initial surveys, a more accurate 10-second theodolite was used. At most sites, the instrument was located over one of the end stakes. At a few lines, where the topography or distance prevented sighting from one end to the other, it was necessary to establish a mid-line instrument station.

The stadia rod was consistently placed at the middle of the uphill side of the stake. A rod level was used for plumbing the rod. The instrument was sighted on the rod as close to the stake as topography and vegetation permitted in order to lessen the effects of inadvertent rod tilt. Stadia distances and vertical and horizontal angles were read at each stake.

Notes concerning stake tilting and apparent changes in ground surface stability were made during each survey. At some stake lines, detailed notes of microtopography, slope, vegetative cover, and soil conditions were made at each stake during the initial survey. Interpretation of movement patterns at all sites has been supplemented by repetitive photography of stake lines and ground-photograph overviews of the sites.

Using measured angles and stadia distances, the position of each stake relative to the line between end points was calculated. Changes in the deviation of each stake from this line were computed in order to measure stake movement between surveys. Computed deviations are expressed as horizontal rather than slope distances. Because of the restrictions on accuracy cited in the following paragraph, stake deviations are generally expressed to the nearest centimeter (Table 8). On stake lines where one or more stakes were lost, on long lines where a trigonometric solution was necessary to establish the base line, and on lines where the instrument stake moved, deviations are rounded to the nearest 3 centimeters (Table 8).

Several conditions introduce inaccuracy to the stake-line surveys. Because of highly irregular microtopography and deep gullies, stakes are often ten or more feet (3 or more meters) lower than the instrument. It is often necessary to sight high on the rod at these sites because the view of the base of the rod and the stakes is obstructed by the topography, vegetation, or debris. Other potential sources of inaccuracies are inconsistent rod placement, tilting of stakes, weather conditions such as high winds or heat shimmer, and operator variance in centering the theodolite sights on the rod to read horizontal angles. Since some stake lines are more than 400 feet (122 m) long, small inaccuracies in the reading of horizontal angles may produce significant differences in stake deviation. At stake lines where the instrument stake is located in the middle of the line, the instrument stake may move relative to the end points. In these cases, a trigonometric solution is needed to determine the movement of the instrument stake. This procedure increases the uncertainty of the surveys.

A major purpose in monitoring mass movement in the Redwood Creek basin was to obtain estimates of the basin-wide range in movement rates.

The need to make frequent measurements of many sites was greater than the need for great precision at a few stake lines. Measurements in nearby basins (Dwyer and others, 1971; Kelsey, 1977) suggest movement rates on active landslides are usually greater than 5 cm per year. Thus, the accuracy of ± 3 cm or better obtained in our field surveys is acceptable for our purposes.

Surveying Results

Table 8 summarizes surveying data collected between 1973 and 1976 at the mass-movement monitoring sites. It also shows rainfall figures from nearby recording gages. Because of its length, the Table is presented at the end of this paper. Graphs showing the deformation of stake lines at each site are shown on Plate 1. Only selected surveys are portrayed because of scale limitations. At line 2 of Site 3 and line 2 of Site 5, some stakes show apparent uphill displacement, owing to the instability of one or both end stakes. Stake lines at Site 6 are not portrayed in Plate 1 because almost no movement has been detected at these lines. In order to lessen some of the confusion associated with plotting the results of multiple surveys, different symbols, colors, and line patterns are used to portray the results of successive surveys. All surveys completed within one limited time period are plotted in the same manner. For example, all surveys completed during the autumn of 1973 are plotted with open red circles to show stake locations and connected with a solid red line, whereas all surveys completed during the spring of 1974 are plotted with solid black circles to show stake locations and are connected with a dashed black line.

Activity During 1973-1974

Persistent mass-movement processes were generally more active than episodic processes in the basin during the 1973-74 winter (1974 water year), probably reflecting exceptionally prolonged rainfall during the storm season. The 1973-74 winter was characterized by record amounts of precipitation, but rainfall intensities were not sufficient to produce significant flooding in the Redwood Creek basin. The total November 1973 rainfall at Prairie Creek State Park was 29.82 inches (757 mm) (U.S. National Oceanic and Atmospheric Admin., 1973). This is the greatest monthly precipitation recorded since establishment of that gage in 1937, and it is over 2-1/2 times the normal November rainfall (Janda and others, 1975, fig. 25). Rainfall was recorded for 33 of 34 consecutive days between October 31 and December 3. In addition to this period of unusually heavy and continuous rainfall early in the winter, the 1974 water year as a whole was the wettest on record since 1937. Rainfall at Prairie Creek State Park was 94.62 inches (2403 mm), well over the mean value of 70.48 inches (1790 mm) computed for Water Years 1938 to 1974 (U.S. National Oceanic and Atmospheric Admin., 1974; Janda and others, 1975, p. 87).

Stake-line surveys during the 1973-74 winter showed that earthflow sites were more active in the early part of the winter than during the later months or during the following winters (Appendix I). Movement was triggered by the unusually heavy and continuous rainfall in November 1973. Although movement continued through the spring, especially on the lower portions of flows, the greatest movement apparently occurred during

November and December. Some stake lines moved several feet, but others, notably most lines at Counts Hill Prairie (Site 7), showed no apparent differential movement. Stake lines on translational slides, at the Bridge Creek Trail (Site 8) and the Quarter Section site (Site 5) showed some movement during the 1973-74 winter, but appeared generally less active than the earthflow sites. At the Bridge Creek Trail Slide (Site 8), lateral cracks along the trail above the stake lines, which were first noted in the spring of 1972, enlarged considerably during the winter.

Activity during 1974-1975

The 1974-75 winter (1975 water year) was a season of nearly average total precipitation, but with one exceptionally intense storm. 71.41 inches (1814 mm) of rain were recorded at Prairie Creek State Park during the 1975 water year (U.S. National Oceanic and Atmospheric Admin., 1975). Rainfall during October through January was below normal. However, frequent heavy rain occurred during February and March, with a flood-producing, intense storm in March (fig. 11). As previously discussed, the regional rainfall distribution for the March 1975 storm suggests that the storm was centered on the middle third of the Redwood Creek basin (fig. 11).

Stake lines on earthflow sites and at some translational slides showed very little movement during the 1974-75 winter. Field observations immediately following the March storm, along with aerial reconnaissance and resurveying of selected stake lines during the last week in March, indicated that the storm did not trigger widespread movement of earthflows and slides within the basin. However, the March storm did result in substantial amounts of gullying and small-scale fluvial erosion, notably in and adjacent to landslides and in recently harvested timberland. The volume of storm runoff and sediment exceeded the capacity of pre-existing channels at several roadside culvert crossings, especially where drainage had been concentrated along roads and skid trails or at the edges of earthflows. These culvert blockages or washouts triggered gullies or mass failures, especially where runoff was diverted onto unstable hillslopes or roadfill. Similarly, enlargement or formation of gullies occurred where drainage was diverted into small water courses after interception and concentration of drainage along roads and skid trails. In addition, large gullies formed or enlarged on the naturally disrupted surfaces of several earthflows, including monitoring Sites 3 and 4 (fig. 33). Surveys of stake lines at these sites showed no mass movement as a result of the storm. Storm-induced fluvial erosion and shallow mass failures appear to have been concentrated in the central basin, where storm rainfall was most intense; sites along the Klamath and Korbel Road (fig. 1), apparently received the greatest storm damage in the basin.

An unusual form of shallow mass movement occurred during or immediately following the March 15 storm in a clearcut timber harvest unit above the Klamath and Korbel Road near Copper Creek (SW1/4 Sec 26 T9N R2E, Coyote Peak quadrangle). This unit had been cable-yarded with a high-lead system during the 1973-74 winter. Cable yarding, rather than tractor yarding was used to mitigate potential adverse impacts of timber harvest on slope stability, because the natural vegetation and ground surface configuration of the area indicated a prior history of mass movement. Tractor yarding was the dominant operating procedure in the basin at the time this slope was logged, and it was planned for this unit before the landowner recognized its inherent instability. However, bulldozer-excavated layouts were used in falling the trees. These shallow failures have not been checked on the ground, but when viewed from the air and from adjacent hillslopes, they appear to be several hundred square feet in area and to involve the uppermost two or three feet of soil (fig. 34). Within this 160-acre (65-hectare) unit, about 10 failures occurred. Movement appears to have been by translational sliding. Most of the slide debris was redistributed locally on the hillslope and did not get directly into through-going drainageways.

The reason for these slides is unknown, but we believe that they are probably related to timber harvest, as no similar failure patterns have been observed on uncut hillslopes in the basin. The slides probably occurred too soon after harvest to be related to a loss of root strength (O'Laughlin, 1974). Some of the failures apparently occurred where the bulldozer-constructed layouts disrupted natural drainageways to form small midslope depressions. The cable yarding of this unit was carried out during November 1974, an exceptionally wet period; it is possible that small slope failures were initiated during yarding, but were not large enough to be seen from a distance or on aerial photographs until after the March 1975 storms. It also is possible that increased runoff from recently harvested areas upslope, or increased soil water pore pressures due to decreased evapotranspiration, played some role. Although

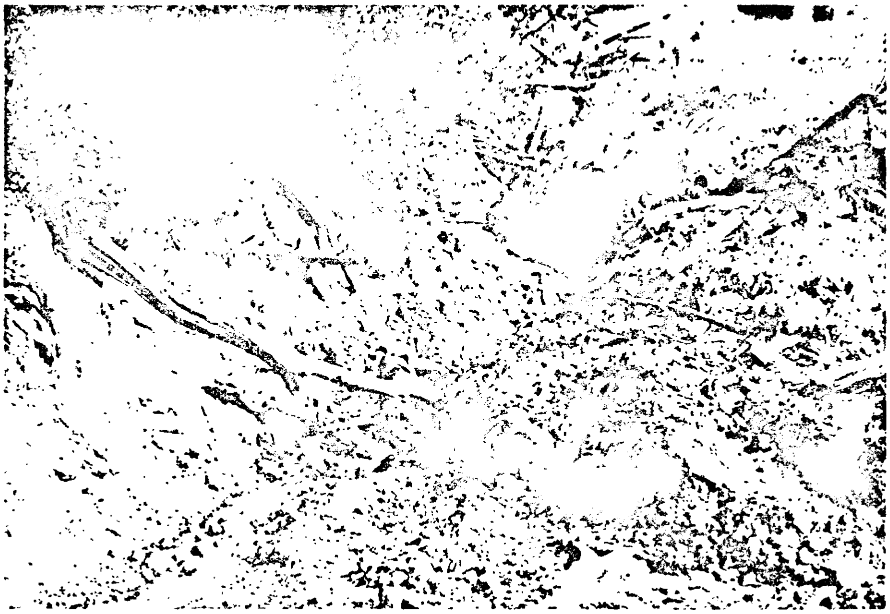

FIGURE 33. Gully at the northern margin of monitoring Site 4. This gully became enlarged, and large amounts of sediment were transported during the March 18, 1975 storm. The depositional cone shown in the right foreground was formed at the intersection of the gully with the Klamath-Korbel road, which is just beyond the foreground of the photograph. The gully is about 10 feet (3 m) across above the cone.

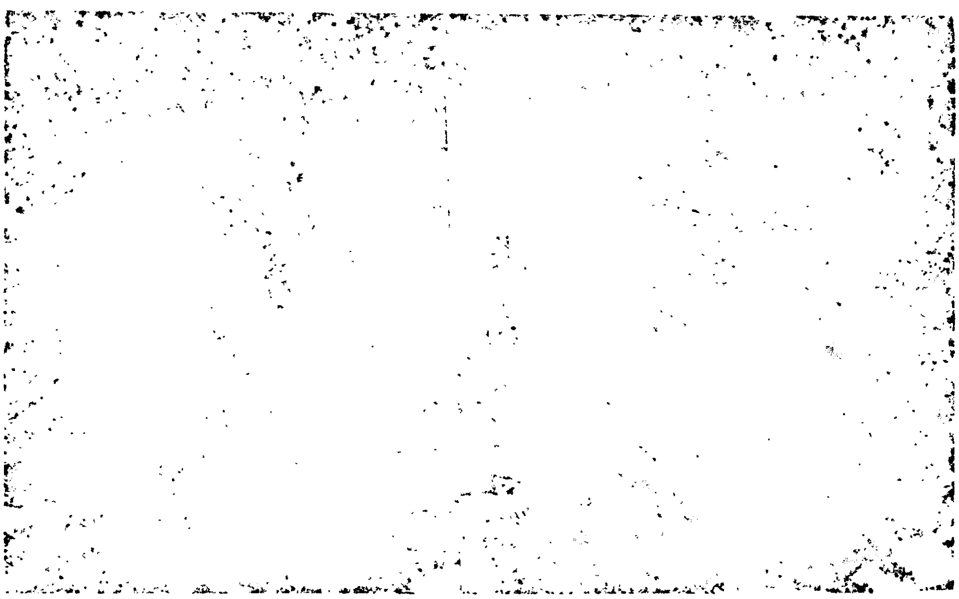

FIGURE 34. Shallow slope failures initiated during the March 1975 storm. The large conifer in the middle right of the photograph is about 250 feet (76 m) tall. Features are most prominent in the lower left corner of each photo included in this stero pair.

these slides have not transported large amounts of sediment to through-flowing streams, they may become major sediment sources if they remain active and become enlarged, as was suggested during January 1976 field inspection. At any rate, these slides will hinder regeneration of the unit. The occurrence of these slides raises questions as to the effectiveness of this mode of logging in reducing harvest-induced erosion on marginally stable hillslopes in the environs of Redwood National Park.

Earthflow-monitoring sites were much less active during the 1974-75 winter than in the previous winter (Plate 1, Table 8). Many stake lines on the upper portions of flows showed almost no detectable movement. Nonetheless, stake lines near the toes of earthflows, where movement is mostly by translational sliding, rather than by slumping or flowing, showed noticeable displacement. For example, the toe of Poison Oak Prairie (Site 1) was very active, especially following the March storm, but the upper line was less active than during the previous winter.

Other mass-movement monitoring sites showed different amounts of movement during the 1974-75 winter. Stake lines on the M-7-5 patchcut harvest unit and adjacent forested unit (Site 6) showed no apparent movement, but considerable small-scale gullying and local sediment movement took place in the harvested unit during storms, especially during the March 18 storm. Most of this erosion took place along bulldozer-constructed fire breaks or layouts. Stake lines on the Berry Glen slide, Site 10, showed little movement, but small blocks of colluvium and rock were observed to be mobilized, especially near the crown and western edge of the slide.

The remaining three sites were active during the 1974-75 winter. At the Elbow slide, Site 9, which has appeared increasingly active on successive aerial photographs since 1973, pull-away scarps and cracks at the head of the slide became more pronounced during the 1974-75 winter. The toe of this slide appeared steeper in August 1975, and more bare mineral soil was exposed than during the previous summer; stakes moved several feet on the lower stake line (Plate 1).

The slide along the Bridge Creek Trail, Site 8, enlarged laterally to increase its area at the crown of the slide about two-fold during the March 18 storm. Because this failure displaced the reference points on both ends of the stake lines, we were unable to document the amount of downhill movement by resurveying the lines, but the locations of the remaining stakes on the hillslope indicate that average displacement was a few feet. Monitoring at Site 8 was discontinued in the summer of 1975. Instability at this site was aggravated by man-made diversion of runoff into the general slide area and by the added weight of the roadfill. At least four other sites along the Bridge Creek trail suffered significant damage from gullying and sliding during the March storm. These slides originate in poorly drained roadfill and supply sediment directly into Redwood Creek (fig. 3).

Stake lines at the Quarter Section slide, Site 5, also showed considerable movement during the 1974-75 winter with the exception of the stake line in the prairie (line 3). Stake line 1, in the cutover portion of an old landslide, was more active than during the previous year. The remaining lines (2 and 4) showed less movement than during the previous year. The area including the upper stake lines (lines 1 and 2) showed visible gullying, small slumps of skid trail walls, and deposition of woody debris over several stakes; most of the debris appears related to logging.

Activity during 1975-1976

Stake lines at several monitoring sites still showed readily detectable movement during the 1976 water year, even though the 1975-76 winter was unusually dry. Only 57.02 inches (1448 mm) of rain fell at Orick-Prairie Creek State Park during the 1976 water year. October rainfall was well above average, as was August rainfall. February rainfall was also greater than average, but the remaining winter months had less than average precipitation.

Poison Oak Prairie, Site 1, was at least as active during the 1975-76 winter as it was during the unusually wet 1973-74 winter. The lower half of the earthflow has apparently become so unstable that small amounts of rain can trigger additional movement. This earthflow has become increasingly active since 1973, and it appears that the entire hillslope below stake line 2 may soon become a bare streamside translational slide.

Stake lines on earthflows other than at Site 1 showed less movement during the 1975-76 winter than during the previous winters. Only lines at the toes of these sites and line 4 at Counts Hill Prairie showed significant displacement. It is interesting to note that detectable movement occurred on active lines on earthflows between April and November, although less than 7 inches (178 mm) of rain fell in this interval. This late movement could have occurred at the end of the rainy season in April or May, in response to the mid-August rain of about 2.5

inches, or at both times. Another possibility is that some movement occurs throughout the dry season, especially at the most unstable lines.

At Site 5, stake lines 2 and 3 were more active during 1975-76 than during the previous winter (Plate 1, Table 8). Lines 1 and 4 also showed considerable movement. Although the cutover areas have regenerated since the 1973-74 winter, instability in those areas has persisted. In the uncut slide areas, both in the forest and the prairie, activity apparently increased in the 1975-76 winter.

Stake lines 1 and 3 at Site 6, M-7-5 patchcut, showed no detectable movement during the 1975-76 winter. Bulldozer construction of a fire break and windfall at the edge of the patchcut destroyed about half the original stakes at line 2. Stake lines at Site 10, Berry Glen slide, showed almost no movement during 1975-76. Site 9, Elbow slide, also showed much less movement than during the previous winter.

Implications Of Field Measurements

Some general conclusions concerning the movement of common types of large landslides in the Redwood Creek basin can be drawn from data collected at the monitoring sites and from other recent field observations. The stake line surveys suggest that during some winters the duration and (or) quantity of rainfall are insufficient to activate the earthflows. In order for earthflows and slides to become active, they must become wet at depth. For earthflows this occurs only after prolonged rainfall. It follows that the maximum annual movement rates could be expected when periods of persistent heavy rainfall occur early in the rainy season, as was the case during the 1973-74 winter. Brief intense bursts of rainfall may not in themselves saturate the full depths of earthflows and potential debris slides, but such bursts may still result in rapid runoff and surface erosion in landslide areas.

Because measured rainfall during the 1973-74 winter, particularly during the early part of the season, was of record magnitude, the observed displacements of our stake lines for this interval may provide a reasonable estimate of the upper limit on surficial movement rates for earthflows and persistent slides in the basin. The stake line on an earthflow that consistently shows the greatest movement between surveys is line 3 at Poison Oak Prairie (Table 2) which transects the steep, raw toe of this earthflow about 100 feet upslope from the stream channel (fig. 22). During the 1973-74 winter the average movement of stakes in this line probably was not more than 30 feet (9 m). This average assumes that all lost stakes moved by some form of landsliding into the Redwood Creek channel and were not washed out of the slide. The intense ground surface disruption and lack of vegetation at this site suggest that it is one of the most active landslides in the Redwood Creek basin. Although more rapid movement rates are reported for nearby areas (Dwyer and others, 1971; Kelsey, 1977), we believe that earthflows and persistent translational slides in the Redwood Creek basin rarely show maximum movement of more than 30 feet (9 m) per year.

Less than five percent of the mass-movement features adjacent to Redwood Creek and its tributaries display displays ground-surface configurations suggestive of the rapid rate of persistent movement observed at the toe of Poison Oak Prairie. This conclusion is based upon a comparison of the appearance of all streamside landslides in the basin on aerial photographs. Of about 146 streambank miles (235 km) of slides, debris avalanches, earthflows, and unstable streambanks shown on the erosional landform map (Nolan, Harden, and Colman, 1976), only about 5 streambank miles (8 km) appear to be highly erodible, persistent earthflows and slides comparable to Poison Oak Prairie. Streamside landslides whose toes are dissected by gullies, or are densely vegetated, are interpreted to be less active than Poison Oak Prairie. In addition, landslides traversed by roads are not included in the most active group of landslides if the road remained intact over a period of years.

Streamside slides and debris avalanches which appear to fail instantaneously or episodically may move tens of feet in a period of minutes or hours. However, these episodic features probably are not as active on an average annual basis as are such features as the toe of Poison Oak Prairie. Indeed, many streamside debris slides and avalanches appear to fail suddenly and then to provide additional sediment to the stream system only by small-scale fluvial processes and sloughing that persists until the failure surface is revegetated. Landslide movement changes the distribution of mass and the stress pattern on hillslopes so that rates and times of movement correlate only roughly with amounts and intensities of rainfall. Recent movement at Poison Oak Prairie (Site 1) has apparently made the site more susceptible to additional movement. Similarly, many small streamside slides initiated during the 1953 and 1955 storms greatly enlarged in subsequent years, particularly during the 1964 flood (fig. 20). On the other hand, landslide movement may temporarily lead to increased stability at some marginally stable sites.

For example, the slides at Line 4, Site 5, Site 8, and Site 10, as well as some of the massive streamside slides resulting from the 1964 flood have apparently achieved a reasonably stable configuration. These areas have recently been eroding primarily by sloughing around the margins of the slides and by sheet and rill erosion of unvegetated parts of the main slide scars.

Field observations indicate that earthflows contribute sediment to stream channels mostly in two contrasting ways: 1) sloughing and washing of material directly into major channels at the unvegetated toes of flows, and 2) fluvial transport of sediment through gullies on the flows themselves. On the basis of the rate of change of morphology of earth-flow toes observed on air photographs and in the field, and on the basis of winter field observations, it appears that even during winters when earthflows are especially active the amount of sediment supplied directly to creeks by sloughing (that is to say, small-scale sliding, slumping, and flowing) is minor in the Redwood Creek basin. However, mass movement also plays an indirect role in accounting for fluvial sediment transported from these landslides. Movement disrupts vegetative cover, exposing bare surfaces, and forms cracks that often initiate gullies. Continued mass movement supplies additional sediment to gullies, and particularly vigorous movement may lead to avulsion and (or) capture of parts of these gully networks. The amount of sediment eroded by fluvial processes from these areas varies greatly from site to site. Although quantitative data from the Redwood Creek basin are lacking, qualitative observations during periods of particularly intense rainfall suggest that at intensively gullied earthflows and slides, such as those at monitoring sites 2 and 3, the amount of sediment removed by fluvial processes is quite substantial. For example, the volume of an alluvial cone deposited during the March 18, 1975 storm on and immediately downslope from the Klamath-Korbel Road by the gully system along the northern edge of Devils Creek earthflow (Site 4) appears to exceed greatly the volume moved en masse past the upper stakelines (Plate 1, Site 4, stake lines 1 and 2) during the entire 1975 water year. In a study of a severely disrupted earthflow in the Van Duzen River basin, Kelsey (1977) estimated that several times more sediment leaves that feature annually by fluvial transport than by mass movement.

CONCLUSIONS

The Redwood Creek basin has been sculpted by a complex suite of fluvial and mass-movement erosion processes. The basin possesses some attributes of both the debris-avalanche terrain and the slump-earthflow terrain described by Swanston and Swanson (1976) and Kelsey (1977). However, the hillslopes are on the average not so steep as in typical debris-avalanche terrain, and the rocks are on the average not so pervasively sheared or hydrothermally altered as in typical slump-earthflow terrain.

The number of landslides along Redwood Creek has increased over four times from 1947 to 1976. Major recent episodes of streamside landslide activity generally occurred during times of intense regional flooding. Erosional impacts of the 1964 and later floods on hillslopes were augmented by destabilizing effects of earlier floods and timber harvest. Photo-interpretive analysis of streamside landslide and timber-harvest history, together with analysis of rainfall patterns of flood-producing storms of the past 25 years, indicate that both recent floods and logging have contributed to increased hillslope instability over the last 30 years. However, complex interactions between storm distribution, storm intensity, and location and timing of streamside timber harvest prevent recognition of one dominant cause of increased slide activity except in a few specific instances. The two most straightforward lines of evidence which point to human activities as a major contributor to dramatic increases in streamside landslide activity in recent years are provided by (1) the frequent association of slides with road cuts, fills, and drainage structures and (2) the disproportionately large erosional impacts of the 1964 and 1972 storms relative to the strikingly lesser impacts associated with storms of comparable magnitude that occurred in the late 19th century as well as in 1953 and 1955.

Stake-line surveys suggest that persistent processes operating on hillslopes, such as earthflow and slumping, are influenced more by prolonged rainfall of moderate intensity than by intense flood-producing storms. In contrast, time-sequential aerial photographs suggest that episodic mass failures, such as debris slides and debris avalanches, are associated with the intense storms. However, landslide movement itself changes the distribution of mass and the stress pattern on hillslopes so that rates and times of movement do not correlate precisely with amounts and intensities of rainfall. Even during periods favoring maximum earthflow movement, the surveys suggest that these features in the

Redwood Creek basin are significantly less active than those in other nearby North Coast basins (Dwyer and others, 1971; Kelsey, 1977). Stake-line surveys on two recently harvested hillslopes have not documented exceptionally high mass-movement rates in the 2-3 years following timber harvest, even in slide-prone areas (monitoring site 5). Our studies of mass movement suggest that it alone cannot account for the nature of the sediment in the Redwood Creek channel. The lithologic diversity of the alluvium suggests that attempts to reduce the sediment load of Redwood Creek will not be able to focus only on one particular process or lithologic terrain. Although the role of fluvial-erosion processes in supplying sediment to Redwood Creek has not been quantitatively evaluated, we have observed that fluvial processes may at times be the dominant erosional mechanisms, even on mass movement features such as earthflows.

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TABLE 8. Summary of stake line surveys at mass-movement monitoring sites.

Date of Survey	Number of Stakes Lost Since Previous Survey	Maximum Movement Since Previous Survey (cm)	Average Movement Since Previous Survey (cm)	Rainfall Since Previous Survey (mm)
		Poison Oak Prairie (Site 1)		
		Line 1 Total distance 107.5 m 37 stakes in original survey		
10/25/73	-	-	-	-
1/15/74		15	3*	1700[2]
3/23/74		55	3	645[2]
7/23/74		68	24	490[2,3]
2/28/75		9	2	1435[4]
4/01/75		21	3	645[4]
1/19/76		31	3	1115[4]
4/05/76		37	10	515[4]
		Poison Oak Prairie (Site 1)		
		Line 2 Total distance 120.5 m 35 stakes in original survey		
10/29/73	-	-	-	-
1/15/74		220	93*	1690[2]
3/23/74		179	58*	645[2]
4/17/74		66	24*	405[2]
7/23/74		92	25*	85[2,3]
12/03/74	1	>150[7]	11*	315[3,4]
2/28/75		181	70*	1120[4]
4/01/75	1	>150[7]	37*	645[4]
1/16/76		396	112*	1115
4/15/76		132	47*	561

TABLE 8. Summary of stake line surveys at mass-movement monitoring sites.

Date of Survey	Number of Stakes Lost Since Previous Survey	Maximum Movement Since Previous Survey (cm)	Average Movement Since Previous Survey (cm)	Rainfall Since Previous Survey (mm)
		Poison Oak Prairie (Site 1)		
		Line 3 Total distance 145.5 m 47 stakes in original survey		
10/29/73	-	-	-	-
3/23/74	25	>1000[7]	-	2335[2]
7/23/74	1	>600[7]	-	490[2,3]
8/08/75	20	>1000[7]	-	2270[3,4]
1/16/76	6	>1000[7]	-	925[4]
4/05/76	2	>500[7]	-	515[4]
10/15/76	4	>500[7]	-	155[4]
		Minor Creek (Site 2)		
		Line 1 Total distance 132.0 m 44 stakes in original survey		
3/24/74	-	-	-	-
7/16/74		18	9	490[2,3]
7/25/75		20	9	2255[3,4]
11/23/76		38	17	1735[4]
		Minor Creek (Site 2)		
		Line 2 Total distance 84.5 m 27 stakes in original survey		
10/23/73	-	-	-	-
12/15/73		152	79	1215[2]
3/24/74		16	4	1145[2]
4/17/74		5	0	405[2]
7/16/74		5	2	85[2,3]
12/03/74		7	1*	315[3,4]
1/30/75		9	3*	650[4]
4/01/75		10	2	1115[4]
7/25/75		5	0	175[4]
4/28/76		9	2	1520[4]
10/01/76		14	6	95[4]

TABLE 8. **Summary of stake line surveys at mass-movement monitoring sites.**

Date of Survey	Number of Stakes Lost Since Previous Survey	Maximum Movement Since Previous Survey (cm)	Average Movement Since Previous Survey (cm)	Rainfall Since Previous Survey (mm)
		Minor Creek (Site 2) Line 3a Total distance 102.0 m 34 stakes in original survey		
10/26/73	-	-	-	-
3/23/74		29	19	2345[2]
3/23/75		27	14*	2495[2,3,4]
8/05/75		9	5*	255[4]
4/06/76		9	5	1455[4]
		Minor Creek (Site 2) Line 3b Total distance 87.5 m 28 stakes in original survey		
10/26/73	-	-	-	-
12/16/73		163	76	1265[2]
3/23/74		54	23	1080[2]
4/17/74		5	0	405[2]
7/16/74		5	2	85[2,3]
1/30/75		9	3	960[3,4]
3/23/75		4	2	1040[4]
8/05/75		9	1	255[4]
4/06/76		10	2	1455[4]
		Minor Creek (Site 2) Line 4a Total distance 100.0 m 31 stakes in original survey		
10/25/73		-	-	-
3/24/74		11	0	2335[2]
7/17/74		16	4	490[2,3]
8/05/75		7	2	2255[3,4]

TABLE 8. Summary of stake line surveys at mass-movement monitoring sites.

Date of Survey	Number of Stakes Lost Since Previous Survey	Maximum Movement Since Previous Survey (cm)	Average Movement Since Previous Survey (cm)	Rainfall Since Previous Survey (mm)
		<u>Minor Creek (Site 2)</u> Line 4b Total distance 74.5 m 23 stakes in original survey		
10/25/73	-	-	-	-
12/16/73		106	29	1180[2]
3/24/74		42	12	1145[2]
4/17/74		22	8	405[2]
1/30/75		26	8	965[3,4]
8/05/75		9	3	1290[4]
4/06/76		6	0	1455
		<u>Minor Creek (Site 2)</u> Line 5 Total distance 73.0 m 18 stakes in original survey		
7/17/74	-	-	-	-
1/30/75		16	3	960[3,4]
8/05/75		55	13	1290[4]
1/21/76		20	6	940[4]
4/06/76		84	15	515[4]
10/14/76		40	12	155[4]
		<u>Rain Gage Slide (Site 3)</u> Line 1 Total distance 58.0 m __ stakes in original survey		
8/20/74	-	-	-	-
12/12/74		5	2	350[5]
1/29/75		ND[8]	ND[8]	500[5]
3/05/75		3	1	545[5]
4/17/75		ND[8]	ND[8]	735[5]
8/06/75		ND[8]	ND[8]	130[5]
1/20/76		7	1	1020[5]
4/15/76		5	0	615[5]

TABLE 8. **Summary of stake line surveys at mass-movement monitoring sites.**

Date of Survey	Number of Stakes Lost Since Previous Survey	Maximum Movement Since Previous Survey (cm)	Average Movement Since Previous Survey (cm)	Rainfall Since Previous Survey (mm)
		Rain Gage Slide (Site 3) Line 2 Total distance 55.0 m 18 stakes in original survey		
8/20/74	-	-	-	-
12/12/74		5	1	350[5]
8/06/75		58	20*	1910[5]
4/15/76		54	15*	1640[5]
		Devils Creek Earthflow (Site 4) Line 1 Total Distance 152.5 m 37 stakes in original survey		
8/14/74	-	-	-	-
8/06/75		14	3	2260[3,5]
10/06/76		14	2	1760[5]
		Devils Creek Earthflow (Site 4) Line 2 Total distance 83.5 m 29 stakes in original survey		
8/19/74	-	-	-	-
1/29/75		6	0	850[3,5]
3/05/75		5	2	545[5]
8/06/75		6	0	865[5]
4/22/76		5	0	1650[5]
		Devils Creek Earthflow (Site 4) Line 3 Total distance 105.5 m 21 stakes in original survey		
8/19/74	-	-	-	-
8/06/75	1	>150[7]	80*	2255[3,5]
4/15/76		95	37*	1640[5]

TABLE 8. Summary of stake line surveys at mass-movement monitoring sites.

Date of Survey	Number of Stakes Lost Since Previous Survey	Maximum Movement Since Previous Survey (cm)	Average Movement Since Previous Survey (cm)	Rainfall Since Previous Survey (mm)
		Quarter Section (Site 5) Line 1 Total distance 78.0 m 31 stakes in original survey		
11/28/73	-	-	-	-
7/10/74		127	37*	2075[2,3]
7/28/75	4	>100[7]	52*	2260[3,5]
10/05/76		71	34	1760[5]
		Quarter Section (Site 5) Line 2 Total distance 41.0 m 27 stakes in original survey		
11/27/73	-	-	-	-
7/10/74		29	14*	2075[2,3]
7/28/75		36	21*	2260[3,5]
10/05/76		62	29*	1760[5]
		Quarter Section (Site 5) Line 3 Total distance 152.5 m 48 stakes in original survey		
11/28/73	-	-	-	-
7/09/74		119	21*	2075[2,3]
7/28/75		14	4*	2260[3,5]
10/03/76		59	16	1760[5]

TABLE 8. **Summary of stake line surveys at mass-movement monitoring sites.**

Date of Survey	Number of Stakes Lost Since Previous Survey	Maximum Movement Since Previous Survey (cm)	Average Movement Since Previous Survey (cm)	Rainfall Since Previous Survey (mm)
		Quarter Section (Site 5) Line 4 Total distance 64.0 m 22 stakes in original survey		
11/29/73	-	-	-	-
12/15/73		4	0	355[2]
7/09/74		98	35	1720[2,3]
7/28/75		23	8	2260[3,5]
10/03/76		24	8	1760[5]
		M-7-5 Slope (Site 6) Line 1 Total distance 35.5 m 12 stakes in original survey		
12/05/73	-	-	-	-
7/14/74		2	0	1875[2,3]
8/07/75		1	0	2260[3,5]
9/21/76		4	1	1760[5]
		M-7-5 Slope (Site 6) Line 2 Total distance 64.5 m 24 stakes in original survey		
1/14/74	-	-	-	-
7/14/74		3	0	1230[2,3]
8/07/75		ND[8]	ND[8]	2260[3,5]
9/21/76		ND[8]	ND[8]	1760[5]
		M-7-5 Slope (Site 6) Line 3 Total distance 56.5 m 20 stakes in original survey		
1/14/74	-	-	-	-
7/14/74		6	0	1230[2,3]
8/07/75		ND[8]	ND[8]	2260[3,5]
9/21/76		ND[8]	ND[8]	1760[5]

TABLE 8. **Summary of stake line surveys at mass-movement monitoring sites.**

Date of Survey	Number of Stakes Lost Since Previous Survey	Maximum Movement Since Previous Survey (cm)	Average Movement Since Previous Survey (cm)	Rainfall Since Previous Survey (mm)
		<u>Counts Hill Prairie (Site 7)</u> Line 1 Total distance 72.0 m 24 stakes in original survey		
10/30/73	-	-	-	-
7/12/74		ND[8]	ND[8]	2825[2,3]
7/29/75		ND[8]	ND[8]	2440[3,5]
5/11/76		ND[8]	ND[8]	1655[5]
		<u>Counts Hill Prairie (Site 7)</u> Line 2 Total distance 86.5 m 28 stakes in original survey		
10/30/73	-	-	-	-
7/12/74		ND[8]	ND[8]	2825[2,3]
7/28/75		ND[8]	ND[8]	2440[3,5]
5/07/76		4	1	1655[5]
		<u>Counts Hill Prairie (Site 7)</u> Line 3 Total distance 224.0 m 49 stakes in original survey		
10/17/73	-	-	-	-
3/04/74		13	4*	2220[2]
7/11/74		8	2	505[2,3]
1/21/76		14	2	3465[3,5]
11/12/76		20	7	795[5]

TABLE 8. **Summary of stake line surveys at mass-movement monitoring sites.**

Date of Survey	Number of Stakes Lost Since Previous Survey	Maximum Movement Since Previous Survey (cm)	Average Movement Since Previous Survey (cm)	Rainfall Since Previous Survey (mm)
		Counts Hill Prairie (Site 7) Line 4 Total distance 152.5 m 32 stakes in original survey		
10/28/73	-	-	-	-
12/14/73		98	23*	1110[2]
3/04/74	2	>150[7]	16*	1120[2]
7/11/74		25	5	595[2,3]
12/12/74		7	2*	420[3,5]
1/29/75		6	1*	545[5]
3/05/75		7	2	545[5]
4/17/75		60	8*	765[5]
7/28/75		16	3*	165[5]
1/20/76		12	4	1025[5]
5/03/76		25	0	630[5]
10/05/76		11	4*	110[5]
		Counts Hill Prairie (Site 7) Line 5 Total distance 141.0 m 32 stakes in original survey		
10/30/73	-	-	-	-
3/22/74		ND[8]	ND[8]	2335[2]
7/13/74		ND[8]	ND[8]	490[2,3]
8/07/75		2	0	2440[3,5]
4/20/76		ND[8]	ND[8]	1645[5]
		Counts Hill Prairie (Site 7) Line 6 Total distance 126.0 m 26 stakes in original survey		
10/30/73	-	-	-	-
3/22/74		57	13	2335[2]
7/28/75		26	3	2930[2,3]
5/11/76		8	2	1655[5]

TABLE 8. Summary of stake line surveys at mass-movement monitoring sites.

Date of Survey	Number of Stakes Lost Since Previous Survey	Maximum Movement Since Previous Survey (cm)	Average Movement Since Previous Survey (cm)	Rainfall Since Previous Survey (mm)
		Counts Hill Prairie (Site 7) Line 7 Total distance 213.5 m 46 stakes in original survey		
10/30/73	-	-	-	-
3/22/74		ND[8]	ND[8]	2335[2]
7/13/74		ND[8]	ND[8]	490[2,3]
8/07/75		ND[8]	ND[8]	2440[3,5]
4/20/76		ND[8]	ND[8]	1645[5]
		Counts Hill Prairie (Site 7) Line 8 Total distance 84.5 m 27 stakes in original survey		
8/28/74	-	-	-	-
8/07/75	1	>150[7]	13*	2410[3,5]
4/13/76		26	9*	1635[5]
11/10/76		-	-	155[5]
		Bridge Creek Trail (Site 8) Line 1 Total distance 24.5 m 17 stakes in original survey		
10/31/73	-	-	-	-
2/11/74		7	3*	1900[2]
7/26/74		1	4*	925[2,3]
4/10/75		See text, page		
		Bridge Creek Trail (Site 8) Line 2 Total distance 32.5 m 19 stakes in original survey		
10/31/73	-	-	-	-
2/11/74		23	8	1900[2]
7/26/74		8	2	925[2,3]
4/10/75		See text, page		

TABLE 8. **Summary of stake line surveys at mass-movement monitoring sites.**

Date of Survey	Number of Stakes Lost Since Previous Survey	Maximum Movement Since Previous Survey (cm)	Average Movement Since Previous Survey (cm)	Rainfall Since Previous Survey (mm)
		Elbow Slide (Site 9) Line 1 Total distance 62.5 m 18 stakes in original survey		
8/06/74	-	-	-	-
8/01/75		97	44	2440[3,5]
9/20/76		12	4	1760[5]
		Elbow Slide (Site 9) Line 2 Total distance 46.5 m 18 stakes in original survey		
8/06/74	-	-	-	-
8/01/75	9	>600[7]	-	2440[3,5]
9/20/76		460	98*	1760[5]
		Berry Glen Slide (Site 10) Line 1 Total distance 67.0 m 20 stakes in original survey		
7/30/74	-	-	-	-
3/06/75		10	3	1165[6]
5/19/75		23	7	625[6]
4/19/76		24	1	1345[6]
		Berry Glen Slide (Site 10) Line 2 Total distance 58.0 m 17 stakes in original survey		
7/30/74	-	-	-	-
3/06/75		3	0	1165[6]
5/19/75		29	0	625[6]
4/19/76		ND[8]	ND[8]	1345[6]

TABLE 8. Summary of stake line surveys at mass-movement monitoring sites.

1 Averages computed are accurate to the nearest centimeter, except where followed by an asterisk (*). In these cases, averages are probably accurate only within 3 centimeters. Limits on surveying accuracy are described on page .
Rainfall values are given to the nearest 5 millimeters.

2 Rainfall at Elk Camp rain gage.

3 Rainfall for summer 1974 months extrapolated from Orick data.

4 Rainfall at rain gage at Minor Creek slide (Site 2), installed October 1974.

5 Rain gage was installed at Site 3 in October 1974. Where possible, rainfall values listed for Sites 3-6 are those measured at rain gage at Site 3; values for Sites 7-9 are those measured at Elk Camp rain gage. During inoperative periods of one gage, values for the other gage were used, as values appear to be similar at the two sites. It should be noted that the Elk Camp gage was inoperative during the entire 1975-76 winter. Inoperative periods are listed below:

Site 3 rain gage inoperative:	Elk Camp rain gage inoperative:
11/25/74 - 11/28/74	12/22/74 - 12/30/74
12/5/74 - 12/20/74	1/8/75 - 1/13/75
3/19/75 - 3/25/75*	1/17/75 - 2/3/75
7/1/75 - 9/30/75	3/14/75 - 4/4/75*
	10/1/75 - 11/12/76

* During period when both gages were inoperative, value was extrapolated from other recording gages and nearby storage gages.

6 Rainfall at Prairie Creek State Park.

7 Indicates that one or more stakes was lost. Values given are less than maximum possible distance from stake line to creek, as some stakes could have been buried after moving only a short distance. Values listed were used in determining average movement. Average movements were not determined if more than 4 of the original stakes were lost and not subsequently replaced.

8 Movement not detectable beyond probable limits of surveying precision.