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

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

K.M. NOLAN, H.M. KELSEY, *and* D.C. MARRON, *Editors*

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–A

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SUMMARY OF RESEARCH IN THE REDWOOD CREEK BASIN, 1973–83

By K.M. Nolan,[1] H.M. Kelsey,[2] and D.C. Marron[1]

ABSTRACT

Concern for the effects of timber harvest activities on resources of Redwood National Park stimulated extensive study of geomorphic processes and aquatic habitat in the Redwood Creek basin. This article summarizes work of 32 investigators working in the Redwood Creek basin between 1973 and 1983. The work of these investigators is reported in the 22 articles that follow. This volume describes a rapidly eroding landscape that is sensitive to effects of both land use and major storms.

INTRODUCTION

In 1968, the U.S. Congress passed legislation establishing Redwood National Park in northwestern California. This 235-km^2 park was designed to preserve significant examples of virgin coastal redwood (*Sequoia sempervirens*) forests. Most of the parkland was located in the downstream one-third of the Redwood Creek drainage basin. The boundaries of the park included a narrow 12.9-km-long, 244-m-wide corridor designed to protect the spectacular redwood groves found on alluvial flats along the lower Redwood Creek channel. The grove of most interest, the Tall Trees Grove, contained the first, third, and sixth tallest known trees.

Soon after Redwood National Park was established, conservation groups and government agencies became concerned that timber harvesting on private lands upstream and upslope was threatening resources of the newly created park. These agencies believed that timber harvesting activities had the potential to increase runoff and sediment production in this rapidly eroding drainage basin and that the increases would lead to degradation of parkland resources. Because of this growing concern, studies of erosion, sediment transport, and aquatic habitat were initiated throughout the basin in 1973.

The studies were designed both to understand natural processes within the basin and to assess how timber harvesting within the basin had affected these processes. Results from much of this research indicated that timber harvesting was capable of increasing the naturally high rates of erosion in Redwood Creek. As a consequence, Congress authorized expansion of Redwood National Park in 1978 to 534 km^2. In addition to the area added, 100 km^2 directly upstream of the park were designated a park protection zone in which timber harvest operations were to be reviewed by the National Park Service.

The papers in this volume are a compilation of work by 32 investigators who studied diverse aspects of geomorphic processes and aquatic habitats in the 725-km^2 drainage basin of Redwood Creek between 1973 and 1983. During this time, land management in the vicinity of Redwood National Park was the subject of three lawsuits and multiple congressional hearings. Consequently, results of much of the initial research conducted in the Redwood Creek basin appeared only in reports prepared for a specific trial or hearing. This volume has been assembled to update these initial findings and to compile results of virtually all research accomplished in the basin.

Most of the Redwood Creek research represents a cooperative effort between the U.S. Geological Survey and the National Park Service. This cooperative effort provided the opportunity to develop an understanding of the physical and biological processes throughout the Redwood Creek basin. Study of erosional processes in this basin has proved rewarding because of the intensity of the study effort and because of the rapid rate at which processes operate. Because processes operate so rapidly, researchers have been able to make frequent observations of geomorphic change and have therefore assembled relatively large data bases upon which to base their conclusions. It is important to note that present regulations for forest practices in California are more rigorous than those regulations that were in effect when much

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of the research was conducted in the basin. For this reason, results contained in some articles may not be completely applicable to present-day practices.

This article summarizes the large amount of information contained in the overall volume. It capsulizes major findings of each article and briefly describes how articles relate both to one another and to the broader basinwide framework of geomorphic processes or aquatic habitat. Because the papers have not resulted from a single coordinated study, this volume is not intended to present a totally integrated description of processes or habitats throughout the basin.

GEOLOGY, CLIMATE, AND LAND USE

The Redwood Creek basin is within a geologic province characterized by some of the highest rates of erosion in the United States (Brown and Ritter, 1971; Milliman and Meade, 1983). The naturally high rates of erosion in this area result from inherently weak rock units situated in a tectonically active area with a Mediterranean climate. These naturally high rates have been accelerated by extensive timber harvesting throughout the basin.

The dominant rocks in the basin are metamorphic and sedimentary rocks of the Franciscan assemblage, with lesser amounts of Plio-Pleistocene shallow-marine and alluvial sedimentary deposits at the north end (chap. B, this volume). Rocks of the Franciscan assemblage are severely fractured and deformed and highly susceptible to landslides. The basin has recently experienced high uplift rates associated with the Mendocino triple junction (chap. B., this volume). Geologic evidence presented by Cashman and others (chap. B, this volume) indicates that the Redwood Creek basin probably did not develop into its general present-day form until the early Pleistocene.

Eighty-one percent of the virgin coniferous forest in the Redwood Creek basin has been logged. Best (chap. C, this volume) discusses the history of this timber harvesting. Although timber harvesting started in the 19th century, it was most intensive in the 15 years prior to a large storm in December 1964. The earliest timber harvest was concentrated in the upper and middle parts of the basin, but starting in the late 1960's, timber harvest was most active in the lower two-thirds of the basin. With expansion of Redwood National Park in 1978, all timber harvesting ceased in the lower one-third of the basin.

Major storms have received a great deal of attention in the Redwood Creek basin because erosion and sediment delivery associated with those storms produced many of the channel changes that threatened parkland resources. Harden's analysis (chap. D, this volume) of major storms for which historical information is available reveals that storms in 1860 and 1890 produced major floods comparable in magnitude to the storm and flood of December 1964. The latter storm, however, caused much more widespread landsliding and channel aggradation in Redwood Creek and other northern California basins than the major storms of the 19th century. Likely causes for the disproportionate impacts of the 1964 storm include small-scale destabilization of hillslopes by storms in 1953 and 1955, concentration of rainfall in the upper basin where streamside slopes are less densely vegetated and unprotected by flood plains, and intensive road construction associated with logging in the upper basin between 1955 and 1964.

EROSION AND SEDIMENT TRANSPORT

Investigations of erosion and sediment transport make up most of the geologic and hydrologic research conducted in the Redwood Creek basin. The papers presented in this volume are divided into hillslope processes, hillslope and channel processes, and channel processes. Papers in the first group describe erosional processes that remove material from slopes; papers in the second group describe interactions between streamside hillslopes and stream channels; and papers in the third group discuss stream processes.

HILLSLOPE PROCESSES

Papers on hillslope processes describe major landslide types, creep, sheetwash and rilling, and gullying. The relative importance of these different processes differs in different parts of the basin. Some of the papers discuss the effects of land use on particular erosional processes.

Swanston and others (chap. E, this volume) discuss creep and earthflow rates in the basin. Inclinometer measurements indicate that creep is particularly active on schist slopes within the basin, with rates ranging from 1.0 to 2.5 mm/a. Complex earthflows occur primarily on slopes underlain by sandstone and mudstone. Inclinometers installed on earthflows indicate that movement rates can be as much as two orders of magnitude faster than creep rates. In both types of mass movement, the timing and magnitude of displacement respond primarily to within-year variations in precipitation.

Nolan and Janda (chap. F, this volume) describe results of 9 years of study of two earthflows within the basin. Annual moisture conditions appear to control the timing of movement in these two earthflows in a fashion similar to that described by Swanston and others. However, variation in mass distribution within the earthflow body, over time, appears to be a major control of temporal and spatial variations in movement rates. Surficial movement rates of these features ranged from 0.01 to 15.3 m/a. Sediment yield from the two earthflows ranged from 730 to 25,100 (Mg/km^2)/a. Earthflow movement rates reported by Nolan and Janda are an order of magnitude faster than those reported by Swanston and others because Swanston and others used inclinometer data to study less active features or portions of features than did Nolan and Janda, who used resurveys of surficial stakelines to monitor movement. Swanston and others purposely avoided extremely active areas to prevent rapid shearing of the inclinometer tubes.

The history of all mass movement processes in the Redwood Creek basin is discussed by Harden and others (chap. G, this volume). Processes discussed include debris slides, debris avalanches, and earthflows. Harden and others' study was based on interpretation of aerial photographs and indicated a dramatic increase in streamside landslides between 1947 and 1976. Debris slides showed the greatest increase, whereas earthflow activity did not increase significantly. Most of the increase occurred in the interval from 1962 to 1966, reflecting both the impact of the December 1964 storm and intensive timber harvest and road construction in the late 1950's and early 1960's. The impact of storms in 1972 and 1975 on streamside landslides was less dramatic than that of the 1964 storm. Harden and others suggest that this may represent the fact that most unstable slopes had failed during the 1964 storm.

Erosion by overland flow and gullying in the Redwood Creek basin has been studied by Marron and others and by Weaver and others (chap. H and chap. I, respectively, this volume). Both chapters emphasize the impact of logging on these processes. Marron and others investigated the effect of logging on rates of rilling and erosion by overland flow on forested slopes underlain by schist and sandstone. There was no discernible difference between rates of these processes on logged and unlogged slopes underlain by sandstone. However, where timber was harvested by tractor- or cable-yarding on slopes underlain by schist, rates were 4 and 15 times greater, respectively, than rates recorded on unharvested schist slopes.

Weaver and others discuss the causes of gully erosion on logged sandstone slopes in the lower one-third of the Redwood Creek basin. They show that extensive disruption of surface drainage by tractor logging and construction of logging roads can lead to major gully erosion. Large storms in 1972 and 1975, which occurred within 1 to 5 years of logging, triggered much of the gully erosion.

HILLSLOPE AND CHANNEL PROCESSES

Essential to the study of geomorphic process in the Redwood Creek basin is the investigation of the interaction between hillslopes and stream channels. Colluvium delivered to channels by streamside landslides is an important sediment source that appears capable of overwhelming the transport capacities of high-order channels. Four papers in this volume explore the linkage between hillslopes and stream channel processes.

Kelsey and others (chap. J, this volume) present a geomorphic analysis of streamside landslides along Redwood Creek and major tributaries. Along the 100 km length of the main channel, landslides are concentrated in two reaches, both of which have a well-defined inner gorge that is the product of streamside landslides coalescing over thousands of years. Even though landslides are the single most significant source of coarse sediment to the main channel, reaches of high landslide input are characterized by high stream gradients and are therefore reaches of low sediment storage in the main channel. In contrast, low gradient reaches with minimal streamside landsliding are reaches of greatest sediment storage.

The relationship of landslides to sediment storage in 16 tributaries of Redwood Creek was studied by Pitlick (chap. K, this volume). Sediment production by landslides in tributaries is comparable in magnitude to the volume of sediment delivered by landslides along the main channel. In the majority of tributaries, the amount of sediment stored in the channel is small compared to the annual supply of coarse sediment from the hillslopes. Most sediment is rapidly flushed out of tributaries into the main channel during moderate to large storm events. The subsequent transport of coarse sediment down the main channel of Redwood Creek is a much slower process (chaps. N, O, this volume).

In another study of tributary streams, Nolan and Janda (chap. L, this volume) used water and suspended sediment discharge data from eight streams to assess the impacts of tractor-yarded clearcut timber harvesting on sediment discharge to Redwood Creek. The results represent the cumulative effects of hillslope and channel processes in these tributaries. Synoptic sampling during nine storms indicated that water discharge per unit area from streams draining harvested terrain was roughly twice that from unharvested terrain. Suspended sediment discharge was as much as 10 times greater from harvested terrain as from unharvested terrain. Sediment transport relationships examined by Nolan and Janda (chap. L, this volume) agree with the findings of Pitlick (chap. K, this volume), which indicate that tributaries are major contributors of sediment to the main channel during periods of high flow. These high-flow periods are exceptionally effective in removing sediment from tributaries, and sediment is delivered to the main channel faster than it can be removed at these times.

A sediment budget describing all major geomorphic processes in the Garrett Creek basin, a 10.8-km^2 tributary draining sandstone and mudstone slopes on the east side of Redwood Creek, is presented by Best and others (chap. M, this volume). The study period, 1956 to 1980, represents a period of accelerated erosion within the basin because it includes a period of widespread timber harvest and a sequence of major storms. During the study period, fluvial erosion contributed 62 percent of the sediment to the main channel of Garrett Creek, and streamside landslides contributed the remainder. Almost all significant sources of fluvial erosion involved gully erosion caused by road construction and logging. The sediment found in storage along the lower main channel of Garrett Creek represented only 6 percent of the total sediment input for the 25-year study period. Most erosion and sediment transport in the Garrett Creek basin occurred during short-duration, large-magnitude events.

CHANNEL PROCESSES

Four papers in this volume deal strictly with channel processes. The report by Nolan and Marron (chap. N) describes changes in the geometry of Redwood Creek that were instrumental in arousing concerns for parkland resources. The main channel widened by as much as 100 percent and aggraded by as much as 4.5 m as a result of the 1964 storm. Land managers were concerned that, if such channel changes continued, the aquatic habitat would be damaged and many of the riparian redwood trees would be destroyed. Observations of effects from the 1964 storm, coupled with poststorm monitoring of changes in channel geometry and grain size distribution of channel bed material, suggest that events such as the 1964 storm impose a strong and long-lasting impact on channel geometry. Data presented by Nolan and Marron indicate that some basinwide recovery has occurred since the period of major channel changes initiated by the 1964 storm.

The article by Madej (chap. O) relates the channel changes noted by Nolan and Marron to changes in sediment stored along the main channel of Redwood Creek. By use of data from the field and from aerial photographs, Madej quantified the role of various alluvial features (flood bars, point bars, channel aggradation, debris jams, and so on) in the storage of sediment in the main channel. Wide channel reaches are particularly important storage sites. Madej also computed residence times for sediment stored in four reservoirs with decreasing probability of transport: active, semiactive, inactive, and stable sites. The 1964 storm increased sediment stored along the channel by 1.5 times. Both Madej's report and that of Nolan and Marron indicate that channel recovery from the 1964 storm has been slow and that storm effects will probably persist for decades longer. Both indicate that there has been a downstream migration of the locus of channel aggradation with time. Long periods of moderated flow will be needed to flush 1964 sediment from the channel. Future high-magnitude flows would probably slow recovery because these events flush sediment from tributaries and trigger landslides (chap. L and chap. K, this volume), and they deposit sediment in storage sites along the main channel (chap. L, this volume).

Channel morphology and sediment storage in small, steep, forested tributaries are strongly influenced by accumulation of large organic debris. Keller and others (chap. P, this volume) describe effects of organic debris accumulations in several tributaries. Data presented in their article indicate that large organic debris is associated with 30 to 60 percent of the total channel elevation drop along studied streams and with the storage of sediment equal to 100 to 150 years of average bedload transport. They find that redwood-dominated organic debris commonly remains in place longer than 100 years and is therefore considered an integral part of the channel system. The article also indicates that large organic debris sustains a healthy population of anadromous fish because it provides both habitat diversity and sites for organic nutrient processing and it buffers the release of stored sediment.

The last of the erosion and sediment transport papers (chap. Q, this volume) describes sediment transport in the estuary and along the beach at the mouth of Redwood Creek. The distribution and transport of sediment in the Redwood Creek estuary were greatly altered by construction of a flood control levee along lower Redwood Creek in 1968. As a consequence, the sloughs and a portion of the estuary have become filled with sediment since 1968, effectively eliminating 50 percent of the lower estuary. Sediment accumulation has altered the seasonal closure of the outflow channel to the ocean and has adversely affected habitat for both upmigrating and downmigrating anadromous fish.

AQUATIC HABITAT

Five additional reports discuss various aspects of the aquatic habitat of Redwood Creek. The articles by Averett and Iwatsubo (chap. R), Bradford (chap. S), and Triska and others (chap. V) consider aspects of timber harvest impacts on the aquatic habitat.

The general aquatic biota of Redwood Creek and selected tributaries are described by Averett and Iwatsubo. Their analysis is based upon diversity in community structure and indicates that the general habitat was of a high quality. They add, however, that, in areas of exceptionally high sediment transport and bed mobility, aquatic productivity was low. They emphasize that most of their data were collected during the period of maximum land disturbance (1973–75). Nolan and Janda (chap. L, this volume) linked timber harvesting to increased sediment yield, and Janda (1978) has linked it to increased frequency of bedload transport. These two reports coupled with the work of Averett and Iwatsubo suggest that timber harvesting was probably responsible for at least some reduction in aquatic productivity.

The effects of timber harvesting on the chemical quality of water in the main channel and selected tributaries was investigated by Bradford (chap. S). He found water quality throughout the basin at the time of his study to be excellent. However, his work did indicate some logging impacts. Bradford found an increase in calcium and bicarbonate in watersheds subjected to logging. He attributed this to accelerated weathering caused by increased exposure of surface soil in these watersheds. This work also has some implication for hillslope processes. Measurements of specific conductance and alkalinity done by Bradford indicate that overland flow is a larger component of peak flow in logged watersheds than in unlogged watersheds.

The effects of recent sediment deposition on the survival of anadromous fish in Redwood Creek has been a major concern of land managers. Increased streambed deposition has the potential to reduce intragravel circulation of oxygen-rich waters, which are needed for the survival of salmonid eggs. Woods (chap. T, this volume) found that intragravel water at the downstreammost of his three sampling sites had a significantly lower dissolved-oxygen concentration than did the upstream sites. He attributed this to reduced mixing with surface waters due to the smooth streambed surface and dense cover of periphytic algae at this site.

A little recognized factor that may affect the survival of anadromous fish are "cold pools" found by Keller and others (chap. U) along the main channel of Redwood Creek. These pools form high-quality summer habitat because water temperatures are commonly several degrees Celsius cooler than in surrounding areas. Keller and others suggest that "cold pools" are formed by cool effluent ground water from point sources such as dry tributary channels.

The final article in the volume, chapter V by Triska and others, discusses the role of the biotic community in nitrate uptake along Little Lost Man Creek, a 9.4-km^2 tributary basin near the mouth of Redwood Creek. This work indicates that, following clearcutting along one bank of a study reach, maximum uptake of dissolved inorganic nitrogen occurred during daylight hours in the years before development of a closed alder canopy. They expect biotic production to remain low until the canopy is reopened by natural mortality of the riparian alders. This reduced production may have impacts further up the food chain, perhaps even to carnivores such as fish. Triska and others point out that few long-term chemical data are available from clearcut reaches such as their Little Lost Man site, and they do not extrapolate their results to others areas or make basinwide predictions about timber harvest impacts. They do indicate that establishment of dense riparian alder growth following timber harvesting is common.

SUMMARY

Few conflicts exist between major findings of studies presented within this volume. There appears to be some uncertainty about the exact role of fluvial erosion in the basinwide sediment budget. Most articles emphasize mass movement processes because of their direct impact on high-order channels. The articles by Weaver and others (chap. I) and Best and others (chap. M) both indicate that fluvial erosion contributed more than one-half the sediment input in the basins they studied. These two studies were concentrated in areas highly disturbed by clearcut timber harvesting, and the degree to which these results can be applied throughout the basin is uncertain. The dispersed nature of fluvial erosion has made basinwide quantification of this process difficult.

In general, papers presented in this volume describe a delicate landscape that is sensitive to effects of both land use and major storms. Significant increases in sediment yield and runoff caused by the ground disruption and road construction associated with timber harvesting have been documented by Marron and others (chap. H), Weaver and others (chap. I), Nolan and Janda (chap. L), and Best and others (chap. M). The greatest impacts have been found in areas harvested by large-scale tractor-yarded clearcutting.

The landscape within the Redwood Creek basin is particularly delicate not only because ground disruption can easily increase erosion at a specific location but also because such increases can affect areas downstream or downslope. Nolan and Marron (chap. N), for example, suggested that one reason effects related to the 1964 storm were so widespread was that channel and hillslope processes are connected by a positive feedback loop. Such a loop was proposed by Colman (1973) and suggests that colluvium introduced by a single landslide is capable of initiating additional streamside landslides downstream. Such a loop can cause hillslope destabilization throughout long reaches of a channel as a result of a minimum number of failures in upstream locations.

Studies completed to date in the Redwood Creek basin have characterized the types and rates of major geomorphic processes operating within this rapidly eroding basin. This work also has described the general aquatic habitat and has focused on a few specific aspects of that habitat. In a basin where erosional processes are operating so rapidly and where these processes are so complexly interrelated, the potential for additional meaningful studies is great. For that reason it is hoped that the information presented in this volume will prove useful not only to studies directed at understanding geomorphic processes and aquatic habitats elsewhere but also to future studies within the Redwood Creek basin.

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Geology of the Redwood Creek Basin, Humboldt County, California

By SUSAN M. CASHMAN, HARVEY M. KELSEY, *and* DEBORAH R. HARDEN

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

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GEOLOGY OF THE REDWOOD CREEK BASIN, HUMBOLDT COUNTY, CALIFORNIA

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ABSTRACT

The Redwood Creek drainage basin of northwestern California is underlain by metamorphic and sedimentary rocks of the Franciscan assemblage of Late Jurassic and Early Cretaceous age and by shallow marine and alluvial sedimentary deposits of late Tertiary and Quaternary age. These units are cut by a series of shallowly east-dipping to vertical north-northwest-trending faults. The composition and distribution of bedrock units and the distribution of major faults have played a major part in the geomorphic development of the Redwood Creek basin. Slope profiles, slope gradients, and drainage patterns within the basin reflect the properties of the underlying bedrock. The main channel of Redwood Creek generally follows the trace of the Grogan fault, and other linear topographic features are developed along major faults. The steep terrain and the lack of shear strength of bedrock units are major contributing factors to the high erosion rates in the basin.

PREVIOUS WORK

Substantial geologic mapping and research have been done in the Redwood Creek area. Pioneering work was done by Hershey (1906), and subsequent regional mapping by Irwin (1960). More detailed maps include those of the Blue Lake quadrangle (Manning and Ogle, 1950), the Willow Creek quadrangle (Young, 1978), the Rodgers Peak quadrangle (P.H. Cashman and others, 1982), and the Coyote Peak quadrangle (S.M. Cashman and others, 1982). A 1:62,500-scale geologic map of the Redwood Creek drainage basin has been published (Harden and others, 1982). In addition, specific studies have been completed on the petrology (Talley, 1976; Leathers, 1978) and structural history (Roure, 1979; Cashman and Cashman, 1982) of the Redwood Creek schist. The depositional and structural history of Plio-Pleistocene sedimentary deposits in the Redwood Creek basin has been studied by Kelsey (1982) and Kelsey and Cashman (1983). Soils in the basin were studied by Alexander and others (1959–62) and Marron (1982).

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INTRODUCTION AND SETTING

Redwood Creek occupies a 725-km^2 drainage basin approximately 80 km long and 10 km wide (fig. 1). Most of the basin is underlain by metamorphic and sedimentary rocks of the Franciscan assemblage of Late Jurassic and Cretaceous age (Bailey and others, 1964; Harden and others, 1982) of the California Coast Ranges (fig. 2). The Franciscan assemblage includes two sandstone and mudstone sequences termed "coherent unit of Lacks Creek" and "incoherent unit of Coyote Creek," a sandstone and mélange unit, a sequence of transitional rocks, and two belts of quartz-mica schist of the South Fork Mountain Schist and schist of Redwood Creek (figs. 1 and 2). All major Franciscan bedrock units in the basin are bounded by faults that trend north-northwest (fig. 1), parallel to the regional structural trend in northwestern California (Strand, 1962). Ultramafic and associated mafic rocks of the Klamath Mountains, mapped as Klamath Mountain rocks of Jurassic age, crop out along the southeastern

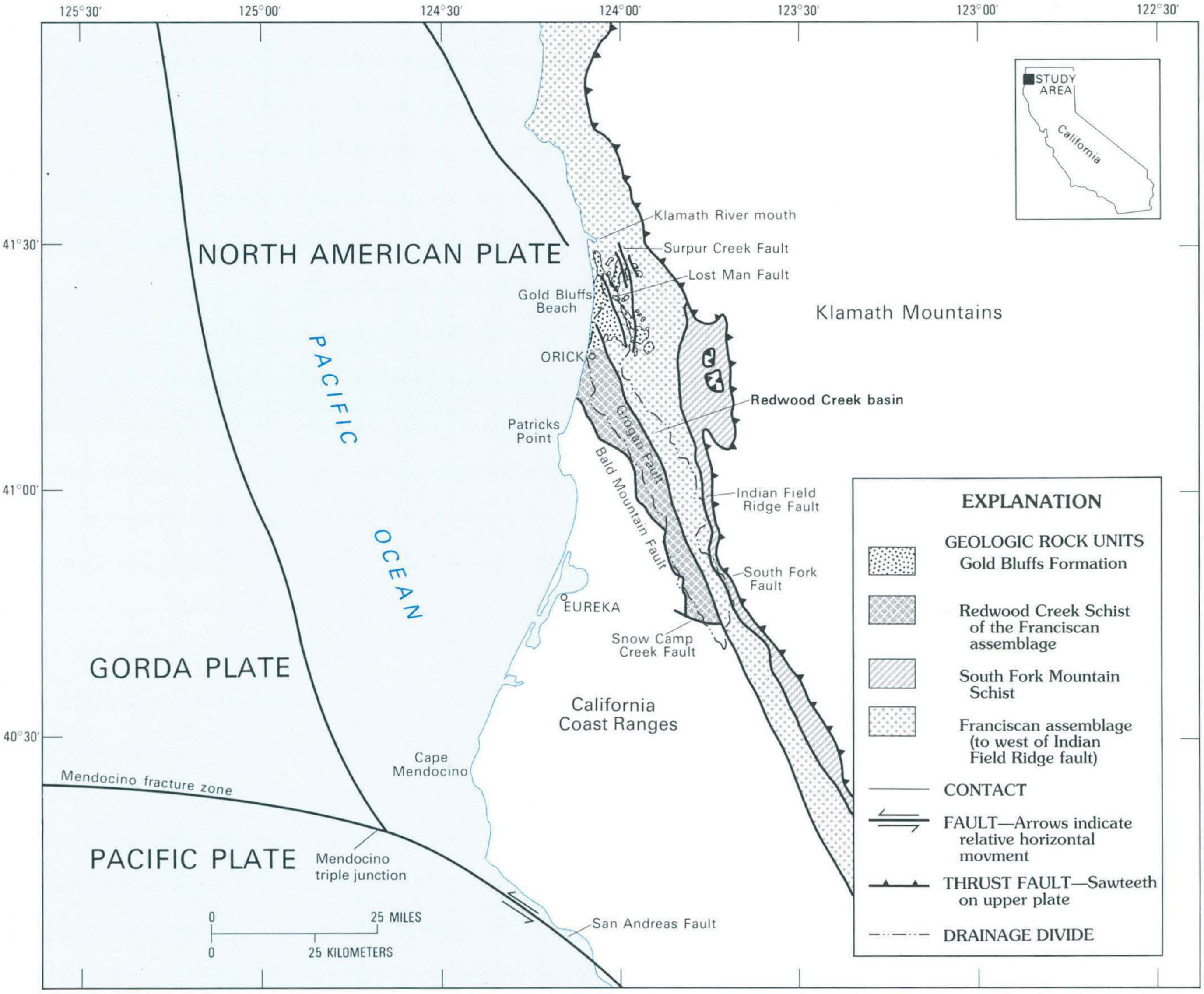

FIGURE 1.—Geologic and tectonic map of north coastal California showing major faults and rock units in the Redwood Creek drainage basin. MTJ=Mendicino triple junction.

margin of the basin. The South Fork fault (Irwin and others, 1974) (fig. 1) separates rocks of the two regions.

Upper Tertiary and Quaternary sedimentary rocks crop out in the northern part of the basin. They were deposited across the Bald Mountain fault and most of the Grogan fault. However, these upper Tertiary and Quaternary sedimentary rocks have been deformed locally by movement on the northern portion of the Grogan fault and associated minor faults (J.C. Young, written commun., 1977; Kelsey, 1982a; Kelsey and Cashman, 1983).

Northern coastal California and the adjacent offshore area constitute one of the most seismically active areas in the State. The high level of tectonic activity in the region is attributed to the proximity of the Mendocino triple junction (McKenzie and Morgan, 1969), a boundary that separates three major crustal plates (fig. 1). High uplift rates and Quaternary faulting result from the high degree of tectonic activity in the area. Unusually rapid uplift rates have been reported at locations along the coast from Cape Mendocino north to Patricks Point (Woodward-Clyde Consultants, 1980; LaJoie and others, 1982; McLaughlin and others, 1983). Faulting of Quaternary age has been recognized throughout western Humboldt County on the basis of geomorphic and structural evidence (Woodward-Clyde Consultants, 1980; Kelsey, 1982; Carver and others, 1983; Kelsey and Cashman, 1983; Kelsey and Allwardt, 1983).

The bedrock geology of the Redwood Creek basin is a major contributor to the high erosion rates in the basin. Much of the area is underlain by pervasively sheared and fractured mudstone, incoherent sandstone, and fine-grained schist. The erodible bedrock and steep terrain make the basin inherently susceptible to mass movement (chap. G, this volume). Landslide terminology used in this paper is based on the classification scheme of Varnes (1978).

ROCK UNITS

KLAMATH MOUNTAINS ROCKS

Klamath Mountains rocks of Jurassic age form the easternmost and structurally highest bedrock unit in the Redwood Creek basin (fig. 2). The most common rock types are sheared serpentinite and partially serpentinized peridotite with associated minor mafic intrusive rocks (Young, 1978). A zone of tectonically mixed greenstone, metagraywacke, serpentinite, and diorite occurs along the South Fork fault zone south of Horse Mountain (Young, 1978). The ultramafic and mafic intrusive rocks are interpreted by Young (1978) as having ophiolitic affinities.

FRANCISCAN ASSEMBLAGE

SCHIST OF REDWOOD CREEK AND SOUTH FORK MOUNTAIN SCHIST

Two bodies of quartz-mica schist occur in the Redwood Creek basin: the schist of Redwood Creek (herein named Redwood Creek schist) and the South Fork Mountain Schist. The Redwood Creek schist underlies the western half of the basin, and its outcrop area is almost entirely within the drainage basin of Redwood Creek (fig. 2). It has been previously mapped as "Kerr Ranch Schist" in the Blue Lake quadrangle by Manning and Ogle (1950), and as the "Redwood Mountain outlier of South Fork Mountain Schist" by Irwin (1960) and Young (1978). The South Fork Mountain Schist crops out to the east of the Redwood Creek schist, along the southeastern edge of the basin (fig. 2) and extends south of the basin for more than 120 km. The South Fork Mountain Schist forms the easternmost and structurally highest unit in the Franciscan assemblage (Blake and others, 1967; Irwin and others, 1974).

Several lithologies occur within the Redwood Creek schist, including metagraywacke, fine-grained schist, and minor laminated to massive greenstone. Considerable variations in texture, composition, and degree of deformation are evident within the unit. The most common lithology is fissile light-green to dark-gray phyllite or fine-grained schist (fig. 3). The typical mineral assemblage consists of quartz, chlorite, white mica, and albite; epidote, actinolite, lawsonite, or opaque graphitic material occur in some samples. Coarser grained textural zone II to III (Blake and others, 1967) metagraywacke also occurs in the Redwood Creek schist. In some metasandstone outcrops, such as those along the coast near Stone Lagoon (fig. 2), graded bedding is preserved.

Greenstone is a less widespread component of the Redwood Creek schist. The common mineral assemblage is quartz, epidote, chlorite, actinolite and albite, with lawsonite in some samples. Greenstone is either massive and homogeneous or has thin (1–2 mm) mineralogic layering. The contacts between greenstone and surrounding schist are commonly obscured, but in two good exposures in a rock quarry in Tom McDonald Creek and in the channel of Pardee Creek (fig. 2), thin-bedded greenstone (metatuff) and pelitic schist are clearly interbedded.

The South Fork Mountain Schist is not as extensive as the Redwood Creek schist in the Redwood Creek basin. The dominant rock type of this unit, quartz-albite-white mica-chlorite schist, is mineralogically similar to most common lithology in the Redwood Creek schist. Other rock types in the South Fork Mountain Schist include foliated greenstone and local highly quartzitic gneissic rocks, reported in the South Fork Mountain Schist by Young (1978).

Characteristically red and clay-rich regolith suggests that the schist units are readily altered by chemical weathering. Soils developed on schist in the Redwood Creek basin are mostly inceptisols, alfisols, and ultisols (Alexander and others, 1959–62). The red colors reflect the oxidation of iron in chlorite and other iron-bearing minerals. High clay contents reflect, at least in part, the micaceous nature of the parent material. Abundant clay seams that follow schistosity demonstrate a linkage between physical and chemical weathering. Physical weathering of schistose rocks yields small platy fragments.

The geomorphic expression of the schist units is variable. Slopes underlain by the Redwood Creek schist have gently convex profiles. Side-slope gradients commonly range from 20 to 40 percent and average approximately 25 percent (Marron, 1982). Ridges underlain by Redwood Creek schist, such as Wiregrass Ridge (fig. 2), typically have rather broad, flat ridge crests. Both the Redwood Creek schist and the South Fork Mountain Schist exhibit knobby topography in areas where

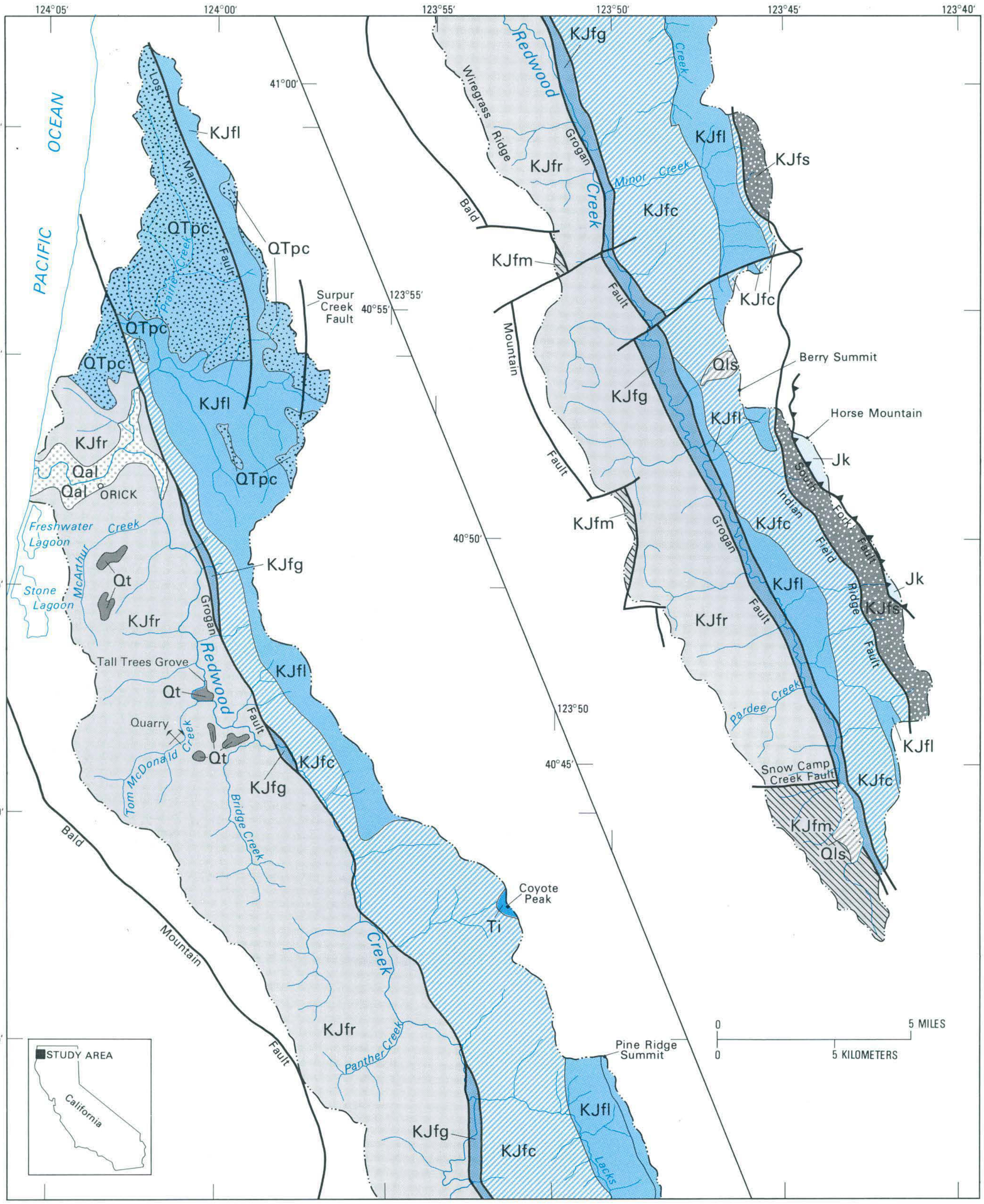

FIGURE 2.—Generalized bedrock geology of the Redwood Creek basin (modified from Harden and others, 1982).

EXPLANATION

QUATERNARY	Qal	ALLUVIUM
	Qt	TERRACE DEPOSITS
	Qls	LANDSLIDE DEPOSITS—Only major deposits shown
QUATERNARY AND TERTIARY	QTpc	PRAIRIE CREEK FORMATION
TERTIARY	Ti	TERTIARY INTRUSIVE ROCK
CRETACEOUS AND JURASSIC		FRANCISCAN ASSEMBLAGE
	KJfm	Sandstone and mélange unit
	KJfg	Transitional rocks of Grogan Fault zone
	KJfl	Coherent sandstone and mudstone unit of Lacks Creek
	KJfc	Incoherent sandstone and mudstone unit of Coyote Creek
	KJfr	Redwood Creek Schist
	KJfs	South Fork Mountain Schist
JURASSIC	Jk	Klamath Mountain rocks

—··— REDWOOD CREEK BASIN BOUNDARY

—— CONTACT—Approximately located

——··· FAULT—Dotted where covered

—▲—▲— THRUST FAULT—Sawteeth on upper plate

FIGURE 2.—Continued.

FIGURE 3.—Outcrop of schist of Redwood Creek.

greenstone units and tectonic blocks are included in the schist. Shallowly incised streams are a typical drainage feature of schist slopes.

FRANCISCAN SANDSTONE AND MUDSTONE UNITS: COHERENT UNIT OF LACKS CREEK AND INCOHERENT UNIT OF COYOTE CREEK

Most of the eastern half of the Redwood Creek basin is underlain by sandstone, mudstone, and minor associated conglomerate, greenstone, and chert of the Franciscan assemblage (fig. 2). These rocks were subdivided by Harden and others (1982) into a coherent sandstone-mudstone unit (coherent unit of Lacks Creek) and an incoherent sandstone-mudstone-greenstone-chert unit (incoherent unit of Coyote Creek) (fig. 2).

The predominant rock types in both units are massive sandstone and interbedded sandstone and mudstone (fig. 4). Where they are not disrupted by faults or pervasive shearing, the interbedded sandstone and mudstone sequences show rhythmic bedding and sedimentary structures characteristic of turbidites. Sandstone occurs as massive beds as much as 10 m thick, but most beds range from 0.1 to 3 m in thickness. The sandstone to mudstone ratio is conspicuously higher in the coherent

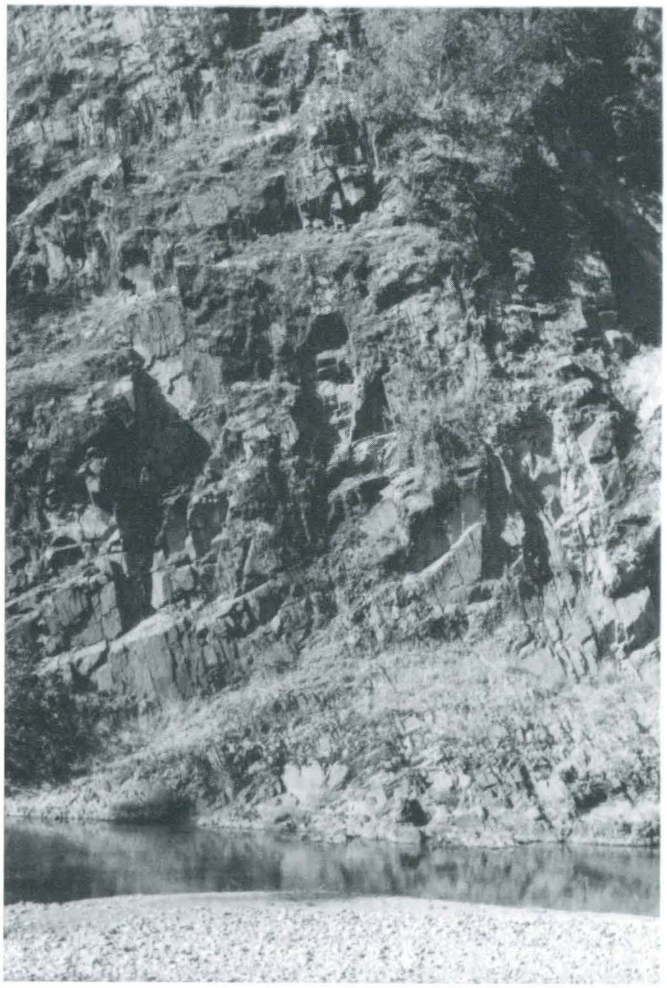

FIGURE 4.—Outcrop of sandstone of the Franciscan assemblage.

sandstone unit. In contrast, only the incoherent unit contains blocks of chert and greenstone, as well as sandstone and mudstone.

Thin-section examination of the sandstones shows them to be lithic graywackes and quartzofeldspathic graywackes. Harden and others (1982) noted that a limited number of sandstone samples studied contained potassium feldspar and are thus compositionally similar to sandstones in a subunit of the Franciscan assemblage that has been mapped to the south as the "Central belt Franciscan" (Berkland and others, 1972).

Soils developed on sandstone and mudstone in the Redwood Creek basin are mostly inceptisols and alfisols (Alexander and others, 1959–62). On sandstone and mudstone slopes of the coherent unit of Lacks Creek, soils are commonly shallow and sandy (Marron, 1982). Slopes underlain by the incoherent sandstone, mudstone, greenstone, and chert unit of Coyote Creek tend to have more clay-rich soils that are bluish gray. Clay-rich soils that have developed on sheared bedrock are highly susceptible to mass wasting (Alexander and others, 1959–62).

The sandstone and mudstone of the coherent unit of Lacks Creek have distinctive geomorphic expression. Sharp ridge crests, steep slopes, and narrow V-shaped tributary canyons are characteristic of the landscape developed on these relatively resistant rocks. Slopes have straight to gently concave profiles, and slope gradients commonly range from 30 to 50 percent, averaging approximately 35 percent (Marron, 1982). In the coherent unit, streamside debris slides and debris avalanches are common in the inner gorges of tributaries.

In contrast to the steep terrain of the coherent unit, the sandstone, mudstone, greenstone, and chert of the incoherent unit underlie a subdued, rolling landscape having less deeply incised drainage networks and a few high points and knobs formed by resistant rock types. Earthflows in the Redwood Creek basin are preferentially developed in this unit, as are streamside debris slides along the inner gorge reaches of Redwood Creek. The largest active earthflow in the Redwood Creek basin is developed on this unit at Berry Summit (figs. 2 and 5).

TRANSITIONAL ROCKS

Rocks intermediate in texture and degree of metamorphism between the Redwood Creek schist and the sandstone and mudstone units crop out locally along the trace of Grogan fault (fig. 2). These rocks belong to textural zone II of Blake and others (1967). Their geomorphic expression is similar to that of other rocks exposed in the fault zone and to that of the incoherent unit of Coyote Creek.

FIGURE 5.—Active earthflow at Berry Summit, on the east side of the Redwood Creek drainage basin.

FRANCISCAN SANDSTONE AND MÉLANGE UNIT

A broad belt of sandstone and mélange of the Franciscan assemblage lies west of the Bald Mountain fault along the southwestern end of the Redwood Creek basin and along the western boundary of the basin (fig. 2). The unit consists of bodies of bedded graywacke intermixed with a pervasively sheared argillite-matrix mélange containing blocks of chert, metabasalt and volcanic breccia (Harrell, 1982), metavolcanic rocks, and glaucophane-lawsonite blueschist. The sandstone and mélange unit is distinct from the incoherent sandstone-mudstone-greenstone-chert unit discussed previously because it contains exotic glaucophane-lawsonite blocks.

The landscape developed on the sandstone and mélange unit is generally more hummocky than other hillslopes in the Redwood Creek basin. Parts of the unit underlain by massive sandstone display steep slopes, prominent ridges, and V-shaped valleys, in contrast to the more rolling, hummocky hillslopes underlain by mélange. Tectonic blocks of greenstone and chert form prominent knobs and summits. The largest landslide in the Redwood Creek basin is an ancient earthflow formed on the mélange unit at the southern headwaters of Redwood Creek (Harden and others, 1982).

The age of the Franciscan rocks in the basin is not well known because few fossils have been found. Two ammonites, the only fossils found in pre-Tertiary units in the Redwood Creek basin, were identified as being middle Cretaceous in age (D.L. Jones, written commun., 1976; Harden and others, 1982). At the mouth of the Klamath River, 30 km to the northwest, a chert and graywacke block in rocks that appear to be equivalent to the incoherent unit of the Redwood Creek basin was found to contain radiolarians of late Jurassic and early Cretaceous (Tithonian to Valanginian) age (Aalto and others, 1983).

Therefore, Franciscan rocks in the basin probably range from Tithonian to Cenomanian in age.

TERTIARY INTRUSIVE ROCKS

At Coyote Peak (fig. 2), on the ridge bounding the eastern side of the basin, an alkalic diatreme intrudes sandstone and related rocks of the Franciscan assemblage. The unusual mineralogy of this rock includes olivine, clinopyroxene, phlogopitic biotite, nepheline, acmite, schorlamitic garnet, titanomagnetite, perovskite, apatite, and several rare sulfide minerals (Blake, 1977; Czamanske and others, 1977). Inclusions of Franciscan sedimentary rocks and of aphanitic, alkalic igneous rocks occur within the diatreme.

PRAIRIE CREEK FORMATION

Most of the Prairie Creek basin at the northern end of the Redwood Creek basin is underlain by weakly consolidated shallow marine and alluvial sediments (figs. 2 and 6). The sediments, covering 150 km^2, possess a distinctive topography of sharp ridges, steep canyons, and a trellis drainage pattern. The sediments are here named the Prairie Creek Formation. Although named for Prairie Creek, the best exposures occur at its type locality along the well-exposed coastal bluffs at Gold Bluffs beach (sec. 4, T. 11 N., R. 1 E.; loc. T on fig. 6).

The Prairie Creek Formation is inferred to represent the onshore sediments of an extensive sedimentary sequence deposited on the continent and the continental shelf at the mouth of the Klamath River (Moore and Silver, 1969; Silver, 1971). The formation is dominantly composed of fluvial sediments but also includes nearshore marine sands and beach and estuarine deposits. Although the formation lies with angular unconformity on the Jurassic and Cretaceous Franciscan assemblage, it is composed almost exclusively of Klamath Mountains section rock types having minor amounts of Franciscan detritus, mainly near the bottom of the section. The Prairie Creek Formation thus appears to be a remnant of the lowermost reaches of the ancestral Klamath River. Both during and subsequent to deposition, the sediments have undergone folding, fracturing, and faulting (Kelsey and Cashman, 1983). Three major faults, the Grogan, Lost Man, and Sulfur Creek faults (fig. 6), cut the Prairie Creek Formation. The thickness of the Prairie Creek Formation exceeds 550 m.

The Prairie Creek Formation is best exposed along the cliff face at Gold Bluffs Beach (fig. 6) but is also exposed on logged areas inland. At the beach exposure, the Prairie Creek Formation grades upward from buff to tan shallow marine sands in the basal part to estuarine and

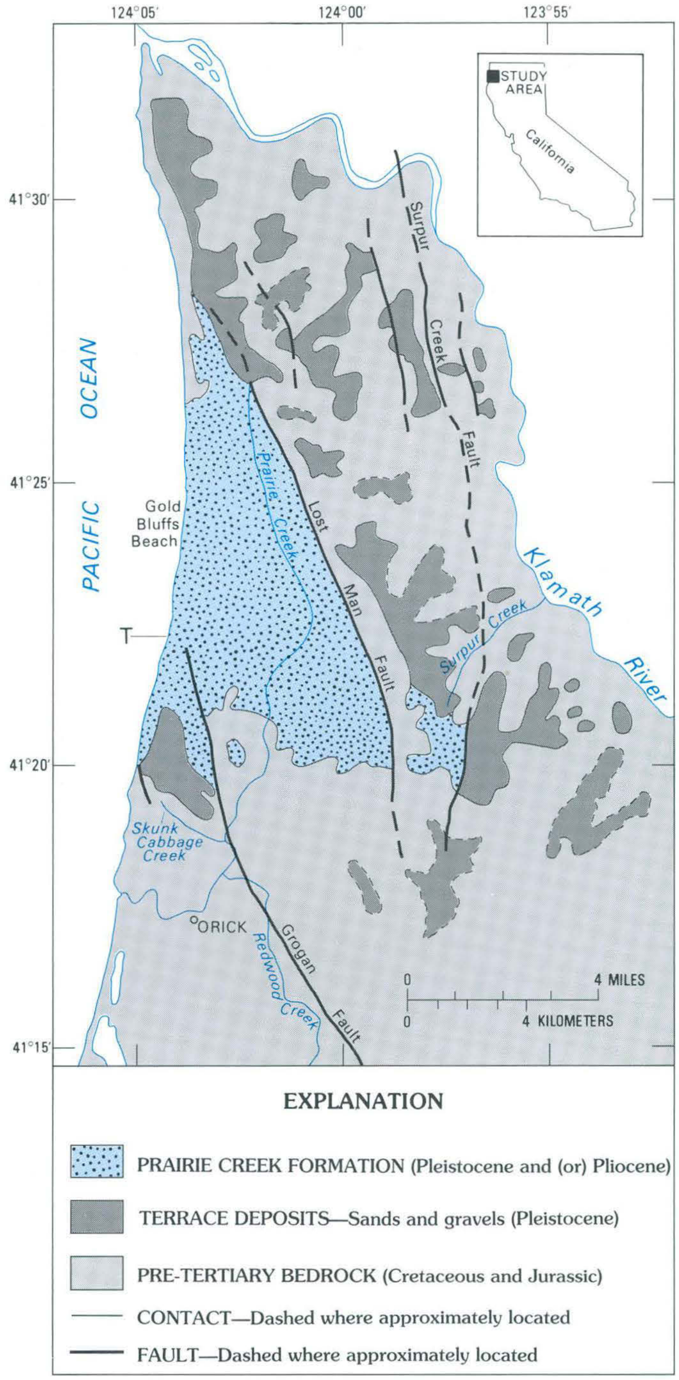

FIGURE 6.—Prairie Creek Formation and Pleistocene terrace deposits (geology by Kelsey, 1980–83).

coarse alluvial sequences near the top. Most of the cliff face at Gold Bluffs Beach consists of alluvial deposits of medium to coarse sand, buff to tan sand, and pebbles and cobbles of mixed metamorphic and igneous lithologies. Total exposed thickness of the Prairie Creek Formation at the type locality is 550 m.

Age data for the Prairie Creek Formation are scarce. A mollusk (*Protothaca hannibali*) occurs near the base of the formation, the only age-diagnostic fossil recovered. This fossil has an age span from about 1 to 4 Ma (Barry Roth, California Academy of Sciences, written commun., 1984) suggesting that the Prairie Creek Formation is Plio-Pleistocene (fig. 6).

QUATERNARY TERRACE DEPOSITS AND MODERN FLOOD-PLAIN DEPOSITS

Quaternary terrace deposits include streamside strath terraces, flood-plain deposits, coastal strath terrace deposits of probable marine origin, and fill terraces (Harden and others, 1982). Streamside strath terraces are best developed along the upper one-third of the Redwood Creek channel. Between 2 and 6 m of gravel cap beveled sandstone surfaces. These terraces reflect Holocene and late Pleistocene downcutting due to uplift. Redwood Creek flood deposits occur along a 9-km reach in the middle of the basin upstream of Lacks Creek. Modern flood deposits also occur in the lower 20 km of the watershed; these deposits include the alluvial flats, such as the Tall Trees Grove at the mouth of Tom McDonald Creek, and the broad flood plain of the lower Prairie Creek and Redwood Creek valleys.

Pleistocene alluvial gravels deposited by the Klamath River are exposed to the east and the north of the Prairie Creek Formation (fig. 6). These gravels parallel the modern course of the Klamath River (fig. 6) and record Pleistocene downcutting of the river.

Coastal strath terrace deposits occur on well-preserved flat surfaces on the southern divide of McArthur Creek (fig. 2) and on the northern divide of Skunk Cabbage Creek (fig. 6). The deposits are less than a meter to several meters thick and consist of sand, silt, and well-rounded, mainly quartzose pebbles. The surfaces are slightly tilted. The deposits are probably of marine origin and are most likely early to middle-Pleistocene in age, based on their topographic position.

Alluvial fill terraces are located on the west side of Redwood Creek on hillslopes a few kilometers upstream of the mouth of Tom MacDonald Creek (fig. 2). The alluvial fill overlies or is adjacent to a prominent north-northwest-trending lineament that follows Bridge Creek. The thickest fill is 50 m and consists entirely of Redwood Creek rock types. Other fills are composed entirely of schist, suggesting a limited provenance within tributary basins. Thick alluvial fills such as these are unusual in a setting where uplift rates are high and downcutting into bedrock is vigorous. The alluvium underlying the terraces is also sheared and faulted. The deformation and location of the fills suggest that they could be the result of local subsidence due to Quaternary faulting along the Bridge Creek lineament. However, no unequivocal evidence has been found to demonstrate that the Bridge Creek lineament is indeed a fault.

LANDSLIDE DEPOSITS

Landslide deposits are widely distributed on the different Franciscan assemblage units. Commonly, steep streamside hillslopes contain unsorted and disoriented regolith that reflects transport by mass wasting. On schist slopes, road-cut exposures of disrupted and disoriented regolith attest to the activity of deeply seated, slowly moving landslides (Marron, 1982). On incoherent sandstone and mudstone, earthflow deposits consisting of a sheared shale matrix that contains blocks of sandstone, chert, and greenstone are common (Nolan and others, 1976; chap. G, this volume). These deposits range from a few meters to more than 40 m thick, and their average thickness is approximately 25 m.

STRUCTURE

The most important element in the bedrock structure of this area is a series of northwest-trending faults. These faults form the contacts between the bedrock units previously discussed. The faults are locally characterized by strings of tectonic blocks of a wide variety of compositions. Some of the blocks are rock types exotic to the Redwood Creek basin and appear to have been emplaced in their present positions during faulting. Although all major faults strike northwest, they exhibit a range of orientations from shallowly dipping to vertical, and they represent several different deformational episodes (Monsen and Aalto, 1980; Cashman and Cashman, 1982; Kelsey and Hagans, 1982).

BALD MOUNTAIN FAULT

The Bald Mountain fault separates the sandstone and mélange unit from Redwood Creek schist along the western edge of the Redwood Creek basin (fig. 2). It is not well exposed and has been interpreted both as a shallow east-dipping thrust fault (Irwin, 1964; Talley, 1976; Monsen and Aalto, 1980) and as a nearly vertical fault (P.H. Cashman and others, 1982). The straight traces of the fault west of Wiregrass Ridge (fig. 2) suggest a vertical fault. On the other hand, the irregular, embayed trace of the fault farther south suggests either that the fault dips more gently at its southern end or that it has been offset by later cross faults (Manning and Ogle, 1950). Poor exposure precludes detailed mapping along most of the Bald Mountain fault, and the overall nature of the fault remains unknown. Tectonic blocks of chert, metavolcanic rocks, serpentinite, and blueschist are clustered along parts of the Bald Mountain fault. The knobby topography formed around these blocks is the only geomorphic expression of the fault.

GROGAN FAULT AND ASSOCIATED STRUCTURES

The Grogan fault, which juxtaposes Redwood Creek schist against the transitional rocks unit, is the best exposed and most studied fault in the Redwood Creek basin. It has a dramatic geomorphic expression where Redwood Creek has cut an imposing canyon along the straight fault zone (fig. 7). Slickenside striations along the fault (fig. 8) are clearly visible in exposures along Redwood Creek, where the fault can be seen to strike northwest and dip from 65° west to 65° east. In places, the Grogan fault zone includes sheared Franciscan rocks of textural zone II sandstone as much as 0.4 km wide; in contrast, other segments of the fault are only a few meters wide. The Grogan fault is also locally marked by the presence of tectonic blocks and serpentinite.

The Grogan fault can be traced 28 km southeast of the Redwood Creek basin by its geomorphic expression, and it may extend even farther south (Kelsey and Hagans, 1982). A fault that may be the northwestern extension of the Grogan fault can be traced in offshore reflection profiles (Field and others, 1980).

Evidence exists for dip-slip and possible strike-slip displacement on the Grogan fault. In an exposure near Prairie Creek, observed by J.C. Young in 1972 (exposure now overgrown), the Grogan fault is a high-angle reverse fault along which Pliocene and Pleistocene sediments are juxtaposed against Franciscan rocks. Although no unequivocal evidence exists for lateral movement on the Grogan fault, Kelsey and Hagans (1982) presented arguments for a minimum of 75 km of right-lateral displacement on the Grogan fault, probably during late Tertiary time.

Two additional faults, the Lost Man and Surpur Creek faults, parallel the Grogan fault and disrupt the Gold Bluffs Formation in the northern part of the basin. All three faults are easily recognized by their topographic expressions and by their strong disruption of the Gold Bluffs sediments. A suite of structures, including fractures, small-scale faults, and folds, are associated with the larger faults. Analysis of these structures suggests that the faults are strike-slip faults with a substantial component of vertical offset as well (Kelsey and Cashman, 1983). The faults are presumably Mesozoic faults that have undergone Quaternary movement. Quaternary activity on these faults has progressively uplifted the Prairie Creek sediments on the east to a cumulative vertical displacement of 300 m. It is not possible to determine the horizontal displacement on these faults because of their poor exposure.

INDIAN FIELD RIDGE AND SOUTH FORK FAULTS

The Indian Field Ridge and South Fork faults define the western and eastern boundaries, respectively, of the South Fork Mountain Schist. Both are interpreted to be shallow east-dipping faults that separate the schist from the structurally lower Franciscan rocks to the west and from the structurally higher rocks of the Klamath Mountains to the east. Neither fault has a marked geomorphic expression, although a narrow belt of sheared rock, expressed as a series of prairies, geomorphically defines the Indian Field Ridge fault near Indian Field Ridge (fig. 2).

The Indian Field Ridge fault crops out along the eastern side of the Redwood Creek basin. Its southern extension in the Yolla Bolly area (Blake and others, 1967) and in the Pickett Peak quadrangle (Irwin and others, 1974) is associated with a textural gradation from textural zone I to textural zone III graywackes. However, mapping by Young (1978) in the Willow Creek quadrangle, by Harden and others (1982) in the Redwood Creek basin, by Monsen and Aalto (1980) at Pine Ridge Summit, and by Aalto (1983) in the Pilot Creek quadrangle revealed no textural gradation along this contact. In the Redwood Creek basin, the fault is marked by a narrow zone of pervasively sheared, unmetamorphosed Franciscan sandstone.

The South Fork fault (Irwin and others, 1974) is exposed on the southeastern edge of the Redwood Creek basin (fig. 2). Igneous and metamorphic rocks of the Klamath Mountains are thrust over the South Fork Mountain Schist. In the Willow Creek quadrangle, Young (1978) mapped a zone of tectonically mixed serpentinite, foliated greenstone, metagraywacke, and diorite between Klamath Mountains ultramafic rocks and the South Fork Mountain Schist along part of the South Fork fault.

SNOW CAMP CREEK FAULT

The Snow Camp Creek fault is the only major east-west-trending fault in the Redwood Creek basin (Harden and others, 1982). It truncates the Redwood Creek schist on the south, separating the schist from Franciscan sandstone and mélange (fig. 2). This fault is clearly older than the Grogan fault, because it is truncated on its eastern end by the Grogan fault (Kelsey and Hagans, 1982). The Snow Camp Creek fault has no marked geomorphic expression.

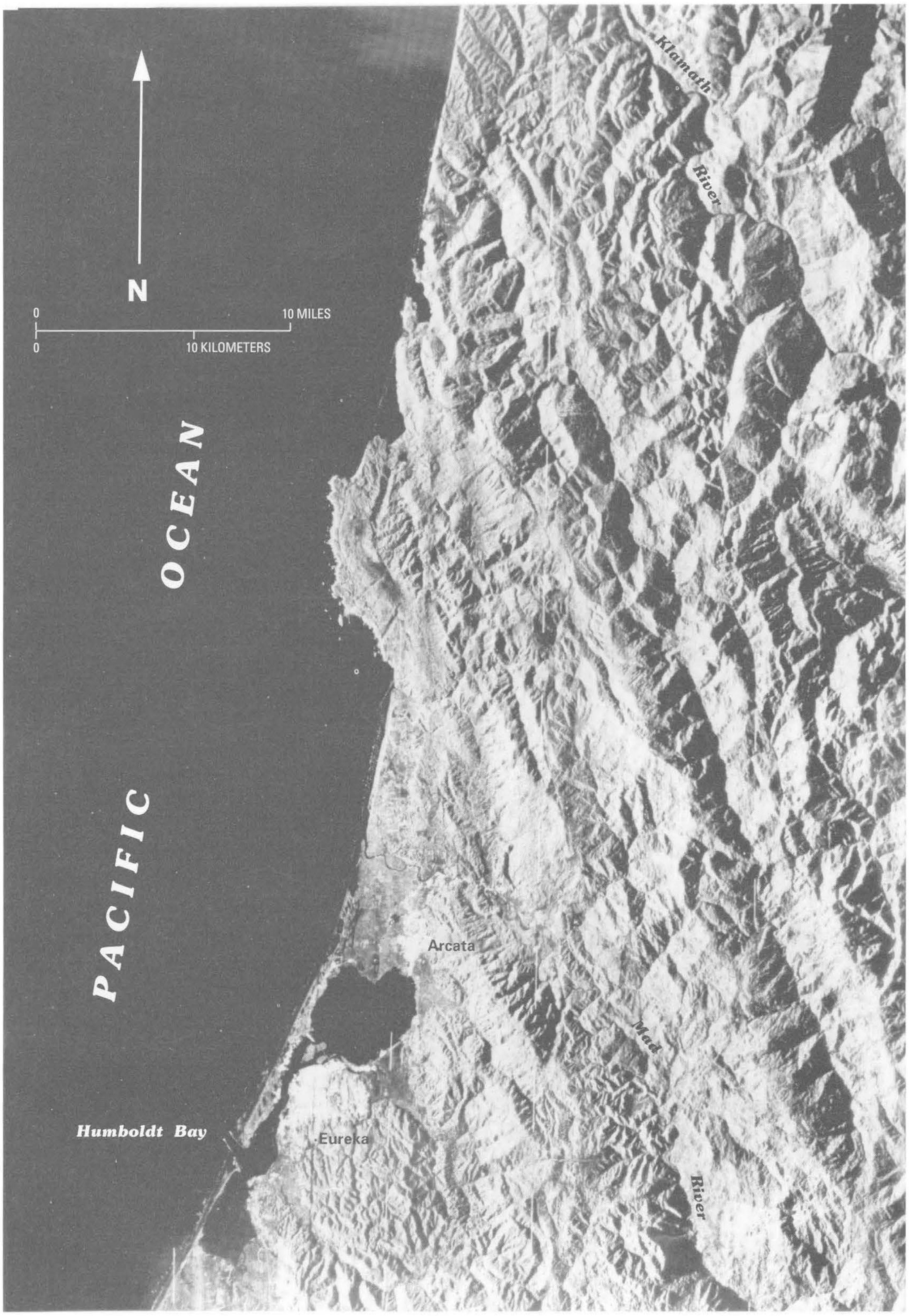

FIGURE 7.—Side-looking aerial radar image of northern Humboldt County, Calif. The prominent north-northwest-trending valley in the center of the image is the valley of Redwood Creek.

FIGURE 8.—Slickenside striations on greenstone of the Franciscan assemblage exposed along the Grogan fault.

OTHER STRUCTURES

The faults described previously are easily recognized because they juxtapose different lithologic units. Other structures, such as low-angle faults within the Redwood Creek schist, may also be of regional extent, but they cannot be traced beyond a single road cut or quarry exposure because of heavy vegetative cover. Distinct, fault-bounded belts of contrasting metamorphic grade were reported in the Redwood Creek schist by Talley (1976). Subsequent mapping by Harden and others (1982) and by Cashman and Cashman (1982) does not confirm existence of these belts, although low-angle faults between compositionally and (or) texturally different rocks in the schist unit have been recognized in the drainages of Panther Creek, Tom McDonald Creek (fig. 2), and one unnamed creek, as well as along the coast.

Several lineaments observed on aerial photographs are prominent geomorphic features in the Redwood Creek basin, and, with one exception, they trend parallel to regional northwest structural trends (Harden and others, 1982). The most conspicuous of these, the 16-km-long Bridge Creek lineament, is formed by aligned segments of the main stem of Bridge Creek and the two streams immediately south of Bridge Creek (fig. 2) (Talley, 1976; Harden and others, 1982). Crenulation cleavage and fracture cleavage in the Redwood Creek schist are more strongly developed along this lineament than they are elsewhere in the schist (Cashman and Cashman, 1982). Previously described Pleistocene fill terrace deposits that straddle the lineament are pervasively fractured. Another set of northwest-trending lineaments, the Snow Camp Mountain lineaments, marked by aligned ponds and undrained depressions, occurs in the southwestern part of the Redwood Creek basin and extends southward beyond the basin (Harden and others, 1982; Kelsey and Allwardt, 1983). Less well defined lineaments are suggested by isolated ponds, undrained depressions, and (or) straight drainage segments.

REGIONAL TECTONIC SETTING

Bedrock units in the Redwood Creek area have been deposited and deformed in an active tectonic setting along the western margin of the North American plate. As a result, Franciscan rocks are highly deformed; deformation includes shearing and formation of mélange in the Franciscan sandstone and mélange unit and both small-scale folding and shearing in the Redwood Creek schist (Cashman and Cashman, 1982). How and when the Franciscan units of northern California were assembled are questions that are far from resolved (Blake and Jones, 1978, 1981; Alvarez and others, 1979). Faults in the Redwood Creek basin include both shallow to moderately east-dipping thrust faults (for example, South Fork fault, Indian Field Ridge fault) that may have formed in conjunction with subduction-related underthrusting and strike-slip faults (for example, Lost Man fault) that have apparently accommodated major right-lateral offset.

Regional tectonics do suggest that the Redwood Creek basin is geologically young. Plio-Pleistocene Prairie Creek sediments record the gradual transition from marine to lagoonal to fluvial deposition, showing recent emergence of the western part of the basin above sea level. The lack of detritus derived from Franciscan assemblage rocks in sediments of the Prairie Creek Formation suggests that the bedrock units now found in the Redwood Creek basin were not eroded by the paleodrainage system represented by the Prairie Creek sediments. These observations suggest that erosion within Redwood Creek commenced no sooner than 2 Ma and that the Redwood Creek basin is entirely a Pleistocene landform.

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History of Timber Harvest in the Redwood Creek Basin, Northwestern California

By DAVID W. BEST

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–C

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HISTORY OF TIMBER HARVEST IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

By David W. Best[1]

ABSTRACT

Timber harvest is the dominant land use in the Redwood Creek basin. The location and timing of timber harvest throughout the basin were determined primarily by interpretation of aerial photographs. The earliest logging activities, which took place in the latter half of the 19th century, entailed the clearing of forests on the broad flood plains at the mouth of Redwood Creek. Pre-1936 commercial logging of redwoods on upper slopes in the lower basin was done with steam donkeys that cable-yarded the logs to ridgetop landings. In the late 1930's, crawler tractors replaced steam donkeys as the yarding machines. From then until the early 1960's, most of the logging was partial cuts, whereby only a portion of the stand was removed. The most intense logging period in Redwood Creek was from 1949 to 1954, and this activity was concentrated in the middle and upper parts of the basin. Logging continued to be most active in the upper two-thirds of the basin until about 1967. The timing and spatial distribution of logging indicate that the most intensive timber harvest in the upper two-thirds of the basin occurred in the 15 years prior to a major storm and flood in December 1964. During the 1960's, the harvest technique changed to tractor-yarded clearcuts, and it was during this time that logging became most heavily concentrated in the redwood-dominated lower watershed. Logging activity in the lower watershed ended abruptly with the expansion of Redwood National Park in 1978. The Z'berg-Nejedly Forest Practices Act in 1973 started a trend to more regulated and smaller tractor harvest cuts, as well as the increased use of cable-yarding systems for timber harvest on steeper slopes. Relogging of previously logged areas to remove residual old-growth timber became the dominant logging activity in the middle and upper watershed by 1978. By that time, 81 percent of the coniferous forests in the Redwood Creek basin had been logged.

INTRODUCTION

The timber of the Redwood Creek basin is unquestionably the basin's resource of greatest economic value (Janda and others, 1975). Over the last half century, 81 percent of the coniferous forests in the basin have been logged, requiring construction of roughly 2,000 km of roads and 9,000 km of skid trails. A combination of logging road construction and timber harvest, a sequence of intense winter storms, and inherently unstable slopes have resulted in severe erosion problems and an acceleration of erosion rates. Most erosion, such as that from hillslope gullies and streamside landslides, occurred during infrequent large storms in 1953, 1955, 1964, 1972, and 1975. Aerial photographs suggest the December 1964 storm caused the most drastic changes, especially in the upper portions of the watershed where logging had been most intense and most recent.

The relationship between logging, intense winter storms, and inherently unstable slopes in causing accelerated erosion is complex and difficult to assess. In an effort to clarify the above relation, this report summarizes the history of timber harvest in the Redwood Creek watershed.

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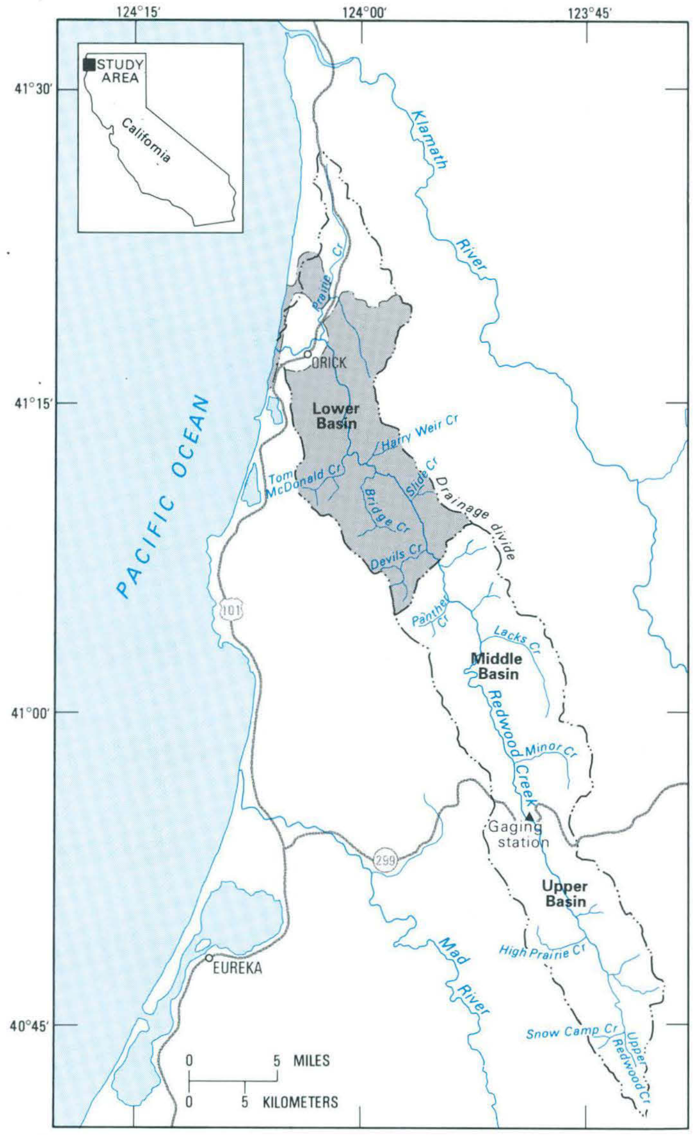
Dave Goodwin of the Humboldt County Assessor's Office provided 1962, 1966, and 1970 aerial photographs and copies of timber harvest maps, all of which were invaluable in determining dates and areas of timber harvest over the interval of the study. Donald Buchanan of the Humboldt County Agricultural Stabilization and Conservation Service provided 1954 aerial photographs. Laura Vander and Paul Routon aided in data compilation and drafting. Annie Kubert drafted the figures for this report. Ray Rice and Mary Ann Madej reviewed the manuscript, and comprehensive editing and review was done by Harvey Kelsey and Steven Veirs.

BASIN DESCRIPTION

Redwood Creek drains a 725-km^2 watershed located in the Coast Ranges of northern California (fig. 1). The



EXPLANATION

REDWOOD NATIONAL PARK

FIGURE 1.—Locations studied in the Redwood Creek basin.

creek descends from elevations of nearly 1,500 m and enters the Pacific Ocean near the town of Orick. There are 74 tributary basins drained by second order or higher streams that flow directly into Redwood Creek. Tributary channels are characteristically low-order, high-gradient streams draining small watersheds. The unusual elongate geometry (elongation ratio=0.34) of the Redwood Creek basin is a reflection of structural control due to north-northwest-trending faults in the Franciscan assemblage of Late Jurassic to Cretaceous age (Harden and others, 1982). The drainage basin is characterized by high relief, moderate to steep hillslopes, and narrow valley bottoms. Average hillslope gradient is 26 percent (Janda and others, 1975). The steepest slopes occur adjacent to stream channels and form an incised canyon called the inner gorge. Inner gorge slopes, which are especially susceptible to mass wasting, were the locations of some of the best timber prior to logging. Moderate- and low-gradient hillslopes are generally found in only midslope and upper slope positions.

Coniferous forests make up 82 percent of the natural vegetation of the watershed, whereas oak-woodlands and grasslands total 9 percent each. The vegetation of the coastal northwestern one-third of the basin is largely redwood forest (community types follow Munz, 1959) dominated by redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*) (fig. 2). The vegetation of the inland southern two-thirds of the basin is dominated by Douglas-fir forest, changing to yellow pine forest at higher elevations near the headwaters. The distribution of coniferous forest (Redwood and Douglas-fir dominated) and prairie (fig. 2) depends largely on available soil moisture during the dry summer months. The redwood-dominated forest occurs nearer the coast where summer coastal fog is frequent. In the lower watershed, prairies occur along the watershed divide on the east side and locally continue downslope along tributary divides. In the middle and upper portions of the watershed, prairies are more common, occur on all hillslope positions (fig. 2), and are most often bounded by oak-woodland. The oak-woodland forests are dominated by Oregon white oak (*Quercus garryana*). The hardwood component of the forests in the basin was largely unharvested until 1979 when tan oak (*Lithocarpus densiflora*) chips began to be used in the manufacture of paper pulp.

DATA COLLECTION

The data compiled in this report are the result of a photointerpretive study of logging in the watershed. Aerial photographs taken in 1936, 1947, 1954, 1962, 1966, 1970, and 1978, as well as logging dates provided by the Humboldt County Timber Assessor's Office, serve as the data base for the logging unit boundaries drawn on mylar overlays of 1:10,000-scale base maps. Information collected for each logging period (defined by dates of aerial photography) included area of timber harvested, yarding methods employed, and an estimate of the degree of ground disturbance. The map areas delineating these data were measured with a planimeter.

Because of differences in climate, vegetation, and logging history, the basin was divided into an upper, middle, and lower watershed. The upper watershed includes all land upstream of the U.S. Geological Survey

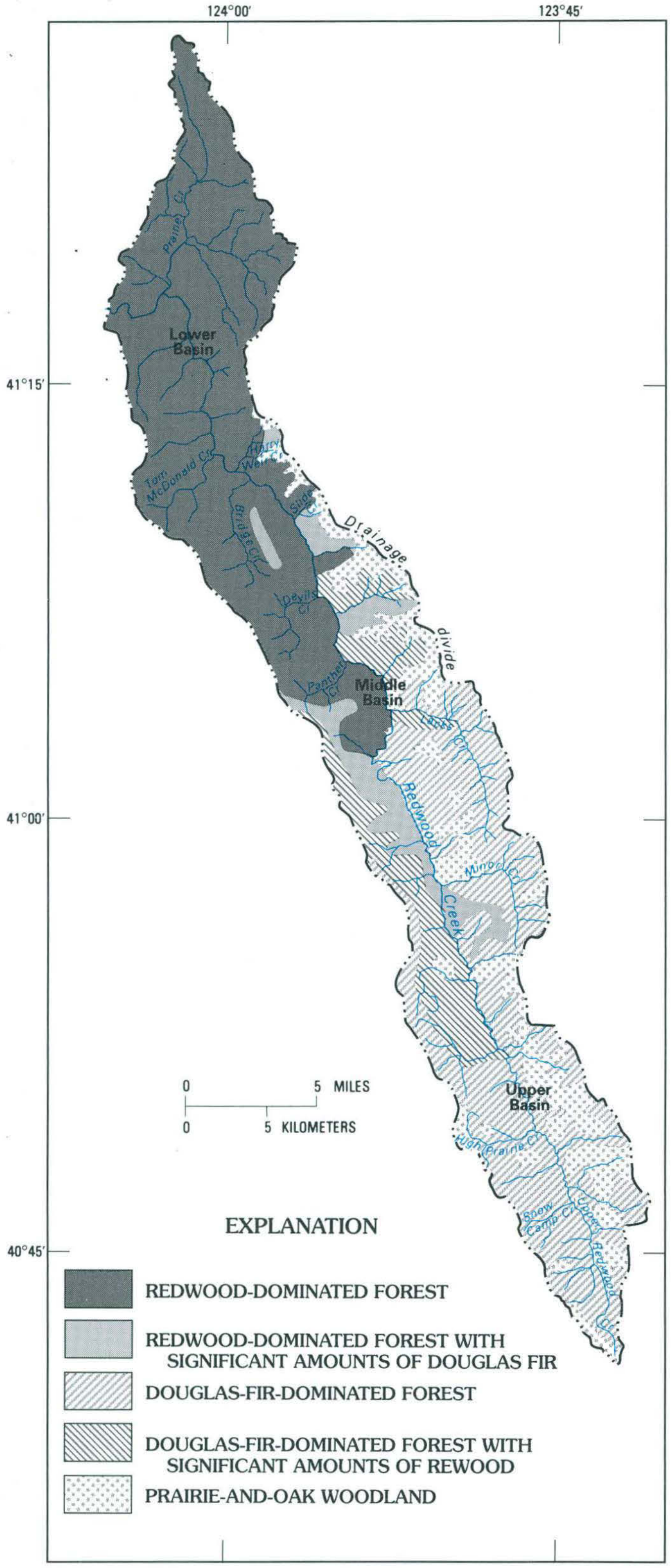


FIGURE 2.—Generalized vegetation of the Redwood Creek basin.

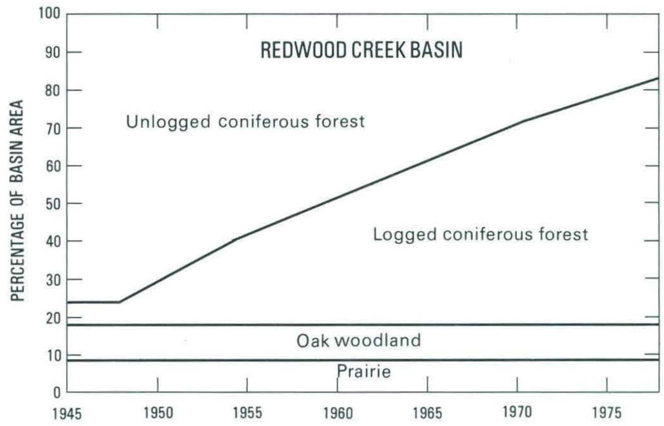


FIGURE 3.—Timber harvest in the Redwood Creek basin, showing changes in percentage of basin logged between 1945 and 1978.

gaging station near State Highway 299 (fig. 1) and has a drainage area of 173 km^2. The middle watershed includes all land downstream of the gaging station but upstream of the Redwood National Park boundary (246 km^2). The lower watershed includes all land downstream of the park boundary including the town of Orick and surrounding flood plain (197 km^2) (fig. 1). Prairie Creek, which enters Redwood Creek near the mouth, is the largest (104 km^2) tributary basin in the watershed but was excluded from the study because it drains terrain that is geologically and physiographically different from the rest of the watershed.

Periods of logging of coniferous forests and the percentage of the watershed areas involved are shown for the entire basin (Prairie Creek excluded) (fig. 3) and separately for the upper, middle, and lower watersheds (fig. 4). The data on logged area refer to only first-entry timber harvest. Many areas have been subsequently relogged to remove residual timber. This type of harvest has become increasingly important in recent years and by 1978 accounted for most of the area logged each year. However, the erosional impact of relogging is quite different from first-entry logging because fewer roads and skid trails are used and little new road construction is required.

FACTORS AFFECTING TIMBER HARVEST HISTORY

LAND OWNERSHIP

Before the establishment of Redwood National Park in 1968, less than 5 percent of the watershed was held in public ownership, mostly as several isolated parcels administered by the U.S. Forest Service and the Bureau of Land Management. Most of the land was owned by

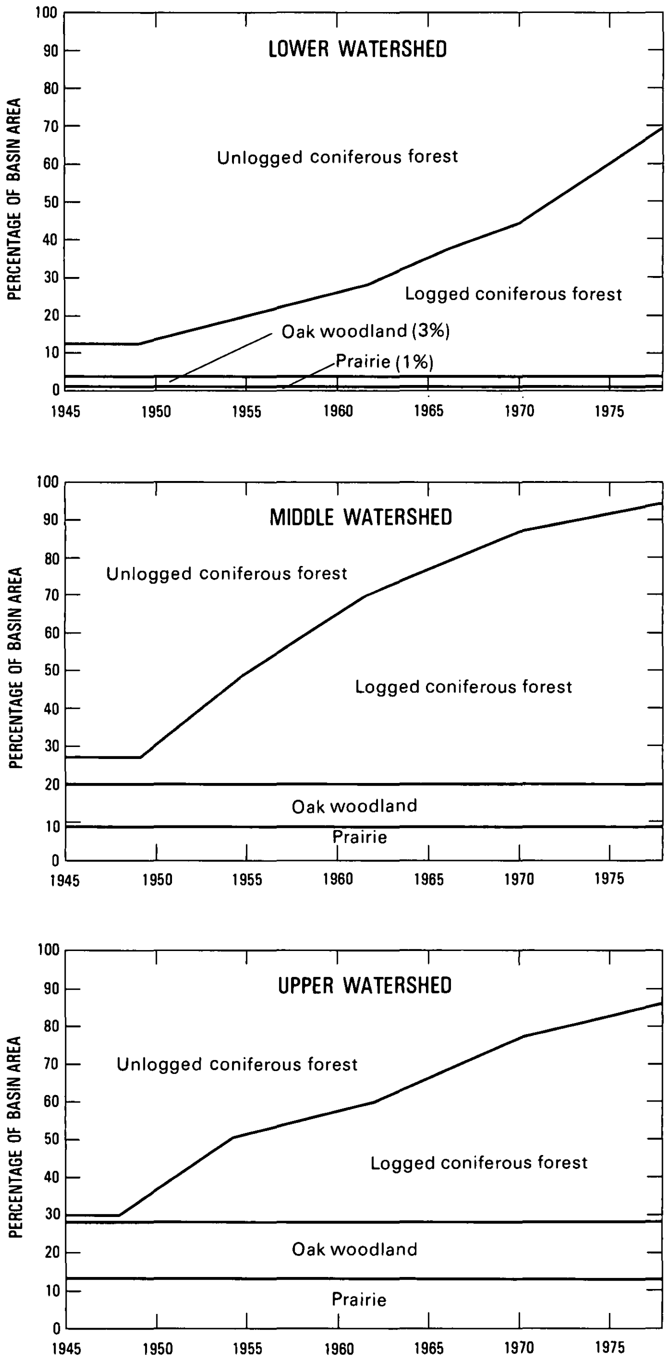


FIGURE 4.—Timber harvest history in the upper, middle, and lower watersheds in the Redwood Creek basin, showing percentage of basin logged between 1945 and 1978.

private timber companies or consisted of large family-owned ranches. As timber values increased after World War II, ranchers began logging their own lands or sold their timber rights to timber companies. As a result, virtually all the privately owned land in the basin has been available for timber harvest.

Although establishment of Redwood National Park in 1968 and its expansion in 1978 removed about 30 percent (18,600 ha) of the Redwood Creek basin from future timber harvest, only 2,550 ha of old growth redwood vegetation remained at the time of legislative taking of the lands. By 1980, nearly all of the remaining blocks of uncut timber were in public ownership, most of these in Redwood National Park, with some small, isolated U.S. Bureau of Land Management and U.S. Forest Service parcels in the middle and upper watersheds.

REGULATION OF TIMBER HARVEST

In 1945, California became the first State to regulate the private timber industry by enacting the Forest Practices Act (Arvola, 1976). Under this act, logging practice rules were formulated by District Forest Practice Committees composed of timber owners and operators. Rules became effective only after ratification by two-thirds of the timber landowners. A 1971 State court decision declared the law unconstitutional, primarily because of the issue of industry self-regulation. In 1973, after 2 years of lobbying by both the timber industry and conservationists, the Z'berg-Nejedly Forest Practices Act was enacted, establishing the current basic policies followed by the California Department of Forestry in regulating timber harvest. Therefore, by the latter half of the 1970's, timber harvest in the Redwood Creek basin was being conducted under statutes that ensured less disruptive harvest practices than were prevalent in the two previous decades.

CHANGING TIMBER HARVEST PRACTICES

Prior to 1936, the redwood forests were in most cases clearcut logged and cable-yarded by using Dolbeer steam donkeys. The yarding machinery usually hauled logs to the ridges and then to the railroads running to the mills. In the process, all the trees were cut or knocked down by the heavy cables. The crawler tractor, introduced in the late 1930's, made clearcutting unnecessary, permitting the removal of only the desired trees and leaving a portion of the stand uncut.

During the 1950's, large tracts within the basin were logged by tractor with varying amounts of timber left standing. Although true selection silviculture was recommended by some experts (Fritz, 1959), timber was left standing due to a combination of factors. These factors included the new forest practices rules for seed trees and minimum diameters and the practice of high-grading (removing only the more profitable material).

In the 1960's, timber harvest methods evolved toward more clearcutting under alternate plans approved by the Board of Forestry. Larger timber cut blocks, increased use of tractor-constructed layouts (smooth beds of dirt onto which trees were felled to reduce stem breakage), and increased reliance on tractor-yarding resulted in increasing surface disturbance. Adjoining blocks of timber were harvested in successive years to minimize the costs associated with road construction and maintenance.

Clearcutting, using crawler tractors, remained the dominant harvest method for more than a decade. In the 1970's, with new forest practice rules and increasing public concern, the use of cable-yarding systems increased, especially on steeper slopes and adjacent to the National Park boundary.

TIMBER HARVEST CHRONOLOGY

EARLY FOREST CLEARING

The wide river bottoms adjacent to Redwood Creek were cleared during the second half of the 19th and early in the 20th century. Settlers cleared the forest from the flood plains and low terraces to create more pastures and agricultural land (Janda and others, 1975). The Sitka spruce (*Picea sitchensi*) was milled locally for lumber. This clearing (visible as cleared areas that are not recently logged on 1936 aerial photographs) is approximately 2 percent of basin area, nearly all of it within the coastal flood plain.

TIMBER HARVEST BEFORE 1936

Commercial logging of redwood in the basin began in the 1930's. Cable-yarded clearcut areas are clearly visible on the 1936 aerial photographs of the lower Redwood Creek watershed. Most of the pre-1936 timber harvest was located in the headwaters of Devils Creek and Panther Creek (fig. 1). The logs were yarded by using steam donkeys and cable systems in conjunction with a logging railroad that transported the logs south out of the basin. Janda and others (1975) evaluated the impact of early steam-donkey logging in Redwood Creek by using aerial photographs and ground photographs from other nearby areas. They concluded that steam-donkey yarding techniques resulted in large clearcuts, heavy concentrations of slash, and intense localized ground disturbance surrounding landings and skid trails. However, there was less road construction and much less alteration of surface drainage patterns than is associated with large-scale tractor-yarded clearcuts typical of the 1960's.

Pre-1936 timber harvest also occurred upstream in the Douglas-fir forest, but the timber was tractor-yarded. Approximately 240 ha opposite the mouth of Minor Creek were selectively logged.

TIMBER HARVEST FROM 1936 TO 1948

Between 1936 and 1948, tractor-yarding became the dominant yarding method in the Redwood Creek watershed. Logging covered approximately 800 ha and was distributed equally in four areas: slopes just northwest of Orick, upper slopes in Tom McDonald Creek, the headwaters of Devils Creek, and the headwaters of High Prairie Creek (fig. 1). By 1948, 8 percent of the coniferous forests had been logged, accounting for 6 percent of drainage basin area (fig. 3).

TIMBER HARVEST FROM 1949 TO 1954

The period from 1949 to 1954 was the most intense interval of timber harvest in the watershed. During this period, 9,872 ha of the coniferous forests were logged, or roughly 27 percent of the original forests and 22 percent of the basin drainage area (fig. 3). Timber harvest was concentrated in the inland, Douglas-fir-dominated forests. More than half the logging during this period occurred in the middle watershed, and about one-third of the logging was located in the upper watershed. By 1954, 15 percent of the lower watershed area, 28 percent of the middle watershed area, and 22 percent of the upper watershed area had been logged (fig. 4).

Crawler tractors were used almost exclusively in timber harvest during this period. Only 15 percent of logging in the middle watershed and 9 percent of logging in the upper watershed were cable-yarded.

TIMBER HARVEST FROM 1954 TO 1962

Between 1954 and 1962, the rate of timber harvest declined substantially in both the middle and upper portions of the watershed and increased moderately in the lower watershed (fig. 3). The harvest rate for the watershed declined to 17 percent of the previous period average, despite a 40-percent increase in rate above the previous period average for the lower watershed. Crawler-tractor-yarding was again the dominant harvest method. Cable-yarding accounted for only 7 percent of the logging in the middle watershed and 14 percent of the logging in the upper watershed.

TIMBER HARVEST FROM 1962 TO 1966

Between 1962 and 1966, there was a slight increase in logging over the previous period average, but logging activity in the basin was only three-quarters of the 1949–54 rate. The 1962–66 rate of timber harvest averaged less than 60 percent the 1949–54 rate in the middle watershed but increased to 250 percent of the 1949–54 rate in the lower watershed and nearly equaled the 1949–54 rate in the upper watershed. By 1966, approximately 55 percent of the original coniferous forests had been logged from 45 percent of the drainage basin area (fig. 3).

Aerial photographs show that much of the recent logging in the upper watershed visible on the 1962 and 1966 photographs occurred in the narrow inner gorge along Redwood Creek and many of its tributaries. For access, numerous near-channel roads were constructed, and the entire area was yarded by using tractors. Many streamside landslides occurred during the 1964 storm (chaps. J and K, this volume) in these same logged areas within the inner gorge.

TIMBER HARVEST FROM 1966 TO 1970

Between 1966 and 1970, timber harvest continued at nearly the same rate in the middle watershed, declined moderately in the lower watershed, and increased considerably in the upper watershed (mostly as a result of one large 830-ha tractor-yarded clearcut) (fig. 4). Timber harvest in the upper watershed was 80 percent of the 1949–54 rate. By 1970, 65 percent of the original coniferous forests of the basin had been logged, comprising 53 percent of the drainage basin area (fig. 3). During this period, practically all logging was tractor-yarded.

TIMBER HARVEST FROM 1970 TO 1978

Timber harvest rates between 1970 and 1978 declined substantially in both the middle and upper portions of the watershed as the supply of old-growth timber was exhausted. Most of the easily accessible timber had been harvested, and logging concentrated on remaining uncut forests in the lower watershed and on the previously cut areas where old-growth timber remained. Increased demand for redwood further stimulated timber harvest in the lower watershed.

By 1978, 81 percent of the original forests had been logged over 66 percent of the drainage basin area (fig. 3). On a subwatershed basis, this logging includes 69 percent of the original forests in the lower watershed, 92 percent in the middle watershed, and 81 percent in the upper watershed, averaging 66, 73, and 59 percent of the respective drainage areas. In this period, cable-yarding became a more common harvesting technique, especially in steep areas adjacent to stream channels. For instance, between 1971 and 1978, cable-yarding in these areas accounted for 22 percent of all logging in the middle watershed.

REENTRY OF PREVIOUSLY LOGGED AREAS, 1960 TO 1981

As the value of timber products increased and the supply declined, timber companies increasingly entered previously logged areas to remove residual timber. In the 1960's, this type of harvest accounted for only 15 percent of total logged area, and such harvests usually occurred in areas of substantial residual timber. By the late 1970's, second entry timber harvest accounted for most of the area logged annually, and this logging occurred in areas with smaller proportions of residual timber.

In the upper watershed, the amount of area relogged increased from 29 percent in 1971 to 1978 to 50 percent in 1979 to 1981. In the middle watershed, relogging accounted for 31 percent of the area logged between 1967 and 1970, 49 percent between 1971 and 1978, and 65 percent between 1979 and 1981. Timber harvest in the lower watershed ended with the expansion of Redwood National Park in 1978.

SUMMARY

Logging is the dominant land use in the Redwood Creek basin. Early logging activities cleared the broad flood plains near the coast for grazing and agriculture. Early commercial logging was done by steam donkeys that cable-yarded timber from extensive clearcut tracts of land in the upper slopes of the middle watershed. In the late 1930's crawler tractors replaced steam donkeys as the yarding machines, and partial cutting of timber became the dominant harvest method. The most intensive logging period in the Redwood Creek basin was from 1949 to 1954, and this activity was concentrated in the upper and middle watersheds. During the 1960's, the harvest technique reverted to clearcutting by tractor yarding. It was during this time that timber harvest became most concentrated in the redwood-dominated lower watershed, and logging continued steadily there until the expansion of Redwood National Park in 1978. The passage of the Z'berg-Nejedly Forest Practices Act in 1973, administered by the California Department of Forestry, started a trend to more regulated and smaller tractor harvest cuts and to the increased utilization of cable-yarding systems for timber harvest on steeper slopes. Reentry of previously logged areas to remove residual old-growth timber became the dominant logging activity in the middle and upper watersheds by 1978. The timing and spatial distribution of logging in the Redwood Creek basin indicate that the most intensive logging occurred in the upper basin in the 15 years before the 1964 flood. Therefore, the logging history provides a data base for the discussion of relative effects of logging and major storms on erosion rates.

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A Comparison of Flood-Producing Storms and Their Impacts in Northwestern California

By DEBORAH R. HARDEN

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454-D

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

A COMPARISON OF FLOOD-PRODUCING STORMS AND THEIR IMPACTS IN NORTHWESTERN CALIFORNIA

By DEBORAH R. HARDEN[1]

ABSTRACT

Major floods resulting from relatively infrequent, intense winter storms are an important geomorphic agent affecting hillslopes and stream channels in the Redwood Creek basin and throughout northwestern California. A series of six flood-producing storms between 1953 and 1975 and an earlier storm series in the late 1800's in northwestern California are documented by precipitation data and historic records. Reconstruction of regional rainfall and runoff patterns for these storms is an important step in analyzing the causes of the observed variability in the impacts of the storms.

The six storms between 1953 and 1975 produced similar instantaneous peak discharges estimated at about 1,400 m^3 at Redwood Creek at Orick, the downstreammost gaging station on Redwood Creek, 3 km from its mouth. The distribution of rainfall, antecedent moisture conditions, and rainfall amounts varied within the basin. However, the amount of precipitation recorded during the 1964 storm does not alone account for the extensive regional damage to hillslopes and channels during the 1964 flood. Likely causes for the disproportionate impacts of this storm include small-scale destabilization of hillslopes by the 1953 and 1955 storms; concentration of rainfall in the upper basin, where streamside slopes are less densely vegetated and also unprotected by flood plains; and intensive road construction associated with logging in the upper basin between 1955 and 1964.

Comparison of the series of 1953–75 storms with major regional storms in northwestern California during the late 19th century, patterns of which were reconstructed from newspaper accounts and other published information, indicates that major storms of 1861–62 and 1890 were at least as intense in the Redwood Creek basin as the 1964 storm. The fact that the earlier flood series had a dramatically smaller erosional impact in the basin is probably attributable to changes in runoff regimes and hillslope stability caused by human disturbance of the basin during the second half of this century.

INTRODUCTION AND SCOPE OF WORK

Regional storms during the winter months are largely responsible for the high rainfall that characterizes north coastal California. The storms are generated when an anticyclonic cell moves north to the Gulf of Alaska during the winter months in the Pacific Ocean. Moderately intense rain falls as a result of orographic and frontal lifting of the air masses as they are carried landward and intersect the Coast Ranges (Coghlan, 1984). The Redwood Creek basin receives about 200 mm of precipitation annually, most of which falls during these regional winter storms within the basin; annual precipitation varies from about 1,525 mm near Orick to over 2,540 mm in the headwaters (Iwatsubo and others, 1975).

During the period of historic records, two series of years with a high incidence of major storms have occurred in the north coast region (northwestern California). Between 1953 and 1975, six storms generated runoff with peak flows greater than 1,282 m^3/s at Redwood Creek at Orick (table 1), 3 km from the mouth of Redwood Creek. These floods have a long-term recurrence interval of about 25 years (Janda and others, 1975).

TABLE 1.—*Instantaneous peak discharges for Redwood Creek near Blue Lake and at Orick during recent major floods*

[From Harden and others (1978)]

Date	Redwood Creek near Blue Lake (drainage area 175 km^2)		Redwood Creek at Orick (drainage area 720 km^2)	
	(m^3/s)	[m^3/s)/km^2]	(m^3/s)	[m^3/s)km^2]
Jan. 18, 1953	([1])	([1])	1,416	1.97
Dec. 22, 1955	342.7	1.96	1,416	1.97
Dec. 22, 1964	464.4	[2]2.66	1,430	1.99
Jan. 22, 1972	195.4	[3]1.11	1,282	1.78
Mar. 3, 1972	388.0	[3]2.22	1,407	1.96
Mar. 18, 1975	345.5	1.97	1,422	1.98

[1] Floodmarks for this event were at a stage of 4.66 m, whereas floodmarks for the 1955 event were at a stage of 4.18 m. No discharge value has been assigned to the 1953 event.

[2] Discharge estimated from floodmarks 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.

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An earlier series of flood-producing storms is documented by historic records and limited rainfall data from northwestern California. During the late 19th century, major regional storms occurred during 1861–62 and in 1890. Additional, less extensive storms affected many north coast basins in the intervening years. The years between 1890 and 1953 were relatively free of major flood-producing storms.

The purpose of comparing storms that generated major floods in the Redwood Creek basin was to account for the fact that the December 1964 storm produced the most damaging flood of the period of record throughout the north coast. The effects of this storm on hillslopes and stream channels are still discernible in the Redwood Creek basin (chap. G, this volume). I have compared the magnitude, intensity, and distribution of the six 20th century storms to evaluate their impact on different portions of the basin. I have also attempted to reconstruct the distribution and magnitude of the storms of the 19th century to see whether that storm series was of comparable magnitude.

One of the major controversies surrounding the Redwood Creek basin has centered on the contribution of major storms to the widespread landsliding and channel aggradation that began in the late 1950's (Janda and others, 1975). The erosional impacts of the storms of 1953 through 1975 on hillslopes in north coastal California are well documented (chap. G, this volume, 1978; Stewart and LaMarche, 1967; Helley and LaMarche, 1973; Kelsey, 1977, for example). Extensive damage to stream channels, in the form of bank erosion and aggradation, is also well documented. The December 1964 storm, which produced the most damaging and widespread floods of this century, has been particularly credited with long-term destabilization of hillslopes and channels in northwestern California. The record of flood-induced damage during the late 19th century storms is far less conclusive. Historic records, aerial photographs taken when landslide scars of the late 19th century were still discernible, and information gained from coring of flood-plain trees show far less evidence of damage to hillslopes and stream channels than was produced during the later storm series (Kelsey, 1977; Harden and others, 1978).

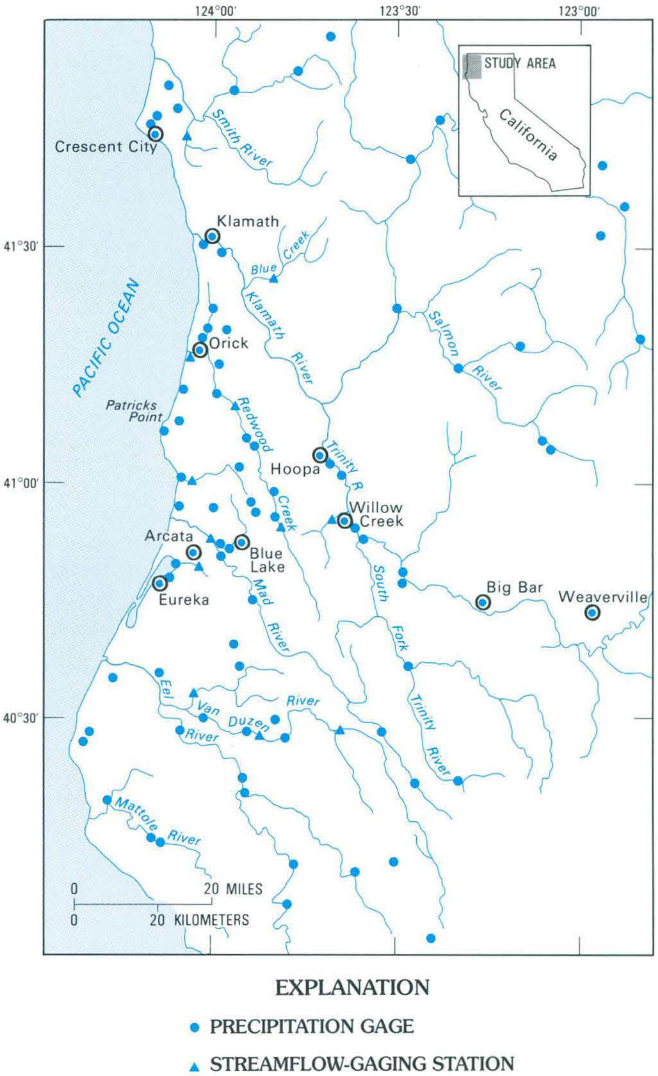


FIGURE 1.—Location of precipitation and streamflow-gaging stations in northwestern California.

METHODOLOGY

I have reconstructed the regional precipitation and runoff patterns for each of the 20th century storms by using available records. Temperature and snowpack records also were used to evaluate antecedent moisture conditions. A search of newspaper accounts and other historic documents was made to reconstruct the late 19th century storms, and limited precipitation records supplemented these accounts. A brief description of data sources and quality of data is given below; a more complete discussion of methodology can be found in Harden and others (1978).

PRECIPITATION RECORDS

For the 20th century storms, daily precipitation records from 81 rain gages in northwestern California were used to reconstruct storm rainfall totals (fig. 1; Harden and others, 1978). Only 16 gages were in operation during all six storms, and records from many stations are available for only one storm (fig. 2). However, many discontinued stations were replaced by nearby gages, and many of the stations with only one storm recorded were those installed during studies in the Redwood Creek basin (Harden and others, 1978). The

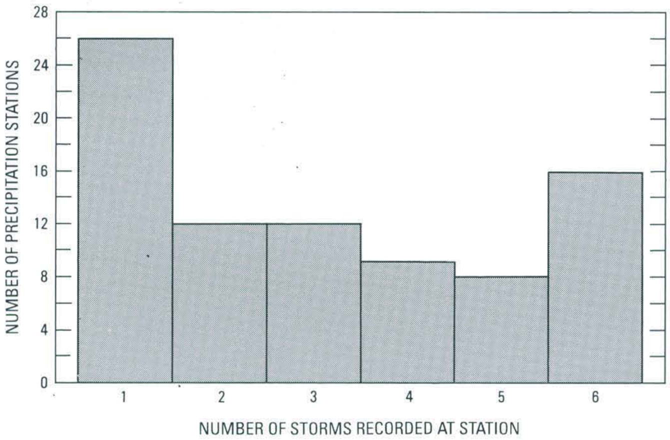


FIGURE 2.—Histogram showing number of precipitation stations operating during storm events.

areal and elevational distribution of gages for each of the six storms is therefore quite good, with 31 (1953) to 53 (1964) records available for each storm. The scarcity of gages near the inland portions of the Redwood Creek basin prior to 1975 necessitates extrapolation of records from adjacent Mad and Trinity River basins (fig. 1) to estimate storm impacts in the upper portion of the basin.

For most of the six storms, the dates of each storm period were clearly defined by the daily precipitation records. However, the complex storm periods of December 1964 and March 1975 were less easily delineated. Even by using flood hydrographs to separate that rainfall contributing directly to the flood peak and its recessional limb, the main flood-producing precipitation could not be isolated.

Three-day precipitation values for the days preceding, including, and following the flood peak for each storm provide a measure of storm intensity. In cases where flood peaks occurred on different days on different streams, the date of the peak at Redwood Creek at Orick was used to define the 3-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 3-day totals at different stations.

Reconstruction of the storm patterns of the late 19th century was more difficult due to the scarcity of rainfall and runoff records. At the time of the 1890 flood, six precipitation stations were operating in northwestern California. However, none of these was located near the Redwood Creek basin. Limited records are also available for the 1888 storm. At the time of the 1861–62 storm, the major flood-producing storm of the 19th century series, only one precipitation gage was operating, at Fort Gaston in the Hoopa River valley. The record from this station is somewhat questionable due to the recording method used at that time (see Harden and others, 1978, p. 62). Reconstruction of the late 19th century flood records therefore relied heavily on the accounts of newspapers (Arcata Union, Humboldt Weekly Times, Humboldt Times, Weaverville Trinity Journal) and other published accounts of the floods (Brewer, 1930; McGlashan and Briggs, 1939).

ANTECEDENT CONDITIONS

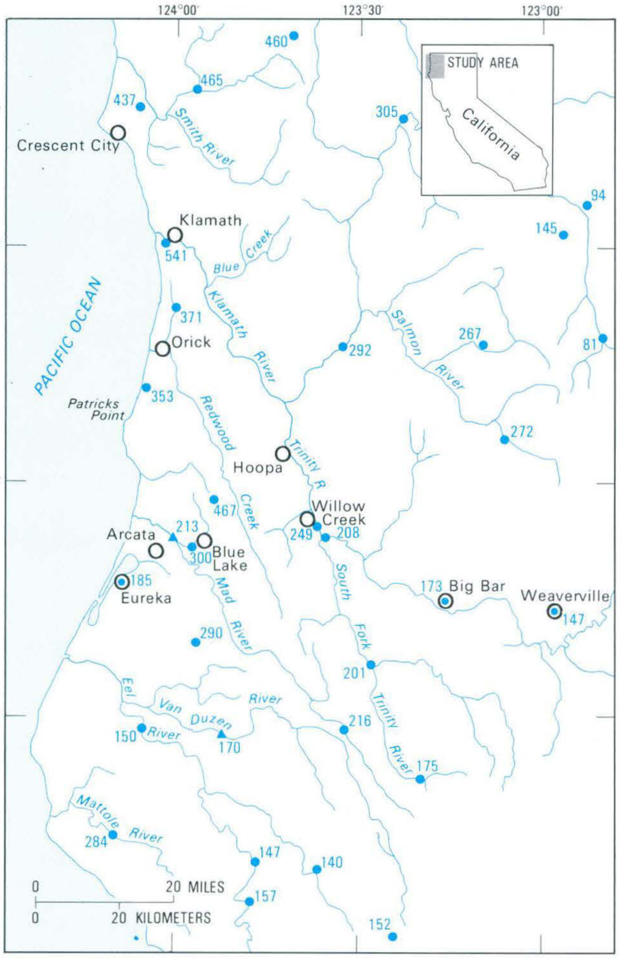
The antecedent precipitation index (API) developed by Kohler and Linsley (1951) provided a means of assessing the soil moisture conditions in this area prior to each storm. The index uses a decay equation to carry over a portion of each day's precipitation to a selected date of interest, in this case the beginning of each storm, and provides a cumulative value for the desired number of days prior to that day. Values of the index were calculated for the 60-day period prior to each of the six 20th century storms and for the 1890 storm. For the 20th century events, the index was computed for Orick and for either one or two inland stations (table 2). The API for Eureka was calculated for the 1890 storm.

Because preexisting snowfall can contribute significantly to peak flows by providing meltwater during a warm storm, temperature and snowfall records were used to determine the elevation of the snowline and hence the extent of preexisting snow in the region, particularly in the upper Redwood Creek basin. Cold temperatures during each storm period, at the beginning when snow could accumulate and later contribute to flood peaks, were also noted. Conversely, snowfall at the end of each storm period was considered to have a dampening effect on storm runoff.

RUNOFF

Streamflow records from 12 U.S. Geological Survey gaging stations are available for portions of the period of interest, with from two to five records available for each storm. The daily discharge records (U.S. Geological Survey, 1964, 1972, 1975; Waananen and others, 1971) were used to generate flood hydrographs for each event at the operating stations. In addition to providing storm runoff totals, the hydrographs aided in isolating the storm periods. The average storm total runoff, in inches, for the area above each station was used as the chief measure of flood magnitude.

For the 19th century floods, reports of flood stages provided a qualitative estimate of flood magnitude. Although these values could not be converted to a volume of runoff for a given drainage basin, the stage records aided in reconstructing the patterns of storm

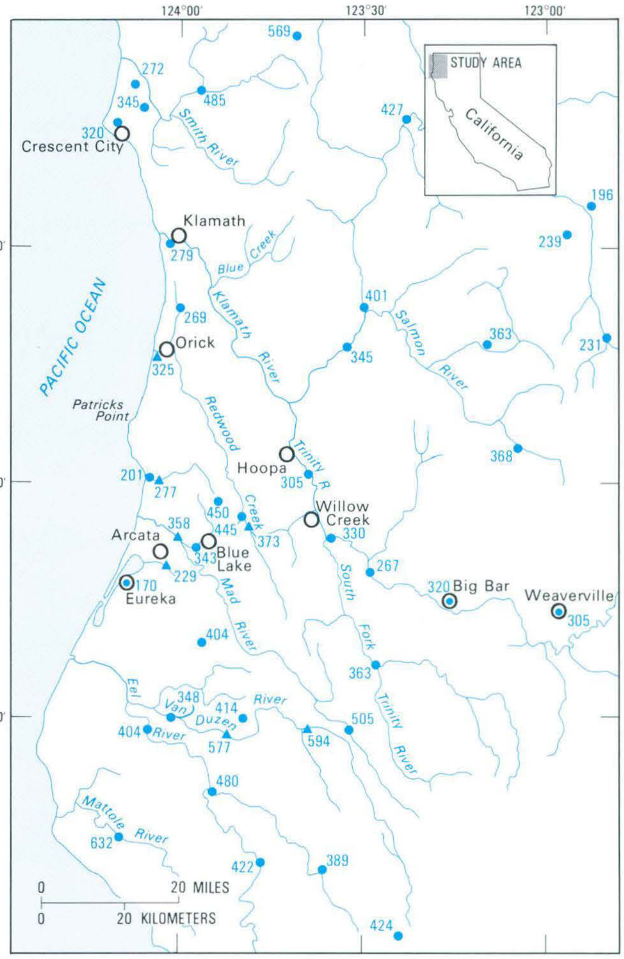


EXPLANATION

140● PRECIPITATION GAGE—Location, and precipitation value in millimeters

170▲ STREAMFLOW-GAGING STATION—Location, and runoff value in millimeters

FIGURE 3.—Precipitation and runoff for January 16 to 20, 1953.



EXPLANATION

389● PRECIPITATION GAGE—Location, and precipitation value in millimeters

594▲ STREAMFLOW-GAGING STATION—Location, and runoff value in millimeters

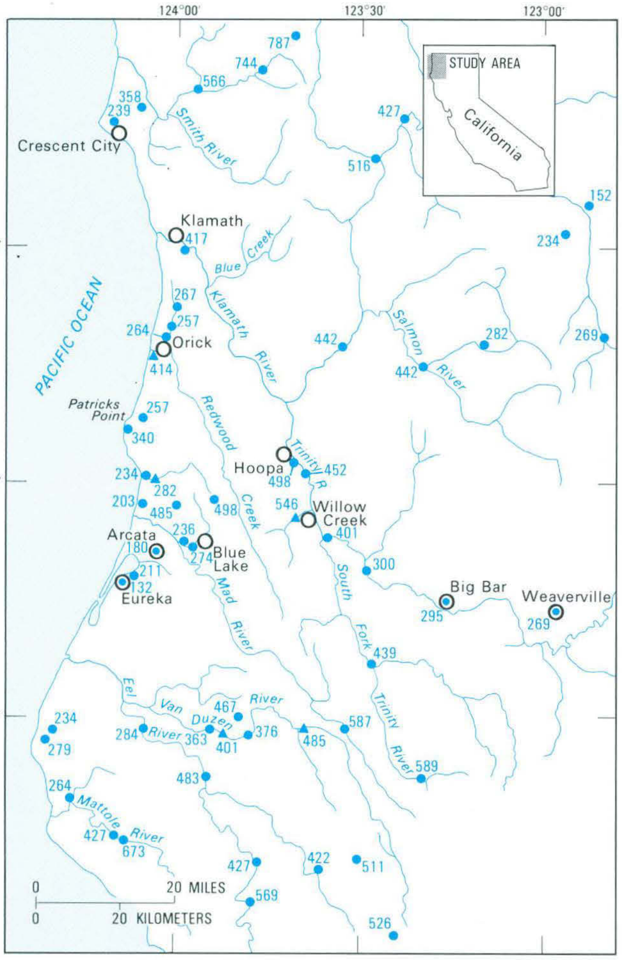
FIGURE 4.—Precipitation and runoff for December 15 to 23, 1955.

distribution. The reports of stream stages also provided documentation that the storms indeed produced major flooding.

STORMS OF 1953 TO 1975

The available climatologic and hydrologic data for the storms occurring from 1953 to 1975 were compiled in a series of maps that show the regional distribution of rainfall and runoff for each storm (figs. 3–9). The following comparisons of precipitation totals, rainfall intensity, storm distribution, antecedent moisture conditions, and runoff provide a basis for comparing storm magnitudes with the erosional impact of each storm.

The regional pattern of precipitation suggests that two contrasting storm tracks are typical of northwestern California. Storms such as the January 1953 and January 1972 events are centered to the north of the Redwood Creek basin and produce intense, heavy rainfall in coastal areas from Patrick's Point northward. These storms have lesser effects along the southern portion of the study area and in the inland portions of the Redwood Creek basin, and they produce only moderate precipitation in the eastern and southern inland portions of the region. The second type of storm track passes directly over the inland portion of the Redwood Creek basin, or even south of it. These storms, typified by the 1955, 1964, and 1975 events, produce high rainfall at inland sites and are frequently more prolonged than the coastal storms. Although the second storm type produces extensive regional flooding, the coastal storms may be more important geomorphic agents in the lower Redwood

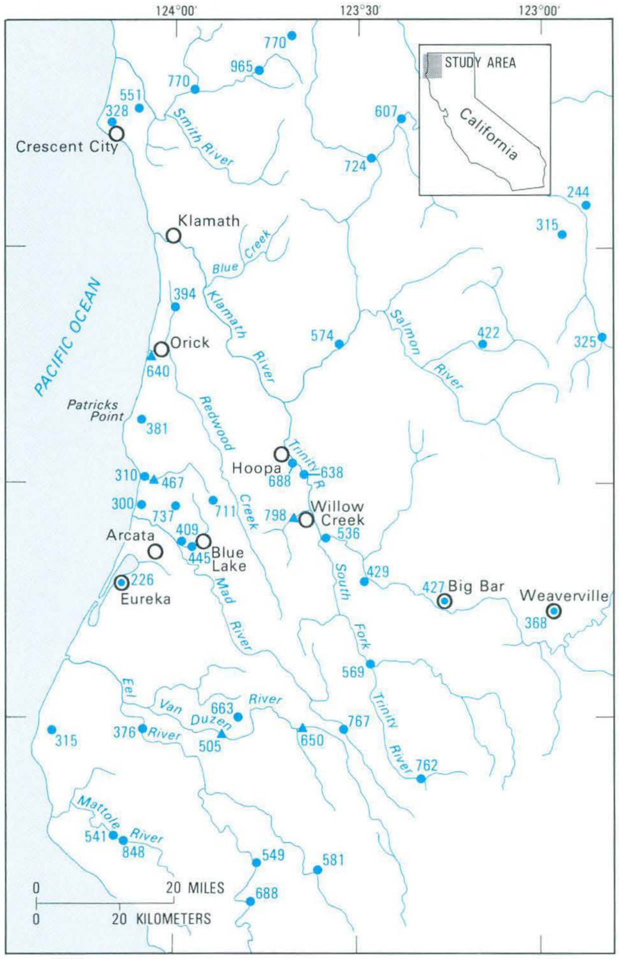


EXPLANATION

269● PRECIPITATION GAGE—Location, and precipitation value in millimeters

485▲ STREAMFLOW-GAGING STATION—Location, and runoff value in millimeters

FIGURE 5.—Precipitation and runoff for December 18 to 24, 1964.



EXPLANATION

581● PRECIPITATION GAGE—Location, and precipitation value in millimeters

650▲ STREAMFLOW-GAGING STATION—Location, and runoff value in millimeters

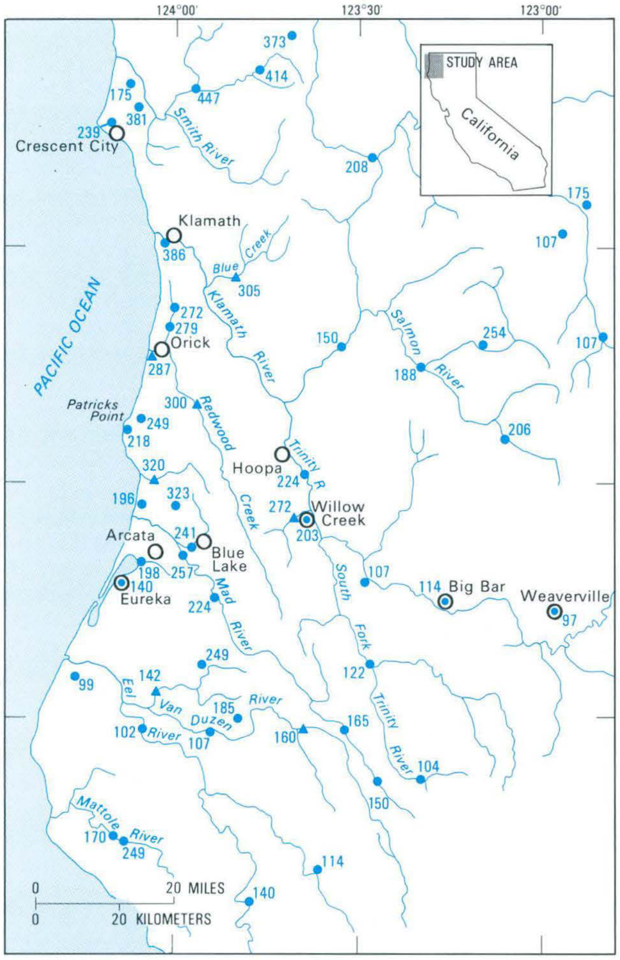
FIGURE 6.—Precipitation and runoff for December 18 to 30, 1964.

Creek and Klamath River basins and in smaller coastal streams.

PRECIPITATION TOTALS

On the basis of available records, the December 1964 storm apparently produced the greatest precipitation totals in the inland portions of the basin (figs. 3–9). Rainfall totals for the complex storm period between December 18 and 30, 1964 (fig. 6), were far greater than storm totals for the other five periods, and totals for the main storm period, December 18–24 (fig. 5), were also generally higher than those for other storms. However, precipitation in the coastal portion of the basin near Orick was greater during the 1953 (fig. 3) and 1975 (fig. 9) storms than during December 18 to 24, 1964 (fig. 5). The December 1955 storm generally produced the second highest precipitation totals for inland and southern portions of the Redwood Creek basin (fig. 4). Like the 1964 storm, this storm was less intense in the vicinity of Orick.

Both the 1955 and 1964 storms produced prolonged periods of rainfall, in contrast to the 1953 and 1972 storms. The March 1975 storm period included both a brief, intense storm similar to the 1953 and 1972 events and a subsequent, prolonged period of lesser rainfall. The 1972 storms were regionally less extensive than the other events, but they produced high rainfall totals in the northern coastal portions of the region (figs. 7 and 8).

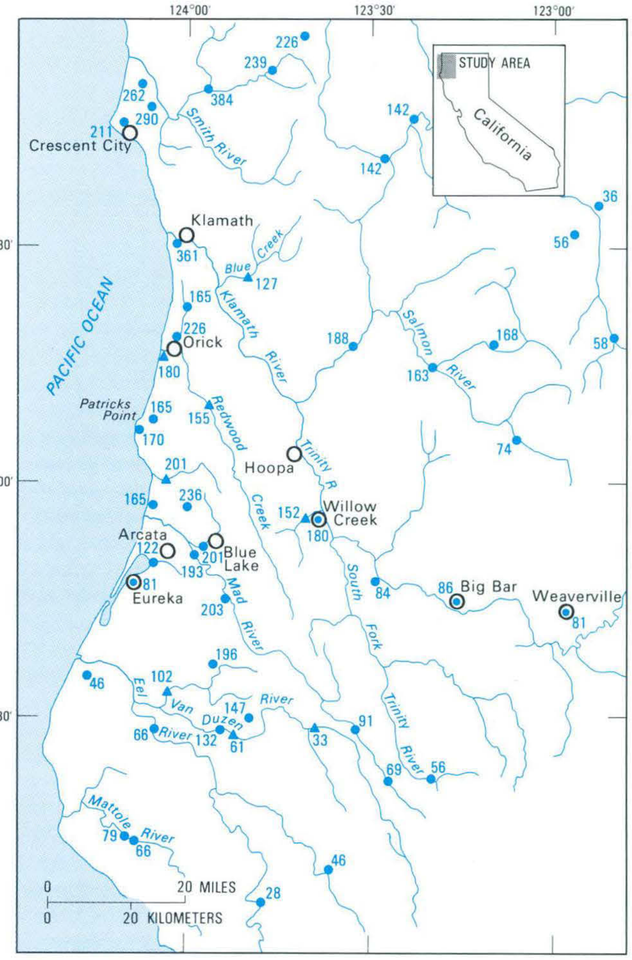


EXPLANATION

150● PRECIPITATION GAGE—Location, and precipitation value in millimeters

160▲ STREAMFLOW-GAGING STATION—Location, and runoff value in millimeters

FIGURE 7.—Precipitation and runoff for January 19 to 24, 1972.



EXPLANATION

46● PRECIPITATION GAGE—Location, and precipitation value in millimeters

33▲ STREAMFLOW-GAGING STATION—Location, and runoff value in millimeters

FIGURE 8.—Precipitation and runoff for March 1 to 4, 1972.

TABLE 2.—*Values of 60-day antecedent precipitation index (API) for flood-producing storms*

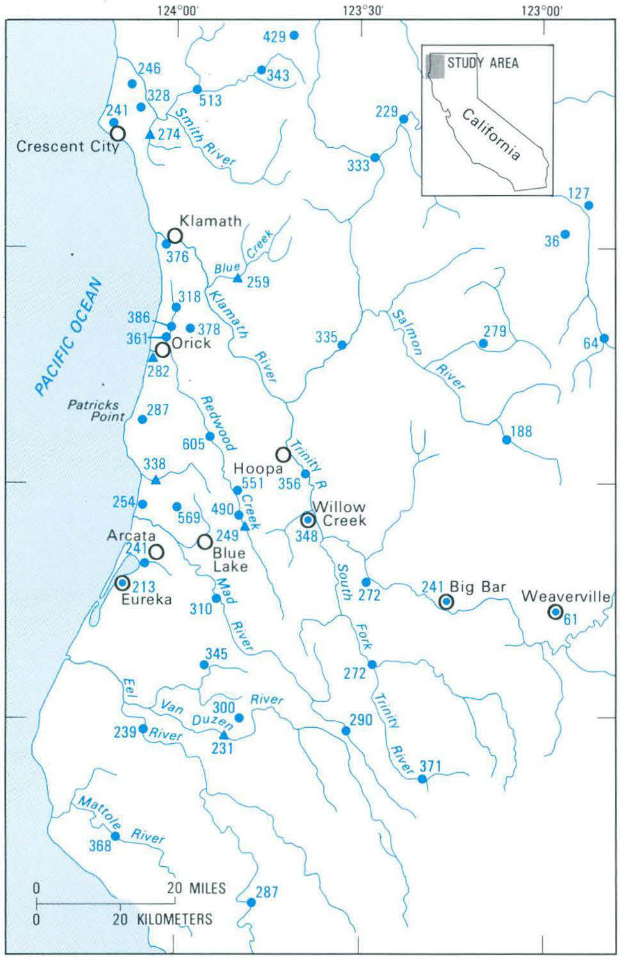
[—, no data]

	API, in millimeters			
Year	Orick	Hoopa	Big Bar	Willow Creek
1953....................	225	—	167	—
1955....................	171	—	117	—
1964....................	174	144	86	—
1972 (January)...........	114	—	57	—
1972 (March)............	218	—	129	206
1975....................	125	106	68	—
1890....................	API at Eureka was 259			

ANTECEDENT MOISTURE CONDITIONS

Comparisons of values of the 60-day antecedent precipitation index for each of the six storm periods indicate that flooding would have been most enhanced by antecedent moisture conditions during the 1953 storm (table 2). Both coastal and inland portions of the basin had high precipitation prior to that storm. Antecedent moisture was apparently lowest during the January 1972 and March 1975 storms (table 2). The low antecedent moisture conditions in 1975 probably diminished the erosional impact of that storm.

The presence of snow in the upper portions of the basin at the time of a major storm also could contribute to peak runoff values for the storm period. Examination of temperature records and recorded snowfall occurrence prior to the six major storms revealed that melting snow may have augmented peak flows during the 1964, March 1972, and 1975 events (Harden and others, 1978). The low temperature during the end of the complex storm



EXPLANATION

290● PRECIPITATION GAGE—Location, and precipitation value in millimeters

231▲ STREAMFLOW-GAGING STATION—Location, and runoff value in millimeters

FIGURE 9.—Precipitation and runoff for March 15 to 24, 1975.

period in December 1964 caused precipitation in high areas to fall as snow and therefore not to contribute to the main flood peaks except where the snow fell directly into channels.

RUNOFF

Runoff at Redwood Creek at Orick was greater for the December 1964 storm (fig. 6) than for any of the other four events for which records are available. Peak discharges at Orick were similar for all six floods (table 1). The 1955 flood produced the second highest runoff total (fig. 4), and the 1975 flood produced slightly less runoff than 1955 (fig. 9).

LATE 19TH CENTURY STORMS

Northwestern California experienced at least five flood-producing storms between 1861 and 1890. From December 1861 to January 1862, several storms produced major floods throughout the region. Many north coast basins experienced more localized floods in 1879, 1881, and 1888 (McGlashan and Briggs, 1939). The 1890 flood was apparently as widespread as the 1861 event, although precipitation totals were probably not as high.

Information about the earlier storms is qualitative and scanty. By the time of the 1890 flood, however, daily precipitation records were kept at several stations in northwestern California. The information for each flood is presented in Harden and others (1978). Only summary data are presented in the following paragraphs.

PRECIPITATION TOTALS

The 1861–62 storm period was by far the wettest ever recorded in northwestern California. Over 1,270 mm of rain fell at Fort Gaston between November 24 and December 8, 1861, and the January 8–11 storm produced an additional 305 mm of precipitation (Harden and others, 1978). At the time of the January 1862 storms, the Sacramento and San Francisco areas also experienced heavy rains and flooding. Although this January storm produced less rainfall in the vicinity of Redwood Creek than the earlier storm, additional flooding was reported at Fort Gaston in January 1862. Rainfall records were not available for the 1867, 1879, 1881, and 1888 floods. The Eureka Humboldt Times reported that over 787 mm of rain fell at the Upper Mattole station during the storm of January 27–31, 1888, storm.

The storm of January 31–February 4, 1890, is the best documented of the 19th century storms. Rainfall totals at Crescent City, Arcata, and Eureka exceeded those during the 20th century storms (fig. 10). However, at the operating inland stations, rainfall totals were less than during 1955 and 1964 (figs. 4 and 5). This precipitation pattern suggests that the 1890 storm was concentrated in northern coastal areas.

ANTECEDENT MOISTURE CONDITIONS

No mention of preexisting snow was made in newspaper accounts for the 1861 through 1888 storms. However, the winter of 1889–90 was characterized by unusually heavy snowfall prior to the February flood. According to newspaper accounts, January snowfall was the heaviest since European settlement of the area, and the trail from Arcata to Hoopa, which traversed the Redwood Creek basin near Minor Creek, was passable only with snowshoes in late January.

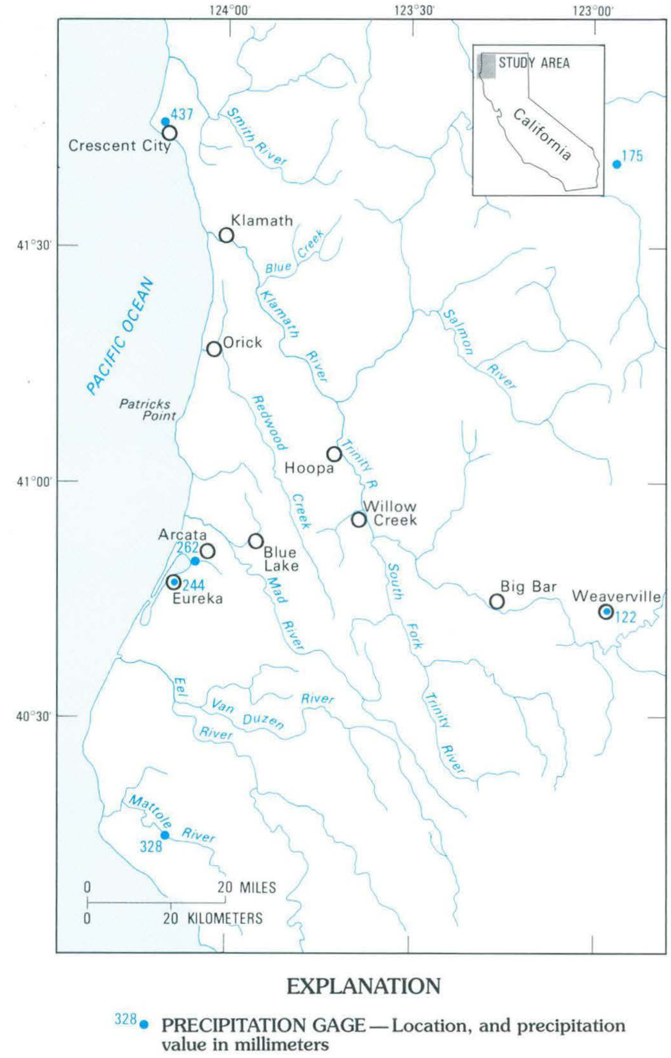


FIGURE 10.—Precipitation for January 31 to February 4, 1890.

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. In fact, snowmelt from high areas was cited as causing the 1890 flood stage on the Mattole River to equal that of 1881. It therefore seems likely that the 1890 flood peaks were augmented by snowmelt from at least some of the high areas.

RUNOFF

Newspaper descriptions of the 1861–62 storms indicate that flooding was widespread in northwestern California, including in the Redwood Creek basin. Flood damage was reported from all of the settled areas, both in the Trinity River mining districts and in coastal ranching areas. Flood stages on the Mad and Trinity rivers were the highest since European settlement and reportedly higher than previously known by Indians (Harden and others, 1978). Most bridges in the region were washed out.

By reconstructing cross sections from terrace surfaces, Helley and LaMarche (1973) estimated 19th century flood discharges relative to 1964 flows at four North Coast localities. At Blue Creek (fig. 1), the preservation of 1861–62 flood deposits after 1964 indicates that the 1964 flood was not of sufficiently greater magnitude. In contrast, the lack of 1861–62 deposits at two sites on the Trinity River and Willow Creek, east of the Redwood Creek basin, was cited by Helley and LaMarche (1973) as evidence of the greater magnitude of the 1964 flood.

Records for the 1867, 1879, 1881, and 1888 floods suggest that these events were less widespread than either the 1861–62 or 1890 floods. Newspaper accounts of flood damage indicate that the 1888 storm was concentrated in the southern coastal portions of the region, whereas the 1879 and 1881 storms affected inland areas, as well as areas along the coast.

Flood damage from the 1890 storm was reported to be the most severe since 1861–62. Flood stages on the Mad River were higher than in 1861–62. All of the remaining north coast rivers experienced major flooding and landslides during the storm.

COMPARISON OF STORMS

The amount of precipitation during December 18 to 24, 1964, does not alone account for the high runoff and the extensive regional damage to hillslopes and stream channels caused by the 1964 flood. 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 natural events that could have preconditioned unstable hillslopes and stream channels to augment the impacts of floods late in each series. In fact, considering the apparently unprecedented magnitude of the 1861–62 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 series of floods in the late 19th century could have been more damaging than the more recent floods.

The 1890 flood had several factors in common with the 1964 flood. First, at least two major floods immediately preceded both events. Second, flood peaks from both storms were probably augmented by snowmelt. Third, both storms were apparently concentrated in the area north of Eureka. Rainfall records indicate that the coastal portions of the Redwood Creek basin probably received more precipitation in 1890 than in 1964 and that rainfall totals in the upper basin may have been comparable.

The erosional impacts of the two storms could therefore be expected to be similar. 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 caused by human activities in the second half of this century. No other major changes in drainage basin conditions have occurred. The impacts of human activities in the basin are discussed elsewhere in this volume by Harden and others (chap. G) and Nolan and Janda (chap. L).

The greater impact on channels and streamside hillslopes of the 1964 storm relative to those of the other storms occurring from 1953 to 1975 is partly attributable to the greater magnitude of the December 18–24 precipitation. 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 many intensively damaged areas, the second phase of the 1964 storm occurred as snow, which would not have contributed to the flood peaks. Rainfall totals during the 1964 storm do appear to have been greater in the upper basin than in the lower basin. The concentration of flood damage in the upper Redwood Creek basin in 1964 may partly reflect rainfall distribution.

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.

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Rate and Mechanics of Progressive Hillslope Failure in the Redwood Creek Basin, Northwestern California

By D.N. SWANSTON, R.R. ZIEMER, *and* R.J. JANDA

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–E

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RATE AND MECHANICS OF PROGRESSIVE HILLSLOPE FAILURE IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

By D.N. SWANSTON,[1] R.R. ZIEMER,[1] and R.J. JANDA[2]

ABSTRACT

Both creep and earthflow processes dominate hillslope erosion over large parts of the Redwood Creek basin. The type of process and the displacement rates are largely dependent on underlying bedrock type and precipitation.

Progressive creep having rates ranging from 1.0 to 2.5 mm/a dominates on slopes west of the Grogan fault underlain by sheared and foliated schists. Movement appears to respond primarily to annual increments of precipitation. Complex earthflows occur predominantly on slopes east of the Grogan fault underlain by sheared graywacke sandstone and mudstone. Movement rates range from 3.0 to 131.0 mm/a and characteristically display dominant rainy season movement.

INTRODUCTION

The Redwood Creek basin is approximately 60 km north of Eureka in the northern California Coast Ranges. Its 725-km^2 drainage basin comprises some of the most rapidly eroding terrain in North America. High rates of erosion, produced by extensive soil mass movement and associated streambank cutting, are the result of a combination of rock types, geologic history, climate, and land use patterns that exist over large areas.

Recent major floods and attendant accelerated mass movement of mantle materials into channels have caused drastic changes in channel characteristics and sedimentation rates; these changes have resulted in part from timber harvest activities within this highly eroded drainage basin. Soil creep and earthflow processes appear to dominate hillslope erosion across large parts of the basin. The mechanics of these processes have been investigated experimentally and theoretically by a number of workers (Goldstein and Ter-Stepanian, 1957; Saito and Uezawa, 1961; Culling, 1963; Bjerrum, 1967), but field measurements are limited. Under field conditions, local variations in soil properties, degree and depth of parent material weathering, and clay and water content of mantle materials lead to substantial variations in movement processes and rates.

In 1974, in response to the needs of public and private land managers for quantitative information on the response of creep and earthflow processes to natural events and to harvest disturbances in the lower Redwood Creek basin, the U.S. Forest Service, in cooperation with the U.S. Geological Survey (USGS), began monitoring movement at eight sites on the east and west slopes of the basin. That study is part of a broad study of creep and earthflow processes in the Coast Ranges and Cascades of Oregon, Washington, and northern California (Swanston, 1981). The study was designed to (1) quantify natural rates of movement and define the mechanics of movement by process (creep or earthflow), (2) determine the influence of geologic materials on movement processes and rates, (3) assess the impact of timber removal on movement, and (4) determine the effects of seasonal and annual rainfall on movement. This paper reports the results of 6 years of data accumulated during the study. An assessment of the impacts of timber removal was not possible because the study sites designated for timber harvest were incorporated into an expansion of Redwood National Park and all logging plans were terminated.

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AREA DESCRIPTION

DRAINAGE CHARACTERISTICS

The drainage basin of Redwood Creek encompasses about 725 km^2 of rugged terrain within the Coast Ranges of northern California. The basin is strongly elongated north-northwestward and is about 90 km long and 7.2 to 11.1 km wide through most of its length (fig. 1). Redwood Creek flows north-northwest along the axis of the basin and turns westward abruptly at the basin mouth to empty directly into the Pacific Ocean. Drainage density is about 4.8 km/km^2 for the basin as a whole, measured from standard 15-minute quadrangle maps; headwaters show slightly greater density than downstream areas (Iwatsubo and others, 1976). Total basin relief is about 1,615 m. Cross-sectional relief normal to the basin axis in the vicinity of this study is about 229 m. The average gradient in the basin is 14.4° (26 percent), but more than half of the individual hillslopes display average gradients in excess of 19° (35 percent).

CLIMATE

The climate of the northern part of the basin where this study was made is of the coastal Mediterranean type with mild, wet winters and short, warm, dry summers having frequent fog. The full spectrum of climatic variability within the basin is not well known because long-term climatological data have not been collected. Sixteen recording rain gages were installed by the U.S. Geological Survey in 1974 in various locations within Redwood National Park (Iwatsubo and others, 1976), but the most usable body of climatological data is the daily recorded precipitation and temperature that have been collected continuously since 1937 near the mouth of the basin at Prairie Creek Redwoods State Park. Prairie Creek data and the data obtained from the USGS gage installed in the study area along the K and K Road show good correlation. Because of this and the 45-year record, it is the Prairie Creek data on which our subsequent analyses are based. Seasonal variations in mean monthly precipitation, runoff, and temperatures for Redwood Creek at Prairie Creek Redwoods State Park for the water years 1954 to 1972 are shown in figure 2.

The estimated mean annual basinwide precipitation is 2,032 mm, but altitude, proximity to the ocean, and slope aspect profoundly influence the amount of precipitation at any given location (Rantz, 1964, 1969). It is common for the mean annual precipitation to vary by as much as 833 mm per thousand meters of altitude. The mean annual precipitation at Prairie Creek Redwoods State Park from 1938 to 1980 is 1,748 mm (fig. 3). Annual precipitation at the Prairie Creek weather station during this study (1975–80) was above the long-term average for two of the years and below average for four of the years. The greatest annual precipitation during the 42-year record occurred during the 1974 water year (the year immediately preceding this study), when rainfall was 143 percent of the mean. The driest year of record was 1977, when annual rainfall was 46 percent of the mean. The seasonal distribution of precipitation is characterized by heavy winter rainfall and pronounced summer drought (fig. 2). Snow is rare in this rain-dominated basin, but infrequent snowfall having subsequent rapid melt contributes to the magnitude of some of the largest and most damaging floods.

VEGETATION

Productive soils, moderate temperatures, and seasonally abundant moisture support a mixed cover of dense forest and prairie vegetation. Mineral soil is exposed under natural conditions only where vegetal cover is disrupted by various forms of mass movement or lateral corrasion adjacent to the stream channel. In the area of study, redwood (*Sequoia sempervirens* [D. Don] Endl.) is the dominant tree on the relatively moist flood plains, low stream terraces, and lower hillslopes adjacent to the main channel. On the upper slopes, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) is the dominant conifer associated with western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), tan oak (*Lithocarpus densiflora* [Hook. & Arn.] Rehd.), and Pacific madrone (*Arbutus menziesii* Pursh). Areas of natural prairie and woodland vegetation are intimately associated with forested areas throughout most of the basin. The most common communities of nonforest vegetation are grass prairies, grass-bracken-fern prairies, oak-grass woodlands, oak-poison oak-grass woodlands, and oak-madrone-brush woodlands. The origin of the grass and grass-bracken-fern prairie is partly the result of mass movement (Coleman, 1973), natural and Indian-set fires (Lewis, 1973), and lateral variability in soil parent materials (Zinke, 1966).

GEOLOGY

The lithologic and structural properties of the rocks of the Redwood Creek basin make them highly susceptible to chemical decomposition and erosion. The entire basin upstream from its mouth is underlain by the strongly indurated Franciscan assemblage of rocks, both Late Jurassic and Early Cretaceous in age.

Virtually unmetamorphosed sedimentary rocks underlie most of the eastern side of the basin. Graywacke

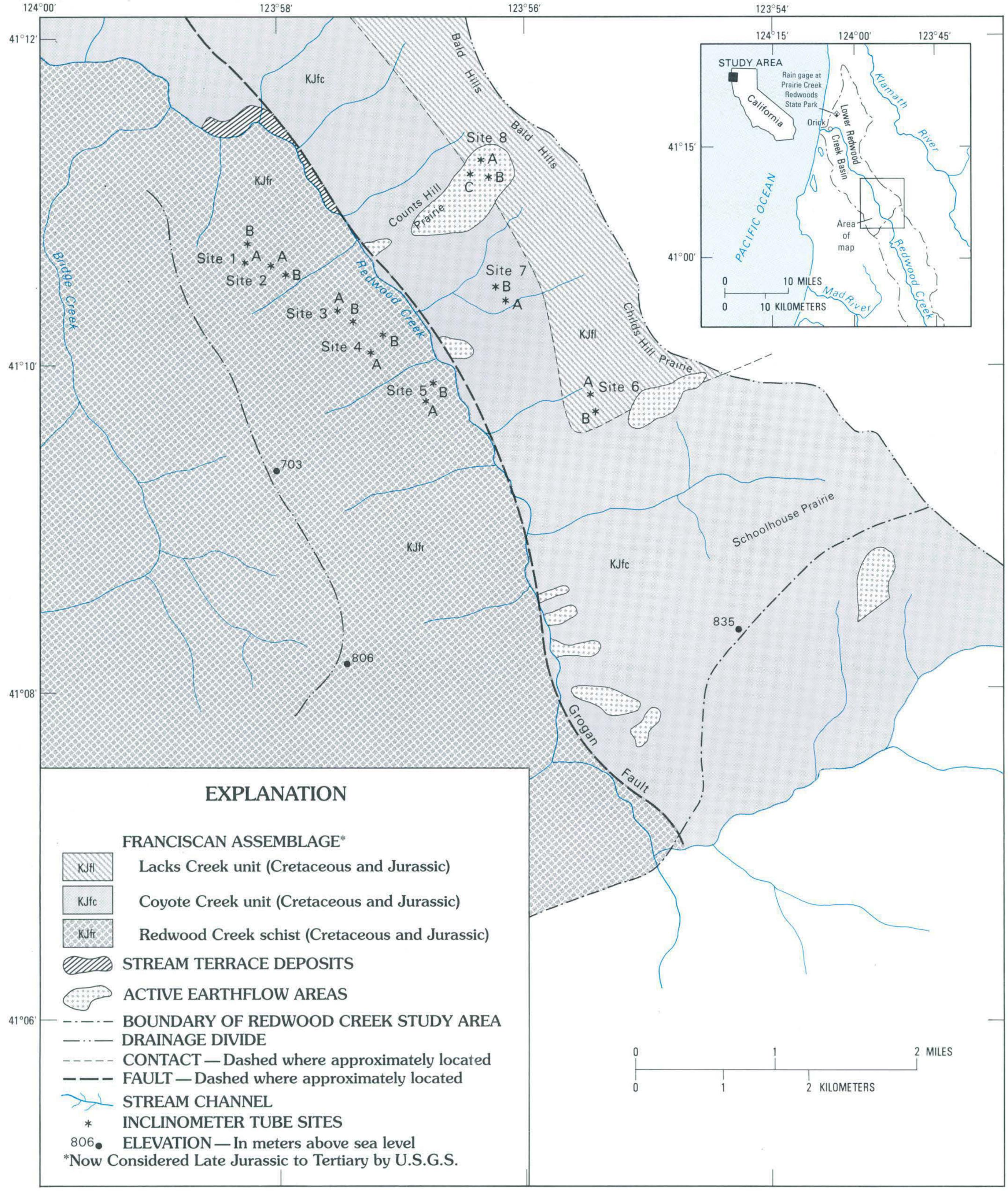

FIGURE 1.—Part of lower Redwood Creek basin showing important geologic units, structure, and monitoring locations (modified from Harden and others, 1981).

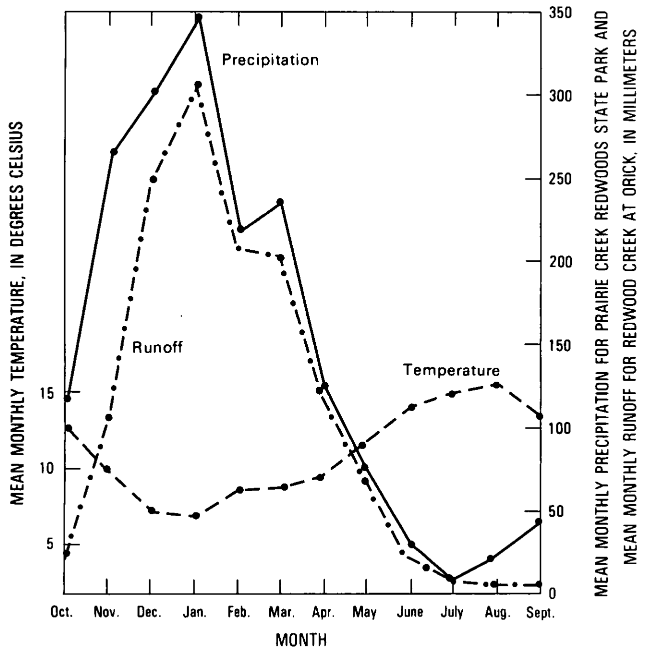

FIGURE 2.—Mean monthly temperature and precipitation for Prairie Creek Redwoods State Park and mean monthly runoff for Redwood Creek at Orick for water years 1954 to 1972 (from Janda and others, 1975).

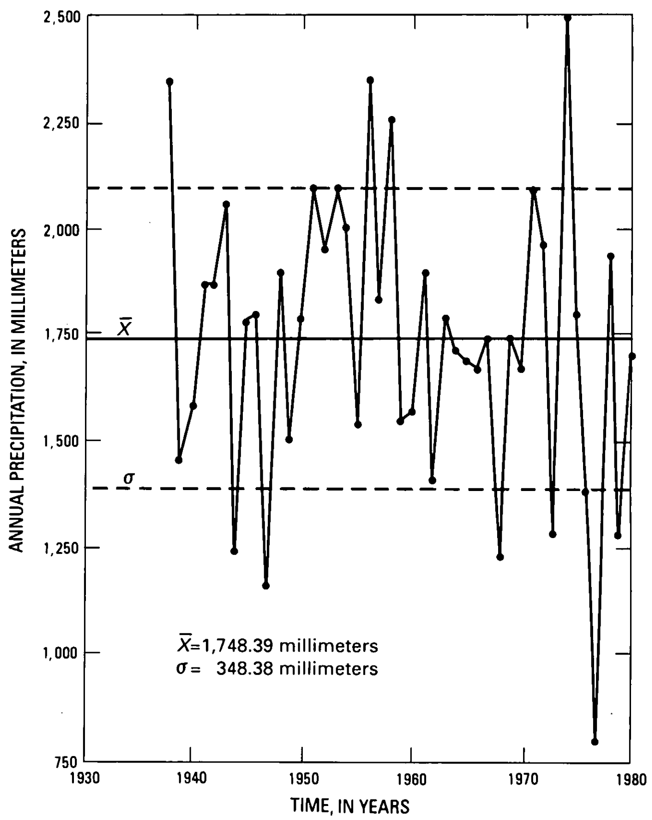

FIGURE 3.—Annual precipitation over the period 1938 to 1980 (42 years) recorded at Prairie Creek Redwoods State Park. Mean annual precipitation ($\bar{x}$) is 1,748.39 mm; standard deviation (σ) is 348.38 mm.

sandstone (lithic and arkosic wacke) is the most abundant. Lesser amounts of mudstone and conglomerate are present.

Metamorphosed sedimentary rocks, mapped as the Kerr Ranch schist by Manning and Ogle (1950) and the Redwood Creek schist by Harden and others (1981), underlie most of the western half of Redwood Creek basin. These consist mostly of light-to-medium gray, well-foliated, quartz-mica-feldspar schists and mica schists. In most localities, the rock is intensively sheared, and foliation is well developed, steeply dipping, and intricately deformed.

These main rock units are separated by the north-northwest-trending Grogan fault, which is closely followed by the main channel of Redwood Creek in the northern part of the basin. Intensively sheared rocks, including serpentine, are associated locally with the fault, and mass-movement failures or active creep movement commonly occur on either side of its trace. The interbedded graywacke sandstone and mudstone underlying the east slope get finer grained and more intensively sheared toward the Grogan fault and southward of the mouth of the basin (Harden and others, 1981). In the vicinity of the monitoring sites, the upper part of the slope is underlain by graywacke sandstone and mudstone sequences of the Coherent unit of Lacks Creek (fig. 1). High sandstone content, the presence of massive beds, and less intense shearing and fracturing result in steeper, straighter hillslopes. In contrast, the middle and lower slopes are underlain by the Incoherent (graywacke sandstone and mudstone) unit of Coyote Creek, which consists of more highly sheared and fractured sequences having greater amounts of mudstone (fig. 1). The incoherent rocks underlie a subdued rolling landscape that has less deeply incised drainages than those developed on the coherent unit. Expanses of grass-oak woodland and grass-bracken-fern prairies commonly develop on active mass-movement terrain.

Naturally occurring bedrock outcrops are scarce in areas away from Redwood Creek because of a nearly continuous mantle of colluvium, deep residual soil, and saprolite produced by hillslope erosion processes and mechanical and chemical weathering. Collectively, such surficial "regolith" thicknesses are highly variable and range from less than 0.6 m on hilltops and divides to more than 15 m beneath landslides and actively moving midslope and lower slope sites.

The colluvium is mostly stony loam and stony-clay loam that appear to represent displaced saprolite and residual soil. The saprolites developed from both the schists and graywacke and mudstone units display alternating zones of fairly competent rock separated by sections extensively altered by chemical decomposition and leaching. Such altered zones are mostly associated with subsurface water movement.

LANDFORMS RELATED TO MASS MOVEMENT

Many hillslopes in the Redwood Creek basin are unstable and highly susceptible to mass-movement failure because of the steepness of the terrain and the low shear strength of much of the underlying saprolite and residual soil. According to Colman (1973), at least 36 percent of the basin shows landforms that are the result of active mass movements or that are suggestive of former mass-movement failures. Steep, straight, colluvium-veneered hillslopes underlain by coherent graywacke and mudstone are sculptured primarily by infrequent, shallow debris avalanches and debris flows. Smooth convex-upward hillslopes typically developed on sheared schists and incoherent graywacke and mudstones reflect erosion by creep and earthflow processes. The steep lower segments of these hillslopes, especially adjacent to the main channel of Redwood Creek, show numerous small-scale discrete failures involving both rotational and translational movement. Such discrete failures may be triggered by excessive strain in the creeping materials due to the loading of lower slopes with material from above or by removal of the slope toe by lateral erosion along Redwood Creek and its tributaries.

Complex associations of rotational slumping, translation, and flowing movement classified as earthflows are the most visually obvious forms of mass movement in the Redwood Creek basin. Such earthflows exhibit subdued scarps, flats, and hummocky and lobate microtopography. Some have clearly defined margins, but many gradually merge with less active areas of soil creep. On many earthflows, grass, grass-bracken-fern, and grass-oak prairie vegetation dominate in marked contrast to the mature coniferous forest or cutover land on more stable slopes.

METHODS

SITE SELECTION AND PREPARATION

During summer 1974, seven sites were selected with the cooperation of Simpson Timber Company and Louisiana-Pacific Corporation on private lands that had been partly logged or that were planned for logging within the following 5-year period (see fig. 1). Where possible, sites were paired to reflect any differences between logged and unlogged slopes. A concerted effort was made to avoid areas of current clearly definable active earthflows. The one exception to this was a recently logged dense conifer forest site (site 6), which exhibited surficial signs of active creep and earthflow. Monitoring instruments were installed at sites 1 through 4, located at midslope on the west side of the basin in saprolite overlying Redwood Creek schist, during fall 1974. Monitoring instruments were installed at sites 5 through 7 during fall 1975. Site 5 was located in saprolite overlying schist near the channel of Redwood Creek. Sites 6 and 7 were located at midslope on the east side of the basin; site 6 in saprolite overlying the Coherent (graywacke sandstone and mudstone) unit of Lacks Creek, and site 7 in saprolite overlying the Incoherent (graywacke sandstone and mudstone) unit of Coyote Creek (Harden and others, 1981) (fig. 1). In cooperation with the U.S. Geological Survey, one additional site was located, and instruments installed in fall 1976 to investigate the subsurface movement occurring within the earthflow deposits of Counts Hill Prairie (site 8, fig. 1). The deposits are developed in deeply weathered graywacke sandstone and mudstone across the boundary of the Coherent and Incoherent units of Lacks Creek and Coyote Creek, respectively.

INSTALLATION OF BOREHOLE TUBES

Movement within the soil mantle was determined by measuring the change in the shape of polyvinyl chloride (PVC) tubes at discrete time intervals after installation. Two access tubes (designated A and B) were installed at sites 1–7 approximately along the fall line of the slope to detect any similarities or differences in the rate and mechanics of movement with slope location. A third tube (designated C) was installed at site 8, the Counts Hill Prairie earthflow, to assess the complex nature of some the movement displayed at that site. The tubes were installed in 130-mm-diameter boreholes, drilled by a truck-mounted auger through active soil materials, and were anchored at the bottom in bedrock.

The anchoring of the access tubes was important for proper interpretation of the resulting data. If it could be reasonably assumed that the bottom of the tube was stable and did not move between surveys, a three-dimensional coordinate system could be defined within which the deformation of the access tube could be calculated. The initial tube configuration and any changes between surveys were then reconstructed from the bottom upward. The depth to which access holes were drilled and the location of underlying stable material or bedrock were determined indirectly during the drilling operation by making penetration tests at 1.3-m intervals until sufficient resistance to penetration was encountered. Bedrock was arbitrarily defined as material having a penetration resistance exceeding 60 blows per 30-cm penetration in a standard penetration test. (Each blow is a constant energy increment of 64 kg being dropped a distance of 76 cm, driving a standard cross-section bit.) Great care was necessary in the interpretation of these penetration tests because solid blocks of bedrock are commonly incorporated into the moving materials. It was not uncommon to intersect such floaters during the drilling process. As the approximate depth of weathering and alteration of these materials was known from local bedrock exposures and existing geologic reports, high penetration resistance at shallow depths was considered potentially anomalous, and drilling was continued for an additional 3 m or until softer materials were encountered. Once bedrock was reached, the hole was drilled an additional 1 m, and the access tube was installed. Subsequent surveys indicated only small changes in inclination of the bottom 1 m of most of the access tubes throughout the study period. Instrument error accounts for a major part of these changes, although some minor deformation appears to be occurring in the more stable layers at sites 6 and 8. All tubes except the one at hole 4B (site 4) were considered fixed for purposes of analysis. At hole 4B, the tube clearly failed to penetrate the active movement zone and was excluded from further analysis.

After the tubes were installed, the annular space between each tube and the borehole wall around it was backfilled with sand and pea gravel to provide maximum stable continuity between the tube and surrounding materials. Ziemer (1977) clearly demonstrated the need for such backfilling to obtain reliable quantitative data on movement rates and direction from borehole inclinometer installations. Based on reanalysis of data obtained over an 8-year period from a network of inclinometer borehole tubes installed in 1964 without backfilling (Kojan, 1967), Ziemer (1977) found that no consistent rate or direction of movement could be detected because of continuing differential settlement in the boreholes. Adequate backfilling was difficult at many of the Redwood Creek sites. During the drilling process, vibration and lateral migration of the drill bit caused by rocks or other resistance produced an irregularly shaped borehole. For maximum continuity, all these spaces had to be filled. In practice, the use of in-place materials proved impossible because of the loss of such materials through their compression into the sidewalls of the borehole as the drill bit was advanced and also because of the rather small volume of material that was recovered from the drill cuttings. The common technique of grouting from the bottom up was considered but proved to be impractical because of the special pumping equipment required and the lack of an adequate water source at most sites. In the earliest installations, fine sand was used to backfill the holes. When air dropped, fine sand should have, in theory, reached a maximum density and should have completely filled the annular space and any voids. Unfortunately, most of the holes intersected ground water at shallow depths and tended to form a slurry with the churned cuttings. The air-dropped sand in these holes was generally supported on the slurry surface, bridged the hole, and made adequate backfilling below the upper level of the slurry impossible. As a compromise, pea gravel was used; it generally sank into the slurry and filled the void spaces around the tubes. Subsequent analysis of survey results indicates that this backfilling technique was successful in developing the required continuity at all but two holes (2A, 5B at sites 2 and 5, respectively). Differential settlement is still occurring in these boreholes, and they have been excluded from further analysis.

INSTRUMENTATION

The inclinometer access tubes placed in the boreholes were constructed of PVC with a 76.2-mm inside diameter and were grooved longitudinally inside at 90°. A mechanical pendulum that had an electronic readout, fixed in a rigid carriage riding in the grooves, was then passed down the tube to measure changes in inclination of the tube after installation.

The orientation of the readings, and thus of the relative movement taking place, is governed by the grooves inside the casing. It is, therefore, essential that the grooves be oriented in space as accurately as possible. The four grooves are conveniently referenced as cardinal compass points (north, east, south, and west), and, as far as practicable, tubes were installed with this orientation. The azimuth of the plane defined by the north-south grooves was measured by using a Brunton compass to obtain true bearings. All subsequent data sets at each hole were oriented by using that azimuth.

The instrument has a sensitivity of 1 part in 1,000 so that a tilt of as little as 3 minutes of arc can be detected. This means that a lateral displacement of less than 2 cm can be detected over a 30-m depth. In practice, displacements of less than 2 mm over this depth were consistently identified in this study.

There were five sources of possible instrument error that had to be contended with in obtaining data for this study. These were:

(1) opposite grooves not parallel due to distortion of the casing, irregular groove depth, or dirt in the grooves;

(2) instrument not tracking in grooves because of misalignment of tube sections or distortion of casing shape;

(3) error in depth relocation during subsequent surveys;
(4) error in circuit balance or recording of readings; and
(5) instrument malfunction, either due to mechanical or electronic difficulties or to moisture entering the circuitry.

Errors 3 and 4 were primarily operator errors and were easily detected in the field by summing the corresponding pairs of readings at each depth for each cardinal plane. These sums should not vary more than three to five units from their mean for each depth in the vertical sequence. Errors 1 and 2 also were detectable by the above field check and, if not resolved by replacement and rereading of the inclinometer at a given depth, required withdrawal of the instrument from the hole and a complete resurvey. The fifth source of error generally required abandonment of the survey, repair or drying of the instrument, and resurvey of the hole at a later date. Rainwater entering the instrument case at the surface was the most common cause of this error source. Any additional recording errors were detected by careful screening of data forms prior to computer analysis.

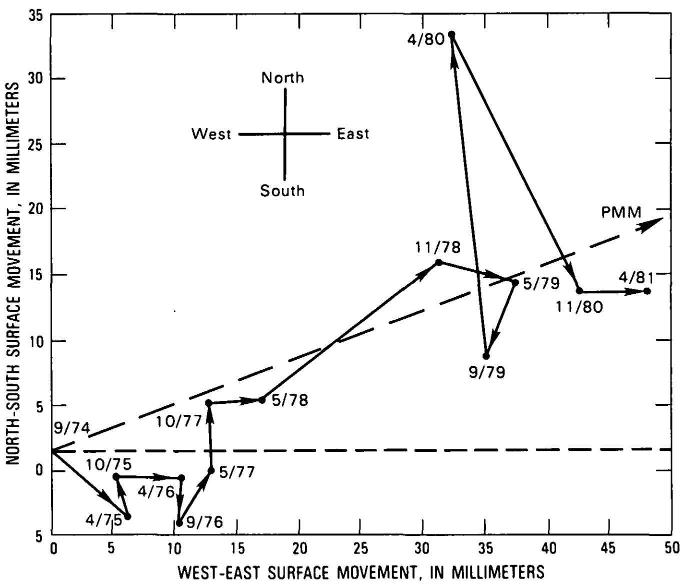

FIGURE 4.—Plot of the surface movement at hole 4A on the west side of Redwood Creek (site 4, fig. 1) showing the variability in distance and direction between successive seasonal readings. The plane of maximum movement (PMM) is determined by the direction of maximum extension of plotted points.

MONITORING PROGRAM

Because the Redwood Creek sites lie within a region characterized by high winter rainfall separated by pronounced summer droughts, each tube was surveyed in late spring after fall and winter storms and in early fall after the summer dry period. The resulting data allowed the development of plots that relate variations in rate of horizontal movement at each site to depth, seasonal and annual rainfall, and any differences in parent material. The changes in water level in the tubes also were measured at each site in an attempt to relate seasonal water table fluctuations in the mantle to periods of maximum movement.

An earthquake registering 7.0 on the Richter scale occurred during the November 1980 survey and had an epicenter at Big Lagoon, about 32 km southwest of the study area. Following this earthquake, tubes at sites 1 through 5 and site 8 were resurveyed to determine if any changes in movement rate or displacement had occurred as a result of the ground motion. No identifiable changes were found at the monitoring sites immediately following the event or in the following year of measurement.

DATA ANALYSIS

Changes in the inclination of borehole tubes were measured at 0.5-m intervals from the bottom of the hole. The bottom of the hole was assumed to be fixed. This assumption was based on the competence of the rock determined during drilling and the lack of change in inclination at the bottom of the tube during successive readings over the monitored period. Measurements at each interval were made in two planes (north and east) at 90°. To estimate the configuration of the tubes, the centerline of the casing was approximated by a series of casing vectors oriented point to tail from the bottom of the casing to the surface. The number of vectors corresponded to the number of measurement intervals, and their orientations were described by inclination (zenith angle), distance between intervals, and resulting coordinates in the north and east planes (azimuth). By adding the respective coordinates cumulatively up the hole, position vectors were defined. The coordinates for these vectors determined the position of the measurement point in three-dimensional space. Subsequent surveys provided the necessary data for vertical profile plots showing distance and direction of movement between successive surveys throughout the depth of the hole. The analytical methodology and computer programs used to display this data were developed by R.B. Thomas and R.R. Ziemer of the U.S. Forest Service, Pacific Southwest Forest and Range Experiment Station, Arcata, Calif.

Variability in direction and distance of movement between successive surveys at each interval were occasionally large (fig. 4). Such disparities were due toseveral

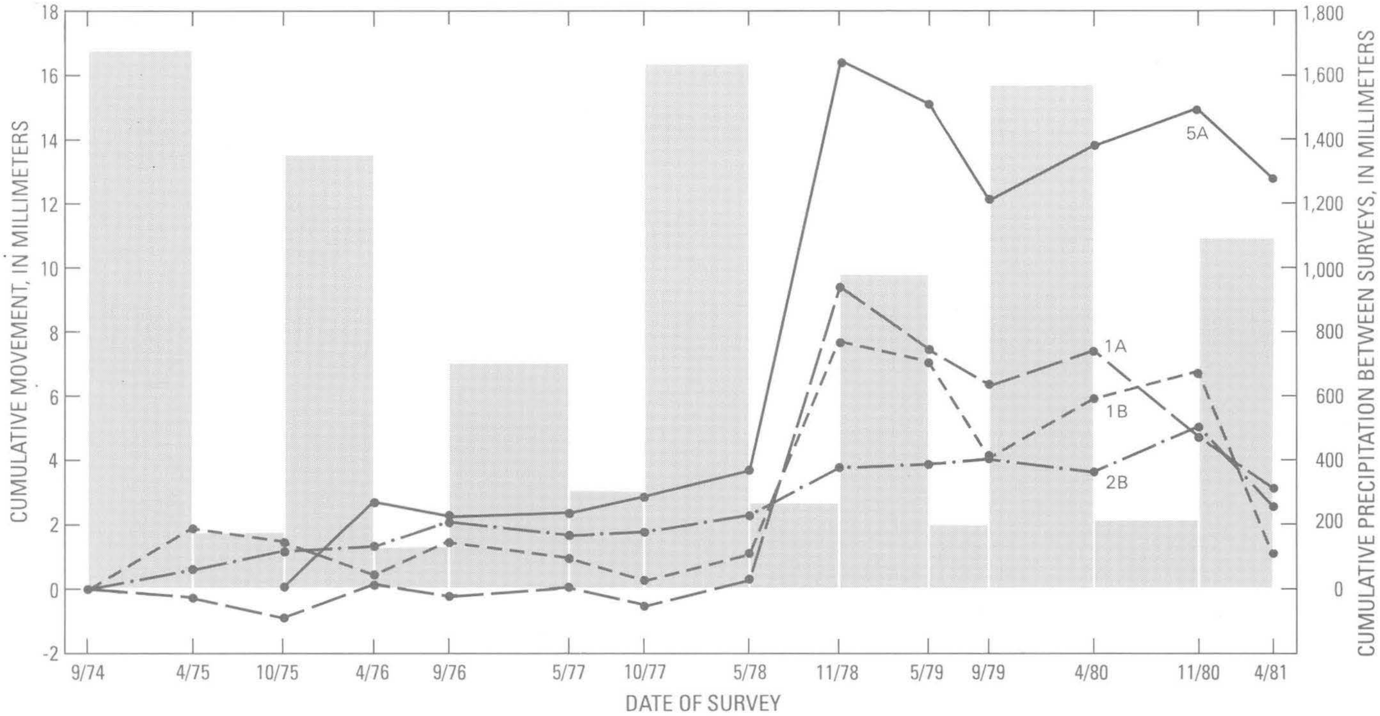

FIGURE 5.—Cumulative movement over the monitoring period showing relation of seasonal precipitation to sites of active creep.

factors including (1) changing movement characteristics of the soil in response to water content, (2) differential adjustment of individual blocks within the moving mantle, (3) settlement and differential movement of the inclinometer tube within the drilled hole due to void spaces and inadequate backfilling, and (4) random instrument error.

For purposes of constructing the vertical profile of movement and comparing profile changes over time, it was necessary to project cumulative position vector coordinates into a single plane having an azimuth approximating the dominant movement direction. This plane was designated the plane of maximum movement (PMM). An approximate PMM for each hole was determined graphically from the general direction of a plot of surface movement points over the total period of monitoring (fig. 4).

Once the profiles had been plotted in the PMM, strain configuration with depth, displacement, and the location of zones of shear or accelerated deformation were ascertained. Both annual and seasonal rates of movement at the surface also were obtained by calculation and graphic scaling from the profiles. Displacement and rates of movement were then regressed against both annual and seasonal precipitation to ascertain any relationships that may exist between movement and prevailing climatic conditions in the Redwood Creek basin.

RESULTS AND DISCUSSION

Seasonal and annual displacement at the surface for all sites is cataloged in tables 1 and 2 and figures 5–7. Profiles constructed for each hole exhibit major types of strain configuration indicative of process mechanics dominating at a particular site. Figures 8–10 show profiles for holes 5A, 4A, and 8B, respectively.

CREEP

Sites dominated by creep processes exhibit a progressive deformation profile with strain increasing toward the surface. Sites 1, 2, and 5, located on the west side of Redwood Creek in Redwood Creek schist, exhibit this type of strain configuration exclusively (see fig. 8, hole 5A). Local zones within all the profiles show minor accelerated deformation or extension flow, but no clearly defined shear zones are present.

Total displacement at the surface is small for all the creep-dominated holes, ranging from a minimum of 0.7 mm for hole 1B to a maximum of 12.6 mm for hole 5A (table 2). The only significant movement measured at these creep-dominated sites occurred as the result of a single surge during summer 1978 (fig. 5). The reason for this surge is not clear. It occurred during one of the wetter years of the study, but the precipitation was not unusual in an historical context (fig. 3).

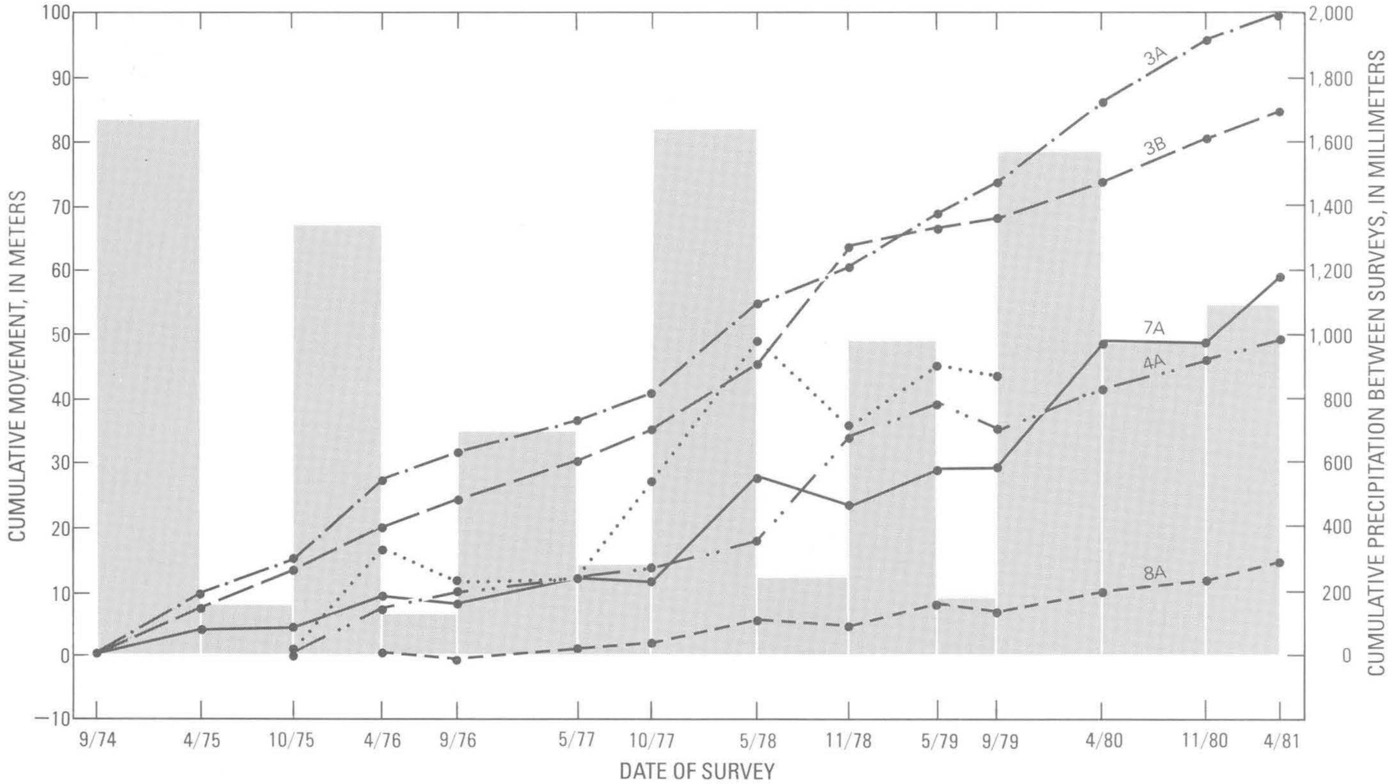

FIGURE 6.—Cumulative movement over the monitoring period showing relation of seasonal precipitation to block-glide-dominated sites.

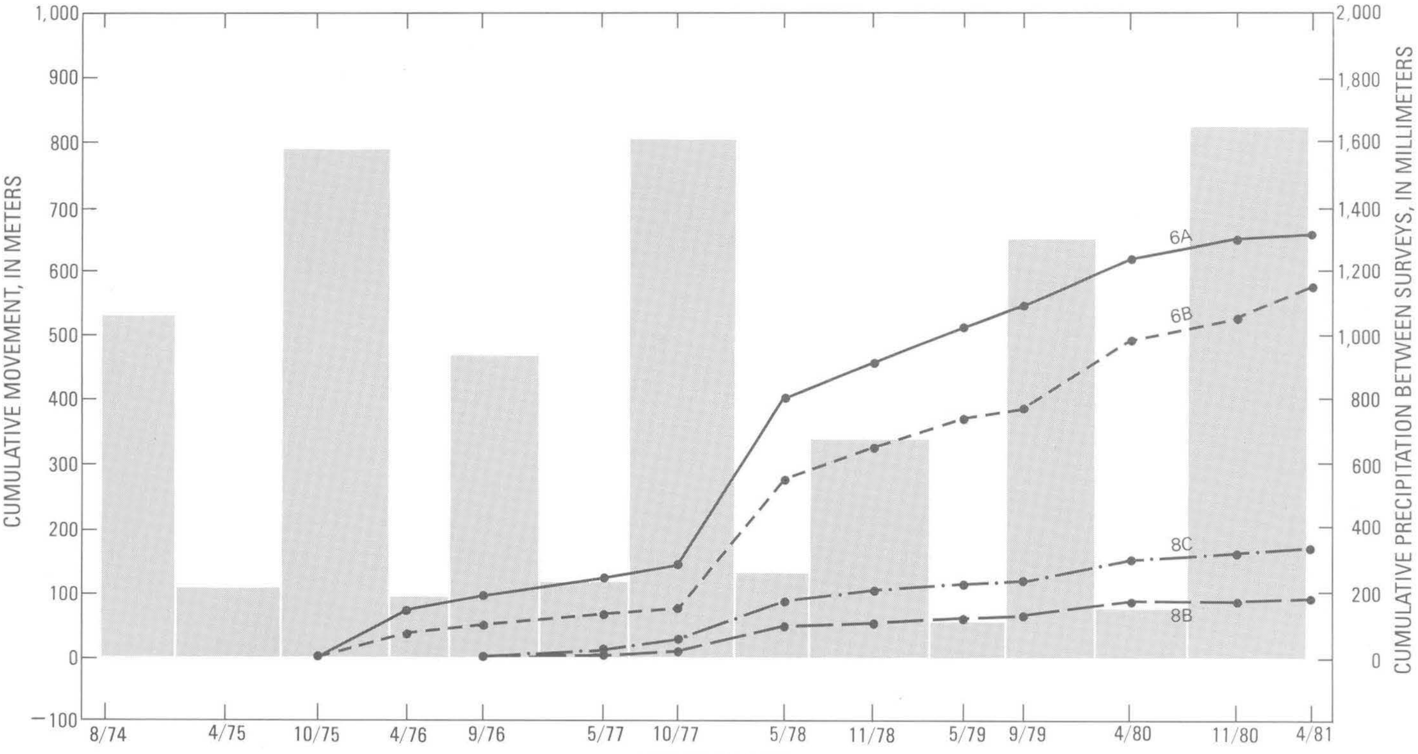

FIGURE 7.—Cumulative movement over the monitoring period showing relation of seasonal precipitation to sites exhibiting combined creep and block glide.

TABLE 1.—*Basic site and survey data from April 1975 to September 1976, May*

[Movement reported is surface displacement along the plane of maximum movement (PMM). Igm,

April 1975 to September 1976							SURVEY DATE							
							4–75		10–75		4–76		9–76	
							PRECIPITATION BETWEEN SURVEYS (mm)							
							1,648		166		1,323		123	
							MOVEMENT BETWEEN SURVEYS							
Hole[1]	Disturbance	Parent material	Movement type	Hole depth/ movement depth (m)	Slope azimuth (degrees)	PMM azimuth (degrees)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)
1A	Logged	Schist	Creep	10.5/9.6	45	55	−0.2	−0.001	−1.1	−0.007	+1.5	+0.012	−1.3	−0.010
1B	Logged	Schist	Creep	9.0/9.0	45	275	+2.0	+.010	−.5	−.003	−1.0	−.005	+1.0	+.007
2B	None	Schist	Creep	4.3/4.3	45	45	+.4	+.002	+.8	+.001	.0	.000	+.9	+.010
3A	None	Schist	Block glide	10.1/5.5	45	47	+8.9	+.044	+5.4	+.032	+12.8	+.060	+4.0	+.030
3B	None	Schist	Block glide	8.1/6.4	45	50	+7.4	+.040	+5.6	+.030	+7.0	+.030	+4.1	+.030
4A	Logged	Schist	Block glide	18.6/12.6	45	70	+4.4	+.020	−.8	−.005	+5.9	+.030	−1.5	−.010
5A	None	Schist	Creep	9.1/9.1	45	90	—	—	—	—	+2.7	+.010	−.6	−.005
6A	Logged	Igm	Creep and glide	11.0/6.5	225	215	—	—	—	—	84.4	+.440	−19.2	+.130
6B	Logged	Igm	Creep and glide	7.6/6.1	225	230	—	—	—	—	48.9	+.250	+7.4	+.051
7A	None	Cgm	Block glide	10.5/6.9	225	215	—	—	—	—	+8.5	+.040	+1.3	+.010
7B	None	Cgm	Block glide	10.6/8.6	225	208	—	—	—	—	+16.5	+.080	−4.6	−.030
8A	None	Igm	Block glide	20.6/16.4	225	240	—	—	—	—	—	—	−.2	−.001
8B	None	Igm	Total creep and glide	10.2/6.6	225	240	—	—	—	—	—	—	—	—
8B	None	Igm	Creep only	10.2/6.6	225	240	—	—	—	—	—	—	—	—
8B	None	Igm	Glide only	10.2/6.6	225	240	—	—	—	—	—	—	—	—
8C	None	Cgm	Total creep and glide	12.1/8.0	225	220	—	—	—	—	—	—	—	—
8C	None	Cgm	Creep only	12.1/8.0	225	220	—	—	—	—	—	—	—	—
8C	None	Cgm	Glide only	12.1/8.0	225	220	—	—	—	—	—	—	—	—

May to October 1977							SURVEY DATE			
							5–77		10–77	
							PRECIPITATION BETWEEN SURVEYS (mm)			
							683		291	
							MOVEMENT BETWEEN SURVEYS			
Hole[1]	Disturbance	Parent material	Movement type	Hole depth/ movement depth (m)	Slope azimuth (degrees)	PMM azimuth (degrees)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)
1A	Logged	Schist	Creep	10.5/9.6	45	55	+0.2	+0.002	−0.6	−0.006
1B	Logged	Schist	Creep	9.0/9.0	45	275	−.5	−.002	−.8	−.006
2B	None	Schist	Creep	4.3/4.3	45	45	−.5	−.002	+.1	+.001
3A	None	Schist	Block glide	10.1/5.5	45	47	+5.0	+.020	+3.8	+.026
3B	None	Schist	Block glide	8.1/6.4	45	50	+6.7	+.030	+3.9	+.030
4A	Logged	Schist	Block glide	18.6/12.6	45	70	+4.0	+.020	+1.4	+.010
5A	None	Schist	Creep	9.1/9.1	45	90	+.2	+.001	+.4	+.003
6A	Logged	Igm	Creep and glide	11.0/6.5	225	215	+28.0	+.120	+13.0	+.090
6B	Logged	Igm	Creep and glide	7.6/6.1	225	230	+13.3	+.057	+7.4	+.054
7A	None	Cgm	Block glide	10.5/6.9	225	215	+2.6	+.010	−.8	−.010
7B	None	Cgm	Block glide	10.6/8.6	225	208	+8.4	+.035	−2.0	−.010
8A	None	Igm	Block glide	20.6/16.4	225	240	+1.8	+.008	−.4	−.003
8B	None	Igm	Total creep and glide	10.2/6.6	225	240	+4.8	+.020	+.8	+.010
8B	None	Igm	Creep only	10.2/6.6	225	240	+4.0	+.018	+.7	+.006
8B	None	Igm	Glide only	10.2/6.6	225	240	+.8	+.002	+.1	+.004
8C	None	Cgm	Total creep and glide	12.1/8.0	225	220	+17.0	+.070	.0	.000
8C	None	Cgm	Creep only	12.1/8.0	225	220	.0	.000	−2.0	−.010
8C	None	Cgm	Glide only	12.1/8.0	225	220	+17.0	+.070	+2.0	+.010

BLOCK GLIDE

Sites dominated by block-glide-type movement display a fairly uniform velocity profile with most of the displacement taking place along a well-defined shear zone (fig. 9). Creep deformation may be occurring within the moving block but generally accounts for only a small part of the total movement. Sites 3 and 4 (located in Redwood Creek schist), site 7 (located in the graywacke sandstone and mudstone of the Incoherent unit of Coyote Creek), and hole 8A at site 8 (located in the Coherent graywacke sandstone and mudstone unit of Lacks Creek) exhibit predominantly block-glide-type movement. Total displacement at the surface of these sites is substantially greater than at creep-dominated sites and ranges from a minimum of 2.9 mm/a at hole 8A in the coherent graywacke and mudstone to a maximum of 16.4 mm/a at hole 3A in the schist (table 2). Inspection of plots of cumulative movement over time for these holes (fig. 6) indicates that all holes experienced a nearly uniform annual displacement over the study period.

Holes 3A and 3B exhibit fairly constant displacement rates throughout the year with only small seasonal variation. Holes 4A, 7A, 7B, and 8A exhibit strong seasonal fluctuations with most of the displacement *to October 1977, May 1978 to September 1979, and April 1980 to April 1981*

incoherent graywacke and sandstone; Cgm, coherent graywacke and mudstone; —, not measured]

May 1978 to September 1979							SURVEY DATE							
							5–78		11–78		5–79		9–79	
							PRECIPITATION BETWEEN SURVEYS (mm)							
							1,608		251		966		188	
							MOVEMENT BETWEEN SURVEYS							
Hole[1]	Disturbance	Parent material	Movement type	Hole depth/ movement depth (m)	Slope azimuth (degrees)	PMM azimuth (degrees)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)
1A	Logged	Schist	Creep	10.5/9.6	45	55	+0.8	+0.003	+11.0	+0.060	−2.1	−0.010	−1.2	−0.010
1B	Logged	Schist	Creep	9.0/9.0	45	275	+.6	+.003	+6.9	+.040	−.8	−.004	−3.0	−.020
2B	None	Schist	Creep	4.3/4.3	45	45	+.4	+.002	+1.6	+.010	+.1	+.001	+.2	+.020
3A	None	Schist	Block glide	10.1/5.5	45	47	+14.6	+.072	+5.1	+.027	+8.2	+.047	+5.4	+.039
3B	None	Schist	Block glide	8.1/6.4	45	50	+10.7	+.050	+17.6	+.090	+2.7	+.020	+1.8	+.010
4A	Logged	Schist	Block glide	18.6/12.6	45	70	+4.4	+.020	+16.5	+.090	+5.2	+.030	−4.0	−.030
5A	None	Schist	Creep	9.1/9.1	45	90	+1.0	+.005	+12.5	+.060	−1.2	−.010	−3.1	−.020
6A	Logged	Igm	Creep and glide	11.0/6.5	225	215	+253.6	+1.220	+58.0	+.310	+56.0	+.310	+25.0	+.180
6B	Logged	Igm	Creep and glide	7.6/6.1	225	230	+189.4	+.954	+49.0	+.260	+42.0	+.280	+17.0	+.120
7A	None	Cgm	Block glide	10.5/6.9	225	215	+16.0	+.080	−5.3	−.030	+6.7	+.040	+.5	+.004
7B	None	Cgm	Block glide	10.6/8.6	225	208	+20.3	+.100	−13.6	−.070	+1.3	+.060	−1.7	−.010
8A	None	Igm	Block glide	20.6/16.4	225	240	+4.2	+.018	−.4	−.002	+3.6	+.020	−1.1	−.006
8B	None	Igm	Total creep and glide	10.2/6.6	225	240	+47.0	+.230	−2.0	−.010	+11.0	+.060	−2.8	−.021
8B	None	Igm	Creep only	10.2/6.6	225	240	+25.0	+.120	−4.4	−.020	+5.8	+.030	−3.6	−.022
8B	None	Igm	Glide only	10.2/6.6	225	240	+22.0	+.110	+2.4	+.010	+5.2	+.030	+.8	+.001
8C	None	Cgm	Total creep and glide	12.1/8.0	225	220	+76.0	+.370	+11.0	+.060	+9.0	+.050	+3.0	+.020
8C	None	Cgm	Creep only	12.1/8.0	225	220	+45.0	+.220	+1.0	+.050	+4.0	+.020	+3.0	+.020
8C	None	Cgm	Glide only	12.1/8.0	225	220	+31.0	+.150	+1.0	+.010	+5.0	+.030	.0	.000

April 1980 to April 1981							SURVEY DATE					
							4–80		11–80		4–81	
							PRECIPITATION BETWEEN SURVEYS (mm)					
							1,551		219		1,076	
							MOVEMENT BETWEEN SURVEYS					
Hole[1]	Disturbance	Parent material	Movement type	Hole depth/ movement depth (m)	Slope azimuth (degrees)	PMM azimuth (degrees)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)
1A	Logged	Schist	Creep	10.5/9.6	45	55	+1.2	+0.010	−1.4	−0.005	−3.2	−0.020
1B	Logged	Schist	Creep	9.0/9.0	45	275	+1.9	+.010	+.9	−.005	−6.0	−.037
2B	None	Schist	Creep	4.3/4.3	45	45	−.5	−.002	+1.5	+.010	+2.8	+.017
3A	None	Schist	Block glide	10.1/5.5	45	47	+12.7	+.060	+9.5	+.047	+3.1	+.020
3B	None	Schist	Block glide	8.1/6.4	45	50	+6.2	+.030	+5.9	+.030	+4.2	+.026
4A	Logged	Schist	Block glide	18.6/12.6	45	70	+6.0	+.030	−4.3	+.020	+2.4	+.015
5A	None	Schist	Creep	9.1/9.1	45	90	+1.8	+.010	+1.1	+.010	−2.2	+.014
6A	Logged	Igm	Creep and glide	11.0/6.5	225	215	+77.0	+.370	+29.0	+.140	+10.4	+.069
6B	Logged	Igm	Creep and glide	7.6/6.1	225	230	+109.0	+.530	+42.0	+.200	+37.0	+.250
7A	None	Cgm	Block glide	10.5/6.9	225	215	+19.3	+.090	−.8	−.004	+10.2	+.069
7B	None	Cgm	Block glide	10.6/8.6	225	208	Tube pinched below 8.6 m					
8A	None	Igm	Block glide	20.6/16.4	225	240	+3.6	+.014	−.7	+.003	+2.6	+.017
8B	None	Igm	Total creep and glide	20.6/16.4	225	240	+23.8	+.120	−3.4	−.012	+12.8	+.079
8B	None	Igm	Creep only	10.2/6.6	225	240	+11.0	+.050	−3.5	−.020	+6.7	+.040
8B	None	Igm	Glide only	10.2/6.6	225	240	+13.6	+.070	+.1	+.008	+6.1	+.039
8C	None	Cgm	Total creep and glide	12.1/8.0	225	220	+40.0	+.190	+5.0	+.020	+8.3	+.050
8C	None	Cgm	Creep only	12.1/8.0	225	220	+23.0	+.110	+5.0	+.020	+8.3	+.050
8C	None	Cgm	Glide only	12.1/8.0	225	220	+17.0	+.080	.0	.000	.0	.000

[1] Numerals refer to sites (fig. 1).

occurring during the winter rainy period (table 2). All the block-glide-dominated holes developed substantial increases in annual displacement rate in summer 1978; this increase followed the largest annual rainfall recorded during the study period. The rate of movement in holes 3B and 4A continued to accelerate over the following summer and winter but returned to pre-1977 levels by summer 1979. Shear at site 3 in the Redwood Creek schist is occurring between 5 and 7 m; at site 4 it is occurring at approximately 12 m. Both these sites are at the same elevation and within 400 m of each other; these circumstances emphasize the local control exerted by different zones of weakness in the parent material. Although both sites show substantial block gliding within the profile, there is little surficial indication of this activity, and both sites were or had been heavily forested.

Shear at site 7 in the incoherent graywacke sandstone and mudstone is occurring between 6 and 9 m. This site is also heavily forested and exhibits little surficial indication of the active movement.

Hole A, drilled near the upper edge of the earthflow deposits of Counts Hill Prairie (Counts Hill Prairie earthflow), indicates shear at a depth between 16 and 17 m. Total movement above this depth is small relative to that recorded in other holes drilled at the site but has a good correlation with climatic events and probably defines the basal plane of failure of the earthflow.

TABLE 2.—*Data analysis summary, including total, annual, and seasonal displacement rates and characteristics of movement for each hole*

Hole[1]	Location	Depth		Record period	
		of movement (m)	to water table (m)	(days)	(years)
1A.......	Midslope, elev. 412 m	Above 9.63 (bottom)	Dry	2,390	6.0
1B.......	Midslope, elev. 381 m; below 1A	Above 8.96 (bottom)	7.0	2,390	6.0
2B.......	Midslope, elev. 366 m; below 2A	Above 4.31 (bottom)	Dry	2,390	6.0
3A.......	Midslope, elev. 305 m	Above shear zone 5.49–7.02	6.1	2,390	6.0
3B.......	Midslope, elev. 290 m; below 3A	Above shear zone 6.35–7.49	6.1	2,390	6.0
4A.......	Midslope, elev. 305 m	Above shear zone at 5.93	6.1	2,390	6.0
5A.......	Lower slope, elev. 198 m; above Redwood Creek	Above 9.13 (bottom)	Dry	2,017	5.0
6A.......	Upper slope, elev. 625 m	Above shear zone at 6.45	6.0	1,894	5.0
6B.......	Upper slope, elev. 549 m; below 6A	Above shear zone 6.09–6.65	6.0	1,891	5.0
7A.......	Midslope, elev. 305 m	Above shear zone 6.94–7.49	Dry	2,004	5.0
7B.......	Midslope, elev. 224 m; below 7A	Above shear zone 8.57–9.12	Dry	2,004	3.0
8A.......	Upper slope, elev. 553 m; above active scarp	Above shear zone 16.37–16.95	4.5	1,797	5.0
8B.......	Upper slope, elev. 518 m; in small, active earthflow	Above shear zone 6.6–7.68	4.0	1,650	4.0
8C.......	Upper slope, elev. 488 m; in small, active earthflow	Above shear zone at 8.04	2.4	1,650	4.0

Hole[1]	DISPLACEMENT				MOVEMENT RATE			Movement characteristics
	Total	Average annual	Average seasonal (mm)		Average annual	Average seasonal		
	(mm)	(mm/yr)	Summer	Winter	(mm/d)	Summer	Winter	
1A.....	+3.5	+0.59	+0.90	−0.26	+0.0015	+0.004	+0.001	Small summer increments; most movement occurred in surge, summer 1978; creep.
1B.....	+.7	+.12	+.75	−.54	+.0003	+.0038	−.0036	Small summer increments; most movement occurred in surge, summer 1978; creep.
2B.....	+2.2	+.37	+.85	−.41	+.0010	+.005	−.002	Small summer increments; creep.
3A.....	+98.5	+16.42	+5.53	+9.33	+.0450	+.034	+.046	Steady movement throughout year; small winter surges 1976, 1978, 1980; block glide.
3B.....	+83.8	+13.97	+6.48	+6.41	+.0380	+.037	+.032	Steady movement throughout year; small surges beginning winter 1977 and continuing through summer 1978; block glide.
4A.....	+48.2	+8.03	+2.65	+4.61	+.0200	+.013	+.024	Small incremental movement throughout year; winter dominant; surge summer 1978; block glide.
5A.....	+12.6	+2.52	+2.06	+.38	+.0069	+.010	+.000	Small summer increment; most movement occurred in surge, summer 1978; creep.
6A.....	+653.6	+130.72	+28.84	+84.90	+.3581	+.170	+.422	Movement throughout year with dominant winter surges; large surges, winters 1977, 1979; creep and glide.
6B.....	+571.4	+114.28	+24.56	+74.77	+.3131	+.137	+.387	Movement throughout year with dominant winter surges. Acceleration 1977, 1979; creep and glide.
7A.....	+58.2	+11.64	−1.02	+10.55	+.0319	−.006	+.016	Dominant winter movement; block glide.
7B.....	+33.6	+11.20	−5.48	+13.88	+.0168	−.030	+.069	Dominant winter movement; block glide.
8A.....	+14.4	+2.88	−.26	+3.16	+.0080	−.002	+.015	Dominant winter movement in small increments; block glide.
8B.....	+92.0	+23.00	−1.85	+19.88	+.0630	−.008	+.102	Dominant winter movement. Large surge 1977, 1979; creep and glide.
	+41.9	+10.48	−2.65	+10.50	+.0287	+.014	+.052	Creep.
	+50.9	+12.73	+.80	+9.54	+.0349	−.006	+.050	Glide dominates.
8C.....	+169.3	+42.33	+4.75	+30.06	+.1160	+.025	+.146	Dominant winter movement. Large surge 1977, 1979; creep and glide.
	+96.3	+24.08	+4.00	+16.06	+.0660	+.020	+.080	Creep dominates.
	+73.0	+18.25	+.75	+14.00	+.0500	+.005	+.066	Glide.

[1] Numerals refer to sites (fig. 1).

COMBINED CREEP AND BLOCK GUIDE

Sites exhibiting a combined creep and block-glide profile typically display a distinct zone of shear displacement that has substantial progressive creep deformation occurring within the moving block (fig. 10). Holes 8B and 8C, which are within the Counts Hill Prairie earthflow, and site 6, which is in the coherent graywacke sandstone and mudstone of Lacks Creek, exhibit this combined movement. The surface at these holes exhibits evidence of active movement.

Total annual displacement at the surface for these holes ranges from a minimum of 23.0 mm/a for hole 8B to a maximum of 131.0 mm/a for hole 6A (table 2). Site 6 proved to be the most active site monitored during the survey, and it developed high displacement rates throughout the profile. These high rates of movement resulted in failure of the access tube in the zone of shear

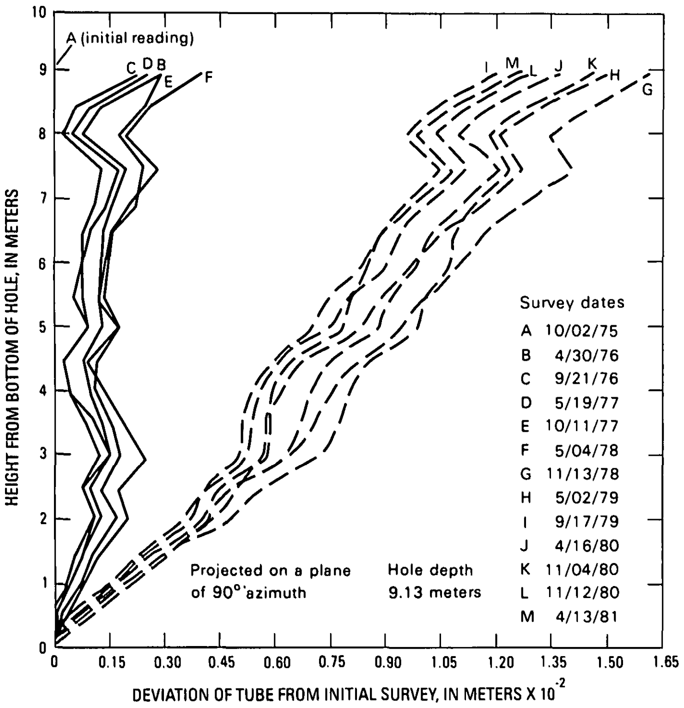

FIGURE 8.—Movement along PMM (plane of maximum movement) recorded at hole 5A (site 5, fig. 1) showing progressive deformation (creep) and strain increases toward the surface. Seasonal movement is very small. Negative or upslope adjustments represent periods of no real displacement and differential adjustment or wandering of the tube in the borehole. Note that most of the displacement recorded at this location occurred in a period of accelerated movement or surge during the summer of 1978 (surveys F–G), after a winter having the highest precipitation recorded during the survey period. (Movement after surge is shown by dotted lines.)

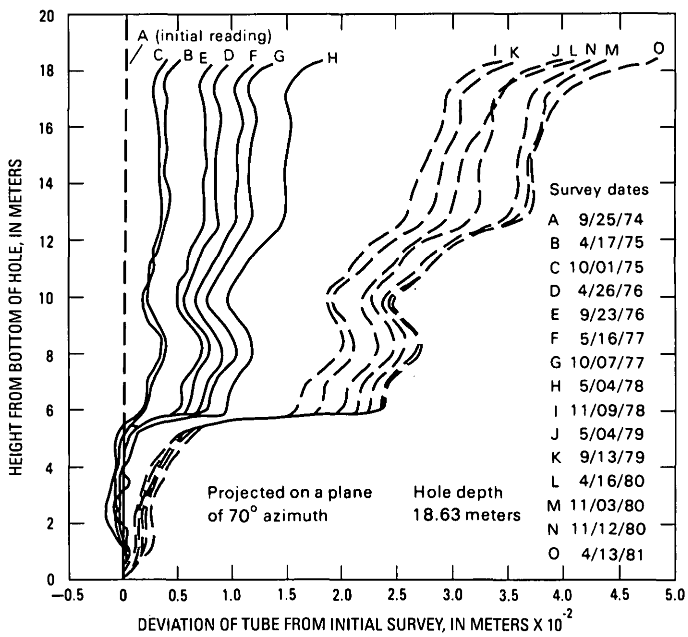

FIGURE 9.—Movement along PMM (plane of maximum movement) recorded at hole 4A (site 4, fig. 1) showing typical block-glide movement with accelerated displacement occurring above a well-defined plane of shear approximately 6 m above the bottom of the hole. Movement is predominantly seasonal. Occasional negative or upslope adjustments represent periods of no real displacement and differential adjustment or wandering of the tube in the borehole. Note that movement occurs predominantly during the winter (surveys C–D, E–F, G–H, I–J, K–L) except for a large surge in movement during the summer of 1978 (survey H–I) in response to the exceptionally high rainfall during the preceding winter. (Movement after surge is shown by dotted lines.)

at a depth of about 6.5 m early in the survey period. Although site 6 was originally located outside of what we felt to be a clearly defined zone of earthflow failure (fig. 1), the extreme rates of movement recorded and subsequent shearing of access tubes suggest that the entire slope below Childs Hill Prairie may be involved in active failure. Holes 8B and 8C, in the Counts Hill Prairie earthflow, reveal shear taking place at a depth of between 6 and 8 m, substantially above the basal failure plane of the earthflow defined in hole 8A. As holes 8B and 8C are below a distinct headwall scarp in an extremely active flow zone with the surface topographically much lower than the more stable surface at 8A, we believe that these holes also define the basal shear plane of the earthflow.

Plots of cumulative movement over time for holes 6A, 6B, 8B, and 8C indicate that displacement is seasonal and that a greater part of the movement takes place during the winter rainy season (fig. 7; table 2). Distinct surges in rates of movement occurred during the wetter winters of 1978 and 1980.

Creep is an important contributor to surface displacement in all these holes, although it cannot be separated from block glide in the total movement reported for site 6. This is because of the shearing of the tube above the established stable reference point at the bottom of the hole. All movement reported at this site after May 1977 is referenced to the configuration of the tube at the last survey prior to failure. All rates reported are thus conservative, and absolute displacement rates cannot be determined.

Differentiation between creep and block-glide movement at holes 8B and 8C was possible and reveals creep to be a major component of surface displacement within the main body of the Counts Hill Prairie earthflow (table 2). Creep accounts for approximately 56 percent of total surface displacement at hole 8C and for about 45 percent of total displacement at hole 8B.

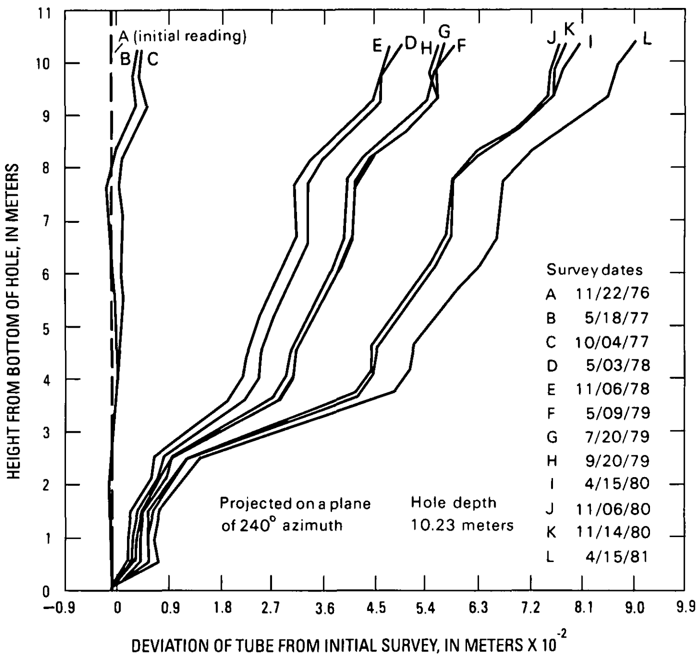

FIGURE 10.—Movement along PMM (plane of maximum movement) recorded at hole 8B (site 8, fig. 1) showing combined block glide and creep deformation occurring within the profile. Accelerated displacement is occurring within a zone between 2.5 and 4 m above the bottom of the hole. Above this zone, progressive displacement (creep) dominates, and strain increases toward the surface. Movement is predominantly seasonal. Occasional negative or upslope adjustments represent periods of no real displacement and differential adjustment or wandering of the tube in the borehole. Note that most movement occurred as winter displacement (surveys C–D, E–F, H–I, K–L).

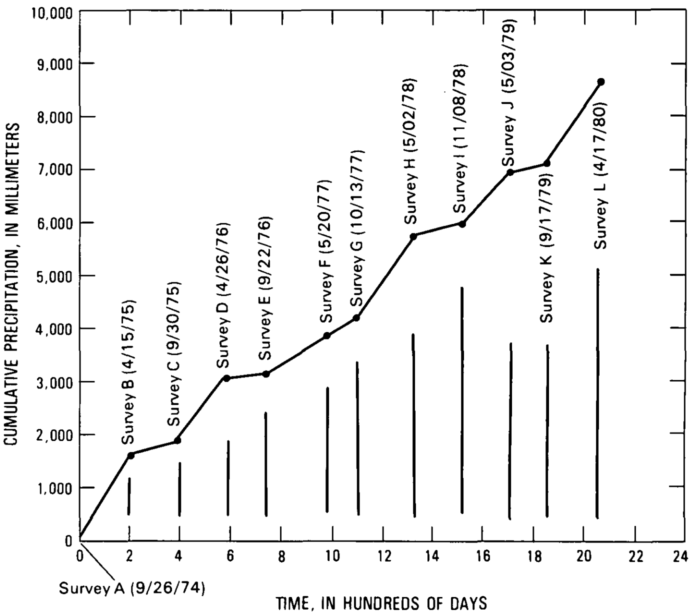

FIGURE 11.—Cumulative precipitation over survey period at Prairie Creek Redwoods State Park.

RELATIONS BETWEEN GEOLOGY AND MOVEMENT

The most active terrain having the highest rates of movement encountered in this study occurs on the east side of Redwood Creek valley in the sheared, interbedded mudstone and graywacke sandstone units. Highest rates of movement are associated with active earthflow terrain occurring at the defined contact zone between the Coherent unit of Lacks Creek and the Incoherent unit of Coyote Creek (fig. 1). Block-glide-type displacement was a major component of movement at all sites in this terrain; movement occurred above well-defined shear zones ranging in depth from 6 to 17 m. A primary or secondary shear zone between 6 and 8 m in depth was common to all monitored sites and probably represents the depth of surface weathering in these materials. Creep deformation constituted an important component in total surface displacement at active earthflow sites 6 and 8, but no purely progressive deformation profiles were encountered, perhaps because of the high rates of strain and subsequent shear failure that dominate this terrain. It would appear, on the basis of these preliminary data, that mantle deformation by block gliding along well-defined shear planes is the dominant soil-mass movement process altering slopes underlain by the incoherent graywacke sandstone and mudstone along the east side of the creek. Where strains are great enough locally, individual earthflows develop, particularly at or near the contact with the coherent unit.

In contrast, the west side of the valley, underlain by well-foliated schist, displays much lower rates of movement, and progressive creep dominates in three of the five monitored sites. Discrete failures of the block-glide type occur locally, particularly on the mid- to lower slopes as intensity and degree of shearing of bedrock increase toward the Grogan fault. Total displacement and annual rates, however, are small relative to those of the east side of the valley. Depth of the active profile at creep-dominated sites ranges from 4 to 16 m. At block-glide-dominated sites, shear generally develops between 6 and 7 m.

RELATIONS BETWEEN PRECIPITATION AND MOVEMENT

Two surveys a year were made of each access tube to assess the effects of winter rain and summer drought on movement. A curve of cumulative precipitation at Prairie Creek Redwoods State Park during the study period with approximate survey dates is shown in figure 11. A study of the data presented in tables 1 and 2, coupled with an inspection of the profiles and cumulative movement plots for each site (figs. 5–10), clearly reveals that

TABLE 3.—*Listing of beta distribution (F) values obtained from regression analysis of movement against seasonal and annual precipitation*

[Regression is significant at 5-percent (*) or 1-percent (**) level; n.d. = no data]

Hole[1]	Number of observations		Beta distribution (*F*) value					
			Annual precipitation vs.		Seasonal precipitation vs.		Precipitation during preceding season vs.	
	Annual	Seasonal	Displacement	Rate	Displacement	Rate	Displacement	Rate
1A..........	6	13	1.42	1.81	0.05	0.00	0.92	0.61
1B..........	6	13	8.04*	7.69	.03	.03	2.47	2.43
2B..........	6	13	22.44**	16.20*	2.49	2.43	10.45*	7.89*
3A..........	6	13	6.62	3.47	10.81**	7.01*	n.d.	n.d.
3B..........	6	13	2.85	2.68	.16	.00	n.d.	n.d.
4A..........	6	13	2.08	1.97	.69	.59	n.d.	n.d.
5A..........	5	11	4.58	4.30	.06	.07	1.84	2.21
6A..........	5	11	4.71	3.76	7.21	6.62*	n.d.	n.d.
6B..........	5	11	17.01*	14.01*	11.42**	12.81**	n.d.	n.d.
7A..........	5	11	6.47	5.25	48.05**	37.65**	n.d.	n.d.
7B..........	3	7	.01	.01	37.73**	39.80**	n.d.	n.d.
8A..........	5	11	20.25*	9.75*	59.48**	26.71**	n.d.	n.d.
8B..........	4	9	5.85	4.59	32.58**	40.62**	n.d.	n.d.
8C..........	4	9	5.93	4.34	10.74*	11.25*	n.d.	n.d.

[1] Numerals refer to sites (fig. 1).

both displacement and movement rate are sensitive to seasonal and annual climatic events in the Redwood Creek basin.

At the sites dominated by creep (1, 2, 5), total displacement was small prior to a movement surge during summer 1978. A regression analysis of the relationship between seasonal movement and seasonal precipitation (current and preceding season) reveals very low *F* (beta distribution) values and suggests that these variables have little predictive ability (table 3). The low *F* values, however, are due in part to most movement occurring during a single summer surge. In regression analysis, when an observation falls far from the fitted line, that observation, even if a probably legitimate one, is often removed and the analysis continued with the remaining data (Weisberg, 1980). In our case, however, nearly all the observed movement occurred during the surge, and a regression on the remaining observations would be of little value in predicting movements at the site based on precipitation. Regressions of annual movement plotted against annual precipitation yielded significant relationships for two of the four access tubes (at holes 1B, 2B) monitoring creep activity (table 3).

Sites that are dominated by block-glide-type processes and that are not within active earthflows (sites 3, 4, 7) typically display predominantly rainy season movement either as a steady movement throughout the year and small winter surges (holes 3A, 3B, 4A) or as winter movement only (holes 7A, 7B). Regression analyses of the relationship between annual movement and annual precipitation yield no significant correlation for these five holes. Three of the five holes have a highly significant relationship, however, between seasonal displacement and seasonal rainfall.

In the active earthflow sites, creep is mostly found above the block-glide zone. These sites typically display movement throughout the year and rainy season surges (holes 6A, 6B) or dominant rainy season movement (8A, 8B, 8C). Regression analyses between annual movement and annual precipitation yield significant relationships for two of the five holes (6B, 8A); however, all five holes have a significant correlation between seasonal displacement and seasonal precipitation (table 3).

RELATIONS OF MOVEMENT TO WATER LEVEL

Water was intercepted in most of the access tubes as the result of penetration of one or more water-bearing zones during the drilling process. The changes in water level in the tubes were measured from survey to survey to try to relate seasonal water-table fluctuations to periods of maximum movement. No consistent changes in water level relative to measurement were detected during the monitoring period. This lack of seasonal change in water level in the tubes may be in part due to the absence of a single, definable water table. The water in the access tubes was derived from multiple sources of water fed into the holes by several confined water-bearing horizons within the active mantle.

CONCLUSIONS

This survey clearly shows the sensitivity of some natural slopes to changes in slope stress produced by annual and seasonal rainfall.

Progressive creep with rates ranging from 1.0 to 2.5 mm/a dominates on slopes west of the Grogan fault underlain by sheared and foliated schists. Complex earthflows occur predominantly on slopes east of the Grogan fault underlain by sheared graywacke sandstone and mudstone units. Movement rates in this terrain range from 3.0 to 131.0 mm/a.

Creep profiles are encountered only on the west side of the valley in the highly foliated, locally sheared schist (sites 1, 2, 5); movement in this part of the valley is predominantly in the summer. This movement was minor over most of the survey period except for a surge developed during summer 1978 following the largest annual rainfall recorded during the study. Two of the four tubes at the creep-dominated sites (holes 1B, 5A) indicated that annual displacement was proportional to annual precipitation. No significant relationships were found between seasonal displacement and seasonal precipitation for any of the four tubes.

Sites exhibiting block glide or combined creep and block-glide movement occur on both sides of the valley (sites 3, 4, 6, 7, 8) but are most active and display the greatest movement in the sheared graywacke sandstone and mudstone units east of the Grogan fault. These sites characteristically display dominant movement during the rainy season. This movement may occur as constant downslope motion and winter surges or as winter movement only. On the schist, neither annual displacement nor movement rate was related to annual precipitation at any of the three holes (3A, 3B, 4A). Seasonal precipitation was related to seasonal movement at only one of the three holes (3A). On the graywacke sandstone and mudstone units (sites 6, 7, 8), annual displacement was related to annual precipitation at only two of the seven holes (6B, 8A). Seasonal precipitation was highly correlated, however, with seasonal displacement or seasonal rate at all seven of the holes.

There is a direct relationship between seasonal precipitation and the corresponding amount of block-glide slope deformation in the graywacke sandstone and mudstone units on the east side of Redwood Creek valley. There is a much less demonstrable relationship between precipitation and slope deformation on the schist on the west side of the valley.

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Movement and Sediment Yield of Two Earthflows, Northwestern California

By K.M. NOLAN *and* R.J. JANDA

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–F

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MOVEMENT AND SEDIMENT YIELD OF TWO EARTHFLOWS, NORTHWESTERN CALIFORNIA

By K.M. NOLAN and R.J. JANDA

ABSTRACT

Movement rates as high as 15.3 meters per year and annual sediment yields as high as 25,100 megagrams per square kilometer have been measured at two earthflows in the Redwood Creek basin of northwestern California. More than 90 percent of the sediment delivered from the earthflows to adjacent streams was delivered by earthflow movement between 1977 and 1982. Less than 10 percent of the sediment measured leaving the earthflows was delivered by fluvial processes operating in earthflow-gully systems. Movement rates and colluvial sediment yields depend upon both the amount and the pattern of seasonal precipitation, as well as the constantly changing mass distribution within individual earthflows. Annual moisture conditions appear to control the timing of movement, and the distribution of mass within the earthflow appears to control temporal and spatial variations in the rate at which movement occurs. Transient mass distributions make extrapolation of the collected data through time difficult. Although the data may only partially characterize the full range of movement rates and sediment yields possible from the studied earthflows, the complex relationship between factors responsible for controlling the behavior of these and similar earthflows has been illustrated.

INTRODUCTION

Many hillslopes in the rapidly eroding Coast Ranges of northwestern California are dominated by large complex earthflows. Although earthflows are obvious sources of sediment that affects instream and near-stream resources, quantification of the sediment yield derived from these persistently active features requires long-term observation. This report characterizes movement and sediment yield from two earthflows, primarily from 1977 to 1982, by presenting information from repetitive surveys of transverse and longitudinal lines of stakes and from borehole inclinometer measurements, recording strain gages, recording rain gages, and records of water and sediment yield from gully systems developed on the surfaces of the studied earthflows.

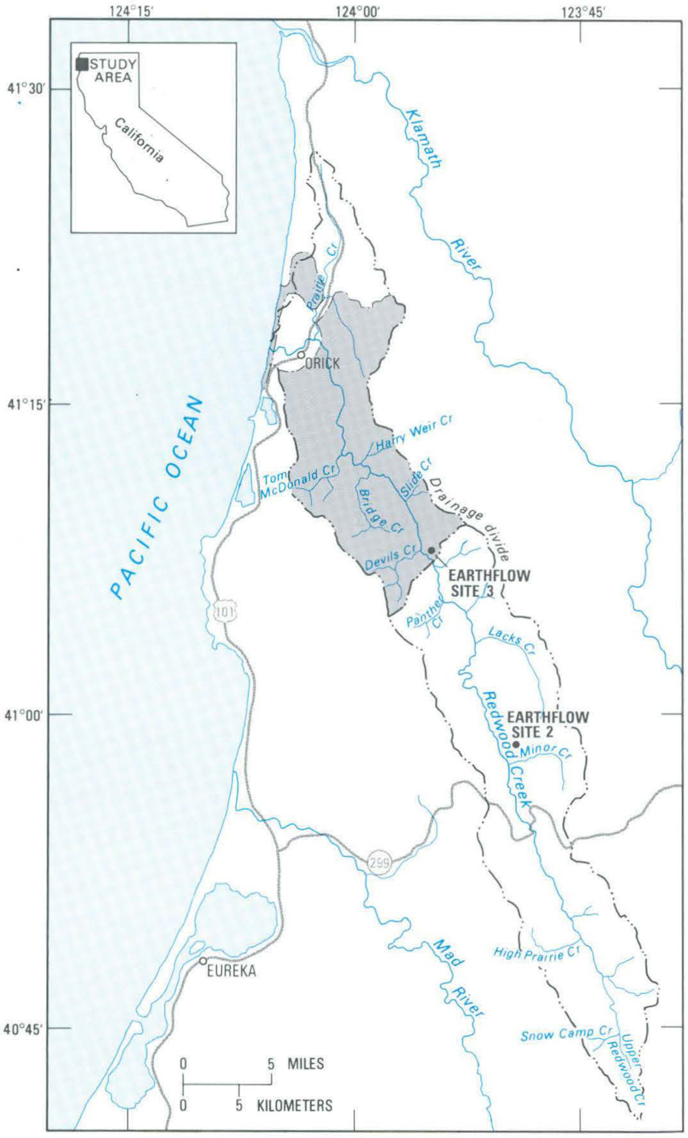
Study sites 2 and 3 (fig. 1), representing the two earthflows studied in this report, are part of a larger network of sites in the Redwood Creek basin of northwestern California at which surficial movement rates have been monitored. Description of this larger network is in Harden and others (1978).

DESCRIPTION OF EARTHFLOWS

The two earthflows studied are complex associations of sheared and fractured earth debris, in elongate or lobate masses, that move downslope relatively slowly along boundary shear zones. At least some parts of these masses move annually. This persistent movement produces depressions in the landscape that are manifested as hummocky ground, scarps, tension cracks, and compressional ridges. The morphology and mechanics of similar earthflows have been described by Varnes (1958), Prior and others (1971), Colman (1973), Swanson and James (1975), Keefer (1977), Kelsey (1978), and others. Ten percent of the Redwood Creek basin is covered by earthflows (Nolan and others, 1976).

The earthflows studied, like most others in the Coast Ranges of northern California, are developed on rapidly eroding hillslopes underlain by rocks of the Franciscan assemblage of late Jurassic and Cretaceous age (Harden and others, 1981). This assemblage consists predominantly of sandstones and mudstones in association with significant amounts of metamorphosed volcanic rocks, serpentinite, chert, and limestone (Bailey and others, 1964; Jones and others, 1978). The sandstones and mudstones often are highly fractured and sheared. Earthflow development, as well as regional sediment yields that are among the highest in North America (Judson and Ritter, 1964; Janda and Nolan, 1979), results from these structurally weak rock units in combination with steep hillslopes and abundant wintertime precipitation.

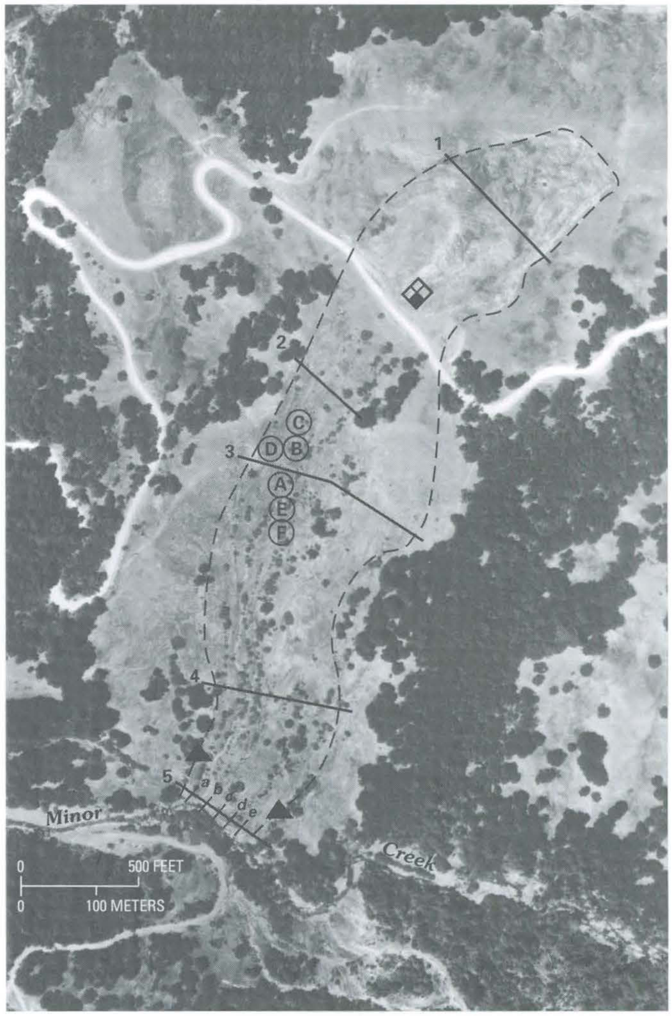
A Mediterranean climate prevails at both study sites. Average annual precipitation, 80 percent of which typi-



EXPLANATION

REDWOOD NATIONAL PARK

FIGURE 1.—Location of sites 2 and 3 in the Redwood Creek drainage basin.



EXPLANATION

5 —— TRANSVERSE STAKE LINE

a LONGITUDINAL STAKE LINE

– – – – – APPROXIMATE BOUNDARY OF ACTIVE MOVEMENT

(A) INCLINOMETER

▲ STREAM-GAGING SITE

◈ RECORDING RAIN GAGE

FIGURE 2.—Location of sampling and measurement sites on earthflow at study site 2. Aerial photograph taken July 14, 1979.

cally falls between October and April, is approximately 2,000 mm at both study sites.

DESCRIPTION OF SITE 2

Site 2 is adjacent to the main channel of Minor Creek (figs. 1, 2). This site displays morphological features characteristic of many earthflows in Franciscan terrane but lacks the typical teardrop shape. The upper one-third of site 2 is dominated by a large upper slump block and a prominent crown scarp. Data from inclinometer tubes indicate that movement at depth occurs below this upper slump block, within a basal shear zone. Observations of compressional ridges, lateral shear zones, hummocky ground, scarps, and tensional cracks indicate that movement above this shear zone involves a complex

FIGURE 3.—Toe of earthflow at study site 2. Photograph taken March 1980. Note effects of undercutting by main channel of Minor Creek and large colluvial blocks that result from persistent movement of toe. Note top of 6-in. flume and gage-height recorder for scale.

assemblage of regions, each characterized by slumping, flowing, and (or) translational sliding. Similar observations were made by Keefer (1977) and Kelsey (1978). The toe of site 2 is dominated by translational sliding and small surficial slumps and slides (fig. 3). The active portion of site 2 is 760 m long and averages 150 m wide. Relief is about 230 m.

The lower two-thirds of site 2 contains several prominent longitudinal gullies that coalesce into two well-defined channels at the earthflow toe and that transport sediment directly into Minor Creek. Vegetation on the earthflow surface is mostly grass and some brush and small oaks. Bare soil is exposed at the head scarp, in gully walls, on a translational slide at the earthflow toe, and where a county road crosses upper portions of the earthflow. The ground is dry during late spring and summer, except in a small area of ponded drainage near transverse stake line 2 and near the base of the earthflow toe, where small amounts of seepage are evident.

DESCRIPTION OF SITE 3

Site 3 is on the east side of Redwood Creek (figs. 1, 4) and is underlain by sandstone and mudstone that are closely fractured and sheared near the earthflow toe but relatively massive in the crown area. Site 3 displays the typical teardrop shape absent in site 2. Movement in the crown area is dominated by slumping or sliding of relatively coherent blocks. Material moving through the relatively narrow midslope portions is highly disrupted and appears to move by a combination of flow and translational movement. The earthflow toe is dominated by a large translational slide, the surface of which is covered by small shallow slides and slumps. Drainage is poorly defined on the upper two-thirds of the earthflow but merges into a single well-defined axial gully in the lower one-third. The active portion of site 3 is 340 m long and 140 m wide and has 110 m of relief.

Vegetation on the earthflow is mostly grass and bracken fern and some brush, small oaks, and conifers. The ground surface is commonly severely disrupted by extension cracks 15 to 30 cm deep, by lateral shear surfaces, and by compressional ridges (fig. 5). Stands of tilted oaks and young conifers are present at the lateral edges of the flow. The ground surface is generally dry in the late spring and summer.

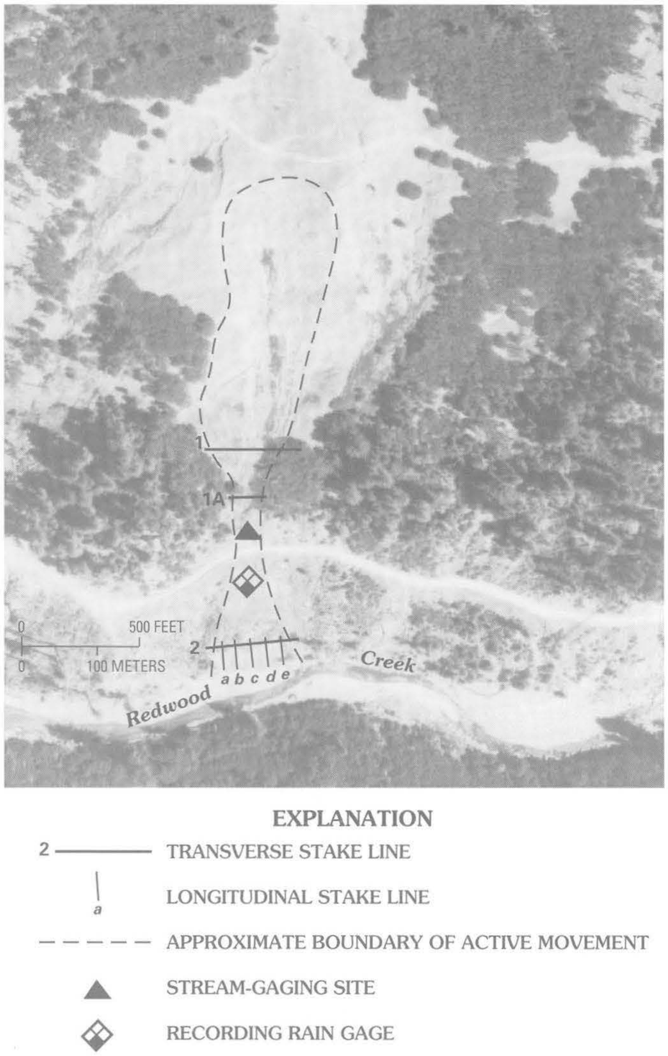


FIGURE 4.—Location of sampling and measurement sites on earthflow at study site 3. Aerial photograph taken July 14, 1979.

FIGURE 5.—Hummocky ground near transverse stake line 1, site 3.

SURFICIAL MOVEMENT OF EARTHFLOWS

TRANSVERSE STAKE LINES

Surficial movement rates were monitored from the 1974 water year to the 1982 water year[1] at site 2 by repetitive surveys of five transverse lines of stakes and from the 1975 water year to the 1982 water year at site 3 by surveys of three transverse lines of stakes. Stakes were spaced at 4.5-m intervals across each feature, and stake positions were surveyed by theodolite at least annually from stable instrument locations at the end of each line. The horizontal component of stake displacement was calculated from the horizontal angle between the location of individual stakes and the line between the two stable end points. Stake line locations are shown in figures 2 and 4, and survey results are summarized in tables 1 and 2 by showing average and maximum stake movement for each water year.

LOCATION OF STAKES AT SITE 2

Transverse stake line 1 on site 2 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 defining the active portion of the feature are 3 to 6 m higher than the flow surface. Stake line 3 crosses the flow where a less active, tributary earthflow enters the main feature. At stake line 4, the earthflow is wider and less steep than at the upper portions. Stake line 5 transects the flow about 30 m upslope from the streamside edge. Portions of line 5 transect the toe translational slide.

LOCATION OF STAKES AT SITE 3

Transverse stake line 1 on site 3 is located immediately above the area indicated by field reconnaissance to be the most active portion of the feature. Line 1A is located at the narrowest portion of the feature where field evidence suggested that movement rates would be the highest. The lower line, line 2, crosses the flow at a gently sloping hummocky area immediately above the toe translational slide.

LONGITUDINAL STAKE LINES

Five lines of longitudinal stakes were placed at the toe of site 2 in the 1977 water year and at the toe of site 3 in the 1978 water year. These lines were installed to better monitor movement of colluvial debris into adjacent streams. Stake movement was determined from triangulation surveys using stable instrument locations near the earthflow toes. Stake line locations are shown in figures 2 and 4, and surveying results are summarized in tables 1 and 2.

MOVEMENT PATTERNS OF EARTHFLOWS

Although slow earthflow movement appears to persist throughout the water year on some regions of site 2, movement generally resumes or accelerates in the late autumn or early winter following the start of the rainy season and the resulting increases in soil moisture and pore-water pressure. The patterns of movement observed in this study illustrate the importance of cumulative moisture on earthflow movement. The movement pattern recorded during the 1979 water year at the two strain gages near the toe of site 2 (fig. 2), as illustrated in figure 6, is typical of patterns monitored at all strain gages between l978 and 1981. Even though brief periods of intense precipitation occurred early in the 1979 water year, movement was not initiated until antecedent moisture conditions were high. Once movement began, it accelerated quickly and continued despite the lack of prolonged periods of intense precipitation. Moisture conditions optimal for maximum movement probably occur when prolonged periods of rainfall occur early in the rainy season. Sufficient moisture to initiate some degree of rapid movement occurred during all years of study. Monthly and annual precipitation recorded at each site is shown in table 3.

[1] Water year extends from October 1 to September 30.

TABLE 1.—*Surficial movement rates (horizontal component) at site 2*

[Average (Avg) refers to average movement of all stakes on line. Maximum (Max) refers to maximum individual stake movement. Locations of stake lines are shown in figures 2 and 4. All measurements are in meters. —, no data]

	Transverse stakes										Longitudinal stakes				
	Line 1		Line 2		Line 3		Line 4		Line 5		Line a	Line b	Line c	Line d	Line e
	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Avg	Avg	Avg	Avg
Stakes per line	37		26		48		49		23		9	9	7	6	9
Total length	130.1		84.7		190.5		174.2		116.1		22.7	23.4	14.3	12.1	19.6
Water year:															
1974	—	—	0.86	1.52	0.56	1.94	0.23	1.55	—	—	—	—	—	—	—
1975	0.09	0.17	.06	.10	.13	.27	.05	.26	0.16	0.55	—	—	—	—	—
1976	.17	.38	.08	.14	.01	.10	([1])	([1])	.33	.84	—	—	—	—	—
1977	.03	.07	.03	.12	.04	.10	.10	.26	.04	.15	0.23	0.12	0.09	0.02	0.18
1978	.60	.87	.10	.23	.08	.13	[2].04	.15	.58	.63	3.78	3.32	.57	.16	.20
1979	.22	.31	.07	.15	.07	.11	[2].06	.15	.39	2.41	1.38	3.39	.65	1.53	.56
1980	.42	.62	.23	.51	.19	.31	.06	.24	2.48	15.30	5.98	10.25	.64	1.13	.43
1981	.17	.26	.07	.17	.09	.15	.05	.10	1.32	6.43	3.07	5.13	.61	.19	.08
1982	.50	.82	.36	.54	.20	.47	.31	1.22	1.81	15.29	4.60	6.67	15.36	.76	.79

[1] End point destroyed during 1976 water year and reestablished.
[2] Includes only movement on left one-half of line.

TABLE 2.—*Surficial movement rates (horizontal component) at site 3*

[Average (Avg) refers to average movement of all stakes on line. Maximum (Max) refers to maximum individual stake movement. Locations of stake lines are shown in figures 2 and 4. All measurements are in meters. —, no data]

	Transverse stakes						Longitudinal stakes				
	Line 1		Line 1A		Line 2		Line a	Line b	Line c	Line d	Line e
	Avg	Max	Avg	Max	Avg	Max	Avg	Avg	Avg	Avg	Avg
Stakes per line	21		13		18		13	14	15	13	14
Total length	58.2		54.2		39.0		33.4	34.9	34.1	27.7	28.9
Water year:											
1975	0.03	0.08	—	—	0.21	0.63	—	—	—	—	—
1976	.01	.12	—	—	.15	.54	—	—	—	—	—
1977	.00	.04	—	—	.07	.32	—	—	—	—	—
1978	.05	.25	—	—	.52	1.92	2.79	2.24	1.38	—	.58
1979	.11	.45	0.02	0.11	.65	2.34	2.17	4.11	.78	[1]1.48	.54
1980	.03	.18	.02	.12	.30	1.08	1.04	1.67	.75	.78	2.26
1981	.03	.10	.04	.10	.04	.15	.22	.34	.09	.05	.00
1982	.10	.36	.30	1.64	.45	1.90	2.74	3.08	.85	.61	2.71

[1] Includes 1978 and 1979 movement.

TABLE 3.—*Monthly and annual precipitation measured at sites 2 and 3*

[All measurements are in millimeters; —, no data]

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Yearly total
Site 2									
1974	No recording data								[1]3,030
1975	60	150	371	404	439	646	120	47	2,255
1976	359	234	183	150	381	136	61	11	1,598
1977	26	94	10	39	126	203	46	91	746
1978	124	356	445	242	184	186	173	61	1,908
1979	3	126	60	266	339	79	132	142	1,205
1980	—	[2]681	51	308	273	257	112	92	2,160
1981	83	163	269	199	177	231	40	66	1,260
1982	220	472	591	291	456	419	195	—	2,721
Site 3									
1975	No recording data								2,259
1976	337	290	225	144	400	150	82	18	1,730
1977	21	97	20	133	141	177	4	96	850
1978	157	426	425	383	270	167	189	8	2,270
1979	1	147	54	246	406	75	169	132	1,297
1980	391	184	291	349	306	318	147	54	2,044
1981	79	165	330	255	224	252	44	79	1,466
1982	No recording data								2,360

[1] Based on correlation with record collected at Prairie Creek Redwoods State Park (U.S. National Oceanic and Atmospheric Administration, 1973–74).
[2] October total added to November total.

In addition to the general relations found between annual moisture conditions and earthflow movement, the individual characteristics of each feature must be considered. Because earthflows consist of distinct units, patterns of movement may vary at different locations within the same feature. This variation in movement behavior is illustrated in figures 7 and 8, which show for study sites 2 and 3, respectively, the cumulative movement of a single stake at each of the transverse stake lines. Stakes chosen for these figures were all located within the active portion of the line. Although there is some similarity in the timing of relative movement at individual stake lines, there also are a number of inconsistencies. For example, the stake on line 5, site 2, showed maximum movement during the 1980 water year, but movement at line 4 during that year was only slightly faster than that for 1979 or 1981. Similarly, maximum movement on line 1, site 2, was recorded during the 1978 water year, while movement rates for lines 2 and 3 for that year were some of the slowest recorded.

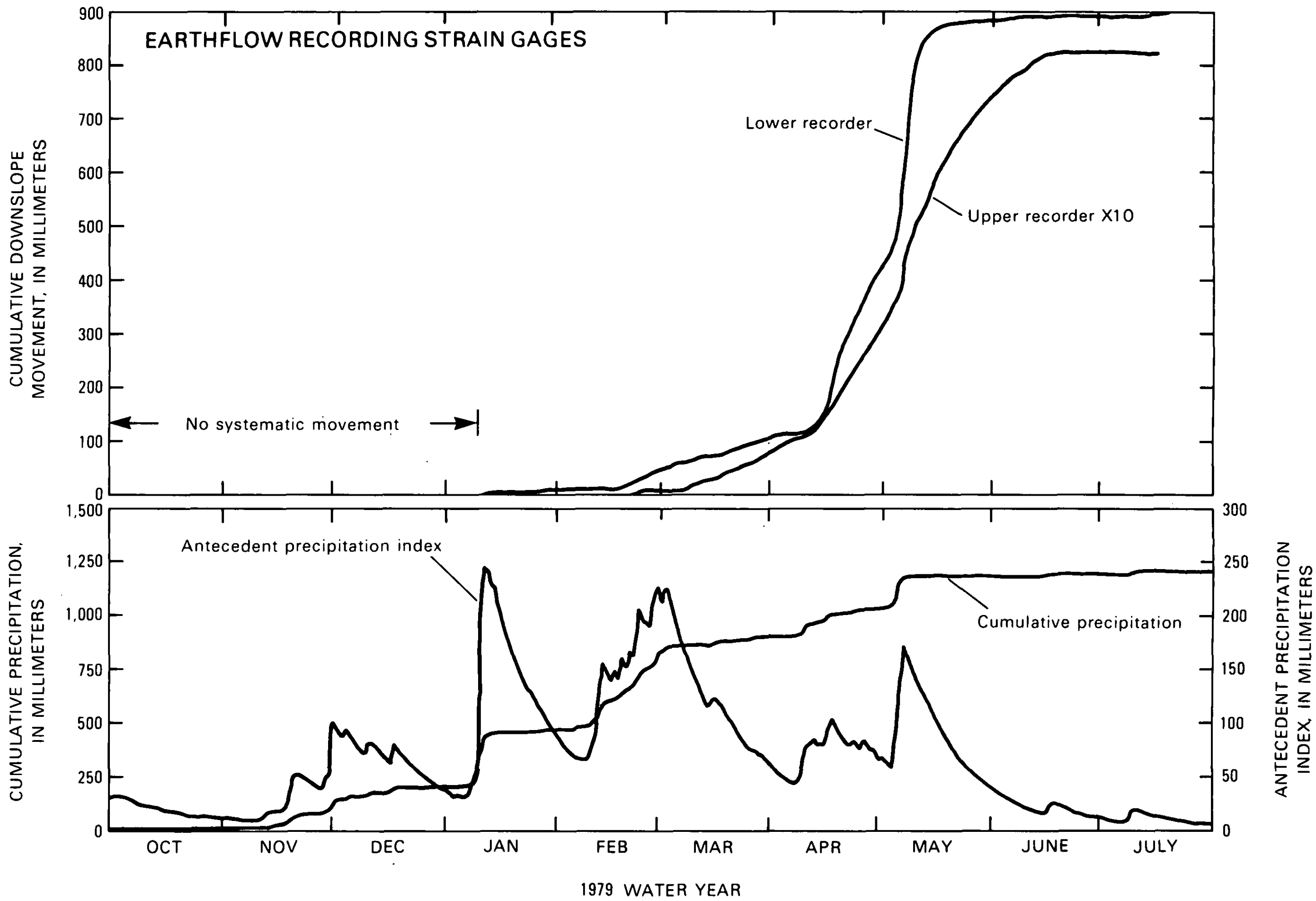


FIGURE 6.—Earthflow movement at site 2 recorded at strain gages during the 1979 water year. Cumulative precipitation is from daily rainfall measured at site. Antecedent precipitation index was determined by using a daily decay constant of 0.94 (Linsley and others, 1949). Lower recorder is at upslope end of longitudinal stake line *b* on traverse line 5 (fig. 2). Upper recorder is 50 m upslope of lower recorder.

Field observations indicate that this irregular earthflow behavior is caused by the constantly changing mass distribution within individual features. The distinct units within earthflows are characterized by different rates and styles of movement, and the movement of any one unit may affect movement of adjacent units. Individual units commonly are bounded by distinct lateral margins, and the fastest movement usually occurs near the center of each unit. The movement pattern recorded at transverse stake line 2, site 3, is illustrated in figure 9.

Movement, at least at earthflow toes, also appears to be controlled by the action of the stream channels adjacent to the toes. The anomalously high movement rates during 1980 at line 5, site 2 (fig. 7), resulted from undercutting of the toe by the main channel of Minor Creek (fig. 3). Conversely, alluvium deposited by the main channel of Redwood Creek appears to have effectively buttressed the toe of site 3 and caused anomalously low movement rates at line 2 during 1980 and 1981 (fig. 8).

MOVEMENT OF EARTHFLOWS AT DEPTH

INCLINOMETER TUBES

In cooperation with the U.S. Forest Service, six inclinometer tubes were installed near transverse stake line 3, site 2, beginning in the 1979 water year (fig. 2). Repetitive measurements in these tubes indicate a distinct basal shear zone at an average depth of 4.9 m. Apparent deformation at inclinometer tube E is shown in figure 10, and the estimated location of the basal shear zone below the inclinometer tube sites is shown in figure 11. Tube D showed no apparent shear zone due to its limited depth (4.42 m) and high relative elevation.

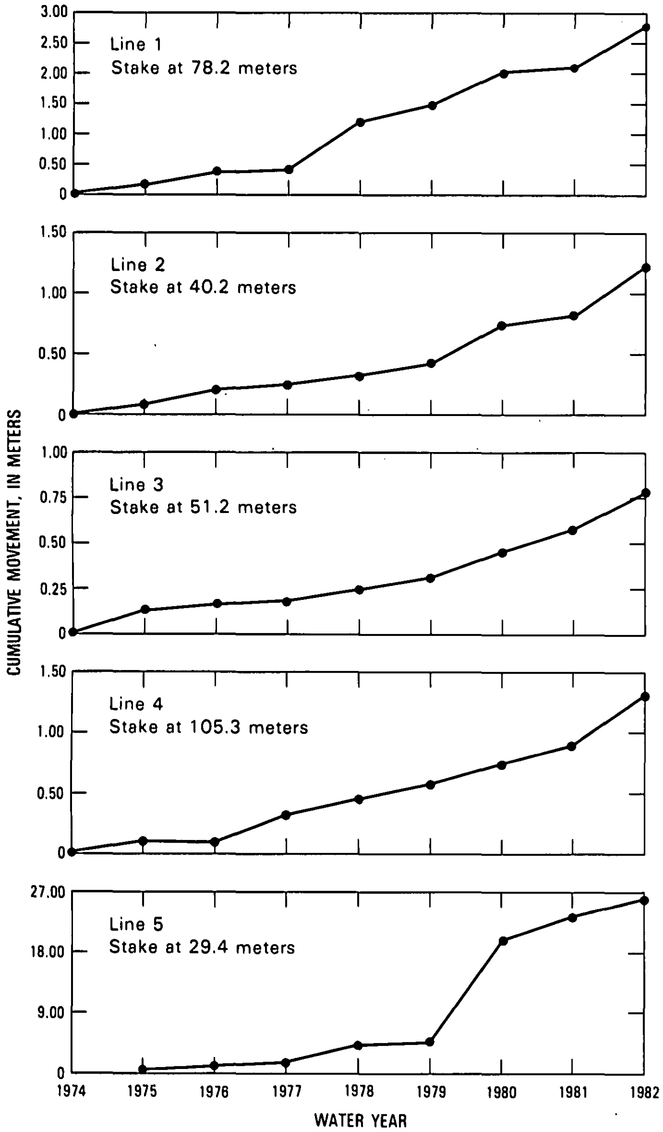


FIGURE 7.—Cumulative movement of selected transverse stakes at site 2. Movement rates are indicated by slope of lines connecting data points. Note variation in movement scale (x-axis). Stake distances are measured from left side of lines as viewed from looking downhill.

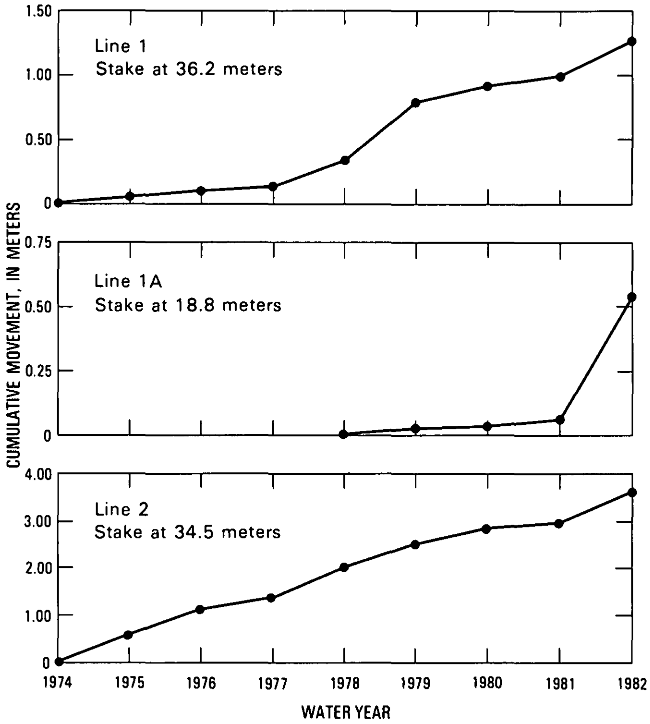


FIGURE 8.—Cumulative movement of selected transverse stakes at site 3. Movement rates are indicated by slope of lines connecting data points. Note variation in movement scale (y-axis). Stake distances are measured from left side of line.

Movement at these sites appears to persist at an almost uniform rate throughout the year. This relatively slow movement contrasts with that of the more rapid, highly seasonal movement seen along at least some portions of most stake lines and at the toe strain gages, site 2. Because the shear zone remains saturated all year long (Richard Iverson, U.S. Geological Survey, oral commun., 1983), this slow movement may reflect movement along this zone under relatively low pore-water pressures. The more rapid seasonal movement may result from the localized increases in pore-water pressures that occur during rainy periods.

DEPTHS OF MOVEMENT AT EARTHFLOW TOES

The steep, actively eroding nature of the earthflow toes precluded installation of inclinometer tubes at these sites. Since repeated field observations indicated that mass movement at the earthflow toes did not disrupt the adjacent channel bottoms, movement was assumed to extend from the surface downward to a concave-upward basal shear zone between the base of the streambanks and the heads of toe translational slide.

SEDIMENT YIELDS FROM EARTHFLOWS

COLLUVIUM

Colluvial yield to adjacent stream channels was calculated from hillslope geometry, movement rates determined during surveys of longitudinal stake lines, and estimated movement depths. The total annual volume of material delivered to adjacent stream channels by mass movement was calculated by using average movement at each of the five longitudinal lines, slope width between each stake line, and estimated depth to the basal shear zone. The cross-sectional geometry used to calculate the volume of colluvium delivered at longitudinal line e in the

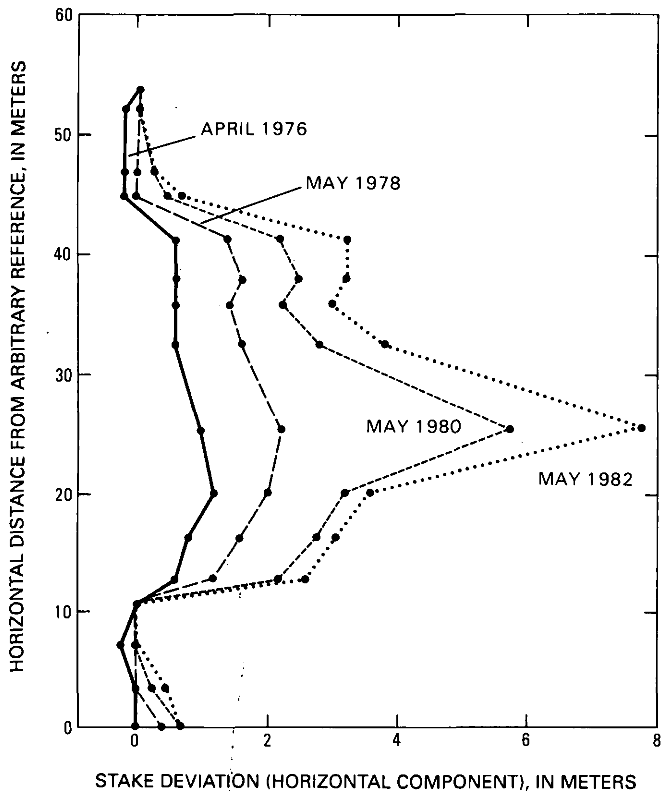


FIGURE 9.—Downslope displacement of stakes at transverse stake line 2, site 3. Only stakes not lost or replaced during period of record are shown to better depict continuous movement. Numbers indicate the number of stakes plotted at that location.

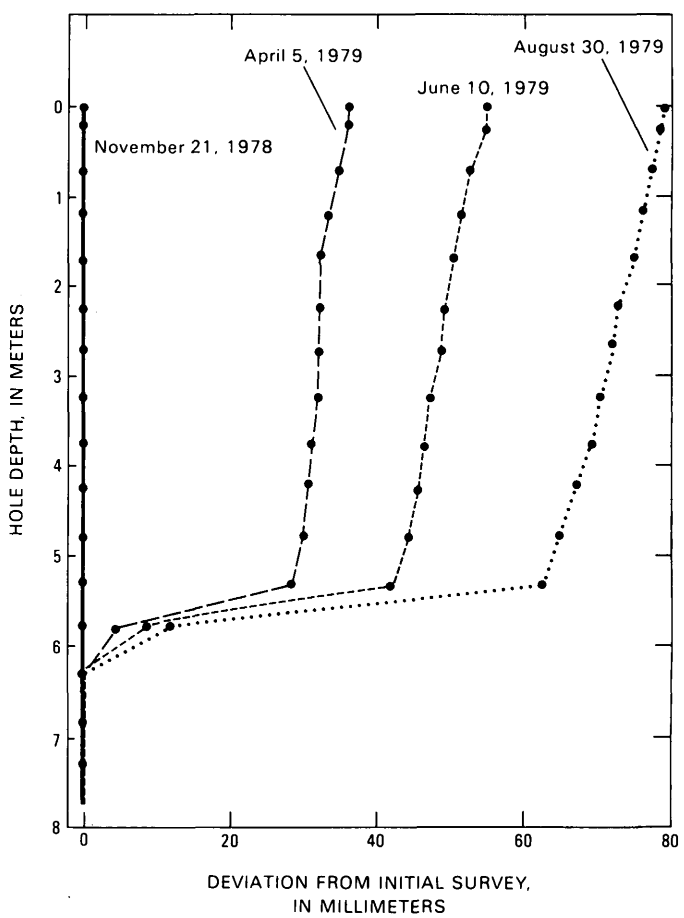


FIGURE 10.—Apparent deformation at inclinometer tube E, site 2. Deformation in tube after August 30, 1979, was too severe to allow penetration by inclinometer. Hole depth was 7.85 m. Data are from R. Ziemer, U.S. Forest Service, Arcata, Calif.

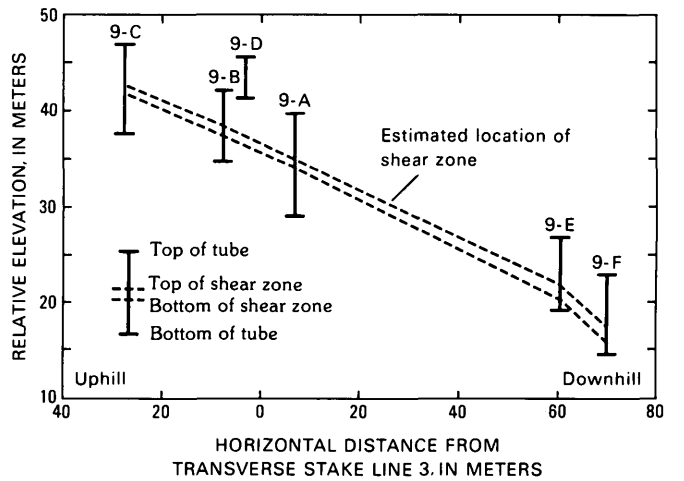


FIGURE 11.—Estimated location of basal shear zone beneath inclinometer tube locations. Inclinometer tubes were installed near transverse line 3, site 2.

1981 water year is illustrated in figure 12. Annual volume estimates were converted to annual sediment yields by applying an average density of 2.08 g/cm^3 (grams per cubic centimeter). Annual colluvial sediment yields determined for both study sites are shown in tables 4 and 5. The colluvium was delivered directly to active stream channels adjacent to the toes of both earthflows. The area where colluvium was deposited was generally inundated on an annual basis, and most colluvium was removed frequently. The rate at which colluvium was removed varied somewhat and depended upon the location of the channel thalweg during individual years.

FLUVIAL SEDIMENT

The highly disrupted material of earthflows is extremely vulnerable to gully erosion, and both sites 2 and 3 are drained by gully systems. For this reason, continuous water-level recorders, located at either weirs or flumes, were installed in 1978 at major gullies draining sites 2 and 3. Total annual sediment yield was determined for each site by using gage-height records and

TABLE 4.—*Sediment discharge by mass movement, fluvial erosion, and runoff at toe of site 2 and amount of material moved past transverse stake line 3 (midslope portion), site 2*

[Drainage area is 0.13 km . —, no data]

Water year	Sediment discharge						Runoff		Movement past stake line 3 (m)
		Suspended sediment		Bedload					
	Mass movement (Mg)	Right gully (Mg)	Left gully (Mg)	Right gully (Mg)	Left gully (Mg)	Total sediment discharge (Mg/km^2)	Right gully (m)	Left gully (m)	
1977	1.50	—	—	—	—	[1]12	—	—	32.3
1978	372.3	—	—	—	—	[1]2,850	—	—	64.6
1979	305.8	[2]125.0	[2]0.50	[2]31.2	[2]0.1	3,550	0.29	0.43	56.6
1980	2,806	112.5	19.1	28.1	4.8	22,800	.85	.96	153.6
1981	705.1	20.1	2.2	5.0	.6	5,650	.41	.52	72.7
1982	3,132	97.6	4.5	26.9	1.1	25,100	1.59	1.75	161.6

[1] Does not include fluvial discharge.
[2] Record starts December 15, 1978.

TABLE 5.—*Sediment discharge by mass movement, fluvial erosion, and runoff at toe of site 3*

[Drainage area is 0.023 km^2. —, no data]

Water year	Sediment discharge				
	Mass movement (Mg)	Suspended sediment (Mg)	Bedload (Mg)	Total sediment (Mg/km^2)	Runoff (m)
1978	230.5	—	—	[1]10,020	—
1979	466.3	2.0	0.5	20,380	1.19
1980	155.2	[2]12.4	[2]25.1	8,380	[2]1.86
1981	3.3	8.5	5.0	730	1.27
1982	376.9	([3])	([3])	16,380	([3])

[1] Does not include fluvial discharge.
[2] Record starts December 13, 1979.
[3] Measuring site destroyed by debris slide.

periodic measurements of water, bedload discharge, and suspended-sediment concentrations. Sampling was concentrated during rainy periods. Two stream-gaging sites were established at site 2 and one at site 3 (figs. 2, 4). Bedload at site 3 was trapped behind an enlarged weir structure beginning in the 1979 water year. Bedload discharges for site 3 in 1978 and for site 2 were estimated by using the median value of the percentage of total load that bedload represented at times of instantaneous measurement of suspended-sediment and bedload discharge. This procedure was necessary due to the lack of significant relationship between water discharge and bedload discharge. Water discharge and suspended-sediment discharge were determined by using standard U.S. Geological Survey field and office techniques (Buchanan and Somers, 1969; Porterfield, 1972). Sampling-site locations are shown in figures 2 and 4, and sampling results are shown in tables 4 and 5.

The amount of seasonal runoff measured at site 3 was consistently high, relative to seasonal rainfall measured at the site. The surface beneath this and similar features is likely to be severely disrupted, and the high runoff percentages may reflect effects of a phreatic drainage divide that differs from the mapped topographic divides.

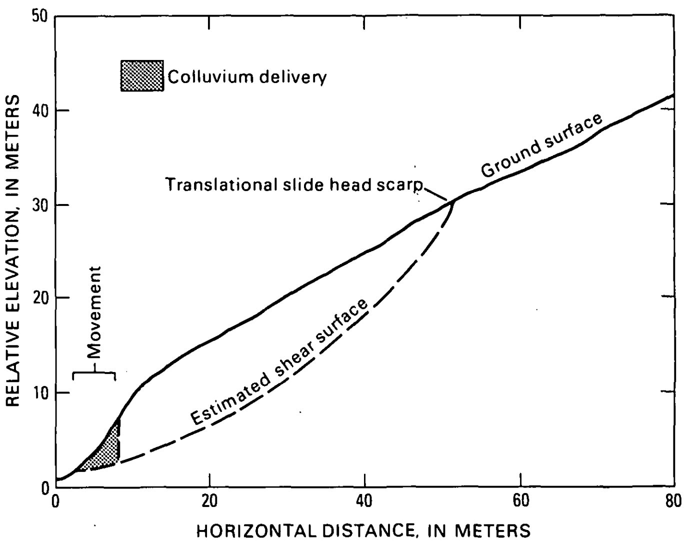


FIGURE 12.—Geometry used to estimate sediment delivery at toe of site 2, longitudinal stake line *e*.

DISCUSSION

TOTAL SEDIMENT YIELD

Total annual sediment yields from earthflow study sites 2 and 3 ranged from 730 to 25,100 Mg/km^2 (megagrams per square kilometer) (tables 4, 5). These values are from 1.6 to 18.3 times the basinwide average sediment yield, which is represented by the yield measured at Redwood Creek at Orick for similar years (table 6). The vast majority of sediment delivered from both sites to adjacent stream channels was delivered by mass movement processes. Although fluvial processes operating in major gully systems delivered up to 80 percent of the annual yield during individual years, such high percentages occurred only during years of minimal colluvial input (tables 4, 5). Ninety-three percent of the yield from site 2 between 1979 and 1982 and 92 percent of

TABLE 6.—*Total sediment discharge measured at the mouth of Redwood Creek*

[Data were gathered from stream-gaging station at Orick (no. 11482500)] [Mg/km², megagram per square kilometer]

Water year	Sediment discharge (Mg/km²)	Water year	Sediment discharge (Mg/km²)
1977	31	1980	1,243
1978	1,610	1981	455
1979	435	1982	Not available

the yield from site 3 between 1979 and 1981 were delivered by mass-movement processes (tables 4, 5).

REGIONAL COMPARISON

Surficial-movement rates monitored at sites 2 and 3 are intermediate among those measured during the same time interval at other earthflows in the Pacific Northwest. Maximum annual movement rates recorded by Kelsey (1978), Keefer (1977), and Swanson and others (1979) are compared in table 7. Data in this table indicate that earthflow movement rates, from a regional perspective, are highly variable. Although much of this variability no doubt results from variations in local moisture conditions, original ground slope, and existing mass distributions, differences in geologic setting are probably primarily responsible for the variations in rates. The rapidly moving earthflows studied by Kelsey (1978) were developed in pervasively sheared rocks of the melange unit of the Franciscan assemblage. The extremely high rates of movement at these sites may reflect the intensity of this shearing. The earthflows mentioned by Keefer (1977) were very shallow seated flows, about 1 m deep, developed in fractured shales and sandstones of the Franciscan assemblage. Movement rates at the forested Lookout Creek earthflow studied by Swanson and others (1979) were much slower than those in Franciscan assemblage terrane; this reference probably reflects the more coherent nature of the underlying volcaniclastic rocks.

Data from the sites mentioned above indicate that the sediment yields from these features also vary widely. Kelsey (1978) estimated long-term annual sediment yields at 51,200 Mg/km² from the exceptionally active earthflows in the Van Duzen River basin, northwestern, California, while Swanson and Swanston (1977) estimated long-term annual yield from the Lookout Creek earthflow in southeastern Oregon at 1,700 Mg/km² or (assuming the bulk density of the colluvium is 2.08 g/cm³) 3,540 Mg/km². Estimated yield from the Van Duzen earthflows is therefore about 14 times that of the Lookout Creek feature and approximately twice the highest annual yield recorded at sites 2 or 3 of this study.

In addition to wide regional variation in sediment yields, there also appears to be wide variation in the mechanisms delivering sediment to stream channels.

TABLE 7.—*Maximum annual movement recorded at earthflows in California and Oregon*

Location	Reference	Year	Maximum movement (m)
Davailla hill (southwestern Oregon)	Keefer (1977)	1975	3.8
Halloween earthflow (northwestern California)	Kelsey (1978)	1974	21.0
Do	....do....	1975	29.0
Do	....do....	1976	28.7
Lookout Creek earthflow (west-central California)	Swanson and others (1979)	1975	.10
		1976	.14
		1977	.01
		1978	.06
		1979	.13

Kelsey (1978) estimated that fluvial processes operating in earthflow gullies annually produced approximately 26,300 Mg/km², whereas the highest fluvial yield recorded at sites 2 or 3 between 1978 and 1981 was 1,875 Mg/km². This contrast in delivery apparently results from differences in the respective sediment-transport relations or in the degree of gully-system development. Gully systems at sites 2 and 3 of this study are only moderately incised into the earthflow surface and are not integrated throughout each entire earthflow. A large percentage of the flow in gullies at sites 2 and 3 resulted from seepage of water into the gullies between rainy periods. This return flow was characterized by relatively low sediment concentrations. Gully systems on the larger features studied by Kelsey (1978) may have been better developed and, therefore, may have transported higher percentages of flow during storm periods; that is, gullies on larger features may be more actively eroding and thus may be responsible for the transport of larger percentages of total sediment discharge.

LONG-TERM SEDIMENT YIELD

Because fluvial sediment constitutes a relatively small percentage of total long-term sediment yield from sites 2 and 3, sediment yield from these features primarily reflects highly variable surficial movement rates at earthflow toes. These movement rates, and the related sediment yields, are highly variable due to factors discussed previously, and this variability is illustrated by the contrast in colluvial sediment yields from sites 2 and 3 as shown in tables 4 and 5. The yield from site 3 was higher than that from site 2 during 1978 and 1979, but the yield from site 2 was considerably higher than that from site 3 during 1980, 1981, and 1982. This change in behavior apparently resulted from the undercutting of the toe of site 2 in 1980 by Minor Creek and the buttressing of the toe of site 3 by alluvium during 1980, as discussed earlier.

Extrapolation of data collected at sites 2 or 3 in space or time appears difficult. This difficulty arises because annual sediment yields are highly dependent upon the constantly changing mass distribution existing within individual earthflows; therefore, annual sediment yields cannot be completely related to easily measured variables such as annual moisture conditions. The similar maximum recorded yields of 25,100 and 20,380 (Mg/km^2)/yr from sites 2 and 3, respectively (tables 4, 5), may indicate that these figures represent maximum yields to be expected from such features and that annual yields can be expected to range from several hundred to approximately 20,000 Mg/km^2. There are, however, indications that sediment yields greater than those recorded to date may be possible from sites 2 and 3.

Instability may be increasing on lower parts of site 2, and rates in the near future could be higher than those recorded to date. This possibility is indicated by data collected at transverse stake line 3 and at the nearby inclinometer tubes. The volume of material moving past stake line 3 has been estimated by using depth to the basal shear zone, as indicated by inclinometer tube measurements, and the earthflow width and average movement measured at stake line 3. The results of these calculations are shown in table 4. The greatest uncertainty in these calculations is the uniformity of depth to the basal shear zone. Recent data collected at additional inclinometer tube locations (Richard Iverson, U.S. Geological Survey, oral commun., 1983) tend to confirm the depth to the shear zone and to substantiate the validity of the mass flux calculations. These calculations indicate that a greater volume of material is presently passing through the toe of site 2 than is being resupplied from upper regions. Although no data are available on density variations at depth, the volume calculations indicate that a substantial mass imbalance is developing between stake line 3 and the earthflow toe, thus increasing instability. The effect of this instability on movement rates and sediment yields is uncertain. Increasing instability may lead to collapse of lower parts of the earthflow and to consequently higher movement rates and sediment yields. The nature of the developing mass imbalance is illustrated in figure 13.

Similarly, there are signs that sediment yields greater than those yet recorded may be possible from site 3. The morphology of portions of site 3 near transverse stake line 1A indicates that movement rates greater than those measured between 1975 and 1981 had persisted for some time prior to monitoring. Prominent tension cracks, lateral shear zones, and longitudinal ridges that existed in 1975 were gradually eroded and overgrown by vegetation between 1975 and 1981. Movement rates during this period did not exceed 0.12 m/yr. Movement rates at stake line 1A increased markedly in 1982 to a maximum of 1.04 m/yr; this increase indicates a possible return to conditions sufficient to cause the features observed in 1975. Although the effects of more rapid movement at this location on movement at the toe are uncertain, persistence of the higher rates would probably lead to overloading of the toe and higher toe movement rates.

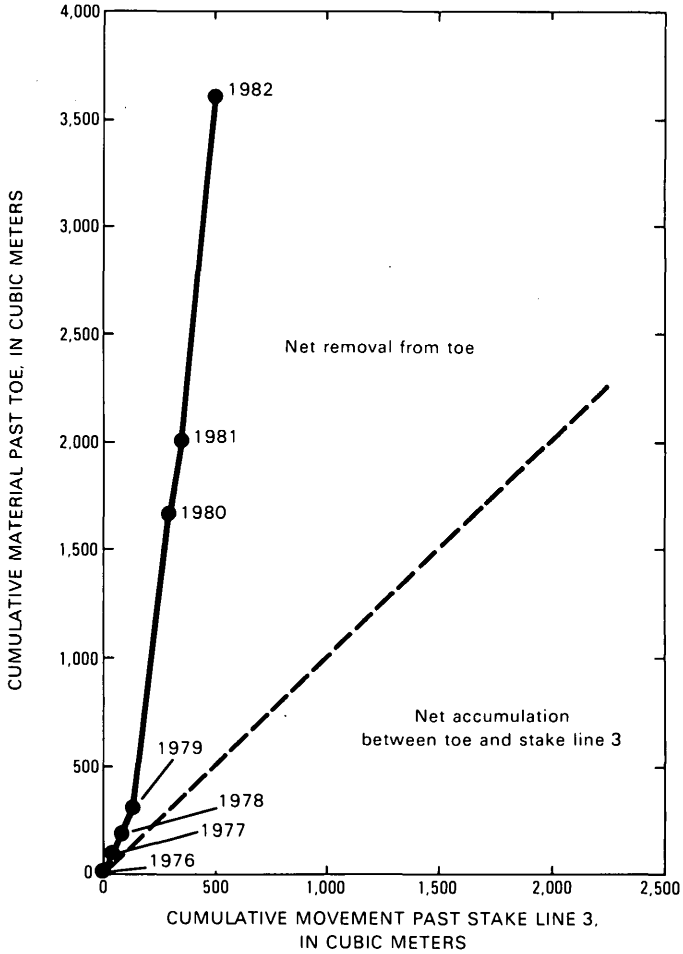


FIGURE 13.—Mass imbalance developing on lower portions of site 2 plotted as cumulative volume of material moved past stake line 3, site 2, versus cumulative volume of material moved past toe of site 2.

CONCLUSIONS

Data collected at study sites 2 and 3 indicate that earthflows are significant sources of sediment having annual sediment yields as much as 18.3 times the basinwide average. Recorded annual yields between 1977 and 1982 ranged from 730 to 25,100 Mg/km^2. Although fluvial processes in gullies on the earthflows delivered up to 80 percent of the sediment during individual years, more than 90 percent of the total sediment delivered between 1979 and 1982 was delivered to adjacent streams by mass-movement processes.

Data from sites 2 and 3, as well as data collected by other workers at earthflows in nearby areas, indicate that earthflow movement rates and sediment yields are highly variable in both space and time. Movement rates and colluvial sediment yields appear to depend upon rock type and upon the constantly changing mass distribution within individual features. From a regional perspective, maximum movement rates and sediment yields are at sites that are the wettest and that are underlain by the most incoherent rocks. Within individual earthflows, maximum movement rates appear to occur when mass imbalances have exceeded stability thresholds. Annual moisture conditions control earthflow movement primarily by influencing the timing of movement and the fluvial sediment yields.

Because of the effects of underlying geology and the complex interaction between mass distribution and annual moisture conditions, extrapolation of movement rates and sediment discharge data as determined at sites 2 and 3 is uncertain, both for other earthflows and for sites 2 and 3 over time. Extrapolation to other features requires consideration of the comparability of underlying geology, climate, or potential effects of constantly changing mass distributions.

The erratic behavior of earthflows at sites 2 and 3 has resulted from a complex relationship between annual moisture conditions and transient mass distributions. Even though absolute rates of movement or sediment yield may differ, the same factors that control movement at these earthflows will control movement at other persistently active earthflows having similar morphology and failure mechanisms.

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Mass Movement in the Redwood Creek Basin, Northwestern California

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

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

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MASS MOVEMENT IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

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ABSTRACT

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

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

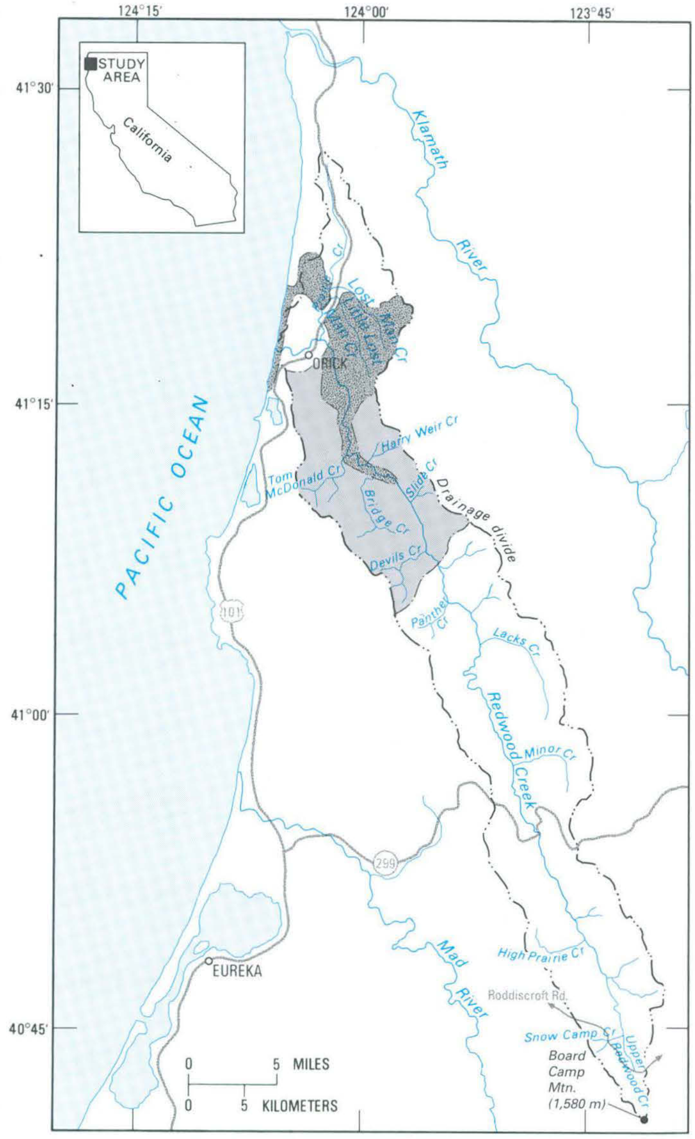
INTRODUCTION

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

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

ACKNOWLEDGMENTS

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



EXPLANATION

REDWOOD NATIONAL PARK

ORIGINAL REDWOOD NATIONAL PARK—1968-77

FIGURE 1.—Redwood Creek basin.

PREVIOUS WORK

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

SETTING

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

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

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

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

TYPES OF MASS MOVEMENT

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

DEBRIS SLIDES

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

DEBRIS AVALANCHES

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

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

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

Category	Percent of basin area above Prairie Creek
Active features:	
Debris slides	1
Debris avalanches	.2
Earthflows[1]	12
Unstable streambanks	3
Total	16.2
Inactive features:	
Old and questionable landslides	10
Amphitheater-shaped basins	5
Total	15

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

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

EARTHFLOWS

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

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

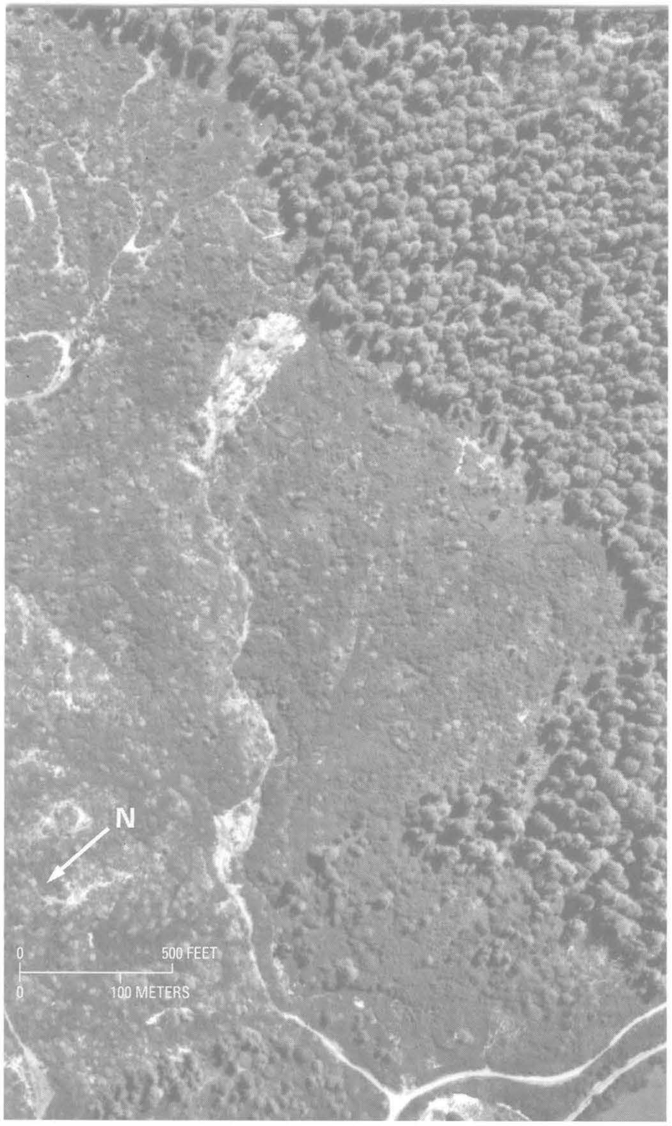


FIGURE 3.—Debris avalanche in the Prairie Creek basin approximately 2 km from the town of Orick.

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

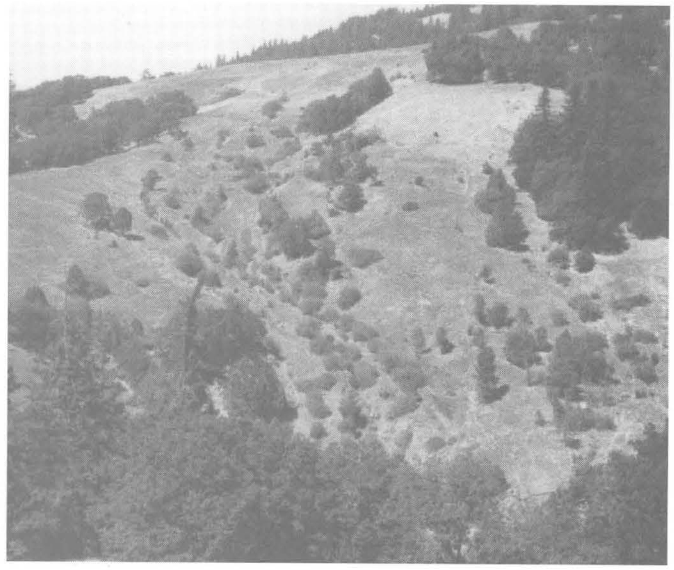


FIGURE 4.—Typical earthflow in the Redwood Creek basin adjacent to the downstream end of Minor Creek. View is toward north; local relief is about 200 m.

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

SLUMPS

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

SOIL CREEP

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

INFLUENCE OF BEDROCK TYPE ON MASS-MOVEMENT PROCESSES

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

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

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

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

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

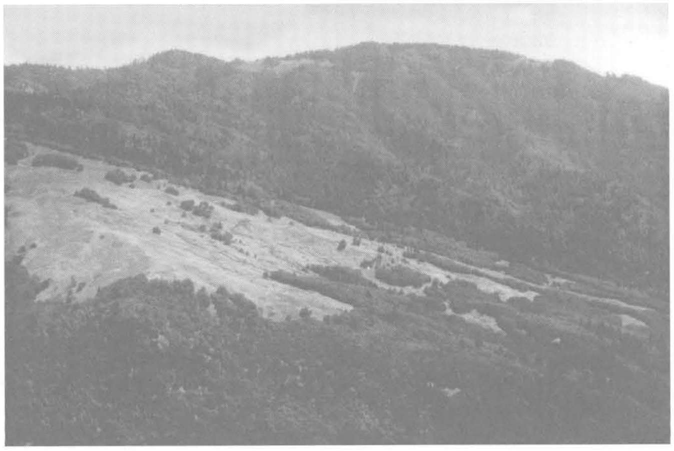


FIGURE 5.—Contrast between earthflow terrain (foreground) and steeper debris-avalanche terrain (background). Area shown is in the Lacks Creek basin. Local relief is about 300 m.

RELATION OF PHYSIOGRAPHY TO MASS MOVEMENT

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

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

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

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

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

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

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

Slope class (gradient in percent)	Total percent of basin area in slope class	Type of mass movement feature: Debris slides and small mass failures	Debris avalanches	Slumps	Active earthflows	Total	Percent features in slope class weighted by basin area in slope class
0–15	8.6	2 (0.5)	1 (1.1)	0 (0)	0 (0)	3 (0.5)	0.1
15–30	35.3	13 (3.6)	3 (3.4)	0 (0)	3 (3.3)	19 (3.5)	.2
30–50	50.2	151 (41.4)	43 (48.3)	4 (57.1)	72 (80.0)	270 (49.0)	1.8
50–70	5.5	120 (32.9)	26 (29.2)	3 (42.9)	8 (8.9)	157 (28.5)	9.5
>70	.4	79 (21.6)	16 (18.0)	0 (0)	7 (7.8)	102 (18.5)	88.4
Total	100	365 (100.0)	89 (100.0)	7 (100.0)	90 (100.0)	551 (100.0)	100.0

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

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

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

RECENT INCREASES IN STREAMSIDE LANDSLIDES

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

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

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

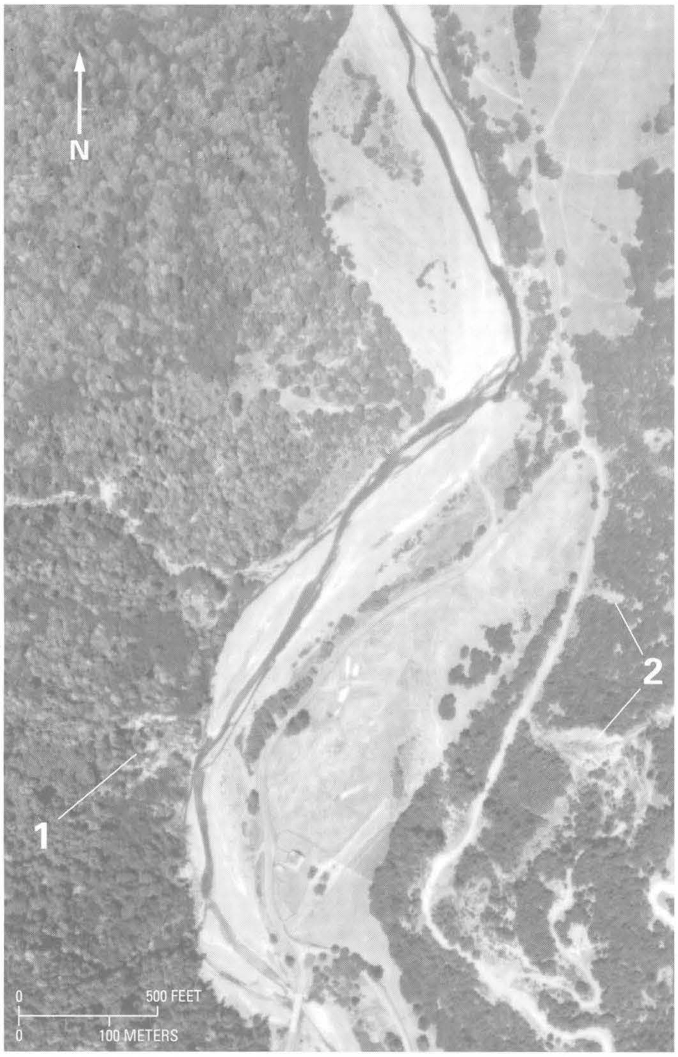


FIGURE 6.—Protective influence of flood plains on streamside hillslopes. Streamside landslides are numerous where Redwood Creek abuts hillslopes directly (1). On opposite bank, landslides (2) are separated from the active channel by a low flood plain. The photograph depicts the main channel of Redwood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

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

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

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

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

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

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

[1] Localities are shown on figure 1.

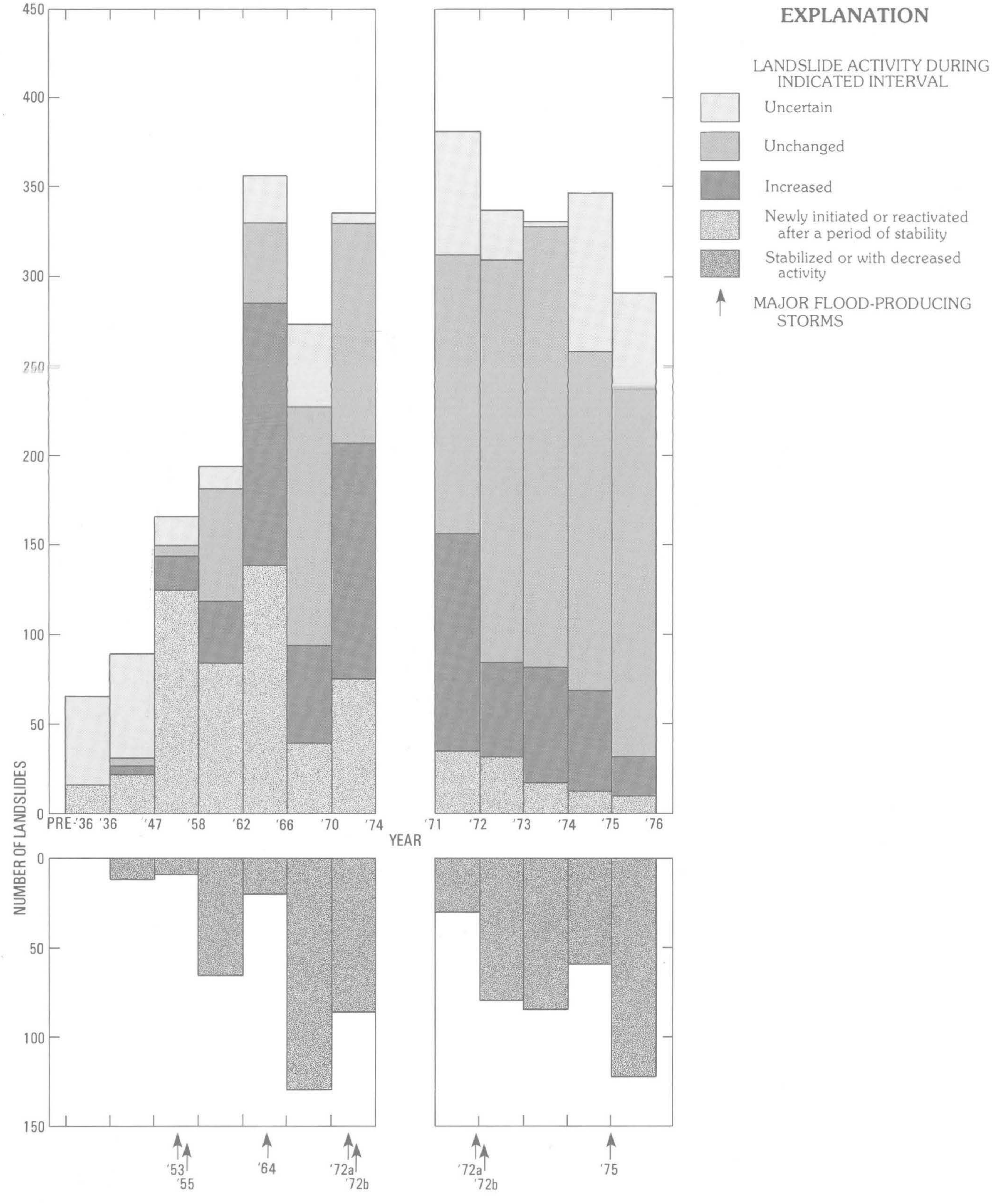


FIGURE 7.—Activity of streamside landslides adjacent to Redwood Creek between Roddiscroft Road and Prairie Creek, 1936–76. Data are based on interpretation of aerial photographs (from Harden and others, 1978). Note that time periods are not even. They represent times of available aerial photography.

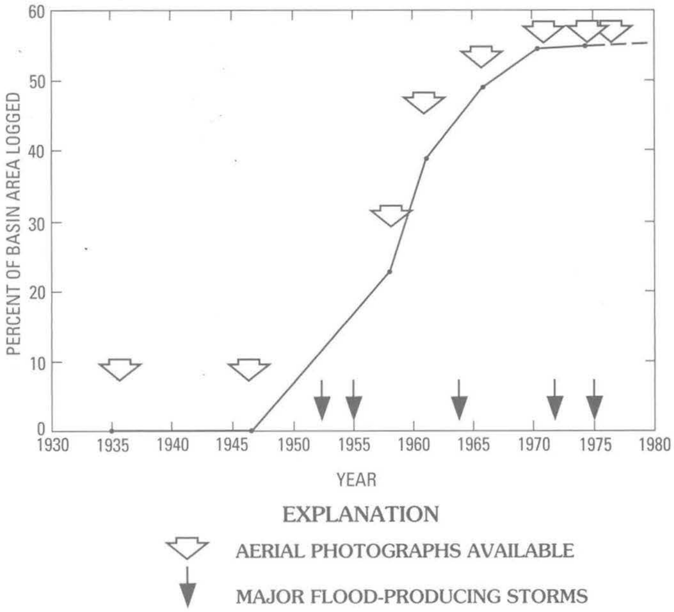
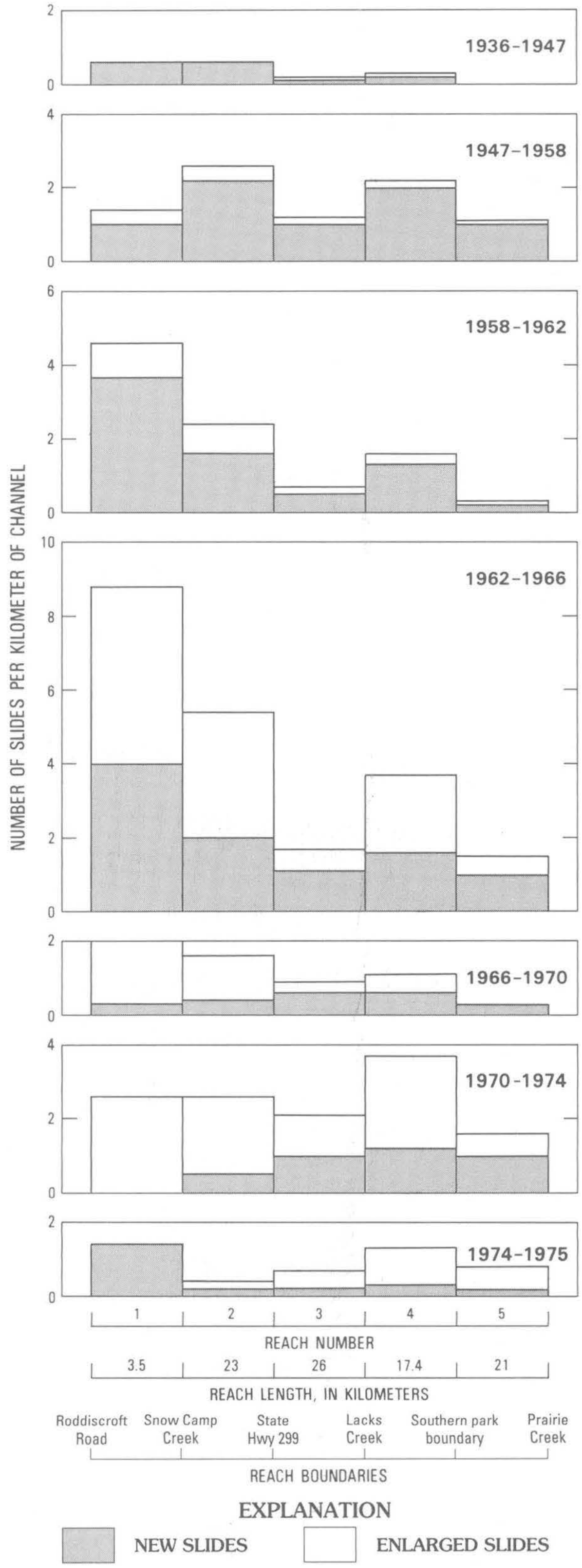


FIGURE 8.—Cumulative percent of Redwood Creek streamside hillslopes logged between 1936 and 1976.

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



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

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

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

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

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

CONTRIBUTION OF TIMBER HARVEST TO STREAMSIDE LANDSLIDES

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

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

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

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

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

SUMMARY

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

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Surface Erosion by Overland Flow in the Redwood Creek Basin, Northwestern California—Effects of Logging and Rock Type

By DONNA C. MARRON, K. MICHAEL NOLAN, *and* RICHARD J. JANDA

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–H

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SURFACE EROSION BY OVERLAND FLOW IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA—EFFECTS OF LOGGING AND ROCK TYPE

By DONNA C. MARRON, K. MICHAEL NOLAN, and RICHARD J. JANDA

ABSTRACT

Ninety sets of erosion-deposition pins were monitored on slopes in the Redwood Creek basin from the summer of 1974 to the summer of 1978. Mean rates of ground-surface lowering were obtained for forested and logged slopes on two bedrock types by adding measurements of erosion and deposition and calculating their arithmetic mean. Erosion and deposition related to the installation of pins caused elevation changes measured during water years 1977 and 1978 to be most representative of elevation changes that occur under forest cover and after logging on the different bedrock types. Measurements for water years 1977 and 1978 indicate that the mean rate of ground-surface lowering was 0.3 mm/yr on forested sandstone slopes, forested schist slopes, and tractor- and cable-yarded sandstone slopes. The mean rate of ground-surface lowering during water years 1977 and 1978 was 1.1 mm/yr on cable-yarded schist slopes and 4.6 mm/yr on tractor-yarded schist slopes.

The data collected in this study indicate that ground-surface lowering due to overland flow on forested sandstone slopes, forested schist slopes, and logged sandstone slopes is minor compared to the modern average rate of ground-surface lowering in the Redwood Creek basin. Ground-surface lowering due to overland flow on logged slopes underlain by schist, however, mobilizes enough sediment to make a significant contribution to Redwood Creek's extremely high modern sediment yield.

INTRODUCTION

Because the Redwood Creek drainage in northwestern California has one of the highest sediment yields in the conterminous United States (Janda and Nolan, 1979; Milliman and Meade, 1983), much attention has been focused both on naturally occurring erosion and deposition processes active within the basin and on the effects of logging on those processes. Although mass-movement features have been identified as major sediment sources in the Redwood Creek drainage basin (Harden and others, 1978), little is known about the movement of soil by overland flow on slopes. Soil moved by such processes as slopewash, rainsplash, and rilling can increase stream sediment yields (Kelsey and others, 1981). In addition, surface soils contain nutrients that affect soil fertility (DeByle and Packer, 1972).

From the summer of 1974 to the summer of 1978, 90 sets of erosion-deposition pins were monitored on slopes in the Redwood Creek basin. Primary objectives of this study were to document rates of erosion and deposition due to overland flow on slope surfaces, to assess the relative importance of different erosion and deposition processes, and to determine differences in rates of erosion and deposition on slope surfaces underlain by different bedrock types and subjected to different logging practices.

The area encompassed by this study is the downstream half of the Redwood Creek watershed (fig. 1). Redwood Creek drains an elongate, northwest-trending, 725-km^2 drainage basin in the Coast Ranges of northwestern California. Average hillslope gradient in the basin is 26 percent (Janda and others, 1975). Over 30 percent of the Redwood Creek drainage contains landforms that reflect former or current mass wasting (Nolan and others, 1976).

A northwest-southeast-trending fault, which is roughly followed by the main channel of Redwood Creek, separates the two principal types of bedrock in the basin (fig. 1) (Harden and others, 1981). Most slopes northeast of the fault are underlain by unmetamorphosed sandstone with interbeds of mudstone and conglomerate. Commonly, these sedimentary rocks are pervasively sheared. Most slopes southwest of the fault are underlain by fine-grained, well-foliated quartz-mica schist.

Within the study area, soils on sandstone slopes commonly belong to the Hugo and Melbourne soil series (Alexander and others, 1959–62). These soils are typi-

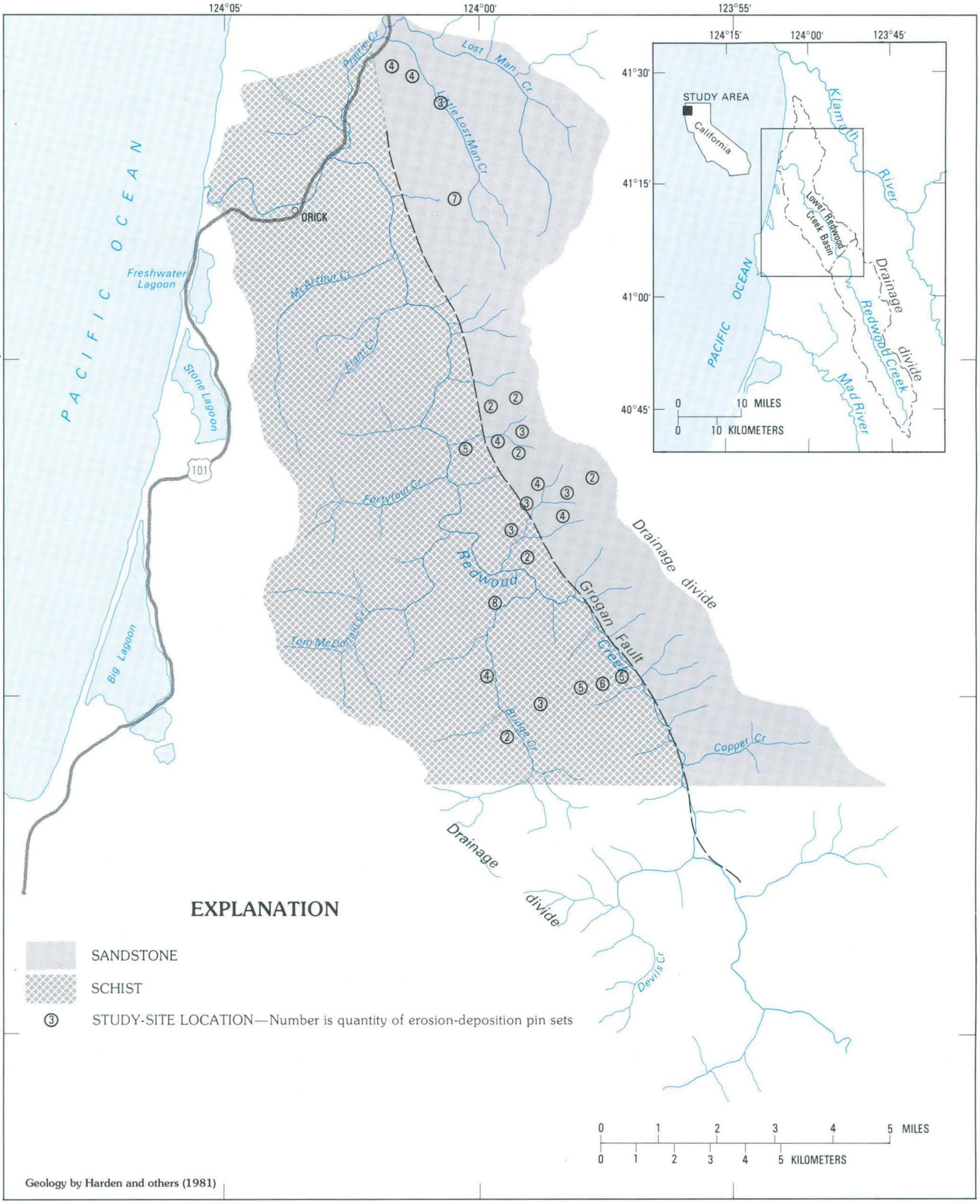

FIGURE 1.—Major bedrock types and study-site locations.

TABLE 1.—*Mean elevation changes and percentages of erosion and deposition attributed to different processes in different land use and bedrock categories*

[Negative mean elevation changes indicate ground-surface lowering. Years refer to water years]

Land use/bedrock category	Number of pin sets	Elevation change (mm) 1975–76		Elevation change (mm) 1977–78		Erosion during 1975–78 (percent)		Deposition[1] during 1975–78 (percent)	
		Mean	Standard deviation	Mean	Standard deviation	Gullying and rilling	Other processes	Shallow sloughing	Other processes
Forested/sandstone	14	−0.2	6.9	−0.6	4.8	5	95	6	94
Logged (tractor-yarded)/sandstone	33	2.1	20.3	−.6	6.2	5	95	17	83
Forested/schist	15	.2	3.9	−.6	5.9	0	100	0	100
Logged (cable-yarded)/schist	17	.3	11.8	−2.2	8.1	33	67	14	86
Logged (tractor-yarded)/schist	13	14.7	33.2	−9.3	14.9	31	69	13	87

[1] Does not include deposition by litterfall.

cally less than 1.25 m thick and have gravelly sandy clay loam to gravelly heavy loam textures (Laacke, 1979). Soils developed on schist commonly belong to the Masterson, Orick, and Sites series (Alexander and others, 1959–62). These soils are typically gravelly clay loams or clays up to 1.8 m thick (Laacke, 1979).

The climate of the Redwood Creek watershed is characterized by mild, wet winters and dry summers. Yearly precipitation ranges from 1,800 to 2,300 mm and occurs almost exclusively from October to June. Rainfall during the study period was average or below average. Annual precipitation in the town of Orick near the mouth of Redwood Creek was 1,810, 1,440, 960, and 1,740 mm for water years 1975 through 1978, respectively (National Oceanic and Atmospheric Administration, 1974–78). The study period included a flood-producing storm in March 1975.

More than 65 percent of the Redwood Creek basin has been logged, mostly within the last 25 years (Harden and others, 1978). Timber was removed by using tractor-yarding and cable-yarding methods. On tractor-yarded slopes, logs are dragged to landings by tractors along tractor-constructed trails, whereas on cable-yarded slopes, logs are dragged or carried to landings by cables. Cable-yarding generally causes less soil disturbance and less compaction than tractor-yarding (Huffman, 1977).

Forested slopes in the study area are dominated by redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), and dense understory vegetation commonly including oxalis (*Oxalis oregana*), sword fern (*Polystichum munitem*), and rhododendron (*Rhododendron macrophyllum*). Following logging, herbaceous vegetation dominates for approximately 5 years, after which shrubs become dominant (Muldavin and others, 1981). Plants that commonly grow in the bare soil exposed by logging include sword fern, oxalis, salal (*Gaultheria shallon*), rhododendron (*Rhododendron macrophyllum*), blueblossom (*Ceanothus thrysiflorus*), coyote brush (*Baccharis pilularis*), whipplea (*Whipplea modesta*), alder (*Alnus oregana*), tan oak (*Lithocarpus densiflora*), and Douglas-fir.

METHODS OF STUDY

Sites for erosion-deposition pin sets were selected on the basis of bedrock type and land use. Sets of pins were located on logged and forested slopes in both sandstone and schist terranes. Logged sites on schist included tractor-yarded and cable-yarded areas. Only tractor-yarded areas were available on sandstone slopes. At all logged sites, logging had been conducted within 5 years of the first measurement. Slope gradients of the study sites were mostly between 15 and 35 percent. A range of slope aspects was sampled.

Each pin set consisted of nine pins spaced 3 m apart. Each pin consisted of a 0.75-m length of 6.4-mm-diameter iron reinforcing bar that was pounded approximately halfway into the ground. Five pins extended along the slope contour. The remaining four pins were placed upslope and downslope of the second and fourth pins of the transverse line of five. Nine percent of the pins that were installed in 1974 were disturbed or destroyed between 1974 and 1978. The pins were measured during the summers of 1974, 1976, and 1978 by placing a 70-mm-diameter template on the ground surface and measuring the distance to the top of the pin. Measurements taken on the uphill and downhill sides of each pin were averaged. Repeated measurements of single pins showed an average difference of 2.0 mm between the individual measurements and their average. In 1976, the sites were inspected for signs of erosion by rilling and gullying and for signs of deposition by litterfall and shallow sloughing of surficial materials.

The study period was divided into two parts to deemphasize elevation changes related to the installation and initial presence of the pins. Means and standard deviations of elevation changes observed at the pins in each land use and bedrock category during the first 2 and the last 2 years of the study (table 1) were calculated by using equations for clustered sampling populations (Snedecor and Cochran, 1967, p. 513–515). Deposition attributed solely to litterfall was not considered an elevation change in these calculations because litterfall does not reflect the movement of soil and rock material. Mean

TABLE 2.—*Probabilities of statistically significant difference between mean elevation changes during water years 1977 and 1978 in different land use and bedrock categories*

[The significance of the difference between means was calculated by using a two-sample *t* test]

Land use/bedrock categories to be compared		Probability of significant difference (percent)
I	II	
Forested/sandstone	Logged (tractor-yarded)/ sandstone	Less than 50
Forested/sandstone	Forested/schist	Less than 50
Forested/schist	Logged (cable-yarded)/ schist	Less than 50
Forested/schist	Logged (tractor-yarded)/ schist	93
Logged (cable-yarded)/schist	Logged (tractor-yarded)/ schist	86

elevation changes indicate the average net thickness of surficial material removed from or added to different slope surfaces. The statistical significance of differences between means was established by using a two-sample *t* test (table 2).

Percentages of erosion measured during water years 1975 through 1978 that were attributed to rilling and gullying were calculated for each land use and bedrock category by dividing the amounts of erosion shown by pins in rills and gullies by the total amounts of erosion measured (table 1). Percentages of deposition measured during water years 1975 through 1978 that were attributed to shallow sloughing were calculated for each land use and bedrock category by dividing the amount of deposition shown by pins surrounded by slough material by the total amounts of deposition attributed to processes other than litterfall.

VARIATIONS IN SURFACE EROSION DURING THE STUDY PERIOD

Mean elevation changes measured during the first half of the study period differ from those measured during the second half in all land use and bedrock categories, although some of these differences are not statistically significant owing to large standard deviations of the elevation changes. Generally, there is a trend toward more erosion relative to deposition during the second half of the study period. The standard deviations of all categories were smaller during the second half of the study period than during the first half. Field observations in 1976 revealed accumulations of soil behind some of the erosion-deposition pins. Accumulations of soil also were observed behind small pieces of organic debris that were caught on pins. These types of deposition, which are related to the installation of the pins, were most prevalent during the years immediately following pin installation and probably account for the marked contrast between net deposition during the first half of the study period and net erosion during the second half of the study period in most of the land use and bedrock categories. The higher standard deviations of elevation changes in water years 1975 and 1976 relative to water years 1977 and 1978 may also reflect soil deposition behind pins in the years immediately following pin installation. In addition, the December 1975 storm may have contributed to those high standard deviations by causing considerable soil mobility during the first half of the study period. In recognition of the problem of deposition behind pins in the years immediately following pin installation, elevation changes measured during water years 1977 and 1978 are considered most representative of elevation changes that typically occur in different land use and bedrock categories.

SURFACE EROSION ON FORESTED SLOPES

Data collected on forested slopes indicate that, under natural conditions, ground-surface lowering due to overland flow takes place at similar rates on sandstone and on schist slopes. There was slightly more evidence of erosion by rilling and gullying, and of deposition by shallow sloughing of surficial materials, on forested sandstone slopes than on forested schist slopes during water years 1975 through 1978 (table 1). For both forested sandstone and forested schist slopes, gradient apparently had no effect on either erosion or deposition.

EFFECTS OF LOGGING ON SURFACE EROSION

Rates of ground-surface lowering were similar on logged and on forested sandstone slopes during water years 1977 and 1978 (table 1). In contrast, greater rates of ground-surface lowering were measured on cable-yarded and particularly on tractor-yarded schist slopes than on forested schist slopes during the same period. Differences in mean elevation changes during water years 1977 and 1978 on schist slopes in the different land use categories are statistically significant despite large standard deviations (tables 1, 2). Greater elevation changes on the logged schist slopes were due, at least in part, to mobilization by gullying and rilling of a larger quantity of soil on those slopes (table 1). Significant relations between either erosion or deposition and slope gradient were not apparent in the data collected on logged sandstone and schist slopes.

Rates of ground-surface lowering on schist slopes subjected to logging were higher than on forested schist slopes, probably because of the compaction of surficial materials and the exposure of bare soil. Increases in overland flow result from compaction and from the removal of forest litter, which is more permeable than the soil below it (DeByle and Packer, 1972). The removal of vegetation and litter increases the vulnerability of soils to detachment and transport by rainsplash and overland flow (Rice and others, 1972). In addition, depressions created during logging can concentrate runoff and promote rill and gully erosion on logged slopes. The greater degree of ground disturbance associated with tractor-yarding, as opposed to cable-yarding (Huffman, 1977), may be responsible for the greater ground-surface-lowering rates on tractor-yarded than on cable-yarded schist slopes.

Several factors may cause logging to have more of an effect on surface erosion of schist slopes than of sandstone slopes. Schist soils are more susceptible to surface erosion than soils developed on sandstone in the Redwood Creek drainage because the schist soils have a lower sand content, a higher percentage of silt and clay, blockier structure, and lower permeability (Marron, 1982). All these characteristics lead to larger values of the commonly used soil-erodibility factor K, as determined by using nomographs developed by Wischmeier and others (1971). These erodibility characteristics may not be significant under forest cover, where soils are held by roots and protected by litter, but may gain importance following the disruption and exposure of soils by logging.

The response of the different soil types to burning and (or) exposure to ash leachate also may cause greater postlogging surface erosion on schist than on sandstone slopes. Approximately half of the pin sets on both logged sandstone and logged schist slopes were on sites that had been burned after logging. Experiments by Durgin (1981) showed that both burning and the mixing of soils with ash leachate cause greater increases in the dispersion ratio of Sites soils, which commonly develop on schist in the study area, than of Hugo soils, which commonly develop on sandstone in the study area. Dispersed soils are more susceptible to transport by overland flow because they are more easily suspended in running water (Mitchell, 1976, p. 218–219). Durgin (1981) attributed the greater increases in dispersion ratios of the schist soils to their greater capacity for anion exchange.

IMPORTANCE OF SURFACE EROSION DUE TO OVERLAND FLOW

Measured rates of surface erosion help to quantify the degree to which sediment removed from slopes by overland flow contributes to the extremely high modern sediment yield of Redwood Creek. Measured rates of ground-surface lowering presented here are approximate owing to the high standard deviations of elevation changes (table 1) and the effects of the presence of vegetation and organic litter at certain study sites. The measured changes may overestimate soil removal because some of the measured lowering of ground surfaces may have resulted from the removal of vegetation and organic litter, rather than the removal of soil, by running water. This latter problem applies particularly to forested slopes, where approximately 80 percent of the measurements that showed erosion during water years 1977 and 1978 were made on vegetation or organic litter. In comparison, only 20 to 30 percent of measurements showing erosion during water years 1977 and 1978 on logged slopes were made on vegetation or organic litter.

Measurements made at erosion-deposition pins on forested slopes indicated a mean ground-surface lowering rate of −0.6 mm from the summer of 1976 to the summer of 1978. When divided by 2 to get a yearly rate, this value constitutes approximately 14 percent of the 2.1-mm/yr mean rate of ground-surface lowering in the Redwood Creek basin estimated by Janda and others (1975) by using recently measured sediment yields. The actual amount of soil transported to streams by surficial processes on the forested slopes is probably much less, considering the high percentage of measurements showing erosion that were made on vegetation and organic litter.

Measurements made at erosion-deposition pins on logged sandstone slopes also yielded a mean rate of ground-surface lowering that is small in relation to Janda and others' (1975) estimate of the modern mean rate of basinwide ground-surface lowering. Measurements at pins on cable-yarded schist slopes yielded a mean lowering rate that is approximately one-half of the basinwide mean. In contrast, the mean yearly rate of ground-surface lowering measured on tractor-yarded schist slopes is approximately twice the basinwide mean, which suggests that erosion by surficial processes on these slopes may be making a significant contribution to the modern sediment yield of Redwood Creek. For example, if one-quarter of the 19 percent of the Redwood Creek watershed that was logged between 1967 and 1978 (chap. C, this volume) consists of tractor-yarded schist slopes, then surficial erosion on these slopes may supply as much as 22 percent of the modern sediment yield of the creek.

CONCLUSIONS

Data from 90 sets of erosion-deposition pins monitored in the lower part of the Redwood Creek drainage basin between the summers of 1974 and 1978 show that rates of ground-surface lowering due to overland flow are related to land use and bedrock type. Measurements of elevation changes during the second half of the study period are considered more useful than measurements of elevation changes during the first half of the study period because the later measurements appear less influenced by erosion and deposition specifically related to the presence of pins.

Data collected on forested slopes indicate that ground-surface lowering due to overland flow is similar on forested slopes underlain by sandstone and by schist. Comparisons of data from logged and forested slopes indicate that schist slopes are more susceptible than sandstone slopes to logging-related increases in surface erosion due to overland flow. On the schist slopes, tractor-yarding was associated with greater surface erosion than cable-yarding. Both types of logging were associated with a greater degree of erosion by rilling and gullying on slopes underlain by schist. Mean rates of ground-surface lowering on forested sandstone, forested schist, and logged sandstone slopes are small in comparison to Janda and others' (1975) estimate of the modern, mean, basinwide rate of soil removal. Mean rates of ground-surface lowering measured on cable-yarded and particularly on tractor-yarded schist slopes, however, indicate that surficial erosion on these slopes may make a significant contribution to the extremely high modern sediment yield of Redwood Creek.

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Magnitude and Causes of Gully Erosion in the Lower Redwood Creek Basin, Northwestern California

By WILLIAM E. WEAVER, DANNY K. HAGANS, *and* JAMES H. POPENOE

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

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MAGNITUDE AND CAUSES OF GULLY EROSION IN THE LOWER REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

By William E. Weaver,[1] Danny K. Hagans,[1] and James H. Popenoe[2]

ABSTRACT

Gullying was found to be a major process of erosion on roaded prairies and logged lands in the 197-km^2 lower Redwood Creek basin. Detailed mapping of over 2,200 hectares of disturbed terrain revealed that 90 percent of the 329,500 m^3 of measured gully erosion on nine study sites was caused by the diversion of first-order and second-order streams. Plugged culverts, failure to install culverts at logging-road stream crossings, and bulldozing of soil and logging slash into shallow hillslope stream channels were the leading causes of stream diversions and consequent gullying.

On all study sites, logging and related practices and the degree of ground disturbance were similar, yet gully yields were highly variable. The highest amounts of postharvest gully erosion were typically associated with lengthy, unmaintained logging road systems in areas underlain by incoherent bedrock and soils low in clay or in rock fragments. In contrast, thin rocky soils or thicker soils having high clay content tended to retard gully development. Although land use, geology, and soils controlled the susceptibility of a site to gullying, areas that had not had a major rainfall and runoff event (recurrence of 10 to 12 years, or more) since logging showed very little gully erosion.

Most gully erosion from areas of similar land use occurred in certain high-yield terrain types, of restricted areal extent, which were characterized by thick, erodible soils. In the lower Redwood Creek basin, these terrains occupy 31 percent of the roaded prairies and tractor-logged land and have contributed an estimated 70 percent of the total volume of material eroded by gullies. In contrast, 16 percent of the lower basin area, making up the low yield category, was estimated to account for less than 1 percent of the total volume of soil eroded by gullies. Fluvial sediment production from rills and gullies on steep, logged, or roaded terrain similar to that of the lower Redwood Creek basin may be reliably estimated by (1) limiting sediment source inventories to gullies produced by stream diversions at logging road and skid-trail stream crossings and (2) restricting actual field measurements to the largest gullies. Small gullies, those 0.1 to 1.1 m^2 in cross-sectional area, were numerous on study sites but relatively unimportant as contributors to sediment production. They made up nearly 60 percent of the cumulative 76 km of gullies measured but yielded only 6 percent of the recorded volume of eroded soil. In contrast, gullies larger than 4.5 m^2 in cross-sectional area were the source of over 80 percent of the sediment production, yet they constituted less than 25 percent of the gully network by length.

Gully erosion in the lower Redwood Creek basin is estimated to account for 25 percent less sediment production than streamside landsliding over the last three decades. Careful land management practices and preventive erosion control following logging and related activities could have eliminated approximately 85 percent of the gully erosion through improved road construction, road maintenance, and road abandonment practices.

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INTRODUCTION

A significant problem commonly associated with timber harvesting and road building in mountainous terrain is increased rates of soil erosion and sediment yield (Anderson, 1979; Kelsey, 1980; Swanson, 1981). Few places in North America display this more graphically than the Redwood Creek basin where physiographic, geologic, and climatic factors, together with certain land use patterns, have contributed to exceptionally high rates of erosion (Janda and others, 1975). For example, during 6 years of record beginning in 1971, Redwood Creek at Orick, Calif., transported a mean annual suspended sediment load of 2,619 mg/km^2, 32 percent higher than the Eel River at Scotia, Calif. (Janda, 1978), which has been characterized as the most rapidly eroding, nonglaciated basin of comparable size in North America (Brown and Ritter, 1969). Although Redwood Creek's suspended sediment discharge has been estimated to be 8.6 times greater than the expected normal rate of delivery (Anderson, 1979), synoptic storm sampling indicates that some tributary basins displaying severe ground disruption from recent timber harvesting have yielded as much as 17 times the suspended sediment, per unit area, as nearby unharvested basins (chap. L, this volume).

As a result of a congressionally authorized watershed rehabilitation program in the lower Redwood Creek basin (fig. 1), cutover forested areas and prairie grasslands have been studied to locate active and potential sources of erosion for eventual erosion control. To achieve this, Redwood National Park geologists have completed detailed erosional inventories and geomorphic maps, at a scale of 1:1,200, on approximately 4,000 hectares (ha) of logged land within the lower one-third of the Redwood Creek basin. This mapping, which began in 1978, has included both the location and dimension of hillslope gullies, landslides, enlarged natural stream channels, and a variety of other erosional features.

Fluvial erosion on cutover lands in the Redwood Creek basin has been significantly increased in relation to erosion under undisturbed conditions, probably to a greater degree than erosion from mass-movement processes (Janda and others, 1975). Nolan and others (1976) noted an increase in the basinwide abundance of gullies from 1947 to 1974. In addition, preliminary data from sediment budget studies suggest that fluvial erosion from hillslopes contributed nearly 70 percent of the sediment input to the upper 175 km^2 of the Redwood Creek basin between 1956 and 1980 (Kelsey and others, 1981). Locally intense gully erosion has also been recorded in several tributary basins (Weaver and others, 1981; chap. M, this volume).

Gullies have been qualitatively defined as distinct, narrow channels that are larger and deeper than rills and that usually carry water only during or after storms or snowmelt (Bates and Jackson, 1980). Considerable effort has been expended to study gully formation and growth (Leopold and Miller, 1956; Schumm and Hadley, 1957; Graf, 1979) and gully control (Ramser, 1932; Heede, 1976, 1978). However, the magnitude of steepland gully erosion and the extent to which various causes of gullying on logged or roaded hillslopes have contributed to elevated sediment yields have not been closely analyzed elsewhere in the literature. Because gullies are widely spaced on the landscape, sediment yields from fluvial hillslope erosion in large mountainous drainage basins have been difficult to determine quantitatively. As a result, sediment budget studies have typically left fluvial erosion as the unmeasured, least well defined term in the budget equation (Kelsey, 1980).

To help reveal the importance of fluvial erosion on logged land, a study was designed to determine the magnitude and causes of gully erosion on selected areas in the lower Redwood Creek basin. For this investigation, gullies were defined as newly formed channels greater than 0.1 m^2 in cross-sectional area. Specific objectives of the study were (1) to quantify the magnitude of gully erosion on a variety of sites where detailed geomorphic mapping had previously been completed, (2) to identify those land use and site variables most responsible for causing the formation of hillslope gullies, and (3) to suggest simplified sampling procedures, based on an analysis of the identified causes and magnitude of gully erosion, which could aid in quantifying fluvial hillslope erosion in large cutover drainage basins elsewhere. Study areas were not specifically selected to be representative of other portions of the Redwood Creek basin. However, as described below, inventoried sites were not atypical either in pedologic and geomorphic conditions or in the style and intensity of land use disturbances.

Results of this investigation indicate that gully formation promoted by land use practices is a principal cause of soil erosion from roaded and tractor-logged hillslopes. Because most gullies are caused by stream diversions, improved logging, road construction, and road maintenance practices could have greatly reduced postharvest fluvial erosion. In addition, several site factors, including both land use and natural variables, were found to exert strong control on the dimensions and volumetric contribution of gully systems on cutover terrain within the study areas.

STUDY SITES

GEOLOGY AND SOILS

Throughout most of the lower watershed, Redwood Creek follows the trace of the Grogan fault, a major geologic structure that divides the basin into two different terranes. Three of the study sites, constituting 805 ha situated west of the fault (fig. 1), are underlain by intensely sheared, well-foliated, mica-quartz-feldspar schist of the Franciscan assemblage of Late Jurassic to Cretaceous age (Harden and others, 1981); these sites generally have steeper hillslopes, a more clay-rich soil, and a higher drainage density than areas on the east slope. In contrast, the remaining six study sites, encom-

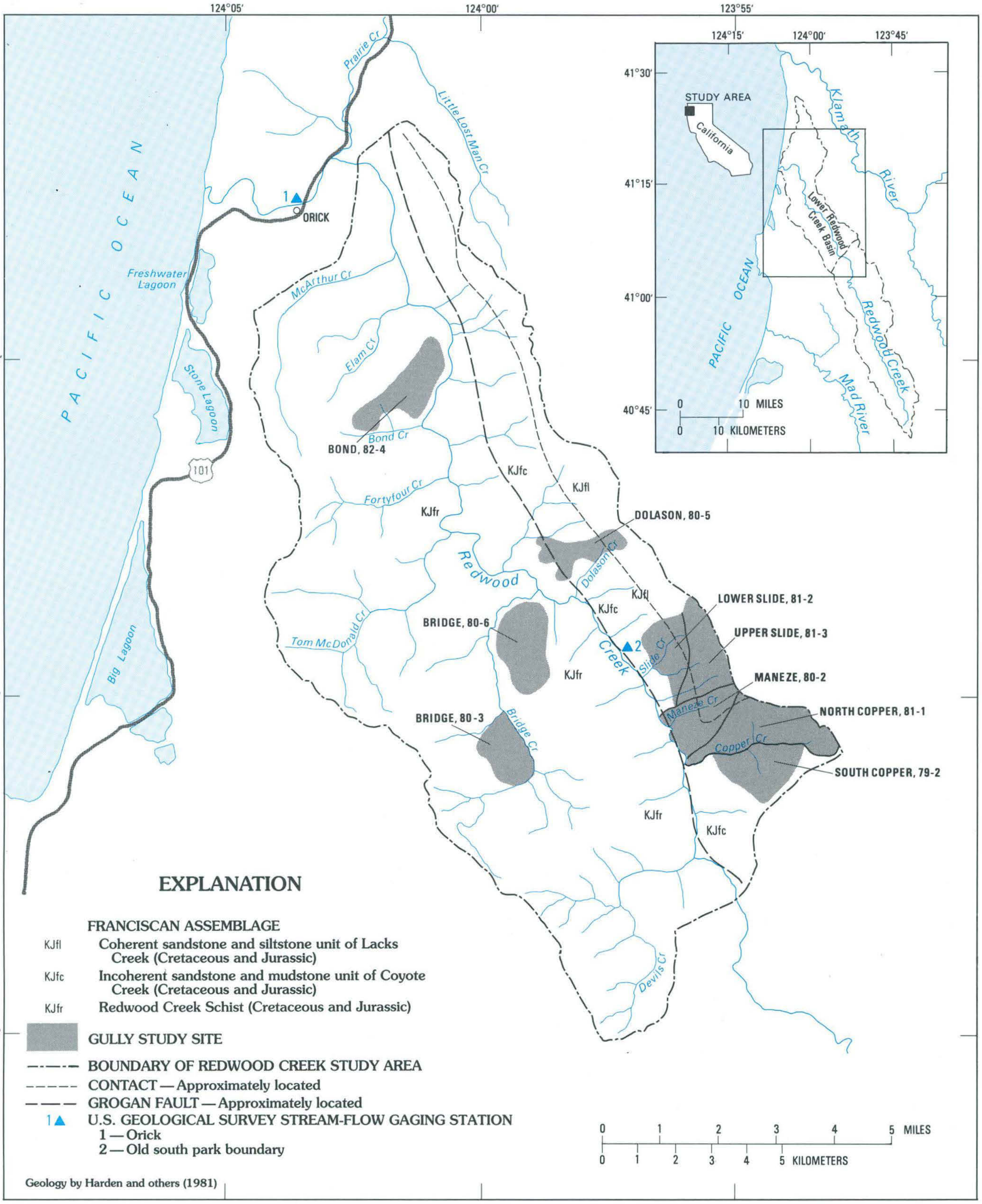


FIGURE 1.—Lower Redwood Creek basin, nine study sites (shaded areas), and generalized bedrock geology. For this study, the lower Redwood Creek basin encompasses all lands within the Redwood Creek unit of Redwood National Park, excluding the Prairie Creek drainage basin and areas downstream from the confluence of Prairie Creek and Redwood Creek.

TABLE 1.—*Classification of principal soils in the lower Redwood Creek basin*

[From Popenoe and Lewis (1983, unpublished). These newly proposed soil names have not yet been approved or reserved by the National Cooperative Soil Survey]

Soil order	Subgroup	Family description	Proposed soil name
Alfisol	Typic Tropudalfs	Fine, mixed, isomesic	Atwell.
Inceptisols	Typic Humitropepts	Loamy-skeletal, mixed, isomesic	Lack, Slidecreek.
Do.	....do....	Fine loamy, mixed, isomesic	Coppercreek, Devilscreek.
Ultisols	Typic Tropohumults	Clayey, oxidic, isomesic	Fortyfour.
Do.	Orthoxic Tropohumults	Clayey, oxidic, isomesic	Trailhead.

TABLE 2.—*Setting and characteristics of principal soils in the lower Redwood Creek basin*

[From Popenoe and Lewis (1983, unpublished) and Harden and others (1981)]

Soil name	Bedrock characteristics	Slope gradient (percent)	Slope morphology	Depth to bedrock contact (cm)	Clay content by horizon (percent)		Rock fragment content by horizon[1] (percent)	
					A	B	A	B
Trailhead	Coherent schist	10–50	Broad ridges, uniform upper slopes.	>150	28–36	40–60	1–25	1–20
Fortyfour	Coherent schist	10–50	Rounded upper slopes and ridges.	50–100	28–32	38–48	10–35	10–35
Devilscreek	Sheared schist	30–70	Steep, uniform to concave slopes.	>150	25–32	27–35	15–35	5–35
Lack	Massive sandstones, mudstones, and coherent schist.	30–75	Steep or strongly convex slopes.	50–100	20–30	24–32	10–45	35–75
Coppercreek	Sheared mudstones, sandstones, and schist.	15–70	Moderate to steep slopes	100–>150	20–30	27–35	1–35	10–35
Slidecreek	Massive sandstone, mudstones	30–75	....do....	>100	20–28	27–35	15–75	5–60
Atwell	Sheared shales, sandstones	15–50	Moderate, concave irregular slopes.	>150	27–32	35–50	2–25	5–35

[1] Gravel- and cobble-sized rock fragments.

passing 1,409 ha east of the Grogan fault, are underlain primarily by unmetamorphosed, pervasively sheared and folded sandstones and siltstones of the Coherent unit of Lacks Creek and the Incoherent unit of Coyote Creek, two units of the Franciscan assemblage (Harden and others, 1981).

Lower hillslope positions, which are underlain by the more brecciated, sheared, and argillaceous rocks of the Incoherent unit of Coyote Creek, have a rolling, subdued topography similar to that formed elsewhere in north coastal California on Franciscan mélange. Drainage networks are less deeply incised than those formed on the coherent unit. In contrast, much of the upper half of the hillslopes east of the Grogan fault is underlain by more resistant sandstone and mudstone turbidite sequences of the Coherent unit of Lacks Creek. Here, hillslopes are steeper and straighter, and major tributary drainages are confined to incised V-shaped canyons.

Differing bedrock lithologies and weathering stages have resulted in the development of several different soil units on study sites in the lower Redwood Creek basin. Durgin and Tackett (1982) used observations made during the original soil surveys (Alexander and others, 1962) together with several quantitative erosion indexes to evaluate the relative erodibility of soils found within the study sites. These evaluations do not indicate a unique relationship between observed erodibility and erosion indexes derived from laboratory analyses of the various soils. Therefore, susceptibility to erosion was inferred to be dependent on such factors as hillslope gradient, soil disturbance, and other site characteristics (Durgin and Tackett, 1982). More recent, detailed remapping, description, and classification of soils within the study sites (table 1) have been initiated by Popenoe and Lewis (National Park Service, unpub. reports, 1983). As will be described in a later section, new data on the distribution and properties of soils specifically found within the lower Redwood Creek area provide useful correlations with erosion rates and gully dimensions as measured at the nine study sites evaluated in this paper.

Five major soil series that developed on the schist of Redwood Creek (Redwood Creek schist) of the Franciscan assemblage have been identified and named (table 2); these soil series occur on study sites west of the Grogan fault. The Trailhead and Fortyfour soils occur together on upper to middle slopes having gradients in the range of 10 to 50 percent. These are well-drained Ultisols whose red-clay argillic horizons are high in iron oxides and gibbsite. The Coppercreek and Lack soils occur together mostly on middle slope positions. These are well-drained Inceptisols having yellowish-brown, gravelly clay loam cambic horizons and mixed clay mineralogy. The poorly to moderately drained Devilscreek soils occur in hillslope hollows and near drainages, primarily on the lower slope positions.

Four major soil series that developed on the Coherent unit of Lacks Creek and the Incoherent unit of Coyote Creek, two units of the Franciscan assemblage, have been identified (table 2); these soil series occur on study sites east of the Grogan fault. Soil patterns are influenced by variation in relief and bedrock lithology. Relief is generally higher and steeper on the coherent sedimentary units. On the whole, soils formed on the sandstone turbidites of the Coherent unit of Lacks Creek (Harden and others, 1981) are thinner and have higher concentrations of rock fragments than soils formed on the Incoherent Coyote Creek mudstones. The Lack, Slidecreek, and Coppercreek soils occur on the Coherent unit of Lacks Creek. These are all well-drained Inceptisols. Coppercreek and Atwell soils predominate on the Incoherent unit of Coyote Creek. The Atwell soils are most common in drainage amphitheaters, which exhibit high drainage density and areas of slope instability. Atwell soils are poorly to moderately drained Alfisols having gray, mottled clay argillic horizons.

LAND USE AND STORMS

Most of the study sites on the east side of the basin are dominated by conifer forests. However, four of the six sites on the east side contain grasslands and oak woodlands ranging from 31 to 66 percent of their upland areas. For example, prior to timber harvesting, 59 percent (445 ha) of the Copper Creek drainage was covered with a conifer forest dominated by coastal redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*). The remainder of the basin consisted of Oregon White oak (*Quercus guarryana*) woodlands on the middle and upper slopes and prairie grasslands along the ridgetop areas. In contrast, two other sites east of the Grogan fault and all three study sites west of the fault consist entirely of cutover coniferous forests.

With the exception of several small, cable-yarded areas on four of the study sites, all of the logging on each site was done by tractors. Felled trees were yarded downhill to the nearest logging road and loaded on trucks. In the process, yarding tractors constructed a network of interconnecting skid trails that crossed nearly every hillslope stream channel at frequent intervals (fig. 2). Typically, upon completion of clearcut operations, from 80 to 85 percent of the total ground surface had been disrupted, and roughly 40 percent of the site was covered by areas of severe ground disturbance; the disturbances included roads, landings, and skid trails (Janda and others, 1975).

The effect is a nearly total disruption of the microtopographic features of the site and obliteration of all but the major channels of the original drainage network. Compacted areas (roads, trails, and landings) promote rapid surface runoff during winter storms, and diverted streams find new paths over the disrupted landscape (fig. 3).

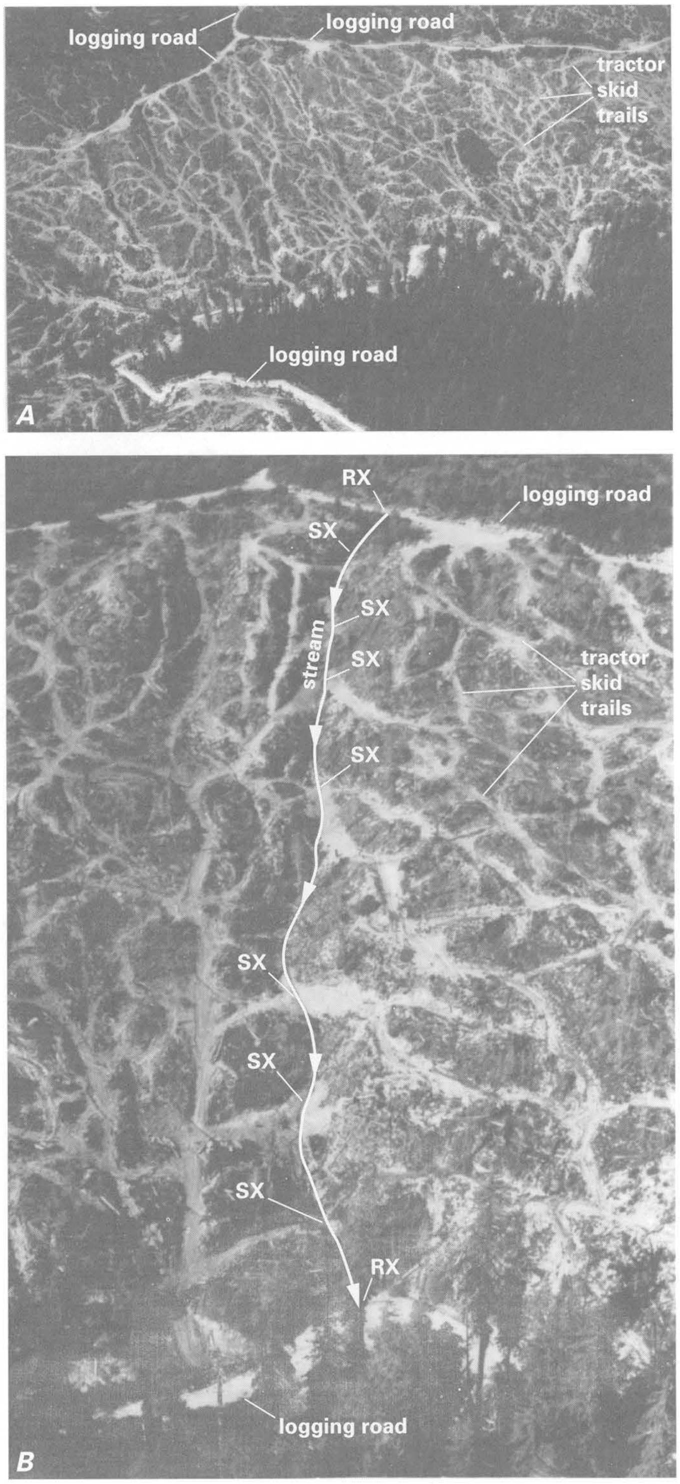


FIGURE 2.—Oblique aerial photographs of a portion of the Bond Creek study site (82–4). *A*, Top photograph taken in 1978, shows intricate web of tractor skid trails and associated haul roads on hillslope that was clearcut in 1975 and 1976. Areas between trails had already begun to revegetate. In contrast, the area at top of photograph was last logged in 1970. Old-growth forests remain at the base of the hill. *B*, Lower photograph shows two road crossings (RX) and at least seven skid-trail crossings (SX) of the intermittent stream that flows from top-center to bottom-center of the photographs.

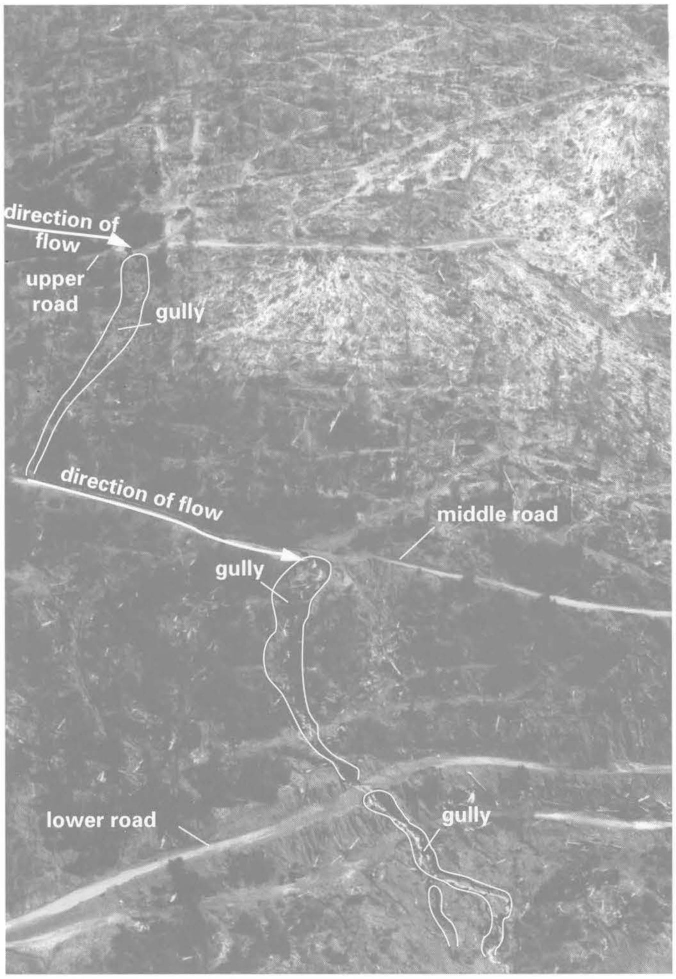


FIGURE 3.—Oblique aerial photograph of a roaded, clearcut hillslope in the lower Redwood Creek basin. Lack of culverts on the upper road resulted in large gully that extended from the end of switchback down to the middle road. The lack of a culvert at the stream crossing on the middle road caused diversion of flow down the ditch and across a road prism near center of the photograph, creating a large, visible gully extending down to and across the lower road system. Photograph was taken soon after the March 1972 storm.

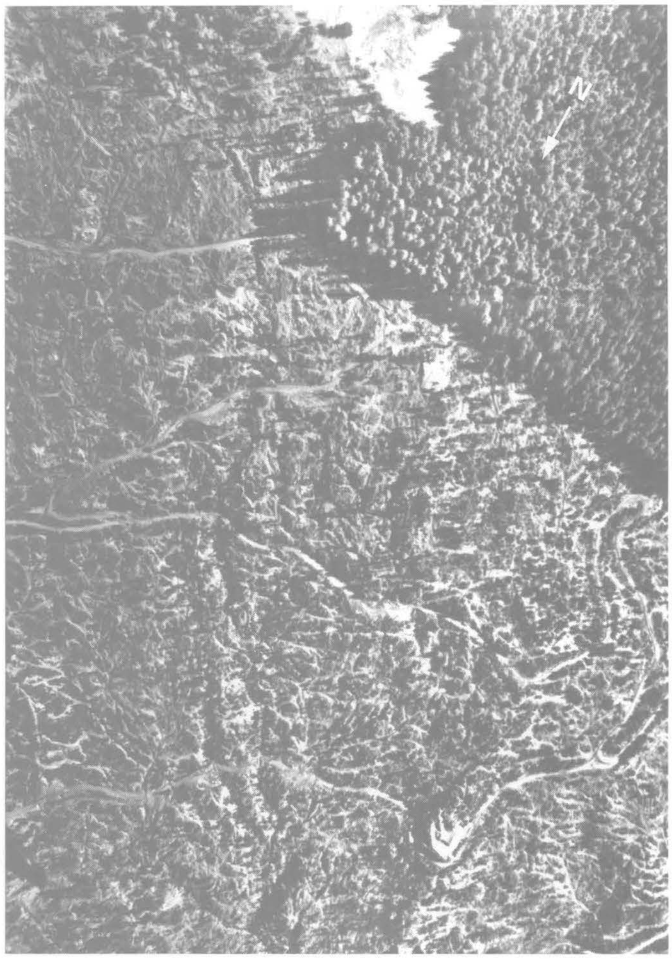


FIGURE 4.—Vertical aerial photograph taken March 7, 1972, of the western portion of the South Copper Creek study site. Note the degree of ground disturbance and the complex pattern of skid trails associated with clearcut tractor-yarding completed in 1971. Old-growth forest (upper right, outside study site) was logged the following year.

The sequence of harvesting in each of the nine study sites has generally consisted of (1) pioneer road construction and limited selective harvesting in the late 1950's and early 1960's and (2) reentry in the early 1970's (table 3), after a period of no activity, for additional road construction and clearcut tractor-yarding over virtually the entire forested portion of each site. For example, in South Copper the conifer forests were logged between 1959 and 1971, with 5 years of intermittent selective tractor logging from 1959 to 1963. The remaining residual timber was clearcut and tractor-yarded from 1970 to 1971. On all sites, this final phase of logging was marked by extreme ground disturbance that left approximately 80 percent bare soil in place of the forested portion of the study site (fig. 4). Road construction history paralleled harvesting operations. In general, 35 to 65 percent of the road network at each site was established during the early periods of selective harvesting. Each road system was then reopened and lengthened in the final period marked by widespread clearcutting.

Dendrochronological evidence not presented in this report (W.E. Weaver, U.S. National Park Service, unpub. data) suggests that timing of the four major storms correlates well with the most active periods of gully development on the study sites. Based on long-term precipitation records from Orick, Calif., and on records from within the Redwood Creek basin since 1974, annual precipitation in the lower one-third of the Redwood Creek basin between 1938 and 1980 averaged approximately 2,000 mm. Four major storms (one in

TABLE 3.—*Physical characteristics and logging history of the nine study sites*

Site name and number (from fig. 1)	Area (ha)	Area upslope from site (ha)	Hillslope position[1]	Mean slope length[2] (m)	Mean slope gradient (percent)	Percent of site steeper than 30 percent gradient	Years logged (19XX)	Logging roads (No.)	Logging roads (km)	Roads upslope from site (No.)	Roads upslope from site (km)	Bedrock characteristics	Principal soils[3]
South Copper (79–2)	246	84	U,M,L	1,340	37	73	59–63,70–71	3	10.8	1	0.6	Sheared mudstone, minor sandstone.	Coppercreek.
North Copper (81–1)	[4]410	0	U,M,L	1,280	32	66	55,62,70	4	6.3	0		....do....	Do.
Maneze (80–2)	172	0	U,M,L	1,620	38	72	58,62,66,71,73	4	5.3	0		....do....	Coppercreek, Atwell.
Lower Slide (81–2)	[5]198	239	M,L	1,830	40	82	59,64,71,76	3	6.1	3	4.5	....do....	Do.
Bridge (80–6)	304	0	U,M,L	1,370	36	77	69,71,73,75	5	11.8	0		Sheared and coherent schist.	Coppercreek, Devilscreek.
Upper Slide (81–3)	[6]239	0	U,M	910	33	59	62,66,71	3	4.5	0		Massive sandstone, minor mudstone.	Lack, Slidecreek, Coppercreek.
Dolason (80–5)	[7]144	11	U,M	1,770	29	54	[8]55,71,77	2	7.7	1	.6	Sheared mudstone, minor sandstone.	Coppercreek, Atwell.
Bridge (80–3)	275	123	M,L	1,830	38	77	71,76	3	5.0	2	4.0	Sheared schist	Coppercreek, Devilscreek.
Bond (82–4)	226	0	U,M	910	24	30	66,71,76	1	2.7	0		Coherent schist	Trailhead, Fortyfour.

[1] U=upper third, M=middle third, L=lower third.
[2] Distance from bottom of unit to drainage divide.
[3] Soils are listed in order of decreasing areal extent; soil characteristics are described in table 2.
[4] Includes 270 ha of grasslands.
[5] Includes 64 ha of grasslands.
[6] Includes 74 ha of grasslands.
[7] Includes 81 ha of grasslands.
[8] 50 percent of site roaded and harvested in 1977; 25 percent of site has been cable-yarded.

1964, two in 1972, and one in 1975) have occurred since logging began on several of the study sites. However, most harvesting and road construction on the nine sites occurred after 1964 but prior to or immediately after the storms of 1972. While the rainfall intensities and durations of the 1972 storms were probably less than for either the 1964 or 1975 storms (Harden and others, 1978), the erosional impact appears to have been greater, perhaps because clearcutting and tractor-yarding on many of the sites had been just completed.

SITE SELECTION

Nine study sites totaling 2,214 ha were selected (fig. 1). Study sites were limited to those that had been mapped in sufficient detail to allow accurate determination of gully volumes as well as the causes of each newly developed gully system. Several sites were specifically chosen because of their apparent low rate of fluvial hillslope erosion. Most of the sites described in this investigation, however, displayed widespread and intense ground disturbance from recent road construction and timber harvesting. These activities had resulted in locally severe gullying and landslide erosion. The study sites covered a variety of bedrock types, soil materials, hillslope positions, and slope gradients (table 3).

As a prerequisite to erosion control activities, detailed geomorphic maps (scale=1:1,200) of each site were compiled. Active and inactive erosion sources, including gullies with cross-sectional areas greater than 0.1 m^2, were located in the field and plotted on enlarged aerial photographs. On eight of the study sites, totaling 1,968 ha, gully widths and depths were estimated at least every 21 m. Volumes were then computed by multiplying the measured cross-sectional area by the corresponding length of gully reach. On the 246-ha South Copper Creek study site, all gullies were carefully measured with tape and survey rod. Cross sections were measured at 6-m intervals or more frequently if a significant change in gully size or shape occurred. Because more frequent measurements and more accurate methods of field measurement were used on the South Copper Creek site, results for that site are discussed in more detail than the other eight less intensively sampled study sites. Analysis of data on these sites reveals similar relationships and confirms conclusions drawn from the South Copper data.

CAUSES OF GULLY FORMATION

Locating and determining causes for gully erosion were often the most difficult aspects of the study. Causes were sometimes obscure, and commonly a single erosional feature could be attributed to more than one cause. Primary and secondary causes were determined for each gully in the South Copper Creek study site. This paper presents only the primary causes. In a few cases, where two causes seemed to have equal influence on a gully, both causes were listed as primary, and the volume was divided between them. Gully volumes in the South Copper Creek site were related to six principal causes:

(1) Plugged culverts at stream crossings on logging roads resulted either in gullying of the road fill at the

crossing site or in diversion of the stream down the road with subsequent gullying of the road prism and adjacent hillslopes (fig. 5).

(2) Lack of culverts at logging road stream crossings resulted in the same mechanism of gully formation as described for plugged culverts (fig. 6). Some ephemeral and intermittent streams were not fitted with culverts during summer road construction. These were comparatively smaller than culverted streams, and the gullies attributed to lack of culverts were shown to be smaller than gullies attributed to plugged culverts.

(3) Channel obstructions, which caused hillslope stream diversions, occurred almost exclusively at locations where tractors had crossed streams or bulldozed soil and logging slash into shallow channels. Streamflow was then diverted across adjacent logged hillslopes and produced gullies that generally followed the network of skid trails (fig. 7).

(4) Misplaced culverts were those installed some distance from the actual stream crossing. Streamflow was diverted along the inside ditch and usually discharged onto the hillslope within 100 m of the crossing. Gullies developed below the culvert outlet and extended downslope until the diverted flow rejoined the natural stream channel (fig. 8).

(5) Interception and concentration of road surface runoff resulted in minor enlargement of inside road ditches and the development of small gullies where culverts released this flow onto bare hillslopes. Sloughing at cutbanks also blocked ditches and diverted runoff across the road surface and onto downslope areas.

(6) Increased surface runoff resulted from soil exposure and compaction and from the interception of near-surface ground water and throughflow in deep skid-trail cuts. Concentration of increased hillslope runoff from roads, landings, and skid trails on bare areas created shallow and narrow, but lengthy, gully systems (fig. 9).

Ninety-four percent of the total volume of gully erosion in the South Copper Creek study site was caused by stream diversions. Given the overriding importance of stream diversions as a cause of gullying, determinant analyses for the remaining study sites were restricted to the three mechanisms by which streams were diverted: culvert plugging, lack of culverts, and channel obstructions at skid-trail stream crossings.

In the following sections, detailed information is presented on gully erosion on South Copper and the other eight study sites in the lower Redwood Creek basin. The South Copper data set consisted of approximately 3,200 cross-sectional measurements from which the total volume of soil eroded by gullies was computed. In the remaining eight study sites, over 2,600 gully cross sections were measured. In all, cross-sectional measurements were taken along a cumulative gully length of nearly 76 km on the nine study sites.

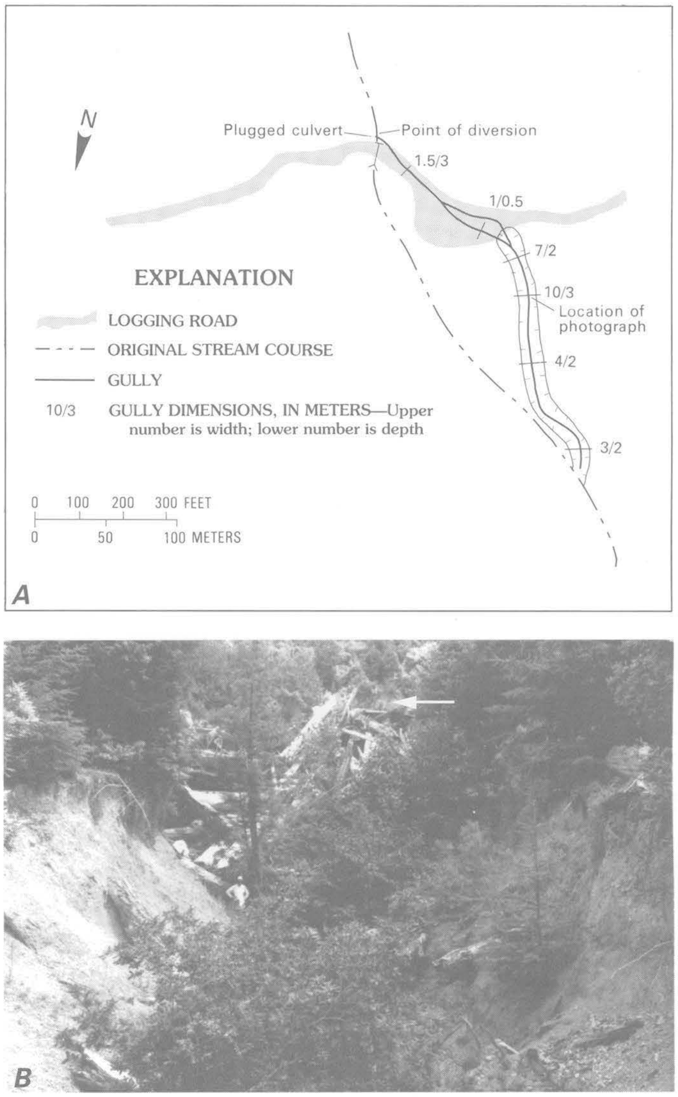
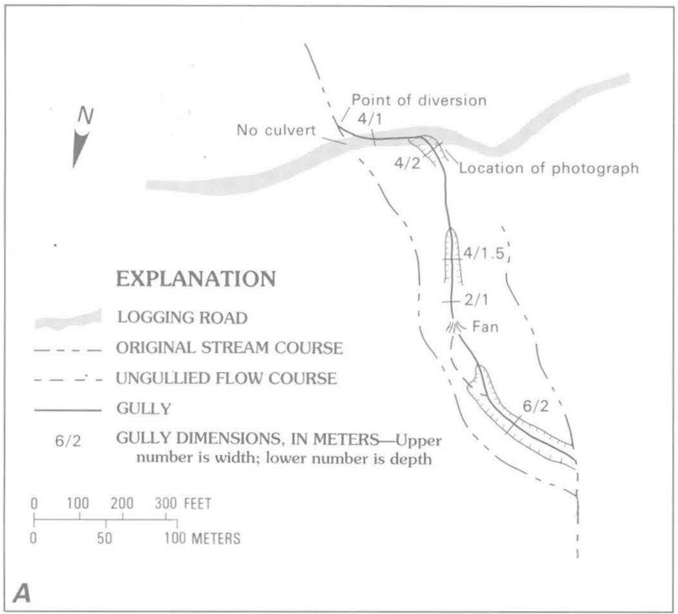


FIGURE 5.—Large gully created when a plugged gully diverted a perennial stream. *A*, Planimetric map of gully showing selected cross-sectional dimensions. Total measured volume of gully is 2,800 m^3. *B*, Photograph of same gully. Scale is indicated by person standing in gully. Arrow indicates logging road at prominent headcut.

RESULTS

INCREASED EROSION IN THE SOUTH COPPER CREEK STUDY SITE

Gully systems on the 246-ha tractor-yarded clearcut area south of the main channel of Copper Creek are widespread and complexly interconnected, and they represent the dominant source of eroded material



◀ FIGURE 6.—Gully attributed to lack of culvert on logging road. *A*, Planimetric map of gully showing diversion of stream down the roadside ditch, across road, and then down several hundred meters of hillslope before entering another stream channel. Total volume of gully system on map is 2,000 m^3. *B*, Photograph taken where gully headcut has migrated across the road prism to a roadside ditch. Note coarse lag deposit that has accumulated in the bed of the gully.

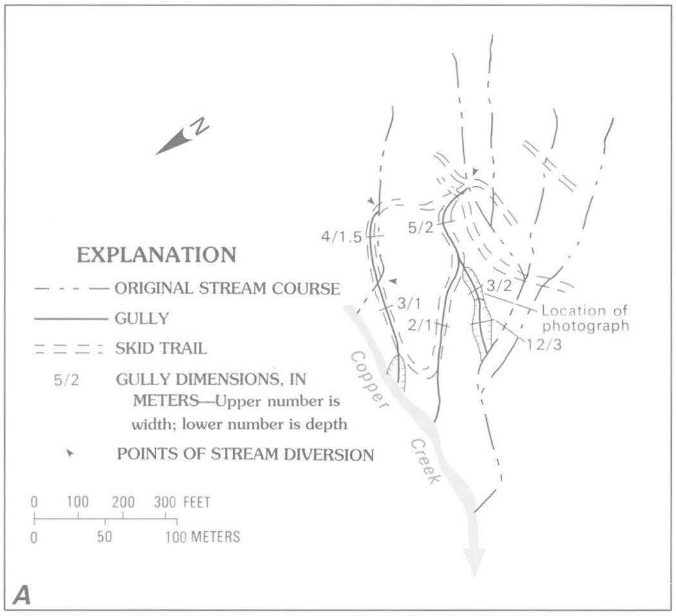
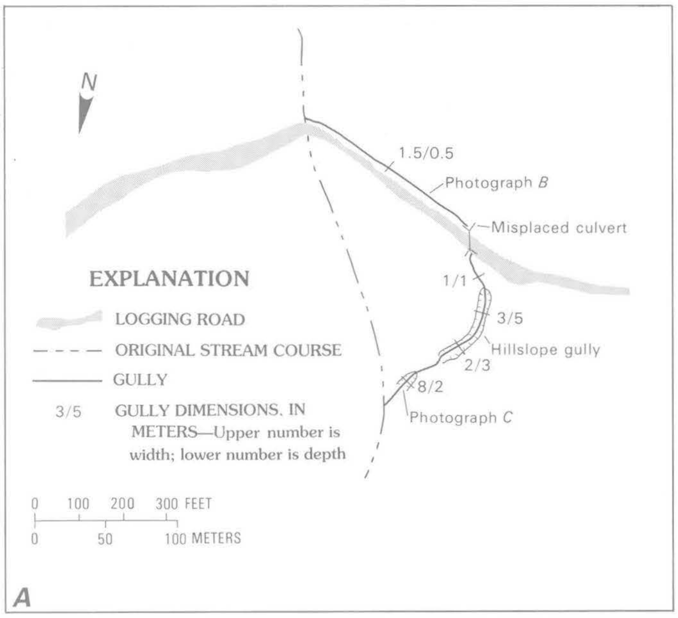


FIGURE 7.—Gullies created by channel obstruction where tractors crossed streams. *A*, Planimetric map of gully system showing selected cross-sectional dimensions. Most diverted streams followed skid trails. Total volume of gully erosion shown on the map is 4,700 m^3. *B*, Photograph of typical gully in the system.



◄ FIGURE 8.—Gully attributed to misplaced culvert on logging road. *A*, Planimetric map showing diversion of a perennial watercourse down the roadside ditch for a distance of 150 m to the misplaced culvert, downslope from which a larger gully was formed. Cross-sectional dimensions of the gully are shown at selected intervals, and the computed gully volume is 1,200 m^3. *B*, Photograph of a gullied roadside ditch on a logging road. *C*, Photograph of gully, which is much larger than gully in *B* above, on hillslope. Note the increase in the cross-sectional area of the gully as slope steepens.

contributing to increased sediment yield in the study site (Weaver and others, 1981) (fig. 10). Most gullies were caused by diversions of low-order stream channels on the clearcut hillslopes (table 4). These diversions resulted from (1) widespread tractor disturbance in and adjacent to the natural channel system, (2) lack of maintenance of the 9.3-km logging road system between the initial selective harvest and subsequent reharvesting in the early 1970's, and (3) the lack of maintenance of the dead-end logging road system after clearcutting activities were completed in 1972. Culvert blockages led to either road washouts or stream diversions and the creation of large hillslope gullies. Water was also diverted onto adjacent bare hillslopes where logging roads and skid trails crossed ephemeral and intermittent streams without culverts. These diversions resulted in the development of extensive gully networks.

Volumetrically, 70 percent of the 124,400 m^3 of eroded material measured from all sources in the South Copper Creek study site can be attributed to newly formed gullies (table 4). An additional 13 percent was derived from gullied, or enlarged, natural stream channels. Although not described in this paper, stream diversions from one channel to another resulted in substantial morphologic adjustments to watercourses that received increased discharges and sediment loads. The remaining 17 percent of eroded material was associated with mass-movement processes, such as landslides and slumps, on unstable logging roads, hillslopes, and cutbanks primarily on lower hillslope positions of the study site. Apparently as a combined result of increased stream discharges, steeper hillslopes and channels, and highly erodible soils, 90 percent of the soil eroded by newly formed gullies, and 96 percent of the sediment generated from the enlargement of natural stream channels, was derived from the lower half of the hillslopes (table 4).

MAGNITUDE AND CAUSES OF GULLY EROSION IN SOUTH COPPER CREEK

Within the South Copper Creek study site, 89 percent of the postharvest gully erosion was attributable to three principal causes (table 5):

(1) Culvert plugging and subsequent stream diversion along logging roads (38 percent);

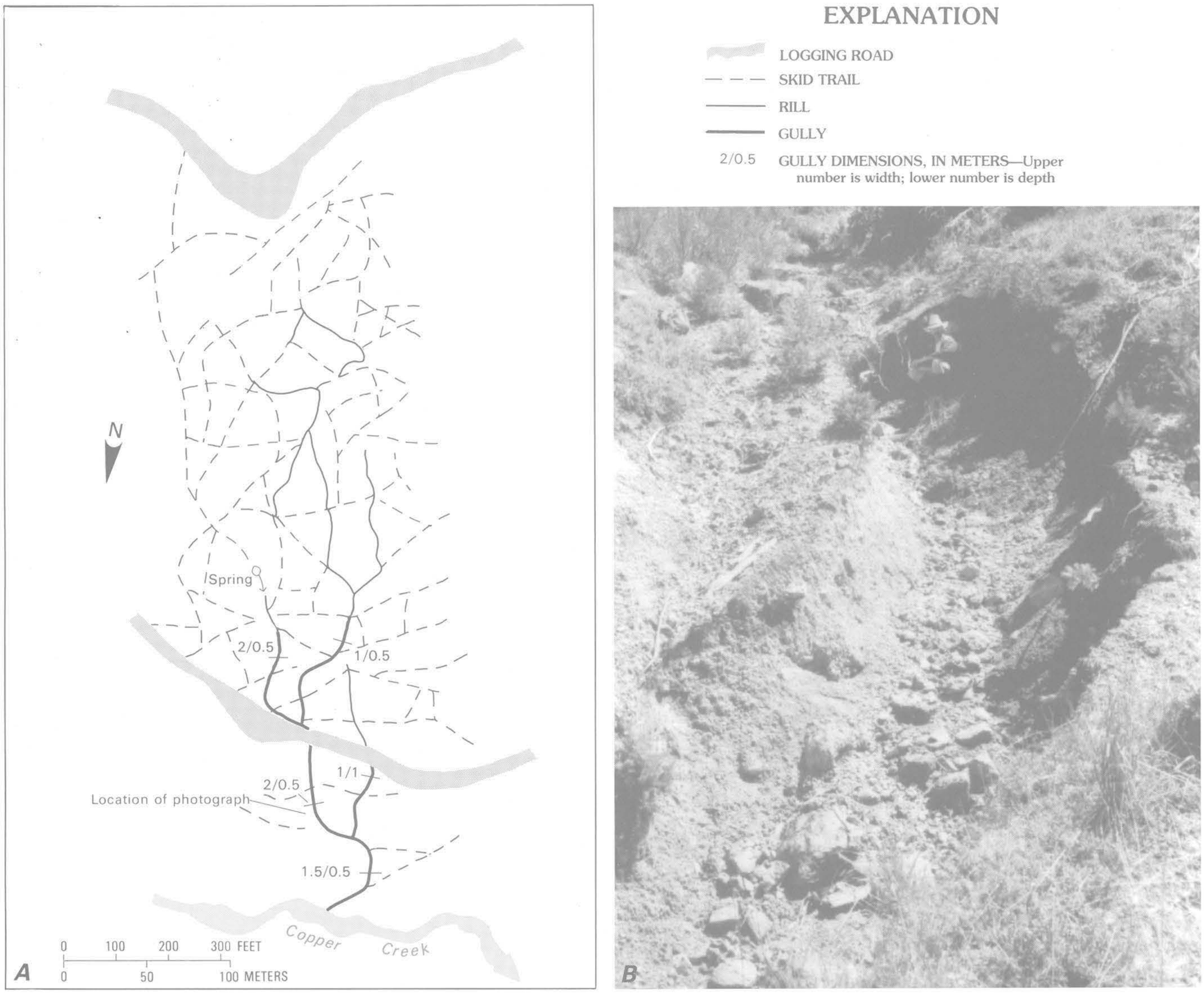


FIGURE 9.—Gullies created by increased surface runoff over the skid-trail network in a tractor-yarded area. *A*, Planimetric map showing gully system caused by concentrated runoff flowing on skid trails. Note the comparatively small gully dimensions shown on the map. Total gully erosion from the network was 350 m^3. *B*, Photograph of typical gully caused by increased surface runoff.

TABLE 4.—*Sources and amounts of sediment produced from the South Copper Creek study site*

[Figures may not add to 100 percent due to rounding]

Sediment source	Percent of total volume of material eroded from: Upper slopes	Upper middle slopes	Lower middle slopes	Lower slopes	Total sediment production[1]: Percent contributed to total volume	Volume (m^3)
Fluvial processes:						
New gully systems developed since logging[2]	1	10	54	36	70	87,100
Gullied or enlarged natural stream channels	0	4	41	55	13	16,200
Mass-movement processes:						
Landslides associated with logging roads	0	0	0	100	8	9,900
Slumps on logging roads	2	3	64	32	4	5,000
Combined failure and gullying of logging road fill	0	9	13	78	3	3,700
Failure of logging road fill	19	12	25	44	2	2,500
Total	1	8	46	45	100	124,400

[1] Does not include 12,030 m^3 of streamside landsliding along the main channel of Copper Creek; also excludes sheet and rill erosion, and isolated bank failures along tributary streams.
[2] Includes all gullies or segments of gullies having cross sections larger than 0.1 m^2.

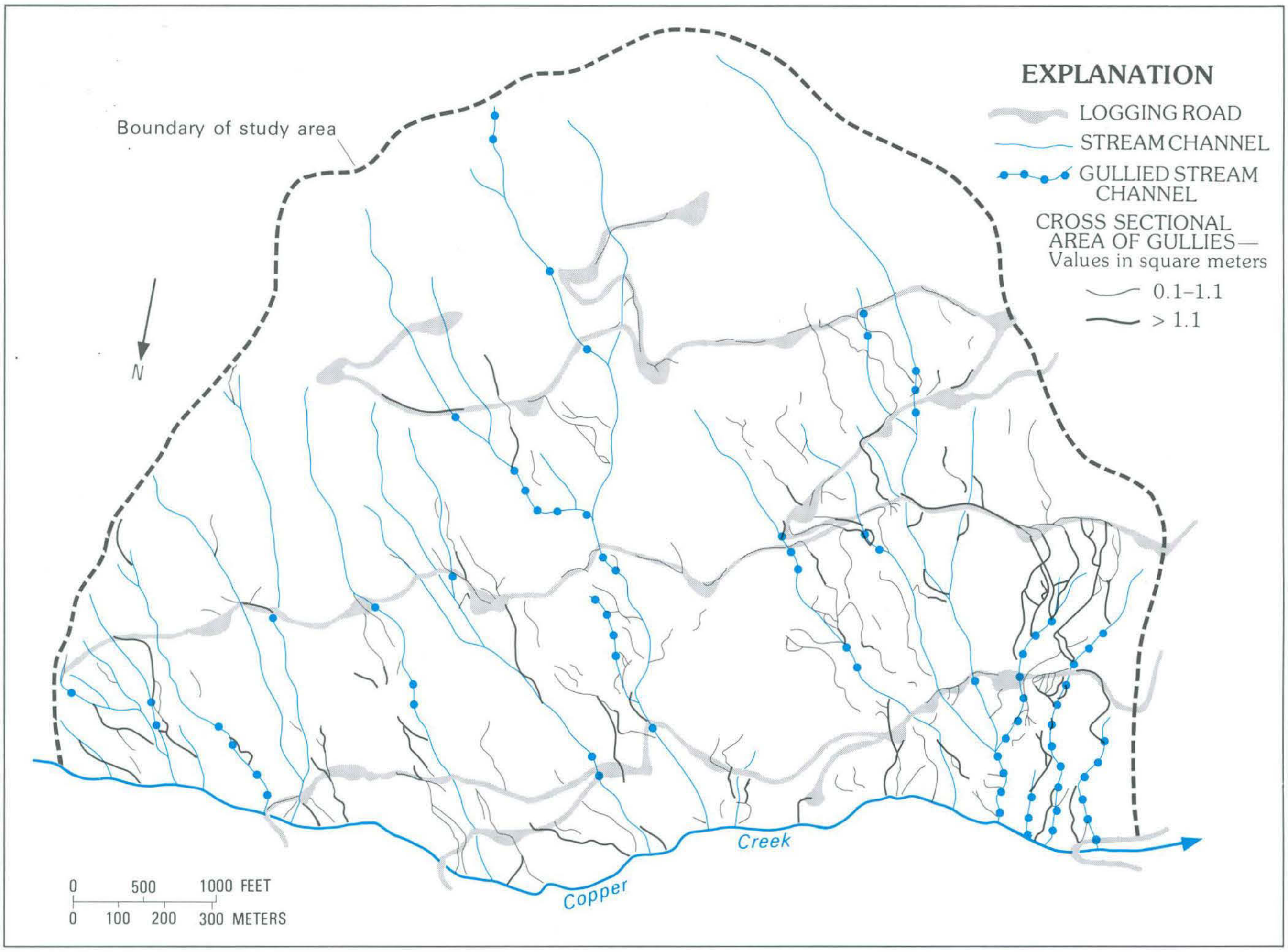


FIGURE 10.—Gully systems on the 246-hectare South Copper Creek study site. Rills less than 0.1 m^2 in cross-sectional area are not shown. Gullies were mapped and measured in 1979.

TABLE 5.—*Mean cross-sectional area, total length, and total volume of gullies attributed to primary causes, South Copper Creek study site*

Primary cause of gullying	Mean cross-sectional area (m^2)	Total gully length (km)	Percent contributed to total volume of eroded material	Volume of eroded material (m^3)
Plugged culverts on logging roads	9	3.4	38	33,400
Hillslope stream diversions at skid-trail crossings.	4	7.6	36	31,300
Lack of culverts on logging roads	4	3.3	15	13,200
Misplaced culverts on logging road	5	.8	5	4,000
Increased surface runoff	1	3.9	4	3,700
Interception and concentration of road surface runoff.	1	1.3	2	1,500
Total	4	20.3	100	87,100

(2) Diversion of streams at tractor-constructed skid-trail stream crossings on logged hillslopes (36 percent); and

(3) Lack of culverts on logging roads at stream crossings and consequent diversion of streams into roadside ditches and eventually across overland areas or into nearby stream channels (15 percent).

Three other identified causes accounted for the remaining 11 percent of the total measured gully volume. At least 94 percent of the total volume of gully erosion on the South Copper Creek study site was caused by stream diversions (table 5).

During road construction, culverts were generally placed only at crossings of the largest streams. In South Copper Creek, the plugging of many of these culverts after the road was abandoned in 1972 caused the diversion of several second-order streams and the development of large hillslope gullies (fig. 11). Although gullies that developed in response to plugged culverts accounted for the greatest volume of sediment production from a single cause (38 percent), they constituted a comparatively short total length of new channel (17 percent of the total measured length; table 5). Thus, the largest stream discharges developed gully systems with the greatest cross-sectional areas. These gullies were more than twice as large, in cross-sectional area, as those attributed to the next leading cause, hillslope stream diversion at skid-trail crossings (table 5). However, the streamflow diverted at plugged culverts quickly rejoined natural, preexisting channels.

In contrast to road crossings, skid-trail crossings on hillslopes were commonly constructed on small, intermittent or ephemeral streams. Fill was generally bulldozed into the channel without the installation of a culvert. The consequent diversions of these streams created extensive gully systems on the dense network of logging skid trails between the major drainage channels. Although gully cross sections were moderate in size (average cross-sectional area of 4 m^2), the gullies derived from stream diversions at skid-trail crossings accounted for over one-third (37 percent) of the total cumulative length and 36 percent of the total volume of eroded material (table 5).

It is noteworthy that gullies that developed on bare-soil areas and whose source of discharge could be attributed only to increased surface runoff from direct rainfall or intercepted subsurface flow accounted for 19 percent of the total length of measured gullies but for only 4 percent of the total volume. Such gullies, although abundant on the study site, eroded comparatively little soil.

VARIABILITY OF GULLY YIELDS AMONG THE NINE STUDY SITES

Besides the gully erosion on the South Copper Creek study site, 242,400 m^3 of material was eroded by gullies within the other eight study sites, which have a total area of 1,968 ha (table 6).

At the time of the inventory, a wide variation in gully yields was discerned between different study sites. Gully yields in table 6 can be divided into three groups (1) Lower Slide, North Copper, Maneze, and South Copper Creek sites have high yields, exceeding 170 m^3/ha, (2) both of the Bridge Creek sites plus the Dolason and Upper Slide Creek sites have more moderate gully yields, ranging from 52 to 77 m^3/ha, and (3) the Bond Creek study site, which yielded only 3 m^3/ha.

Much of the variability among sites is apparently due to differences in physical site variables and, to a lesser degree, to the timing of logging relative to major storm events. Inasmuch as all the study sites were clearcut and tractor-yarded by the same techniques and to nearly the same degree of ground disturbance, differences in land use practices cannot readily explain the wide range of gully yields. Likewise, each area had nearly the same rainfall rates and volumes during storms in 1964, 1972, and 1975.

TABLE 6.—*Data on gullies at nine study sites in the lower Redwood Creek catchment*

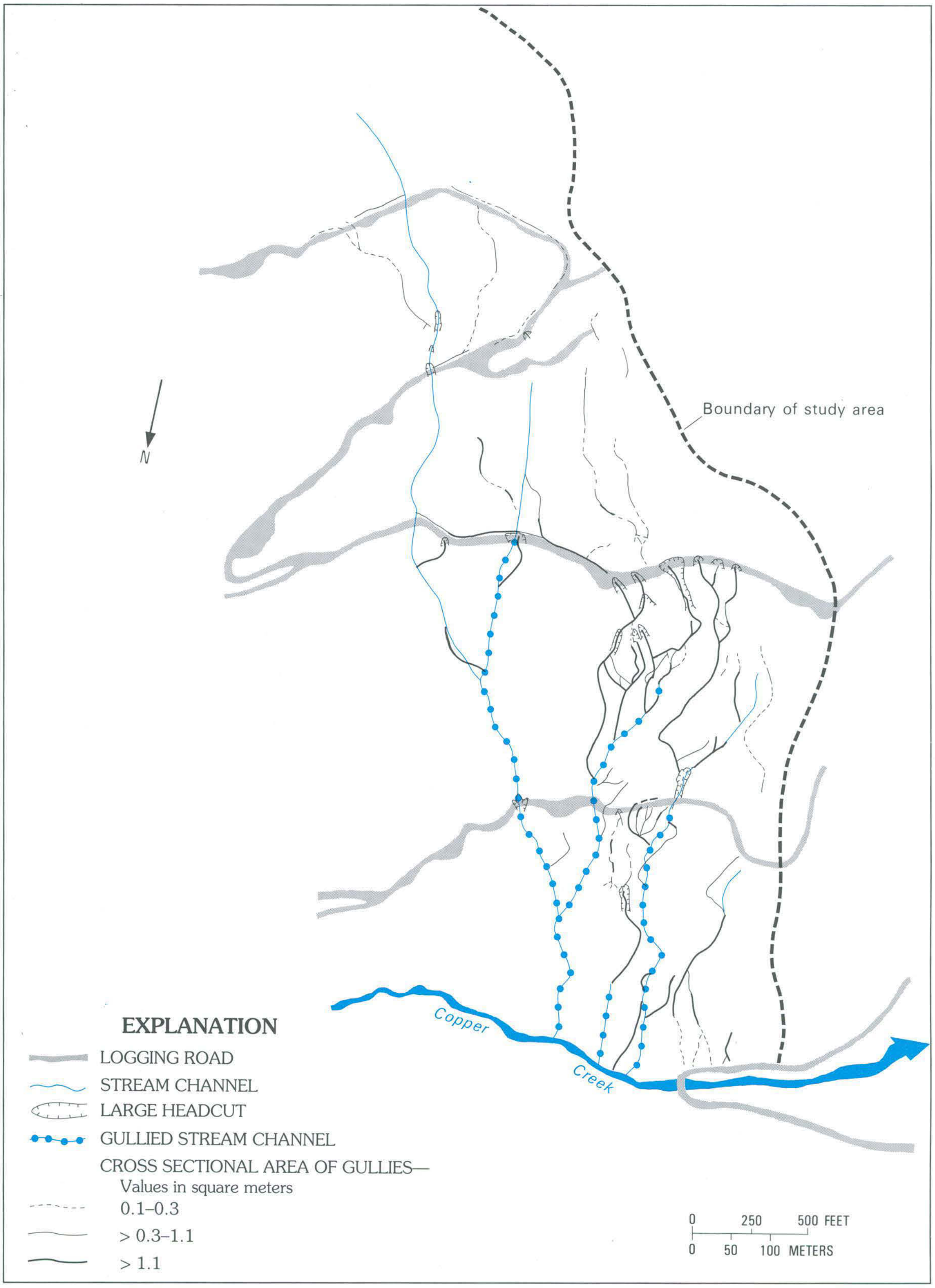
Site name and number (from fig. 1)	Area (ha)	Gully length (km)	Number of cross sections measured	Total gully volume (m^3)	Gully yield (m^3/ha)	Gully density (m/ha)	[1]Mean gully cross-sectional area (m^2)
High yield sites							
South Copper (79–2).	246	20.3	3,168	87,100	354	83	4.3
North Copper .....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

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

Study sites within the high yield group are all underlain by sheared mudstones and sandstones of the Incoherent unit of Coyote Creek (table 3). The dominant soil mantling the high yield sites is the Coppercreek series. This soil is deep and, compared to soils on the sites displaying lower gully yields, is characterized by relatively low clay content and very low gravel-sized rock-fragment content in the A and B horizons. The subsoil lacks both sufficient clay to develop cohesive, resistant structural aggregates and sufficient rock fragments to produce a stabilizing armor once soil erosion has begun.

Less intense gullying on the four sites in the middle-yield category (table 6) is explained by several different factors. Cutover land in the Dolason study site is underlain by the same erodible Coppercreek soil that dominates the four high yield sites. However, two factors have acted to moderate gully erosion. First, slightly over half of the forested land at Dolason was cut, and 40 percent of the logging roads were built in 1977, more than 2 years after the last major storm in the Redwood Creek basin. Basinwide peak runoff since 1977 has not exceeded the 2-year return period event. Second, 56 percent of the Dolason study site consisted of prairie grassland traversed by a single logging road. Disruption of the drainage network was much less severe than on either Upper Slide or North Copper Creek grassland areas.

Bedrock and soil characteristics on the Upper Slide Creek site (tables 2, 3) probably account for its moderate gully yields. The steep slopes on massive sandstones of the Coherent unit of Lacks Creek have developed comparatively shallow soils. Although the shallow soil is low in clay content, its high content of rock fragments reduces the probability that large gullies will form.


Boundary of study area
N
Copper Creek
EXPLANATION
LOGGING ROAD
STREAM CHANNEL
LARGE HEADCUT
GULLIED STREAM CHANNEL
CROSS SECTIONAL AREA OF GULLIES—
Values in square meters
0.1–0.3
> 0.3–1.1
> 1.1
0 250 500 FEET
0 50 100 METERS

Developing gullies quickly reach bedrock or are armored by a lag of coarse rock fragments.

The gully yield from the Bridge Creek study sites was also within the moderate range (table 6). Both sites are remarkably similar in area, underlying bedrock, average slopes, and timber harvest history (table 3). The predominate soils on both sites are a complex of the deep, highly erodible Devilscreek and Coppercreek series, with Lack soils on the broad, rocky ridges. Although all the large gullies were located on the more erodible soils, the yield from each site was moderated by one or more factors. First, drainage areas are small, so many of the stream diversions resulted in relatively small gullies. Second, minimal erosion on the Lack soil areas effectively diluted average yields from each site. Third, unlike the highyield sites, most logging roads on these two sites were kept open, active, and maintained, and so stream diversions were quickly repaired or stabilized. Finally, approximately one-half the area of each site was clearcut after 1972 and therefore experienced only one significant gully-producing storm (1975).

The moderate, comparable gully yield from both Bridge Creek sites also arises from two contrasting characteristics of their logging road systems. The 80–6 Bridge Creek unit contained over 11 km of logging roads, which contoured the hillside at five separate elevations. As a result of the lack of maintenance on several roads after final clearcutting, many diversions of small streams contributed to the high density (49 m/ha) of small gullies on the site (table 6).

By contrast, only 4.8 km of road were constructed on the 80–3 Bridge Creek site, including a 1.6-km section that climbed obliquely up and across the unit. The probability of stream diversions along roads that cross contours is far greater than on roads that follow hillslope contours or dip into the stream crossing at both approaches (chap. M, this volume). Multiple diversions of second-order streams along the continuously ascending logging road on the 80–3 Bridge Creek unit produced fewer gullies than on the 80–6 Bridge Creek site (table 6), but the average cross-sectional area (gully volume/gully length) was almost twice as large. For example, 77 percent of the measured gully cross-sectional areas on site 80–3 exceeded 4.5 m^2, whereas only 49 percent of those on the 80–5 site were in this category of large gullies. Because gully frequency compensated for gully size, the yield from both Bridge Creek study sites was comparable.

Finally, two factors explain the anomalously low gully yield on the Bond Creek site. First, approximately one-half of the unit had not been disturbed by timber harvest until 1976. By the time of the erosion inventory in 1981 to 1982, the clearcut area had not experienced a major runoff event. Second, the low gullying rate can also be explained by the site's stable soil characteristics. Most of the Bond Creek study site is underlain by Trailhead and Fortyfour soils (table 3). Both series are marked by relatively high concentrations of clay and iron in their B horizons. This content appears to significantly retard surface erosion by reducing the rate at which flowing water is able to cut down below the more erodible A horizon material. High clay and iron content, and a blocky soil structure, greatly increase aggregate stability (Singer and others, 1978) and therefore decrease the potential for formation of rills and gullies.

In summary, stream diversions—the main cause of gullying—were observed at all sites. The frequency of diversions was positively related to the density of logging roads and to the number of major storms (of 10- to 20-year recurrence interval) at each site since road construction and harvesting. For example, the parts of the Dolason and Bond Creek study sites that were logged since 1975 had relatively few diversions, and the small streams that were diverted had caused very little erosion in the following 5- to 7-year period after logging.

Road systems that had been abandoned and not maintained through one or more major storms were associated with substantially more gully erosion than regularly used logging roads. For example, the entire road system in the South Copper Creek study site had been completely abandoned, for the second time, by 1972. Consequently, gully densities and gully yields from that site were unmatched in the lower Redwood Creek basin.

Regardless of the association between road density and frequency of stream diversions, these factors are not consistently correlated with gully yield. The volumes of gullies caused by diversions of similar-size streams are clearly related to properties of the underlying soil. For example, the high content of clay and iron and the blocky structure of the Trailhead soil in Bond Creek made it very resistant to erosion. Likewise, although the A horizon of the Lack soils of Upper Slide Creek is more easily eroded, the abundance of coarse rock fragments in the shallow B horizon armored newly formed gullies and prevented the formation of large channels. Finally, the deep Devilscreek and Coppercreek soils lacked both sufficient clay and rock fragment content to prevent or minimize erosion when subjected to concentrated surface

◀ FIGURE 11.—Measured gully network on a portion of the western side of the South Copper Creek study site. (The same area is shown in the 1972 aerial photograph of fig. 4.) This was the most intensely gullied of the nine study sites. The abundance of large gullies and enlarged stream channels on the middle and lower slopes was a result of stream diversions at crossings of streams by roads and skid trails. Total measured gully erosion for the mapped area was 40,600 m^3. Gullies larger than 1.1 m^2 in cross-sectional area accounted for 97 percent of this volume.

TABLE 7.—*Comparison of gully erosion caused by stream diversions on four study sites*

Study site and number (from fig. 1)	Area (ha)	Gully volume (m^3)	Gully erosion attributed to stream diversions (m^3)	Gully erosion attributed to stream diversions (percent of total)	Percent of total volume of eroded material according to cause of stream diversion: Plugged culvert[1]	Hillslope diversion[2]	Lack of culvert[3]
South Copper (79–2)	246	87,100	81,900	[4]94	41	38	21
Upper Slide (81–3)	239	17,300	11,300	65	4	10	86
Bridge (80–3)	275	14,300	12,200	85	77	11	12
Bond (82–4)	226	700	600	86	83	1	16
Total	986	119,400	106,900	89	41	32	27

[1] Streamflow diverted by plugged culvert on logging road.
[2] Flow diverted out of channel at tractor-constructed skid-trail crossing.
[3] Culvert not installed at logging-road stream crossing; flow diverted out of channel. Includes misplaced culvert category of table 5.
[4] Causes 1–4, table 5.

runoff or diverted streamflows. Sites mantled by these soils were especially prone to gullying.

VARIABILITY OF GULLY YIELDS AND GULLY DIMENSIONS WITHIN STUDY SITES

In the four sites that were studied in sufficient detail to permit comparisons between the cause of erosion and eventual gully yield, 89 percent of the gully erosion was attributed to stream diversions (table 7). Three major causes of stream diversions were identified: plugged culverts (41 percent), unculverted skid-trail crossings (32 percent), and unculverted logging-road crossings (27 percent) (table 7).

The size of the drainage area of a diverted stream strongly influenced gully dimensions and yield. For example, stream diversions were about equally common on the upper and lower slopes of the South Copper Creek study site. However, 93 percent of the gully erosion from diversions occurred in the lower half of the hillslope where stream discharges were comparatively greater (that is, larger drainage area). The relatively high frequency of large gullies in the lower hillslope areas of South Copper Creek is apparent in figure 10.

Both the volume of eroded material (table 7) and the total length of gullies attributed to stream diversions varied widely from one site to another. In the Upper Slide Creek study site, 86 percent of the total measured gully volume and 45 percent of the total gully length was attributed to a lack of culverts at some road crossings. By contrast, 77 percent of the measured gully volume and 84 percent of the total gully length on the 80–3 Bridge Creek study site was attributed to plugged culverts and the consequent diversion of streams along inside road ditches, from which the gullies eventually cut across the road prism and down unprotected, bare hillslopes. Gully erosion at the Bond Creek site was more than an order of magnitude lower when compared to the other study sites, yet the proportion of total erosion attributable to the three mechanisms of stream diversion remained high. In South Copper Creek, streams diverted at tractor-constructed skid-trail crossings accounted for 36 percent of the measured gully volume, whereas such diversions had accounted for no more than 11 percent of the measured gully volume on each of the other sites.

TABLE 8.—*Total gully length and volume as distributed among four cross-sectional size categories on nine study sites in the lower Redwood Creek basin*

[Figures may not add to 100 percent due to rounding]

Study site and number (from fig. 1)	Percent of total volume of eroded material according to gully cross-sectional size categories: <0.1 m^2	0.1 to 1.1 m^2	>1.1 to <4.5 m^2	≧4.5 m^2
South Copper (79–2)	1	4	14	81
North Copper (81–1)	1	2	8	89
Maneze (80–2)	1	7	12	80
Lower Slide (81–2)	1	4	6	89
Bridge (80–6)	5	14	32	49
Upper Slide (81–3)	3	9	19	69
Dolason (80–5)	3	6	23	68
Bridge (80–3)	2	9	12	77
Bond (82–4)	18	12	2	68
Total gully volume (m^3)	4,280	16,510	41,828	266,992
Percent of total	1	5	13	81
Total gully length (km)	18.2	26.4	17.4	13.7
Percent of total	24	35	23	18

At all nine study sites, gullies formed on cutover lands had a wide range of lengths and cross-sectional areas (table 8). Small gullies, although widespread on all sites, produced comparatively little sediment. Gullies that averaged less than 1.1 m^2 in cross-sectional area accounted for nearly 60 percent of total gully length but only 6 percent of the measured volume of material eroded (table 8). The largest gullies, those 4.5 m^2 or larger in cross-sectional size, were the major contributors to fluvial sediment production. Approximately 50 percent or more of the gully yield on every site was produced by the formation of these large gullies (table 8).

Analysis of data from the detailed South Copper Creek inventory suggests that streams diverted by the plugging of logging-road culverts produce the largest gullies in downslope areas. Plugged culverts commonly result from the installation of undersized structures or from lack of maintenance following road construction.

Although diversions by plugged culverts account for only 17 percent of the total length of gullies formed in South Copper Creek, gullies formed by this process had an average cross-sectional area of 9 m^2 and produced roughly 38 percent of the total volume of material eroded by gullies (table 5). By comparison, gullies that were formed by stream diversions at skid-trail crossing on hillslopes averaged 4 m^2 in cross-sectional area. Although such hillslope stream diversions produced gullies that were less than half the average cross-sectional area of those caused by plugged culverts, their total length (7.6 km) was twice as great. Thus, the total volume of eroded material produced by these two mechanisms of stream diversion was about equal.

In the third category of causes shown in table 5, small unculverted streams crossed by a logging road were commonly diverted down an inside ditch and discharged through a ditch relief culvert, or at the next culverted stream crossing, before reentering a natural stream channel. Gullies formed by these intentional diversions were similar in average cross-sectional area to those produced by skid-trail stream diversions but had a much shorter total length. Gullies attributed to the last three causes in table 5 were either very short or very small, or both, and accounted for only a small percentage of the total sediment production.

DISCUSSION AND CONCLUSIONS

MAGNITUDE AND CAUSES OF GULLY EROSION

Stream diversions produced most of the largest gullies and the bulk of fluvial erosion from the roaded and tractor-logged hillslopes. Extensive gullying commonly occurred when culvert inlets became plugged with sediment and debris, diverting streamflow from the natural channel. Undersized culverts, the absence of debris trash racks (wooden structures that keep organic debris from plugging culvert inlets), and lack of maintenance on abandoned roads were typically responsible for such diversions. Streams that were culverted at road crossings were larger, well-incised, intermittent or perennial watercourses that carried flow during the summer logging season. Thus, diversions caused by plugged culverts frequently involved comparatively large streams and produced large gullies (table 5). However, the lengths of these gullies were limited because the natural channels were well incised into the hillslope, and diverted flow often returned quickly across the steep sideslopes to the original or an adjacent watercourse.

Skid-trail crossings of stream channels were generally constructed on watercourses that were either poorly incised or nearly dry during the summer period, when most harvest operations occurred. Diversion of these ephemeral and small intermittent streams during the subsequent winter created moderate-sized gullies that commonly traversed long segments of hillslope, following skid-trail paths without encountering either natural stream channels or logging-road obstructions that might route the water into a nearby stream. Hillslope stream diversions caused by skid-trail crossings can produce extensive gullying as occurred at the South Copper Creek study site (table 7).

In addition to the influence of land use variables, physical soil characteristics have a strong influence on gully yields. Gullies developed on cohesive, clay-rich soils in Bond Creek (tables 2, 3) averaged less than 1.0 m^2 in cross-sectional area (table 6). Those formed on the shallow rocky soils of Upper Slide Creek averaged an intermediate 2.7 m^2 in area. Finally, the sites of high gully yield were exclusively located on soils that contained comparatively low concentrations of clay and rock fragments. Mean gully dimensions on these areas ranged from 4.2 m^2 on the Maneze Creek site to 8.5 m^2 on the North Copper Creek site (table 6).

The magnitude of gully erosion in the study sites did not vary consistently with average hillslope gradient, with the abundance of steep hillslopes, with slope length, or with hillslope position (tables 3, 6). However, while these variables were less important than land use factors and soil characteristics, they apparently still had some influence on gully yields. For example, slopes less than 20 percent in gradient were rarely gullied. All study sites having over 40 percent of their area in gentle upland slopes ($\leq$30 percent gradient) showed low to moderate gully yields.

Similarly, all the high yield sites included both lower and middle hillslope positions, and at least 66 percent of each site was moderate to steep, having a slope gradient greater than 30 percent (tables 3, 6). However, the inverse situations were not as consistently correlated with gully yields. That is, not all sites in the low or moderate yield category (3 to 77 m^3/ha, table 6) were dominated by gentle slopes, and several of the steepest sites did not show high rates of gully erosion (tables 3, 6). In the latter situations, differences in soil characteristics and the timing of land use in relation to storm events were of overriding importance.

SEDIMENT SOURCES AND TRANSPORT IN THE LOWER REDWOOD CREEK BASIN

Although not a principal objective of this investigation, gully yields for the lower Redwood Creek drainage basin (fig. 1) were estimated from data obtained in the nine study sites. Logged areas in the lower basin were first divided into units of similar land use practice (table 9). On study sites, virtually all gully erosion emanated from tractor-yarded hillslopes and prairie areas traversed by logging roads. Areas subjected to this type of logging or road building occupy 55 percent of the lower basin and constitute the source region used for calculating postharvest gully erosion. Overall road density in the nine study sites is virtually equivalent to that for the 10,770 ha of tractor-logged forest lands and roaded prairie areas of the lower Redwood Creek basin (table 9).

Early logging methods (which utilized steam donkeys and cable-yarding, together with ridgetop railroad systems for log hauling) caused much less ground disturbance and drainage-pattern disruption than recent tractor-yarding techniques (Janda and others, 1975). Gully formation in areas logged by early methods was assumed to be negligible. Although more modern cable-yarding practices require extensive road networks, such logging became common in the lower basin only after the last major flood in 1975. Field observations and data from the study sites suggest that gullying on these recently cable-yarded hillslopes has also been negligible.

However, on roaded grasslands and tractor-yarded hillslopes logged prior to 1975, soil properties and related site conditions (an undifferentiated combination of factors including bedrock lithology, structure, hillslope gradient, slope morphology, and drainage density) were found to be closely related to expected gully yields. For this reason, the lower basin source area was divided into three major terrain categories, based principally on major soil types and their corresponding geologic and geomorphic associations (table 10). Expected gully yields were then assigned to each category according to measurements from the nine study sites (table 6).

Gully yields from cutover study sites varied greatly (table 6), even though these areas experienced similar land use practices and histories. High yield terrain, where gully erosion was estimated to average 260 m^3/ha, occupies only 31 percent of the selected land base in the lower basin but yielded approximately 70 percent of eroded volume (table 10). In contrast, 16 percent of the land base, which made up the low yield category, was estimated to account for less than 1 percent of the total gully erosion in the lower basin. Clearly, a small percentage of the disturbed land in a watershed can contribute a large proportion of the total sediment production by gullies.

In addition, basins that contain large areas of highyield terrain (lands that are especially subject to fluvial gully erosion) may undergo far more erosion from gullying than from landsliding. For example, Kelsey (1980) has estimated that, for the period 1941 to 1975, over 90 percent of the hillslope fluvial erosion in the upper 575 km^2 of the Van Duzen River drainage basin (located 70 km south of the lower Redwood Creek basin) was derived from 38 percent of the watershed area. Because

TABLE 9.—*Land use status and land base data used to compute gully yields from areas in the lower Redwood Creek basin*

[Land use status is from chapter C, this volume]

	Nine sites of this study	Lower Redwood Creek basin
Land data (ha)		
Total area	2,214	19,650
Grassland	489	800
Uncut	0	5,900
Logged area	1,725	12,950
Percent of cutover land area		
Logging method:		
Steam donkey; no roads; pre-1948	0	4
Unknown methods; probably pre-1948	0	9
Cable-yarding; road construction; post-1948	5	10
Tractor-yarding; road construction; post-1948	95	77
Land base data		
Total land base used to compute gully yields (ha) (tractor-yarded area plus roaded grasslands)	2,214	10,770
Logging road density in land base (km/ha)	.027	.026

TABLE 10.—*Estimated gully erosion in the lower Redwood Creek basin (1948–80), according to major terrain categories*

Terrain category	Principal soils	Expected gully yield[1] (m^3/ha)	Distribution of major terrain types in the lower Redwood Creek basin[2] (Percent of basin area)	Distribution of major terrain types in the lower Redwood Creek basin[2] (ha)	Volume of material eroded by gullies in lower basin (m^3)
High yield	Coppercreek, Atwell.	260	31	3,340	868,400
Moderate yield	Devilscreek, Lack, Slidecreek.	65	32	3,450	224,250
Low yield	Trailhead, Fortyfour.	5	16	1,720	8,600
Undifferentiated	Unsampled	5–65	21	2,260	[3]56,500
Total			100	10,770	1,157,750

[1] Averaged values (rounded to the nearest 5 m^3/ha) based on gully yields from study sites where gully yield equals total gully volume divided by total site area within each terrain category (from table 6).

[2] Restricted to tractor-yarded areas logged since 1948 and roaded prairies (from table 9).

[3] We estimate that two-thirds of the undifferentiated soils will be classified in the low yield category and that the remainder will fall in the moderate yield range.

of widespread disruption of the natural grass cover by earthflow movement and road construction, gully yields accounted for about 75 percent of the total sediment production. Similarly, a preliminary sediment budget for the upper 175 km^2 of the Redwood Creek basin (Kelsey and others, 1981) indicates that fluvial erosion from hillslope areas may have accounted for nearly 70 percent of the sediment input to that reach of the Redwood Creek channel from 1956 to 1980.

In contrast to these high yield areas, gully erosion in the 197-km^2 lower Redwood Creek basin is estimated to have contributed about 25 percent less sediment than streamside landslides over approximately the same time period (1948–80) (table 11). This yield contrasts with the relative importance of fluvial sediment production measured in the Garrett Creek basin, a 10.8-km^2 tributary to Redwood Creek 11 km upstream of the Copper Creek

TABLE 11.—*Sediment sources, storage, and transport in the lower Redwood Creek basin (1954–80)*

Sediment source	Sediment quantity[1]		Sediment yield (Mg/km^2)
	(10^6 m^3)	(10^6 Mg)	
Gully erosion[2] (1948–80)	1.16	1.74	23,500 (Gully erosion, other fluvial erosion, and landslides combined)
Other fluvial erosion[3] (1948–80)	.35	.53	
Landslides along Redwood Creek and major tributaries[4] (1959–80)	1.57	2.36	
Sediment stored in major tributary channels[5] (as of 1981)	.35	.67	
Sediment stored in lower Redwood Creek channel[6] (1947–80)	3.10	5.95	
Sediment discharge of Redwood Creek at Orick, Calif.[7] (1954–80)	21.31	40.92	66,400
Sediment discharge of Redwood Creek at old south park boundary[7] (1954–80)	16.72	32.10	67,000

[1] Soil density of 1.50 g/cm^3 used for landslide and gully erosion; 1.92 g/cm^3 used for channel-stored sediments and transported sediment.
[2] Gully volumes from table 10 (this study).
[3] Hagans and Weaver, 1987; includes sheet erosion, rill erosion, and washed out (eroded) stream crossings.
[4] Kelsey and others (chap. J, this volume).
[5] Pitlick (chap. K, this volume).
[6] Madej (chap. O, this volume)
[7] J.R. Crippen, U.S. Geological Survey, written commun.; gaging stations at Orick and old south park boundary are shown on figure 1; data exclude yield from Prairie Creek.

study site. In Garrett Creek, fluvial sources delivered 62 percent of the total measured volume of eroded material (chap. M, this volume). Much of the Garrett Creek basin is underlain by the same incoherent geologic bedrock as high yield terrain in the lower Redwood Creek basin. For this reason, actual fluvial erosion during the measurement periods was 61 percent greater in Garrett Creek (18,500 Mg/km^2) than in the much larger lower Redwood Creek basin (11,500 Mg/km^2).

Over the last three decades, sediment yield from the upper Redwood Creek basin has been much higher than from downstream areas (table 11). Measured sediment production in the lower basin, including both landsliding and fluvial erosion, was only 11 percent of the measured sediment discharge at Orick. Significantly, 43 percent more sediment was stored in lower basin stream channels during this period than was produced by local erosion. U.S. Geological Survey gaging records show unit sediment yields for upstream areas (old south park boundary, table 11) to be approximately equal to that for the basin as a whole. Thus, measured hillslope erosion in the lower Redwood Creek basin directly contributes to channel aggradation and increases in the volume of channel-stored sediment. Gully erosion in the lower basin, while a significant source of sediment in that region, contributes much less to total yield than the volume of sediment derived from upstream areas and moved through, or stored in, the lower Redwood Creek channel.

IMPLICATIONS FOR DETERMINING GULLY EROSION IN LARGE BASINS

Detailed measurements of gully systems on the South Copper Creek study site indicate that only a very limited, select number of gullies need be measured to reliably estimate the total quantity of sediment produced by gullies on logged and roaded lands. For example, 95 percent of the gully erosion in this one study site can be accounted for by measuring only those gullies over 1.1 m^2 in cross-sectional area (table 8). In addition, only 51 percent of the cumulative length of gullies on the site require measurement. Similarly, by limiting an investigation to only those gullies having cross-sectional areas larger than 4.5 m^2, 81 percent of the total gully volume would be obtained by measuring less than 25 percent of the cumulative network length. The continuous function relating gully length, gully cross-sectional area, and cumulative volume of soil erosion is shown in figure 12.

Documentation of gully erosion on the study sites reveals almost precisely the same relationship as shown in figure 12 between gully size and contribution to sediment production. That is, gullies over 1.1 m^2 in cross-sectional area accounted for 94 percent of the total measured fluvial erosion, whereas those larger than 4.5 m^2 contributed 81 percent (table 8). By measuring these larger features, only 18 percent of the gullies, by length, would need to be measured (table 8).

Gully-derived sediment production from steepland coastal terrain similar to that of the lower Redwood Creek basin can be closely determined by limiting sediment source inventories to gullies formed by stream diversions at road and skid-trail crossings. In forested or grassland basins that have been subjected to road building or timber harvesting, gullies produced by diversions will include, almost without exception, all the largest fluvial erosion features to be found in a basin. An accurate estimate of sediment production can then be made by measuring only the largest gullies. These account for a large percentage of the total volume of fluvial erosion but only a small portion of the cumulative length of the gully network (fig. 12).

One factor that may help limit the areal scope of inventories could include the identification and elimination of areas that are likely to have low gully yields. These include sites dominated by gentle slopes, upper hillslope positions, cohesive or rocky soils, and few or no roads or streams. A second factor is the prediction of areas of potentially high yield. These include regions of moderate to steep slopes, lower hillslope positions, high

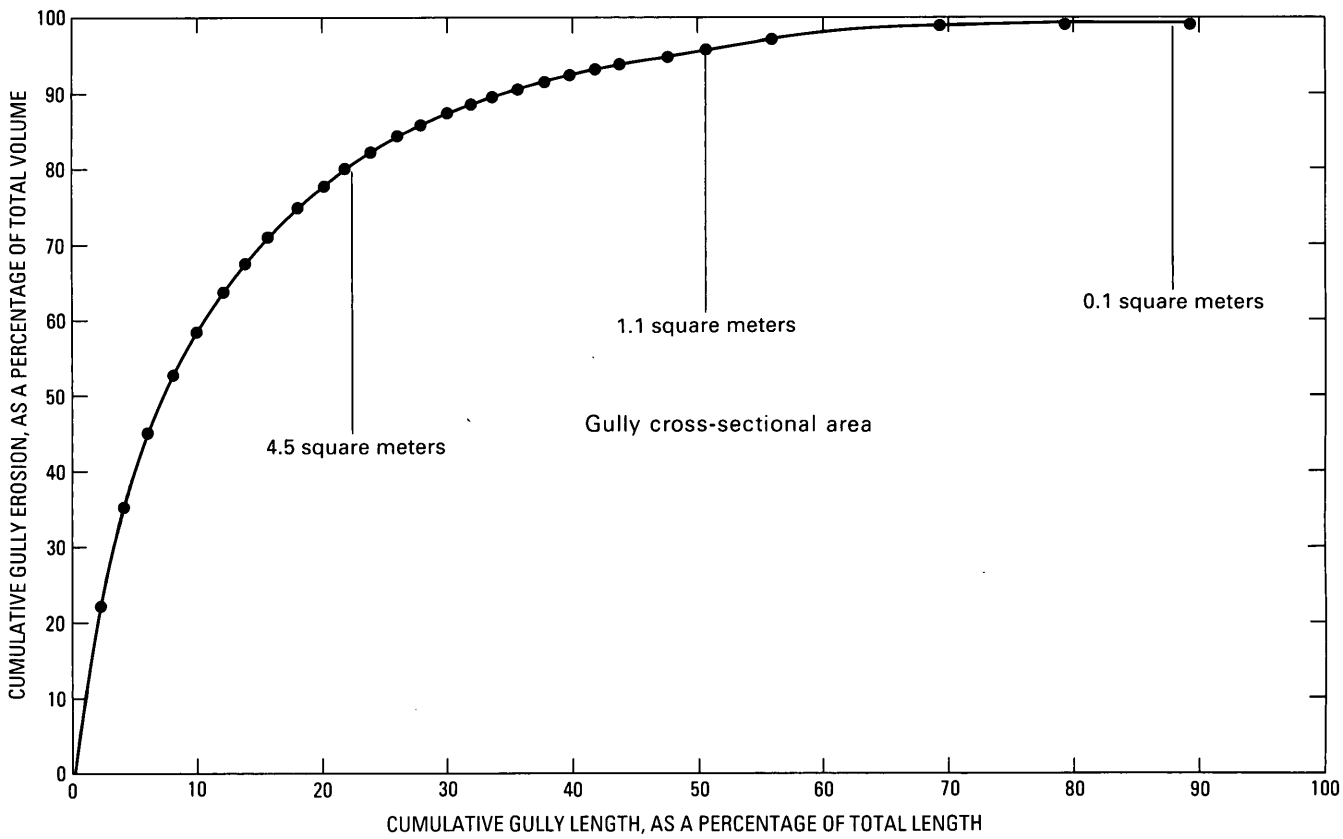


FIGURE 12.—Relations among cumulative gully length, gully cross-sectional area, and cumulative volume of gully erosion on the South Copper Creek study area. Gullies are plotted in order of descending cross-sectional area. (Largest cross sections are plotted first, followed by successively smaller sizes, and ending with the smallest gullies.) The relationship indicates that the largest gullies (for example, those over 4.5 m^2 in cross-sectional area) accounted for the bulk of total erosion, yet constituted a relatively small proportion of the total gully network. Small gullies were abundant but produced comparatively little sediment.

road and stream densities, old or abandoned (unmaintained) road systems, and erodible soils that are noncohesive and low in clay and in rock fragment content.

CONTROL AND PREVENTION OF GULLY EROSION ON LOGGED LANDS

Most of the increased gully-derived sediment production in the lower Redwood Creek basin could have been prevented by careful land management and erosion control practices. For example, such techniques as (1) excavating or dishing-out skid-trail stream crossings, (2) installing properly sized culverts wherever logging roads crossed channels of perennial, intermittent, or ephemeral streams, and (3) maintaining roads and drainage structures (especially during and immediately following storms) could have prevented approximately 85 percent, or more, of the documented gully erosion. To minimize long-term postharvest erosion from logged areas, roads can be either continually maintained or "put to bed" through the practices of water-barring, culvert removal, and stream-crossing excavations. These measures will virtually eliminate postharvest stream diversions and the resulting increase in gully-derived sediment production.

Logging activities constitute only one of the factors contributing to greatly increased rates of gully erosion. Factors such as climate, topography, soil type, and geology affect the susceptibility of logged land to postharvest erosion. Information gathered from study sites within the lower Redwood Creek basin suggests that the amount of postharvest fluvial erosion closely reflects specific logging practices, as well as physical site conditions.

On sites of equal erodibility, the severity of the erosional problems reflects not so much the actual logging methods as the practices employed to reduce stream diversions during and following the harvest operations. Postharvest erosion control, while potentially beneficial, is more costly and less effective than careful planning and prevention, since many of the sources of increased post-harvest sediment production may become inaccessible, uncontrollably large, or inactive over time.

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Geomorphic Analysis of Streamside Landslides in the Redwood Creek Basin, Northwestern California

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–J

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GEOMORPHIC ANALYSIS OF STREAMSIDE LANDSLIDES IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

By Harvey M. Kelsey,[1] Mike Coghlan,[2] John Pitlick,[3] and David Best[4]

ABSTRACT

Debris slides and earthflows are the two main types of mass movement in the Redwood Creek basin. All the large, volumetrically significant landslides occur on steep slopes of the inner gorge adjacent to the main channel and major tributaries. We measured all landslide contributions for the period 1954 to 1980. Examination of aerial photographs showed that almost all these landslides occurred before 1966. The storm of December 1964 triggered the majority of the pre-1966 landslides. Along the 100-km length of the main channel, landslides are concentrated in two high-input reaches, one in the uppermost watershed from kilometers 0 to 29, and one in the uppermost lower watershed from kilometers 58 to 77. High-input reaches are also reaches of highest stream gradient and reaches where clastic sedimentary rocks (as opposed to schist) crop out in the channel. A cumulative volume-frequency analysis of all main-stem landslides shows that the smallest 50 percent of the landslides account for only 5 percent of the total volume and the largest 10 percent of the landslides account for 60 percent of the total volume. For tributaries, the volume-frequency relations are similar, although more of the landslides are smaller, and the few large landslides are volumetrically more significant. Both sets of landslide data are log-normally distributed, although constraints on geomorphic process cause a flattening at the extremes of the distribution curves. The most significant constraint is the upper limit to landslide size imposed by the slope length of the inner gorge, which limits landslide length.

Virtually all major landslides were triggered by storms. However, storms and logging together are the causes of widespread landslide activity. The degree to which logging increased slope failure is speculative because of a lack of data on physical slope conditions at failure and on the rainfall and runoff during large storms. On the basis of results of the investigation, we speculate on the long-term influence of landslide activity on the geomorphic evolution of the watershed.

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INTRODUCTION

This paper presents results of a detailed investigation of streamside landslides in the 725-km^2 Redwood Creek basin (fig. 1). The investigation includes all major landslide activity during the period from 1954 to 1980. The major goals of the investigation are (1) to determine the volume of sediment produced by landslides, (2) to assess the temporal distribution of landslide contributions to the main channel of Redwood Creek relative to the occurrence of major storms, (3) to analyze the spatial distribution of landslide contributions along the 100-km length of the main channel of Redwood Creek, and (4) to evaluate the statistical distribution of landslide volumes along both the main stem and tributary channels of Redwood Creek. Landslide data presented in this paper include data for earthflows, which are discussed separately as appropriate.

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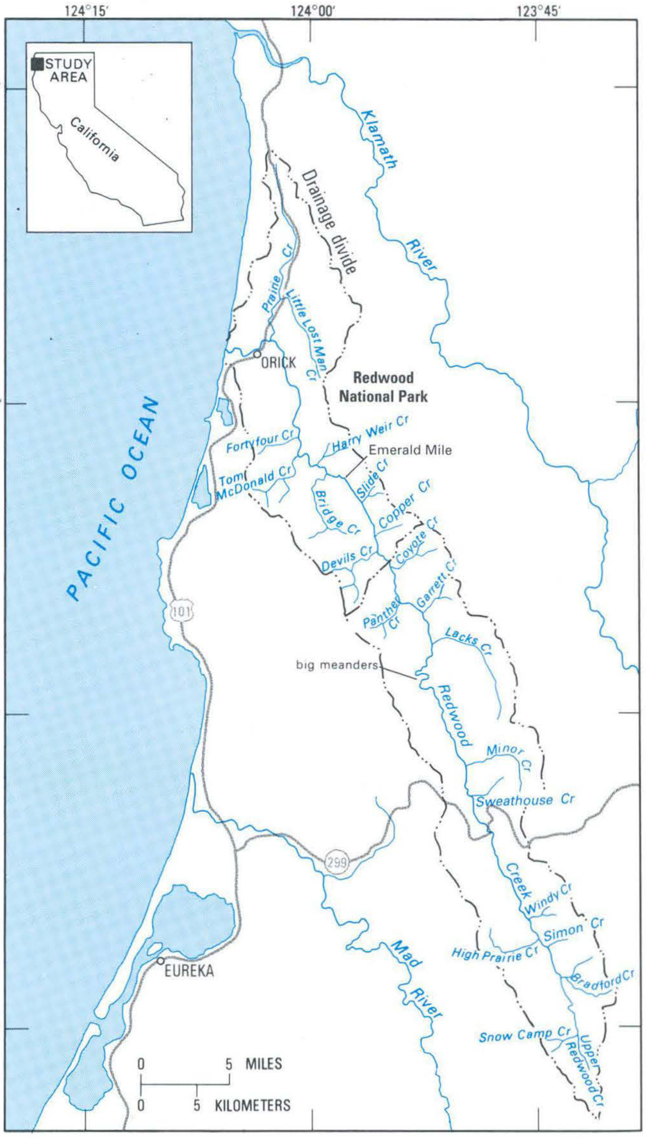

FIGURE 1.—Redwood Creek basin, showing major tributaries and reference locations.

Park for excellent assistance. Annie Kubert drafted the figures. This paper was reviewed by Jerome DeGraff, Mary Ann Madej, William W. Weaver, and Robert R. Ziemer.

BACKGROUND

The Redwood Creek basin is underlain by the Franciscan assemblage, which is Late Jurassic to Cretaceous in age (Harden and others, 1982) and consists of mudstone, siltstone, schist, and scattered blocks of greenstone and chert. The basin is bisected by the Grogan fault. The main stem of Redwood Creek closely follows the trend of the fault zone for the upper 78 km of its 100-km length. Slopes west of the Grogan fault are underlain by schist, and slopes east of the fault are underlain by sandstone and mudstone (Harden and others, 1982). Both rock units are deformed by numerous fractures and shear zones, and the rock incompetence due to this deformation contributes to the high erodibility of the watershed.

The landscape of the Redwood Creek basin dramatically changed in the 28-year period between 1950 and 1978. An essentially unlogged watershed underwent extensive timber harvesting. Before 1950, only 8 percent of the coniferous forests in the basin had been logged, and by 1978, logging had eliminated 81 percent of these forests (chap. C, this volume). Two major storms occurred in northern California in 1955 and 1964, followed by later storms equally as intense in Redwood Creek, though not as regionally significant (Harden and others, 1978). The most obvious erosional change was the increase in incidences of streamside landsliding. Colman (1973) analyzed landslides in the Redwood Creek basin by individually documenting landslide history for 363 slides along the 100-km main channel. He showed that past mass-movement processes have sculpted many Redwood Creek hillslopes. He clearly documented an increase in mass-movement processes in the years between 1948 and 1973 and cited both timber harvesting and severe floods as causes of this increase. However, Colman stressed that the concentration of landslides adjacent to stream channels and the temporal distribution of landsliding suggest that storms had the most direct effect on the increased slide activity.

Prompted by the relation of recent storms to the streamside landslides in Redwood Creek, Harden and others (1978) investigated historic major storms in the Redwood region and concluded that the location and timing of streamside landslides are influenced both by logging history and by variations in the localized intensity of storms. They further noted that in the late 19th century a series of severe storms occurred in the Redwood Creek watershed that appear to have been as intense as those of the period from 1950 to 1975. These storms, well prior to any timber harvesting, did not initiate extensive streamside landsliding (Harden and others, 1978).

Furbish and Rice (1983) studied the incidence of debris slides in steeplands of northern California in terrain similar to that of Redwood Creek by using discriminant analysis to distinguish slide sites from stable slopes. Their results indicated that areas most prone to failure are immediately downslope from major breaks in slope, adjacent to actively eroding channels, and within topographic depressions. Furbish and Rice also found that 95 percent of the debris slides in his study area occurred on streamside hillslopes that were 30° or steeper, in a slope

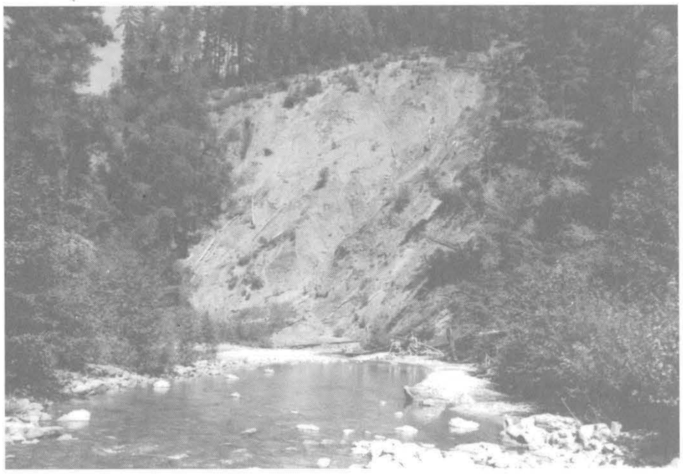

FIGURE 2.—Upstream view of a typical streamside debris slide along the main channel of Redwood Creek. This debris slide is at kilometer 16.9 on the main channel, 2.0 km downstream of Lake Prairie Creek, and is the 14th largest landslide of a total of 877.

zone known in northern California as the inner gorge. The inner gorge (Kelsey, 1988) is formed over time by coalescing debris slides that deliver sediment directly to the channel.

TYPES OF MASS MOVEMENT

Many types of mass movement occur on the steep slopes bordering the tributaries and the main stem of Redwood Creek. In this report, we treat three main categories of mass-movement features on the basis of morphology and process: debris slides, streambank failures, and earthflows. Debris slides, and the closely related debris avalanches, are almost exclusively confined to the steep slopes of the inner gorge. Streambank failures are not confined to the inner gorge but rather are distributed throughout the basin. Earthflows are located mainly in the midbasin area where incompetent rock units occur adjacent to Redwood Creek. Virtually all landslides in the Redwood Creek basin occur along streamsides and deliver sediment directly to perennial channels. Unlike other nearby watersheds where major debris avalanches occurred at headwaters between 1954 and 1980 (Buer and James, 1979; Kelsey, 1980), there was an insignificant amount of avalanching in the headwaters of Redwood Creek basin for the same period.

DEBRIS SLIDES AND STREAMBANK FAILURES

The most common streamside landslides in the Redwood Creek basin are debris slides (fig. 2). These slides are shallow (0.5–2.0 m) relative to their areal extent. Movement rates are rapid, and the slides expose a fresh sliding plane after failure. The long axis of the slide is most often perpendicular to slope contours. These slides generally occur in preexisting slope hollows that were probably sites of previous sliding.

Parent materials for debris slides are mainly fractured sandstones and metasandstones. The slide material consists of fractured rock with a thin veneer of poorly developed soil. The failure plane most often occurs within the fractured rock zone below the depth of tree root penetration; this location suggests that the effective shear strength provided by roots is mainly a tensile strength that prevents rupture at the surface.

Streambank failures, in contrast to the larger debris slides, seldom extend more than 50 m upslope from the channel edge. Streambank failures contribute sediment along the entire main stem of Redwood Creek, but they are most numerous in the lower part of the basin. Unlike other landslides, streambank failures tend to coalesce into a linear, basal-slope zone of streambank instability rather than being manifested as discrete landslides extending up the hillslope. They are more the product of streambank undercutting, whereas discrete landslides often result from saturation of a steep, inner-gorge slope by an intensive storm. Approximately 99 percent of the total volume of material eroded by mass-movement processes comes from debris slides and streambank failures. The transition from debris slides to streambank erosion is gradual, and because of the small volumes involved in streambank erosion, its sediment contribution is relatively minor.

EARTHFLOW LANDSLIDES

Earthflows are slowly moving landslides that move seasonally each winter after being thoroughly wetted by rainstorms. Seasonal movement ranges from a few centimeters to a few meters, and the raw, unvegetated toe slope is annually eroded by Redwood Creek as the earthflow moves toward the channel (fig. 3). These landslides have been described by Kelsey (1978), and both Harden and others (1978) and Nolan and Janda (chap. F, this volume) discuss rates of earthflow movement in the Redwood Creek basin.

Figure 4 shows the locations of earthflow activity in the Redwood Creek basin during the 1955 to 1980 study. Of the 16 active earthflows, all except 1 occur along the right bank of Redwood Creek along two distinct reaches of the creek. All earthflows except two occur on a west-facing slope exposure, and their distribution is strongly controlled by the geology. In both reaches, the Grogan fault zone coincides with the steep basal hillslopes next to the main channel, and the west-southwest slope exposures along the channel are underlain by sandstone of the Incoherent unit of Coyote Creek.

FIGURE 3.—The raw, unvegetated toe of the Sweathouse Creek earthflow, which is annually eroded by Redwood Creek as the earthflow toe moves in to the channel. Height of toe is approximately 20 m.

Despite their high visibility and recognition as an erosion source, earthflows are not major contributors to sediment production compared to debris slides or streambank failures. Earthflows produced 1 percent of the total sediment contributed by streamside slope movements to the main channel during the study period.

VOLUMETRIC DATA

EXTENT OF COVERAGE

We measured all landslides and earthflows along the main channel of Redwood Creek. Those failures along the upper 34.4 km of the main channel were measured in the field, and the rest were measured from aerial photographs. Landslides and earthflows into major Redwood Creek tributaries were also investigated (chap. K, this volume), and the data for the tributaries were used in determining the total debris contribution to the main channel of Redwood Creek. On the main stem, we measured the volumes of 877 failures, 580 by field measurement and the remainder by measurement on photographs; on the tributaries we measured 975 failures, all except 7 by field measurement.

TECHNIQUES FOR MEASUREMENT OF DEBRIS SLIDES AND STREAMBANK FAILURES

In the field, we determined the volume of landslide-derived erosion by measuring the depressions left on the hillslopes after failure. Latest movement on most of the landslides postdates the early 1960's, and landslide scars measured during the 1980 field season were still recog-

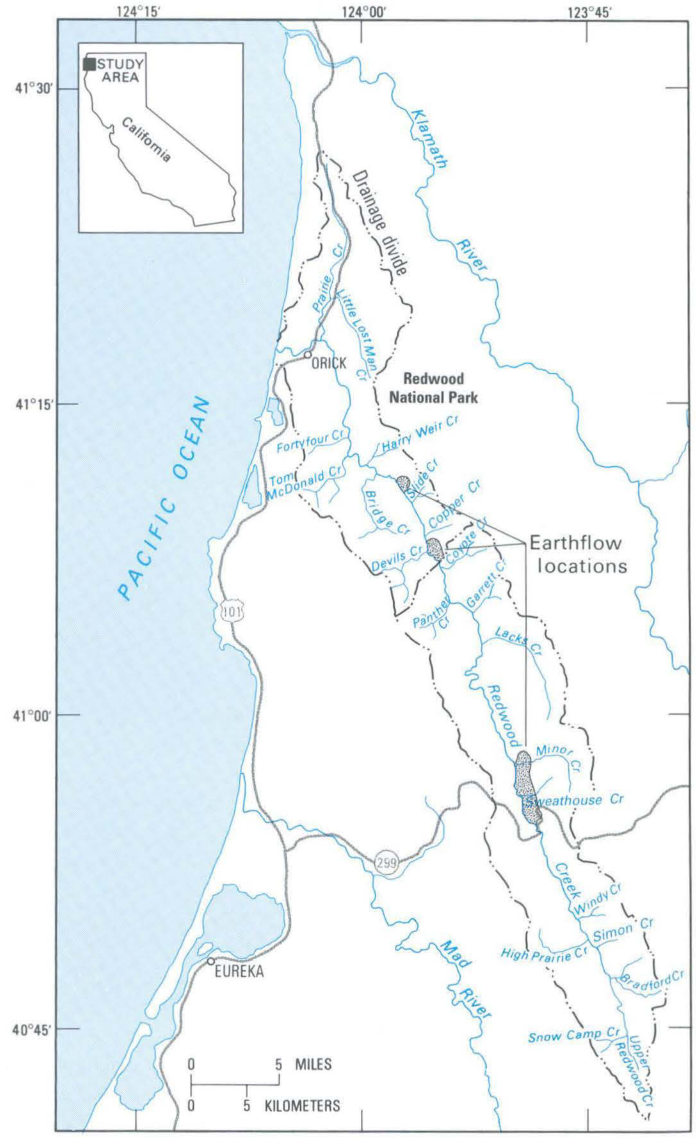

FIGURE 4.—Reaches where earthflows are abundant on the right bank of Redwood Creek (stippled areas). With one exception (the northernmost Counts Hill earthflow), the 16 earthflows occur along two distinct reaches of Redwood Creek.

nizable both in the field and on 1978 aerial photographs. Extensive revegetation, however, made field measurement difficult in many instances. Both 1966 and 1978 photographs were used during fieldwork to ensure that revegetation did not obscure the full extent of the landslides. Depth of the landslide areas was measured with a tape and a rangefinder. Landslide depth was estimated by visually reconstructing the original hillslope shape prior to failure and estimating the average thickness of material lost. This procedure was usually straightforward. Only that material determined to have actually been delivered to the channel was counted, as there were numerous landslide sites where colluvial debris was still perched on the hillslope.

Estimating depth was the greatest potential source of error in field measurement. Individual slide volumes could be in error by as much as 100 percent on those hillslopes where outlines of the original topography were no longer apparent. Ambiguities of this sort were the exception rather than the rule, however, because head and sidewall scarps were clearly visible in most instances. In addition, we believe that, because of our tendency to be conservative when making depth estimates, our measurements may tend to underestimate rather than overestimate the actual slide volumes.

Landslide volumes along the lower two-thirds of the main channel were measured from aerial photographs having a scale of 1:6,000. Scales for the photographs were determined from measured ground distances transferred to each photograph. We used time-sequential aerial photographs taken in 1954, 1958, 1966, 1974, and 1978 to measure landslide volume and to separate landslide contribution by time interval. A series of 1948 aerial photographs that cover the entire length of Redwood Creek documents physical conditions there before major storms and the start of logging.

For analysis of the timing of sediment contribution by landslides, the two most important indicators were the landslides visible on the 1966 photographs, taken 18 months after the December 1964 storm, and the new or expanded landslides first visible on the 1974 and 1978 photographs. Pre-1966 landslides refer to all landslides that presumably occurred before, during, or shortly after the 1964 storm.

MEASUREMENT TECHNIQUE FOR EARTHFLOWS

The volume of material contributed by earthflows was computed by measuring the toe area of the earthflow along the streambank and the total movement of the toe into the channel during the study period. Total movement was either measured from aerial photographs or estimated from measurements of annual movement rates for selected earthflows in the Redwood Creek basin (Harden and others, 1978).

VOLUMES OF ERODED MATERIAL

Table 1 shows volumes of material eroded by landslides and earthflows for 1954 through 1980. The data show that, along the main stem, 84 percent of the total volume of material eroded landslides occurred in the period from 1954 to 1966. For both main-stem and tributary landslides, 82 percent of total volume of eroded material occurred in the period from 1954 to 1966.

TABLE 1.—*Volume of material eroded by landslides and earthflows, Redwood Creek basin*

Period of measurement	Main stem only[1] (m^3)	Main stem and tributaries[2] (m^3)
1954–66	3,343,700	5,246,700
1966–80	656,400	1,168,931
1954–80	4,000,100	6,415,600

[1] 877 sites.
[2] 1,952 sites.

PRE-1950 LANDSLIDES

In 1948, the timberlands within the Redwood Creek watershed were largely untouched, and the slopes adjacent to Redwood Creek were totally unlogged. The only road across the watershed was State Route 299, which split the upper one-third of the basin from the lower two-thirds (fig. 1). As shown on 1:12,000-scale aerial photographs taken in 1948, the slopes adjacent to the main channel above State Route 299 were completely unlogged, and the only watershed development consisted of two powerlines crossing from east to west and a few small roads. We surveyed the uppermost 17 km along the main stem of Redwood Creek by using the 1948 aerial photographs to determine the condition of hillslopes that would later be subject to major streamside landslides. Along this 17-km main-stem channel reach, 83 percent of the slopes that became landslides by 1966 were densely forested in 1948, while 6 percent showed evidence of a small landslide scar or a bare area at the toe of a slope, and 11 percent were already landslides of significant size. Several small landslide scars were contained within older, much larger revegetated scars. The survey of 1948 aerial photographs showed no scars from major landslide activity in the mid-19th century, despite well-documented evidence that major storms occurred in the latter part of the 19th century, especially in 1861 (Harden and others, 1978; Coghlan, 1984).

DISTRIBUTION OF LANDSLIDES

Analysis of the geographic distribution of slope failures along Redwood Creek shows two channel reaches of high landslide-derived input from kilometers 0 to 29 and from kilometers 58 to 77 (fig. 5*A*). Data for landslide-derived inputs include the inputs for earthflows, which contributed 1 percent of the total sediment volume contributed by streamside slope movements to the main channel during the study period. Reaches of low input extend from kilometers 29 to 58 (State Route 299 bridge to downstream end of big meanders; fig. 1) and from kilometers 77 to the mouth (from the Emerald Mile downstream to the mouth) (fig. 1). The amount of landslide input in the two high-volume reaches, 62,000

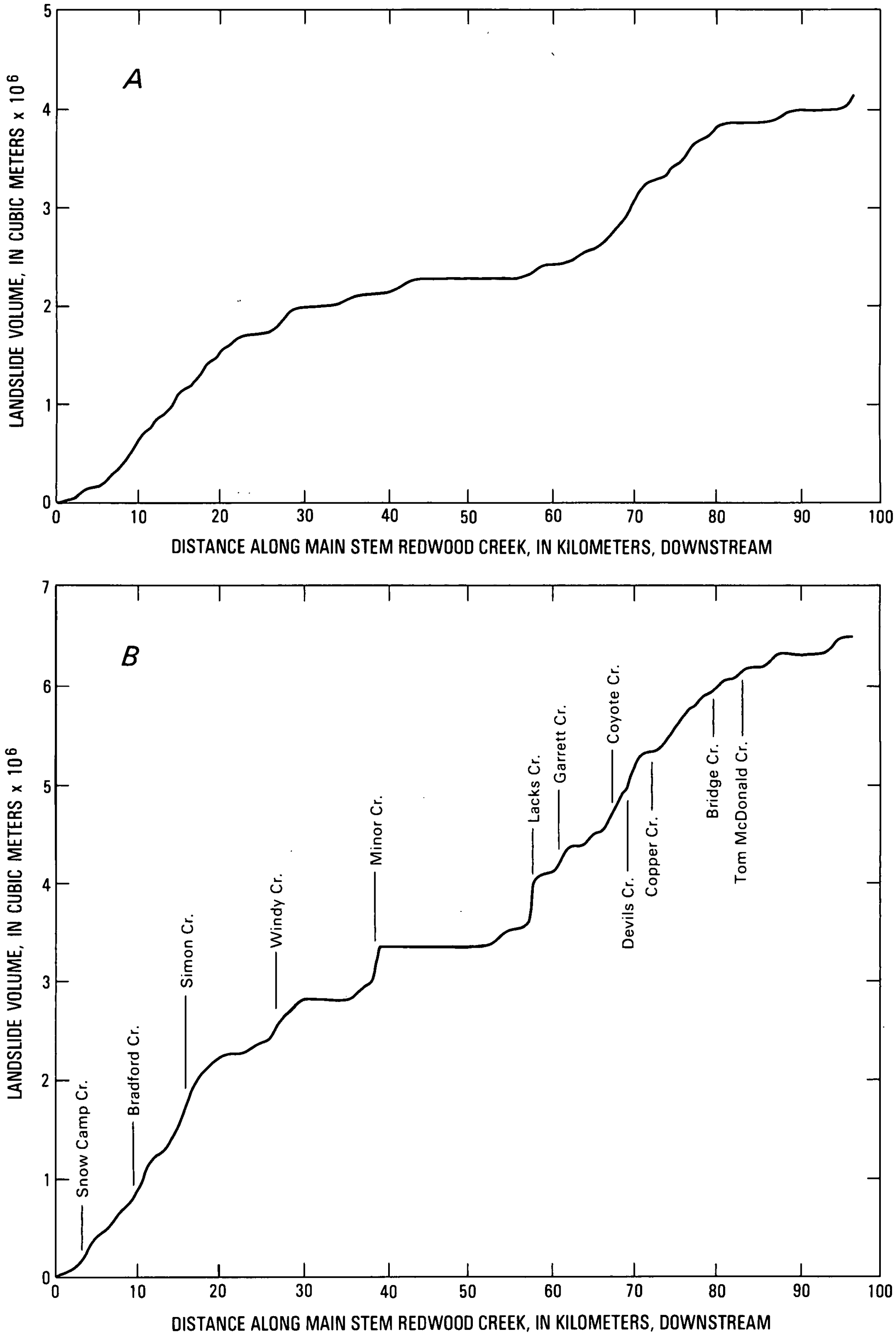

FIGURE 5.—Volume of sediment, cumulative through distance downstream along main-stem Redwood Creek, contributed by landslides for the period 1954–80. *A*, Volume contributed only by landslides along main stem, and *B*, Volume contributed by landslides along main stem and tributaries; location of tributary mouths is shown on graph. Note the two reaches of high input, kilometers 0 to 29 and kilometers 58 to 77.

m^3/km, is identical. Landslide input distribution is different when data from tributaries are included (fig. 5*B*). Tributaries rapidly transport approximately 80 percent of all landslide-derived material to the main stem (chap. K, this volume). Because little landslide debris is stored in tributary channels, tributary landslides are indicated as a single point-source contribution to the main stem at the tributary mouth (fig. 5*B*). Twenty-two tributaries are included in the cumulative volume totals, and these tributaries increased the landslide-derived sediment contribution to the main stem by 60 percent. Landslides along 12 of the tributaries (fig. 5*B*) contributed enough debris to noticeably influence the slope of the cumulative curve. Snow Camp Creek, Bradford Creek, Simon Creek, Windy Creek, Minor Creek, and especially Lacks Creek substantially increased the cumulative total of landslide-derived detritus delivered to the main stem.

Landslide distribution varies systematically with the topography and geology of the Redwood Creek basin. The high-input reach from kilometers 0 to 29 parallels the Grogan fault, and the stream course is cut in sandstone just east of the fault. The valley is narrow and has a well-defined inner gorge. The reach of low input, from kilometers 29 to 58 begins where the Grogan fault trace obliquely crosses the creek and the stream channel is cut in schist (Harden and others, 1982). In this low-impact reach, valley width increases and an inner gorge is absent or poorly developed. In the lower basin, along the high-input reach (kilometers 58–77), the inner gorge becomes more obvious again and valley width narrows. Farther downstream, in the low-input reach from kilometer 77 to the mouth, the stream course diverges west, away from the Grogan fault trace and into the schist. In this lower reach, the valley continually widens, and an inner gorge is absent or poorly developed.

According to this distribution, high-input reaches are generally in the steeper, inner gorge reaches composed of sandstone, and low-input reaches are generally in schist. Though schist bounds the main stem of Redwood Creek for 63 percent of its length above Orick, only 41 percent of the volume of landslide-derived contributions to the main stem comes from schist slopes. For tributaries, only 23 percent of the landslide-derived contributions originate in schist basins.

Landslide distribution has a systematic relationship to the distribution of channel-stored sediment. Landslides are one of the significant sources of the coarse sediment stored in the channel. Figure 6 shows the spatial relation between reaches of high landslide-derived sediment input and reaches of marked net increase in channel sediment storage. Channel storage data are from Madej (chap. O, this volume). Figure 6 shows that the boundaries of segments A through D separate reaches of high and low input of landslide-derived material. Reaches of high input are those where storage is relatively low, and reaches of low input are those where sediment storage increases most rapidly. Madej (chap. O, this volume) shows that channel storage is best correlated with valley width and stream gradient, the wider, lower gradient reaches being the areas of maximum increases in storage. Therefore, low-input reaches are generally the wide, low-gradient reaches, and the high-input reaches are the narrow, higher gradient reaches having less tendency to store sediment.

CUMULATIVE VOLUME-PERCENT RELATIONS FOR LANDSLIDES

How large must an individual landslide be to contribute significantly to the total volume of landslide-erosed material? Cumulative volume-frequency analyses for 877 landslides along the main stem of Redwood Creek (fig. 7*A*) and for 975 tributary landslides (fig. 7*B*) indicate the relative importance of the smallest and the largest landslides. Along the main stem, landslides having volumes of less than 1,280 m^3 accounted for 53 percent of the landslides measured but for only 5 percent of the total measured volume. The main stem frequency curve (fig. 7*A*) also indicates that the largest 10 percent of the landslides measured account for 60 percent of total landslide volume (4×10^6 m^3, see table 1).

For tributaries, the volume frequency relations are similar to those for the main stem, though there are more small landslides, and the few large landslides are volumetrically more significant. Landslides of less than 708 m^3 account for 61 percent of total volume (fig. 7*B*).

In the main stem and the tributaries, 95 percent of the volume of landslide-derived material is contributed by well less than half the total number of landslides. Therefore, all erosionally significant landslides are large enough to be visible on 1:6,000- and 1:12,000-scale aerial photographs, and landslides hidden by tree cover are volumetrically insignificant.

TEST FOR LOG-NORMAL DISTRIBUTION OF MAIN-STEM LANDSLIDES

Normal probability plots of the logarithm of volumes for 877 main-stem landslides (fig. 8*A*) and 975 tributary landslides (fig. 8*B*) show that in both cases the plotted points approximate a straight line, though the upper and lower ends of each curve are deflected to give a subtle S curve. Because the data plot in a straight trend, both sets of landslide volumes appear to be log-normally distributed. We performed both a chi square test and a Kolmogorov-Smirnov test on both data sets to test the

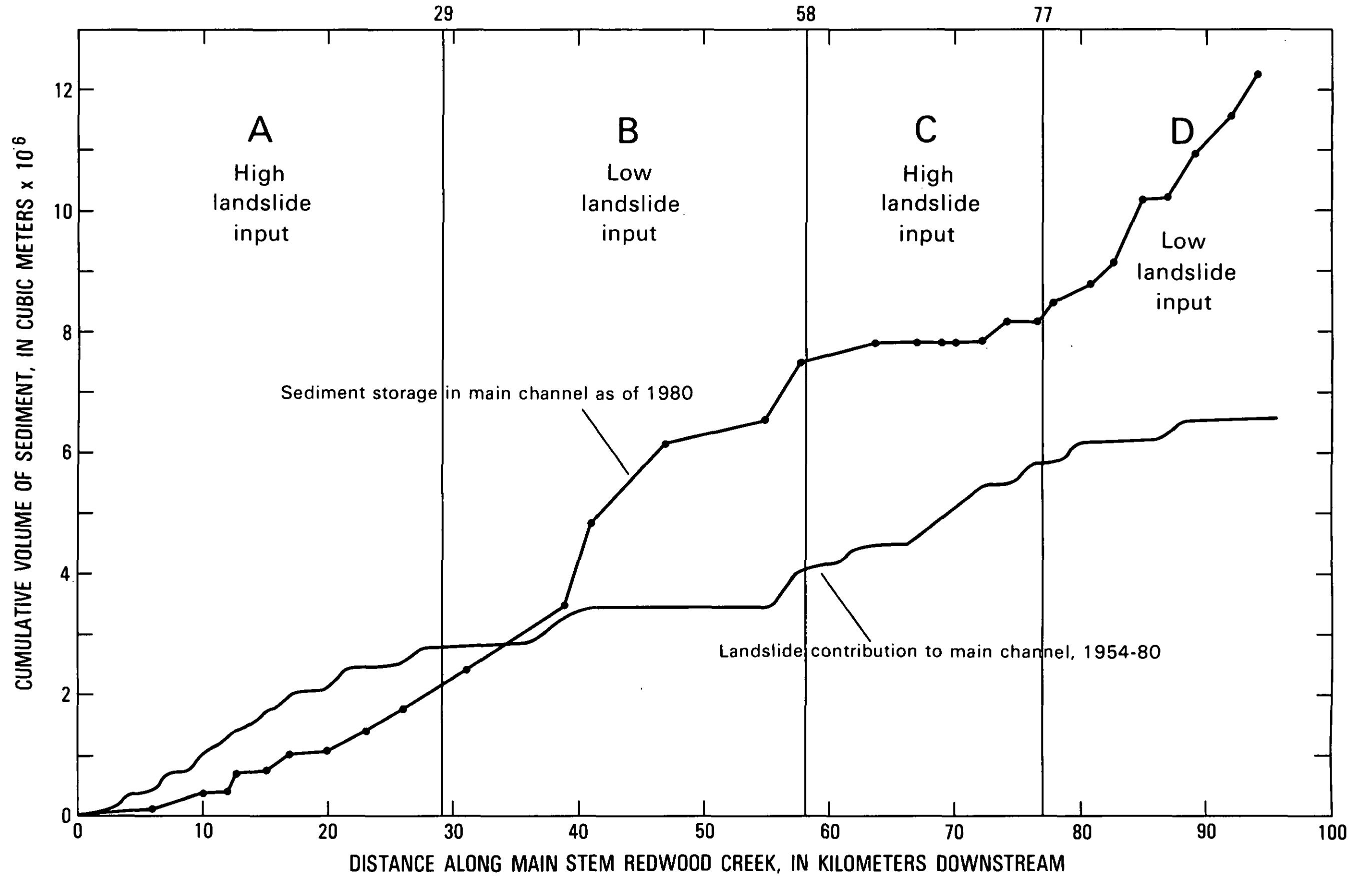

FIGURE 6.—Comparison of volume of sediment stored in main channel and volume of sediment contributed by landslides to main channel, both cumulative through distance downstream along the main channel of Redwood Creek. Reaches from kilometers 0 to 29 and 58 to 77 are high-input reaches but reaches of low sediment storage. Reaches from kilometers 20 to 58 and from kilometer 77 to the mouth are reaches of low input where sediment storage increases most rapidly.

null hypothesis that landslide volumes approximate a log-normal distribution. For both tests we could not reject the null hypothesis.

GEOMORPHIC IMPLICATIONS OF THE LOG-NORMAL DISTRIBUTION OF LANDSLIDE VOLUMES IN THE REDWOOD CREEK BASIN

The geomorphic significance of the apparent log-normal distribution of landslide volumes lies in the poor fit at the upper and lower ends of the distribution curve (fig. 8). These extremes probably represent constraints on landslide size due to geomorphic process. At the lower end, the volumes of streamside landslides do not reach zero, but rather there are many small landslide and bank erosion events. These small slope failures are more numerous than in a log-normal distribution. However, the very small failures are absent from the distribution curve because steep streambank slopes impose a lower limit of 10 m^3 on the size of most failures. However, all sizes of failures do occur, down to volumes less than 1 m^3 of bank erosion.

The flat upper ends of the curves in figure 8 indicate an upper limit to landslide size due to the constraint of inner-gorge slope length. Above the break in slope of the inner gorge, landslide scarps advance headward much more slowly, effectively imposing an upper limit on landslide size. The flat upper end of the log-normal distribution emphasizes the importance of the break in slope transition at the top of the inner gorge.

FACTORS INFLUENCING THE TIMING OF LANDSLIDES

Virtually all landslides occur during large storms. We measured the volume of landslides that occurred from 1954 to 1966 and the total landslide volume contributed to the main channel from 1954 to 1980 (fig. 9). Most of the pre-June 1966 landslide volume entered the channel during the 1964 storm. About half the 1964 landslides existed before December 1964, but they were greatly enlarged that December. Approximately 18 percent of

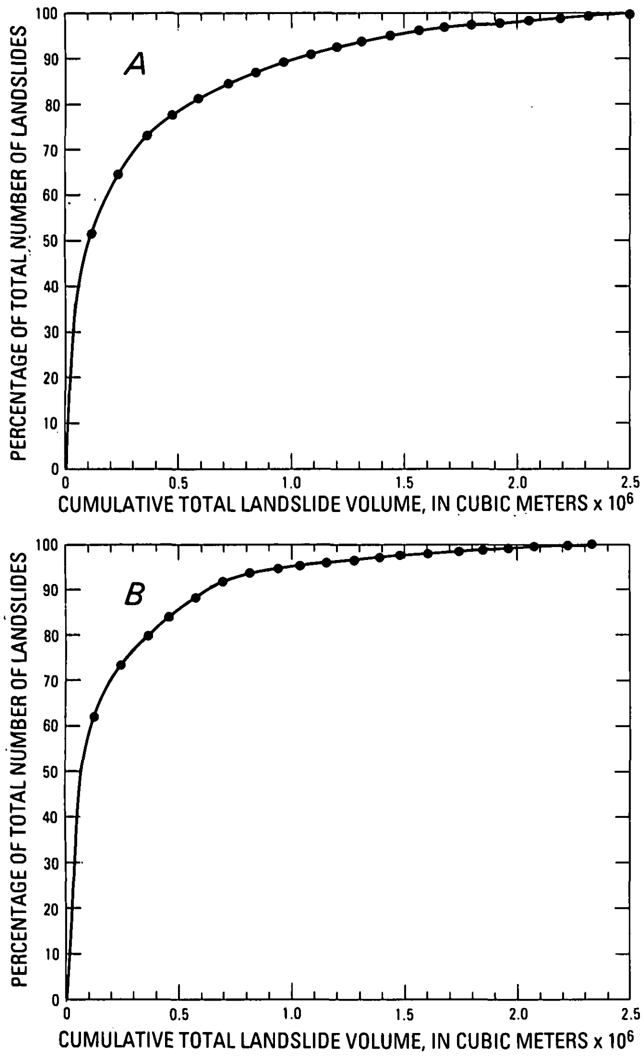

FIGURE 7.—Cumulative volume-frequency relations for streamside landslides. *A*, Landslides along the main stem of Redwood Creek, n=877. *B*, Landslides along tributary channels, n=975.

the total landslides occurred from 1966 to 1980 (fig. 9), and most all the 1966–80 slope failures occurred downstream from kilometer 12 and were concentrated in the 13-km reach starting just below Lacks Creek (km 58) and continuing to 3 km upstream of Bridge Creek (km 76) (fig. 1).

For the 1964 storm, it is not possible to analyze the relative importance of the storm and of land use because the exact physical factors causing the failures are not known. However, for landslides along the upper 35 km of the main stem where the 1964 landslide damage was especially severe, logging and (or) logging roads were present on a vast majority of the sites (table 2). Pitlick (chap. K, this volume) also shows that, for Redwood Creek tributaries, 80 percent of the total landslide volume came from slopes logged prior to failure.

TABLE 2.—*Logging and logging roads on landslide sites along the upper 35 km of main-stem Redwood Creek, 1954–66*

Reach (km downstream from headwaters)	No. of slides	Landslide volume (m^3)	No. of slides with no roads or logging	No. of slides with no roads	No. of slides with one or more roads
0–8.35	98	115,700	4	24	50
8.35–10.55	50	133,100	30	34	16
10.55–11.65	23	78,800	4	5	18
11.65–13.25	39	193,900	0	9	30
13.25–14.25	25	42,200	7	7	16
14.65–16.70	45	271,600	20	21	24
16.70–18.35	23	146,800	6	11	12
18.35–20.15	26	195,000	0	3	23
20.15–21.65	25	119,400	12	16	9
21.65–25.25	64	265,800	11	24	9
25.25–27.60	46	81,900	10	20	7
27.60–30.60	60	103,700	14	23	15
30.60–33.40	39	184,600	3	10	22
33.40–35.75	23	58,400	0	2	5

The 1972 and 1975 storms caused more hillslope erosion in the mid-to-lower basin than in the headwater reaches. The post-1966 landslides in the lower basin are most likely a combined result of these storms (Harden and others, 1978). By the late 1960's, most of the timber harvest activity was concentrated in the lower watershed (chap. C, this volume), and logging-related road construction near the main channel and tributary channels increased the incidence of landslides during the 1972 and 1975 storms.

LANDSLIDE CAUSES AND GEOMORPHIC THRESHOLDS

Recent research has suggested that geomorphic processes change due to the crossing of thresholds (Schumm, 1979). The threshold for landslides occurs when slope shear strength decreases to the magnitude of the downslope driving forces. The most important factors influencing slope shear strength are normal stress, angle of internal friction, soil cohesion, and the height of the water table (Carson, 1971). The height of the water table determines the pore water pressure, which acts in opposition to the normal stress. Cohesion is the soil strength that remains when the effective stress (normal stress minus pore water effects) is zero. In forested soils, cohesion is highly dependent on reinforcement by the root network (Burroughs and Thomas, 1977). The height of the water table is directly related to precipitation and storm size; it is the most transient of these factors and acts as a trigger in most north coast landslides. In addition, over longer periods of time, average soil shear strength gradually decreases due to weathering.

The number and spatial distribution of places where landslide threshold conditions occur determine the severity of landsliding. The 1964 storm in the upper watershed pushed physical conditions on many lower hillslopes past this threshold, causing extensive slope failures. In the

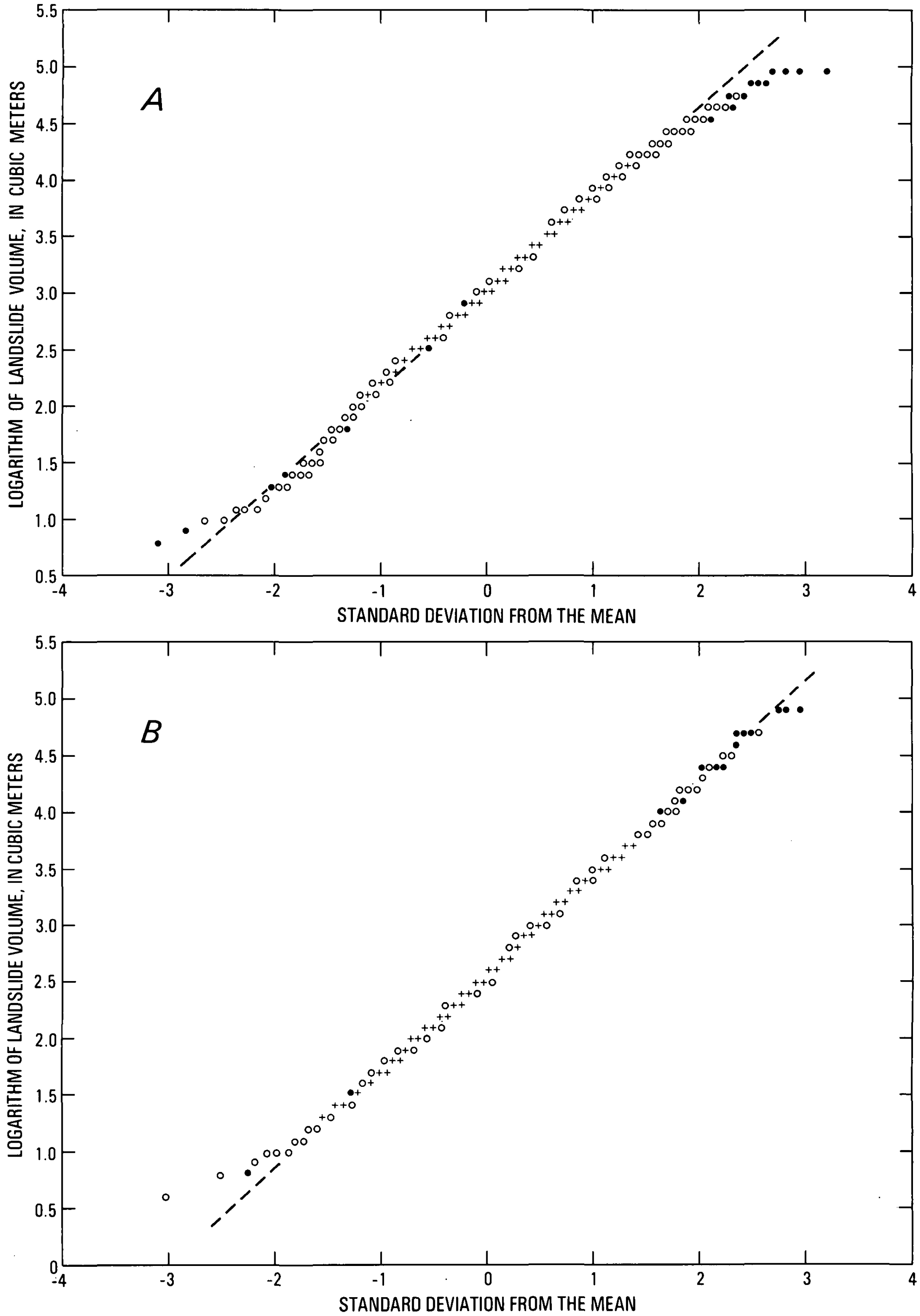

FIGURE 8.—Normal probability plot of the logarithm of landslide volume (m^3). *A*, Landslides along the main stem of Redwood Creek, n=877. *B*, Landslides along tributary channels, n=975. Solid dots=1 landslide; open dots=2–9 landslides; crosses=≥10 landslides.

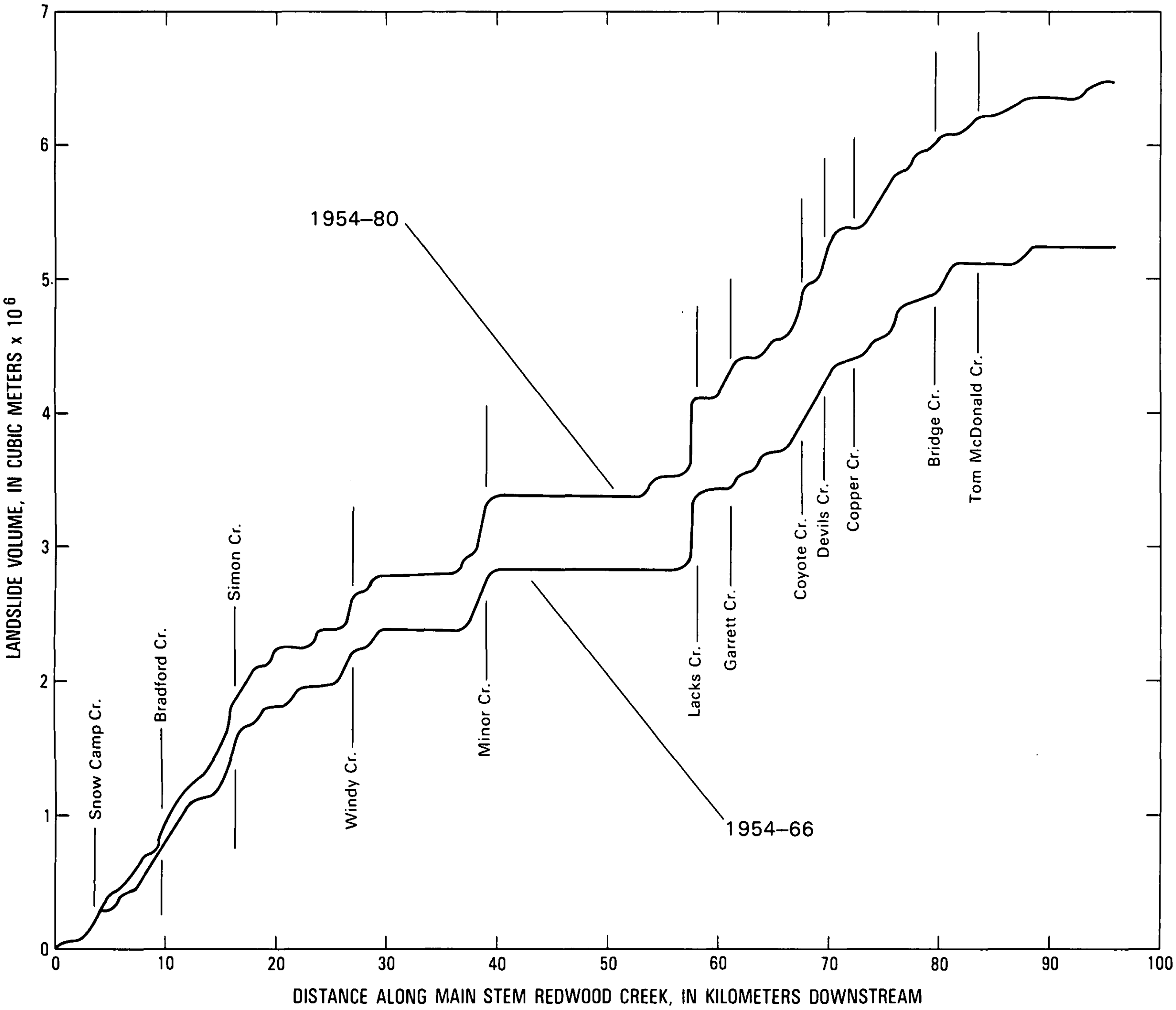

FIGURE 9.—Volume of landslide contributions for 1954–66 and for 1954–80 as accumulated in a downstream direction, including contributions from tributaries.

upper watershed, extensive logging during the 1950's had resulted in the loss of root-related cohesion on many hillslopes. Additionally, road construction both increased slope angles on road cuts and rerouted surface drainage. Shortly thereafter, the 1964 storm occurred and brought prolonged and, at times, high-intensity rainfall.

We speculate that it was the combination of individual, high-intensity storms and the widespread slope-weakening effects of logging that was responsible for the severe landslides of 1964. Precipitation totals in the upper watershed appear to have been very high during this storm (Harden and others, 1978). Though detailed storm data for December 1964 are not available, the internal structure of a large storm in mountainous mid-latitude areas is highly variable. These storms contain short-lived high intensity precipitation pulses that appear as rain bands or even more localized precipitation cells (Houze and others, 1976; Amorocho and Wu, 1977). During a large storm, the size of a single cell may determine the spatial limit of streamside slope failures. The concentration of debris slides along reaches of Redwood Creek suggests the existence of such cells during the 1965 storm.

In sum, road-building activities and logging both reduce slope shear strength. These activities alone are not sufficient to cause failure in most cases, but major storms are the events that push physical conditions past a stability threshold. It is likely that the level of that threshold is significantly lower on slopes that have roads or have been recently logged. Storms also may cause widespread failure in areas not subjected to human activity, but the intimate association of logging and landsliding suggests that, in Redwood Creek, timber harvest played a decided role in many failures.

LONG-TERM PERSPECTIVE: LANDSLIDE FREQUENCY CHANGES AND SOIL DENUDATION

The geomorphic significance of the 1954 to 1980 episode of landsliding on Redwood Creek can best be appreciated in a long-term perspective. Major floods occurred in approximately 1590 and 1750 on the East Fork of Willow Creek (Helley and LaMarche, 1973), which is 10 km east of the midpoint of the Redwood Creek drainage. Deposits in the East Fork suggest that flood peaks in both 1590 and 1735 were at least as high as those of 1964 in that drainage. Given the proximity of upper Redwood Creek, high storm intensities for the earlier dates must have occurred there too. However, evidence of large landslides in upper Redwood Creek appears to be at least 200–300 years old, and no major deposition related to the storm of 1861 is recorded in the channel. The 1964 landslides in Redwood Creek demonstrate a different geomorphic response to the more recent storm compared to similar, earlier storms.

Both land-management and climatic variables presently determine landslide frequency. On mountainous slopes managed for timber production, slope shear strength can be kept at a reduced level by periodic but repeated logging and by permanently maintained roads that locally increase slope angle. Without proper land management, failure frequency will increase even if storm frequency does not fundamentally change, resulting in higher rates of landslide erosion.

Higher rates of erosion can alter the conditions of soil denudation. The development and preservation of regolith on top of bedrock depend on weathering rates that proceed faster than, or equal to, the rate of denudation. On forested slopes in Redwood Creek having a regolith that supports vegetation, denudation rates are presently limited by regolith-transporting processes, which include debris slides. Were rates of erosion to increase, more regolith would be stripped away until the surface consisted of resistant, unweathered bedrock. We believe that rates of erosion will increase if poor land management practices continue, in which case, bare hillslopes will become more prevalent locally. Once established, these bare hillslopes will likely persist because of the transition from a transport-limited to a weathering-limited condition of denudation.

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

By JOHN PITLICK

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–K

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

By JOHN PITLICK[1]

ABSTRACT

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

INTRODUCTION

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

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

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

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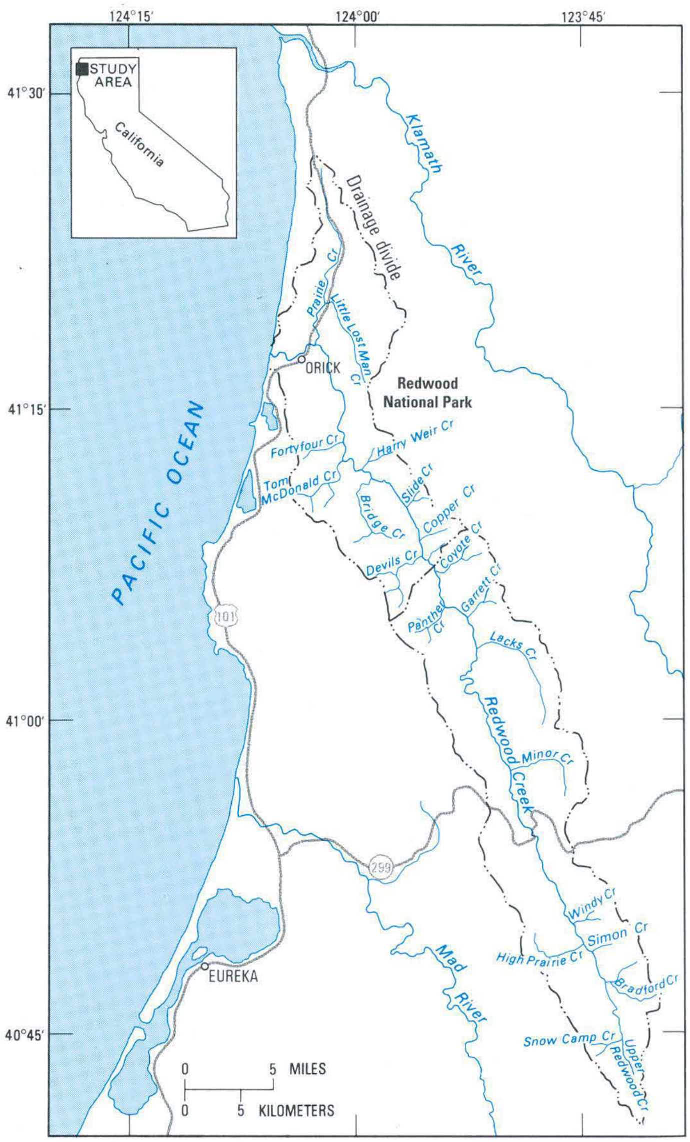

FIGURE 1.—Redwood Creek basin, showing Redwood National Park and tributary basins.

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STUDY AREA

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

GEOLOGY AND PHYSIOGRAPHY

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

Tributary streams are nearly equally divided between those draining sedimentary rocks and those draining metamorphic rocks. The soils developed on these rock types are moderately coarse in texture. They have high infiltration capacities but possess little cohesion and very low shear strength.

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

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

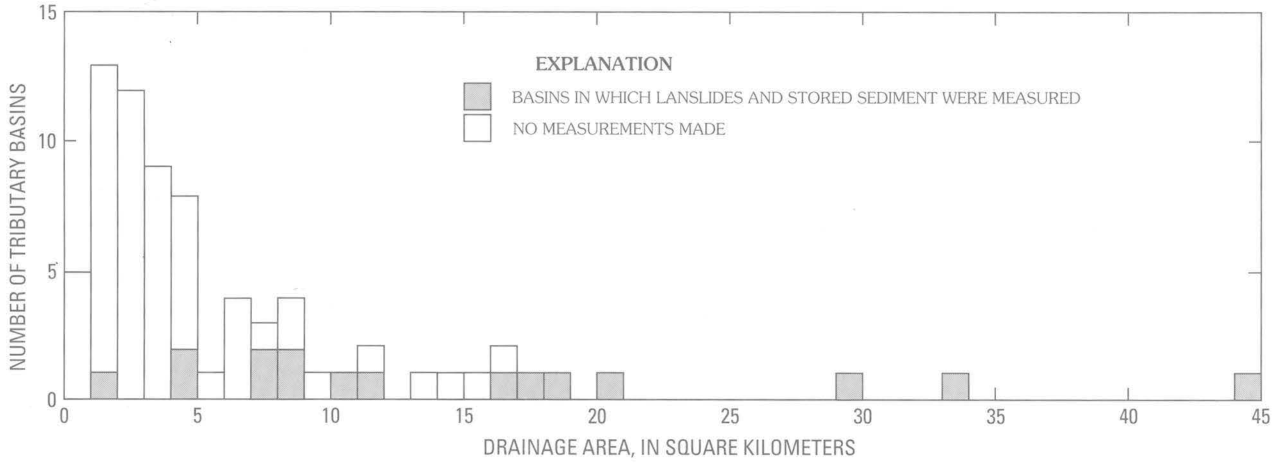

FIGURE 2.—Frequency distribution of tributary basins by drainage area. Drainage areas were measured on 1:24,000-scale topographic maps by using a polar planimeter. The data include only those tributaries upstream of Prairie Creek. Shaded areas indicate the 16 basins in which streamside landslides and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

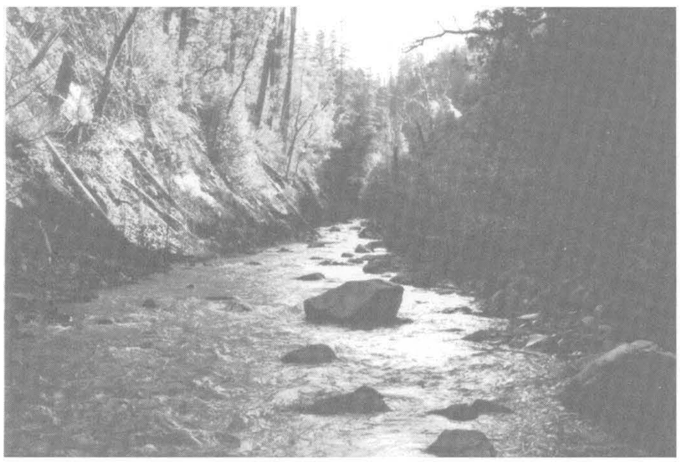

FIGURE 3.—Lacks Creek channel. The steep sideslopes, coarse bed material, and narrow flood plain are typical of Redwood Creek tributaries. Average channel width is approximately 10 m.

mass wasting by shallow debris slides and debris avalanches.

VEGETATION AND LAND USE HISTORY

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

CLIMATE

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

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

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

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

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

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

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

STUDY METHODS

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

Sediment stored in fill terraces and in association with large organic debris was measured along a total of 67 km of tributary channel. The volume of material stored in terraces was determined by measuring terrace surface area and average height above the present thalweg. The amount of sediment stored upstream of a debris jam was

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

[Modified from Harden and others, 1978]

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

determined by treating the trapped sediment as a wedge. The surface area of the deposits associated with the debris was measured, and the depth of stored sediment taken as one-half the height of the debris jam. Buried tree stumps, root wads, boulders, and other objects that are now partially exhumed were used to determine the depth of recent aggradation.

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

STREAMSIDE LANDSLIDES ALONG TRIBUTARIES

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

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

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

TIMING OF STREAMSIDE LANDSLIDES

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

The marked differences between the number of landslides initiated during the 1964 storm and during storms of similar magnitude may be due to several factors. The exceptional amount of erosion that occurred in the upper 175 km² of the Redwood Creek basin suggests that the 1964 storm was more intense at higher elevations in the upper basin. Storms and land use practices of the 1950's were important in "conditioning" the basin for an event such as the 1964 storm (Harden and others, 1978). These authors reported that an exceptionally large number of landslides that were visible on 1958 aerial photographs

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

Tributary	Drainage area (km²)	Landslide mass[1] delivered between 1954 and 1981 (Mg)	Landslide mass per unit drainage area (Mg/km²)
Lacks Creek	44.0	917,700	20,900
Minor Creek	33.6	465,500	13,900
Bridge Creek	29.5	311,000	10,600
Coyote Creek	20.4	231,800	11,400
Devils Creek	18.0	53,900	3,000
Tom McDonald Creek	18.0	50,000	2,800
Bradford Creek	16.5	213,100	12,900
Upper Redwood Creek	11.1	169,800	15,300
Garrett Creek	10.8	108,300	10,000
Snow Camp Creek	8.2	215,500	26,300
Fortyfour Creek	8.1	29,900	3,700
Harry Weir Creek	7.8	47,500	6,100
Copper Creek	7.4	92,000	12,400
Windy Creek	4.6	241,600	52,500
Simon Creek	4.5	323,200	71,800
N. Fork Slide Creek	1.6	36,700	23,000
Mean			18,600
Standard deviation			18,800
Main stem of Redwood Creek upstream of State Highway 299	175.3	3,736,800	21,400

[1] Landslide mass computed by taking the product of the measured volume and assumed soil density of 1.6 g/cm³ (100 lb/ft³) (James Popenoe, National Park Service, oral commun., 1981). The reported values represent data from only those landslides measured during the tributary landslide surveys. Survey coverage accounted for between 80 and 98 percent of the total sediment production from landslides in individual basins.

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

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

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

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

	Unlogged[1] slopes	Logged slopes			
		Road-related[2] failures	Clearcut		Selectively cut
			Tractor-yarded	Cable-yarded	Tractor-yarded
Number of slides measured larger than 450 Mg	222	109	47	46	37
Total mass of sediment produced (Mg)	687,900	1,199,700	606,800	464,300	243,800
Average slide mass (Mg)	3,099	11,006	12,910	10,094	6,590
Percent of total inventoried slide mass	21.5	37.5	18.9	14.5	7.6

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

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

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

LANDSLIDES AND LAND USE

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

SEDIMENT STORAGE AND SEDIMENT TRANSPORT IN TRIBUTARIES

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

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

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

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

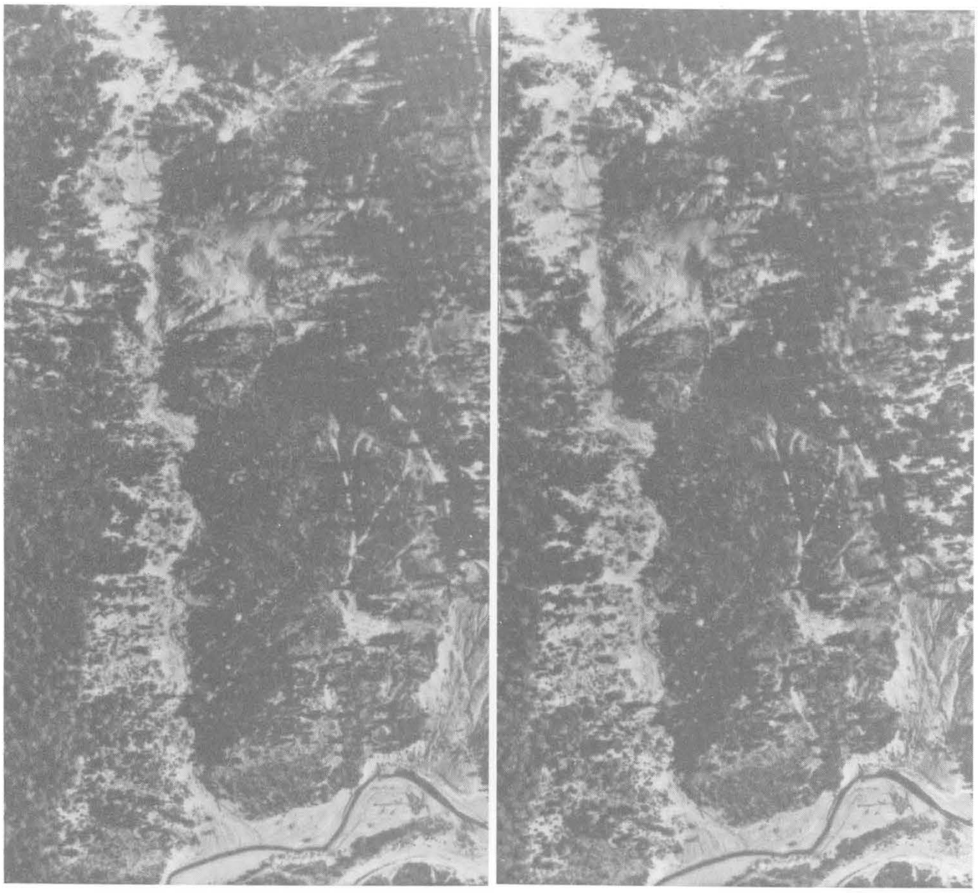

FIGURE 4.—Stereoscopic pair of aerial photographs (acquired 1966; scale 1:12,000) showing the confluence of Simon Creek and Redwood Creek. Note that the landslides along both the tributary and main-stem channels are of similar size, but the amount of sediment stored in the narrow, deeply incised tributary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

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

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

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

1954 to 1981 and the amount of sediment in storage as of 1981 serves as another measure of tributary sediment transport or storage efficiency (table 7). Tributary basins characterized by high relief and dominated by Douglas-fir forests store a significantly smaller proportion of sediment supplied by streamside landslides than do redwood-dominated tributary basins, even though average sediment production from streamside landslides is much higher in Douglas-fir basins. Of the 74 tributary channels within the Redwood Creek basin, only a few would be characterized as low-relief and redwood-dominated basins. The more typical tributary basins, characterized by high relief and dominated by Douglas-fir and redwood, contain streams in which sediment yield is limited only by sediment supply. The data from table 7 also imply that the residence time of sediment along the higher gradient tributary channels is necessarily short.

Changes in stored sediment provide an incomplete measure or record of sediment transport through a drainage basin. Continuous or periodic measurement of water discharge, suspended sediment concentration, and bedload discharge generate data on sediment yield more directly. Nolan and Janda (1981) used water discharge and suspended sediment discharge records to assess the

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

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

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

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

TABLE 7.—*Data on channel-stored sediment for three groups of study basins*

[N/A, not applicable]

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

[1] Stored sediment mass was computed by taking the product of the measured volume and an assumed density of 1.9 g/cm³ (120 lb/ft³) (James Popenoe, National Park Service, oral commun., 1981).
[2] Landslide mass was computed by taking the product of measured volume and an assumed soil density of 1.6 g/cm³ (100 lb/ft³) (James Popenoe, National Park Service, oral commun., 1981).
[3] Data on sediment storage in Bridge Creek provided by David Leslie, Department of Earth Sciences, University of California, Santa Cruz, Calif.
[4] Data on sediment delivery from Minor Creek earthflow provided by Mike Nolan, U.S. Geological Survey, Menlo Park, Calif. An additional 169,000 metric tons of sediment were delivered to Minor Creek by large gullies.

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

CONCLUSIONS

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

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

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

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

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Impacts of Logging on Stream-Sediment Discharge in the Redwood Creek Basin, Northwestern California

By K. MICHAEL NOLAN *and* RICHARD J. JANDA

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–L

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IMPACTS OF LOGGING ON STREAM-SEDIMENT DISCHARGE IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

By K. MICHAEL NOLAN and RICHARD J. JANDA

ABSTRACT

Sediment-transport data resulting from periodic and synoptic sampling of water and suspended-sediment discharge have been used to estimate the degree to which extensive tractor-yarding and clearcutting of timber have accelerated the naturally high erosibility of the Redwood Creek basin, northwestern California. Suspended-sediment transport curves (SSTC's) of eight streams draining basins of diverse geology and land use were compared by using analysis of covariance. Adjusted mean values of suspended-sediment discharge per unit area for streams draining recently harvested terrane were at least twice as great as adjusted means for streams draining physically comparable, but nearly uncut, basins. Relations between SSTC's of higher order streams and those of lower order tributary streams draining areas with contrasting amounts of timber harvest further indicated that timber harvest caused tributary streams to become major sediment sources at times of high water discharge. Sampling conducted during nine storms indicated that water discharge per unit area from streams draining harvested terrane was roughly twice that from unharvested terrane under similar hydrologic conditions. Synoptically measured values of suspended-sediment discharge were roughly 10 times greater from harvested terrane than from unharvested terrane.

INTRODUCTION

Records of suspended-sediment discharge collected over the last 20 years indicate that the Coast Ranges and Klamath Mountain provinces of northern California and southern Oregon constitute some of the most actively eroding terrane in North America (Judson and Ritter, 1964; Holeman, 1968; Janda and Nolan, 1979a). The impacts of these high sediment discharges on productive wildland soils, anadromous fish habitat, and streamside parklands are of considerable interest to environmentally concerned groups. Although high rates of erosion occur naturally in these areas as a result of their geologic setting and climate, recent changes in land use patterns have accelerated the naturally high rates in many areas (Anderson, 1979). The degree to which land use practices have accelerated erosion rates has been the focus of considerable public discussion and controversy (U.S. House of Representatives, 1976, 1977).

Recent controversy has focused on the 725-km^2 drainage basin of Redwood Creek, which contains in its downstream end a major portion of Redwood National Park. Water and suspended-sediment discharge data presented in this report resulted from studies conducted in cooperation with the U.S. National Park Service to assess human impact on erosional and depositional processes operating within that basin. Basic data resulting from these studies, as well as complete descriptions of all study basins, are contained in Iwatsubo and others (1975, 1976).

STUDY AREA

Water and suspended-sediment discharge data from eight tributary basins in the northern (downstream) third of the Redwood Creek basin (fig. 1; table 1) are included in this report. North coastal California is characterized by a Mediterranean climate with high, moderately intense, wintertime precipitation. Average annual rainfall is approximately 1,800 mm in the eight tributary basins studied.

These basins are underlain by sandstone and quartz-mica schist of the Franciscan assemblage of Late Jurassic to Cretaceous age (Bailey and others, 1964; Harden and others, 1982) (table 1). Pervasive tectonic shearing has greatly increased the susceptibility of some sandstone units to deep-seated slump-earthflow movement. These units are described in table 1 as incoherent. Average hillslope gradients range from 15.9° to 20.8°.

The study basins are forested predominantly by redwood (*Sequoia sempervirens*), but prairie grass, brush, and grass-oak woodland are found in up to 10 percent of their area. Up to 87 percent of some basins was subject

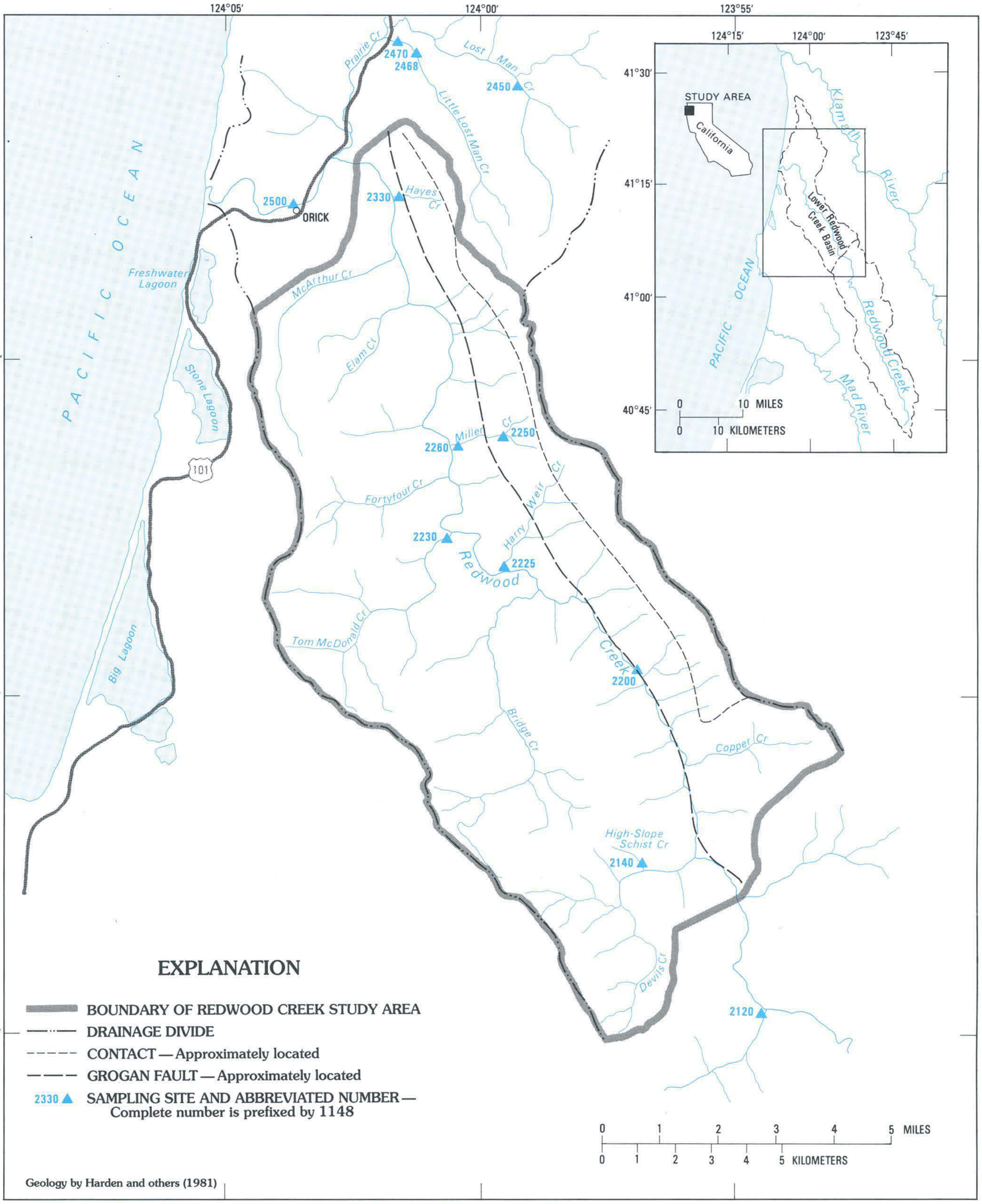

FIGURE 1.—Location of sampling sites in the northwestern half of the Redwood Creek basin.

TABLE 1.—*Descriptive data for tributary basins studied in this report*

[Percentage of major rock types measured on maps by Harden and others (D.R. Harden, U.S. Geological Survey, written commun., 1979). Percentage harvested is from Iwatsubo and others, 1975. Percentage highly disturbed are areas displaying bare mineral soil measured from color-infrared aerial photographs. Station numbers are U.S. Geological Survey station identification numbers. —, no data]

Station name and number	Drainage area (km^2)	Percent of major rock types in basin			Percent logged before 1968	Percent logged after 1968	Percent highly disturbed in 1976
		Coherent sandstone	Incoherent sandstone	Schist			
High-Slope Schist Creek, 11482140	1.37	—	—	100	0	0	0
Harry Weir Creek, 11482225	7.67	40	40	20	0	44	35
Tom McDonald Creek, 11492230	17.8	—	—	100	80	6	27
Miller Creek, 1142250	1.74	44	56	0	0	87	39
Miller Creek at mouth, 11482260	3.52	19	56	22	0	77	46
Hayes Creek, 11482330	1.58	36	58	1	4	0	1
Lost Man Creek, 11482450	10.3	100	—	—	87	0	15
Little Lost Man Creek, 11482468 and 11482470[1]	8.96	100	—	—	6	0	2

[1] Station 11482470 was moved approximately 0.4 km upstream at the end of the 1974 water year.

to highly disruptive, large-scale tractor-yarded clearcutting, which began in the early 1960's (table 1). The percentage of each tributary basin that displayed a high amount of ground disruption at the time of this study was measured from 1976 color-infrared aerial photographs (table 1).

High sediment yields from the tributary basins apparently result from a combination of complex mass-movement processes and fluvial erosion (Janda and others, 1975), which occur in response to the interaction of climate, geology, and land use. The most visually apparent erosional landforms are active earthflows, streamside rock and debris slides, and gullies associated with roadway drainage (Nolan and others, 1976). Long-term annual suspended-sediment discharge for Redwood Creek at Orick (fig. 1) has been estimated at 2,100 (Mg/km^2)/yr by J.M. Knott (U.S. Geological Survey, written commun., 1975), by using extrapolation of sediment-transport relations observed in Redwood Creek, and at 2,540 (Mg/km^2)/yr by H.W. Anderson (1979) by using a multiple-regression equation based on regional observations.

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STUDY METHODS

Data gathered during periodic and synoptic sampling of water and suspended-sediment discharge during 5 successive water years have been used to estimate the degree to which human activities have affected erosion rates within the Redwood Creek basin. Legislative requirements for rapid estimates of probable causes of resource degradation and the lack of appropriate unharvested drainage basins precluded use of before-and-after paired-basin studies such as those listed by Fredriksen and Harr (1979).

Periodic measurements of water and suspended-sediment discharge were taken at eight sites on seven different streams between October 1973 and September 1977, by using standard U.S. Geological Survey techniques. Synoptic sampling was used to measure water and suspended-sediment discharge simultaneously in six of these streams during nine separate storms. Basins chosen for synoptic sampling were as similar as possible in geology, physiography, and natural vegetation but were in various stages of the cutover-regeneration cycle.

Sediment-transport characteristics of the study basins were compared by using suspended-sediment transport curves (SSTC's) and values of total water discharge per unit area (WD/A in cubic meters per second per square kilometer, or (m^3/s)/km^2) and suspended-sediment discharge per unit area (SSD/A in megagrams per day per square kilometer, or (Mg/d)/km^2) measured during synoptic sampling. Total WD/A and SSD/A for two storm seasons were also synthesized by using mean daily values measured during synoptically studied storms and mean daily values measured at Little Lost Man Creek, site of a continuous water-stage recorder.

Measurements of bedload transport using the Helly-Smith sampler were made at all study sites but have not been used in this report because the infrequency and variability of movement resulted in a small, hard-to-interpret data set. In cases where closely spaced measurements of both suspended-sediment and bedload discharge of acceptable accuracy were made, bedload discharge constituted between 20 and 60 percent of total sediment discharge (Janda, 1978).

TABLE 2.—*Descriptive statistics for relations describing individual suspended-sediment transport curves and analysis of covariance results*

[*N*, number of data points; *A* and *B*, intercept and slope, respectively, of relation describing SSTC's; r^2, correlation coefficient squared; *F*, *F*-statistic; WD/A, water discharge per unit area; SSD/A, suspended-sediment discharge per unit area]

Stream Name	Individual relationships $y=Ax^B$						Analysis of covariance results				
	N	Range in sampled WD/A, in (m³/s)/km²	*A*	*B*	r^2	Standard error of estimate	Adjusted mean SSD/A, in (Mg/d)/km²	95-percent confidence limits about adjusted mean: Upper	95-percent confidence limits about adjusted mean: Lower	*F* Similarity of means	*F* Common slope
Group I—Stream draining incoherent sandstone terrane[1]											
Harry Weir Creek	68	0.001–1.03	206	3.03	0.84	0.292	2.21	2.65	1.84		
Miller Creek at mouth	53	0.006–0.76	405	3.07	.68	.336	3.84	4.83	3.05	21.39	0.00
Hayes Creek	21	0.010–0.55	73.8	2.78	.60	.467	1.11	1.53	.80		
Group II—Stream draining coherent sandstone terrane[2]											
Little Lost Man Creek	60	0.002–2.1	51.3	2.95	0.89	0.357	0.77	0.88	0.67	19.52	0.00
Lost Man Creek	51	0.001–2.8	75.5	2.89	.91	.195	1.24	1.43	1.08		
Group III—Stream draining schist terrane											
High-Slope Schist Creek	5	0.025–0.62	1.80	2.50	0.99	0.096	0.07	0.27	0.02	57.68	0.00
Tom McDonald Creek	10	0.004–0.88	155	2.52	.54	.551	5.81	12.05	2.80		
Group IV—Streams draining unharvested or nearly unharvested terrane											
High-Slope Schist Creek	5	0.025–0.62	1.80	2.50	0.99	0.096	0.05	0.12	0.02		
Hayes Creek	21	0.010–0.55	73.8	2.78	.60	.467	1.39	1.95	.99	40.8	0.31
Little Lost Man Creek	60	0.002–2.1	51.3	2.95	.89	.357	.75	.90	.62		

[1] Incoherent unit of Coyote Creek.

[2] Coherent unit of Lacks Creek.

SUSPENDED-SEDIMENT TRANSPORT CURVES

SSTC's, as used here, are graphs of logarithmically transformed instantaneous values of WD/A and SSD/A. SSTC's for each of the eight tributary sites listed in table 1 were described by linear relations determined by regression analysis. WD/A generally ranged through three log cycles, and SSD/A through five cycles. SSD/A was used in these comparisons rather than suspended-sediment concentration because our interest was in the role of suspended-sediment discharge, as an increment of total sediment discharge, in accounting for changing channel morphology and riparian habitat. This form of data presentation is also comparable to that developed by other authors in nearby terrane (Knott, 1971; Brown, 1973). Because of the interdependency caused by the presence of water discharge in both variables, correlation tests of individual relations have no physical significance. Values of the coefficient of determination (r^2) and standard error of estimate provide only a general indication of the goodness of fit.

A pronounced increase in the slopes of the SSTC's commonly occurred between 0.11 and 0.17 (m³/s)/km². Three changes in channel conditions appear to occur at about this discharge: (1) Initiation of bedload transport results in removal of bed armoring, (2) flow reaches bank-to-bank stage and initiates widespread bank erosion, and (3) sediment stored behind small, unstable debris barriers is released to transport. Two separate regression equations were drawn to represent the data when such change in slope occurred. The lowest value of WD/A through which the upper relation could be extended for all sites was 0.13 (m³/s)/km². Comparison of SSTC's for different streams is based solely upon linear regressions developed for observations of WD/A equal to or greater than 0.13 (m³/s)/km². Most sediment transport and all channel-sculpting flows occur above this discharge value.

SSD/A and WD/A associated with flows greater than 0.13 (m³/s)/km² were fitted to the power function $y=Ax^B$ (table 2). Many of these generalized relations consist of internal relations representing individual storms or even different hydrographic limbs of the same storm. SSTC's therefore describe generalized conditions and may not accurately characterize individual storms.

Comparison of SSTC's by analysis of covariance (Dixon and Massey, 1969) permitted testing the statistical significance of differences in SSD/A predicted for different sites at the same WD/A. This analysis tests for differences between regressions that describe SSTC's within groups by comparing slopes of individual regressions and mean SSD/A (dependent variable) after adjusting for differences in sampled ranges of water discharge. Adjustment of means is performed by using a regression line common to all data. The significance of differences in slopes and adjusted mean SSD/A was tested against the *F* (*F*-statistic) distribution. Regressions within a group were considered different if either the slopes or intercepts tested were found to be significantly different at the 95-percent confidence level.

COMPARISON OF SUSPENDED-SEDIMENT TRANSPORT CURVES

SSTC's of the studied streams were placed in four groups (table 2). Groups I to III are defined by similarities in basin geology, size, and location but by contrasts in timber-harvest history (table 1). Group IV is characterized by similarities in timber-harvest history but by contrasts in geology. Each group was analyzed to estimate whether the primary within-group contrast (timber-harvest history for groups I–III and geology for group IV) was responsible for statistically different slopes of SSTC's and (or) adjusted mean SSD/A's. Results of the analysis of covariance for all groups are contained in table 2.

Data in table 2 indicate significant differences between adjusted mean values of SSD/A in all groups but a general similarity in slopes. The impact of recent timber harvest on adjusted mean SSD/A is shown by groups I and III. Adjusted mean values for streams draining recently harvested terrane (Harry Weir, Miller, and Tom McDonald Creeks) were at least twice as high as those for the stream within the same group draining uncut or nearly uncut terrane (High-Slope Schist and Hayes Creeks). The persistence of timber-harvest impact on adjusted mean SSD/A values is indicated by group II. The adjusted mean SSD/A for the recovering basin of Lost Man Creek (logged more than 10 years prior to study) is 1.6 times greater than that from the nearly uncut basin of Little Lost Man Creek.

Group IV has been included to indicate the effect of geology on adjusted mean SSD/A by including streams in uncut or nearly uncut basins draining geologically different terrane. The adjusted mean SSD/A of Hayes Creek, 58 percent of which is underlain by incoherent sandstone, is 28 times greater than the adjusted mean SSD/A value for High-Slope Schist Creek, which is entirely underlain by schist. Geology therefore must be held as a constant factor when choosing stream groups for sediment-discharge comparison in this terrane. Twelve physiographic parameters listed by Iwatsubo and others (1975, tables 1 and 3) were analyzed by multiple regression analysis to determine possible impacts on the variability of SSD/A. None of these 12 parameters was found to explain a significant amount of the variability in SSD/A, and they were not considered when forming stream groups for analysis of covariance.

Comparison of SSTC's for 20 streams in northwestern California by Janda and Nolan (1979b) indicated that elevated levels of SSTC's (as inferred from higher adjusted SSD/A at low water discharges) for streams draining cutover areas reflect increased availability of readily transportable material. The similarity of slopes of SSTC's appears to indicate similar sediment-delivery mechanisms and therefore a lack of significant change in those mechanisms as a result of logging activities. This hypothesis is substantiated by field observations and photointerpretive mapping (Nolan and others, 1976), which show that, although timber harvest greatly accelerated erosion, the erosional processes delivering sediment to major stream channels after timber harvest were the same basic mechanisms that had operated prior to timber harvest. Moreover, hydrologic and geologic parameters also influence slopes and levels of SSTC's elsewhere (Bauer and Tille, 1967).

Comparison of SSTC's of higher order streams and those of lower order tributaries having contrasting amounts of harvesting in their basins indicates that timber harvest caused tributaries to become major sediment sources during periods of high water discharge. SSTC's of higher order streams have, in general, higher levels at low WD/A values but lesser slopes than the SSTC's of their tributaries. Therefore, at high water discharges the SSTC's cross, and their relative levels are reversed. For recently harvested tributary basins, this reversal occurs at water discharges that can reasonably be expected to occur several times in a decade. SSTC's of unharvested tributary basins, however, have such low levels throughout the full range of reasonably expected water discharges that such reversal would not be expected to occur under present basin hydrologic conditions (fig. 2).

Repetitive surveys of stream-channel cross sections and other field evidence (Janda, 1978; Nolan, 1979) tend to substantiate the relation displayed in figure 2. This information indicates that during periods of low to moderate discharge much of the suspended sediment transported by the main channel of Redwood Creek is derived from channel scour and bank erosion along the main channel. However, during periods of high water discharge, main-channel aggradation occurs at tributary mouths because an excess of material is supplied by bank erosion, streamside landsliding, and scour in tributary channels draining recently harvested basins.

SYNOPTIC STUDIES

Synoptic sampling was conducted at six sites during nine storms between 1974 and 1976. Hydrographs of these storms indicate that the percentage of precipitation appearing as storm runoff from basins harvested within 5 years prior to study was 1.3 to 12 times greater than that from the comparable nearly uncut basin of Hayes Creek (table 3). Relative runoff differences were generally greatest during storms of low to moderate magnitude. The similarity in runoff during high-magnitude storms is most likely due to the prevalence of saturated ground conditions throughout all basins and thus to an equalization of partial areas contributing to runoff. Sim-

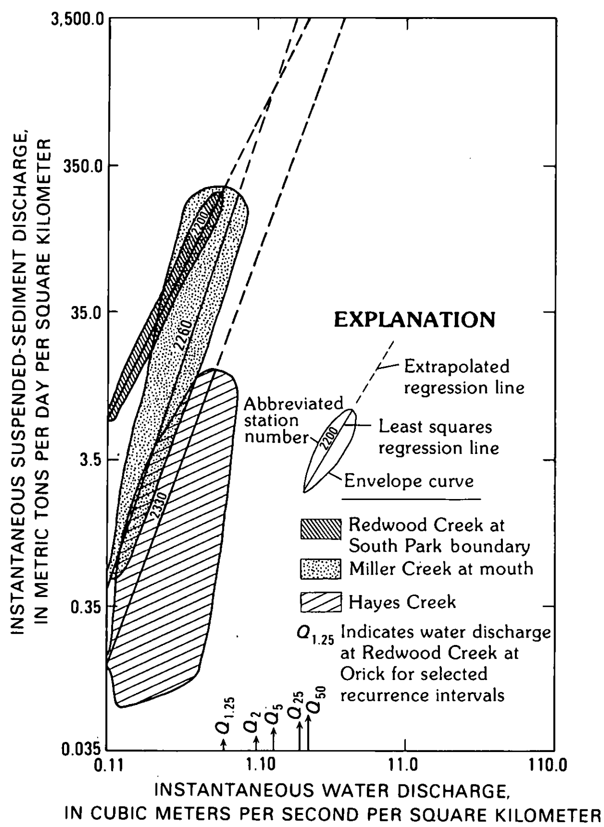

FIGURE 2.—Sediment-transport relations for the main channel of Redwood Creek at South Park Boundary and for tributary streams (Miller Creek at mouth and Hayes Creek) showing envelope curves around actual data points and extrapolation of developed relations. Extrapolation of suspended-sediment transport curves (SSTC's) beyond actual observations appears reasonable up to at least Q_{25}. No change in slope was found, up to Q_{25}, in the upper ends of the (SSTC's) for main-channel or tributary sites for which data exist (Janda, 1978, p. 53).

ilar conditions have been found by other authors (Fredriksen and Harr, 1979) working in similar terrane.

Runoff percentages from the partially revegetated basin of Lost Man Creek were generally higher than those from the nearly uncut, geologically comparable basin of Little Lost Man Creek except for synoptic event 1, when unexplainable high runoff was measured from Little Lost Man Creek.

Field observations during synoptically sampled events indicate that large increases in surface compaction along roads and skid trails and in the number of seeps and springs along banks of road cuts were responsible for some of the increased runoff. Up to 46 percent of the ground surface of some study basins was highly disrupted by timber harvest and related road activity. These observations are supported by Bradford and Iwatsubo (1978), who in a study of water chemistry found evidence for significantly greater overland flow in recently harvested basins during synoptic studies. Similarly, Lee and others (1975), studying rainfall-runoff relations in the Redwood Creek basin, suggest that ground disruption due to timber harvest caused a 20-percent increase in annual runoff and even greater increased runoff for individual storms associated with moderate antecedent soil moisture conditions.

Values of SSD/A measured during synoptically sampled storms were consistently higher from recently harvested basins than from unharvested basins. During individual storms, values of total SSD/A from Miller Creek were 3.8 to 70 times greater than SSD/A from Hayes Creek (table 3). SSD/A values from Lost Man Creek were 1.8 to 5.1 times greater than values from Little Lost Man Creek.

Flow-duration curves were synthesized for each periodic-record station included in the synoptic sampling program by correlating mean daily water discharges measured during synoptic sampling with simultaneous mean daily water discharge determined at Little Lost Man Creek, which is equipped with a continuous stage recorder. The synthesized curves, plus the one calculated for Little Lost Man Creek, were then combined with mean daily SSTC's to compute total water and suspended-sediment discharge for the 1975 and 1976 storm seasons. These computations indicate that total runoff from recently harvested basins for the 1975 and 1976 storm seasons was roughly twice that from the unharvested basin of Hayes Creek (table 3). This large difference in runoff reflects, in part, generally greater precipitation in the higher, more inland, recently harvested basins. During individual synoptically sampled storms, average basin rainfall in Harry Weir Creek ranged from 0.75 to 1.6 times that in Hayes Creek. SSD/A values synthesized for the same period were between 8.4 and 17.5 times greater from recently harvested basins than from Hayes Creek. The synthesized SSD/A value for Lost Man Creek was twice that from Little Lost Man Creek.

CONCLUSIONS

Comparison of adjusted mean values of SSD/A, which were determined by analysis of covariance on relations describing SSTC's, indicates that the large-scale, highly disruptive timber harvest conducted in the Redwood Creek basin probably increased values of SSD/A associated with values of WD/A above 0.13 $(m^3/s)/km^2$ in several tributary streams. Most sediment transport and all channel-sculpting flows occur above this discharge value. The magnitude of this increase appears in many cases to have been at least twofold and to have persisted to some degree for at least a decade.

TABLE 3.—*Water and suspended-sediment yield for basins studied during nine synoptic events and one synthesized flow period*
[logged, percent of basin logged after 1968 (see table 1); SSD/A, suspended-sediment discharge per unit area; WD/A, water discharge per unit area; Mg/km^2, megagrams per square kilometer; mm, millimeters; RO, runoff; —, no data]

Period of data collection	Harry Weir Creek (% logged=44)			Miller Creek (% logged=87)			Miller Creek at mouth (% logged=77)			Hayes Creek (% logged=0)			Lost Man Creek (% logged=0)			Little Lost Man Creek (% logged=0)		
(Date) (Time)	SSD/A (Mg/km^2)	WD/A (mm)	RO (%)	SSD/A (Mg/km^2)	WD/A (mm)	RO (%)	SSD/A (Mg/km^2)	WD/A (mm)	RO (%)	SSD/A (Mg/km^2)	WD/A (mm)	RO (%)	SSD/A (Mg/km^2)	WD/A (mm)	RO (%)	SSD/A (Mg/km^2)	WD/A (mm)	RO (%)
11/07/73 2100 to 11/09/73 1000	45.5	28	42	30.1	30	51	59.5	23	42	—	13	33	11.6	28	48	6.6	46	100?
01/11/74 2000 to 01/13/74 1800	2.0	8	13	1.6	8	13	1.3	5	13	0.07	1	2	—	—	—	—	—	—
02/20/74 2000 to 02/22/74 0700	.84	3	12	1.0	1	1	1.6	5	17	.21	1	1	.42	13	53	.21	1	1
02/28/74 2200 to 03/03/74 0800	2.5	24	68?	1.4	7	30	3.1	8	22	.46	1	3	1.37	3	9	.42	4	9
11/07/74 0100 to 11/09/74 1200	.04	1	2	.05	1	4	.05	1	5	.00	1	1	.00	1	2	.00	1	1
11/21/74 1200 to 11/24/74 1200	.10	2	5	.70	3	7	.70	3	7	.00	1	2	.07	3	7	.04	1	3
02/08/75 1800 to 02/09/75 1200	.67	3	10	.91	2	9	2.0	2	7	.04	1	3	.32	4	17	.11	2	7
02/12/75 1800 to 02/14/75 1000	7.7	8	18	4.9	10	23	24.5	9	21	.35	4	10	2.28	9	31	.88	6	15
02/18/76 1200 to 02/19/76 1200	.74	1	6	.92	1	6	.53	1	6	.14	1	4	.71	3	11	.14	2	6
10/01/74 0100 to 04/30/75 2400 and 10/01/75 0100 to 04/30/76 2400	305	2,210	—	235	2,515	—	490	2,311	—	28	1,270	—	108	2,337	—	52	2,108	—

Comparison of the levels and slopes of SSTC's of studied streams, along with earlier reported field observations and studies of sequential aerial photographs, indicates that timber harvest has increased the amount of sediment readily available for transport by tributary streams without introducing new sediment delivery mechanisms and that harvested tributary basins have become major sources of sediment during periods of high water discharge.

Comparison of total water and suspended-sediment discharge measured during synoptic sampling indicates nearly twofold increases in WD/A and tenfold increases in SSD/A following timber harvest. These effects appear to persist to some degree for at least a decade. Postlogging increases in SSD/A estimated by the synoptic studies are greater than those estimated by comparison of adjusted mean values of SSD/A. This contrast exists because total values of SSD/A measured during synoptic sampling are the product of both increased water runoff and elevated levels of SSTC's. Runoff differences were removed by the analysis of covariance when comparing adjusted mean SSD/A values.

If erosion rates implied by observed differences in WD/A and SSD/A had persisted for long periods, the present physiographic similarities between synoptically studied basins would not exist. By increasing runoff and making more sediment available to naturally existing delivery systems, recent timber harvesting probably accounts for a substantial part of the observed differences between WD/A and SSD/A.

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Role of Fluvial Hillslope Erosion and Road Construction in the Sediment Budget of Garrett Creek, Humboldt County, California

By DAVID W. BEST, HARVEY M. KELSEY, DANNY K. HAGANS, *and* MARK ALPERT

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–M

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ROLE OF FLUVIAL HILLSLOPE EROSION AND ROAD CONSTRUCTION IN THE SEDIMENT BUDGET OF GARRETT CREEK, HUMBOLDT COUNTY, CALIFORNIA

By David W. Best,[1] Harvey M. Kelsey,[2] Danny K. Hagans,[3] and Mark Alpert[4]

ABSTRACT

The Garrett Creek sediment budget is based on detailed measurements of fluvial hillslope erosion, streamside landsliding, and main-channel sediment storage in Garrett Creek. The study period, 1956 to 1980, which includes both an interval of widespread timber harvest and a sequence of major storms, represents a period of accelerated erosion in the watershed. Of the sediment contributed to the main channel during this time, fluvial slope erosion contributed 62 percent, and streamside landsliding contributed the rest. Of the total sediment input for the 25-year period, only 6 percent remained in storage in the lower main channel of Garrett Creek.

The sediment budget study concentrates on the measurement of fluvial hillslope erosion. Our fluvial erosion survey determined that almost all significant sources of fluvial erosion were created by road construction and logging. Because of this observation, we did a detailed study of stream crossings by roads. Two major causes of erosion accounted for 80 percent of all road-related fluvial slope erosion. Stream diversions caused by plugged culverts at crossings initiated 68 percent of road-related fluvial erosion, and the failure of road fills at established crossings initiated another 12 percent of such erosion. Because of the dominance of stream diversions as a cause of accelerated erosion, we have devised a diversion potential rating for road crossings. Steep-gradient roads that have inboard ditches and roads that cross drainage swales without dipping into them have the greatest diversion potential.

Most erosion in the Garrett Creek basin occurs during storm runoff of short duration but of sufficient magnitude to transport sediment. Land management is a major influence on geomorphic processes. Any attempt to assign long-term rates of denudation to erosive processes in this watershed must incorporate human influence as a permanent and significant independent variable.

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INTRODUCTION

The objective of this study was to investigate the processes and the magnitude of hillslope erosion in Garrett Creek (drainage area of 10.8 km^2) and to place this erosion in the context of Garrett Creek's sediment budget. The study period 1956 to 1980 was selected because it includes (1) widespread timber harvest; (2) intense storms in 1955, 1964, 1972, and 1975 (Harden and others (1978); and (3) an excellent photographic record with aerial photographs for 1954, 1958, 1962, 1966, 1972, and 1978. The contribution of fluvial hillslope erosion was stressed in this study, although other sediment sources were measured as well. Contributions from fluvial hillslope erosion have been treated as an unknown in all previously proposed budgets for this region (Kelsey, 1980; Kelsey and others, 1981). From the studies of the magnitude and causes of fluvial hillslope erosion, it was concluded that logging roads are by far the major cause of such erosion. In the Garrett Creek basin, much of this erosion could have been prevented by better designed logging roads. The magnitude of road-related fluvial hillslope erosion approaches that of streamside landslide erosion, which is the only other significant sediment source in the Garrett Creek watershed.

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CHARACTER OF THE GARRETT CREEK WATERSHED

Garrett Creek is a 10.8-km^2 elliptically shaped watershed on the east side of Redwood Creek, just upstream from Redwood National Park (fig. 1). Predominant rock types in the basin are unmetamorphosed and slightly metamorphosed sedimentary rocks of the Franciscan assemblage (Harden and others, 1981). Locally, tectonic blocks of greenstone are found. The fourth-order channel of Garrett Creek is moderately steep and has an average gradient of 0.18 m/m. Drainage density is 5,700 m/km^2. The predominant forest type is Douglas-fir. Oak woodlands and prairies are found on south-southwest slope exposures and on ridgetops. Minor amounts of redwood mixed with Douglas-fir are found on north-facing slopes. Basin hillslopes are generally convex in profile. Upper slope gradients range from 0.30 to 0.35 m/m, while gradients of footslopes average 0.65 to 0.70 m/m.

The headwater channels of Garrett Creek are in an incoherent sandstone-siltstone unit that is prone to mass movement. Channels of the middle portion are cut in coherent massive sandstone and interbedded sandstone, siltstone, and graywacke along approximately 760 m of channel length. A steep canyon is formed in this channel reach; sideslopes range from 70 percent to nearly vertical and average 80 to 100 percent. The channel has many waterfalls 3 to 5 m in height, and the canyon is inaccessible except along the channels. Conifers on the steepest canyon slopes near the channel have not been harvested. The lowermost portion of Garrett Creek flows through alternating coherent and incoherent rock units. Slope and channel gradients are less steep (averaging 50–55 and 13 percent, respectively) than the canyon reach upstream, and significant quantities of sediment are stored in channel bars. An active earthflow currently enters the lower creek along the left (southeast) bank.

LAND USE IN GARRETT CREEK

Prior to the initiation of timber harvest in the early 1950's, 46 percent of the basin supported old-growth coniferous forests, principally Douglas-fir with minor amounts of redwood in north-facing exposures. Roughly 30 percent of the basin is presently prairie grassland, and 25 percent is hardwood forests (fig. 1). Nearly all of the coniferous forests have been logged; the remaining uncut coniferous forests are found along the steep inner gorge of Garrett Creek and where such forests are interspersed with areas of uncut hardwood.

Most road construction in the basin accompanied periods of intense timber harvest. Between these periods, the roads for the most part were not used and were only sporadically maintained. Three major roads, and associated spur roads, give access to the watershed (fig. 1). Much of the fluvial hillslope erosion in the watershed between 1956 and 1980 relates to the histories of these major haul roads after their construction. Mainline Road is a permanent all-season road constructed prior to 1954 and originally paved for most its length. It enters the southern portion of the watershed at a midslope elevation of 300 m and climbs continuously for 4.8 km to the watershed divide at 902 m. Middle Garrett Road was constructed in several segments between 1954 and 1977. It is a high standard, unrocked road that traverses the middle to lower portions of the basin. Several spur roads provide access to the north and middle forks as well as to the recently logged northern slopes of the watershed. Nelson Road provides access to the lowermost, southern portions of the watershed. Construction first began prior to 1954, and the road was completed by 1965.

Early logging of the watershed involved annual cuts between 1948 and 1954, and averaged 50 acres per year. Logging downslope of Mainline Road was done by cable systems; logging upslope of Mainline Road was done by tractors. By 1954, 25 percent of the coniferous forest in the basin had been logged. Between 1955 and 1958, there was additional logging, and Middle Garrett Road was constructed to site A in figure 1. Between 1958 and 1962, there was little logging, and no additional road construction. The most intense logging occurred from 1962 to 1966 when approximately 27 percent of the coniferous forests was cut. By 1965, Nelson Road was completed, and Middle Garrett Road had been extended almost to the Middle Fork. By 1970, 78 percent of the forests had been logged, and Middle Garrett Road had been extended to site B in figure 1. Spur roads up both the north and middle forks also had been completed. During the next 7 years, there was again virtually no logging or road construction. In 1977, intense timber harvest recommenced with logging along all road systems and construction of the final segment of Middle Garrett Road. From 1978 to 1980, several additional logging plans were executed, including construction of a major spur road. Between 1978 and 1982, most of the previously cut areas were relogged; as a result, reconstruction of nearly all roads in the basin was required. The total length of the three major road systems is 12.7 km.

METHODS OF INVESTIGATION OF SEDIMENT SOURCES AND STORAGE

MEASURED SEDIMENT SOURCES

Major sediment sources in the drainage basin were identified, and sediment contributions from each were estimated. These sources consist of streamside land-

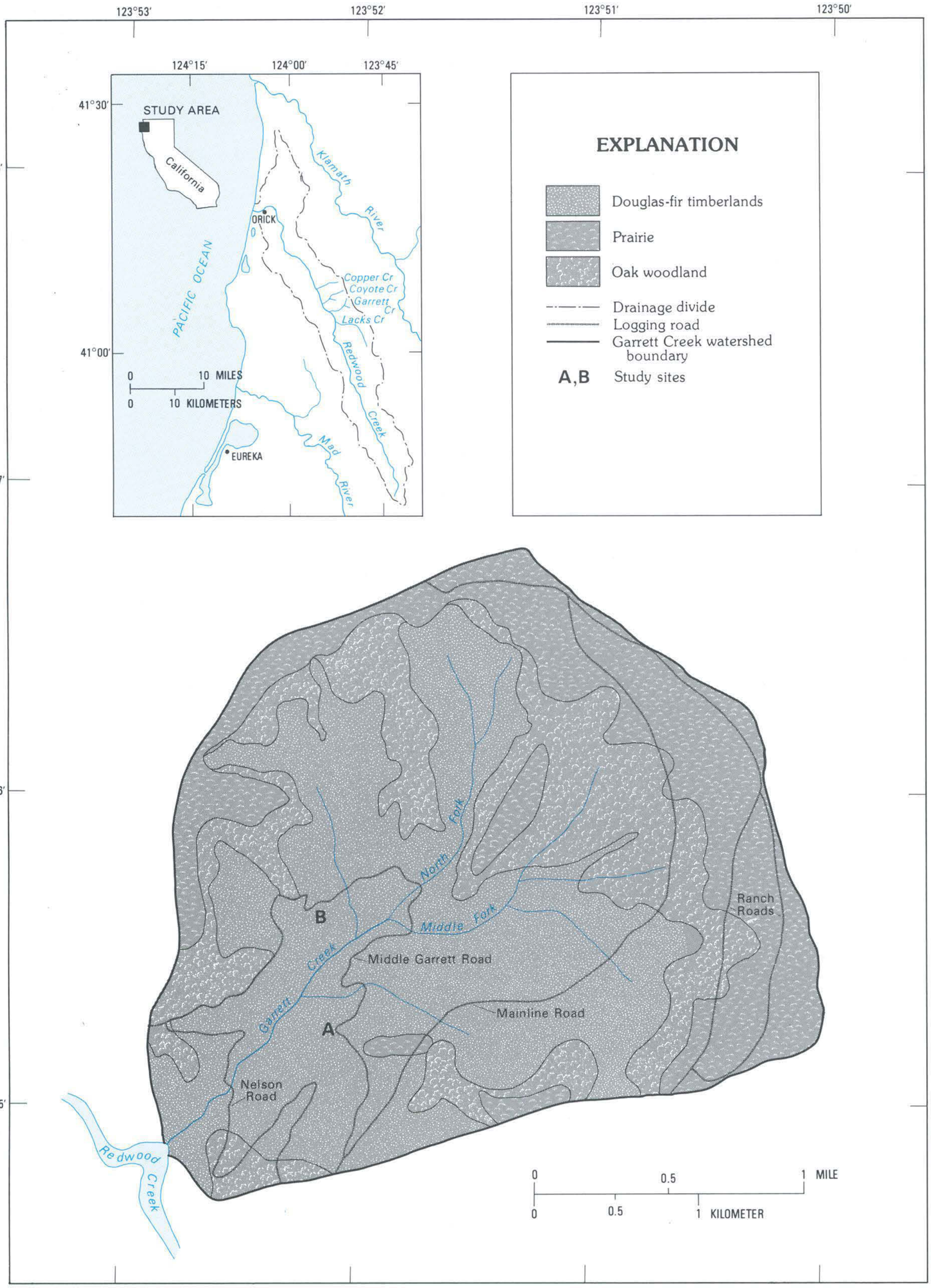

FIGURE 1.—Location map of the 10.8-km^2 Garrett Creek watershed showing the logging road network and the distribution of Douglas-fir timberlands and the prairie-oak woodlands. The inset map shows the relative locations of Copper Creek, Coyote Creek, Garrett Creek, and Lacks Creek within the Redwood Creek drainage basin.

TABLE 1.—*Significant causes of road-related fluvial erosion in the Garrett Creek watershed*

Cause of erosion	Explanation of process
Stream diversions	Erosion resulting from the diversion of a stream by a crossing. Includes erosion within a diversion channel (such as a road ditch), as well as erosion that subsequently occurs in a natural channel further downstream. Diversions are often the result of plugged or unmaintained culverts.
Failures of logging haul roads at crossings	Erosion resulting from road-fill failure at stream crossings, including culvert, bridge, and Humboldt crossings. (A Humboldt crossing is an installed crossing where logs, placed parallel to the direction of flow, are substituted for the installation of a culvert; as of about 1978, installation of Humboldt crossings ceased.)
Crossing not to grade	Erosion of the channel in the vicinity of crossing when the culvert or water conduit is not placed at channel grade. Other causes include poorly constructed fills, lack of energy dissipation measures at culvert outlets, and conduits that deflect flow into stream banks.
Road-intercepted runoff	Erosion resulting from the interception, diversion, and concentration of surface runoff by roads; an example is erosion caused by water emanating from road cutbanks.
Misplaced culvert or crossing	Erosion resulting from misplacement of culvert or crossing; such misplacement usually forms a gully originating at the downspout of the culvert. The gully continues downslope, generally for 15 to 50 m, until it rejoins the proper channel.
Failure of a fill crossing	Erosion resulting from the placement of fill where a culvert was needed, or failure to identify a stream channel during road construction.
Inboard ditch erosion	Erosion resulting from concentration of surface runoff in road ditches; this concentration causes small gullies less than 0.4 m^2 in cross-sectional area.

slides, road-fill and cutbank failures, road-related fluvial erosion, skid-trail-related fluvial erosion, debris torrents, erosion of natural channels in prairie and hardwood areas, and sediment stored in channels. Previous studies in the watershed furnished the streamside landslide (Kelsey and others, 1981) and sediment storage data (chap. K, this volume).

STREAMSIDE LANDSLIDES

The volumes of the 23 largest landslides in the basin were measured; all of these landslides occurred along the lower 1.8 km of the channel below the confluence of the north and middle forks of Garrett Creek. Landslide volumes were determined by first measuring the surface area of the slide with a tape and rangefinder. Average depths were then estimated from the height of slide scarps and by mentally reconstructing the prelandslide ground surface. Data presented by Kelsey and others (1981) indicate that approximately 85 percent of the volume of sediment contributed by streamside landslides can be measured by using the above techniques.

SEDIMENT STORAGE IN CHANNELS

Sediment stored in fill terraces and in association with large organic debris was measured along the lower 3,300 m of the Garrett Creek channel (the lower three-quarters of the channel from the headwaters to the mouth). The volume of material stored in terraces was determined by measuring terrace surface area and average height above the present thalweg. The amount of sediment stored upstream from a debris jam was determined by treating the trapped sediment as a wedge. The surface area of the deposits associated with the debris was measured, and the depth of sediment in storage was taken as one-half the height of the debris jam. Buried tree stumps, root wads, boulders, and other objects that are now partially exhumed were used to determine depth of recent aggradation.

FLUVIAL HILLSLOPE EROSION

This study concentrates on the measurement of fluvial hillslope erosion. Total fluvial hillslope erosion was estimated from measurements made in the field and on aerial photographs. The largest fluvial erosion features were identified through aerial photographs and field reconnaissance and then measured in the field by using tape-and-compass techniques. These fluvial erosion features included three large debris torrents. Although these debris torrents are mass-movement features, the sediment mobilized by them was fluvially transported and then reworked by gully erosion during later storm events. The volumes of more moderate-sized features were calculated from aerial photographs or from tape-and-compass measurements recorded during field mapping. Each feature was classified according to one of seven erosion causes (table 1). The survey indicated that all the significant sources of fluvially eroded sediment were caused by road construction and logging. Fluvial erosion on undisturbed grassland or hardwood forest areas was minor compared to logging-related fluvial erosion. Because of the above observations, stream crossings along the entire length of Mainline Road, Middle Garrett Road, Nelson Road, and all spur roads were classified according to their type, size, previous failure history, and resulting erosion.

TABLE 2.—*Inventory of the three main road systems for road crossings, crossing diversions, and the amount of sediment eroded due to diversions in the Garrett Creek watershed*

Road system	Number of road crossings	Number of crossings that diverted	Percent that diverted	Mass of eroded sediment (megagrams)
Mainline Road	27	13	48	63,472
Mainline spurs	24	1	4	82
Middle Garrett Road ...	20	1	5	60
Middle Garrett spurs ...	28	0	0	0
Nelson Road...........	10	0	0	0
Nelson spurs...........	2	0	0	0

[1] Crossings included culverts, bridges, Humboldt crossings, and fill. A Humboldt crossing is an installed crossing where logs, placed parallel to the direction of flow, are substituted for the installation of a culvert; as of about 1978, installation of Humboldt crossings ceased.

SOURCES OF FLUVIAL HILLSLOPE EROSION

MAJOR CAUSES AND SITES OF FLUVIAL EROSION

Measurable fluvial erosion that clearly occurred between 1956 and 1980 was studied most intensively. Most instances of erosion during this time involved crossings; that is, sites where a road crosses an established drainage channel on the hillslope. A fill crossing is a crossing in which drainage through the fill was not accommodated by a culvert, bridge, or other installation. An installed crossing does contain such an installation. Table 1 summarizes significant causes of fluvial erosion in the Garrett Creek watershed.

STREAM DIVERSIONS

Stream diversions at road crossings are the most important causes of fluvial erosion in the watershed. Such diversions typically occur when a culvert plugs and flow is diverted down the inboard ditch instead of breaching the road fill. Diversions are more prone to occur on insloped roads with inboard ditches than on outsloped roads (fig. 2). There were 15 separate stream diversions within the watershed, and all except 1 were on the Mainline Road system (table 2). These diversions eroded about 64,000 Mg of sediment (assumed density of sediment=1.6 g/cm^3).

The occurrence of stream diversions is highly variable throughout the basin and depends on how a road crosses the stream. A stream within a well-incised drainage, where the road descends to the crossing from either side, cannot be diverted, even when flow exceeds culvert capacity. In such cases, flow crosses the road surface and results in erosion of a part of the crossing. Such erosion is only a minor portion of total fluvial erosion measured in the Garrett Creek watershed.

The most important factor in determining the probability of stream diversion is the gradient of the road at the point of crossing. If the road is steep, as Mainline Road is, it has at least one approach that lies below the crossing. The potential for diversions at such crossings is high, especially when an inboard ditch is present and the road surface slopes toward the inboard ditch (fig. 2). Whenever stream discharge exceeds culvert capacity, a pond forms behind the road. When the pond height reaches the road surface, flow must either cross the road (as in the case of an outsloped road) or divert down the inboard edge. Outsloping of the road surfaces tends to encourage flow to cross the road surface, whereas an inboard ditch tends to become a spillway for any ponded water. Once a diversion occurs, the increased flow contributed to an adjacent road crossing may be enough to exceed the discharge capacity of that crossing, regardless of the level of maintenance or condition of the crossing. Even when the culvert at the adjacent crossing can accommodate the combined flow, the increased flow may still result in channel scour and bank erosion below the culvert. A diversion on a continually descending, slightly insloped road with an inboard ditch may set off a series of diversions. Such chain-reaction diversions may result in the combined flow being diverted onto a hillslope, where far more erosion results than if the flow entered a stream channel.

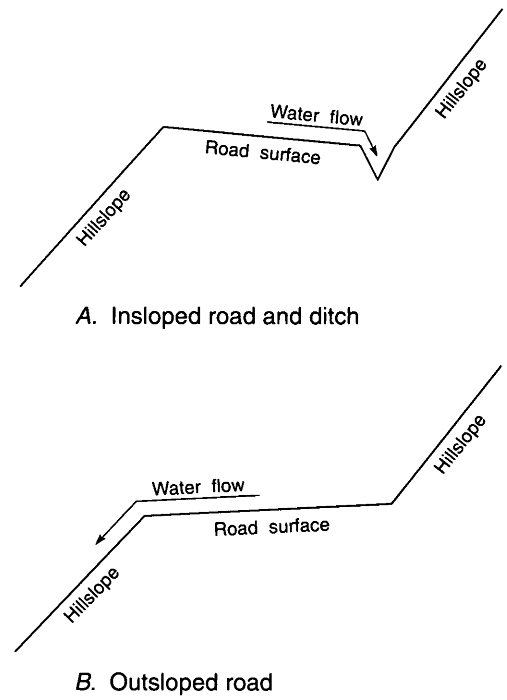

FIGURE 2.—Logging road profiles showing (*A*) Insloped road with inboard ditch and (*B*) Outsloped road with no drainage ditch. Arrows show direction of flow of any water that would pond on the road surface if an adjacent culverted crossing became clogged. In *A*, the water is diverted down the inboard ditch; in *B*, the water traverses the road and flows back into the stream channel.

Stream diversions at major crossings can concentrate large volumes of sediment-laden water in a single small channel with erosionally catastrophic results. Three large debris torrents (channel-confined debris flows) in the Garrett Creek watershed were caused by such diversions on the Mainline Road. The debris torrents contributed 44,000 Mg of sediment to Garrett Creek, and an additional 9,400 to 26,700 Mg remain on the slopes in a debris fan near Nelson Road. These debris torrents account for 67 percent of all erosion caused by diversions at crossings. The second largest debris torrent resulted from a chain reaction of stream diversions along 300 m of road. The combined flow at two crossings was diverted down the inboard ditch and onto the slope. A similar chain reaction occurred farther upslope on the same road, where flow from six crossings was diverted down the inboard ditch and concentrated into one channel; substantial channel bank erosion and scour resulted.

Diversion potential is a measure of the probability that a diversion will occur if flow at a crossing exceeds the capacity of the culvert. A diversion potential rating based on road characteristics and slope morphology has been developed. The size of the installed culvert, erodibility of the channel bed, and drainage area above the crossing were not considered. Each crossing was examined in the field and assigned one of three ratings. For crossings that have low diversion potential, the road dips into and out of the drainage swale as the road crosses the stream. Road crossings that have a moderate diversion potential dip only slightly into drainage depressions; should a diversion occur, the length of the diverted channel would likely be less than 30 m. For crossings that have a high diversion potential, the road surface slopes steeply (greater than 5 percent) away from stream crossing, and there is no well-defined berm that separates the pond area behind the crossing from the inboard ditch continuing downslope. Often the road surface is slightly insloped, and there is an inboard ditch.

Table 3 compares diversion potential with frequency of stream diversions for the major roads. Diversions occurred in 50 percent of the high-diversion-potential crossings, 38 percent of the moderate-diversion-potential crossings, and in none of the low-diversion-potential crossings. Of total mass of sediment eroded, 94 percent came from high-diversion-potential crossings. Differences in stream incision or stream order at the major crossings were not as significant a factor in causing diversion as road gradient at the crossings. Mainline Road, having an average gradient of 11 percent and a high number of crossings, accounted for nearly all the high-diversion-potential crossings. Even though most of the crossing diversions on the Mainline Road have been rebuilt, diversion potential remains just as high because road gradient, road inslope, and road ditch remain the same.

TABLE 3.—*Comparison of the diversion potential with observed frequency of stream diversions at stream crossings along the major road systems*

Mainline Road within Douglas-fir terrain				
Diversion potential	Low	Moderate	High	
Number of crossings	1	4	6	
Crossings that divert	0	1	5	
Percent that divert	0	25	83	
Mass of sediment eroded (Mg)	0	2,357	57,912	
Mainline Road within hardwood terrain				
Diversion potential	Low	Moderate	High	Unknown
Number of crossings	3	5	4	4
Crossings that divert	0	4	3	0
Percent that divert	0	80	75	0
Mass of sediment eroded (Mg)	0	1,439	1,764	0
Middle Garrett Road				
Diversion potential	Low	Moderate	High	
Number of crossings	10	5	[1]5	
Crossings that divert	0	1	0	
Percent that divert	0	20	0	
Mass of sediment eroded (Mg)	0	60	0	
Nelson Road				
Diversion potential	Low	Moderate	High	
Number of crossings	7	2	1	
Crossings that divert	0	0	0	
Percent that divert	0	0	0	
Mass of sediment eroded (Mg)	0	0	0	

[1] Four of five crossings that had high diversion potentials were constructed on small ephemeral streams in 1977, and none have experienced a major storm.

The two roads having lower diversion potential are significantly different from Mainline Road. Both are outsloped and lack an inboard ditch. The roads climb steeply in several locations but tend to be horizontal at major stream crossings.

FAILURE OF HAUL-ROAD CROSSINGS

Failure of haul-road crossings is a significant source of fluvial erosion, and road crossing size is the variable most responsible for determining the magnitude of this erosion source. Three factors are important in determining the size of haul-road crossings: stream incision and gradient, road width, and road type. A more incised stream channel requires more fill to reach a level surface suitable for a road. In addition, a 12-m road requires considerably more than twice the fill of a 6-m road; the additional width usually must be added to the outside edge of the road where the depth of fill is greater. Finally, major haul roads usually have minimal dips at the crossing and require a greater depth of fill. Also, in minimizing turns in the road as the crossing is approached, there is a tendency to "bridge" the steep inner gorge of channels rather than to contour the road to the hillslope.

TABLE 4.—*Erosion data for fills at installed crossings on the three main road systems in the Garrett Creek watershed*

Road system	Hillslope position	Average volume of fill in road crossings (m^3)	Average volume of erosion (fill and native material) from crossings that failed (m^3)	Percent of road crossings that failed
Mainline Road	Upper middle	178	186	51
Middle Garrett Road	Middle lower	158	144	42
Nelson Road	Lower	104	74	50

TABLE 5.—*Histories of road crossings in the Garrett Creek watershed*

[Numbers refer to crossing history and do not imply present state or condition of the road crossing. Most crossings have subsequently been rebuilt]

Crossing history	Number	Percent of total
Installed crossings that failed	[1]43	29
Fill crossings that failed	5	4
Installed crossings that remained intact	33	30
Fill crossings that remained intact	25	22
Unknown	5	4
Total	111	

[1] The 43 crossings (of 111) that failed represent at least 52 failures; thus, some crossings failed more than once.

Although the Mainline Road crosses the middle and upper portions of the basin, where streams are smaller and less incised, the large width of this road results in larger fills overall than are needed along either Middle Garrett Road or Nelson Road. Table 4 shows that fills in the Mainline Road crossings, despite their positions higher on the hillslope, failed more often than those on the lower roads. These data suggest that culvert size and proper installation are more important than hillslope position and upslope drainage area in determining the magnitude of crossing failures. Improved road construction practices in the early 1980's have demonstrably reduced crossing failures.

The road-crossing history for Garrett Creek (table 5) shows that 48 of 111 crossings failed during the study period. Only 5 of these 48 crossings were fills that had no drainage conduit; the remaining 43 sites had a culvert or Humboldt fill that clogged and caused failure. Despite the prevalence of crossing failures, sediment contributions to Garrett Creek from these failures account for only 12 percent of road-related fluvial erosion.

OTHER SOURCES OF FLUVIAL EROSION

Most remaining fluvial erosion was either road related or caused by skid-trail construction during logging. Sources and quantities of road-related fluvial erosion are summarized in table 6. After diversions and the failures of installed crossings, erosion resulting from culverts not placed at grade was most important, amounting to 12 percent of total road-related fluvial erosion. Approximately 85 percent of this erosion occurred at crossings on Mainline Road. Most of these culverts were originally Humboldt crossings. When these crossings failed, they were replaced with culverts, but the remaining fill was generally not excavated, and the logs used in the Humboldt crossings were left in place. The culverts were placed above the logs and commonly created a vertical drop of a meter or more at the outlet. As a result, considerable bank erosion and channel scour occurred below many of the crossings.

TABLE 6.—*Summary of causes of road-related fluvial erosion in the Garrett Creek watershed*

[Data include logging haul roads but not skid trails]

Cause of erosion	Mass of sediment (Mg)	Number of individual features	Average size (Mg)
Stream diversions	63,614	15	4,240
Failures of installed crossings	11,192	43/52	196
Crossing not to grade	11,524	12	960
Misplaced culvert	2,951	5	590
Road-intercepted runoff	2,002	10	200
Failures of fill crossing	498	5	100
Erosion of inboard ditches	2,086	23	91
Total	96,107	123	

Erosion resulting from misplaced culverts contributed 5 percent of sediment (table 6). Only five crossings in the basin, all on the Mainline Road System, had misplaced culverts. The misplaced culverts were chiefly reconstructions of failed Humboldt crossings. Misplaced culverts were all placed within 20 m of the true channel, and they all resulted in short (less than 30 m) gullies that had relatively large cross-sectional areas.

Skid-trail-related fluvial erosion came from two sources: stream diversions at trail crossings and rill development on skid trails. There were four skid diversions contributing 47 percent of skid-trail-related fluvial erosion. Plot studies of rill erosion in the Redwood Creek basin on terrain similar to that of the Garrett Creek watershed provide the erosion rate that we used for Garrett Creek skid trails. Total skid-trail-related fluvial erosion was 29,182 Mg (table 7).

FLUVIAL HILLSLOPE EROSION: COMPARISON WITH ADJACENT BASIN

Both Garrett Creek and an adjacent Redwood Creek tributary to the northwest, Copper Creek (fig. 1), have been the sites of detailed surveys of fluvial erosion. The Copper Creek (drainage area=7.3 km^2) study (Weaver and others, 1981) documents an 8-year episode of extremely rapid, storm-caused fluvial slope erosion following intensive logging and road construction in a 2.5-km^2 portion of the watershed.

In both watersheds, stream diversions at installed crossings and skid-trail crossings were the single largest cause of fluvial hillslope erosion (75 percent and 43 percent, respectively, of the total measured fluvial slope erosion in the Copper and Garrett study areas). A higher volume of eroded material from the slopes of Copper Creek is the result of multiple diversions. In Copper Creek, Weaver and others (Chap. I, this volume) concluded that most fluvial slope erosion from diversions occurred during major storms in 1972 and 1975.

Although sites and causes of fluvial slope erosion in the two watersheds are similar, the volume of erosion at Copper Creek was much higher. Fluvial slope erosion for Copper Creek from 1971 to 1979 was 177,300 Mg (chap. I, this volume). For comparison, road-related and skid-trail-related fluvial erosion in Garrett Creek for 1956 to 1980 was 123,050 Mg. The greater erosion at Copper Creek is due to a different land use history. Logging in Copper Creek took place rapidly over a few years, and then the entire dead-end road network was abandoned in 1971. Garrett Creek has been more or less continually harvested and contains through-going roads, so that most crossing failures and diversions were corrected fairly soon after they occurred. The sporadic but nonetheless more frequent maintenance at Garrett Creek prevented the repeated diversions and rediversions of gullied streamflow that contributed the extremely high volumes of eroded material to Copper Creek.

SEDIMENT BUDGET FOR GARRETT CREEK

Our sediment budget for Garrett Creek is based on measurements of fluvial hillslope erosion, streamside landslides, and stored sediment in the main channel of Garrett Creek. The budget data (table 7) are presented in terms of total volumes for the 1956–80 period rather than in terms of rates of sediment input and output. The latter method may be preferable because it assigns rates to processes. However, it is not known how the rates that were measured during the 1956–80 period of intensive land use compare to long-term rates.

The sediment budget in table 7 shows five major sources of sediment input. For the first four sources (77 percent of input), the entire population of erosion sites was measured in the field and did not involve extrapolation from the erosion rate of a sample. To this extent, data shown in the first four rows of table 7 differ from other sediment budget data for the Pacific Coast Ranges (Dietrich and Dunne, 1978; Kelsey, 1980; Kelsey and others, 1981; Lehre, 1982), where most of the sediment contribution has been determined from sample rates or from previous field studies.

The fluvial contribution from prairie and hardwood areas (table 7) in the basin not otherwise influenced by road building is difficult to quantify because these erosion sources involve enlargement of previously existing gullies and the increase in volume can only be estimated. A uniform sediment yield rate of 509 (Mg/km^2)/yr has been applied for this area. This rate is based on a measured rate of erosion for a geographically similar 22-hectare sample plot in Lacks Creek, an adjacent basin to the southeast (fig. 1). The Lacks Creek plot was undisturbed except for a minor ranch road. The sample erosion rate is conservative and includes enlargement of natural channels, as well as gully and rill erosion within relatively stable hardwood terrain.

TABLE 7.—*Simplified sediment budget for the 10.8-km^2 Garrett Creek watershed, 1956–80*

Budget component	Mass of sediment (Mg)	Percent of total input
Input		
Road-related gully erosion[1]	50,442	16
Road-related debris torrents[1]	43,426	14
Skid-trail-related fluvial erosion	29,182	9
Streamside landslides	121,412	38
Fluvial erosion from prairie-hardwood areas (estimated)	73,776	23
Storage		
Additions to alluvial storage	18,800	100
Output		
Inferred sediment yield for 25-year budget period	299,438	100

[1] Road-related erosion sources are itemized by cause of erosion in table 6.

Bank erosion and channel downcutting in forested areas, which are neither obvious from field surveys nor visible on aerial photographs, have been neglected in all measurements done to date. Such erosion may be significant and is highly variable throughout the basin. Rainsplash and sheet erosion was considered to be insignificant in all budget calculations. Reid and others (1981) have measured rainsplash and sheet erosion rates from logging roads. If their rates are applied to roads in Garrett Creek, the sediment yield for the study period increases by a maximum of 0.5 percent. Other surface area plot studies by U.S. National Park Service scientists in the Redwood Creek basin have similarly concluded that sheet erosion is insignificant compared to channel processes (K.J. Kveton and R.A. Sonnevil, Redwood National Park, written commun., 1982).

The sediment budget for Garrett Creek (table 7) shows that roughly 318,000 Mg of sediment has entered the main channel of Garrett Creek between 1956 and 1980. Approximately 31 percent of the total input resulted from the seven forms of road-related fluvial erosion listed in table 6. Three road-related debris torrents alone account for 14 percent of total sediment input (table 7). Most of the fluvial erosion, 63 percent, came from the Douglas-fir portion of the basin (drainage area=5.0 km^2; 46 percent of total drainage area of Garrett Creek). The road-related fluvial erosion resulted in large measure from poor road and skid-trail construction and design and

TABLE 8.—*Comparison of watershed characteristics and sediment yields for Coyote Creek, Garrett Creek, and Lacks Creek*

Drainage basin	Drainage area (km^2)	Drainage length (km)	Average gradient	Estimated sediment yield [(Mg/km^2)/yr]
Coyote Creek	20.4	6.5	0.13	[1]2,500
Garrett Creek	10.8	4.5	.18	1,110
Lacks Creek	44.0	13.6	.06	[1]1,600

[1] Based on U.S. Geological Survey gaging station records for water year 1980.

could have been prevented. Fluvial hillslope erosion from the remaining unlogged prairie and oak woodlands portion of the basin (drainage area=5.8 km^2; 54 percent of total drainage area of Garrett Creek) constitutes 37 percent of fluvial slope erosion. Comparative fluvial sediment yields from the Douglas-fir and prairie-oak woodland areas are 1,002 and 509 (Mg/km^2)/yr, respectively. Prairie-oak woodland areas generally have considerably higher rates of erosion than forested Douglas-fir areas in northern California (Kelsey, 1980). Erosion from logging roads in Garrett Creek has reversed this situation for the period 1954–80.

Of the total sediment input from the basin, only 6 percent, or about 19,000 Mg, remained in storage—the remaining sediment has been flushed downstream to Redwood Creek. The actual amount of remaining sediment is probably less than 6 percent because some of the stored sediment was present prior to the beginning of the budget period.

The lack of a gaging station prevents the direct calculation of sediment yield from the Garrett Creek basin for 1956–80. Based on calculations from the sediment budget in table 7 (input to channel minus storage), the inferred sediment output is about 299,000 Mg or 1,100 (Mg/km^2)/yr. This inferred sediment yield seems reasonable when compared to sediment yields estimated from gaging station data for the adjacent similar watersheds of Coyote Creek and Lacks Creek (table 8), though sediment yields for the three basins are not strictly comparable because of the different measurement periods. The sediment yield for Coyote Creek, Garrett Creek, and Lacks Creek ranges from 1,110 to 2,500 (Mg/km^2)/yr. This range in yield is comparable to long-term estimates (1954–80) for Redwood Creek at Orick (drainage area=720 km^2) of 2,100 (Mg/km^2)/yr (James Knott, U.S. Geological Survey, written commun., 1981).

CONCLUSIONS

The dominant erosion processes that deliver sediment to perennial or intermittent channels in Garrett Creek are related to major storms of brief duration. The significant erosion of the last 25 years occurred during storms that lasted hours or a few days. Even prior to intensive logging of steep forest lands, most geomorphic change in northern California occurred within hours or a few days per year (Kelsey, 1980). The Garrett Creek study shows that the construction of logging roads greatly increases the rate of hillslope erosion. For this reason, land management must be considered in the long term as another independent variable, together with climate, tectonic processes, and geology, in determining erosion rates. Long-term models of sediment transport, as well as short-term predictions of erosion, require probabilistic analysis of all these independent variables.

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History, Causes, and Significance of Changes in the Channel Geometry of Redwood Creek, Northwestern California, 1936 to 1982

By K. MICHAEL NOLAN *and* DONNA C. MARRON

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–N

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HISTORY, CAUSES, AND SIGNIFICANCE OF CHANGES IN THE CHANNEL GEOMETRY OF REDWOOD CREEK, NORTHWESTERN CALIFORNIA, 1936 TO 1982

By K. MICHAEL NOLAN and DONNA C. MARRON

ABSTRACT

The configuration and behavior of the Redwood Creek stream channel changed markedly between 1936 and 1982. Increases in bank-to-bank width in excess of 100 percent and channel fill in excess of 4.5 m were observed. These changes, which occurred primarily in response to major storms in 1964 and 1972, adversely affected riparian resources of Redwood National Park. Timber harvest in the area may have exacerbated effects of these storms but did not trigger processes other than those that occur in the basin naturally. Effects of the 1964 and 1972 storms were still evident in the channel in 1981, but changes in channel geometry and grain size of alluvium indicate that some basinwide recovery may have begun.

Major storms can produce catastrophic changes in channel geometries in the study area because they trigger landslides throughout the unstable terrain. The resulting landslides introduce volumes of sediment sufficient to overload channel transport capacities for decades. In addition to channel fill, gravel berms deposited by floodflows persist because moderate flows do not rise high enough to erode them. Study of the Redwood Creek channel has shown that, as a result of naturally occurring processes, major storms strongly affect channel geometry for long periods of time. Channel geometry reflects the length of time since major storms and the levels of moderate flows that modify flood-related effects.

INTRODUCTION

The configuration and behavior of the Redwood Creek stream channel have changed markedly since the mid-1950's. The most apparent changes have been major increases in channel width and decreases in channel depth. These changes occurred in response to (1) a sequence of major storms and (2) large-scale timber harvest throughout the basin. Concern regarding the effects of these channel changes on riparian resources of Redwood National Park prompted numerous studies aimed at characterizing the magnitude and cause of the changes. Preliminary data collected in many of these studies are presented and discussed in papers by Iwatsubo and others (1975 and 1976), Janda and others (1975), Harden and others (1978), Nolan and Janda (1979), and Nolan (1980). Although recent channel changes similar to those observed in the Redwood Creek watershed have been noted in nearby watersheds (Ritter, 1968; Hickey, 1969; Kennedy and Malcolm, 1978; Kelsey, 1980; and Lisle, 1981), studies along the main channel of Redwood Creek have produced the longest and most complete basinwide record of channel response in the region.

PURPOSE AND SCOPE

The purpose of this paper is to summarize, update, and augment existing literature describing the history, causes, and significance of the changes in the main channel of Redwood Creek during the period 1936 to 1982. Channel behavior during this period, which was observed by using a variety of qualitative and quantitative methods, is described. The role that interactions of active physical processes in the basin played in producing the observed changes is discussed. Finally, the geomorphic significance of the channel changes is assessed.

THE STUDY AREA

Redwood Creek drains an elongate 725-km^2 drainage basin in the Coast Ranges of northwestern California (fig. 1). The main channel of Redwood Creek roughly bisects the drainage basin. Slopes in the watershed, which are naturally susceptible to mass wasting and fluvial erosion, have an average gradient of 26 percent (Janda and others, 1975). Total basin relief is 1,615 m.

Most of the Redwood Creek drainage basin is underlain by sedimentary and metasedimentary rocks of the

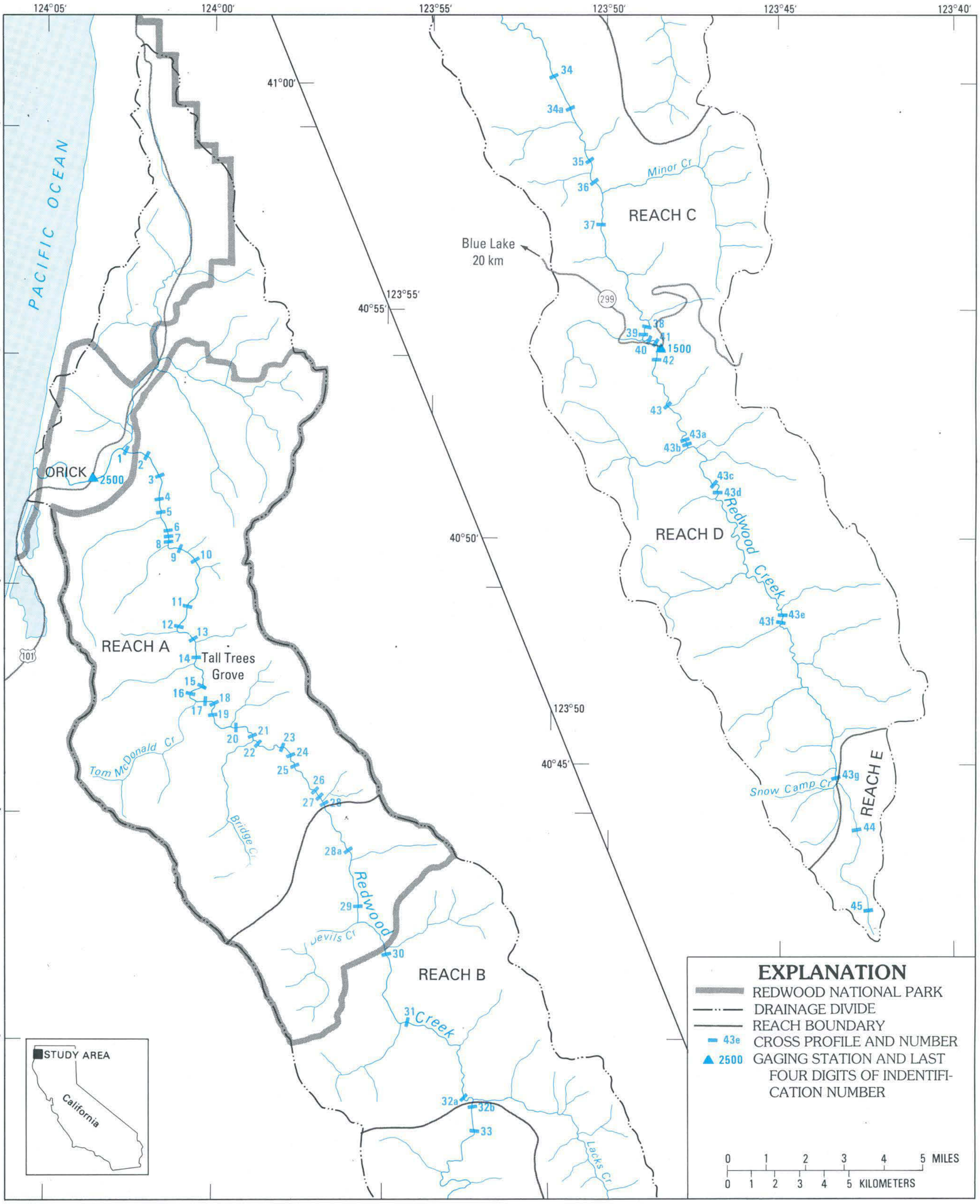

FIGURE 1.—Location of the Redwood Creek drainage basin and stream-channel cross profiles.

Franciscan assemblage of Late Jurassic and Cretaceous age (Bailey and others, 1970; Harden and others, 1982). Dominant rock types include unmetamorphosed, interbedded sandstone and shale and fine-grained, well-foliated quartz mica schist. The main channel of Redwood Creek roughly coincides with the Grogan fault, which separates the sandstone and schist units. Sandstone and related unmetamorphosed rocks dominate on the eastern side of the basin, whereas schist dominates the western half. Sandstone and shale in the basin are pervasively sheared at most localities.

The Redwood Creek watershed has a Mediterranean climate—warm, dry summers and cool, wet winters. Basinwide average rainfall is approximately 2,000 mm, 80 percent of which falls between the months of October and March. Regional storms of light to moderate intensity produce much of this precipitation. Approximately 66 percent of the annual precipitation appears as runoff, producing an average daily flow of 29.51 m^3/s (cubic meters per second) at Orick.

Forest, chiefly coastal redwood and Douglas-fir, covers most slopes in the Redwood Creek watershed. Prairies of grass and shrubs are also common on slopes. On most stream terraces and upper flood-plain surfaces in the lower part of the basin are stands of redwood and redwood mixed with Douglas-fir, whereas Douglas-fir dominates on these surfaces upstream and farther inland. Alder thickets are common throughout the basin where soil and rock have been exposed by overbank deposition, bank erosion, mass movement, or timber harvest.

During periods of moderate flow, Redwood Creek flows within a lower gravel flood plain that varies in width between 30 and 130 m. During periods of low flow, the channel is contained within a low-flow channel that is typically 0.1 to 0.5 times as wide as the lower flood plain and is incised 0.5 to 2.0 m into the lower flood plain (figs. 2, 3). Low-flow channels alternate in pattern from meandering to braided along the unvegetated lower flood plain. The entire lower flood plain is inundated for long periods during normal winters.

Along most of the length of Redwood Creek, the lower flood plain abuts directly against colluvial hillslopes (Nolan and others, 1976). Bedrock along streambanks, although present in some locations, is not common. Along some reaches, a narrow upper flood plain consisting of 2 to 5 m of unweathered, fine sandy loam and silt loam borders the lower flood plain. Its surface is commonly 1 to 2 m above the lower flood-plain surface. Inundation of upper flood plains during a single major storm commonly results in 0.15 to 0.30 m of deposition (Janda and others, 1975). Upper flood-plain surfaces are most prevalent along wider downstream reaches of the channel. Large, flood-deposited gravel berms, which resemble those found elsewhere in northwestern California by Stewart and LaMarche (1967) and Helley and LaMarche (1973), are found throughout the basin. These berms, which commonly consist of a 1- to 2-m thickness of gravel, are located on the insides of channel bends or in reaches characterized by abrupt increases in channel width or decreases in gradient (figs. 4, 5). Vegetation on these berms is distinguished by even-aged stands of young conifers that date to recent storms. A schematic representation of a typical cross section of the flood plain of Redwood Creek is shown in figure 6.

FIGURE 2.—Low-flow conditions along midbasin reach of Redwood Creek below mouth of Minor Creek. Photograph taken August 1975.

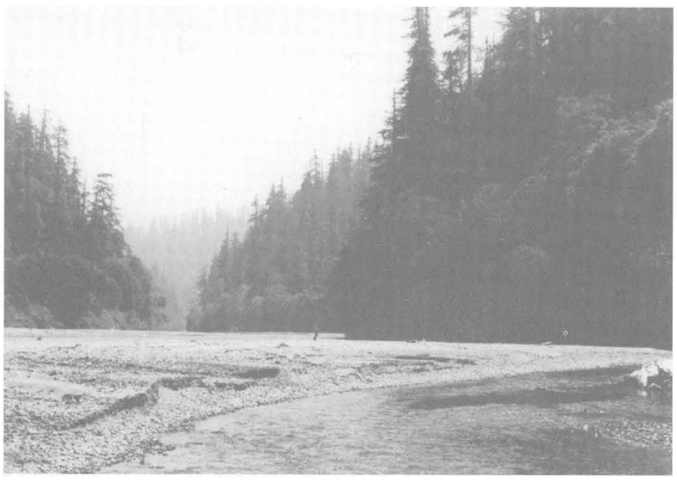

FIGURE 3.—Low-flow conditions along a lower reach of Redwood Creek near cross profile 3. Photograph taken August 1975.

BACKGROUND

Beginning in the mid-1950's, the Redwood Creek basin experienced five flood-producing storms (Harden and others, 1978); widespread clearcut timber harvesting took place as well. Major storms, which occurred in 1953, 1955, 1964, 1972, and 1975, were associated with rainfall totals of up to 500 mm. Peak discharges associated with the storms ranged between 1,283 and 1,430 m^3/s at the gaging station on Redwood Creek near Orick (table 1). Prior to 1964, a peak discharge of 1,416 m^3/s was considered to have a recurrence interval of 50 years. Concurrently with the major storms, nearly 65 percent of the basin was logged, and much of this logging was by tractor-yarded clearcutting, which was highly disruptive to the ground surface (Harden and others, 1978; Nolan and Janda, 1981).

FIGURE 4.—Surface of gravel berm deposited (along a midbasin reach of Redwood Creek) during flood of December 1964. Photograph taken in August 1978. Alders in foreground are 1 to 1.5 m tall. Note small pack for scale.

The combination of inherently unstable bedrock, extensive timber harvest, seasonally intense precipitation, and moderately steep slopes in the Redwood Creek basin produces one of the highest annual sediment yields in the conterminous United States (Janda and Nolan, 1979). The long-term average annual suspended-sediment discharge for Redwood Creek at Orick (fig. 1) has been estimated at 2,100 Mg/km^2 (J.M. Knott, U.S. Geological Survey, written commun., 1975) and 2,540 Mg/km^2 (Anderson, 1979). When the discharges of bedload and suspended sediment were measured simultaneously, bedload was 20 to 60 percent of the total sediment discharge (Janda, 1978).

FIGURE 5.—Gravel berm deposited (along midbasin reach of Redwood Creek) during flood of 1972. Photograph taken August 1975.

TABLE 1.—*Instantaneous peak discharge and runoff measured at the Redwood Creek gaging stations near Blue Lake and Redwood Creek at Orick during recent major floods*

[Runoff data are from Harden and others (1978). (—), no data]

Date	Peak discharges				Date	Runoff	
	Redwood Creek near Blue Lake[1]		Redwood Creek at Orick[2]			Redwood Creek near Blue Lake[1]	Redwood Creek at Orick[2]
	(m^3/s)	[(m^3s)/km^2]	(m^3/s)	[(m^3s)/km^2]		(cm)	(cm)
Jan. 18, 1953	—	—	1,416	1.97	Jan. 16–20, 1953	—	35.3
Dec. 22, 1955	342	1.96	1,416	1.97	Dec. 15–23, 1955	37.3	32.5
Dec. 22, 1964	464	2.66	1,430	1.99	Dec. 18–24, 1964	—	41.4
Jan. 22, 1972	195	1.11	1,283	1.78	Jan. 19–24, 1973	—	28.7
Mar. 3, 1972	387	2.22	1,407	1.96	Mar. 1–4, 1972	—	18.0
Mar. 18, 1975	345	1.97	1,422	1.98	Mar. 15–24, 1975	28.2	24.9

[1] Station 11481500.
[2] Station 11482500.

TABLE 2.—*Description of study reaches along the main channel of Redwood Creek*

Reach	Length (km)	Average gradient (m/m)	Average bank-to-bank width of surveyed profiles (m)	Boundaries[1]		Cross profiles included
				Upstream	Downstream	
A	28.0	0.003	85.4	Mouth	Cross profile 28	1–28
B	15.4	.005	51.6	Cross profile 28	Lacks Creek	29–32
C	26.0	.003	54.8	Lacks Creek	Highway 299	32a–41
D	23.0	.009	56.5	Highway 299	Snow Camp Creek	42–43g
E	6.3	.15	13.0	Snow Camp Creek	Cross profile 45	44–45

[1] Locations of various features are shown in figure 1.

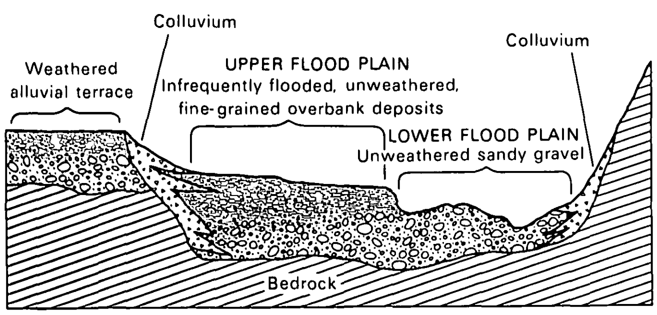

FIGURE 6.—Schematic representation of a typical cross section of the Redwood Creek flood plain. Cross section is not to scale.

CHANNEL HISTORY

The behavior of the Redwood Creek channel between 1936 and 1982 was observed by a variety of methods. Channel history between 1936 and 1973 was documented by using time-sequential aerial photographs, records from stream-gaging stations operated by the U.S. Geological Survey (USGS), and interviews with long-term residents of the area. These observations documented major increases in channel width and significant channel aggradation. Beginning in 1973, channel behavior was observed by repeated surveys of channel cross profiles and measurements of the size and composition of bed material at selected locations. In general, these more detailed observations have documented the persistence of the earlier channel changes. However, data collected during the last 2 years of study indicate that some channel recovery from these major changes may have begun.

For the purpose of analysis, the main channel has been separated into five reaches characterized by distinctive morphologies. Each reach is described briefly in table 2.

CHANNEL CONDITIONS IN 1936

Early documentation of the nature of the Redwood Creek stream channel is provided by aerial photographs taken in 1936 and 1947. Photographs taken in 1936 depict the part of the Redwood Creek basin north of the mouth of Minor Creek (fig. 1), and the 1947 photographs depict the part of the basin south of the mouth of Devils Creek. Basin conditions in 1947 were assumed to resemble closely those in 1936 because (1) weather records indicate that no major storms occurred between 1936 and 1947, (2) the history of land use indicates that no major disturbances occurred during the period, and (3) no significant changes in channel width or patterns were noted in areas where the two sets of photographs overlap. Channel conditions depicted on these photographs are therefore subsequently referred to as 1936 conditions.

In 1936, study reach A (table 2) was characterized by a predominantly braided pattern on a lower flood plain generally devoid of vegetation. Around this time the low-flow channel within this lower flood plain probably shifted frequently. Land surveys done during low flow at several locations below Bridge Creek showed that the low-flow channel migrated up to 30 m between 1946 and 1951 (Janda and others, 1975). Through reach B, the channel was alternately narrow and wide. Narrow subreaches within reach B were bounded by steep, V-shaped valley walls, whereas wider areas displayed morphology similar to that of reach C. Through reach C, the channel was mostly sinuous and moderately incised into a wide alluvial flood plain. Examination of aerial photographs suggests that this flood plain had numerous conifers 3 to 7 m high, many of which lined the narrow, active channel. Study reaches D and E, those above State Highway 299, were characterized by a narrow sinuous channel. A closed vegetation canopy existed along most of the length of these reaches. The canopy was broken only occasionally by a streamside landslide or a wide alluviated reach.

VARIATIONS IN CHANNEL GEOMETRY BETWEEN 1936 AND 1982

VARIATIONS BETWEEN 1936 AND 1974

Recollection of local residents, examination of aerial photographs taken in 1968 and 1974, records from the stream-gaging station on Redwood Creek near Blue Lake, and field observations of streambank stratigraphy and riparian vegetation indicate that, beginning in the mid-1950's, the lower gravel flood plain of Redwood Creek began to aggrade and widen and to shift across large parts of the former upper flood plain. Aerial photographs indicate that the lower flood plain in many areas of reaches D and E was more than twice as wide in 1974 as in 1947 (Harden and others, 1978). Stereograms in figure 7 show conditions of the channel in 1947 and 1973 near cross profiles 43e and 43f. Many of the 3- to 7-m-high conifers on the upper flood plain of reach C in 1947 were removed by 1973 (fig. 8). The only location where systematic increases in channel width did not occur was through reach A (fig. 9).

Data from the stream-gaging station on Redwood Creek near Blue Lake (USGS gaging station 11481500; fig. 1), together with interviews with local residents, indicate that the rapid changes in channel width were accompanied by major increases in streambed elevation. Evidence for as much as 4.5 m of channel fill near the mouth of Minor Creek and 3.0 m of fill near the mouth of Tom McDonald Creek (fig. 10) has been given by residents and local forest workers (Janda and others, 1975). Records from the stream-gaging station near Blue Lake indicate that the mean streambed elevation of Redwood Creek rose at least 1.5 m (fig. 11) and that the channel increased significantly in width between 1958 and 1973.

TABLE 3.—*Variations in channel geometry and velocity for Redwood Creek at the gaging station near Blue Lake*

[Station no. is 11481500. Values shown are those predicted by hydraulic geometry formulas developed for individual periods and applied to water-discharge values for the mean daily flow (7.45 m^3/s) and the 2-year flood (174 m^3). Station was discontinued in 1958 and reactivated at the same location in 1973]

Period	Channel geometry and velocity during mean daily flow			Channel geometry and velocity during 2-year flood		
	Width (m)	Depth (m)	Velocity (m/s)	Width (m)	Depth (m)	Velocity (m/s)
1956–58	19.2	0.43	0.92	32.0	2.06	2.68
1973–74	24.1	.29	1.06	41.4	1.33	3.18
1975–82	19.1	.37	1.03	35.9	1.55	3.13

Aggradation in this reach was probably anomalously low relative to reaches upstream and downstream because the channel is confined at this gaged site and because fill deposited in 1964 may have been removed prior to 1973.

Aerial photographs, botanical evidence, and interviews with local residents indicate that, although some changes began in the mid-1950's, the most dramatic changes occurred in response to major storms in December 1964 and March 1972 (Janda and others, 1975). The relatively minor changes observed by residents in the mid-1950's probably resulted from the flood of January 1953 and (or) the flood of December 1955. The locus of maximum erosion and deposition associated with the 1964 flood was concentrated in upper parts of the watershed, and that associated with the 1972 flood was concentrated in the lower part of the basin (Harden and others, 1978). Along upper Redwood Creek, stands of young conifers on flood-deposited gravel berms are even-aged and in 1984 were about 18 years old, suggesting that these berms are related to the December 1964 flood (fig. 4). Along downstream reaches, the ages of recently established conifers indicate that the flood berms in those reaches are primarily related to the 1972 flood (fig. 5).

The magnitude of channel changes that occurred between 1956 and 1974 at the gaging station near Blue Lake can be seen in table 3. This table shows the channel width and depth and stream velocity determined by applying hydraulic geometry formulas (Leopold and Maddock, 1953) to streamflow measurements made at the gaging station during three separate periods. The first period, 1956 to 1958, illustrates conditions just prior to the station's discontinuance and shows channel conditions prior to major storms of 1964 and 1972; the second period, 1973 to 1974, provides the earliest data available after the floods.

The channel changes resulting from the floods of 1964 and 1972 had adverse impacts on riparian vegetation along many reaches. Bank undercutting toppled many old-growth redwood trees (fig. 12). Elsewhere, gravel deposition completely filled the former lower flood plain and spilled onto extensive areas of the former upper flood plain. This gravel deposition killed numerous trees,

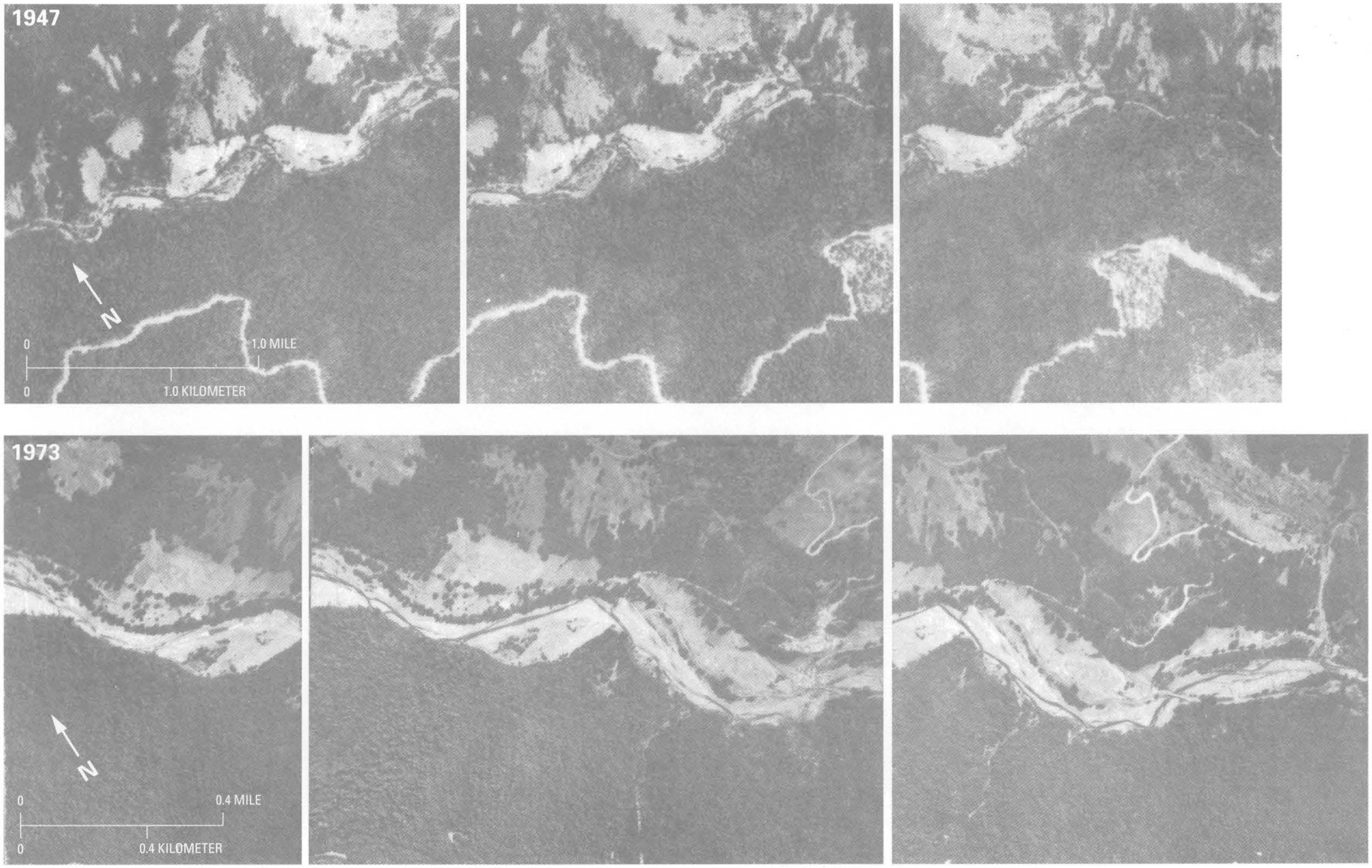

FIGURE 7.—Stereograms showing conditions of the Redwood Creek channel in 1947 and 1973 near cross profiles 43e and 43f (reach D). Arrows point to identical location on each set of photographs. Note large increases in streamside landslides and removal of vegetation canopy between 1947 and 1973.

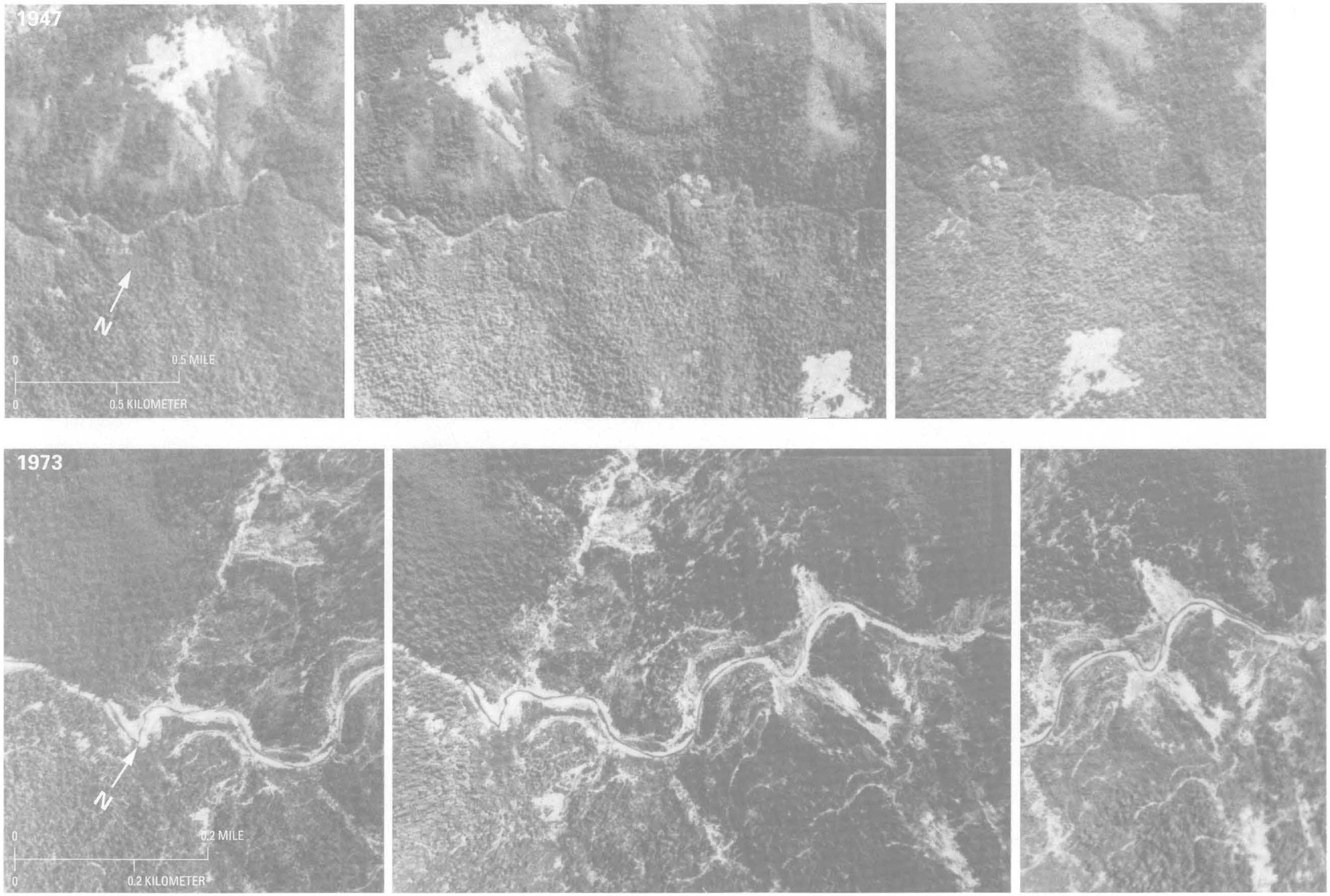

FIGURE 8.—Stereograms showing conditions of the Redwood Creek channel in 1947 and 1973 near cross profiles 35 and 36 (reach C). Arrows point to identical location on each set of photographs. Note removal of large amounts of midchannel vegetation by 1973.

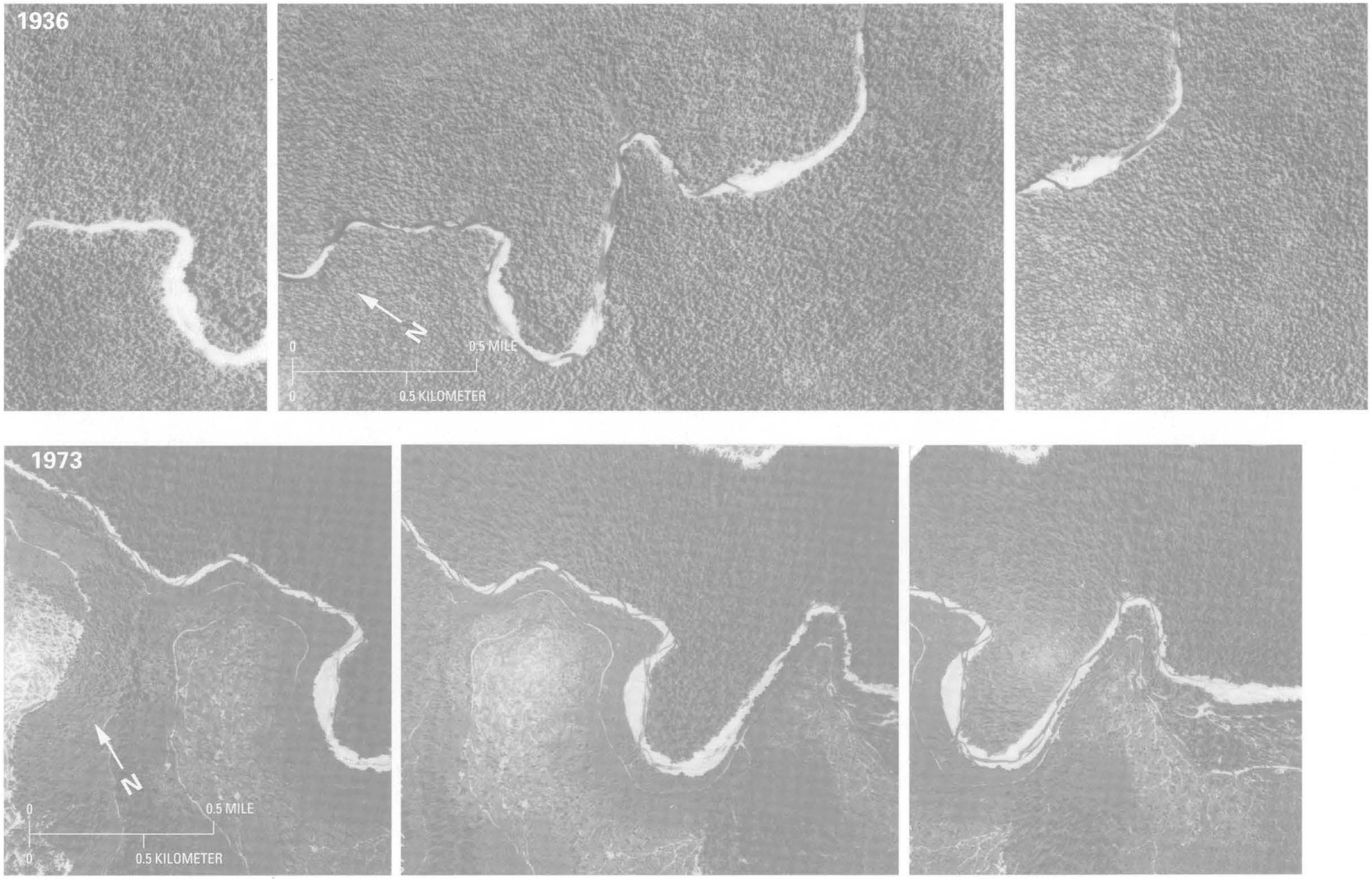

FIGURE 9.—Stereograms showing conditions of the Redwood Creek channel in 1936 and 1973 near the Tall Trees Grove in reach A. Note lack of significant changes in these reaches. Both sets of photographs are at approximately the same scale.

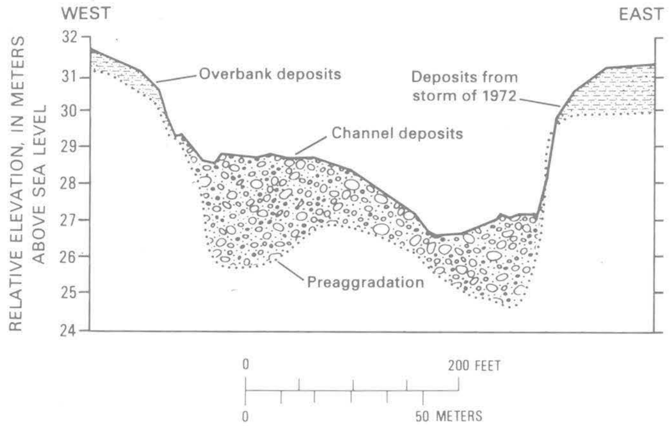

FIGURE 10.—Recent changes in the geometry of Redwood Creek at the mouth of Tom McDonald Creek. Preaggradation configuration was estimated from reports of local forest workers and road construction records. Configuration in 1972 is from ground surveys.

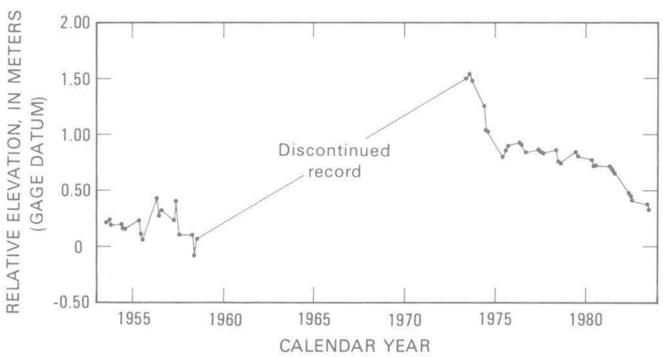

FIGURE 11.—Variation in mean elevation of the low-flow channel of Redwood Creek at the gaging station near Blue Lake (11481500). Mean streambed elevations were determined by using methods described by Hickey (1969).

FIGURE 12.—Trees toppled by bank erosion immediately downstream of the Tall Trees Grove. Photograph taken March 1976.

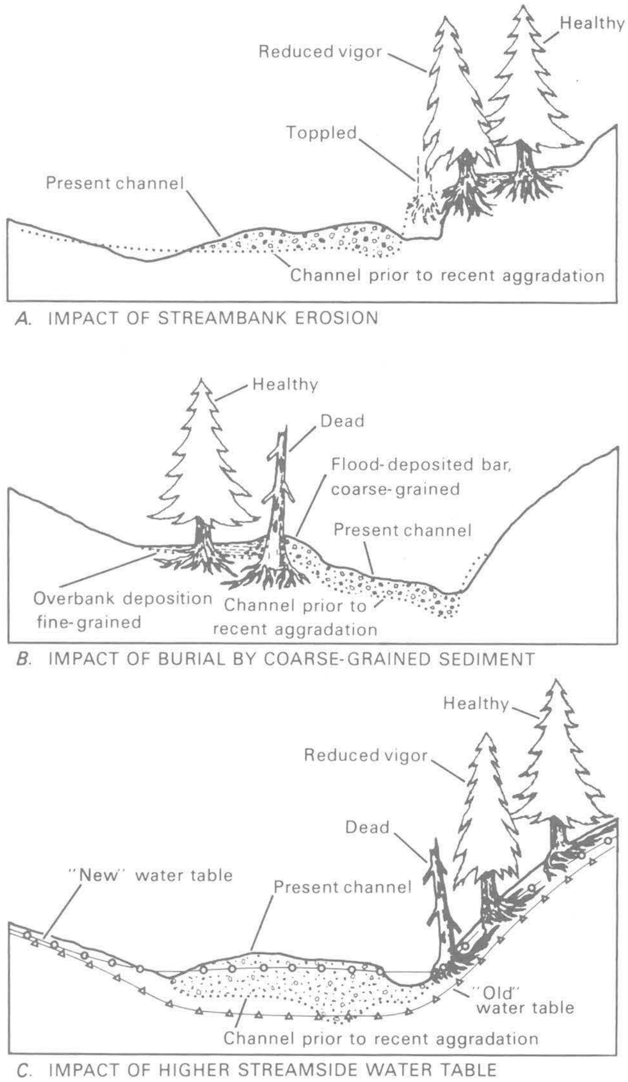

FIGURE 13.—Schematic representation of observed impacts of channel aggradation on riparian vegetation.

many of which were 200–300 years old (Janda and others, 1975), on the flood plains. Coarse, gravel-sized sediment may limit the supply of nutrients to the shallow root systems common to redwood trees and increase desiccation during warm, dry summer months (Zinke, 1981). Elevated water tables associated with channel aggradation also affected the health of many streamside trees (fig. 13).

VARIATIONS BETWEEN 1974 AND 1982

Changes in the cross-sectional area of Redwood Creek between October 1973 and August 1981 were monitored by a network of surveyed cross profiles (figs. 1, 14). This

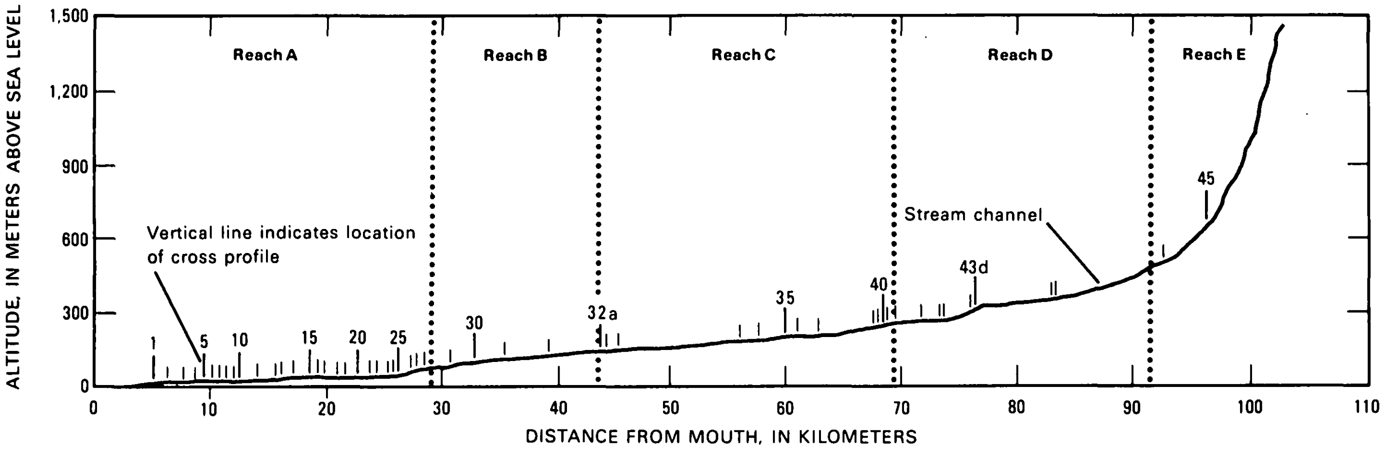

FIGURE 14.—Longitudinal profile of Redwood Creek showing location of study reaches and surveyed stream-channel cross profiles.

network, which consisted of 43 profiles in 1973, was expanded to include 53 profiles by 1978. End points were monumented by a 12.5-mm reinforcing bar, and profiles were determined by using a self-leveling level and stadia measurements. The slow recovery process following the floods of 1964 and 1972 is also illustrated by hydraulic geometry data for the period 1975 to 1982 (table 3).

Generalized channel behavior in each of the five study reaches from water years 1974 to 1981 is summarized in figure 15 and tables 4 and 5. Figure 15 presents changes in streambed area at all cross profiles for each study reach. Data in this figure have been normalized by dividing changes in cross-sectional area by bank-to-bank channel width to provide a better measure of the impact of the change at a given cross profile. Table 4 lists the number of cross profiles in each study reach that showed either scour, fill, or no change in streambed and streambank areas. Table 5 presents a brief description of channel behavior as indicated by data presented in earlier text, as well as in figure 15.

Although some annual variations occurred, the channel geometry data indicate a general pattern of channel scour in upstream reaches and channel fill in lower reaches between the 1974 and 1981 water years. Channel scour was particularly pervasive in reaches C, D, and E, and channel fill was generally found in reaches A and B. Channel fill was particularly prominent directly downstream of the steep rocky gorge that marks the upstream end of reach A. The magnitude of channel changes in 1974 and 1975 was relatively high, probably owing, at least in part, to relatively high streamflow during these years (table 6). The relatively minor changes recorded during the 1977 water year probably reflect the relatively low streamflow that occurred during that year.

The general pattern of channel behavior changed markedly in 1981 when 17 of 24 sections in reach A showed channel scour. This year was characterized by streamflow that was slightly below normal. Scour occurred at 31 of the 48 cross sections surveyed in 1981 at reach A. Streambank erosion was generally more common than streambank deposition throughout the period of resurveys (table 4).

GRAIN-SIZE DISTRIBUTION OF BED MATERIALS

The size distribution and lithologic composition of the bed material of Redwood Creek were determined by grid sampling of surficial material. Bed material was sampled at all 45 cross profiles surveyed in 1976 and was resampled at 13 of those sites during the summers of 1979 and 1982. The 13 resampled sections were chosen to represent conditions along major reaches that have distinctively different channel characteristics.

Field methods used for grid sampling follow those suggested by Wolman (1954). Five transects perpendicular to the channel were established at each survey site. One transect was on the survey line, while the others were spaced at distances equal to one-quarter and one-half the channel width upstream and downstream of the survey line. The median axis and lithology of bed-material clasts were noted at 30 points on each transect to sample a total of 150 points at each cross-profile site.

For all data, size-class frequency distributions and weight percentages per size class were determined by following methods presented by Leopold (1970). Size-class frequency distributions indicate the percentage of streambed area covered by various sizes, whereas weight percentages provide data roughly comparable to those obtained by sieve analysis. Phi values of D_{16}, D_{50}, and D_{84} were determined from cumulative curves of weight percentages (D refers to median diameter and the subscripts 16, 50, and 84 refer to the percentage of sediment with median diameters smaller than those values). Mean values were determined by summing phi

TABLE 4.—*Number of cross profiles showing either scour, fill, or no change of streambed and streambanks from water years 1974 to 1981*

Year and reach	Streambed			Streambanks		
	Scour	Fill	No change	Scour	Fill	No change
1974:						
A	7	18	0	19	3	3
B	5	2	0	3	4	0
C	8	1	0	4	0	5
D	1	0	0	1	0	0
E	None established			None established		
1975:						
A	8	17	0	9	14	2
B	0	7	0	5	2	0
C	5	7	0	9	1	2
D	2	0	0	0	0	2
E	1	1	0	1	1	0
1976:						
A	8	17	0	14	5	6
B	6	1	0	4	0	3
C	11	1	0	6	2	4
D	2	0	0	0	1	1
E	1	1	0	1	1	0
1977:						
A	11	13	0	5	4	15
B	5	2	0	3	0	4
C	6	6	0	2	1	9
D	0	2	0	1	0	1
E	0	1	0	0	0	1
1978:						
A	9	15	0	14	9	1
B	5	1	1	3	4	0
C	10	2	0	5	5	2
D	2	0	0	2	0	0
E	1	1	0	1	1	0
1979:						
A	9	14	0	6	3	14
B	4	3	0	5	0	2
C	4	5	0	4	1	4
D	1	1	0	0	0	2
E	2	0	0	1	0	1
1980:						
A	8	16	0	8	16	0
B	4	3	0	0	7	0
C	3	5	0	3	4	1
D	3	2	0	3	2	0
E	Not surveyed			Not surveyed		
1981:						
A	17	6	1	14	1	9
B	4	3	0	4	0	3
C	5	4	0	4	1	4
D	4	3	0	2	1	4
E	2	0	0	1	0	1

values of D_{16}, D_{50}, and D_{84} and dividing by 3, as suggested by Folk and Ward (1957).

The lithologic composition of the bed material was assessed by assigning clasts to one of the two major rock units in the basin (unmetamorphosed rocks or schist) or to an "others" category for rock types not diagnostic of either unit or for clasts too small to identify lithologically. Weight percentages of unmetamorphosed clasts include clasts identified as shale, siltstone, sandstone, or conglomerate, whereas weight percentages of schist include schist and metavolcanic clasts (Harden and others, 1982).

BED MATERIAL CHARACTERISTICS IN 1976

In 1976 the bed of Redwood Creek was dominated by gravel-sized clasts (phi=−2 to −6). Longitudinal variations in mean grain size reflected gross channel morphology and distance from the mouth. Steep, incised reaches such as B, D, and E had relatively large mean grain sizes. Wider reaches, such as A and C, which flow through well-defined alluvial flats, were characterized by relatively small grain sizes (fig. 16). Generally, mean grain size decreased in a downstream direction (fig. 16).

The lithologic composition of the clasts sampled in 1976 indicates that disproportionately high percentages of recognizable clasts on the bed of Redwood Creek were derived from terrane underlain by unmetamorphosed rocks relative to terrane underlain by schist. Even though roughly similar amounts of the basin above Bridge Creek are underlain by unmetamorphosed rocks and schist (Harden and others, 1982), the pebble-count data indicate that unmetamorphosed rocks consistently constituted greater percentages of the streambed in reaches B–E (fig. 17). The percentage of schist in the streambed clasts about equaled that of unmetamorphosed rocks only in reach A, which is mostly below the mouth of Bridge Creek, where schist begins to underlie a large percentage of the drainage area. The disproportionate contribution of unmetamorphosed rocks to the alluvium of Redwood Creek most likely reflects the fact that more area characterized by recent mass-movement activity is underlain by unmetamorphosed rocks than by schist (Harden and others, 1978). However, since the fine-grained, foliated schist clasts may be more easily broken down by abrasion during transport within the channel, a greater proportion of small, unrecognizable clasts may be derived from schist, so that the discrepancy may appear greater than it actually is.

BED MATERIAL CHANGES BETWEEN 1976 AND 1982

Mean grain size increased between 1976 and 1982 at 11 of the 13 cross profiles at which pebble counts were repeated (fig. 18). Increases in D_{16} were generally greater than in D_{84} (fig. 19), which suggests that the winnowing out of fine material was largely responsible for the increases in mean grain size. The selective removal of fine material is also suggested by the fact that, at 11 of the 13 cross profiles, the percentage of area covered by sand, silt, and clay decreased between 1976 and 1982 (fig. 20).

From 1976 to 1982, the ratio of weight percentages of unmetamorphosed clasts to weight percentages of schist clasts increased at all of the resampled cross profiles (fig. 21). This increase may be related to the sorting and weathering processes that were responsible for increases in mean grain size, as the schist clasts are commonly

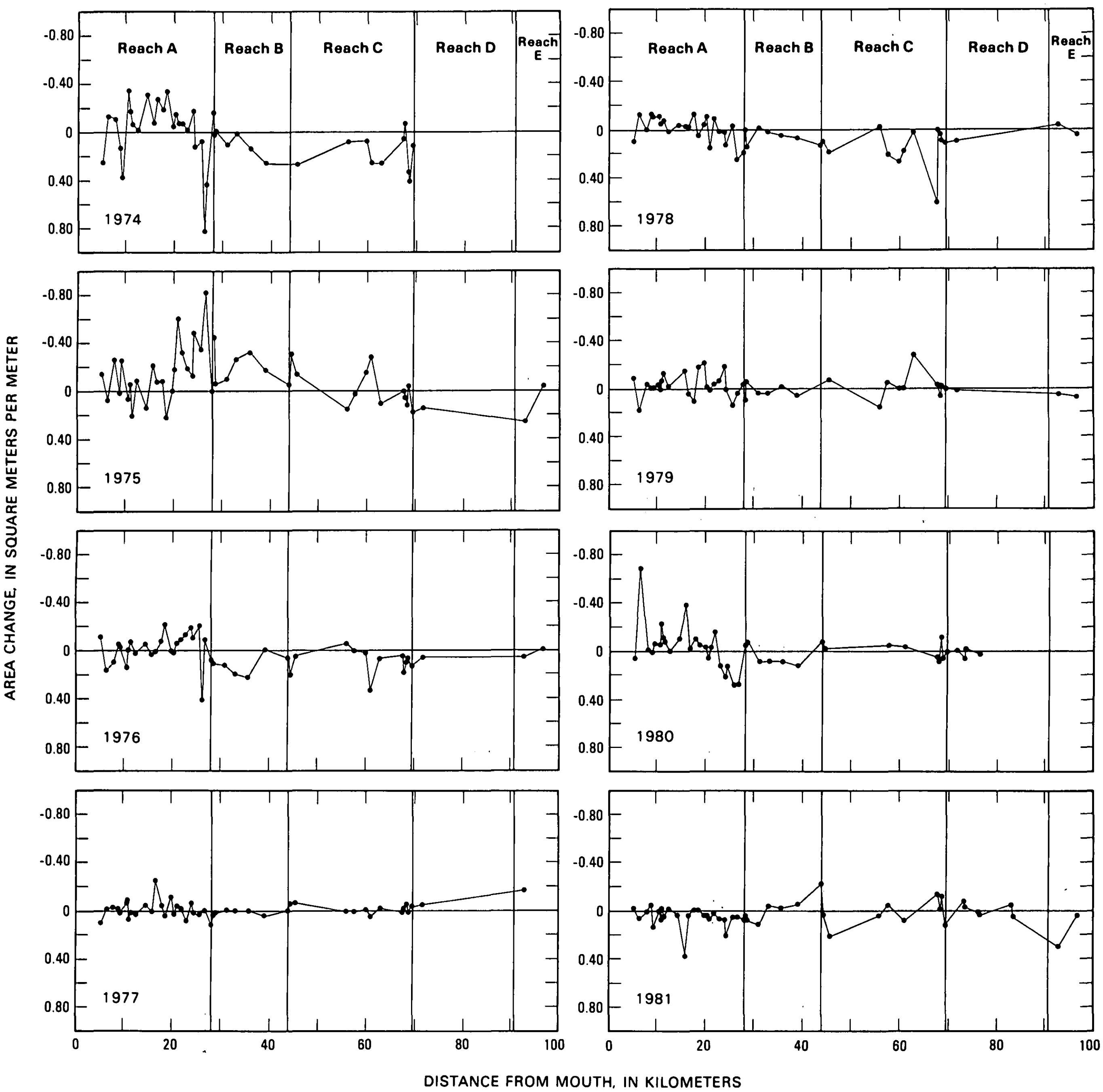

FIGURE 15.—Change in area of the streambed at cross profiles between water years 1974 and 1981. Area change is expressed in square meters of change per meter of bank-to-bank width. Channel scour is indicated by a positive change in area, and channel fill by a negative change. The lines connecting data points have no physical significance. They are presented only to aid in interpreting the data.

more breakable and consequently smaller than unmetamorphosed clasts in the streambed. The increase also may indicate that between 1976 and 1982 processes contributing sediment to Redwood Creek continued at more rapid rates on slopes underlain by unmetamorphosed rocks than on those underlain by schist.

Although net changes between 1976 and 1982 show pervasive increases in mean grain size as well as in the ratio of unmetamorphosed rock to schist bed material, these trends were not everywhere continuous. At two sites in reach B, a decrease in mean grain size was noted from 1976 to 1979, followed by an increase in mean grain

TABLE 5. *Summary of observed behavior of the Redwood Creek channel*

[Observations prior to 1974 are from a combination of aerial photograph interpretation, interviews with long-term residents, and gaging-station records. Observations after 1974 are from repetitive surveys of channel cross profiles]

Period	Reach A	Reach B	Reach C	Reach D	Reach E
1936–50	Wide gravel flood plain; inner channel shifted frequently.	Alternately narrow and wide gravel channel; narrow reaches bounded by steep valley walls.	Sinuous channel moderately incised into wide alluvial flood plain; channel lined with conifers.	Narrow sinuous channel with closed vegetation canopy.	Same as D.
1950–74	Wide gravel flood plain; inner channel shifted frequently; some increase in width of flood plain; channel fill in excess of 1.5 m noted; some riparian trees damaged by battering and burial.	Alternately narrow and wide gravel channel; some riparian vegetation damaged.	Channel filling in excess of 4.6 m noted; most conifers on flood plain removed.	Channel widening in excess of 100 percent noted; closed canopy gone due to abundant streamside debris slides.	Same as D.
1974	Channel fill dominant; some widening.	Channel scour dominant	Channel scour dominant	Channel scour dominant	Not surveyed.
1975	Pervasive channel fill accompanied by bank deposition.	Channel fill dominant	Channel filling slightly more prevalent than scour.	Channel scour dominant	Scour equal to fill.
1976	Minor fill	Minor scour	Minor scour at nearly all profiles.	Minor scour	Scour equal to fill.
1977	Minor fill	Scour equal to fill	Scour equal to fill	Minor scour	Minor fill, but only one profile surveyed.
1978	Minor fill	Minor scour	Scour about equal to fill	Minor scour	Channel scour dominant.
1979	Minor fill	Minor scour	Scour about equal to fill	Minor scour	Minor scour.
1980	Pervasive fill	Pervasive scour	Scour about equal to fill	Scour about equal to fill	Not surveyed.
1981	Scour at nearly all profiles	Minor fill	Scour about equal to fill	Scour about equal to fill	Scour.

TABLE 6.—*Summary of streamflow recorded for Redwood Creek at Orick during period of channel cross-profile surveys*

[Average annual runoff for 30 years of record was 1,290 mm. Peak of record was 1,430 m^3/s on December 22, 1964. Peak discharges listed are those above a base of 255 m^3/s. Gaging station no. is 11482500]

Water year	Total runoff (mm)	Date of peak discharge	Peak discharge (m^3/s)
1974	2,141	Oct. 23	459
		Nov. 8	303
		Nov. 12	306
		Nov. 30	422
		Jan. 16	445
		Feb. 19	314
		Mar. 30	377
		Apr. 1	702
1975	1,618	Jan. 8	340
		Feb. 13	276
		Feb. 19	558
		Mar. 18	1,422
		Mar. 25	569
1976	1,048	Dec. 4	286
		Feb. 28	343
1977	238	No peak above 255 m^3/s	
1978	1,448	Nov. 22	265
		Nov. 24	273
		Dec. 14	600
		Jan. 17	300
1979	785	Jan. 11	399
1980	1,374	Nov. 24	357
		Jan. 12	405
		Mar. 14	549
1981	801	Dec. 2	256

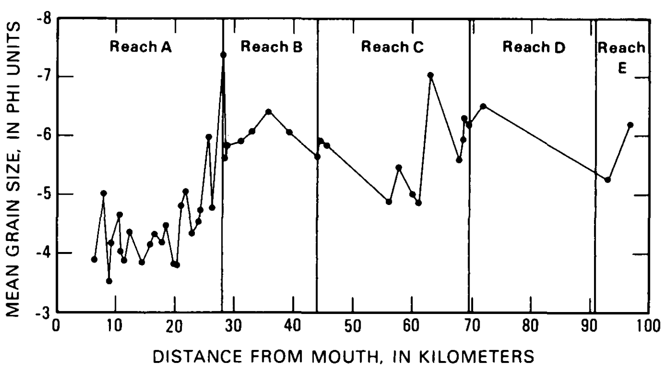

FIGURE 16.—Mean grain size of bed material at cross profiles during the summer of 1976.

size from 1979 to 1982 (fig. 18). In addition, most cross-profile sites in reaches B and C and in the downstream half of reach A showed an increase in the ratio of weight percentage of unmetamorphosed clasts to weight percentage of schist clasts from 1976 to 1979 followed by a decrease in that ratio between 1979 and 1982 (fig. 21).

CAUSES OF CHANGES IN CHANNEL GEOMETRY

Major changes in streambed elevation and width of the Redwood Creek channel coincided with major storms

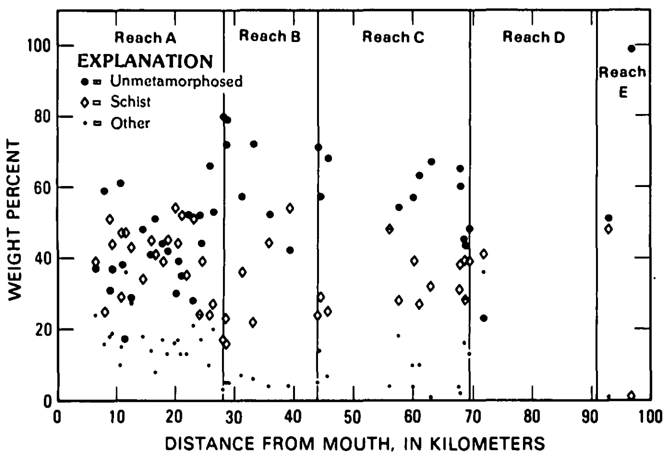

FIGURE 17.—Lithologic composition of bed material at cross profiles during the summer of 1976. "Unmetamorphosed" refers to conglomerate, sandstone, and mudstone clasts. "Schist" refers to schist and foliated metavolcanic clasts. "Other" refers to quartz and unfoliated greenstone clasts, and clasts too small for lithologic identification.

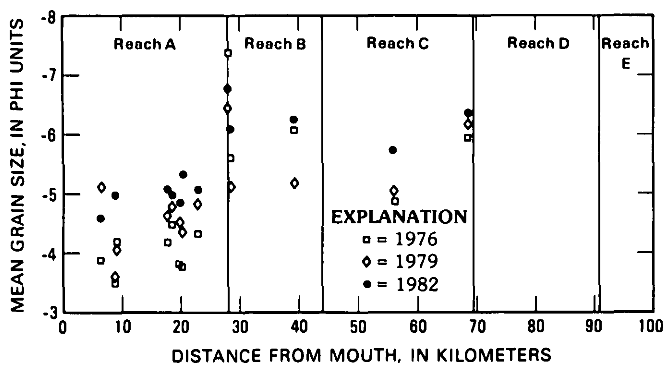

FIGURE 18.—Mean grain size at selected cross profiles in summers of 1976, 1979, and 1982.

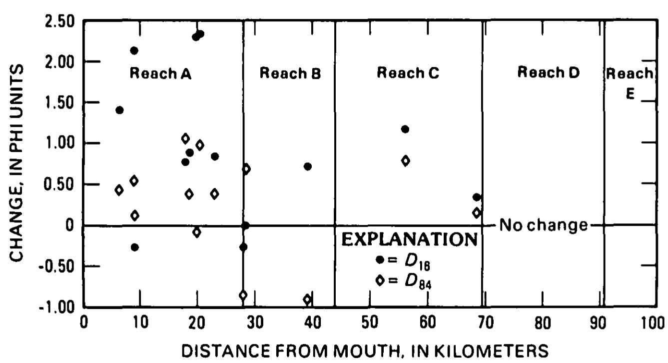

FIGURE 19.—Changes in D_{16} and D_{84} at selected cross profiles between the summers of 1976 and 1982. See p. XX for an explanation of D_{16} and D_{84}.

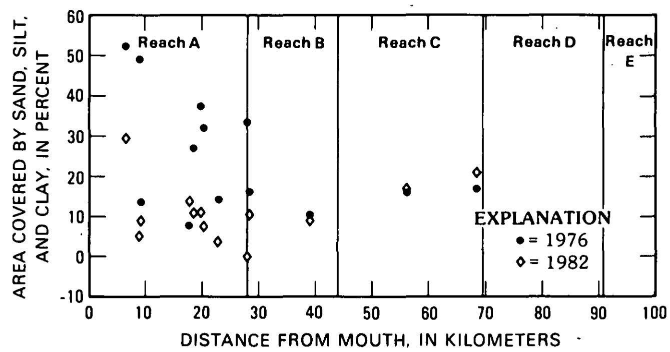

FIGURE 20.—Percentage of streambed area covered by sand, silt, and clay at selected cross profiles, summers of 1976 and 1982.

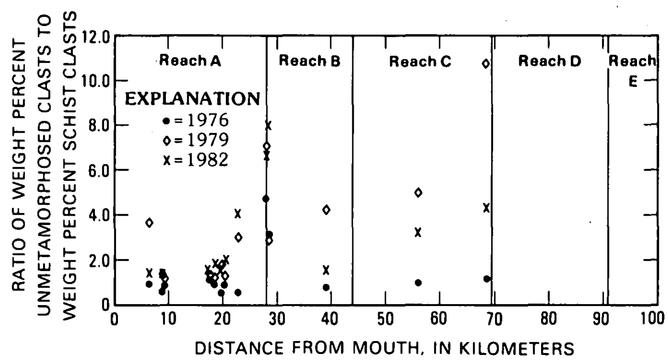

FIGURE 21.—Ratio of weight percent unmetamorphosed rocks to weight percent schist in bed material at selected cross profiles, summers of 1976 and 1982.

and with large increases in the percentage of the basin subjected to timber harvesting (fig. 22). These storms and land use greatly accelerated erosion and sediment-transport processes that were already active before the study period (Janda and others, 1975). Large increases in sediment supply, caused by the storms and the wide-spread timber harvesting, overloaded channel transport capacities. Channels filled and widened to accommodate this increase in sediment. In addition, increases in runoff caused by timber harvest probably accelerated channel widening. The observed causal relation between increased sediment supply and runoff and increased channel instability has been documented by several field and laboratory studies (Gregory, 1977; Schumm, 1977; Lisle, 1982).

The 1964 storm caused the most dramatic of the observed changes in channel geometry. The effects of this storm were far greater than those associated with either earlier storms in 1953 and 1955 or with later storms in 1972 and 1975, even though all of these storms were associated with roughly similar peak streamflow

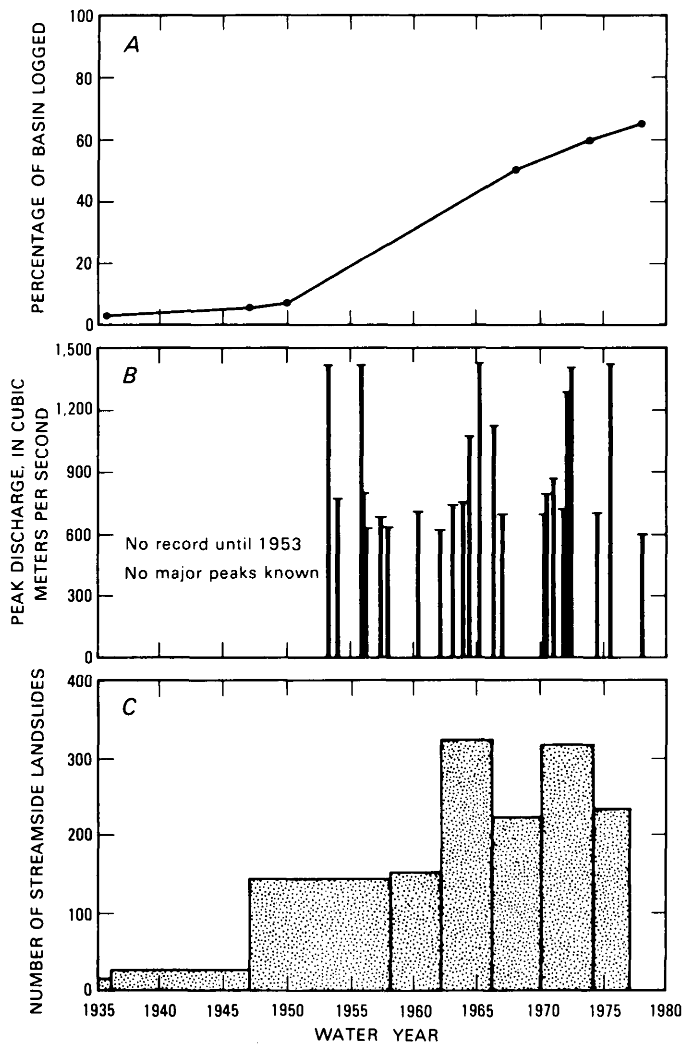

FIGURE 22.—Summary of storms, land use, and streamside landsliding in the Redwood Creek basin, 1936 to 1981. *A*, The percentage of the basin logged; logging history information is from Janda and others (1975), Iwatsubo and others (1975 and 1976), and Harden and others (1978). *B*, Peak discharge above a base of 600 m^3/s as measured at the gaging station, Redwood Creek at Orick (11482500). *C*, Number of streamside landslides mapped by Nolan and others (1976) and Harden and others (1978).

(table 1). The second most damaging storm, which occurred in January 1972, produced some channel filling and widening, particularly along downstream reaches. Vegetation established on gravel flood berms along downstream reaches dates to the 1972 storm. Channel filling in downstream reaches during 1972 also may reflect the downstream transport of sediment stored along upper reaches as a result of the 1964 storm.

The channel filling and widening related to these storms appear to have been primarily the result of large volumes of colluvium introduced to channels by streamside landslides during the storms. Observations of time-sequential aerial photographs indicate that the number of streamside landslides adjacent to the main channel of Redwood Creek approximately doubled around the time of the 1964 storm (fig. 22*C*). The fairly unstable colluvial streamside hillslopes commonly found adjacent to the Redwood Creek channel fail easily when undercut by high streamflow. Similar undercutting appears to have triggered many of the storm-related landslides (Colman, 1973; Harden and others, 1978).

INTERACTION OF HILLSLOPE AND CHANNEL PROCESSES

The ability of major storms to trigger exceptionally large numbers of landslides throughout the drainage basin may be related to the manner in which physical processes operating in stream channels interact with those operating on hillslopes in this highly erosive terrane. Colman (1973) suggested that a positive feedback loop exists between these two sets of processes in the Redwood Creek watershed. A single landslide along the naturally unstable hillslopes may trigger additional landslides downstream by deflecting streamflow or causing local channel fill, which raises water levels and undercuts banks (fig. 23). Such interaction leads to abundant landslides throughout entire watersheds and results in the introduction of large volumes of colluvium directly into high-order channels.

IMPACTS OF TIMBER HARVEST

Investigators have found it difficult to quantify the extent to which timber harvesting has increased the amount of sediment introduced to the channel of Redwood Creek. The increase appears to be due primarily to the superimposition of timber harvesting effects on an erosional system that is extremely active naturally. Colman (1973), Janda and others (1975), and Harden and others (1978) have all found that timber harvesting and related road construction are associated with a higher than normal incidence of landsliding. Nolan and Janda (1981) found that the massive ground disruption and rearrangement of natural drainage systems caused by timber harvest accelerated fluvial erosion in harvested basins. As much as 80 percent of the ground surface insome areas of the watershed was disturbed by harvesting activities (Janda, 1978), and bare soil was exposed in over 40 percent of some tributary basins (Nolan and Janda, 1981). Figure 24 shows the results of particularly disruptive practices near the mouth of Bridge Creek. Synoptic sediment sampling reported by Nolan and Janda (1981) indicates that tributaries subjected to large-scale harvesting were characterized by sediment yields as much as 10 times greater than those from comparable

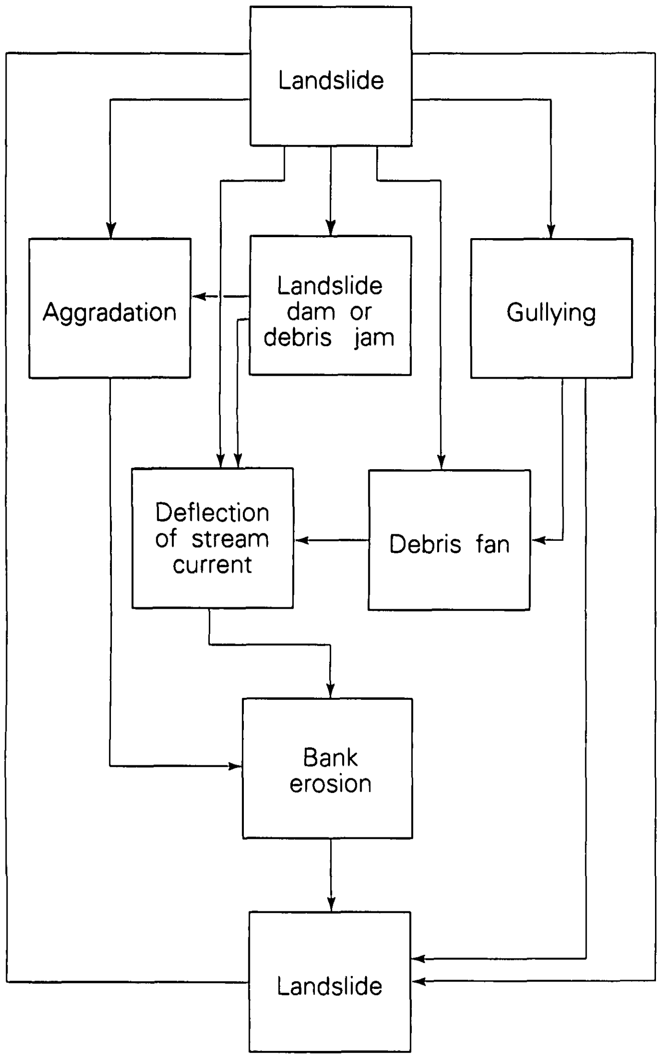

FIGURE 23.—Positive feedback loop, proposed by Colman (1973), between physical processes.

unharvested basins. Sediment introduced either directly by fluvial erosion or from harvest-related landslides may have helped trigger the positive feedback loop described by Colman (1973) among physical processes. This observation prompted Harden and others (1978) to suggest that timber harvesting caused the 1964 and 1972 storms to have impacts disproportionate to storm magnitude. Perhaps without timber harvesting these storms would have had effects similar to those of the 1953 and 1955 storms.

In addition to the effects on sediment yield, timber harvesting also is related to increased storm runoff throughout the basin, probably because of increases in the area of impervious surfaces. Lee and others (1975) suggested that timber harvesting increased storm runoff throughout the basin by about 20 percent. Nolan and Janda (1981) reported that runoff from harvested basins

TABLE 7.—*Relation between behavior of the streambed and streambanks at surveyed cross profiles*

[Numbers indicate the number of measurements in which a relationship was found. Streambank behavior reflects net change at both banks. Numbers in parentheses indicate frequencies to be expected if no relationship exists between streambed and streambank behavior. Total chi square=6.41]

Streambed behavior	Streambank behavior		Total
	Erosion	Deposition	
Fill	123 (134)	58 (47)	181
Scour	148 (137)	38 (49)	186
Total	271	96	

during synoptic storm sampling was between 1.3 and 12 times greater than that from comparable unharvested basins.

Analysis of stream-channel behavior during the period of resurveys (1973–82) indicates some of the effects of this increased runoff. Table 7 presents the distribution of streambank erosion and deposition relative to the behavior of the channel bed. This contingency table indicates the dominance of streambank erosion over deposition. In addition, a chi-square analysis (Dixon and Massey, 1969) indicates that, at the 95-percent confidence level, streambank behavior depends on streambed behavior. The numbers in parentheses in table 7 are the expected frequencies of occurrence if there were no association between streambank and streambed behavior. These data indicate that streambank erosion was associated with streambed scour more frequently than expected, and conversely that streambank deposition was associated with streambed filling more frequently than expected. This association between streambank and streambed deposition suggests that much of the observed streambank erosion resulted from general enlargement of channel cross-sectional area rather than from channel widening that resulted from streambed filling. These data indicate that general channel enlargement was important enough to cause an unexpectedly high frequency of streambank erosion relative to that associated with channel filling. Such general channel enlargement was most likely caused by the increases in basinwide runoff noted by Lee and others (1975). The observed channel behavior was clearly not the result of normal channel migration because under such conditions streambank erosion is about equal to streambank deposition.

DISPROPORTIONATE IMPACTS OF THE 1964 STORM

In addition to possible effects of timber harvest, the seemingly disproportionate impacts of the 1964 storm may be related to the sequencing of storms, the greater severity of the 1964 storm along inland parts of the basin, and the duration of high streamflow associated with the

FIGURE 24.—Highly disruptive timber-harvest practices along lower reaches of Bridge Creek. Photograph taken April 1975.

storm. Harden and others (1978) suggested that the 1955 storm may have slightly destabilized streamside hillslopes and left them more susceptible to future failure. Their report also suggests that, inasmuch as the 1972 storm was most severe along downstream reaches of Redwood Creek, it may not have triggered as many landslides because those downstream reaches contain less steep streamside slopes and because hillslopes are commonly buffered from the channel in these areas by wide flood plains. Although the 1972 storm reactivated many of the landslides triggered by the 1964 storm, it did not produce an increase in slide occurrence (fig. 22) (Harden and others, 1978), possibly because most of the likely sites for landslides had failed during the 1964 storm and additional failure sites did not have time to develop before the 1972 storm. Many of these sequencing effects are similar to those described by Bevin (1981). One more factor that may help explain the catastrophic impacts of the 1964 storm relates to the length of time high stream stages were maintained during the storm. As table 1 shows, the 1964 storm was associated with 41.4 cm of runoff, much more than that associated with any of the other storms, so that stream stages would have been elevated for longer periods of time than during the other storms and thus more bank erosion could have occurred. Bank erosion in turn destabilized hillslopes and thus resulted in more streamside landslides.

INDICATIONS OF CHANNEL RECOVERY, 1974 TO 1982

CHANGES IN CHANNEL GEOMETRY

The patterns of channel change noted at channel cross profiles between 1974 and 1982 appear to reflect the general removal of sediment from upstream reaches and redeposition of at least some of this sediment in downstream reaches. Net removal of sediment from upstream reaches is also illustrated by preliminary sediment-budget data presented by Kelsey and others (1981). According to these data, 16,728,000 Mg of sediment entered the channel above the gaging station near Blue Lake between 1956 and 1980, and 15,800,000 Mg of that material had been transported past the gaging station as of the 1980 water year.

The decrease in the magnitude of channel changes starting in 1976 and the widespread channel scour that occurred during 1981 may mark the beginning of a basinwide recovery from the large volume of introduced material. Weather patterns and improved land use practices between 1976 and 1980 probably helped to initiate the apparent channel recovery. No major storms hit the Redwood Creek basin during this period, peak streamflows were not exceptionally high, and timber harvesting proceeded at a slower rate and under stricter controls than during earlier years.

BED MATERIAL CHANGES

In addition to changes in channel geometry, the trend toward increasing mean grain size of bed material with time also may indicate that some recovery has occurred from a previous period of rapid erosion and aggradation. Because the earliest available data describing grain-size distribution in Redwood Creek were collected in 1976—subsequent to the period of major channel aggradation—no data are available to quantify the effects of channel aggradation on the size of alluvium in Redwood Creek. However, interviews with residents in the Redwood Creek basin (Janda and others, 1975), together with studies in nearby areas (Ritter, 1968; Kelsey, 1980; Lisle, 1981), suggest that aggradation is accompanied by a decrease in mean grain size. These observations suggest that, following the storms of 1964 and 1972, the channel of Redwood Creek was characterized by anomalously small grain sizes. The impacts of these storms persisted to an unknown degree until 1976, and the increases documented after 1976 reflect continued recovery from the earlier period of rapid erosion and channel aggradation. Reduction in the rate at which sediment entered Redwood Creek has apparently allowed winnowing of fine-grained alluvium from the bed, so that mean grain sizes increased.

The degree to which the grain-size data represent significant recovery in channel geometry is not clear. Attempts to correlate changes in cross-sectional area with changes in grain size at individual cross sections over a 1- to 2-year period were inconclusive. Trends in geometric changes were less consistent than those in grain size, and no meaningful correlations were found between the two data sets. Changes in grain-size distribution may represent incipient changes in channel geometry that are presently too subtle to distinguish in cross-sectional surveys.

Although the degree to which recent changes in bed material composition signal changes in channel geometry is questionable, the observed decreases in the percentage of streambed area covered by sand, silt, and clay do indicate considerable improvement in the aquatic habitat. The induration of streambed gravels with sand, silt, and clay impedes the construction of redds by spawning fish and affects emergence of young fry (Phillips, 1971). By reducing circulation of water through gravels, fine sediments also reduce the supply of oxygen to eggs and young fry, as well as the rate at which toxic waste products are removed.

PERSISTENCE OF CHANNEL CHANGES

Data presented in this paper indicate that the major changes in channel geometry that began in 1964 have persisted for decades and may persist for decades longer. All data available indicate that the channel of Redwood Creek did not show signs of widespread recovery from the recent period of rapid changes until the 1981 or 1982 water year. Although total recovery time depends upon the magnitude and sequencing of future storms, complete recovery will probably require at least several decades. The sediment budget presented by Kelsey and others (1981) suggests that, even without additional inputs of sediment, about 30 additional years are needed to transport sediment stored above the 1947 thalweg out of the basin. Recovery will probably take longest in downstream reaches.

It is difficult to judge whether the persistence of the channel filling and widening noted should be measured from 1964 or from 1972. Although the 1972 storm did not initiate large numbers of landslides, it did reactivate many of the 1964 landslides and no doubt added significant volumes of sediment to the channel. At least, the 1972 storm delayed basinwide recovery from the 1964 storm.

Basinwide recovery from the introduction of storm-related sediment has probably also been delayed by cumulative effects of timber harvesting. Often, new logging was begun adjacent to already logged areas in basins that had not been allowed enough time to recover from the increased water discharge, increased sediment yield, and hillslope instability triggered by the initial logging (Janda, 1978). As progressively larger parts of drainage basins were logged, basinwide impacts on runoff and sediment yield accumulated in a downstream direction. Impacts in downstream locations were therefore greater than at individual sites upstream or upslope.

Despite the uncertain effects of the 1972 storm and the timber harvesting, examination of the physical processes operating in the basin suggests that major storms exert long-lasting controls on channel geometries. The large volumes of sediment introduced by storm-related landslides are sufficient to overwhelm channel transport capacities for decades (Kelsey and others, 1981). Long periods of moderate flow are required to remove this sediment from the basin, as was indicated by analysis of sediment-transport relations reported by Nolan and Janda (1981) and by the observation of storm effects within the basin. The analysis and observations indicate that periods of high streamflow are associated with channel fill in the main channel of Redwood Creek and with scour along tributary channels. Conversely, periods of moderate flow are associated with scour along the main channel and fill in tributary channels.

Besides the need for long periods of moderate flow to transport storm-related sediment from the basin, the complex interaction between stream-channel and hillslope processes seems to dictate that long periods of slight erosion are needed for recovery. If landslide scars are not healed and channels remain filled with storm-related sediment, subsequent high flow may trigger the positive feedback loop and reactivate many of the original landslides, as apparently happened in the 1972 storm. Recovery from the period of exceptionally severe channel changes caused by the 1964 storm has apparently begun along many reaches of Redwood Creek. However, if the basin is subjected to a major storm before recovery is complete, the persistence of this apparent recovery is uncertain.

GEOMORPHIC SIGNIFICANCE OF RECENT EVENTS

The persistence of channel changes caused by recent storms in the Redwood Creek basin suggests that such storms play an important role in shaping channel morphology in the region. The use of persistence of impacts as a measure of geomorphic effectiveness was suggested by Wolman and Gerson (1978). Other measures of effectiveness such as the "most work" concept of Wolman and Miller (1960) do not appear to be as appropriate as the persistence of impacts in the Redwood Creek system. The "most work" hypothesis, which appears to hold in many stream systems, suggests that stream discharges with moderate return frequencies transport the most sediment over long periods of time and therefore have the greatest effect on channel morphology. In the Redwood Creek system, as well as in some other steep and highly erosive terranes (Stewart and LaMarche, 1967; Helley and LaMarche, 1973), however, the amount of sediment introduced during and after major storms totally overwhelms channel systems. Channel morphology during the long recovery period following major storms reflects flood effects in combination with effects of more moderate flows. The geometry of the channel is strongly dependent on the length of time since a major flood and on the level of postflood flows available to modify flood effects and to transport flood-deposited alluvium. Some features that are out of reach of moderate flows, such as the gravel flood berms, may be modified only by another major flood. The need to consider the effects of both high and moderate flows has recently been noted by Gupta (1983).

Timber harvest does not appear to cause fundamental changes in the response of the channel to major storms. Harden and others (1978) have shown that all the erosional processes triggered by the 1964 and 1972 storms and the manner in which these processes interacted occur naturally in the area. By initiating streamside landslides and increasing runoff, however, timber harvesting may have exacerbated effects of the 1964 and 1972 storms by triggering the positive feedback loop discussed on page XX.

The key to assessing whether or not the 1964 and the 1972 storms were truly significant in the geomorphic sense lies in knowing whether or not effects generated by these storms will persist longer than the expected recurrence interval of the storms themselves (Wolman and Gerson, 1978). Such an assessment is complicated in the Redwood Creek basin because of the close succession of the 1964 and 1972 storms and the uncertain role played by timber harvesting. The sequencing of the 1964 and 1972 storms raises questions as to whether channel recovery should be measured from 1964 or from 1972. Since timber harvesting appears to have caused the storms to have impacts disproportionate to storm magnitude, it is difficult to determine the recurrence interval against which to measure storm impacts. The 1964 storm may have produced effects that would have occurred only during a storm with a much longer recurrence interval under natural conditions. Despite this difficulty, the 1964 and 1972 storms provided the opportunity to study the processes triggered by major storms and the interaction of processes operating in stream channels with those operating on hillslopes. Considering the observed operation of these processes and the effects produced by the 1964 and 1972 storms, major storms can be expected to produce long-lasting effects on the main channel of Redwood Creek. Storm-related effects persist along the channel for long periods of time, during which those effects are modified by more moderate flows.

CONCLUSIONS

Study of the historical behavior of Redwood Creek suggests that major storms play an important role in shaping the morphology of the channel. These events introduce exceptionally large volumes of sediment that totally overwhelm channel transport capacities. Long periods of slight erosion are necessary for channel configurations to return to prestorm conditions.

Time-sequential aerial photographs, gaging-station records, and interviews with local residents all indicate that beginning in the mid-1950's the main channel of Redwood Creek began to aggrade and widen. Channel aggradation as much as 4.5 m and width increases of more than 100 percent occurred. Initiation of nearly all major changes in geometry coincided in general with the initiation of large-scale timber harvest and more specifically with the occurrence of major storms in 1964 and 1972.

Monitoring of channel configurations between 1973 and 1982 has documented a general pattern of channel scour in upstream areas and fill along lower reaches. This pattern probably reflects the removal of large volumes of sediment deposited in upstream areas as a result of the major storm in 1964 and the redeposition of at least part of this sediment along downstream reaches. Bank erosion was common throughout this period owing to the combined effects of increased sediment supply and increased runoff. Resurvey of channel cross profiles in 1981, and measurements of the grain size of channel bed material in 1982, indicates that channel recovery may have started basinwide. Scour was pervasive along downstream reaches for the first time in 1981, and mean grain sizes increased significantly in 1982.

The catastrophic impacts of major storms on channel geometry originate, at least in part, from the delicate balance between physical processes operating in stream channels and those operating on adjacent hillslopes. Undercutting of inherently unstable hillslopes causes many landslides, which introduce large volumes of sediment throughout long channel reaches. Human activity can affect this delicate balance. The landslides and increased storm runoff caused by timber harvesting may have helped trigger the positive feedback loop between physical processes, causing the 1964 storm to have a much greater impact than it would have had under natural conditions. In addition to the effects of timber harvesting, the particularly dramatic channel changes associated with the 1964 storm may have been related to the length of time that high stream stages were maintained, the sequencing of storms, and the location of maximum rainfall within the basin.

The relative importance of factors that may have caused the 1964 storm to be so significant in relation to other major storms is speculative, but the evidence given in this report illustrates the complex association of events and processes that must be considered when assessing the types of climatic events most responsible for shaping the main channel of Redwood Creek. In view of the long-lasting nature of storm impacts, channel geometries at any given time probably bear a strong imprint of the effects of major storms, even though those effects may have been modified by the effects of moderate flows.

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Changes in Channel-Stored Sediment, Redwood Creek, Northwestern California, 1947 to 1980

By MARY ANN MADEJ

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–O

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CHANGES IN CHANNEL-STORED SEDIMENT, REDWOOD CREEK, NORTHWESTERN CALIFORNIA, 1947 TO 1980

By Mary Ann Madej[1]

ABSTRACT

Stream channels form a link between hillslope erosion and sediment transport processes because they temporarily store sediment before it is transported out of the system. Storage of alluvium in the main stem of Redwood Creek was quantified for three time periods totaling 35 years. An unusual amount of aggradation during the December 1964 flood (a 50-year flood) increased the total volume of sediment stored on the valley floor by almost 1.5 times to 16×10^6 m^3. Although moderate to high floodflows (2–20 year recurrence intervals) in subsequent years eroded sediment in the upper basin and redeposited it in downstream reaches, little change in the total amount of sediment stored on the valley floor occurred. The potential of stored sediment for transport was characterized as active, semiactive, inactive, or stable. Depths of scour in the gravel bed were computed from scour-chain data and from successive discharge measurements made from selected cableways. In this gravel-bed stream, depth of scour increases downstream for equivalent discharges and also increases with increasing discharge at a given station.

Sediment is stored in several types of geomorphic features. Some of these features (such as recent flood-deposited gravel terraces, debris jams, stable alluvial terraces, and strath terraces) are found only locally along Redwood Creek. Landslide activity exacerbated by the 1964 flood contributed 5.25×10^6 m^3 of sediment to the main stem of Redwood Creek, and channel storage increased by 4.74×10^6 m^3. Maximum sediment deposition did not, however, occur at sites of the most intense landslide activity but rather occurred in areas of prior deposition. Valley width is the most important control on sediment distribution.

Erosion of bed sediment deposited by the 1964 flood contributed greatly to annual bedload transport in the upper reaches of Redwood Creek for several years after the 1964 flood. Current sediment yields for Redwood Creek are 2,700 $(Mg/km^2)/yr$ in the upper basin, where bedload is 20 percent of total load, and 2,200 $(Mg/km^2)/yr$ at the mouth, where bedload is 11 percent of total load. The particle sizes of Redwood Creek bed materials decrease rapidly during transport. A tumbling experiment indicated that schist clasts break down more quickly than sandstone clasts.

Residence times of active and semiactive sediment generally decrease downstream, but residence times increase in a downstream direction for stable sediment. Residence times range from decades for sediment in the active channel bed to thousands of years for sediment in stable flood-plain deposits. When stored sediment is mobilized, average velocities are highest for active sediment. The channel has recovered slowly from effects of the 1964 flood. Total channel recovery will take more than a century.

INTRODUCTION

Historically, geomorphologists have studied both hillslope erosion processes and sediment transport in rivers, but few studies have quantified a linkage between these two processes—the storage component of channels. Channels may temporarily store sediment derived from hillslope erosion before transporting it out of the system. The quantity of sediment stored and its residence time vary with the type of fluvial system. Streams in steep mountainous terrain store little sediment for relatively short periods of time, whereas rivers in broad alluvial valleys store large quantities of sediment in their flood plains for thousands of years.

In the latter case, channel storage of alluvium can buffer the release of sediment from a drainage basin. Sediment eroded from hillslopes can reside in stream channels for long periods before eventually being transported out of the basin. In such situations, downstream sediment yields will not completely document upstream erosion rates. Some estimates of the volume of sediment stored in channels, knowledge of when that sediment was put into storage, and the rate at which sediment moves through the basin must be known.

Recent changes in the storage of alluvium along the channel of Redwood Creek in northern California present a dramatic example of the capacity of a channel to buffer the release of sediment. Extensive land use changes in recent years, combined with several large storms, caused widespread erosion in Redwood Creek (Janda and others, 1975). Massive amounts of landslid-

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ing, gullying, and bank erosion occurred, causing widespread channel aggradation and dramatic increases in the volume of sediment stored along the channel of Redwood Creek. Deposition of coarse alluvial sediment in low-lying areas was sufficient to threaten aquatic and riparian resources of Redwood National Park.

This paper discusses recent changes in the storage of sediment in Redwood Creek. The volume of sediment stored on the valley floor under pre-1947 conditions, increases in volume of stored sediment due to a major flood in 1964, and the volume of sediment present in 1980 are quantified. In addition, factors that controlled deposition and factors responsible for transfer of those flood deposits downstream are described.

To accomplish the objectives listed above, the main stem of Redwood Creek has been treated as a continuous conduit of sediment composed of several storage features: debris jams and fans, midchannel bars, point bars, the channel bed, and flood-plain deposits. Sediment in these storage features was divided into four classes or sediment reservoirs—active, semiactive, inactive, and stable—according to its potential mobility. All stored sediment has been considered to be in transit downstream, but the rate at which it moves varies with its size and location on the valley floor. A continuity equation was applied to several reaches of the stream to document sediment input (I), the change in storage (ΔV_s), and the output (O) from each reach. These factors must balance, as shown in the continuity equation:

$$I+\Delta V_s=O \qquad (1)$$

These data were then used to compute residence times and average particle velocities for the four sediment reservoirs and for different locations on the valley floor, according to the method laid out by Dietrich and Dunne (1978). This study addresses only storage in the main stem; channel storage in tributaries is discussed by Pitlick (chap. K, this volume).

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PREVIOUS STUDIES

The sediment budget concept as applied to forested drainage basins is relatively new, and only recently have studies from a wide variety of field areas been published. The use of sediment budgets has been explored by several investigators (Swanson, Janda, and others, 1982). Dietrich and Dunne (1978) discussed the construction of sediment budgets with an example from a small undisturbed basin in western Oregon. Lehre (1981) described sediment sources and sediment yield in the Coast Ranges of California, and Kelsey (1977) formulated a sediment budget for the Van Duzen River in northern California. Reid (1981) and Madej (1982) extended sediment budget calculations to basins disturbed by recent logging and road construction. Swanson, Fredrickson, and McCorison (1982) used a sediment budget to analyze the transport of inorganic and organic material in both old-growth and logged drainage basins.

Most sediment budget studies to date have been on small drainage basins (area less than 25 km^2) in steep forested areas where little sediment is stored in channels or flood plains. Few studies have quantified the role of alluvial storage in sediment budgets. Dietrich and others (1982) described an approach for such quantification, which uses the age distribution of alluvial deposits to calculate residence times for sediment. Trimble (1981) addressed the question of sediment storage in a disturbed basin in Wisconsin where flood-plain storage is significant.

Several investigators addressed changes in channel storage through studies of changes in channel cross sections (Ritter, 1968; Hickey, 1969; chap. N, this volume). Stewart and La Marche (1967) calculated net scour and fill for several reaches that were modified by a large flood. From a study of cross-sectional changes in northern California streams, Lisle (1982) described the effects of changes (by aggradation and degradation) in stored sediment on riffle-pool morphology and the implications for bedload transport rates.

STUDY AREA

Redwood Creek drains a 725-km^2 basin in northern California (fig. 1). For much of its 108-km length it flows along the trace of the Grogan fault, which juxtaposes two distinct bedrock types. The east side of the basin is generally underlain by unmetamorphosed sandstones and siltstones of Mesozoic Franciscan assemblage, whereas the western side is predominantly underlain by

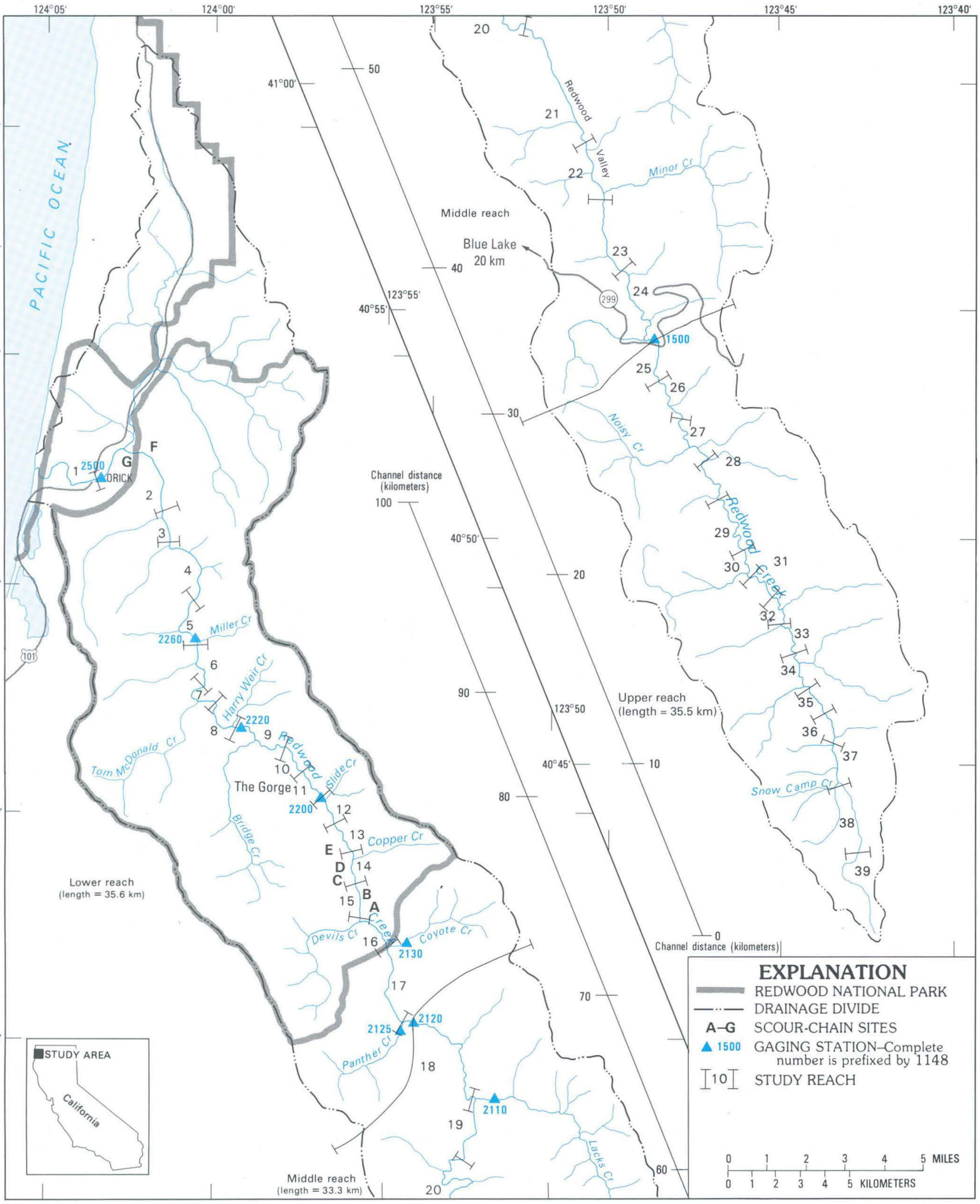

FIGURE 1.—Locations of study reaches, gaging stations, and scour-chain sites, Redwood Creek.

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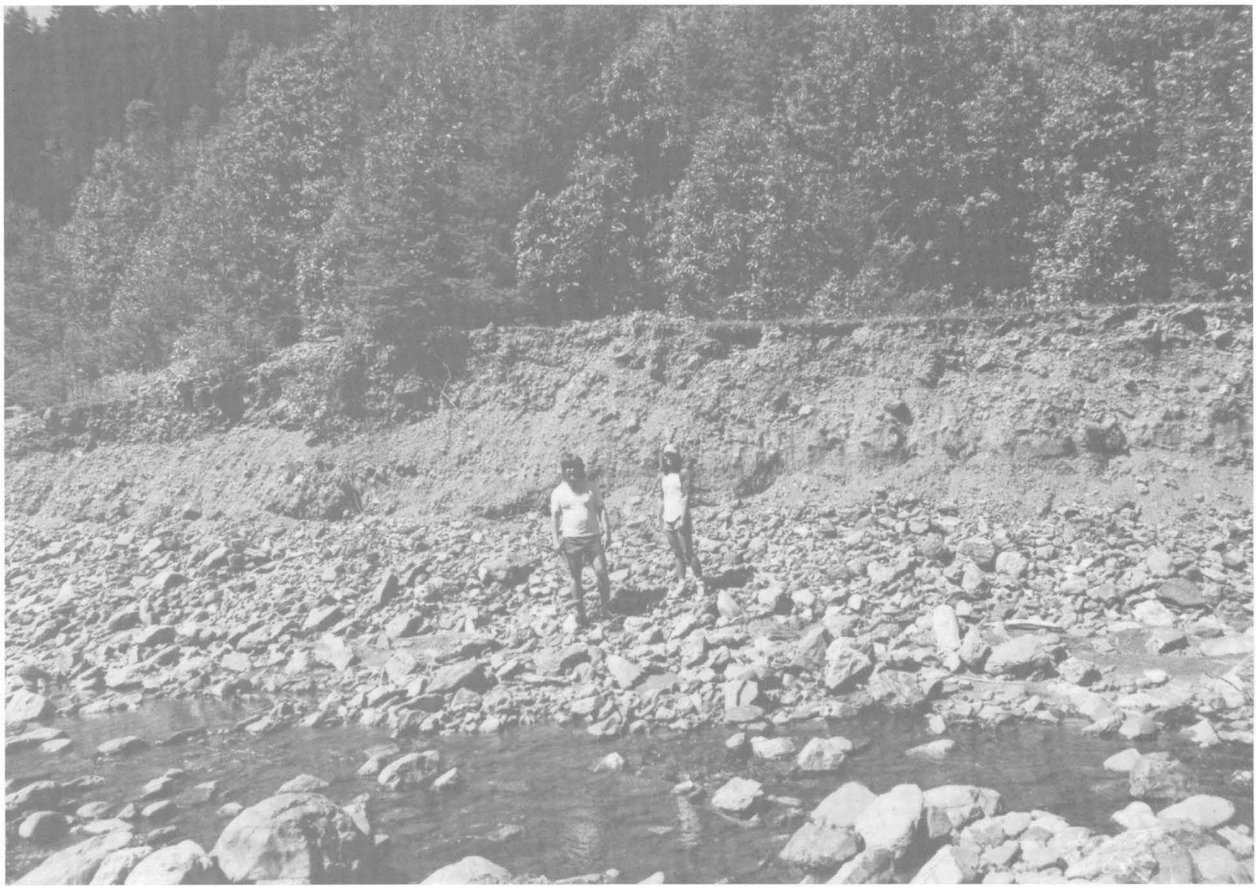

FIGURE 2.—Flat-topped gravel berm deposited in upper reach of Redwood Creek during December 1964 flood (photographed August 1983). Note coarse, unsorted nature of material, young trees growing on the surface, and location against valley wall away from active channel. Deposit was more extensive in 1964.

a quartz-mica schist. The basin receives an average of 2,000 mm of precipitation annually, most of which falls between October and March. Total basin relief is 1,615 m; average hillslope gradient is 26 percent.

Early aerial photographs taken in 1936 and 1947 show that the basin was covered with old-growth redwood and Douglas-fir forests and a few areas of prairie. Redwood Creek was narrow and sinuous in most reaches, with a thick canopy of trees over much of its length. Wide alluviated reaches were apparent in Redwood Valley and near the mouth of Redwood Creek. Many of the alluvial deposits were vegetated with conifers and hardwoods. Very little logging or road construction had occurred by 1947.

Timber harvest began in earnest in the Redwood Creek basin in the early-1950's, and by 1966, 55 percent of the old-growth coniferous forest had been logged. By 1978 this figure rose to 81 percent (chap. C, this volume). Thousands of kilometers of logging roads were built during this time. Recent erosion rates measured by Janda (1978) are about 7.5 times greater than the natural rate estimated by Anderson (1976).

Large floods occurred in the Redwood Creek basin in 1861, 1890, 1953, 1955, 1964, 1972, and 1975. The flood of 1964 was especially damaging and caused drastic changes in Redwood Creek, even though the peak flow of the 1964 flood was not unusually high (recurrence interval of 45–50 years; Coghlan, 1984). Harden and others (1978) discussed the disparity between flood size and magnitude of hillslope erosion and attributed it in part to the change in timber harvest activities.

The 1964 flood caused widespread aggradation in Redwood Creek and other nearby rivers. Channel changes were most severe in the upper basin, where both the storm and previous logging activity had been most intense. The most prevalent deposits in the upper reaches of Redwood Creek are gravel berms that are as much as 9 m high and consist of coarse gravel (fig. 2). Previous studies of the effects of the 1964 flood on nearby rivers (Helley and LaMarche, 1973) mention similar deposits. The berms were deposited almost continuously on both sides of the river in upstream areas, and in many areas they buried preexisting vegetated bars. Janda and others (1975) dated some conifers killed by the burial as over 200 years old. Also, in lower reaches sandy deposits from the 1964 flood overlie soils on flood-plain deposits that formerly received only fine-grained overbank deposits. This arrangement suggests that the 1964 aggradational event has been unmatched in historic time. Although Helley and LaMarche (1973) and Kelsey (1977) presented evidence of other periods of aggradation (in 1590, 1735, and 1861) in nearby drainage basins, evidence for such events in Redwood Creek is poorly documented.

Redwood Creek changes drastically in character from steep and narrow in headwater reaches, to wide and gently sloping in downstream reaches. In this study, Redwood Creek was divided into 39 reaches for detailed mapping (fig. 1). Reaches were distinguished on the basis of field observation and interpretation of aerial photographs regarding channel and valley width, bed material and bedforms, channel gradient, and streambank stability. Reaches range from 1 to 7 km in length. Kelsey and others (1981) described details of most study reaches.

In addition to the 39 reaches mentioned above, three general reaches (upper, middle, and lower) were defined (fig. 1). The upper reach is relatively steep (average channel gradient=1.2 percent) and bouldery. The valley is narrow and shows evidence of many past streamside landslides. Extensive gravel berms were deposited in this area during the 1964 flood, and many debris jams block the channel. The forest on the surrounding slopes is predominantly Douglas-fir, of which 80 percent has been tractor logged since 1948. At the downstream end of the upper reach is a U.S. Geological Survey (USGS) gaging station, above which the drainage area is 175 km^2.

In the middle reach, the valley becomes abruptly wider in the area called Redwood Valley. Earthflows are a dominant erosional process on hillslopes, and low (5-m high) alluvial terraces are prominent. With the exception of reach 20, which has a narrow meandering channel incised deeply into Pleistocene terraces, the channel in the middle reach is wide and has an average channel gradient of 0.45 percent. Logging impacts have not been as severe here as in the upper reach, but grazing, residential development, and road construction have affected this part of the basin. Downstream from Redwood Valley the valley narrows again, and here the channel is rocky with a moderate gradient of 0.35 percent and few terraces. Ninety-two percent of the forest in this middle reach was tractor and cable logged between 1948 and 1978 (chap. C, this volume). A gaging station upstream from Panther Creek measures flow from a drainage area of 424 km^2.

The lower reach flows mostly through national park lands. The upstream portion has a steep section called the gorge (1.4 percent gradient) where Redwood Creek flows among large boulders at the base of a prominent earthflow. Downstream of the gorge, the valley becomes very wide, and the channel gradient is gentle (0.1–0.2 percent). Little evidence of streamside landslides is present in this reach. The forest is predominantly redwood, of which 70 percent was logged by 1978. A gaging station is located at the U.S. Highway 101 bridge in Orick. The channel in the remaining 4 km downstream from the Orick gaging station is confined by flood protection levees built in 1968 and is influenced by tidal fluctuations.

METHODOLOGY

AERIAL PHOTOGRAPHIC AND FIELD MEASUREMENTS

The first step in this study was to quantify the amount of alluvium stored in the Redwood Creek channel under pre-1947, undisturbed conditions. Under these conditions, sediment was stored in Redwood Creek as gravel bars, flood-plain deposits, and channel sediment below the thalweg. An estimate of the volume of this sediment was determined by using aerial photographs taken in 1936, 1947, and 1954. The resolution and scale varied among three sets of photographs. The areas of the deposits were measured from the photographs with a planimeter, and heights of bars were estimated by comparison with surrounding trees, boulders, bridges, and other objects of known dimensions. The volume of sediment was calculated from the product of area of deposit and height above thalweg. Historical photographs and records were used to verify dimensions estimated from photographs. The tree canopy obscured the channel in some reaches, but, in general, major features were visible. All measurements of bar heights were based on the elevation of the 1947 thalweg because it was assumed to be stable, neither aggrading or degrading. This assumption seemed reasonable because no significant aggradation had occurred in nearby basins since 1861 (Helley and LaMarche, 1973).

No attempt was made to estimate the amount of sediment below the 1947 thalweg, although this storage compartment may be significant in geologic time. Only a few drill logs are available (California Department of Transportation, unpub. data, 1927, 1963, 1987), which show alluvium in Redwood Creek to be less than 1.5 m thick at the State Highway 299 bridge and greater than 25 m thick near the mouth at the Orick U.S. Highway 101 bridge (fig. 1).

The type of field evidence used to distinguish the deposits that resulted from the 1964 flood are discussed

FIGURE 3.—Coarse lobate bar located at kilometer 30 in Redwood Creek (photographed in August 1983). Note thick growth of alder on bar surface, which dates from 1972. There is no evidence of recent movement of bar surface. Height of rod is 2 m.

in the following two paragraphs. Evidence for aggradation resulting from the 1964 flood is best preserved in the upper reach (fig. 1) where flat-topped gravel berms (fig. 2) were deposited. The top of the flood berms were assumed to represent the height to which sediment filled the channel during the flood. High water marks (silt lines and abrasion marks on tree trunks) found several meters above the tops of the berms provide evidence that the berm surfaces were actually the channel bed at flood stage. Also, aerial photographs taken in 1965 and 1966 show some areas where the berm surfaces were not yet incised at that time.

Downstream of the area where the massive, flat-topped berms were deposited, aggradation during the 1964 flood did not occur to as great of depths as above but was still widespread. In the downstream areas, large lobate bars composed of coarse cobbles and boulders were deposited. In 1980 these bars bore a thick growth of alder dating from 1964 to 1972 (fig. 3). In these downstream reaches, channel aggradation was still sufficient to bury trees and large boulders (fig. 4). The volume of sediment deposited in this area as a result of the 1964 flood was estimated by using the field evidence discussed above; aerial photographs taken in 1962, 1965, and 1966; bridge surveys; and discussions with local residents.

During the 1980 field season, field evidence of 1964 flood deposition was best preserved in the uppermost third of the watershed. Farther downstream, where channel changes were not as severe, later floods had reworked the 1964 deposits. Thus, the reliability of the volume estimates of sediment related to the 1964 flood decreases downstream. Accuracy of volume estimates probably ranges from ±15 percent in the upper basin to ±40 percent downstream.

Volumes of sediment stored in the 1980 channel of Redwood Creek were measured in the field. Where storage features were small, the dimensions were measured by tape or rangefinder in the field. For larger bars and terraces, an accurate ground scale was measured in the field and transferred to 1978 aerial photographs (enlarged to 1:2,000 scale), and the area of the feature was planimetered from the photographs. Heights of gravel bars and terraces above the 1980 thalweg were surveyed with a hand level and stadia rod for both small

FIGURE 4.—Trees buried and killed by aggradation attributed to flood of 1964. Photographs taken August 1983 near kilometer 9.

and large features. In addition, all bars were described in terms of the age and type of vegetation growing on them, the size of material (boulder, cobble, pebble, or sand), and the presence of buried trees or artifacts. The accuracy of the 1980 measurements of volume of sediment stored above the thalweg is considered excellent (probably within ±10 percent of the actual value).

Several approaches were used to estimate the volume of sediment stored due to channel bed aggradation (that is, stored below the 1980 thalweg but above the 1947 level). Descriptions of channel changes by local landowners provided some information. Buried tree stumps, boulders, car bodies, and other objects that were partly exhumed gave an indication of recent amounts of aggradation at many locations. At a few sites, records from bridge surveys showed a history of aggradation and subsequent downcutting.

Use of time-sequential aerial photographs also helped determine changes in the amount of sediment stored on the channel bed. At several localities, boulders in the channel, which were visible on the 1962 aerial photograph but totally buried on the 1966 photographs, were partly exposed in 1980. Locally, bedrock outcrops were exposed in the channel bed, indicating no aggradation in 1980 at those points. Finally, annual surveys of channel cross profiles document changes in bed elevation in Redwood Creek for the last 9 years. Nolan and Marron (chap. N, this volume) discuss details of the cross-profile surveying and its results. Estimates of volumes of channel bed sediment were subject to substantial error, probably up to 50 percent of the true value.

The thickness of recent overbank deposits was estimated by digging shallow trenches or taking soil auger samples on flood-plain deposits. Fresh deposits were distinguished by the lack of weathering or organic accumulation in the sands and silts lying above an older humic horizon. Recent layers ranged in thickness from 0.1 to 1.0 m.

SCOUR AND FILL MEASUREMENTS

To calculate residence times of stored sediment, the quantity of sediment mobilized in the channel bed during high flows must be known. Two approaches were used to estimate the depth of scour and fill in the thalweg and on bars during winter flows. First, scour chains were installed in 1981 at seven cross sections in Redwood Creek (fig. 1). Three to five chains were installed at each section. Pits were dug with a backhoe as deeply as possible (1.2–2 m) into the channel bed. Lengths of steel chain 0.6 cm thick were anchored with steel rods 0.6 cm in diameter at the base of each pit, and pits were backfilled while the chain was held vertically. Excavated areas were compacted and smoothed to reestablish original bed elevation and shape. Cross sections and chain locations were surveyed and photographed. Because backfilling a pit does not restore the fabric and stratigraphy of the original bed material, scour chain areas might behave differently than the rest of the channel bed at high flows. Nevertheless, postwinter surveys showed no differential scour or fill at scour-chain locations compared with adjacent unexcavated portions of the channel bed. After winter flows receded, chains were excavated with a backhoe, the depth of burial was measured, and the entire cross section was resurveyed to determine the amount of scour and subsequent fill at chain locations.

The second method of determining depth of scour was the use of USGS discharge measurement notes. These measurements are available for seven stations on Redwood Creek for a range of discharges. They indicate the magnitude of scour and fill during successive measurements at a cross section during periods of high discharge from 1975 to 1981.

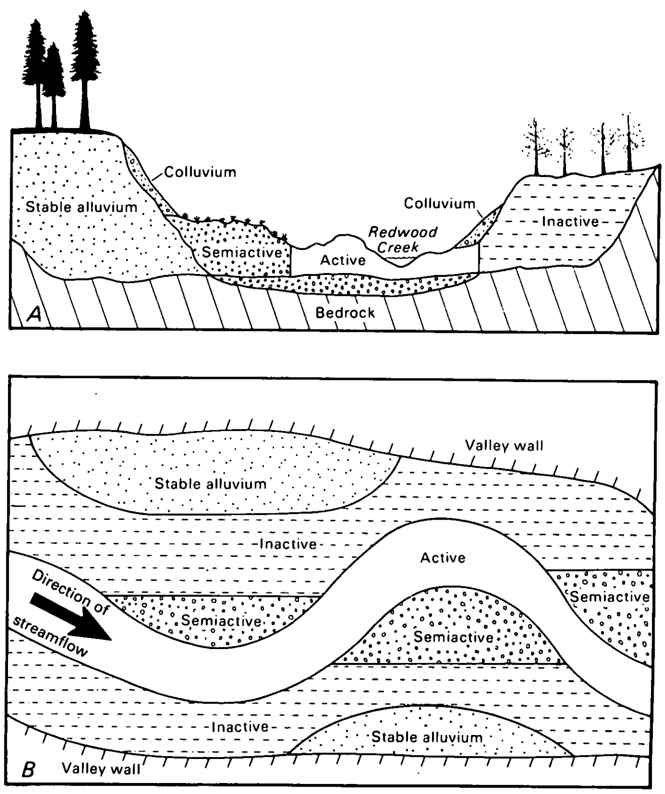

FIGURE 5. —*A*, Schematic cross section of four sediment reservoirs in Redwood Creek: active, semiactive, inactive, and stable. *B*, Schematic plan view of four sediment reservoirs in Redwood Creek.

RELATIVE AGE ESTIMATES FOR SEDIMENT

To estimate the length of time sediment will remain on the valley floor, it is necessary to know the age of a deposit; that is, the time since the sediment was deposited (Dietrich and others, 1982). Because the absolute age of many deposits in Redwood Creek was not known, a relative age scale was used to categorize deposits. Estimates of relative age were based on the "activity level" of a deposit, ranging from easily mobilized to stable.

Several lines of evidence were used to support the relative age estimates. Trees growing on deposits were dated wherever possible to obtain a minimum age for the sediment. The presence of annuals, shrubs, and other perennials indicated whether or not sediment had moved recently. Time-sequential aerial photographs showed the time period in which a new feature was deposited or when an old feature was eroded. Scour chains and successive discharge measurements from cableways indicated to what depth the channel bed was active during floodflows.

By using the indicators mentioned above, a rating scheme was developed to classify sediment deposits ranging from "young" or active to "old" or stable. The four categories, or sediment reservoirs, defined within this range are active, semiactive, inactive, and stable (fig. 5).

Active sediment is transported during moderate flood flows having a recurrence interval of 1 to 5 years. Vegetation on active sediment is absent or sparse. Cross-section survey data and scour-chain data show channel shifting, or scour and fill of active sediment, during moderate flows. Bed sediment that occurs to the depth of scour estimated from chains and cross-sectional surveys is categorized as active. In upstream areas, active sediment may be trapped by weak or unstable debris jams that are subject to collapse under moderate floodflows. Active sediment may also be found in bars less than 1 m high that are composed of pebbles, sand, and some cobbles.

Semiactive sediment is mobilized during higher flows, such as a 5- to 20-year flood. At such flows, sediment covered with shrubs and young trees is mobilized, as well as some cobble and boulder deposits.

Inactive sediment is stationary until 20- to 100-year floods occur. Such flows may mobilize inactive sediment

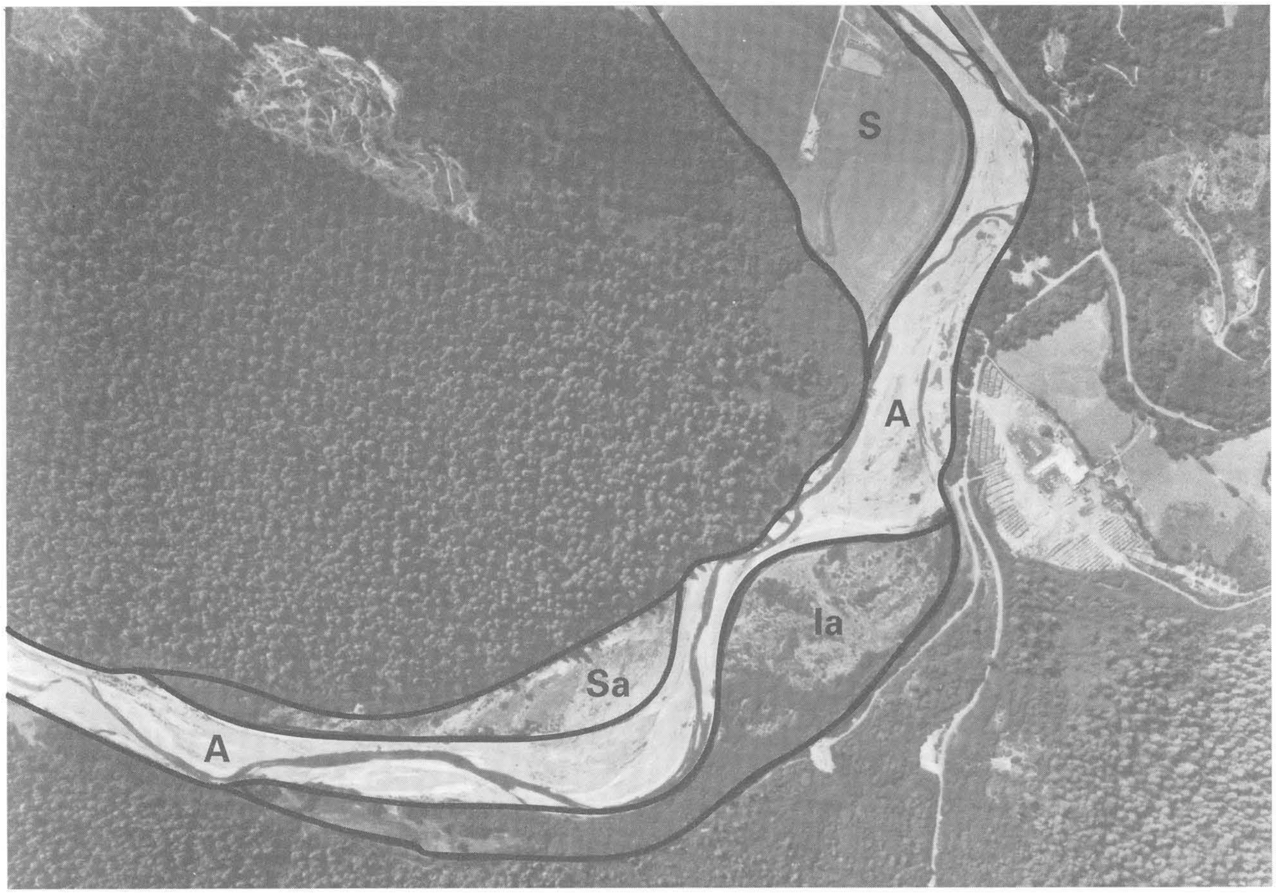

FIGURE 6.—Classification of sediment reservoirs shown on a vertical aerial photograph (1978; scale 1:6,000) of Redwood Creek, kilometer 100 near Orick; flow is from left to right. Classes are active (A), semiactive (Sa), inactive (Ia), and stable (S).

found in coarse lag deposits; gravel berms 3 to 5 m high; strong, coherent log jams; and flood-plain deposits.

Stable sediment has not been mobilized historically and constitutes some flood-plain and terrace deposits (fig. 6). Most sediment stored in alluvial terraces covered with old-growth forests is not in transport in the short term, although a fresh veneer of silt and fine sand may be deposited on them at very high flows. In this respect these terraces are not abandoned flood plains (as terraces are defined by Leopold and others, 1964), because fine-grained deposition still occurs on them during large floods. Some bank erosion of stable terraces occurs, and mass movement occasionally reactivates sediment stored on terraces well above the present channels. For this study, only stable terraces adjacent to the channel are included; sediment on terraces more than 10 m above the channel was not measured because such sediment is not currently affected by Redwood Creek.

In the flood plain near the mouth of Redwood Creek, great quantities of stable alluvium are stored, down to an unknown depth. However, flood levees built in 1968 isolate the flood plain from the channel, and no erosion or deposition has occurred on the flood plain since the levees were built. Because the flood plain has been artificially stabilized, it is not included in the analysis of the present distribution of stored sediment. Nevertheless, an estimated 23.4×10^6 m^3 of fine-grained alluvium is stored in the flood plain above the elevation of the present stream thalweg.

RELATION BETWEEN SEDIMENT MOBILITY AND SIZE

Physical characteristics of sediment in storage influence whether it will be transported as bedload or suspended load. The character of stream sediment reflects properties of the soil mantle, underlying geology, dominant hillslope erosion processes, and fluvial sediment transport processes. Size distribution analyses of sediment samples from Redwood Creek (Iwatsubo and others, 1975) indicate that 2 mm is the particle-size division between bedload and suspended load. Size distribution and lithologic analyses of bed material are presented by Nolan and Marron (chap. N, this volume). Bulk densities of stored sediment were measured with a Soiltest Volume Measurer at several sites in the drainage basin. Relative resistance of bed material to breakdown during transport was determined through an attrition experiment, as described below.

TEMPORAL CHANGES IN SEDIMENT STORAGE

Under undisturbed conditions, before 1947, the Redwood Creek channel was narrow and sinuous, with a thick canopy of trees and few landslides. Nolan and Marron (chap, N, this volume), Janda and others (1975), and Best (1984) describe undisturbed basin conditions in more detail. Measurements from aerial photographs indicate that under pristine conditions 11×10^6 m^3 of sediment was stored along Redwood Creek. Fifty percent of this sediment was stored in stable terraces. Differentiation of active, semiactive, and inactive sediment from early photographs was not feasible.

As a result of the 1964 flood, the total volume of stored sediment along Redwood Creek increased to 16×10^6 m^3, which is 1.5 times greater than the volume stored in 1947. After the 1964 flood and its associated aggradation, several years of moderate flows eroded roughly half of the sediment from aggraded upstream reaches. Some of this eroded material was deposited in downstream reaches, where cross-section surveys show recent aggradation.

Large floods in 1972 and 1975 did not cause major deposition in the upper reach, but they did leave flood deposits downstream. For example, flat-topped gravel berms were deposited in Redwood Valley, and alluvial terraces in the park received fresh layers of silt. Deposition resulting from the 1972 and 1975 floods was not quantified separately in this study. Because of the redistribution of 1964 flood deposits downstream, and the addition of sediment from the 1972 and 1975 floods, the total volume of sediment measured along Redwood Creek in 1980 was slightly greater than the 1964 total. The total volume of sediment in 1980 would have been even greater than it was, but approximately 1.15×10^6 m^3 (2.2×10^6 Mg) of gravel was excavated from the bed of lower Redwood Creek between 1953 and 1978 (Milestone, 1978). This amount represents 23 percent of the increase of sediment storage over 1947 levels.

The spatial distribution and cumulative volumes of total stored sediment for the three time periods (1947, 1964, 1980) are displayed in figure 7. In 1947, the center of mass of total stored sediment along Redwood Creek was at kilometer 64; in 1964 it shifted upstream to kilometer 61, and by 1980 it had shifted downstream to kilometer 78. Nolan and Marron (chap. N, this volume) describe how the locus of maximum aggradation has moved downstream in recent years, as inferred from cross-sectional data.

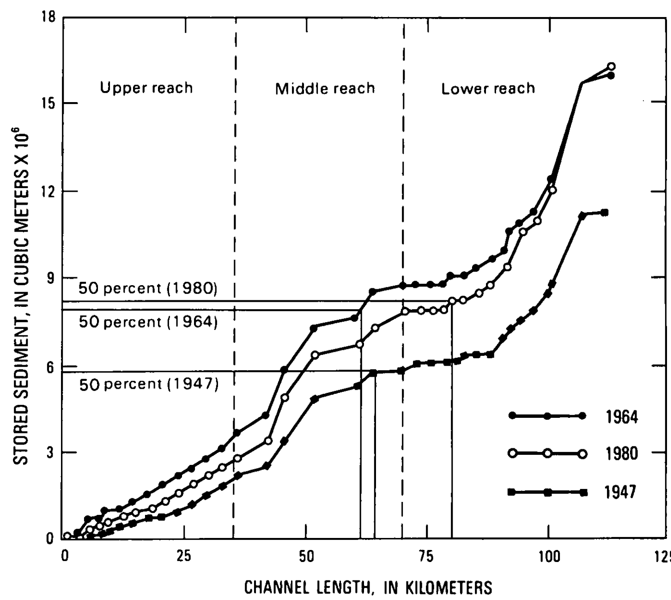

FIGURE 7.—Cumulative volumes and spatial distribution of stored sediment in Redwood Creek as of 1947, 1964, and 1980. Center of mass for each time period indicated by the "50%" line.

A comparison of the three curves in figure 7 shows some other differences between the three time periods. The slopes of the three curves increase sharply at kilometer 42 (near Redwood Valley). These increases indicate that Redwood Valley was a high-storage area in 1947 and has remained so. The reach between Lacks and Slide Creeks (kilometer 63 to kilometer 80) is narrow and stores relatively little sediment, as indicated by gentle slopes of the three curves. High storage areas downstream from the gorge (kilometer 80) show a rapid increase in storage volume, as indicated by the increase in slope of the curves. The rate of increase of stored sediment under pre-1947 conditions downstream from the gorge was less than in either 1964 or 1980.

Figure 8 shows that all individual study reaches stored more sediment in 1980 than in 1947, although storage in some areas was not much higher in 1980 than in 1947. All reaches upstream from reach 14 stored more sediment in 1964 than in 1980, and downstream reaches stored more in 1980 than in 1964. This increase in storage is due to the downstream transport and redeposition of sediment originally deposited in upstream areas in 1964, deposition from the 1972 and 1975 floods in lower reaches, and an increase in the volume of material from landslides in the lower basin between 1966 and 1980 (chap. J, this volume, fig. 9).

Table 1 summarizes changes in stored sediment along the three sections of the creek in 1947, 1964, and 1980. Excess sediment is defined as the increase of sediment over 1947 levels. As of 1964, a total of 4.7×10^6 m^3

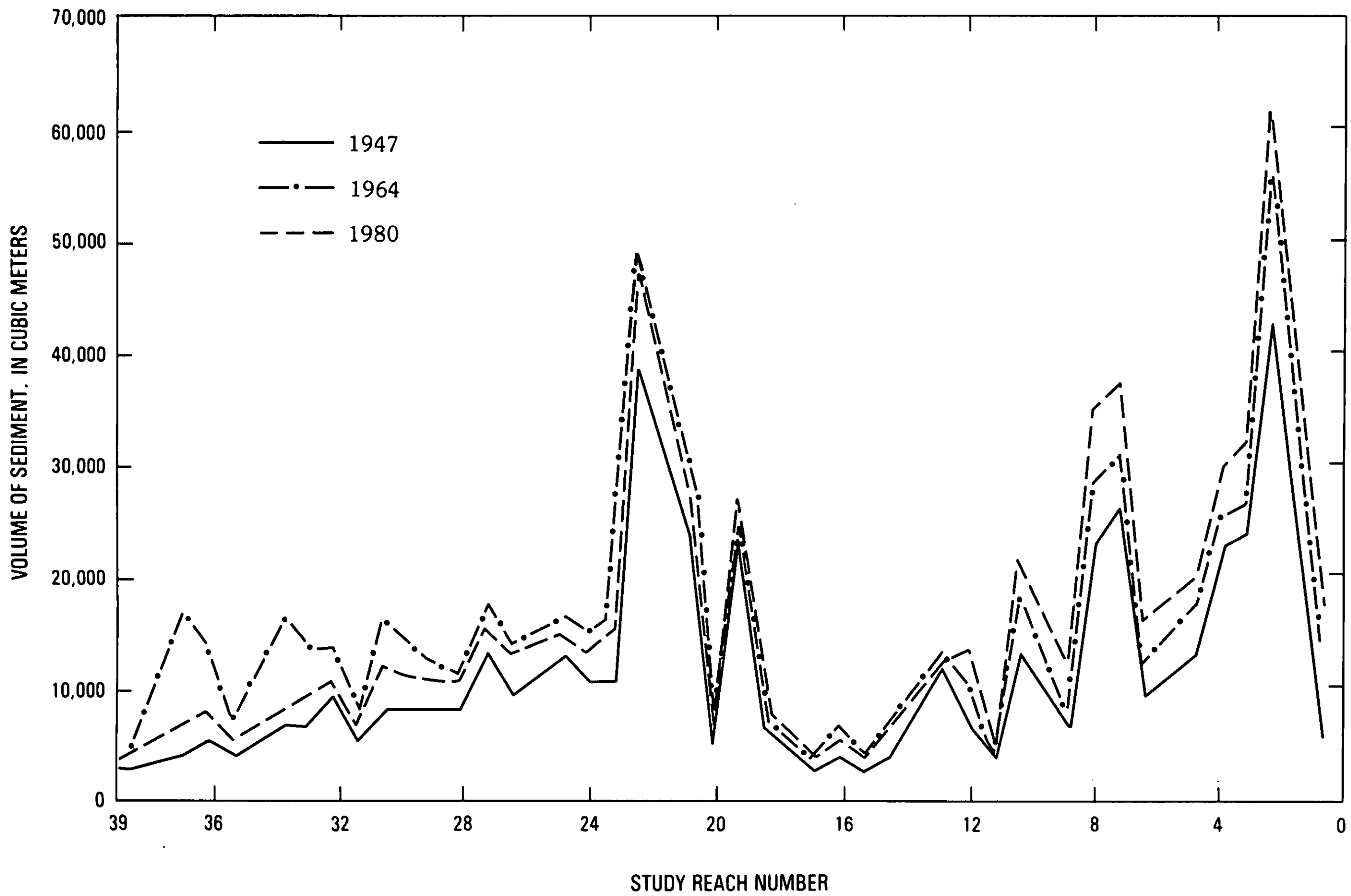

FIGURE 8.—Volumes of stored sediment in individual study reaches as of 1947, 1964, and 1980. Locations of study reaches shown on figure 1.

TABLE 1.—*Net changes in stored sediment at Redwood Creek, 1947–64, 1964–80, and 1947–80*

["+" indicates deposition; "−" indicates erosion]

Reach	Change in stored sediment (Mg)[1] 1947 to 1964	Mg/km^2	Change in stored sediment (Mg)[1] 1964 to 1980	Mg/km^2	Increase in 1980 stored sediment over 1947 levels (Mg)	Mg/km^2	Current bedload transport rates[2] [(Mg/km^2)/yr]
Upper........................	$+2.8\times10^6$	16,000	-1.5×10^6	−8,600	$+1.3\times10^6$	7,400	530
Middle........................	$+2.5\times10^6$	11,700	$-.3\times10^6$	−1,400	$+2.2\times10^6$	10,300	400
Lower........................	$+3.8\times10^6$	11,500	$+2.1\times10^6$	+6,300	$+5.9\times10^6$	17,800	240
Total channel............	$+9.1\times10^6$	12,600	$+.3\times10^6$	+400	$+9.4\times10^6$	13,000	

[1] Assumes a bulk density of 1.92 g/cm^3.

[2] Based on sediment discharge measurements from 1971 to 1980.

(9.1×10^6 Mg) of "excess" sediment had been deposited. An excess of sediment over 1947 volumes still existed for all reaches of Redwood Creek in 1980 (table 1). The total volume of excess sediment was greatest in the lower reach (5.9×10^6 Mg). As of 1980, 1.3×10^6 Mg was still in the upper basin, which represents 46 percent of the 1947 to 1964 sediment increase.

The total volume of excess sediment is not a direct indication of future sediment movement. Instead, the type of storage reservoir will determine the potential for future erosion and transport of excess sediment. For example, in the upper reach, 850,000 Mg (or 65 percent) of the present excess sediment is stored in inactive gravel berms. The channel bed itself has degraded very slowly since 1977 (chap. N, this volume). Much of the excess sediment in the upper reach will probably persist for decades.

In contrast to the upper reach, the lower reach stored 5.9×10^6 Mg of excess sediment in 1980, and 70 percent of that amount is in the aggraded active channel bed. Here

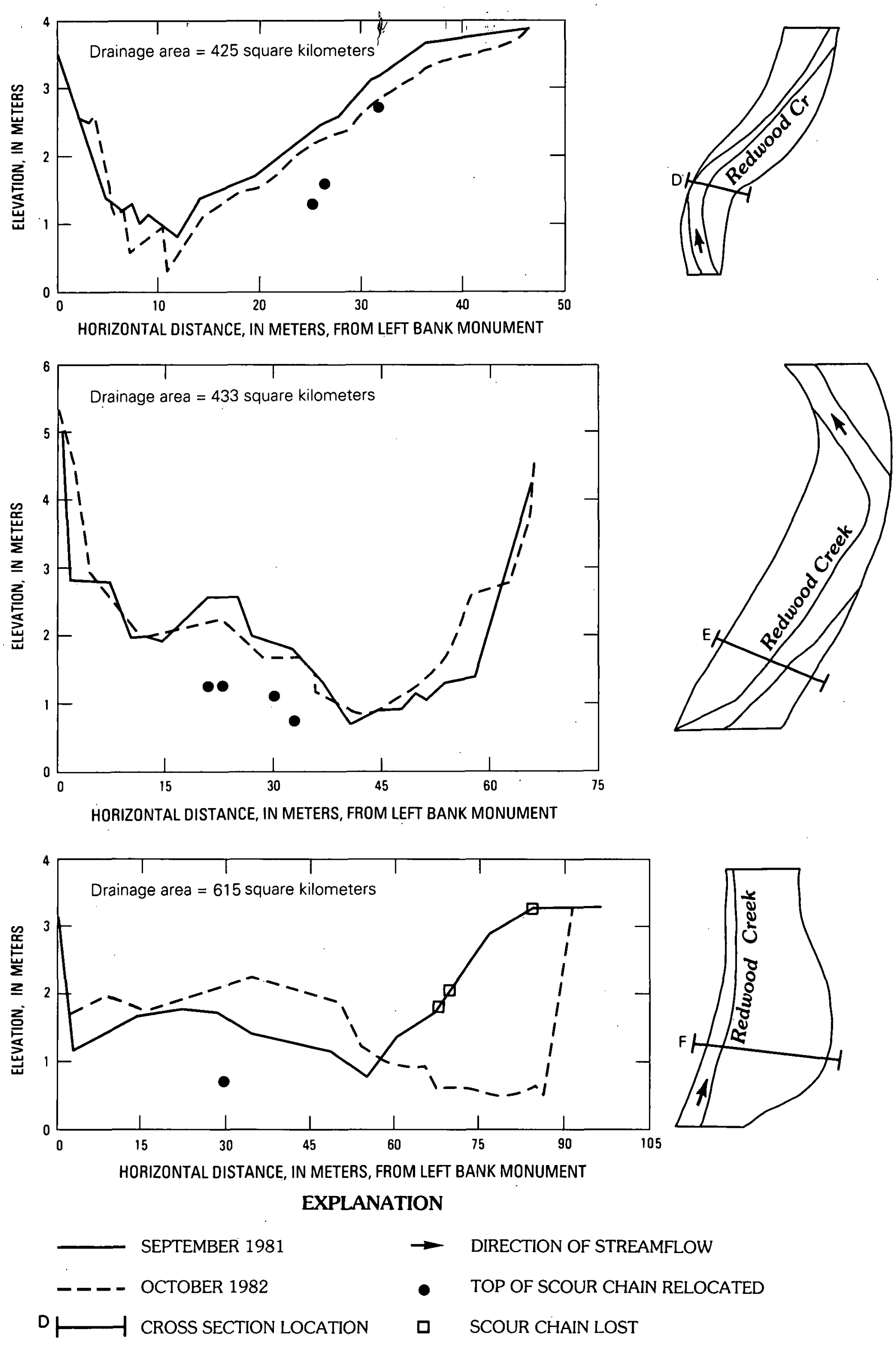

FIGURE 9.—Cross-sectional profiles of Redwood Creek for 1981 and 1982. Plan maps show relation of cross section to channel. Scour-chain sites are shown in figure 1.

it is likely that the channel will continue shifting and braiding for many years. Several years of moderate flows will begin to flush excess sediment downstream and out of the system. Cross sections in this reach show the greatest magnitude of recent change (chap. N, this volume, fig. 15).

As of 1980, total stored sediment above the 1947 datum in Redwood Creek is equivalent to 13,000 Mg/km^2. This amount of storage represents a large in-channel sediment supply and indicates that bedload transport rates will be high in the future.

EFFECTS ON BEDLOAD TRANSPORT

An example of the strong effect channel-stored sediment can have on bedload transport can be seen by examining data from the upper reach. Between 1965 and 1980, 1.5×10^6 Mg of sediment (or 8,600 Mg/km^2) were eroded from the upper reach (table 1). Aerial photographs taken in 1972 and field evidence suggest that most of this sediment was eroded within 8 years of its initial deposition in 1964. This means that the bedload sediment yield due to erosion of flood deposits at the Blue Lake gaging station was probably 8,600 Mg/km^2, or 1,075 (Mg/km^2)/yr, for the first 8 years following the 1964 flood. Currently, the bedload transport rate measured at this station is only 530 (Mg/km^2)/yr (James Knott, USGS, written commun., 1981). Unfortunately no sediment discharge measurements are available before 1973 for this station. Stations on nearby rivers, however, showed large increases in sediment yield for several years after 1964 (Knott, 1974). On the Trinity River at Hoopa, for example, the long-term bedload transport rate is 100 (Mg/km^2)/yr. In water year 1965 (which includes the December 1964 flood), bedload transport was about 1,300 (Mg/km^2)/yr, and in the following 5 years bedload transport rates remained elevated at about 300 (Mg/km^2)/yr (Knott, 1974). These measurements reflect not only bedload from the erosion of flood deposits but also bedload derived from several sediment sources active in the basin (tributary input, landslides, gullies, and bank erosion), as well as channel scour.

A similar comparison at the old South Park Boundary gaging station (kilometer 80) shows an estimated 1965–72 bedload sediment yield of 475 (Mg/km^2)/yr due to erosion of flood deposits, as opposed to the current measured value of 400 (Mg/km^2)/yr. These data suggest that erosion of the 1964 flood deposits in the period from 1965 to 1972 resulted in bedload transport rates as high as the total bedload sediment yield currently measured in Redwood Creek from all sediment sources. Because other sediment sources also were active from 1965 to 1972, total bedload sediment yield for that period was probably much higher than at present.

TABLE 2.—*Depths of scour and fill in channel bed at scour-chain sites*

[* = Chains not recovered. Scour depth listed is depth of hole dug at scour-chain sites without hitting chain. NA, not available]

Site	Chain number	Scour (m)	Fill (m)
A	1*	>0.2	NA
	2*	> .6	NA
B	1*	> .6	NA
	2*	> .6	NA
	3*	> .6	NA
C	1*	>1.2	NA
	2*	>1.2	NA
	3*	>1.2	NA
D	1	.9	.7
	2	.8	.4
	3	.3	.1
E	1	1.2	.8
	2	1.2	.7
	3	.7	.6
	4	.9	.8
F	1	1.0	1.3
	2	1.0	1.3
	3*	>1.8	NA
	4*	>1.8	NA
	5*	>1.8	NA
G	1*	>1.2	NA
	2*	>1.2	NA
	3*	>1.2	NA

Several other studies support the suggestion of high bedload transport rates for the period 1965 to 1972. Nearby rivers responded to an increase in sediment load from the 1964 flood with changes in channel geometry that resulted in high bedload transport rates (Lisle, 1982). Madej (1982) found that a stream in western Washington became wider and shallower and that bed shear stress changed to transport an increased sediment load. Redwood Creek responded similarly in that width increased and depth decreased, suggesting that the resulting distribution of bed shear stress should have permitted higher bedload transport rates after the 1964 flood.

DEPTHS OF SCOUR AND FILL

Scour-chain data indicate the depth of channel bed mobilization during moderate floodflows and the degree to which storage features were active. The data show that the magnitude of scour and fill in Redwood Creek is large, even at moderate flows. Scour and subsequent fill did not modify the shape of gravel bars in many cases. Although a gravel bar retains the same form from year to year, a substantial amount of material may be transported through it (Leopold and others, 1964).

Figure 9 shows examples of scour and fill from three of the seven scour-chain sites (fig. 1). The depth at which chains were found indicates the depth of scour and subsequent fill during winter flows of 1981 to 1982. In table 2, the actual amount of scour and fill at each scour-chain location is given. At sites D and E, general cross-section form did not change after episodes of scour and fill. It was not possible to install chains directly in the thalweg; however, scour in the bed adjacent to the thalweg and on low bars was 0.7 to 1.2 m deep. At sites D and E, the channel bed was mostly cobbles (D_{50}[2]=32 mm), but boulders 25 to 55 cm in diameter were deposited on top of the chains during the fill episode. Bed material below a coarse armor layer generally consisted of coarse sands and pebbles. At a depth of 1–2 m, however, there was generally a layer of large boulders (1–1.2 m in diameter). Scour did not extend below this layer of large boulders, and it is unlikely that this layer would be mobilized even at higher flows. The high bar at the right bank of site D was classified as semiactive because little modification occurred. Otherwise, sediment in sites D and E was classified as active.

Site F showed major changes after winter flows. The thalweg shifted toward the right bank. A scour chain near the left bank indicated 1.0 m of scour and 1.3 m of fill. Several other chains, 2 m in length, were lost because of 25 m of lateral erosion at the right bank. Bank erosion was widespread in this area and was not localized at chain locations. The gravel deposit at the right bank had previously been classified as semiactive because of its vegetative cover of grasses and shrubs. Excavation of gravel from the bed downstream from site F during the fall of 1981 may have caused the thalweg to shift in this direction and erode the bar. The remainder of the sediment in this cross section was classified as active and consisted mostly of sand and pebbles.

Discharge measurement notes indicate the magnitude and location of channel bed scour and fill during moderate to high floodflows (flows with recurrence intervals of 1 to 10 years). Discharge measurement notes were available for seven stations on Redwood Creek for various storms. Figure 10 shows examples of scour and fill at three stations during the flood of January 13–14, 1980, at discharges near bankfull. Station 11481500 (kilometer 35.5) is located in the upper basin, and the channel bed consists of cobbles and some boulders (D_{50}=45 mm). During this flood, the channel bed was mobilized to a depth of 0.1 to 0.2 m with some fill at the right bank. Downstream at station 11482260 (kilometer 92), where the bed consists of sand and pebbles with a few cobbles (D_{50}=22 mm), the bed was scoured to a depth of 0.6 to 1.3 m at the peak of the flood and filled during receding flows. The postflood and preflood cross sections are similar. Successive cross-section surveying done only at low flows would not have indicated the depth of sediment movement at these sections.

[2] D_{50} is particle size representing the 50th percentile of the grain size distribution.

TABLE 3.—*Scour depths estimated from U.S. Geological Survey current meter discharge measurements*

Date	Maximum depth of scour (m)	Discharge (m^3/s)	$Q/Q_{1.2}$[1]
Redwood Creek near Blue Lake, kilometer 35.5, $Q_{1.2}$=120 m^3/s			
2/19/75	0.6	180	1.5
2/26/76	.3	78	.7
2/26/76	.3	65	.5
2/28/79	.3	40	.3
1/13/80	.2	59	.5
1/14/80	.3	77	.6
12/22/81	.5	32	.3
1/26/83	.9	158	1.3
Redwood Creek above Harry Weir Creek, kilometer 85.8 ($Q_{1.2}$=224 m^3/s)			
4/01/74	1.6	379	1.7
2/26/76	.8	207	.9
2/26/76	.8	200	.9
12/14/77	1.0	456	2.0
12/15/77	.6	259	1.2
1/19/78	.6	136	.6
2/28/79	.4	140	.6
1/14/80	.8	231	1.0
1/14/80	.5	259	1.2
2/10/82	.6	270	1.2
2/16/82	.3	213	1.0
Redwood Creek at Orick, kilometer 104.4 ($Q_{1.2}$=289 m^3/s)			
1/22/72	2.9	974	3.4
3/03/72	1.5	631	2.2
3/19/75	1.3	416	1.4
2/26/76	.9	252	.9
12/15/77	.9	311	1.1
1/19/78	.4	171	.6
1/14/80	.5	328	1.1
12/14/81	.4	163	.6
12/22/82	1.3	195	.7
1/24/83	1.2	121	.4

[1] $Q/Q_{1.2}$ is a dimensionless index where $Q_{1.2}$ is the discharge with a 1.2-year recurrence interval.

Sediment at the sites of channel cross profiles shown in figure 10 was all classified as "active" because it was mobilized at moderately low flows. Because gaging stations are usually located in straight narrow reaches without extensive gravel berms or low terraces, or are located at bridge sites where the channel is confined, semiactive and inactive sediment are not likely to be represented at such sites.

U.S. Geological Survey current meter discharge measurement notes for 1972 to 1983 (table 3) were used to generalize the extent of scour at different flows at different gaging stations. To compare equivalent discharges for different stations, discharge data were transformed into a dimensionless index, $Q/Q_{1.2}$, where $Q_{1.2}$ is the discharge with a 1.2-year recurrence interval for that station. Estimates of $Q_{1.2}$ were based on equations given in Young and Cruff (1967, p. 12). The maximum depths of scour for several discharges were plotted for three

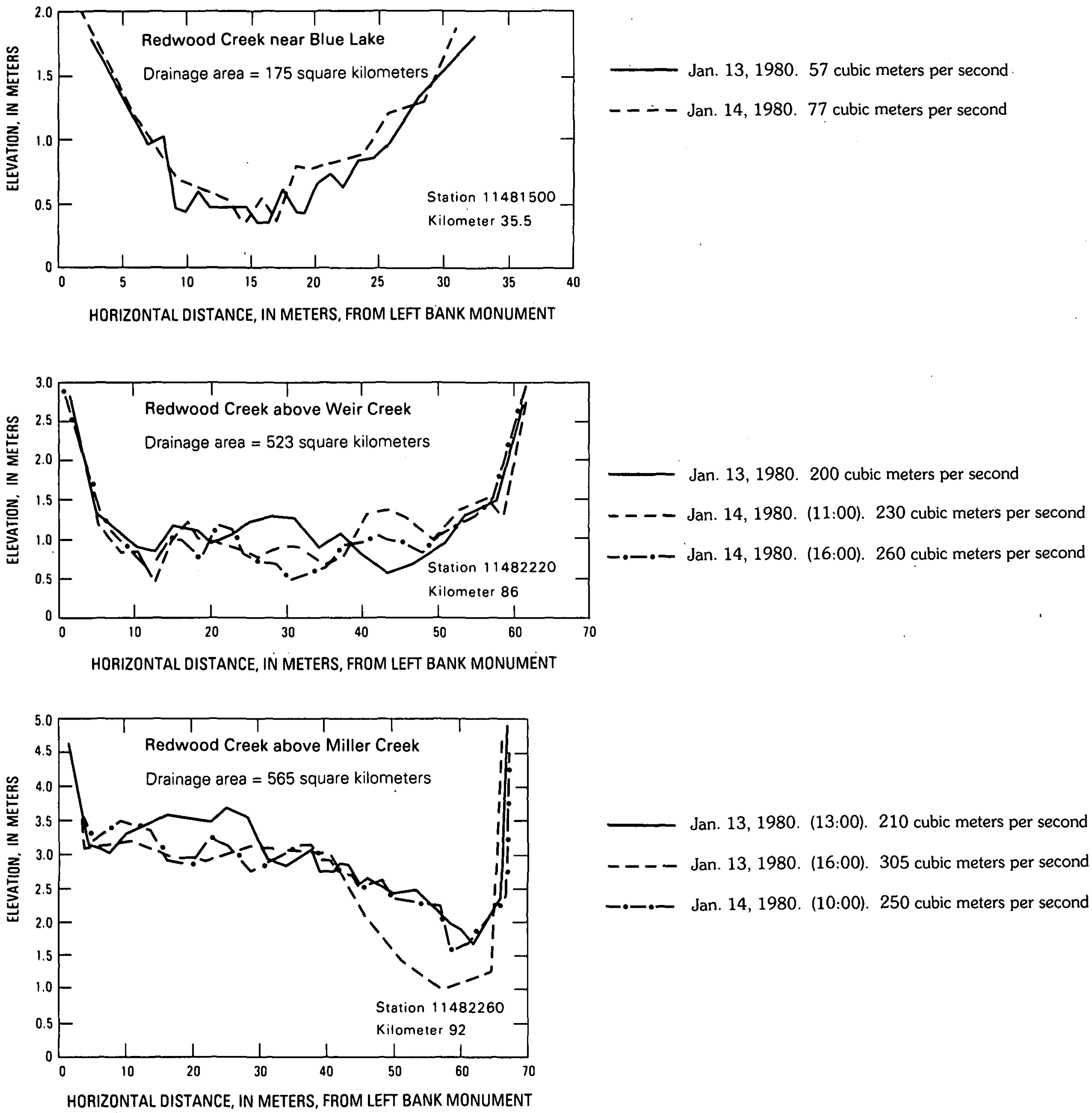

FIGURE 10.—Cross-sectional profiles of Redwood Creek at stream-gaging stations showing changes in bed elevation during flood of January 13–14, 1980.

stations (fig. 11). Best fit regression curves were computed for each station. The plotted points are scattered, but the correlations are significant at the 95-percent confidence level. In general, depth of scour increases downstream for equivalent discharges, and depth of scour increases with increasing discharge at a given station.

BREAKDOWN OF BED MATERIAL

Several lines of evidence indicate that bed material breaks down rapidly into smaller clasts in Redwood Creek. First, bedrock in the basin is highly sheared and fractured and in general is very friable. Preliminary data suggest that roundness of bed-material particles gener

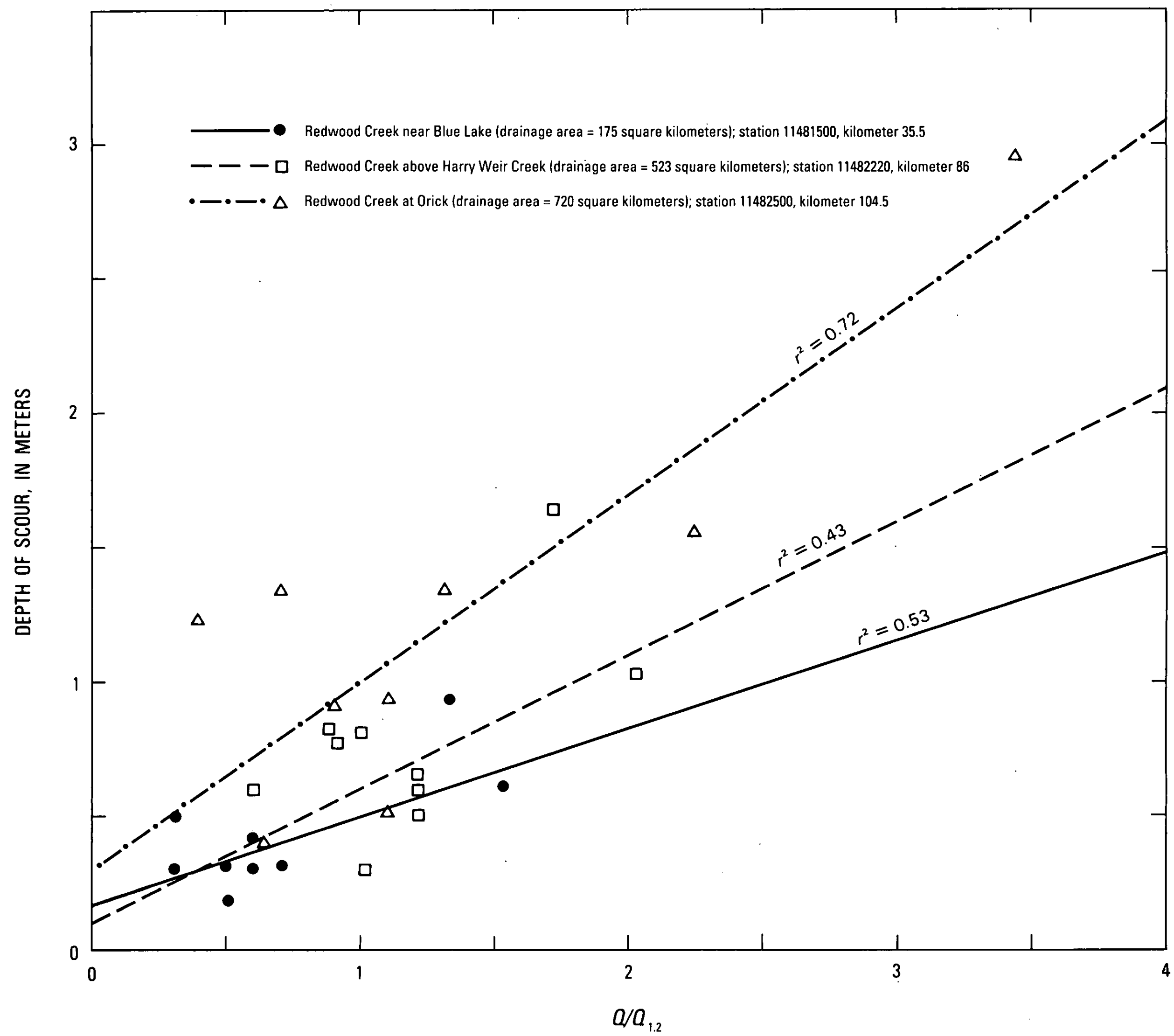

FIGURE 11.—Plot of maximum depths of scour versus dimensionless discharge index, $Q/Q_{1.2}$, for three gaging stations in Redwood Creek. Data include measurements from 1972 to 1983. Best fit regression lines (α=0.05) shown for the three stations. $Q/Q_{1.2}$=α dimensionless index where $Q_{1.2}$ is the discharge with a 1.2-year recurrence interval for that station. r^2=coefficient of linear correlation.

ally increases downstream. In the upper basin, bedload makes up 20 percent of the total load; at the mouth, 11 percent (Knott, 1981, unpub. data). Suspended sediment discharge evidently increases slightly downstream, from 2,100 (Mg/km^2)/yr in the upper basin to 2,200 (Mg/km^2)/yr at the mouth (Knott, 1981, unpub. data). The incidence of cracked cobbles exposed at low flow on gravel-bar surfaces is high throughout the basin. Lastly, a tumbling experiment showed a high rate of reduction in weight for particles 2 to 90 mm in diameter.

The tumbling experiment used a Los Angeles Rattler Machine, a 0.7-m-diameter revolving steel barrel. Mounted on the interior wall was a steel shelf, 9 cm in width, which caused material to freefall in the cylinder during part of each revolution. Sediment was tested dry because water could not be used in the machine. These two factors created an environment different from a natural stream channel. Attrition rates calculated from these "tumble kilometers" cannot be directly converted to actual stream transport distances, but relative changes in weights of size classes should represent relative attrition rates in the true stream channel.

For the experiment, two 12-kg core samples of bed material were collected. One core was collected upstream from Copper Creek at kilometer 77 (sample 1), and the other at kilometer 89 upstream from Tom

McDonald Creek (sample 2). These cores were analyzed for size distribution and lithology. Analyses of the samples showed 5 percent (sample 1) and 15 percent (sample 2) of the sediment particles by weight were less than 2 mm in diameter. The samples were run for a total of 13 "tumble kilometers," at which point two-thirds of the material (sample 1, 64 percent; sample 2, 69 percent) had broken down into the less-than-2-mm size fraction (fig. 12).

Bed material greater than or equal to 8 mm in diameter used in the experiment was classified according to rock type: sandstone, schist, or other (chert, conglomerate, or metavolcanic). The size fraction greater than or equal to 8 mm composed over two-thirds (66 and 78 percent) of the original bed material. Schist originally made up 20 and 27 percent of the bed material by weight for samples 1 and 2, respectively, and sandstone, 63 and 67 percent. The fact that more sandstone by weight exists in the channel bed, even though the portions of the basin underlain by schist and sandstone are approximately equal, suggests that either breakdown of schist particles is more rapid or that sandstone terrain contributes more coarse sediment.

The percentage of weight loss or attrition by size class, during the experiment, varied with lithology. At the end of the run, the percentage of schist material equal to or greater than 8 mm in diameter was reduced 83 to 85 percent, whereas the sandstone percentage was reduced only 46 to 52 percent. Although these specific attrition rates are not directly equivalent to those occurring in Redwood Creek, they do indicate that attrition is an important process in this basin and that schist breaks down more readily than sandstone. Results of this experiment are similar to those found by other investigators. Cameron and Blatt (1971) showed that sand-sized fragments of schist were mechanically destroyed by less than 25 km of transport in a stream in the Black Hills of South Dakota. By using rocks from New Zealand in a tumbler experiment, Adams (1978) also found that schist pebbles broke down much more readily than sandstone pebbles.

Schist is a fairly common bed material in the lower 20 km of Redwood Creek (chap. N, this volume) but, as described above, it breaks down quickly. Thus, there must be a high replacement of schist particles from tributaries in this lower reach. Because schist breaks down easily, it probably provides a large fraction of the particles less than 8 mm in diameter and contributes greatly to the suspended load.

A high attrition rate for Redwood Creek bed material implies that much of the sediment presently in channel storage will be broken down to suspended sediment size during future transport. In addition, as Dietrich and Dunne (1978) have argued, the long residence times of inactive and stable sediment allow the weathering and breakdown of stored sediment in place. Thus, estimates of residence times of deposits based on bedload transport rates alone will overestimate the persistence of those storage compartments. Some sediment stored in the Redwood Creek bed in the upper basin, especially schist particles, will be transported as suspended sediment by the time it reaches the mouth of Redwood Creek.

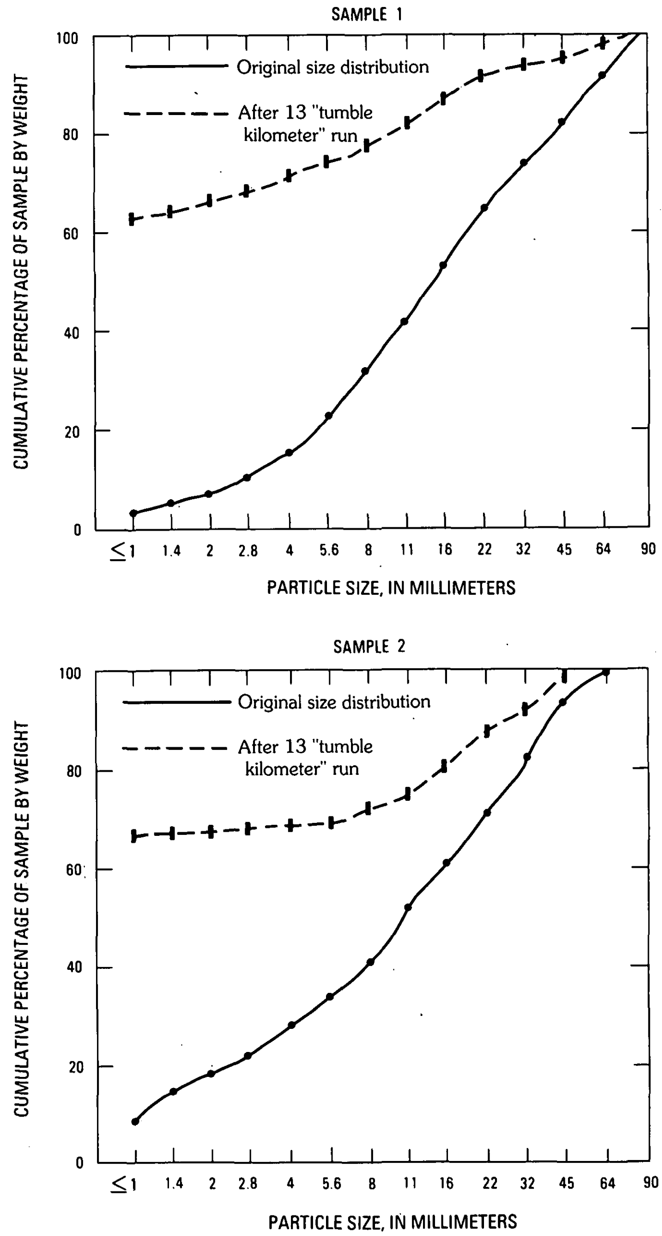

FIGURE 12.—Cumulative particle-size distribution curves for samples used in attrition experiment. Note that in both cases nearly two-thirds of the material broke down to the less-than-2-mm fraction after 13 "tumble kilometers." The tumbling experiment involved a Los Angeles Rattler Machine, which was used to determine attrition rates on dry sediment samples.

DISTRIBUTION AND QUANTITY OF CHANNEL-STORED SEDIMENT

Sediment is stored in the Redwood Creek channel in several types of storage features that differ from place to place along the channel. Stability and persistence of storage features also differ, according to the size and location of the features in the channel. Figure 13 shows the relative amount of sediment in each storage feature. It is interesting to note that 23 percent of the total sediment is stored in features that were not present in Redwood Creek before 1947 (flood-deposited gravel berms and aggraded channel bed). A single storage feature may consist of several different sediment reservoirs. For example, a point bar (storage feature) may have active, semiactive, and inactive sediment (sediment reservoirs) stored within it (fig. 5*B*).

Some kinds of storage features are found only in particular reaches of Redwood Creek (fig. 14). For example, terracelike gravel berms deposited by the 1964 flood (fig. 2) are found predominantly in the upper reach, and berms deposited during the floods 1972 and 1975 are found in the middle reach. They are similar to those described by Scott and Gravlee (1968) in the Rubicon River. The berms are poorly sorted, ranging from sand-sized particles to boulders 0.3 m in diameter. In some berms, the gravel is very angular, indicating little fluvial transport before deposition. Also, some landslides that occurred during the 1964 flood (as documented in aerial photographs) have unmodified berm deposits at their toes. This indicates that, at least locally, major landslides occurred prior to the deposition of the berms and that no slide activity has occurred since.

Strath terraces as much as 60 m in height are common between kilometer 12 and kilometer 50 (fig. 14). The lower terraces in this reach have fresh deposits of sand and gravel from recent floods. Extensive alluvial terraces are located in the downstream third of the channel and are important in supporting stands of old-growth redwoods.

Although organic debris is important in storing channel sediment in Redwood Creek tributaries (chap. K, this volume), debris jams store less than 1 percent of the total stored sediment in the main stem of Redwood Creek. Jams that span the channel width, and thus form effective sediment traps, occur only where the drainage area is less than 65 km^2. Keller and Swanson (1979) also found that debris concentrations generally decrease in number downstream. Cut logs are a major component of debris jams, and so jams may have been even less numerous under natural conditions.

Even though woody debris does not directly trap much sediment in Redwood Creek, such debris does influence channel and flood-plain deposits. Large logs that lie parallel to the streambanks often act as bank protection

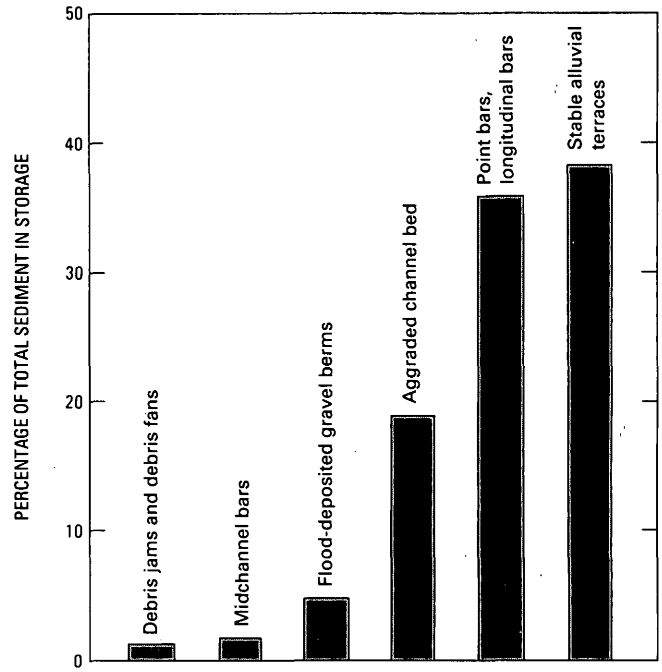

FIGURE 13.—Distribution of stored sediment in various features in Redwood Creek as of 1980.

and hinder bank erosion. Small log jams on bars form an environment locally protected from high flows, and vegetation often becomes established around these jams sooner than elsewhere on the bars. Jams thus give some stability to bars through the establishment of vegetation. Swanson and Lienkaemper (1982) found this to be true on the Hoh River in Washington as well. Alternately, jams can divert or deflect flow, which promotes local bank instability and scour of bed material.

A total volume of 16×10^6 m^3 of sediment is stored in the main Redwood Creek valley, and an additional 23×10^6 m^3 is stored in the flood plain at Orick. In tributaries, however, 95 percent of total sediment volume is stored in the lower 50 percent of their drainage lengths (chap. K, this volume), whereas alluvial storage in the main channel of Redwood Creek is spread over 85 percent of its length. Ninety-five percent of the total stored sediment in Redwood Creek is located in 65 percent of its drainage length.

The distribution of sediments of different relative mobility changes significantly along the length of the channel (fig. 15). Active sediment makes up a greater percentage of the total stored sediment in the upper 10 km than does any of the other classes. It decreases in relative importance in the midbasin and increases again downstream from the gorge (kilometer 80). The increase in mobile sediment in downstream reaches does not necessarily indicate that transport rates are higher or that the threshold of movement is lower than in

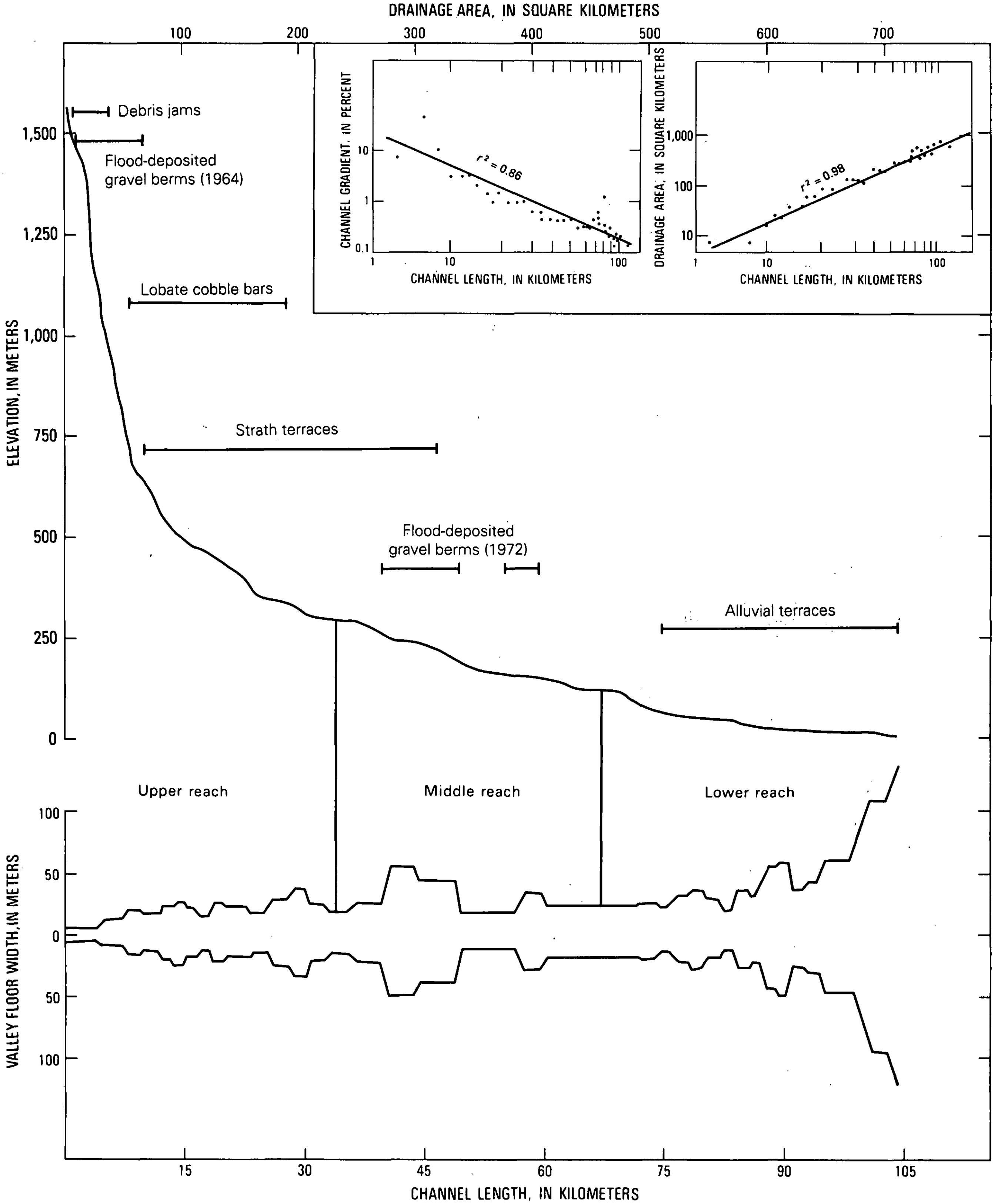

FIGURE 14. —Longitudinal profile of Redwood Creek showing distribution of localized features along certain reaches of the creek. Valley widths for Redwood Creek are drawn on the channel gradient and same horizontal scale as the profile. Strong relationships exist between channel length and between drainage area and channel length (r^2=0.86 and 0.98, respectively).

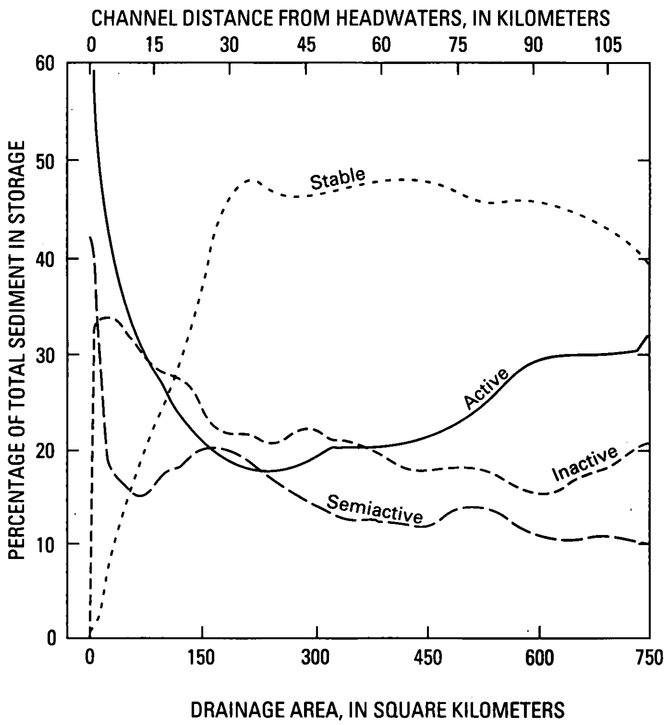

FIGURE 15.—Plot of distribution of sediments of different relative mobility (sediment reservoirs) versus drainage area, Redwood Creek basin.

upstream reaches but rather that a higher percentage of sediment is frequently transported. Frequent channel shifting, a braided channel pattern, and large expanses of unvegetated bars attest to the importance of active sediment in these lower reaches.

The percentage of semiactive sediment (fig. 15) generally decreases downstream, as does the percentage for inactive sediment. Inactive sediment increases in relative importance near the mouth of Redwood Creek where large areas of alluvial deposits occur.

Stable alluvial sediment is rare in steep headwater channels and becomes most important downstream of kilometer 30 (Redwood Valley area). From this point downstream, the percentage of stable sediment in the basin decreases slightly, even though stable sediment remains volumetrically the largest storage feature from kilometer 30 to the mouth. More than a third of all sediment in Redwood Creek is stable, and this stable sediment is a major component of alluvial storage for most of the drainage length.

CONTROLS ON SEDIMENT DISTRIBUTION

Stored sediment is not distributed uniformly along a channel; some reaches store more than others. This study identifies the factors controlling sediment distribution in stream reaches having different physical char-

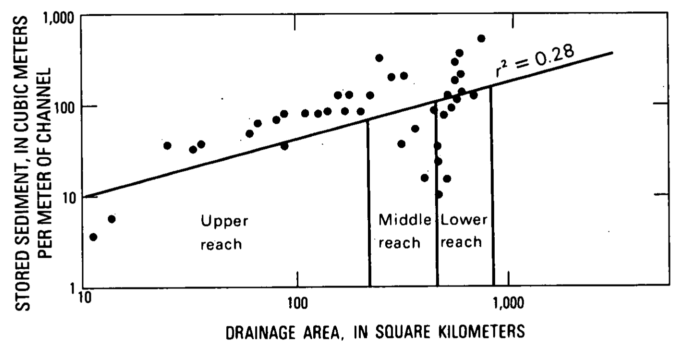

FIGURE 16.—Logarithmic plot of volume of stored sediment per unit distance (V_s) versus drainage area.

acteristics. The factors used for comparing volumes of stored sediment per reach were drainage area, sediment input to that reach, channel gradient, boundary shear stress, and valley width (table 4). Because study reaches are not of equal length, sediment storage volumes in different reaches were compared on the basis of the index "cubic meters of sediment per meter of channel" (V_s). All correlations used in the following analysis are significant at the 95-percent confidence level, unless stated otherwise. V_s in the basin ranges from 5 m^3/m in the headwaters to 600 m^3/m near the mouth (fig. 16). Lower Redwood Creek and Redwood Valley are the highest storage areas in the basin. Storage volume per unit distance generally increases with drainage area (A), but there is much variation (fig. 16). In this case, the data do not fit a simple power function well (r^2=0.28), especially at a drainage area of about 475 km^2 (the gorge). The third degree polynomial $V_s = -3{,}992 + 227\ A - 0.084\ A^2 + 0.0009\ A^3$ (r^2=0.58) describes the data better than a simple power function, but 42 percent of the variation in stored sediment is still left "unexplained" by that approach. Storage volume must be controlled by factors other than drainage area along much of Redwood Creek (table 4).

Large amounts of the sediment stored in Redwood Creek have come from landslides triggered during the 1964 storm. Kelsey and others (chap. J, this volume) describe sediment discharge by landslides into the main stem of Redwood Creek for the periods 1954 to 1966 and 1966 to 1980. In general, most pre-1966 landslides occurred during the 1964 storm. Total landslide input to the main stem of the Redwood Creek is the sum of main stem landslides and the estimated input from tributary landslides that reached the main stem. Figure 17 shows the cumulative volumes of total landslide input to the main stem (5.25×10^6 m^3; chap. J, this volume, table 1) and the deposition in Redwood Creek (4.74×10^6 m^3) resulting from the 1964 flood. Thus, the sediment that remained in the valley was 90 percent of the volume of

TABLE 4.—*Data for the 39 study reaches on Redwood Creek*

[Study reaches are shown in figure 1]

Study reach	Drainage area (km^2)	Channel length (km)	Stored sediment in study reach (1947) (m^3)	Stored sediment in study reach (1964) (m^3)	Stored sediment in study reach (1980) (m^3)	Valley width (m)	Channel gradient (percent)	Boundary sheer stress (dyn/cm^2)	Pre-1966 landslide volumes (m^3)
39	11	4.90	2,400	23,500	23,500	15.2	9.10	2,730	0
38	14	3.45	6,500	45,300	25,500	17.7	12.20	9,100	93,700
37	25	2.20	29,200	319,300	96,000	36.6	4.00	2,635	254,200
36	35	1.10	35,200	124,500	54,600	31.4	3.30	2,970	76,300
35	37	1.60	24,600	74,300	54,000	30.5	3.00	2,682	198,700
34	63	1.40	54,900	205,000	84,300	42.7	1.90	1,724	184,200
33	66	2.05	89,500	218,800	157,000	51.2	1.25	1,054	205,300
32	86	1.65	110,200	179,000	148,500	39.3	1.20	1,245	136,900
31	89	1.80	59,400	98,800	81,200	27.7	1.24	1,341	113,300
30	109	1.50	87,100	212,300	148,200	57.0	1.20	910	385,100
29	122	3.60	220,100	332,100	300,000	51.2	1.20	1,054	223,100
28	145	2.35	139,300	211,100	203,300	36.3	.90	1,293	70,100
27	159	3.00	355,100	457,000	407,900	51.2	.80	766	85,300
26	169	2.80	212,700	320,500	295,400	76.8	.60	527	277,100
25	176	2.35	268,500	325,800	302,300	45.7	.50	575	43,700
24	200	3.40	275,400	440,700	381,900	40.5	.50	445	41,800
23	216	4.45	398,500	626,300	604,500	48.8	.45	484	72,000
22	261	2.85	1,075,300	1,352,700	1,327,900	104.9	.44	460	325,100
21	292	5.95	1,303,700	1,670,000	1,577,300	85.3	.38	398	48,300
20	314	7.50	253,500	347,445	327,700	33.2	.35	364	31,200
19	319	2.80	614,700	682,000	724,600	61.0	.35	733	6,900
18	372	6.15	222,700	330,700	326,000	39.6	.30	718	696,000
17	410	3.65	22,100	69,400	65,100	42.7	.27	445	235,600
16	433	1.80	19,600	70,600	51,200	52.7	.48	656	213,000
15	454	1.10	7,000	16,000	10,700	39.6	.40	599	271,000
14	458	1.60	27,500	67,200	67,200	57.9	.32	671	42,400
13	468	1.75	170,000	185,500	178,600	76.2	.66	1,183	157,100
12	475	1.30	63,500	117,600	137,800	54.9	.31	833	56,600
11	479	1.65	20,000	20,300	21,000	33.5	1.40	3,760	181,300
10	485	1.50	166,500	255,500	286,400	76.2	.30	625	68,400
9	520	2.65	100,500	164,600	267,000	62.5	.26	625	162,300
8	531	1.80	376,800	475,800	605,000	106.7	.26	390	22,800
7	551	2.05	517,800	606,500	739,200	115.8	.23	412	61,700
6	562	2.10	142,200	211,700	280,000	65.5	.23	412	52,900
5	573	2.55	300,400	389,600	473,100	82.3	.20	390	58,500
4	584	2.95	610,000	713,200	829,800	111.3	.17	305	49,300
3	593	1.40	308,300	362,400	427,700	111.3	.14	290	25,200
2	719	5.70	2,426,900	3,198,700	3,483,200	213.4	.18	430	18,600
1	729	3.60	125,200	448,600	551,300	140.2	.12	290	0

sediment influx from landslides to the main stem. Kelsey (1977) showed that, in the nearby Van Duzen River drainage area (A=1,115 km^2) for the same time period, landslide input was 8.54×10^6 m^3, and the increase in valley storage was 64 percent of this volume (5.5×10^6 m^3). In addition to landslide input, however, fluvial erosion due to hillslope gullying and bank erosion during the 1964 flood was also a major sediment contributor, but the sediment volume from these sources has not yet been quantified for Redwood Creek.

The slopes of the curves in figure 17 indicate that, in the upper 15 km of Redwood Creek, landslide input and sediment deposition increased at about the same rate. Between kilometer 15 and kilometer 80, landslide input generally continued to increase sharply, whereas deposition did not, except in Redwood Valley (kilometers 35–65) where much sediment was deposited. From kilometers 80 to the mouth (downstream from the gorge) this trend reversed, and deposition increased sharply, while landslide input leveled off.

If the three general reaches of Redwood Creek are considered, a pattern of sediment input from landslides and deposition emerges (table 5). The areas with the highest landslide input showed the highest percent increase in storage over previous levels. However, if the actual amount of deposition in individual study reaches is compared with landslide input to that reach (fig. 18), there is no discernible relationship. This suggests that

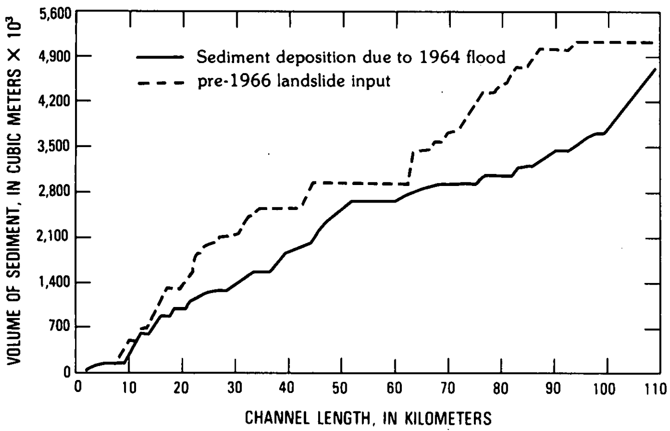

FIGURE 17.—Cumulative volumes of total landslide input to the main stem of Redwood Creek and the deposition in Redwood Creek resulting from the December 1964 flood. Landslide data are from Kelsey and others (chap. J, this volume, table 1).

TABLE 5.—*Comparison of landslide input and changes in channel-stored sediment due to the 1964 flood in the upper, middle, and lower reaches of Redwood Creek*

Reach	Reach length (km)	Landslide input[1] 1954–66 (m^3/km of channel)	Increase in stored sediment in 1964 (m^3/km of channel)	Increase in stored sediment 1947–64 (percent)
Upper...	35.5	66,000	41,000	190
Middle...	33.3	37,000	39,000	120
Lower...	35.6	47,000	56,000	130

[1] Derived from Kelsey and others (chap. J, this volume, fig. 9).

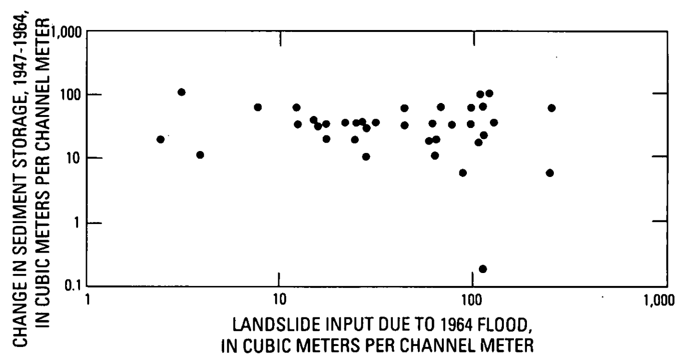

FIGURE 18.—Logarithmic plot of changes in stored sediment in Redwood Creek (due to the 1964 flood) versus input due to the same flood. No line was drawn because the regression analysis showed no relationship (r^2=0.02).

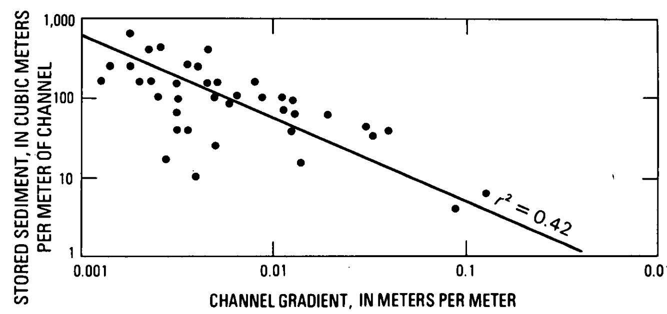

FIGURE 19.—Logarithmic plot of volume of stored sediment per unit channel length (V_s) versus channel gradient.

channel and valley characteristics in a reach, rather than sediment input at a point, control where deposition occurs.

An important reach characteristic related to the storage and transport of sediment is channel gradient. Other studies (chap. K, this volume) have shown that deposition is generally confined to low-gradient reaches. In Redwood Creek, the amount of channel-stored sediment per unit channel length (V_s) in 1980 increased with decreasing channel gradient (S) (fig. 19). Channel gradient decreases with an increase in drainage area ($S=87A^{-0.9}$; r^2=0.89). Nevertheless, a comparison of figure 16 and figure 19 shows that, in Redwood Creek, V_s correlates better with channel gradient than with drainage area (r^2=0.42 and 0.28, respectively). Channel gradient, in turn, is controlled to a certain extent by bedrock geology and sediment input. For example, where earthflows have delivered huge boulders to Redwood Creek that cannot be transported by present flows, the channel gradient is steeper than in adjacent reaches (reaches 11 and 38).

Deposition may also be related to the amount of tractive force available to move sediment on the streambed. In river channels, the average total tractive force per unit area on the stream boundary (τ_b) is approximately equal to the downslope component of the weight of water, or γds, where γ is the specific weight of water, d is depth of flow, and s is water surface slope. This assumes that water surface slope is close to bed gradient S on the average over long reaches. Resistance to flow is generated by bank curvature and irregularities, bed topographic features such as bars, and stationary and moving sediment. If it is assumed that stationary roughness or resistance features of the channel changed little along Redwood Creek, then as τ_b decreases, less tractive force is available to move sediment, and deposition will tend to occur.

For reaches in Redwood Creek, τ_b was defined for bankfull discharge as determined from 1980 channel surveys. The relationship of V_s to τ_b is described by $V_s=4.5\times10^6\ \tau_b^{-0.94}$, for which r^2=0.44 (fig. 20). The fact that the relation is not stronger may be because much of

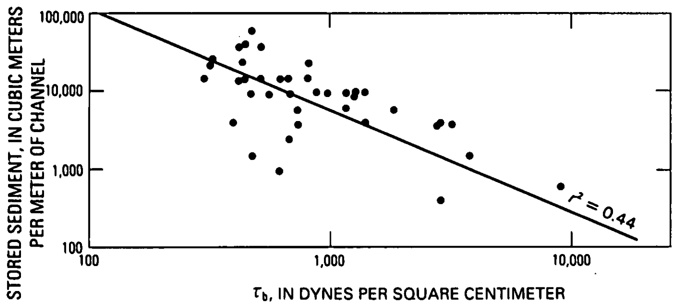

FIGURE 20.—Logarithmic plot of volume of stored sediment per unit distance (V_s) versus the boundary shear stress (τ_b) calculated for Redwood Creek at bankfull discharge.

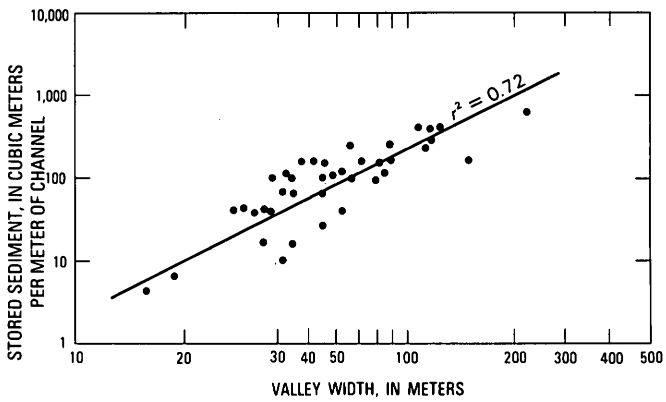

FIGURE 21.—Logarithmic plot of volume of stored sediment per unit channel length (V_s) versus valley width in a study reach.

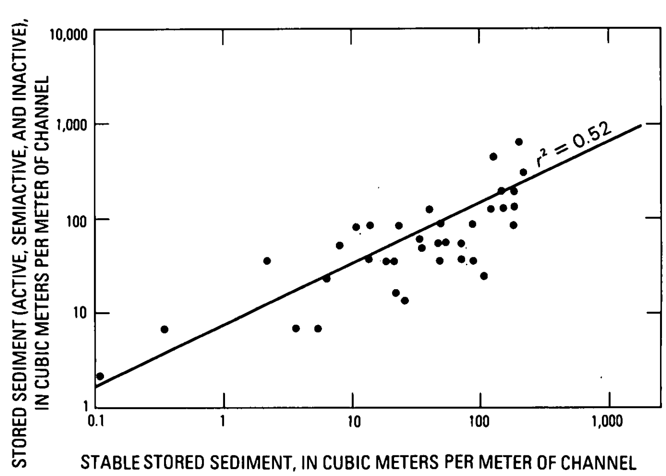

FIGURE 22.—Logarithmic plot of volume of active, semiactive, and inactive sediment per unit channel length (V_s) versus volume of stable stored sediment per unit channel length for study reaches in Redwood Creek.

the deposition of V_s occurred during different hydraulic geometry and flow conditions (and thus different τ_b conditions) than were present in 1980. Few data are available for determining accurate values of τ_b during the 1964 flood. Also, the assumption that resistance changes little along Redwood Creek may not be valid.

Of the parameters tried, V_s correlates best (r^2=0.72) with valley width (fig. 21). Valley width was defined as the average width in a study reach that was inundated by the 1964 flood, and valley widths are shown schematically in figure 14. V_s is highest in areas of large valley widths. In the Redwood Creek basin, geologic structure and bedrock influence valley width. Climate, tectonics, and general landscape evolution may affect width, but in terms of recent changes in Redwood Creek, valley width can be assumed constant through time. If V_s is related to valley width, then it follows that relatively recent deposits (active, semiactive, and inactive sediment) should occur in the same reaches that ancient deposition (stable sediment) occurred. This is indeed the case, as is shown in figure 22.

Thus sediment deposition in a reach is most strongly controlled by valley width. Generally, deposition in Redwood Creek due to the 1964 flood occurred downstream from areas of high sediment input, and specifically, deposition occurred in areas of large valley width and gentle stream gradient. If a large influx of sediment occurs in the future, sites of deposition could be predicted by considering sites of past deposition—that is, reaches with large valley widths and gentle stream gradients.

RESIDENCE TIMES OF STORED SEDIMENT

A critical part of describing sediment storage in channels is defining the residence time, or persistence, of the stored sediment. To do this, the volume of sediment in various reservoirs must be known, as must the rate of sediment transport through the system. Residence times for sediment in Redwood Creek were estimated for the four types of sediment reservoirs (active, semiactive, inactive, and stable) by dividing the volume of sediment per meter of channel length (V_s) by the bedload discharge rate (Q_B). Following the approach of Dietrich and Dunne (1978), the volumes of sediment and bedload discharge were defined as power functions of drainage area A: $V_s = aA^m$ and $Q_b = bA^n$ (table 6). Drainage area is defined as a function of channel length (X): $A = cX^p$. Then the residence time per meter of channel length, $\frac{dt}{dX}$, is:

$$\frac{dt}{\delta X} = \frac{aA^m}{bA^n} = \frac{a(cX^p)^m}{b(cX^p)^n} = \frac{ac^{(m-n)}X^{(m-n)p}}{b} \qquad (2)$$

A more complete discussion of this equation is given by Dietrich and Dunne (1978). Dietrich and others (1982)

TABLE 6.—*Definition of power functions for the four types of sediment reservoirs in Redwood Creek*
[Sediment reservoirs: A, active; Sa, semiactive; Ia, inactive; S, stable. See p. XX for explanation of symbols used]

Reservoir	Relation	a	b	c	m	n	p	r^2
Entire channel	$Q_B=bA^n$		272			1.04		0.88
	$A=cX^p$			1.28×10^{-4}			1.34	.98
A sediment	$V_s=aA^m$	0.64			0.70			.49
A+Sa sediment	$V_s=aA^m$	1.29			.65			.47
A+Sa+Ia sediment	$V_s=aA^m$	.79			1.05			.45
A+Sa+Ia+S sediment	$V_s=aA^m$	.04			2.20			.45

have subsequently shown that this estimation of residence time is not dependent on the actual process of sediment transport through a given reservoir. A modified approach to this model is presented by Kelsey and others (1987).

The relations among drainage area, channel length, and volume of sediment were defined on the basis of values measured in the field (described in previous sections) and from topographic maps. The power function for channel length and drainage area has an excellent fit (r^2=0.98) (fig. 14). The relationship for bedload discharge (fig. 23) used in table 6 is based on bedload measurements made for 8 to 10 years at three gaging stations on Redwood Creek and for 3 years on three tributaries draining three types of terrain typical of the Redwood Creek basin:

Gaging station	Drainage area (km^2)	Bedload as percent of total load	Bedload transport rate (Mg/yr)
	Main stem		
Blue Lake	175	20	93,500
South Park Boundary	474	16	193,000
Orick	720	11	173,000
	Tributaries		
Lacks Creek	44	35	11,000
Coyote Creek	20	23	15,000
Panther Creek	16	19	2,100

The relation defined by figure 23 is good (r^2=0.88) and is used in table 6; however, because the bedload data are based on different lengths of record, the relation may need to be modified slightly as more hydrologic data become available.

Four separate power functions were computed to define the relations of the four types of sediment reservoirs to drainage area. As discussed previously, several factors contribute to considerable variance in the downstream increase of sediment in storage. To use a simple power function relation between sediment in storage and channel length, anomalously low values for reaches near kilometer 80 (the gorge) were omitted, and a least-squares regression through the remaining data was computed. The four power functions used for the four sediment reservoirs are listed in table 6. For active sediment, this relation is $V_s=0.64\ A^{0.70}$, for which r^2=0.49. When sediment in the active reservoir is mobilized, it moves down the channel through the active

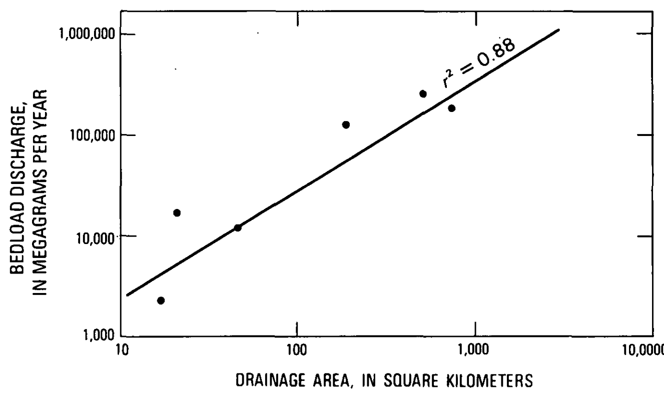

FIGURE 23.—Logarithmic plot of annual bedload discharge versus drainage area computed for six gaging stations on Redwood Creek.

reservoir, and residence time is V_s/Q_B, as stated earlier. However, when sediment in the semiactive reservoir is mobilized, sediment moves into the active reservoir. Because the sediment moves down the channel through both semiactive and active reservoirs, the residence time is $[V_s\ (\text{active})+V_s\ (\text{semiactive})]/Q_B$. When sediment in the stable reservoir is mobilized, sediment is transported through all four reservoirs. In defining the "stable" power function, the stable sediment near the mouth that is now protected by flood levees was included because this sediment is 79 percent of the total amount of stable sediment in the basin. Integrating equation 2 between two points (x_1 and x_2) in a reservoir gives the residence time (t_2-t_1) through that section of the reservoir (Dietrich and Dunne, 1978):

$$\int_{t_1}^{t_2} dt=\int_{x_1}^{x_2} \frac{a}{b}\, c^{(m-n)} X^{(m-n)p} dX \qquad (3)$$

$$t_2-t_1=\frac{\frac{a}{b}\, c^{(m-n)}}{1+(m-n)p}\, X^{(1+(m-n)p)} \Big|_{x_1}^{x_2} \qquad (4)$$

By using this approach, residence times for active, semiactive, inactive, and stable sediment in the upper, middle, and lower reaches of Redwood Creek were computed (table 7). The three main channel reaches are approximately equal in length (35.5, 33.3, and 35.6 km,

TABLE 7.—*Residence times of sediment in storage reservoirs in the three main reaches of Redwood Creek*

[Approximate boundaries of reaches are shown in figure 1. x_1, x_2 are two points in a reservoir]

Reach	Equation for residence time	Number of years	Velocity (m/yr)
	Active		
Upper		26	1,365
Middle	$0.09\ [x_2^{\ 0.54} - x_1^{\ 0.54}]$	11	3,030
Lower		9	3,950
	Semiactive		
Upper		50	710
Middle	$0.33\ [x_2^{\ 0.48} - x_1^{\ 0.48}]$	19	1,750
Lower		15	2,370
	Inactive		
Upper		104	340
Middle	$2.63\times10^{-3}[x_2^{1.01}-x_1^{1.01}]$	99	335
Lower		106	335
	Stable		
Upper		700	50
Middle	$1.76\times10^{-9}[x_2^{2.55}-x_1^{2.55}]$	3,100	10
Lower		7,200	5

respectively). Velocity of sediment is simply defined as the length of the main channel reach in question divided by the residence time of a sediment reservoir in that reach (table 7). As expected, sediment in the active reservoir has the shortest residence time. For example, a particle entering the active channel bed at kilometer 35.5 (the upstream end of the middle reach) would take 11 years under average transport conditions to travel out of the middle reach. This residence time is of the same order of magnitude as estimated for gravel bars on Rock Creek by Dietrich and Dunne (1978). Residence time for active sediment decreases downstream, and particle velocity increases. This seems reasonable because widespread channel aggradation in the lower reach has caused channel adjustments (channel widening, decrease of depth) (chap. N, this volume) that would tend to increase sediment transport there. A velocity on the order of 3,000 to 4,000 m/yr, as predicted for active sediment in the middle and lower reaches, is much higher than the 234 m/yr reported by Milhous (1973) for Oak Creek and much higher than the estimated velocities in Rock Creek (Dietrich and Dunne, 1978), both of which are small streams transporting considerably less bedload than Redwood Creek. This rate is also supported independently by an analysis of changes detected through cross-section surveys.

Residence times for semiactive sediment, as with active sediment, decrease downstream. Semiactive sediment moves more slowly than active sediment in the upper reach, but the difference is negligible in the downstream reach. The velocities of both active and semiactive sediment are within the same order of magnitude. Scour and fill data indicate frequent erosion of semiactive sediment in the downstream reach. Because most sediment transport in north coast streams occurs at relatively high discharges (Ritter, 1968), at which both active and semiactive sediment are mobilized, the similarity in residence times is not unexpected.

The residence time for inactive sediment is an order of magnitude longer than for active or semiactive sediment. Residence times are approximately constant throughout the length of the channel. In the upper reach, sediment in the inactive reservoir consists of high, flood-deposited gravel berms in a narrow valley. Downstream, flood deposits are found on a wider flood plain removed from the inactive reservoir. This situation indicates that some effects of a large depositional event such as the 1964 flood will persist on the order of a century.

Stable sediment has the longest residence time—an order of magnitude greater than for inactive sediment. Residence times increase downstream, where a wide valley permits the formation and preservation of broad alluvial terraces. Old-growth redwood trees on these terraces are 400 to 800 years old, and some of them may have sprouted from even older trees. The long residence times of inactive and stable sediment probably allow the weathering and breakdown of coarse stored sediment to suspended load size, as Dietrich and Dunne (1978) have argued.

The bedload discharge function is based on total-load measurements made during the last 10 years. This period includes the flood of 1975, which had a recurrence interval of approximately 10 to 20 years. The transport relationship defined in table 6 is probably accurate for discharges up to the 20-year peak flow. The above discussion of residence times, however, assumes that the volume of sediment in each reservoir and the bedload transport rates remain constant through time. Because Redwood Creek is not in a state of equilibrium, the bedload transport function may shift in the future. If a flood of an extreme magnitude occurs, the bedload function and residence times may need to be recalculated.

IMPLICATIONS FOR CHANNEL RECOVERY FROM MAJOR STORMS

The effectiveness of an event is measured not only in terms of sediment transport but also by net erosion and changes in channel form (Wolman and Gerson, 1978). If the recovery time of a system is greater than the recurrence interval of the event, the channel will not be in equilibrium with the present channel-forming discharge. Wolman and Gerson cited examples of rivers in temperate regions that regained their original width in a matter of months or years after the occurrence of channel-widening floods that had recurrence intervals of 50 to 200 years. In Redwood Creek, however, it appears that changes in sediment storage (and related changes in channel geometry) due to a flood having a recurrence interval of 50 years will persist for a century or more. In this case, recovery time is longer than the recurrence interval of the 1964 flood. The recurrence interval of the 1964 episode of hillslope erosion is unknown; nevertheless, it is probably greater than that of the 1964 peak flow discharge. Beven (1981) discussed the effects of sequencing on effectiveness of events, which may indeed be important in Redwood Creek.

In some basins, recovery is lacking because a threshold of competence has not been exceeded (Wolman and Gerson, 1978). In Redwood Creek, however, particle sizes of stored sediment can be transported at 5- to 20-year peak discharges if they are located near the thalweg. Nonrecovery in Redwood Creek results from the inability of moderate flows to erode the vast amounts of "excess" sediment deposited throughout the valley width.

CONCLUSION

As a result of the December 1964 flood in Redwood Creek, the distribution and quantity of sediment stored in the main channel changed drastically. New storage features (flat-topped gravel berms and an aggraded channel bed) were created. This stored sediment was responsible for exceptionally high bedload transport rates after the 1964 flood. Sediment input to a reach is related in a general way to increases in stored sediment, but characteristics of a specific reach control the local distribution of stored sediment. The volume of stored sediment is greatest in reaches having large valley widths and gentle channel gradients. The net amount of sediment stored in Redwood Creek in 1964 had decreased by 1980. Much of the active sediment originally stored in the upper basin had been transported and redeposited in lower reaches. Unless sediment input to Redwood Creek from hillslope processes increases in the future, the volume of stored sediment will slowly decrease through time. The residence time of deposits differs according to storage reservoirs. Residence times of sediment in active and semiactive reservoirs are on the order of a few decades; of sediment in inactive reservoirs, a hundred years. The residence time for sediment in stable reservoirs is thousands of years. These data indicate that recovery of the entire system from a major aggradational event is extremely slow. In-channel storage provides a ready supply of bedload-sized material for future transport at high flows. High bedload transport rates will probably continue for several decades due to the residence time of sediment deposits.

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Effects of Large Organic Debris on Channel Morphology and Sediment Storage in Selected Tributaries of Redwood Creek, Northwestern California

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–P

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EFFECTS OF LARGE ORGANIC DEBRIS ON CHANNEL MORPHOLOGY AND SEDIMENT STORAGE IN SELECTED TRIBUTARIES OF REDWOOD CREEK, NORTHWESTERN CALIFORNIA

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ABSTRACT

Large organic debris (stems greater than 100 mm in diameter) exerts a major control on channel form and process, and thus on anadromous fish habitat, in streams draining coastal redwood forests. Total debris loading for a particular channel reach represents the relation between rates of debris entering and leaving the reach and is primarily a function of the following interrelated variables: number and size of trees in the vicinity of the channel, rate of decomposition, geology, valley-side slope, landslide activity, channel width, discharge, and upstream drainage area. Approximately two-thirds of the variability of the debris loading in old-growth forests may be explained by variability of the number of mature redwood trees per hectare within 50 m of the channel. Generally, there is an inverse relationship between debris loading and upstream drainage area, but in some instances third-order reaches may have a higher loading than adjacent second- or fourth-order reaches.

Effects of large organic debris on channel morphology and sediment storage tend to be complex for several reasons. First, large organic debris may reside in the stream channel for centuries and is a permanent part of the fluvial system. Minimum residence times for more than 30 individual pieces of large organic debris have been determined by dendrochronology, and about half of these exceed 100 years, with the oldest exceeding 200 years. Second, large organic debris exerts considerable control over channel morphology, particularly in the development of pools. In headwater regions of drainage basins, nearly all the pools may be either directly formed by, or significantly influenced by, large organic debris. As the size of stream increases, the percentage of pools formed by large organic debris decreases, but debris still may significantly influence the morphology of the pool environment. Third, large organic debris produces numerous sediment storage sites, supporting a sediment buffer system that modulates the routing of sediment through the fluvial system. A volume of sediment equivalent to approximately 100 to 150 years of average annual bedload is stored in debris-related sites along Little Lost Man Creek, and a volume equivalent to about 50 to 100 years of average annual bedload is available for future storage. Finally, large organic debris in steep streams significantly concentrates potential energy expenditure over short reaches where accumulations of debris exist. In headward reaches of drainage basins, approximately 30 to 60 percent of the total decrease in elevation of the channel may be associated with large organic debris. Thus, energy is dissipated at these locations, where it might otherwise cut a more deeply incised channel with unstable and eroding banks.

The study of large organic debris in streams is pertinent to two interrelated management problems brought about by road building and timber harvesting in northwestern California: (1) reduction of sediment pollution and (2) restoration and enhancement of anadromous fish habitat. In the management of streams to maximize production of anadromous fish in the coastal redwood environment, the role of large organic debris should be considered. Large organic debris in unusually large amounts may block fish migration and cause adverse channel erosion. However, within limits, large organic debris is necessary for streams to sustain healthy populations of anadromous fish; its presence provides habitat diversity, sites for organic nutrient processing, and a modulated release of sediment to trunk streams. Therefore, managers of stream-clearing operations must carefully weigh the benefits of locally stabilizing streambanks, opening up anadromous fish habitat, or marketing merchantable timber against the potential dangers of losing hydrologic variability and mobilizing large quantities of sediment stored in conjunction with large organic debris.

INTRODUCTION

The primary purpose of this paper is to discuss relations between in-channel large organic debris (logs, stems, limbs, and rootwads greater than 100 mm in diameter) on the one hand and channel morphology, sediment storage, and formation and maintenance of anadromous fish habitat on the other. A secondary purpose is to discuss briefly the implications of these relations for management of streams to improve anadromous fish habitat.

Large organic debris in the active stream channel has a major control on channel form and process (Swanson and Lienkaemper, 1978; Keller and Swanson, 1979;

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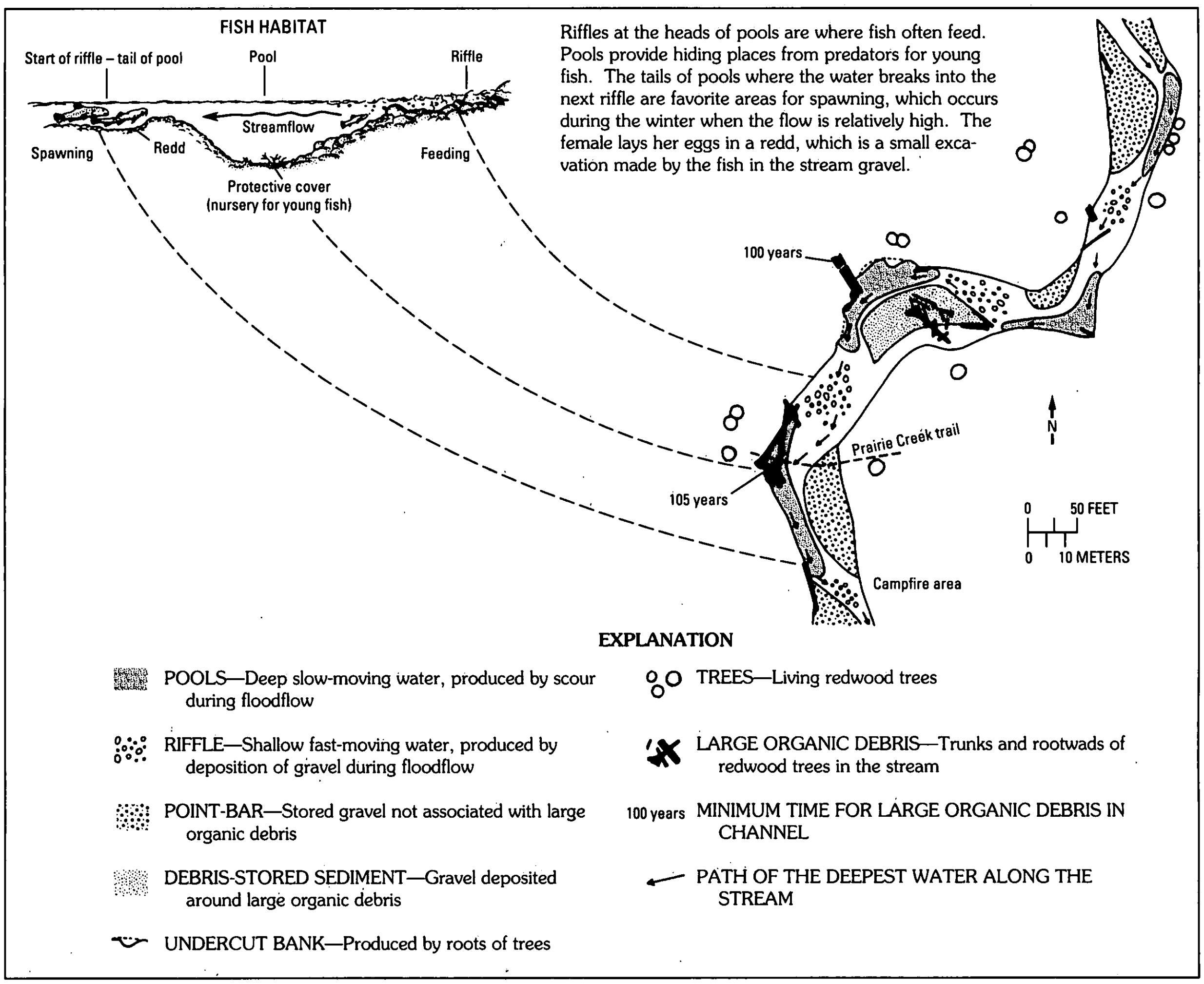

FIGURE 1.—Generalized relation between the various morphologic features of the stream channel and anadromous fish habitat.

Keller and Tally, 1979). Such debris may reside in the stream channel for centuries, providing a large roughness element that serves to fix the position of the thalweg and the spacing of large pools (Lisle and Kelsey, 1982). Large organic debris also facilitates storage of much bedload material and provides a natural buffer to modulate downstream discharge of sediment (Tally and others, 1980; Mosley, 1981). In steep headwater reaches of streams, a significant part of the decrease in channel elevation is locally concentrated at organic steps or other accumulations of large organic debris. Therefore, debris is pertinent to the solution of two interrelated management issues in northwestern California: restoration or enhancement of anadromous fish habitat and sediment pollution associated with timber harvesting or other land use change that directly or indirectly affects fish habitat.

Decline in recent years of anadromous fish populations in streams of the north coast of California is well documented; many rivers and streams that once supported relatively large runs of salmon and steelhead trout now have significantly fewer fish (Denton, 1974). Causes for the decline in numbers of anadromous fish are multiple and complex, but many likely are related in part to habitat degradation caused by human uses of hillslopes (such as timber harvesting and urbanization) adjacent to stream channels and to in-stream modifications exacerbated by natural processes such as floods. The decline in noncommercial steelhead populations indicates that overfishing in the ocean is not the primary cause of the observed pattern.

Generalized habitat for anadromous fish is shown in figure 1; stream environments emphasized are pools and riffles. Pools and riffles are formed and maintained by a complex scour-fill sequence related to the morphology and hydraulics of the stream (Keller, 1971; Keller and Melhorn, 1973, 1978). Pools are topographic low areas produced by scour during relatively high channel-forming flows that occur every year or so. Riffles are topographic high areas produced by deposition during the same relatively high channel-forming flows. In gravel-bed streams, only the relatively fine sediment (sand-sized or finer) is transported at lower flows, and the pattern of transport is for fine sediment to be transported from riffles to pools. For gravel-bed streams that have little sand available for transport, movement of bedload may be confined entirely to channel-forming flow events, and pools may scour to bedrock and contain little if any bed material. Thus, for streams having available bed material ranging from gravel to sand and finer, pools tend to scour during relatively high flows and fill during lower flows, whereas riffles tend to fill during relatively high flows and may scour at lower flows.

Gravel-bed streams not affected by human activity often have little fine sediment, and so pools are areas of deep, slow-moving water during the summer low-flow times. Such pools provide good rearing habitat for many species and ages of juvenile anadromous fish. Land use changes such as those associated with timber harvesting and road building can adversely affect pool environments during the summer low-flow period, however, by filling pools with fine sediment. The filling results in degradation of nursery areas for anadromous fish, which remain in the stream for a year or so before migrating to the ocean. Therefore, an important limiting factor to fish production is the pool environment during summer (low-flow) months (Burns, 1971). Fine sediment that enters the stream channel also may fill the void spaces between gravel particles on riffles, prevent the aeration necessary to sustain fish eggs, and pose a physical barrier to emerging fry. Better understanding of channel morphology, sediment routing and storage, and effects of land use changes will facilitate improved management of anadromous fish habitat in streams of the coastal redwood environment.

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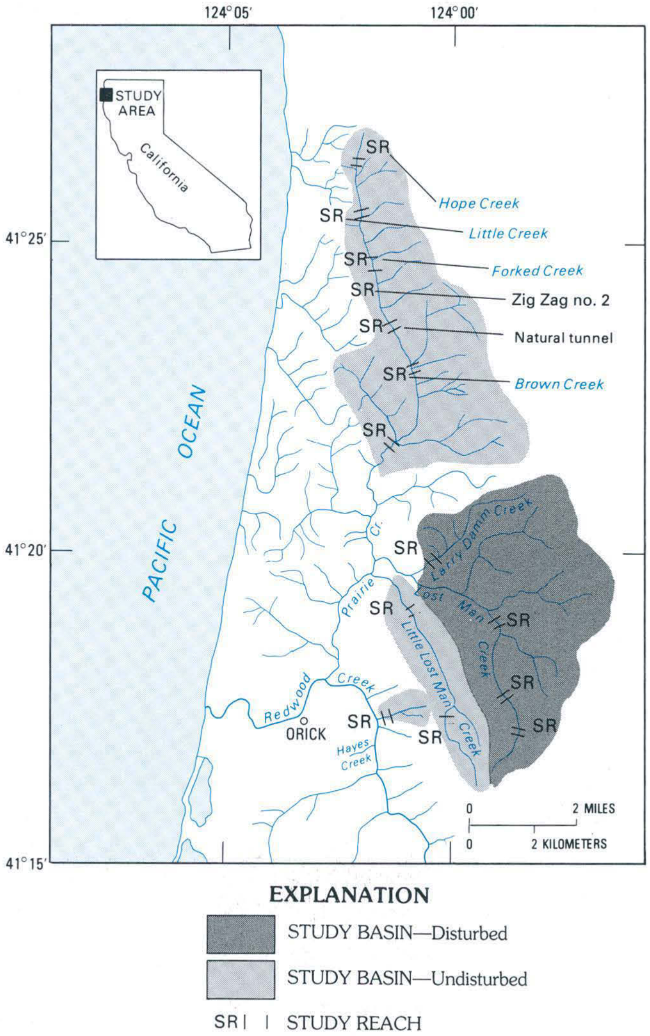

FIGURE 2.—Location of study reaches in the Redwood Creek drainage basin, northwestern California.

STUDY AREAS

The streams studied (with the exception of Caspar Creek, near Fort Bragg, Calif.) are located in the Redwood Creek drainage basin, near Orick, Calif. (fig. 2). Five streams were studied in detail, mostly during summer low-flow periods. Study reaches were chosen at locations that could be identified on topographic maps or aerial photographs, thus facilitating better measurement of drainage area and channel slope, as well as other properties. Research methods included measuring channel profiles and cross sections, sediment size distributions, and debris loading; estimating minimum residence time of large organic debris in the channels and estimating debris-stored sediment; and mapping.

Data summarizing the channel morphology of the stream reaches studied are shown in table 1. Three of the watersheds, Hayes Creek, Little Lost Man Creek, and

TABLE 1*A*.—*Morphologic data for undisturbed watersheds (tributaries to Redwood Creek) in northwestern California*

[Total percentages in stream environments may be less or greater than 100 percent due to overlaps such as pools that contain debris-stored sediment or to existence of other environments not listed]

Study reach	Hayes Creek	Little Lost Man Creek, Upper	Little Lost Man Creek, Lower	Prairie Creek, Hope Creek	Prairie Creek, Little Creek	Prairie Creek, Forked Creek	Prairie Creek	Prairie Creek natural tunnel	Prairie Creek, Brown Creek	Prairie Creek, Campground
Upstream basin area (km^2)	1.5	3.5	9.1	0.7	3.5	6.6	8.2	11.2	16.7	27.2
Stream order	2	2	3	2	2	2	2	2	3	4
Slope	.12	.033	.048	.02	.014	.012	.009	.01	.01	.005
Debris loading (m^3/m^2)	.340	.283	.098	.436	.025	.026	.043	.212	.170	.039
Pool-to-pool spacing (in no. of channel widths)	2.4	[1]1.9	[1]1.8	[1]6.2	[1]4.7	2.6	6.6	2.7	6.0	4.0
Percent channel area in pool[2]	12	22	18	49	34	46	36	41	26	25
Percent channel area in riffle[2]	26	15	21	21	46	49	20	15	18	25
Percent channel in debris-stored sediment[2]	40	39	39	30	18	30	15	21	29	13
Percent channel area in undercut banks[2]	4	3	1	1	4	3	4	1	<1	1
Percent pool morphology influenced by debris[2]	83	100	90	86	71	87	50	80	67	50
Debris-controlled drop in elevation of the channel (percent)[3]	38	59	30	43	27	34	8	<1	18	<1

[1] Spacing controlled by organic debris.
[2] At low flow.
[3] Ratio of cumulative loss of channel elevation associated with large organic debris to total fall of the stream reach.

TABLE 1*B*.—*Morphologic data for disturbed watersheds (tributaries to Redwood Creek) in northwestern California*

[Total percentages in stream environments may be less or greater than 100 percent due to overlaps such as pools that contain debris-stored sediment or to existence of other environments not listed]

Study reach	North Fork Caspar Creek, Upper[1]	North Fork Caspar Creek, Lower[1]	Lost Man Creek, Upper	Lost Man Creek, Middle	Lost Man Creek, Lower	Larry Damm Creek
Upstream basin area (km^2)	1.6	3.9	1.1	3.4	9.8	3.7
Stream order	2	2	2	3	4	3
Slope	.016	.013	.048	.024	.047	.014
Debris loading (m^3/m^2)	.042	.048	.210	.181	.142	.152
Pool-to-pool spacing (in no. of channel widths)	[2]3.5	3.8	[2]4.1	[2]2.6	1.3	2.2
Percent channel area in pools[3]	24	36	33	43	14	27
Percent channel area riffles[3]	30	30	25	14	11	14
Percent channel in debris-stored sediment[3]	44	34	43	31	41	59
Percent channel in area undercut banks[3]	2	1	4	2	1	2
Percent pool morphology influenced by debris[3]	82	43	79	100	57	59
Debris-controlled drop in elevation of the channel (percent)[4]	57	37	69	33	30	17
Approximate period of timber harvest	1890's	1890's	Post-WW II-1960(?)	Post-WW II-1960(?)	Post-WW II-1968	1954–68

[1] Not in the Redwood Creek drainage basin.
[2] Spacing controlled by organic debris.
[3] At low flow.
[4] Ratio of cumulative loss of channel elevation associated with large organic debris to total fall of the stream reach.

Prairie Creek, are undisturbed; their basins are vegetated with old-growth redwood and associated flora. Both Lost Man Creek and Larry Damm watersheds have been disturbed. Approximately 87 percent of the 9-km^2 Lost Man Creek watershed above the gaging station was logged prior to 1968, and 15 percent was still highly disrupted as recently as 1976. The upper reaches of Larry Damm were logged from 1954 to 1968.

Prairie Creek is a relatively low-gradient, gravel-bed, meandering stream and, along most of the reaches studied, is entrenched as much as several meters into conglomerates and consolidated sands of the Prairie Creek Formation of Pliocene and (or) Pleistocene age. Some of entrenchment is hypothesized to be in response to recent and ongoing tectonic activity.

Little Lost Man and Lost Man Creeks are steep, gravel-bed tributaries of Prairie Creek. They both flow across steeply dipping sandstones, siltstones, shales, and conglomerates of the Franciscan assemblage of Late Jurassic and Cretaceous age (Harden and others, 1982). Local stream gradients of Little Lost Man Creek and, presumably, of Lost Man Creek are adjusted to the resistance of the various rock types (Tally, 1980).

Hayes Creek is a small, steep, gravel-bed tributary to Redwood Creek. The stream in the study reach flows over Franciscan sedimentary rocks, metapelites of the schist of Redwood Creek (schist), and the Grogan fault zone, which separates them.

Larry Damm Creek is a relatively low-gradient, sand- and gravel-bed tributary to Lost Man Creek. The drainage basin is predominantly underlain by sands and gravels of the Prairie Creek Formation; Mesozoic Franciscan assemblage sandstones and shales are exposed in the lowermost portion of the basin.

FACTORS INFLUENCING LARGE ORGANIC DEBRIS LOADING

Debris loading, in cubic meters of large organic debris per square meter of active channel (m^3/m^2), is determined by measuring the length and diameter of all large organic debris having diameters greater than 100 mm. Redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), big-leaf maple (*Acer macrophyllum*), and red alder (*Alnus oregonia*) are the main contributors of large organic debris to the streams of the coastal redwood forest. However, because redwood debris tend to be very large and resistant to decay, they usually dominate the total loading; a few large pieces may account for most of the debris loading in a particular reach. For example, 60 percent of the total loading along both the 200-m-long Zig-Zag no. 2 reach of Prairie Creek and the 400-m upper reach of Little Lost Man Creek consists of one redwood trunk in each reach. (See fig. 3 near *A–A′* and fig. 4 at DD6.)

Total debris loading in a particular channel reach is a function of the rate of debris entering and leaving that reach. Large organic debris may enter a channel by natural processes such as landslides, blowdown of whole trees or portions of trees, bank erosion, and flotation from upstream. Several of these processes often work in concert to deliver debris to a particular location in a stream channel, although the dominant process delivering debris to the channel often depends upon local geologic conditions. On steep sections of Little Lost Man Creek, for example, where the stream flows over resistant conglomerates and massive sandstone, the valley sides tend to be steep, and landslides commonly deliver large organic debris to the channel. Landslides adjacent to the banks of Hayes Creek also deliver considerable large organic debris to the channel. On the other hand, at locations where tributaries enter the stream, or along relatively low-gradient sections where streamside trees are rooted in thicker soils, blowdown and undercutting of the streambanks may deliver most of the material to the channel.

Large organic debris that are anchored in the stream or on the banks and extend out into the channel may be stable for decades. Such debris may be stabilized by having much of their mass resting outside of the channel or may become stabilized by partial burial in sediment within the channel. Debris also may be stabilized by being wedged between other debris, boulders, or other obstructions. Finally, debris may also be stabilized by the growth of "nursed trees" that send roots over the debris and into the soil, binding debris accumulations and substrate together.

Once debris collects in the channel, complex feedback mechanisms often influence additional debris input. For example, debris itself may increase bank erosion, which in turn may undermine additional trees that subsequently fall into the channel. Furthermore, large debris in the sediment storage sites produced by the debris may trap additional large organic debris delivered from upstream by flotation. Accumulation continues until the debris are removed by a combination of erosion, decay of supporting logs, or flotation during high flows. Debris thus released may move downstream to be incorporated in still other accumulations, again significantly affecting sediment routing and discharge patterns. Relations between these processes associated with organic debris in streams are shown on figure 5.

Debris loading in a particular reach under natural conditions is directly related to the availability of potential debris stored in living trees adjacent to the stream. Figure 6 shows that approximately 64 percent of the variability of large organic debris loading may be explained by the variability in the number of mature redwood trees per hectare within 50 m of the streambanks. The remaining 36 percent of the variability of large organic debris loading is presumably associated with local geologic and biogeographic conditions, such as those that differentiate the Prairie Creek and Little Lost Man Creek watersheds.

Debris loading values for Prairie Creek and Little Lost Man Creek range from about 0.02 to 0.44 m^3/m^2 and 0.1

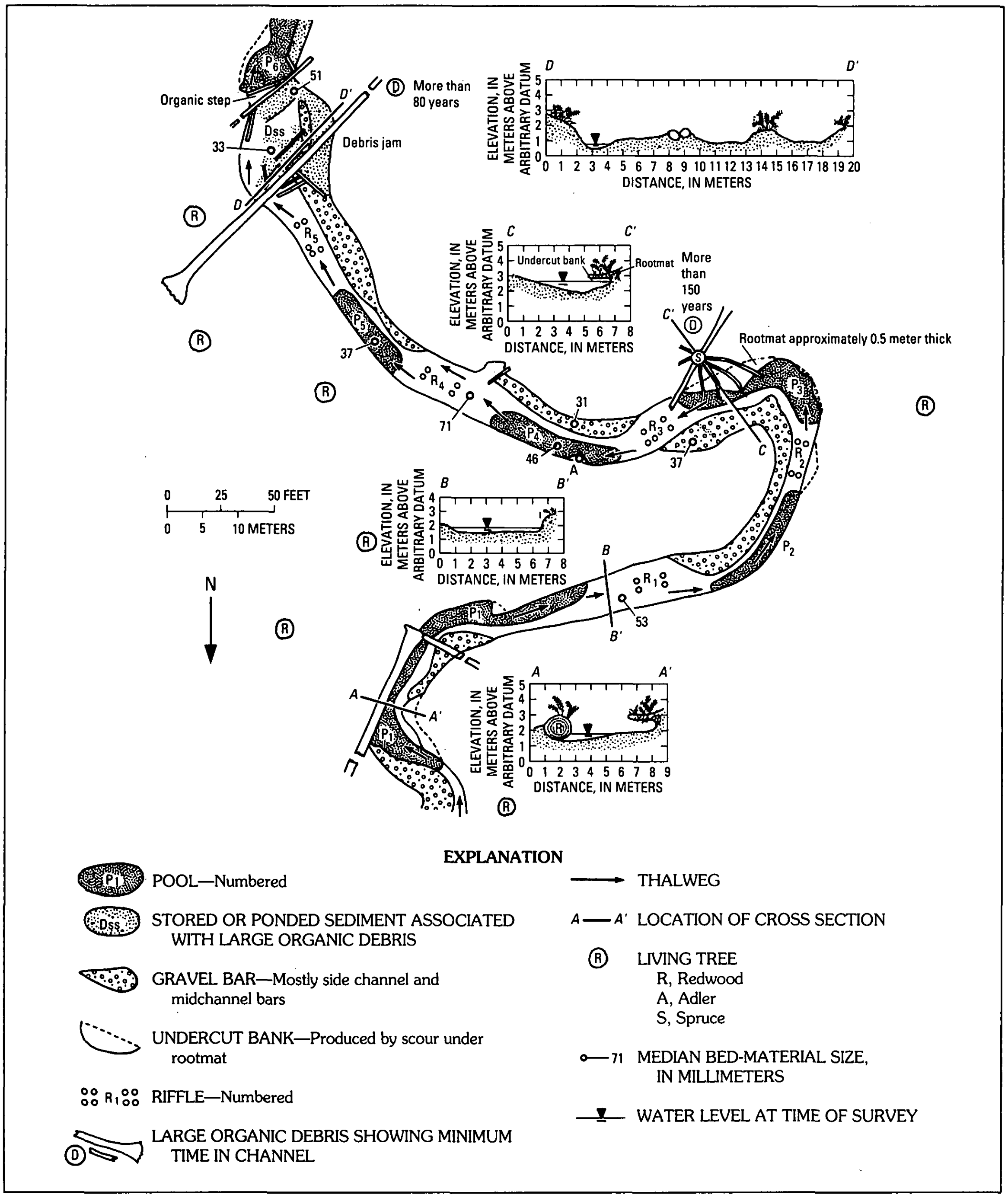

FIGURE 3.—Morphologic map of Zig Zag no. 2 reach, Prairie Creek. Reach location is shown in figure 2. Pool and riffle numbers correspond to those on the long profile shown in figure 19*A*.

to 0.54 m^3/m^2, respectively. Examination of figure 6 shows that with one exception the debris loading in Prairie Creek is consistently less than that predicted by the regression line and that Little Lost Man Creek has debris loading that tends to be higher than would be predicted. The differences primarily reflect variable availability of debris near the channel and perhaps, to a lesser extent, differences between the ways in which large organic debris are delivered to the streams. Prairie Creek is a lower gradient meandering stream with a well-developed flood plain in some locations, and debris are introduced directly into the channel by tree fall and bank erosion. Little Lost Man Creek, on the other hand, is a small steep stream with little flood-plain develop-

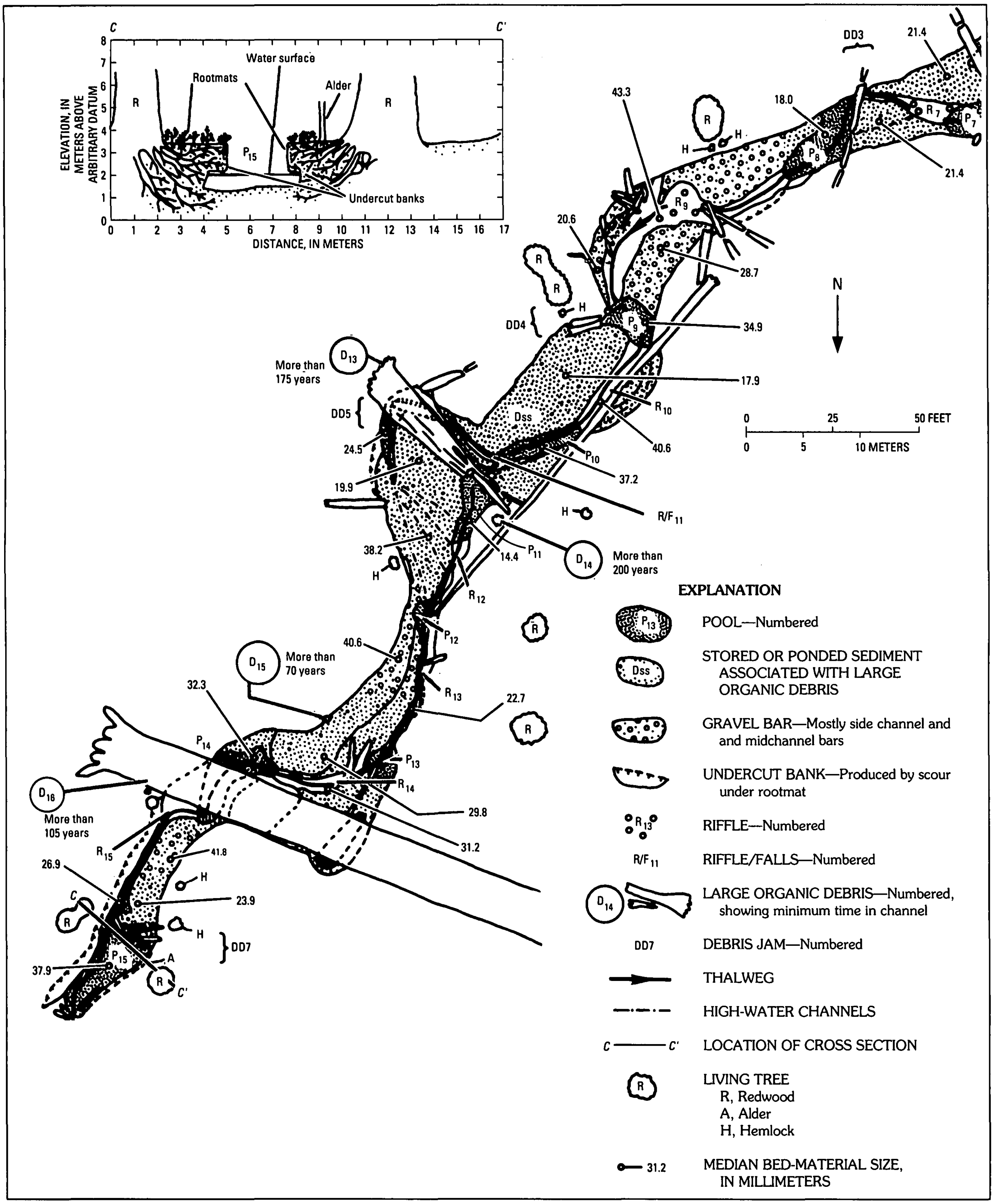

FIGURE 4.—Morphologic map of Little Lost Man Creek, upper reach (part), downstream extension of figure 7. Pool, riffle, and riffle/falls numbers correspond to the long profile shown in figure 16. Reach location is shown on figure 2.

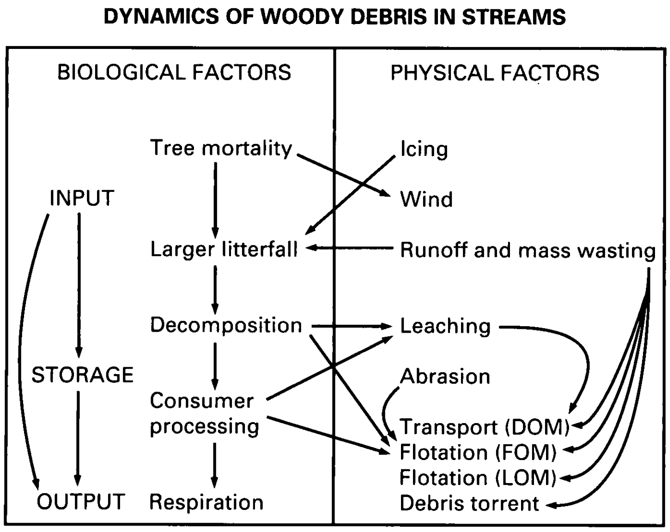

FIGURE 5.—Dynamics of woody debris in streams. DOM=dissolved organic matter; FOM=fine organic matter; LOM=large organic matter.

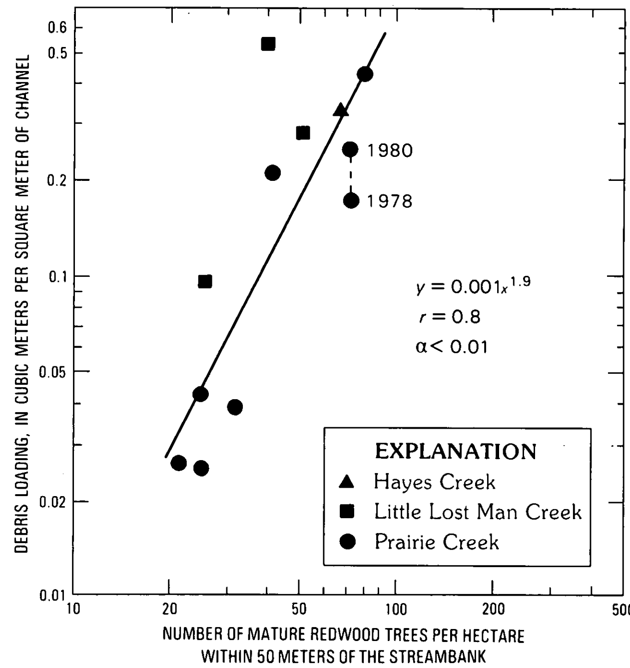

FIGURE 6.—Relation of debris loading to density of mature trees adjacent to the stream channel.

ment and relatively steep valley walls adjacent to the stream channel; mass wasting and other slope processes, as well as tree fall and bank erosion, are therefore important in transporting and concentrating large organic debris downslope to the stream channel.

Streams in the same drainage basin flowing through timber stands where trees are about the same size (other factors being similar) might be expected to have a debris loading that decreases as drainage basin area increases. This is because (1) tree density is partially related to topography (greater areal density on steeper slopes), (2) area of active channel increases downstream, and (3) flow in the upper reaches may not be sufficient to float large organic debris, whereas farther downstream there is sufficient stream power and water depth to move and sort debris into distinct debris accumulations or jams. Farther downstream even the largest debris may be floated away. The above relation between debris loading and drainage basin area is documented in streams that flow through Douglas-fir forests (Swanson and Lienkaemper, 1978) of the Pacific Northwest and in second-growth northern hardwood forests of New England (Bilby and Likens, 1980). Although redwood debris occur in a larger range of sizes, the same tendency can be observed: debris loading generally decreases in the downstream direction as channel width and drainage area increase (table 1). Debris accumulations in the lower reaches may be larger, however, more complex, and spaced farther apart than in the headwater areas. Some of these relations are shown diagrammatically on morphological maps for the upper reach of Little Lost Man Creek (figs. 4, 7) and lower reach (figs. 8, 9).

Debris loading in specific instances, over relatively short reaches, may deviate from the general relation with drainage basin area. For example, with the exception of the very headwaters of Prairie Creek, the Brown Creek reach has a debris loading higher than that found in either the upstream or downstream study reaches (see table 1). Examination of the Brown Creek reach suggests that there are several anomalies. A particularly significant anomaly may be the convex portion of the profile of Prairie Creek in the vicinity of the Brown Creek and Campground study reaches (fig. 10). The origin of the convex section of the profile is not known but may be related to the geology and, in particular, to recent tectonic uplift. Regardless of whether the entrenchment is due to recent tectonic activity, it influences debris loading by producing locally narrow valleys and steep valley sides adjacent to the channel, which can be seen in the cross-valley profile of the Brown Creek study reach (fig. 10). Figure 11 shows a morphologic map of part of that study reach. The relatively steep valley sides, more frequent entrance of tributary channels, and entrenchment into the Prairie Creek Formation increase the likelihood of large organic debris entering the stream channel. Tributary junctions are apparently significant because at these sites erosion acts along two adjacent banks, increasing the chances of a tree falling into the channel (Keller and Tally, 1979). Thus, the relatively

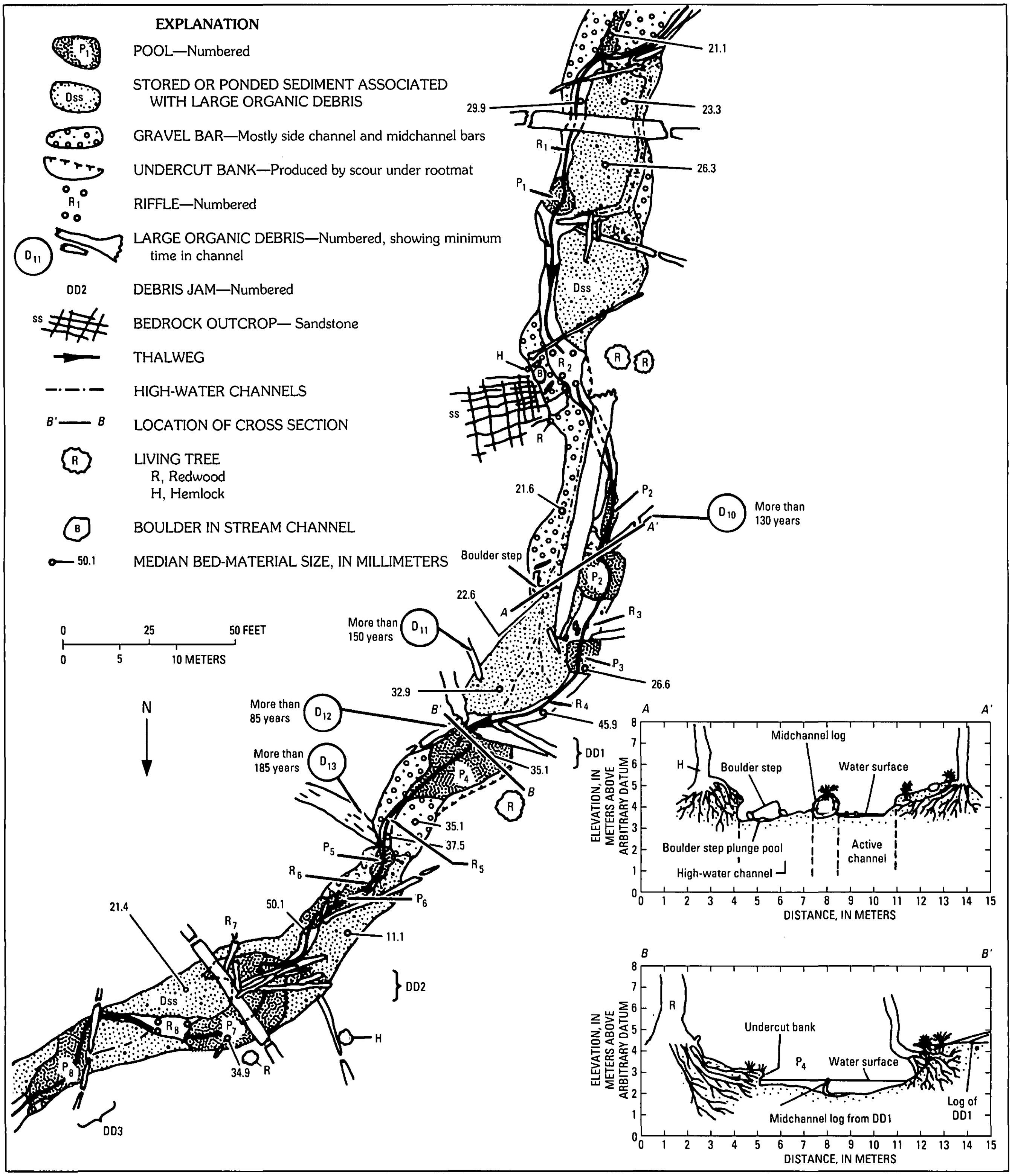

FIGURE 7.—Morphologic map of Little Lost Man Creek, upper reach (part). The downstream extension of this map is shown in figure 4. Pool and riffle numbers correspond to the long profile shown in figure 16.

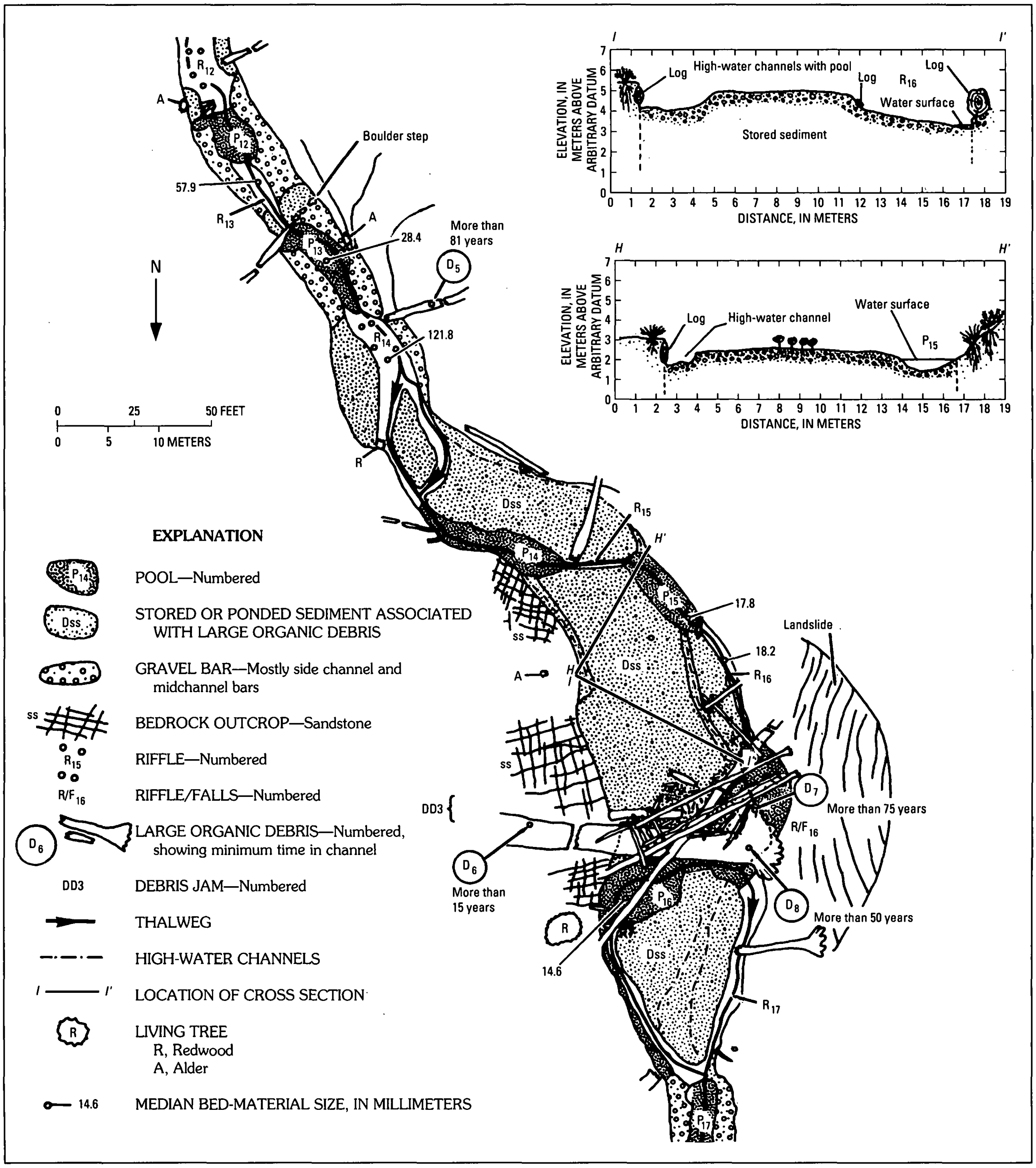

FIGURE 8.—Morphologic map of Little Lost Man Creek, lower reach. Location of reach is shown in figure 2. The corresponding long profile is shown in figure 17. The debris jam adjacent to the landslide has been in place for more than 75 years.

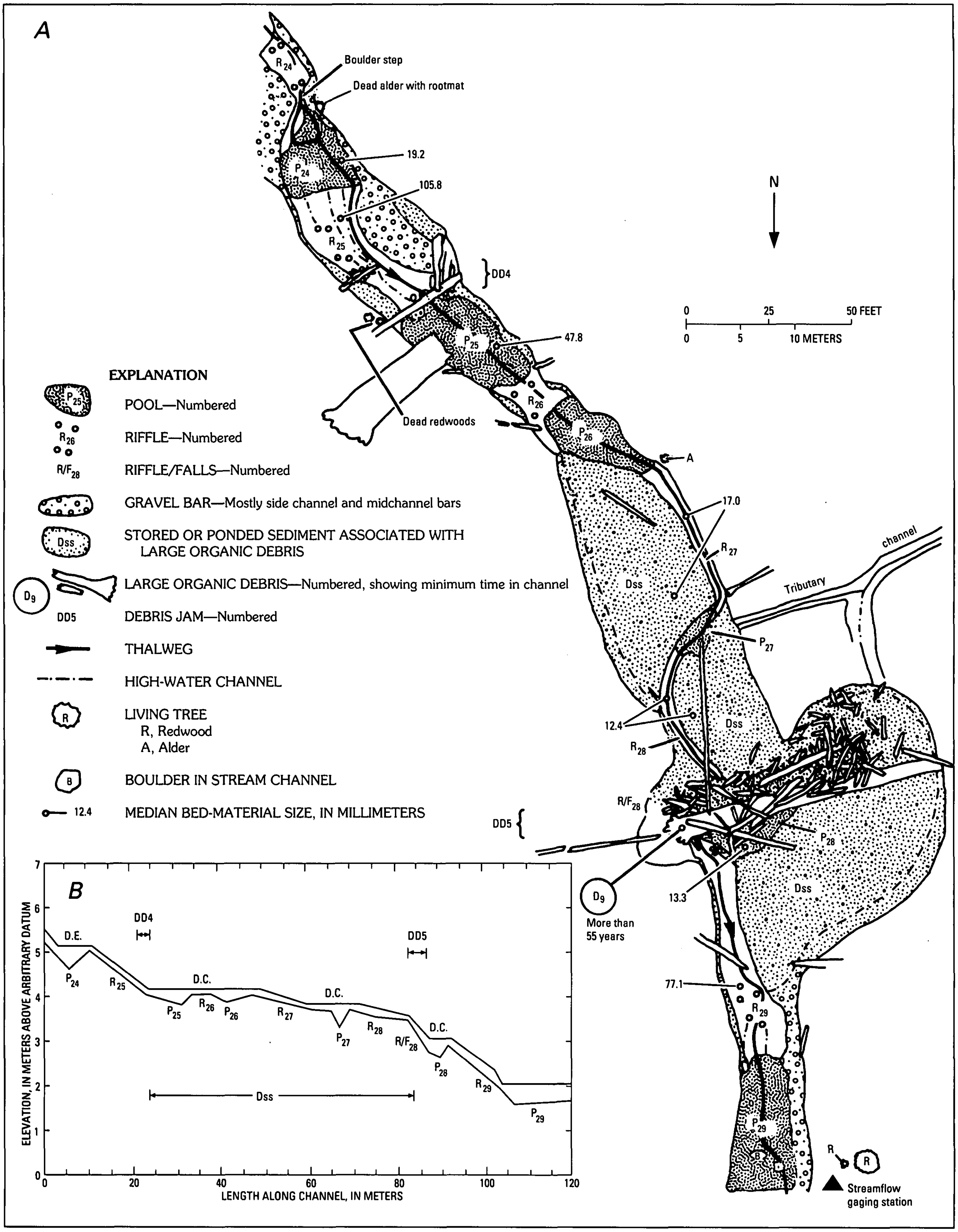

FIGURE 9.—*A*, Morphologic map and, *B*, Long profile of Little Lost Man Creek, lower reach (part), downstream from area shown in figure 8. Notice the marked channel widening associated with the debris dam and the finer particle size of the debris-stored sediment.

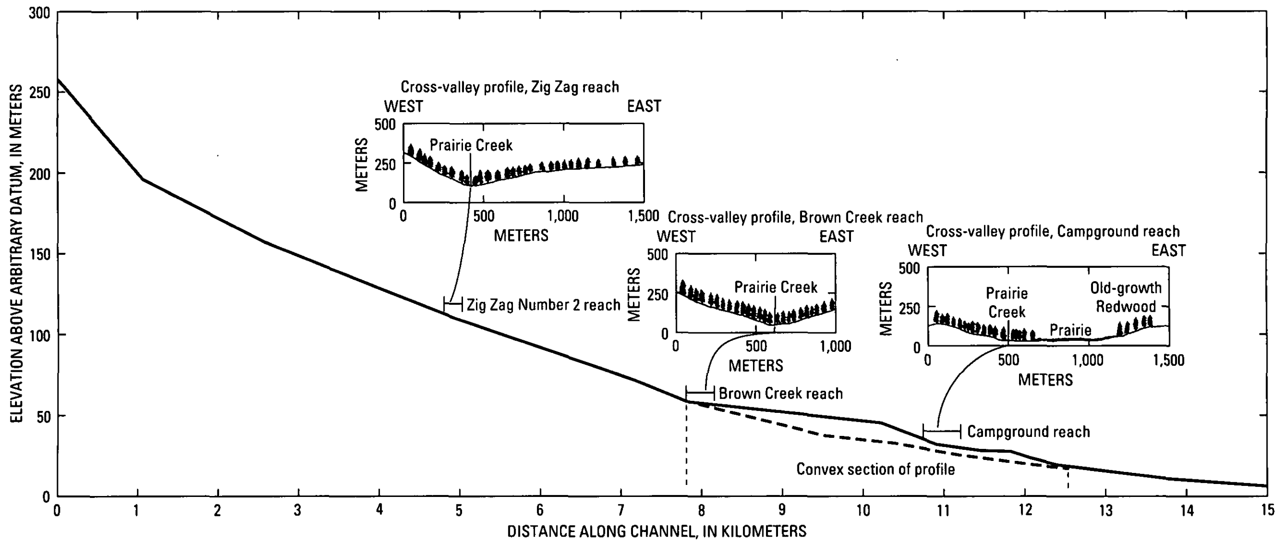

FIGURE 10.—Long profile of Prairie Creek showing the locations of study reaches discussed in this paper and cross-valley profiles at those reaches. Drawn from 7.5-minute topographic maps.

high debris loading at the Brown Creek reach is apparently directly related to both the number of redwood trees in the vicinity of the channel and local geomorphic conditions.

Marston (1982) reports that the frequency of log steps (not total debris loading) is greater for third-order streams than for second- or fourth-order streams. He believes that this situation results from the fact that the headward portions of streams may have V-shaped narrow valleys in which there is little likelihood of large organic debris actually falling in and blocking the active channel. Farther downstream in third-order streams, where valley sides are not as steep, it is more likely that debris actually reaches the channel; thus, there is a greater frequency of log steps. Certainly this hypothesis, although possibly reasonable for log steps, may not be generally true for total debris loading because often large organic debris in headwater reaches of streams do not form specific log steps, but rather the debris lie adjacent to the stream channel or extend only part way into the stream channel.

RESIDENCE TIME OF LARGE ORGANIC DEBRIS

Movement of large organic debris through the fluvial system is postulated to be primarily by flotation during high flows or perhaps, in very steep sections of some streams, by debris torrents (Swanson and Lienkaemper, 1978; Keller and Tally, 1979). Individual pieces of redwood debris in streams draining old-growth redwood forest (Prairie Creek, Hayes Creek, Little Lost Man Creek) may be very large, often several meters in diameter and several tens of meters long. Such large debris move only rarely and thus are semipermanent parts of the channel morphology. This conclusion was determined by examining trees such as hemlock, spruce, big-leaf maple, and redwood trees that grow on downed redwood trees. Coring of these trees provides a minimum time that the debris have been in the stream channel. Table 2 lists minimum residence times in Prairie Creek and Little Lost Man Creek for more than 30 pieces of debris. About half of these exceed 100 years, and the oldest exceeds 200 years, suggesting that large redwood debris may reside in the stream channel for at least several centuries.

CHANNEL MORPHOLOGY AND LARGE ORGANIC DEBRIS

Large organic debris in small- to intermediate-size forest streams significantly influences channel morphology. For example, a stream having an active channel width of several meters may have one entire bank, for a distance of several channel widths, completely formed and defended by a single downed redwood tree. (See fig. 3, *A–A′*.) The role of large organic debris is particularly significant in affecting channel width, depth, local slope, development of the long profile, and channel forms such as pools and riffles.

CHANNEL WIDTH

In many gravel-bed alluvial stream channels, the width of the active stream channel or bankfull channel

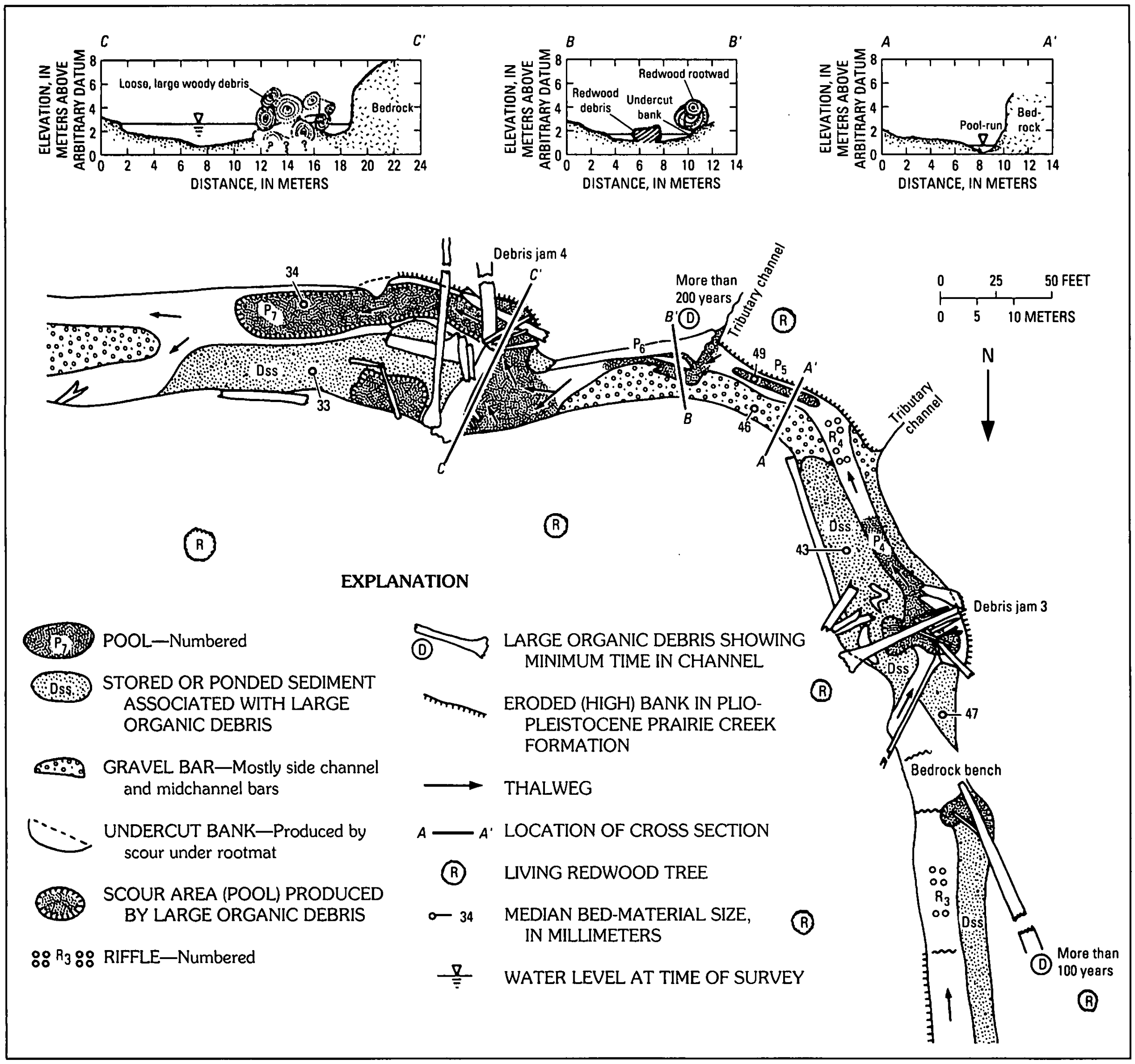

FIGURE 11.—Morphologic map of the Brown Creek reach of Prairie Creek (part). Reach location is shown in figure 2. Pool and riffle numbers correspond to those on the long profile shown in figure 19*B*.

width is relatively easy to measure, particularly at riffles where channel banks often are well defined. However, in many forested environments, large organic debris in the channel may make the definition of channel width difficult. The range of widths along a particular stream reach is often so variable that one or several measurements are nearly meaningless. The range of channel widths for selected study reaches of Little Lost Man Creek and Prairie Creek are shown on table 3, as are the mean widths of pools, riffles, and debris accumulations. To relate channel width to other variables such as upstream drainage area, we developed the "characteristic width," defined as the area of active channel in a reach divided by the channel length, as measured down the center line of the channel. Thus, the characteristic width is actually an average width over a reach. The length of reach measured is approximately 30 channel widths to ensure that several examples of various stream environments such as pools, riffles, and debris accumulations are included within the reach. As shown on table 3, the characteristic width is approximately the average width for pools and riffles (measured at their maximum width) but is quite different from the widths of debris accumulations. This disparity results because the channel width at a debris accumulation is often two or more times greater than the characteristic width of the channel. The characteristic width was measured at several locations in Prairie Creek, and the relation between width and drainage

TABLE 2.—*Minimum ages for large organic debris in the study reaches of Little Lost Man Creek and Prairie Creek*

[Study reaches are shown in figure 2]

Study reach	Tree type	Age (years)	Location[1]	Environment[2]
		Little Lost Man Creek		
Upper	Hemlock	130	Not shown	Partial D.D./ B.D.Tr.
	....do....	130	Fig. 7; P 2	Partial D.D./ B.D.Tr.
	....do....	150	Fig. 7; R 4	B.D.Tr. on debris-stored sediment.
	....do....	85	Fig. 7; P 4	D.D.
	....do....	185	Fig. 7; P 5	Partial D.D./ B.D.Tr.
	....do....	175	Fig. 4; P 11	D.D.
	....do....	200	....do....	D.D.
	....do....	70	Fig. 4; P 13	M.C.B. behind D.D.
	....do....	105	Fig. 4; P 14	D.D.
Lower	Alder	60	Not shown	M.C.B. behind D.D.
	Redwood	75	....do....	Log over stream.
	....do....	220	....do....	B.D.Tr. downed trunk.
	....do....	100	....do....	D.D.
	....do....	80	....do....	Partial D.D.
	Alder	70	....do....	M.C.B.
	Sitka spruce	22	....do....	Partial D.D./ B.D.Tr.
	....do....	35	Fig. 8; R 14	B.D.Tr.
	....do....	115	Fig. 8; P 16	D.D.
	Redwood	75	....do....	D.D.
	....do....	50	....do....	D.D.
	Sitka spruce	65	Not shown	D.D.
	....do....	40	....do....	B.D.Tr. downed trunk.
	Hemlock	20	....do....	B.D.Tr. downed trunk.
	Redwood	55	Fig. 9; P 28	D.D.
		Prairie Creek		
Zig Zag no. 2...	Sitka spruce	150	Fig. 3; P 3	B.D.Tr. with root mat.
	Maple	80	Fig. 3; P 6	D.D.
Brown Creek...	Redwood	160	Not shown	D.D.
	Hemlock	100	....do....	D.D.
	....do....	100	Fig. 11	Partial D.D.
	Redwood	>200	Fig. 11; P 6	B.D.Tr. downed trunk.
Campground ...	Redwood	50	Fig. 20; P 5	M.C.B. after D.D.
	....do....	100	....do....	Partial D.D.
	Hemlock	100	Fig. 20; P 6	B.D.Tr. with root mat.

[1] P=pool; R=riffle.

[2] Partial D.D.=debris dam blocking part of channel; B.D. Tr.=bank-defending tree; D.D.=debris dam blocking entire channel; M.C.B.=midchannel bar.

TABLE 3.—*Comparison of channel widths for pools, riffles, and debris accumulations for selected channel reaches*

Reach	Upstream drainage area (km^2)	Characteristic width[1] (m)	Mean pool width[2] (m)	Mean riffle width[2] (m)	Mean debris-jam width[2] (m)	Range of widths (m)
			Little Lost Man Creek			
Upper	3.5	6.4	7.1	6.6	8.1	2.4–15.6
Lower	9.1	9.6	10.8	11.4	17.2	2.0–24.0
			Prairie Creek			
Zig Zag no. 2..	8.2	6.7	7.3	5.6	15.0	3.0–15.0
Brown Creek..	11.2	11.0	7.0	8.3	16.1	6.5–20.0
Campground ..	27.2	18.5	20.1	16.0	25.5	10.0–31.0

[1] The characteristic (average) width is the area of the active channel in the study reach divided by the channel length.

[2] The mean widths of the pools, riffles, and debris jams are the average of the widths measured at the location of maximum width for each pool, riffle, or debris jam.

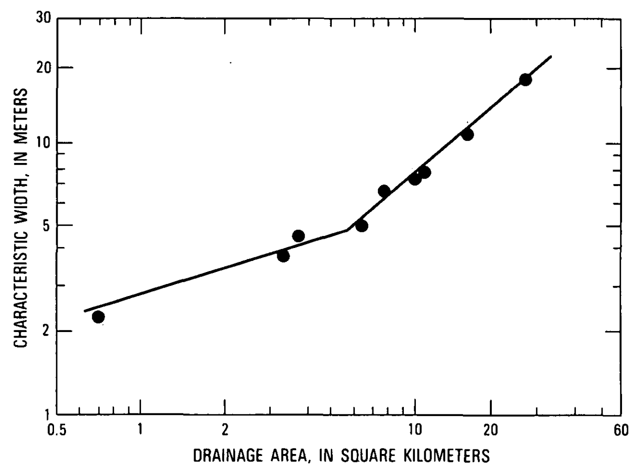

FIGURE 12.—Relation between characteristic channel width and drainage basin area for Prairie Creek.

basin area is shown in figure 12. These data suggest that, in the upper part of the Prairie Creek drainage basin, the rate of change of characteristic width with drainage area is less than that farther downstream. This is consistent with observations by Zimmerman and others (1967) and probably reflects the importance of bank vegetation in stabilizing channel width in the upper part of the basin. However, as the drainage basin area increases, discharge and thus stream power also increase until a threshold is exceeded and the rate of change in channel width with increasing drainage area increases. In Prairie Creek the threshold may be at about 6 km^2 as suggested by the apparent change in slope on figure 12.

Channel width is often greatest at the site of debris dams because such dams often produce horizontal divergence of flow away from the center of the channel, causing deposition of a midchannel bar (stored sediment) upstream from the debris dam. The bar diverts the flow toward the sides of the channel, producing bank erosion and a locally wider channel. A plunge pool may form at the base of the debris dam as in P_{28} at debris dam no. 5 (DD5) on figure 9. Here a large redwood trunk has fallen across the channel, and the local stream width has been significantly increased. Debris that extend across part of the channel are common and may also affect channel width. Figure 13, for example, shows a short reach of Hayes Creek that has been highly modified by a large redwood stem that is subparallel to the channel.

CHANNEL SLOPE, DEPTH, AND THE LONG PROFILE

Channel slope and depth are related to the long channel profile and thus will be discussed together. Channel slope, one of the important dependent variables in the fluvial system, is a function of several independent variables including mean annual discharge of water and sediment, bedrock type, and recent tectonic activity. These factors, and others, interact to produce a long profile that is adjusted to produce a compromise between least work and equal work (Leopold and Langbein, 1962). The long profile and slope of a channel tend to adjust over a period of years (Mackin, 1948) and thus reflect relatively recent adjustment of the stream channel. Hack (1957) noted that channel slope is adjusted to bedrock resistance in such a way that the steepest reaches are underlain by the most resistant rock. Our discussion here will focus on effects of bedrock geology and large organic debris on profile development.

The effect of varying rock type on local channel slope was investigated along Little Lost Man Creek, where several sedimentary rock types crop out (Tally, 1980). The long profile, from headwaters to a point several kilometers downstream, where bordered by old-growth redwood forest, was surveyed with a hand level and tape during the summer of 1978. Figure 14 shows a 500-m segment of this survey. The profile clearly demonstrates an adjustment between geology and channel slope. The channel slope is steepest where the stream flows over conglomerate and massive sandstone, of intermediate value where flow is over thin-bedded sandstones, and relatively gentle when flow is over relatively nonresistant shales. A significant variable affecting channel slope is the percentage of massive sandstone; the correlation coefficient between the two for the entire profile (fig. 15*B*) of Little Lost Man Creek is 0.81, significant at the 0.05 level. Thus, about 64 percent of the variability of channel slope may be explained by the variability of underlying rock type (Tally, 1980).

The long profile for Little Lost Man Creek, drawn from U.S. Geological Survey 7.5-minute topographic quadrangles, is shown on figure 15*A*; figure 15*B* shows much of the same profile as surveyed by hand level. The surveyed profile is approximately 10 percent longer for the same elevation change because it was measured along the thalweg rather than down the channel midline. Both profiles are convex, particularly in the central part. Convexity of a long profile may result from lithologic variability, tectonic uplift, or downstream decrease in discharge (Morisawa, 1968), and it is not an indicator of stream equilibrium or disequilibrium. Discharge increases in the downstream direction in Little Lost Man Creek. While tectonic control is possible (especially because of the proximity of Little Lost Man Creek to northwest-trending shears along the plate boundary between the American plate and Humboldt plate as hypothesized by Herd (1978) and Dott (1979)), probably most of the convexity of the profile is due to lithologic control. As discussed above, there is good agreement between the resistance of the rock and the slope of the stream channel. In the central part of the basin, where the percentage of massive sandstone is relatively large, the convexity is the greatest (fig. 15).

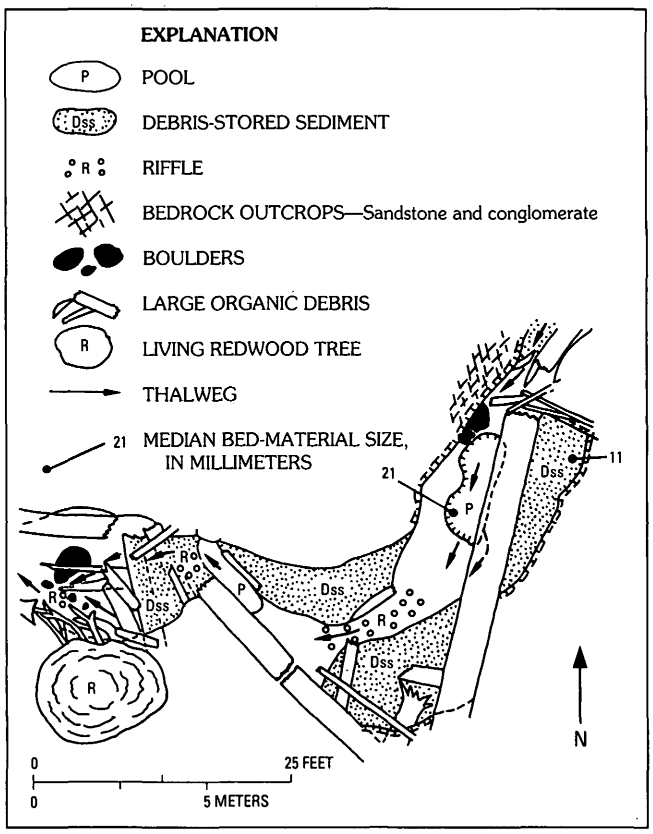

FIGURE 13.—Morphologic map of part of the Hayes Creek reach illustrating the potential stabilizing effect of large organic debris on channel banks.

On massive sandstone, which underlies approximately 43 percent of the surveyed channel, the average channel slope is 0.097 m/m, and 63 percent of the drop in elevation occurs. On thin-bedded sandstone, which underlies approximately 49 percent of the channel length, the average channel slope is 0.045, and 33 percent of the drop in elevation along the channel occurs. On shale, which underlies about 8 percent of the channel, the average slope is 0.029, and only about 4 percent of the drop in elevation occurs. These data are summarized in

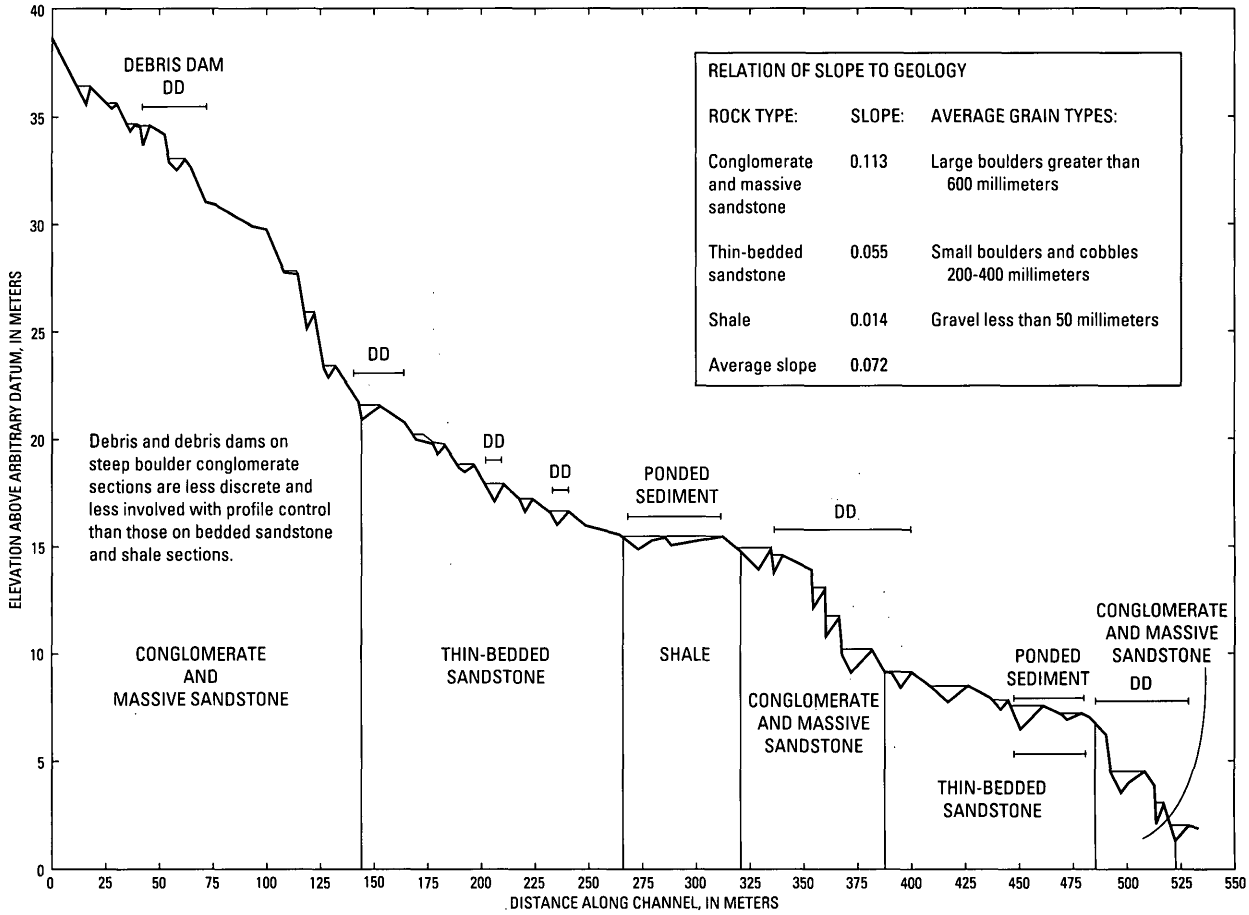

FIGURE 14.—Long profile of Little Lost Man Creek, upper reach, demonstrating adjustment of channel slope to the resistance of the underlying bedrock.

table 4 and further demonstrate the importance of lithologic control in influencing the convex profile of Little Lost Man Creek.

The average grain size of the bed material in the stream is also related to the bedrock type and channel slope (see fig. 14). The largest boulders are found in the steepest part of the channel where it is cut in massive sandstones and conglomerates. Smaller boulders and cobbles are associated with the thin-bedded sandstones and moderate channel slopes, and the smallest gravel is found at the gentler slopes on shale. This relation has been demonstrated in detail by Hack (1957) in his study of the long profiles of streams in Virginia and Maryland.

Effects of debris on the channel profile are shown also on figure 14. Notice that 59 percent of the decrease in elevation along the channel is associated with organic steps or debris dams. Furthermore, for some of the large accumulations there is extensive ponded or stored sediment upstream from the debris. However, in Little Lost Man Creek, it was also observed that debris dams on some of the steeper sections, where the channel is in

TABLE 4.—*Influence of rock type on channel slope, Little Lost Man Creek*

[From Tally, 1980]

Rock type	Length of channel controlled (m)	Percent length	Change in elevation of channel (m)	Percent change	Average slope
Massive sandstone	2,265	43	219.2	63	0.097
Thin-bedded sandstone	2,580	49	115.5	33	.045
Shale	445	8	13.3	4	.029
Total	5,290	100	348.0	100	0.066 (avg)

conglomerate, have less effect on the thalweg profile than do dams on the less resistant shale and sandstone. This situation occurs because bed material in the steeper reaches of Little Lost Man Creek often consists of very large boulders, and the large organic debris rest on these boulders, above the active stream channel.

Steep-gradient sections of Little Lost Man Creek and Hayes Creek often contain waterfalls interspersed with riffles. We have designated these sections as riffle/falls. Waterfalls over woody debris or rock outcrops often form pools.

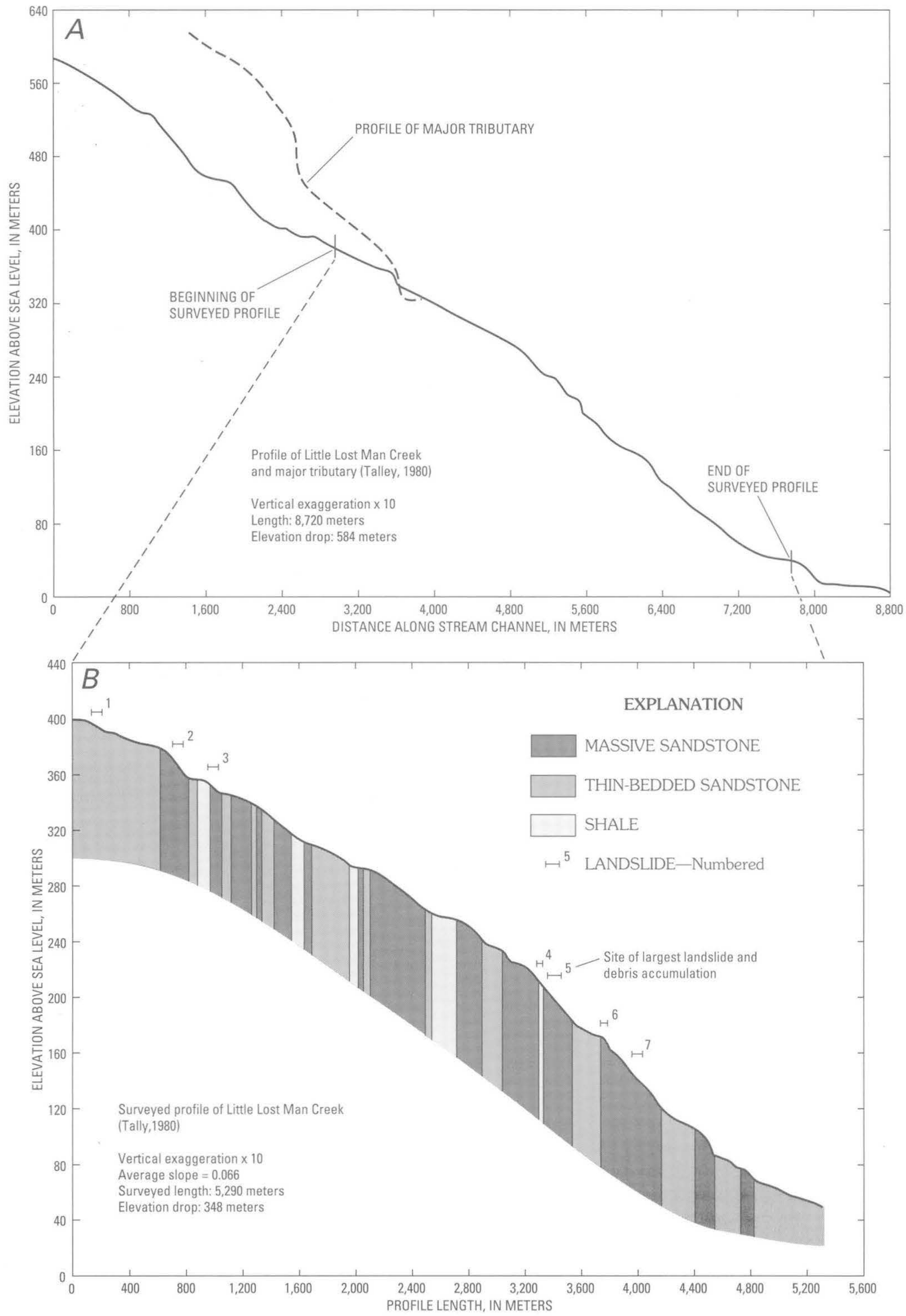

FIGURE 15.—*A*, Long profile of Little Lost Man Creek, drawn from 7.5-minute topographic maps. *B*, Surveyed profile of Little Lost Man Creek showing distribution of rock types along the channel.

Variations in channel depth were analyzed on detailed long profiles of the study reaches. In Little Lost Man Creek and Hayes Creek, the role of large organic debris in increasing the variability of channel depth is very pronounced. Figures 16, 17, and 18 show profiles for the upper and lower reaches of Little Lost Man Creek and

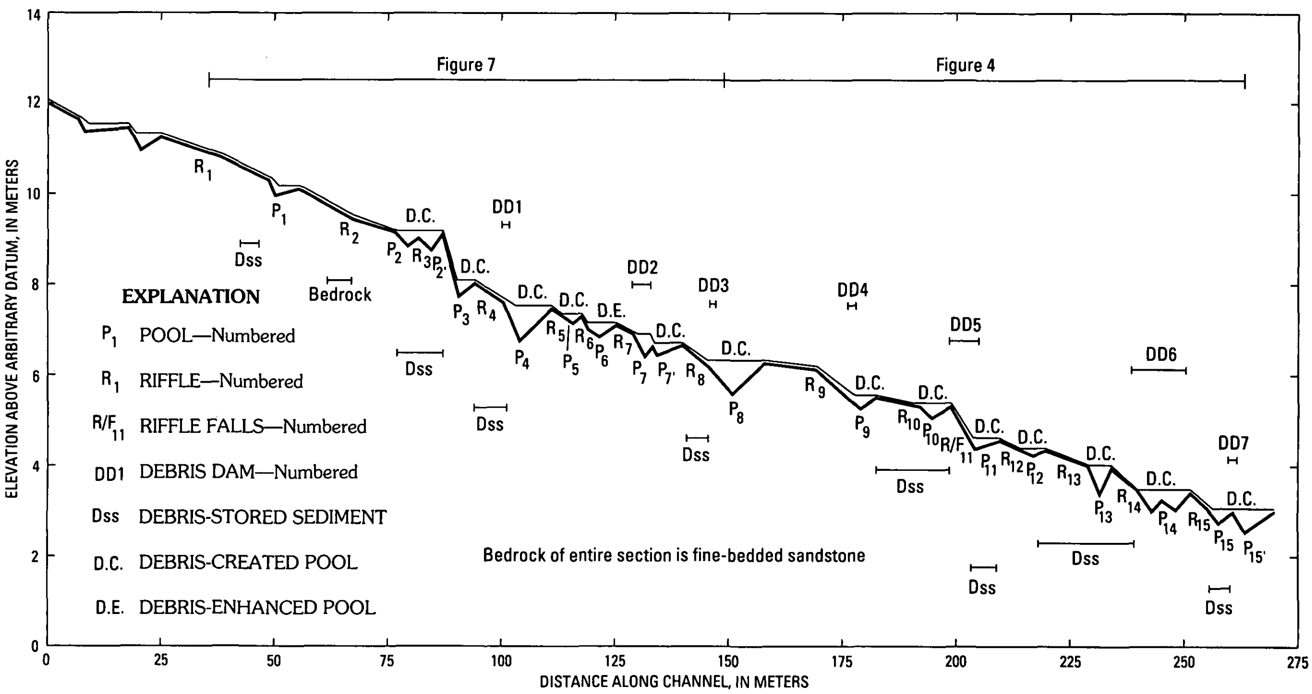

FIGURE 16.—Long profile of Little Lost Man Creek, upper reach. Corresponding morphologic maps are shown in figures 4 and 7.

the study reach for Hayes Creek and demonstrate some of the variability associated with large organic debris. In the upper reach of Little Lost Man Creek, debris are discrete and numerous, creating organic steps and a variety of channel depths (Keller and Tally, 1979). Similarly, the long profile for Hayes Creek (fig. 18) demonstrates the variability of depth produced by interactions among large organic debris, rock outcrops, and channel morphology. A series of organic steps produces a stream profile characterized by relatively long sections of stored sediment with relatively low gradient. These long sections alternate with short, steep cascades or falls spilling into a scour or plunge pools.

Large organic debris cause a less pronounced variation of water depth in Prairie Creek than in Little Lost Man Creek or Hayes Creek, because Prairie Creek has a lower gradient and tends to meander more. Pools and riffles are well developed, and in the lower reaches up to 50 percent of the pools form independently of large organic debris (see table 1). Profiles for three of the study reaches along Prairie Creek are shown on figure 19.

The stepped profile associated with large organic debris is important because loss of potential energy takes place at cascades or falls, thus reducing the energy available to erode the streambed and banks (Keller and Tally, 1979). Examination of table 1 reveals that a significant amount of the total decrease in elevation along a channel may be controlled by large organic debris, either in the form of organic steps or complex accumulations of stems and rootwads. Furthermore, this effect significantly decreases with decreasing channel slope in undisturbed reaches (rank-sum correlation $r=0.81$, significant at the 0.005 level) and also decreases as drainage basin area increases or along reaches where the channel is bordered by flats that reduce the input of large organic debris to the channel. For the steeper and smaller channels, the percent drop in elevation is approximately 30 to 60 percent. This drop is consistent with the results of Heede (1972), who concluded from studying small steep mountain streams that cumulative height of the steps in some cases nearly equals the total fall of the stream along a particular study reach. In contrast, Marston (1982) studied 163 km of streams in central Oregon and concluded that log steps accounted for only about 6 percent of the total decrease in elevation of the stream channels. Some of the discrepancy can be accounted for by the fact that Marston considered only log steps that completely block the stream channel, whereas Heede considered organic debris that were not fully incorporated into the channel but that were affecting flow and causing some storage of sediment. Furthermore, the average spacing of log steps in the streams that Marston studied was several hundred meters, compared to only a few meters in those studied by Heede. For the present study, the percentage of decrease in channel elevation associated with organic debris includes organic steps that block all or part of the stream and

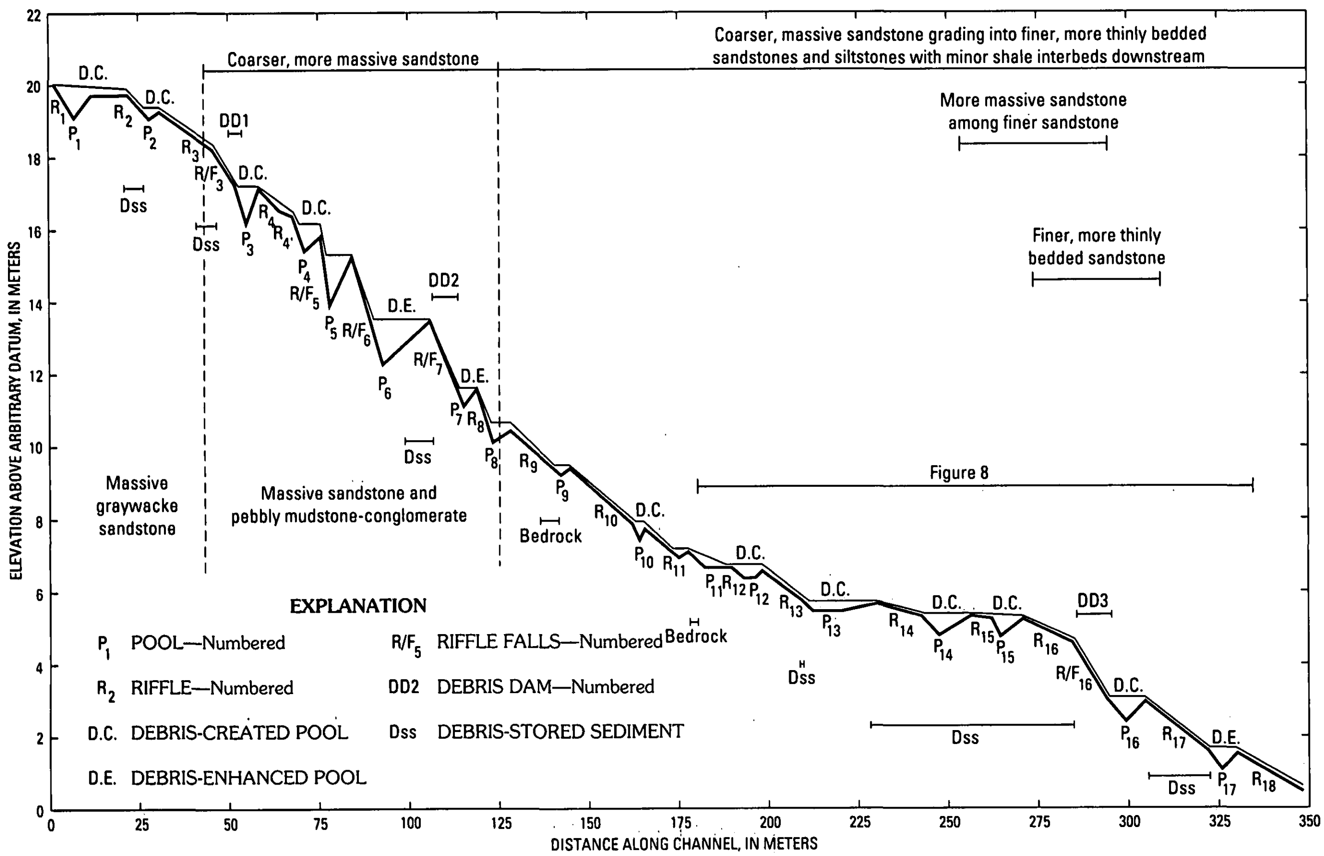

FIGURE 17.—Long profile of Little Lost Man Creek, lower reach (upper 60 percent of study reach). Corresponding morphologic map is shown in figure 8.

complex accumulations of debris that are associated with a drop in elevation of the streambed. Thus, the three studies are not directly comparable. Nevertheless, the conclusion remains that a significant amount of energy loss is associated with turbulent dissipation through debris jams and organic steps and that this energy might otherwise be dissipated in eroding channel bed and banks.

In Prairie Creek, the percentage of channel drop associated with large organic debris varies from less than 1 percent in the lower reaches to as much as 43 percent in the headwaters. Thus, as with debris loading, there is a general tendency for the percentage of decrease in elevation along a channel associated with large organic debris to decrease as the drainage basin area increases.

POOLS AND RIFFLES

Pools and riffles are major morphologic elements of streams that tend to be spaced at about five to seven channel widths along the length of the channel. However, if substantial inhomogeneity in bed or bank material is present to form large rough elements (obstacles to flow such as large boulders, bedrock outcrops, and large organic debris), then these may cause scour and thus control size, location, and spacing of pools (Lisle and Kelsey, 1982). Material scoured from the pools is deposited downstream in riffles and also in bars, which may or may not be stable.

Observations and measurements of channel morphology that forms during relatively high channel-forming flows were made during the summer low-flow periods. Thus we recognize that the distribution of pools, riffles, and other channel features observed during low flow are relics of the higher channel-forming discharges.

The effect of organic debris on pools is shown by the percent of pool morphology (area of active channel) influenced or enhanced by debris and by the pool-to-pool spacing, both of which vary strongly with slope in undisturbed reaches (table 1*A*). Rank-sum correlation of these values shows that the percent debris-influenced pool morphology increases with increasing channel slope ($r=0.78$, significant at the 0.008 level), while the pool-to-pool spacing increases with decreasing channel slope ($r=-0.62$, significant at the 0.06 level). In study reaches impacted by recent timber harvesting, similar but

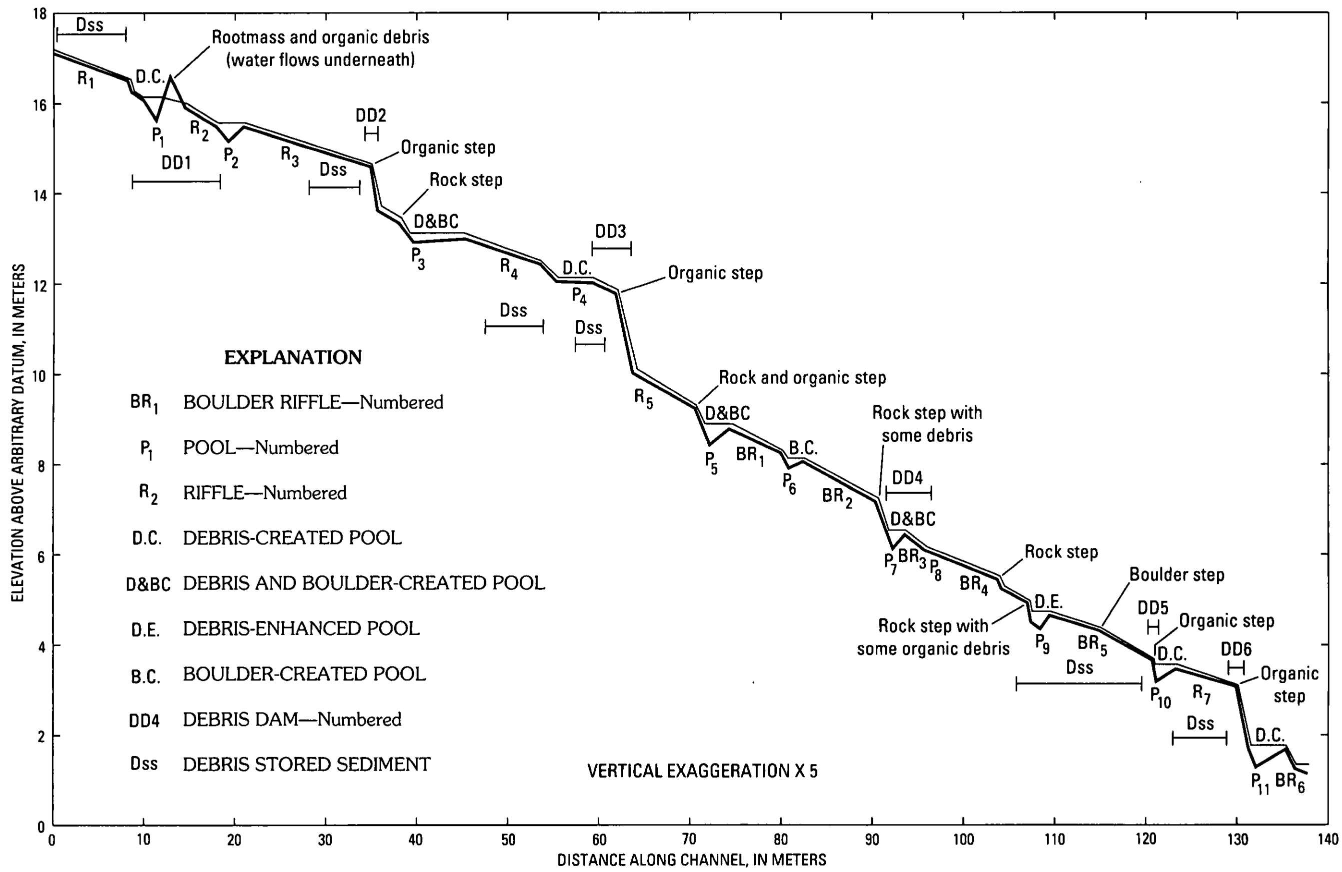

FIGURE 18.—Long profile of Hayes Creek.

weaker correlations are found among upstream channel area, the independent variable, and both debris-influenced pool morphology and pool-to-pool spacing.

In low-gradient streams such as Prairie Creek, pools may form by scour during relatively high channel-forming flows without the influence of large organic debris. Other pools in Prairie Creek are influenced or enhanced by large organic debris. Large organic debris may enhance a pool by forming a buttress along the outside bank and fixing the location of the pool for a long time. An example of such a pool is found along the Campground reach of Prairie Creek (see pool 6, fig. 20). The large rootwad on the right bank has been in that location for more than 100 years, and a very large pool has developed. This pool has water several meters deep during the summer and provides excellent habitat for juvenile anadromous fish. Other pools enhanced by large organic debris are shown on figure 11, which is a morphologic map of part of the Brown Creek reach of Prairie Creek. Pools 4, 6, and 7 are all enhanced by large organic debris. Notice that the log defending pool 6 has been in the stream channel for more than 200 years.

Farther upstream in the Brown Creek reach, there has been a significant change in the basic channel morphology. Figure 21 shows a sketch map of that section as it was in 1978 and changes that occurred in 1979 to produce the 1980 morphology. A large redwood tree on the left bank shown in the 1978 map fell into the stream channel in 1979, blocking the flow. The channel has been adjusting to the input of the new debris, and a period of a few years might be required before the channel returns to stable conditions. Interestingly, the addition of this one large redwood trunk to the stream has increased the debris loading in the Brown Creek reach by approximately 40 percent. (The new debris loading is not shown on table 1, which contains only data during the 1978 field season; we have not been able to remeasure the debris loading in all the stream reaches for comparative purposes.) The 1978 value of debris loading for the Brown Creek reach also was used in all the calculations and comparisons in this study. The addition of the new debris is mentioned because of its significance to the change in morphology of the stream channel.

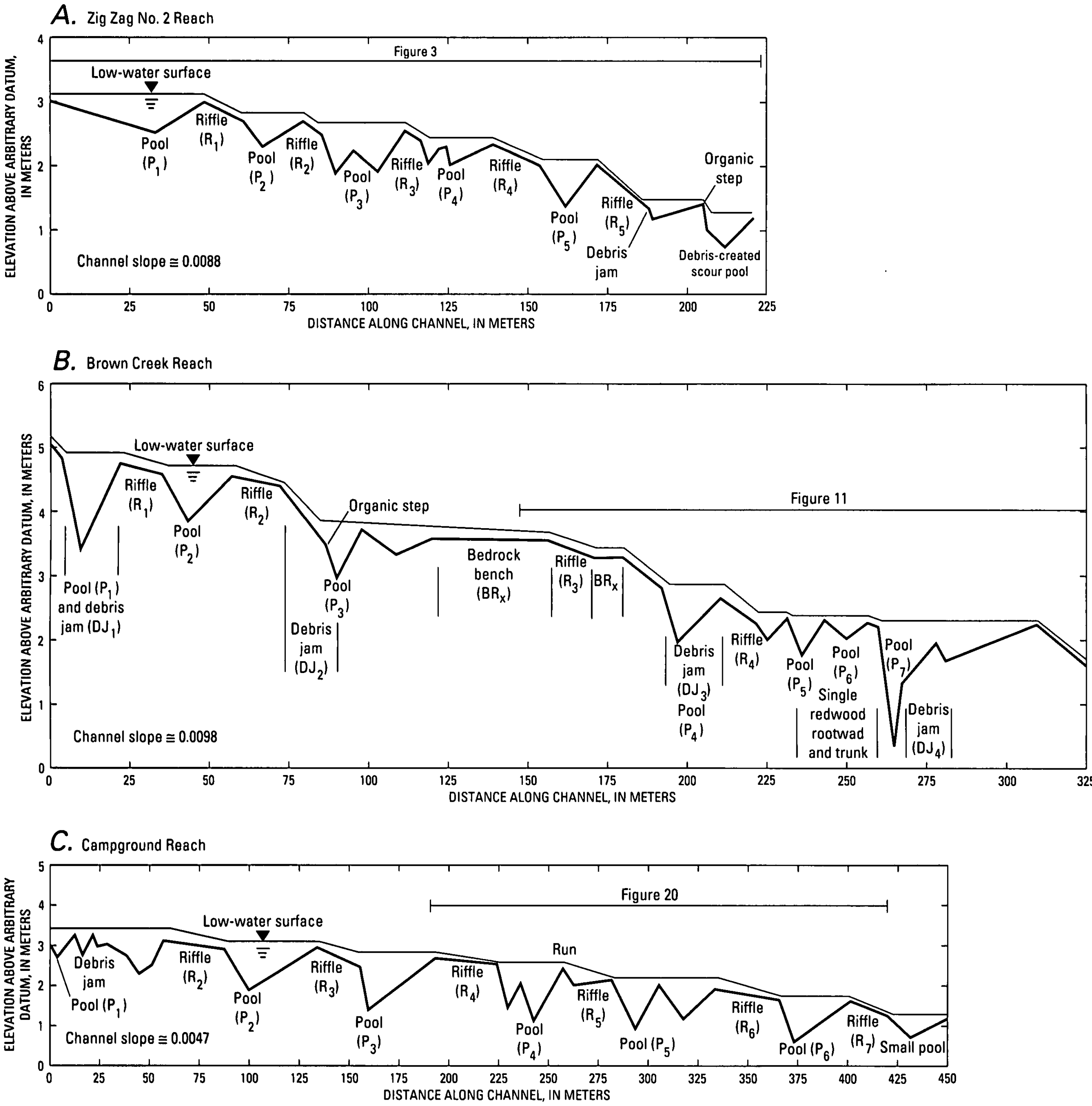

FIGURE 19.—Long profiles of selected reaches along Prairie Creek. *A*, Zig Zag no. 2 reach; *B*, Brown Creek reach; and *C*, Campground reach. Corresponding morphologic maps are shown in figures 3, 11, and 20.

In summary, nearly all the pools in the upper reaches of Prairie Creek are either produced directly by large organic debris or are influenced by it, and in the lower reaches 50 percent of the pools are influenced by large organic debris (table 1). Spacing of pools in Prairie Creek is more variable than in alluvial channels not influenced by debris owing to the influence of large organic debris. Pool spacing is generally two to six times the channel width in Prairie Creek compared to five to seven channel widths for gravel-bed streams in other environments (Leopold and others, 1964; Keller and Melhorn, 1973). Spacing of pools in the upper reaches of Prairie Creek is directly related to the spacing of large organic debris. Farther downstream near Campground reach, pools may form independent of large organic debris. That is, the pools begin to develop a scour-fill pattern similar to the general case of alluvial channels, which is different from the processes that form pools as a result of organic steps.

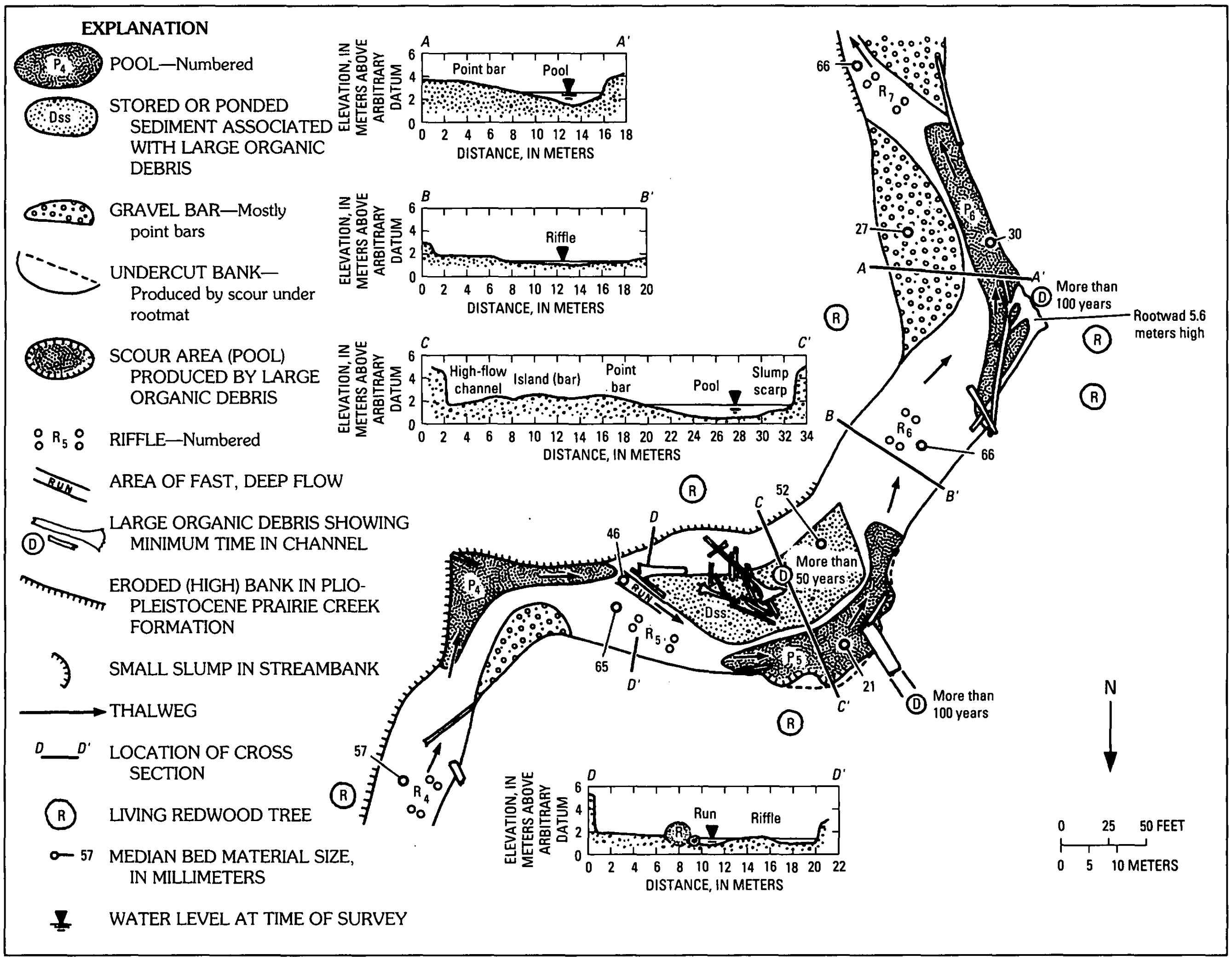

FIGURE 20.—Morphologic map of Prairie Creek, Campground reach (part), showing the pronounced effects of large organic debris on pool formation and the areal sorting of bed material, even at low levels of debris loading.

In Hayes Creek and Little Lost Man Creek, nearly all of the pools are either formed directly or significantly influenced by large organic debris. Most remaining pools are formed adjacent to bedrock outcrops or large boulders. Average spacing of pools in Little Lost Man Creek is about two times the channel width. This spacing of pools reflects spacing of large roughness elements and the fact that, in these small steep streams, organic steps are important in controlling local erosion and depositional patterns. Thus, the pool environment in Little Lost Man Creek and Hayes Creek, and the upper reaches of Prairie Creek, are characteristic of mountain streams described by Heede (1972, 1981), Swanson and Lienkaemper (1978), and Swanson (1981), whereas the pool environment in the lower part of Prairie Creek is more similar to that observed in meandering gravel-bed alluvial streams lacking significant large organic debris.

The pool environment is of particular importance to fish because the deep water, particularly in the summer, provides necessary cover and living space for young fish. Furthermore, pools that have undercut banks provide additional habitat. In Prairie Creek, some pools have undercut banks that extend several meters beneath root mats (see, for example, pool 3, fig. 3). The percent of the active channel area with undercut banks may be as high as 3 to 4 percent in some reaches of Prairie Creek, Hayes Creek, and Little Lost Man Creek (table 1). Actual percentage of channel area (at low flow) in pools varies from 12 percent in Hayes Creek to about 20 percent in Little Lost Man Creek and as high as about 50 percent in Prairie Creek. There is no clear relation between channel slope and the percentage of the active area in pool, but it is clear that, if large organic debris were not present in some of the steeper reaches, there would be considerably less pool environment.

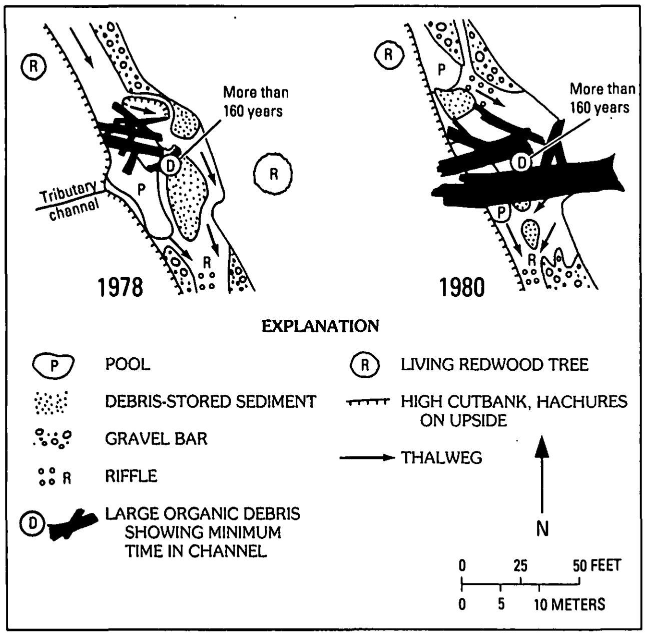

FIGURE 21.—Channel changes in part of the Brown Creek reach of Prairie Creek following the addition of a large redwood trunk.

Riffles are topographic high areas in the channel produced at channel-forming flows (bankfull flow and greater) by processes of deposition of relatively large bed material. Riffles are important to anadromous fish as spawning habitat. The intergranular flow of water is greatest at drops in the water surface profile as on riffles, providing oxygen-rich water to developing fish eggs buried in spawning gravel. In Hayes and Little Lost Man Creeks, the percentage of active channel at low flow covered by riffles varies from 15 to 26 percent. In Prairie Creek, the percentage of area covered by riffles varies from approximately 15 to almost 50 percent (table 1*A*).

LATERAL MIGRATION

In steep streams such as Hayes Creek and Little Lost Man Creek, there is little lateral migration of the stream channel owing to the very steep valley walls adjacent to the channel. On the other hand, one might expect thatPrairie Creek, because it has a relatively low gradient with well-developed pools and riffles and numerous meander bends, would migrate laterally in its flood plain as do many meandering streams. This does not seem to be the case, however.

Lateral migration was studied by mapping the distribution of large living redwood trees near the channel. Estimates of the ages of these trees were determined by first counting the rings of large downed trees in the vicinity to determine a rough diameter-age relation for the local environment. This age relation was then used to date the living trees in the vicinity of the stream channel. The diameters and ages of three downed trees are 1.9 m, 568 years; 2.2 m, 898 years; and 2.8 m, 1,006 years. Therefore, it is conservatively estimated that living trees in the same environment with diameters of 3 to 5 m are at least 800 to 1,000 years old. Locations of these trees suggest that in several instances lateral migration of Prairie Creek has been less than one channel width in the last several hundred to 1,000 years. This apparent lateral stability does not mean that there is no change in the position of the channel with time. Meander cutoffs have occurred at some locations along Prairie Creek, but they appear to be fairly rare events. In several locations, abandoned channels were observed along Prairie Creek in areas of old-growth redwood. What may occur is that the stream periodically abandons one channel for another without a meander cutoff—that is, stream position may jump to an adjacent high water chute rather quickly, abandoning the old channel without lateral erosion. Debris jams have been shown to hasten such changes elsewhere (Keller and Swanson, 1979), and it is reasonable to assume that they could trigger sudden channel shifts in Prairie Creek as well. However, our work has not yet documented such occurrences. The strongest evidence for the lack of lateral migration is the redwood trees that grow in close proximity to the channel. When two large old-growth trees are located adjacent to both banks (see fig. 20 near sections *A–A′* and *C–C′*), then one may presume that the channel has been between the trees at least as long as the trees have been in their present location.

SEDIMENT STORAGE AND ROUTING: THE BUFFER SYSTEM

Large organic debris play a significant role in the routing and storage of sediment. Debris such as organic steps or more complex debris jams produce sediment storage compartments. Forested streams with a high debris loading may have many such compartments. Morphologic maps (figs. 3, 4, 7, 8, 9, 11, 13, and 20) show several examples of stored sediment found along Prairie Creek, Little Lost Man Creek, and Hayes Creek.

Newly formed organic steps and debris dams produce "open" sediment storage sites that collect sediment during high-flow events when bedload is transported. The storage site fills because the available stream power is less than the critical stream power necessary to transport the load at that location (fig. 22*A*). As the water flows over the organic step or accumulation, the available stream power exceeds the critical stream power, and so a plunge pool develops; immediately downstream, the available stream power may again be less than the

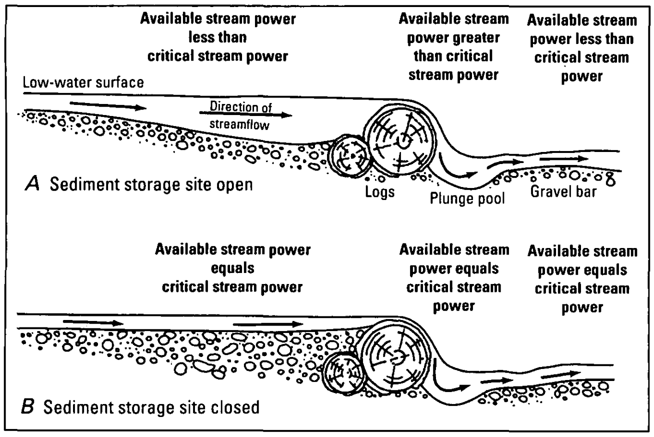

FIGURE 22.—Distribution of available (ωa) and critical (ωc) stream power over an organic step (*A*). This distribution changes to allow substantial sediment transport over the step if the upstream storage compartment is filled (*B*).

critical amount, and a bar may form (fig. 22*A*). As the sediment storage site becomes filled, the available stream power eventually becomes equal to the critical stream power, and sediment is transported through the storage site without net deposition (fig. 22*B*). Thus equilibrium of action is reached, and sediment is pumped through the system. This explanation involves the utilization of the "threshold of critical power," which is based on the ratio of available to critical stream power (Bull, 1979).

The distribution of stream power over a single organic step with a filled upstream storage compartment is shown in figure 23. At the highest discharge measured in Larry Damm Creek, 95 percent of bankfull discharge, stream power was much more evenly distributed through the reach than at lower discharges, and predominantly sand-sized material was transported across the entire width of the active stream channel. The more evenly distributed stream power and pattern of sediment transport shown on figure 23 support the general model for a filled sediment storage site (fig. 22*B*).

Debris accumulations can reside in the channel for long periods of time, but they eventually do rot and wash out or else are removed by floods. New accumulations are periodically being formed, while others are maintained, and still others destroyed. Thus, the pattern of sediment transport through channels containing large organic debris may be complex and difficult to accurately determine (see Mosley, 1981).

An important generalization about debris-stored sediment is that the storage sites create a buffer system that modulates the movement of bed-material load through the fluvial system. As a result, the output of sediment from the watershed will be spread out over a relatively

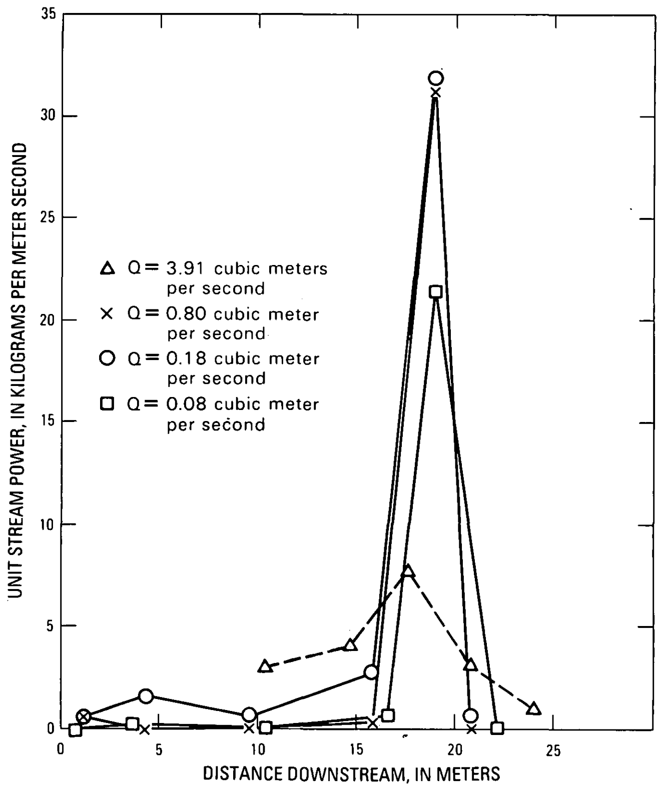

FIGURE 23.—Change in distribution of unit stream power with change in discharge over a simple organic step on Larry Damm Creek, which is 18.5 m below the head of the reach. Upstream storage compartment is filled. *Q*, discharge.

long period, even though the sediment may have been input during a short period of time. Because it will cause a lag time between input and output of sediment from the basin, the sediment buffer system has important ramifications for watersheds affected by land use changes that increase the sediment yield. If the buffer system is overwhelmed by sediment input and storage sites are filled, however, then sediment will be transported through the channel at higher rates than when the buffer system was operative.

That debris is effective in buffering high sediment input to the channel is suggested by examining the areal extent of debris-stored sediment in both disturbed and undisturbed basins. In undisturbed basins, the areal extent of debris-stored sediment increases with increase in reach slope (rank-sum correlation r=0.91, significant at the 0.0002 level). However, the mean area in debris-stored sediment is higher in channels draining disturbed basins than in those draining undisturbed basins (40 percent compared to 30 percent), suggesting that more of the potential storage is filled in basins affected by timber harvesting.

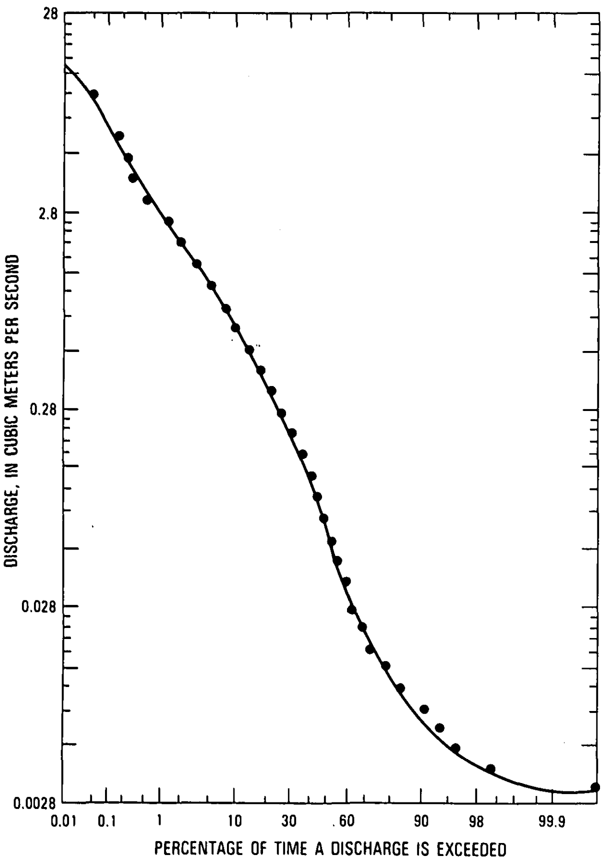

FIGURE 24.—Flow-duration curve for Little Lost Man Creek.

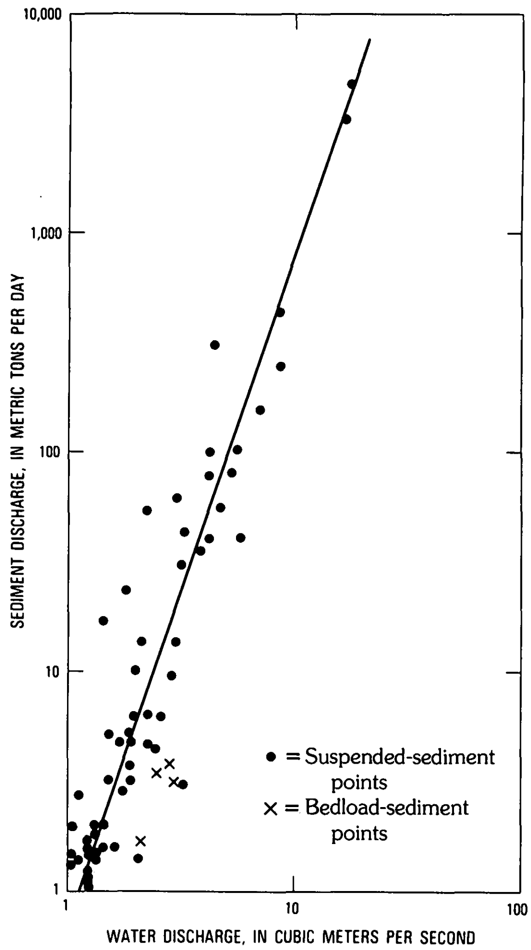

FIGURE 25.—Sediment-rating curve for Little Lost Man Creek.

The volume of the sediment buffer system for Little Lost Man Creek was evaluated by estimating the amount of debris-stored sediment in the stream channel and comparing this with the estimate of mean annual bedload transport (Tally, 1980). Several uncertainties are involved with the evaluation of the sediment buffer system, but estimates of volume are probably accurate within an order of magnitude. First, we assume that the amount of debris-stored sediment may be calculated from the observation that about 40 percent of the streambed is covered by debris-stored sediment to a depth of at least 0.35 m. This percentage for the areal extent of debris-stored sediment was observed on both study reaches on Little Lost Man Creek and for the study reach on Hayes Creek, all of which have channel slopes greater than 0.03 (see table 1). The estimate of average depth of debris-stored sediment is conservative, as many such accumulations are significantly thicker than 0.35 m, which is the depth of scour (in debris-stored sediment) observed by means of scour chains after winter storms (1978–79). A second assumption is that the annual bedload transport rate is about 25 percent of the annual rate of suspended load transported from the basin. Annual suspended sediment discharge for Little Lost Man Creek was computed by using the flow-duration curve (fig. 24) and sediment-rating curve (fig. 25), following the procedure outlined by Strand (1975). The average annual discharge of suspended sediment for water years 1975 to 1979 is approximately 50.2 (Mg/km^2)/yr, a value in close agreement with that of Nolan and Janda (1981), who determined that annual suspended sediment yield for Little Lost Man Creek was approximately 52 (Mg/km^2)/yr for water years 1973 to 1976. Only six measurements of bedload were made during the 5 years of available stream-gage data. The bedload yields range from 6 to 58 percent of the suspended load with an average of 25 percent. Thus, we assume that the bedload is approximately 25 percent of the suspended load, or approximately 13 (Mg/km^2)/yr. The unit weight of debris-stored sediment, which consists mostly of gravel and sand, is assumed to range from 1.36 to 2.00 Mg/m^3, values recommended by Geiger (1965) for these types of materials.

TABLE 5.—*Kruskal-Wallis one-way analysis of variance for pebble-count data from Little Lost Man Creek*

[From Tally, 1980]

Environments tested	Size fraction	pHo > chi-square	Ho[1]
Upper reach			
Pools, riffles, debris-stored sediment, bars..	D_{10}	$p=0.28$	A
....Do....	D_{50}	$p<0.01$	R
....Do....	D_{90}	$p<0.002$	R
Lower reach			
Pools, riffles, debris-stored sediment	D_{10}	$p<0.01$	R
....Do....	D_{50}	$p<0.002$	R
....Do....	D_{90}	$p<<0.001$	R

[1] Ho=null hypothesis of no significant difference between the samples. A=accepted. R=rejected.

The average annual suspended sediment yield for Little Lost Man Creek drainage basin is about 450 Mg, and the bedload yield is about 25 percent of this, providing an annual bedload yield of approximately 113 Mg. The total available debris-related sediment volume in Little Lost Man Creek is estimated from field observation to be approximately 14,000 m^3 (19,000–28,000 Mg), and approximately 64 percent, or 8,960 m^3 (12,000–18,000 Mg), of this volume if presently full (Tally, 1980). Using the above assumptions, approximately 100 to 150 years of average bedload sediment yield is stored in debris-related sites along Little Lost Man Creek, and about 50 to 100 years of average bedload yield is available for future storage. Thus, if the storage system was filled to capacity, it would contain a volume equivalent to 150 to 250 years of average annual bedload. These estimations should not be interpreted to mean, however, that the sediment storage compartments associated with large organic debris effectively trap all of the bedload that moves into a particular reach.

Debris-stored sediment tends to be significantly finer than that found on riffles on Little Lost Man Creek. Tables 5 and 6 summarize the results from statistical analysis of pebble-count data for the upper and lower study reaches of Little Lost Man Creek (Tally, 1980). These data suggest that, for both the D_{50} and D_{90} particle sizes, there are significant differences between the materials found on riffles and those found associated with debris-stored sediment. Furthermore, the differences between the size of bed material in pools and in debris-stored sediment is generally not significant; this is expected, because both debris and pools tend to trap finer sediment during similar flow events. Because debris-stored sediment tends to be finer, it is transported more frequently in response to moderate flow. On the other hand, coarse material on riffles tends to armor the bed and is probably moved only during more extreme events. For example, the threshold for bedload transport of the D_{90} fraction of debris-stored sediment past the

TABLE 6.—*Mann-Whitney U-test for pebble counts from Little Lost Man Creek*

[From Tally, 1980]

Environment tested	Size fraction	pHo will occur two-tailed	Ho[1]
Upper reach			
Riffles vs. pools	D_{50}	<0.10	A
Debris-stored sediment vs. pools	D_{50}	>>0.10	A
Bars vs. pools	D_{50}	>>0.10	A
Debris-stored sediment vs. riffles.........	D_{50}	=0.02	R
Bars vs. riffles	D_{50}	>0.10	A
Debris-stored sediment vs. bars..........	D_{50}	=0.328	A
Riffles vs. pools	D_{90}	>0.10	A
Debris-stored sediment vs. pools	D_{90}	<0.02	R
Bars vs. pools	D_{90}	<<0.05	R
Debris-stored sediment vs. riffles.........	D_{90}	<0.02	R
Bars vs. riffles	D_{90}	<<0.02	R
Debris-stored sediment vs. bars..........	D_{90}	=0.838	A
Lower reach			
Pools vs. riffles........................	D_{10}	<<0.02	R
Pools vs. debris-stored sediment	D_{10}	>>0.10	A
Debris-stored sediment vs. riffles.........	D_{10}	<0.05	R
Pools vs. riffles........................	D_{50}	<0.02	R
Pools vs. debris-stored sediment	D_{50}	>0.10	A
Debris-stored sediment vs. riffles.........	D_{50}	<<0.002	R
Pools vs. riffles........................	D_{90}	<0.02	R
Pools vs. debris-stored sediment	D_{90}	<<0.05	R
Debris-stored sediment vs. riffles.........	D_{90}	<0.002	R

[1] A=Accepted; R=rejected. Ho=null hypothesis of no significant difference between two environments.

[2] D_{10}'s for Little Lost Man Creek, Upper, not tested, as no significant difference was found between environments under Kruskal-Wallis analysis. (See table 5.)

Little Lost Man Creek gaging station during the 1978 water year was 30 percent of bankfull discharge, a flow equaled or exceeded 3 percent of the time (Tally, 1980). When debris-stored sediment is mobilized, it probably moves from one storage site to another, as observed by Mosley (1981).

RELATION OF LARGE ORGANIC DEBRIS TO THE MANAGEMENT OF ANADROMOUS FISH HABITAT

In the management of streams to maximize production of anadromous fish in the coastal redwood environment, the role of large organic debris in the entire fluvial system should be considered. The recommendations that follow are based upon observations made in the Redwood Creek basin. Occasionally, large organic debris may block fish migration and cause adverse channel erosion. Such accumulations (especially when delivered to the stream channel in response to land use change) should be removed following the development of a specific plan for that site. However, within limits, large organic debris are necessary for a biologically productive stream environment (Swanson and others, 1976). Therefore, in clearing operations, the benefits of locally stabilizing stream-

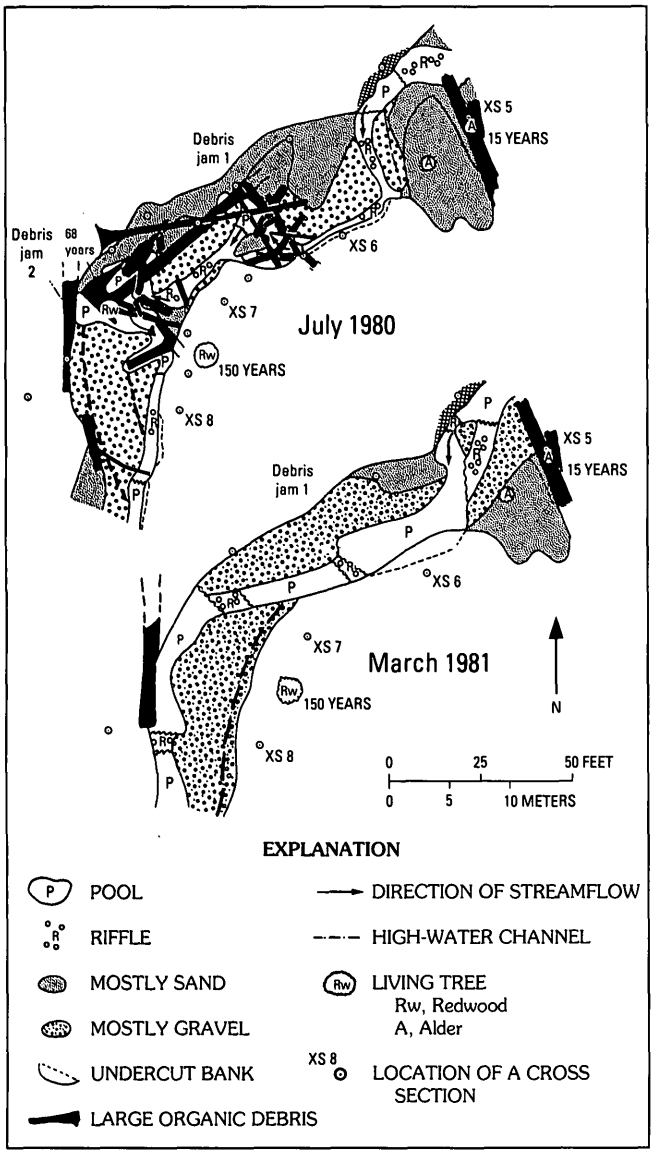

FIGURE 26.—Morphologic maps of the upstream portion of Larry Damm Creek before and after debris removal.

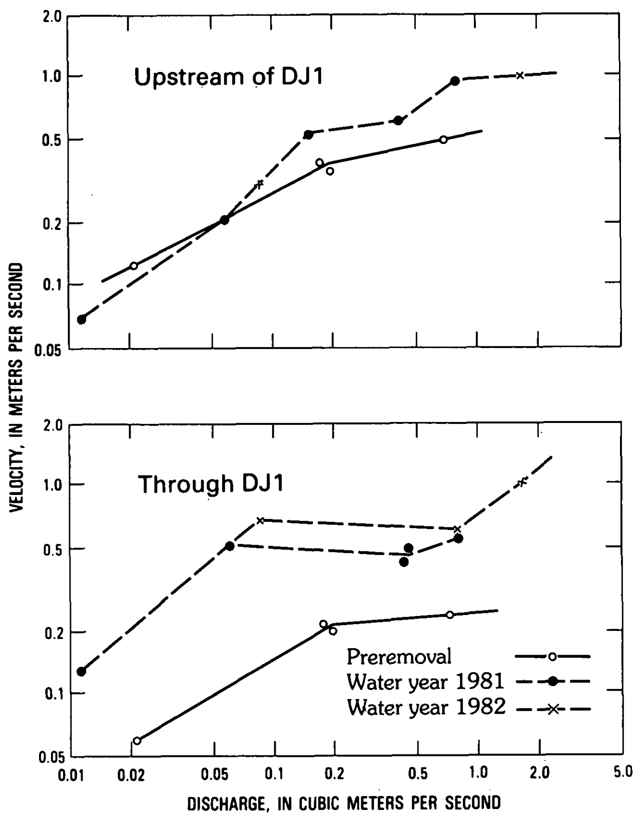

FIGURE 27.—Mean water velocity versus discharge for the reach above and through debris jam (DJ) no. 1, Larry Damm Creek, before and after debris removal. Maps of this reach are shown in figure 26.

banks, opening up anadromous fish habitat, or marketing merchantable timber must be considered in relation to the potential dangers of losing variability in habitat and mobilizing large quantities of bed material stored by large organic debris.

It is probably best to leave large organic debris that falls into the stream channel in watersheds having old-growth forest. Debris probably helps to create fish habitat by providing cover and also pool environments for juvenile anadromous fish. In addition, debris jams often create extensive backwaters at higher flows. Such low-energy habitat is necessary for overwinter survival of fish. An example of such habitat is shown in figure 26, maps of a portion of Larry Damm Creek. Although both debris jams shown on the maps create backwaters at high flows, the upstream jam (debris jam no. 1) created the larger and more persistent backwater. Mean water velocity both above and through the jam is shown in figure 27 for discharges ranging from less than 1 to 20 percent of bankfull. The jam significantly reduced water velocity from cross section no. 5 (XS5, fig. 26) through the debris jam at discharges greater than 5 percent of bankfull discharge. After the removal of all woody debris greater than 10 cm in diameter from the channel in this location, this backwater was no longer present.

Management of large organic debris in streams affected by timber harvesting should consider two potential problems: (1) loading of large organic debris after logging may increase due to the introduction of slash into the channel and (2) the long-term budget of large organic debris is changed when a forest is cut. Removal of large logs and slash introduced by logging may be necessary. Such removal should involve only logs derived from the logging; large organic debris present in the channel prior to logging and contributing to habitat should not be removed. Overzealous removal of large organic debris will result in unnecessary damage to the aquatic ecosystem. Mitigating the effects of changing the long-term large-organic-debris budget is difficult because the size of debris delivered to the channel from second-growth timber will be relatively small until about 100 years after logging ceases. Two aspects of large organic debris are pertinent to the budget problem: (1) it is the distribution of large organic debris rather than total debris loading that determines the quality of habitat and (2) large organic debris existing in the channel prior to logging may continue to reside there for several hundred years. Therefore, management plans for utilizing and enhancing "habitat-producing" large organic debris present in the channel prior to logging are advisable. By enhancement we mean increasing or decreasing the total large-organic-debris loading, or the spacing of debris, to maximize the quality and residence time of habitats such as pools produced by large organic debris. Such plans should strive to duplicate as much as possible natural occurrences in undisturbed basins. This "design-with-nature" approach recognizes that the natural fluvial system has evolved over hundreds and thousands of years in response to the presence of large organic debris. The more we learn about large organic debris, the more we recognize that it is intimately related to the fish habitat and thus to the production of anadromous fish. In many subtle ways the debris is interacting in positive ways to produce and maintain desired fish habitat. Therefore, a conservative practice concerning its removal should be adopted.

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Effects of Channelization on Sediment Distribution and Aquatic Habitat at the Mouth of Redwood Creek, Northwestern California

By CYNTHIA L. RICKS

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–Q

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EFFECTS OF CHANNELIZATION ON SEDIMENT DISTRIBUTION AND AQUATIC HABITAT AT THE MOUTH OF REDWOOD CREEK, NORTHWESTERN CALIFORNIA

By CYNTHIA L. RICKS[1]

ABSTRACT

Since the early 1950's, the distribution of sediment at the mouth of Redwood Creek has been altered by the effects of channel aggradation and channelization along the lower reach. Severe flooding in 1953, 1955, and 1964 caused bank erosion, landslides, and changes in channel geometry upstream along Redwood Creek. The increased sediment load also resulted in channel aggradation and widening along the lower flood plain. Flood-control levees constructed from 1966 to 1968 channelized the lower reach of Redwood Creek and cut off the last downstream meander. The distribution of erosional and depositional sites at the mouth has been more drastically altered by channelization than by aggradation. Channelization was accompanied by smoothing the roughness of the streambed, shaping a trapezoidal channel with an increased hydraulic radius, and steepening the channel gradient. These changes caused an increase in the mean velocity and frequency of mobilization of the bed material between the levees. With streamflow confined between the levees, sediments deposited in the last downstream meander (south slough) and north slough are no longer flushed from the mouth of Redwood Creek. Since 1966, 50 percent of the lower estuary (between 0 and 1.2 m above sea level) has filled with sediment or become isolated from the embayment. Data on heavy minerals and on sediment size distribution indicate that, during high to moderate streamflow, sand- and gravel-sized sediment is flushed through the embayment. Overwash across the storm berm and transport by tidal currents are the dominant processes delivering sediment from the nearshore zone to the sloughs. Sediment accumulation has altered the seasonal sequence of migration and closure of the outflow channel, which determines the substrate distribution, water quality, and embayed water volume during the low-flow period from spring to early fall. More frequent closure and flooding of backwater areas and adjacent pastures have historically led to artificial breaching of the berm. Recently, such premature breaching released 75 percent of the embayed water, which was inhabited by 20,000 juvenile salmonids.

INTRODUCTION

The mouth of Redwood Creek is located 4.0 river km west of Orick, Calif. (fig. 1). The lower Redwood Creek flood plain encompasses the Orick valley from Prairie Creek to the ocean. Prior to 1966, a series of damaging floods deposited sediment and debris across the lower Redwood Creek flood plain. Concern for flood protection prompted the U.S. Army Corps of Engineers to channelize Redwood Creek in the vicinity of Orick. Levees were constructed along 5.1 km from the confluence with Prairie Creek to the mouth, between April 1966 and October 1968. The narrow trapezoidal channel was designed to contain a peak discharge of 2,180 m^3/s, about 50 percent larger than the peak flow of record (U.S. Army Corps of Engineers, 1961, 1966).

The lowermost section of the levees diverted streamflow directly to the ocean, bypassing the last downstream meander (fig. 2). The mouth presently consists of the main channel of Redwood Creek between the levees, a north slough, a south slough (the cutoff meander), and an embayment. The embayment is the relatively deep, broad part of the mouth landward from the beach.

Estuarine habitat at the mouth of Redwood Creek is transitory and limited in extent. During favorable conditions, saltwater has been detected only 1.5 km upstream from the mouth (Gregory, 1982). By increasing the historically steep stream gradient along lower Redwood Creek, channelization reduced the maximum upstream intrusion of saltwater.

In recent years, changes in the distribution of sediment at the mouth have isolated the north and south sloughs, thereby reducing the quantity and quality of aquatic habitat. Accumulation of sediment has been attributed to processes resulting from channelization and to increased fluvial sediment input. To distinguish between the effects of flooding under natural and channelized conditions, morphological, dendrochronological, and historical evidences of flooding along lower

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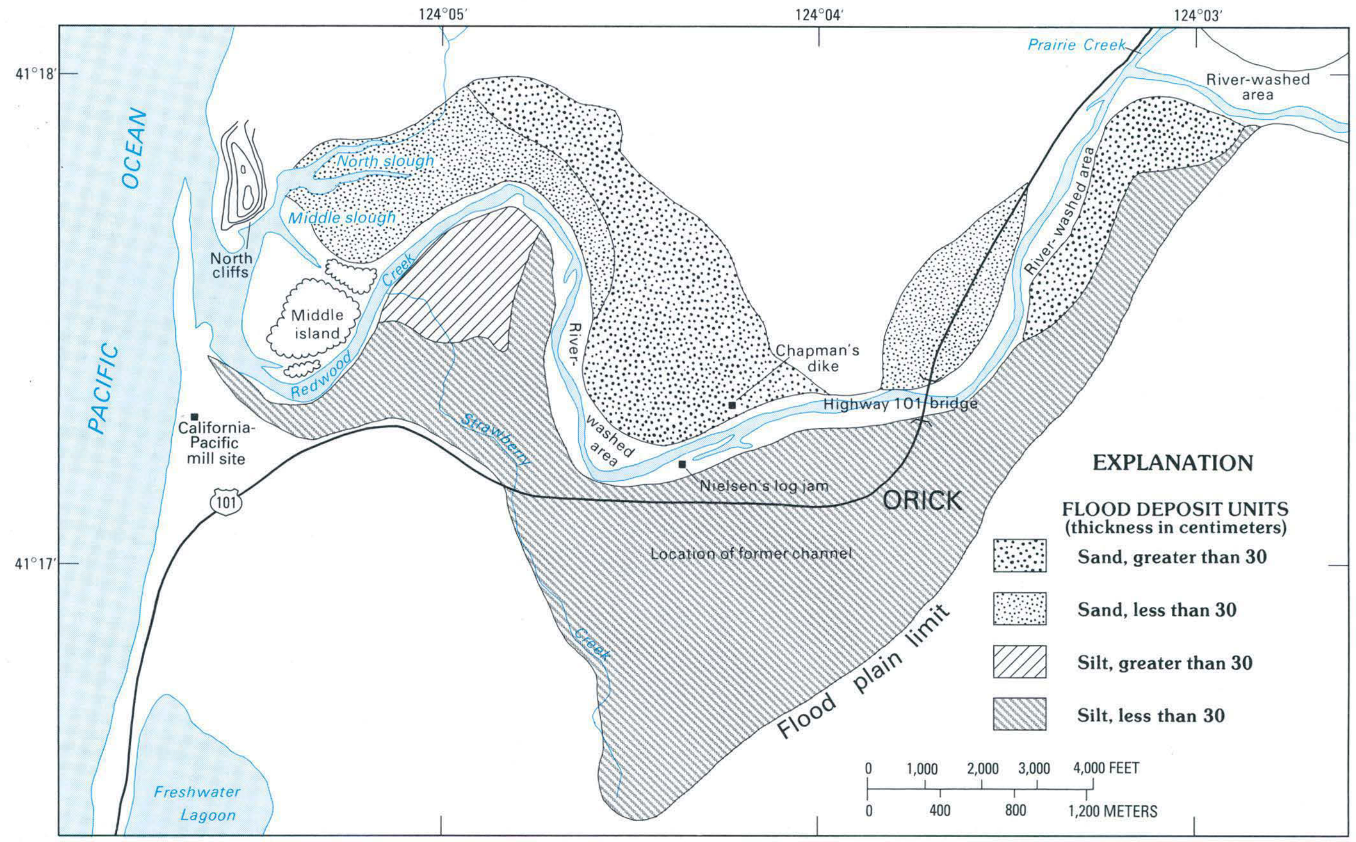

FIGURE 1.—Redwood Creek flood plain showing 1964 flood deposits and selected cultural features. This map shows the configuration of the mouth of Redwood Creek 2 weeks after the 1964 flood. Flood deposit units are from McLaughlin and Harradine (1965).

Redwood Creek are examined. The effects of channelization include direct alteration of stream configuration and habitat, as well as changes in the relative importance of fluvial and marine sediment input. Textural and mineralogical analyses, topographic surveys, and frequent field observations document sediment sources and transport processes. Typical seasonal variations in the configuration of the embayment are differentiated from sites and rates of net sediment accumulation. The outflow channel from the embayment to the ocean follows a seasonal progression that influences substrate distribution, water quality, and embayed water volume. Accumulation of sediment appears to have altered the seasonal progression of the outflow channel, thereby further restricting circulation and the volume of aquatic habitat.

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DATA COLLECTION AND ANALYSIS

Long-term changes along the lower flood plain were documented by dendrochronological techniques and survey comparisons and by interpretation of aerial photographs. The stability of the last downstream meander prior to channelization was evaluated by mapping age relations in the spruce-alder forest located on the middle island (fig. 1). Live trees were dated from increment cores, and ring counts were taken on stumps of trees cut in 1978.

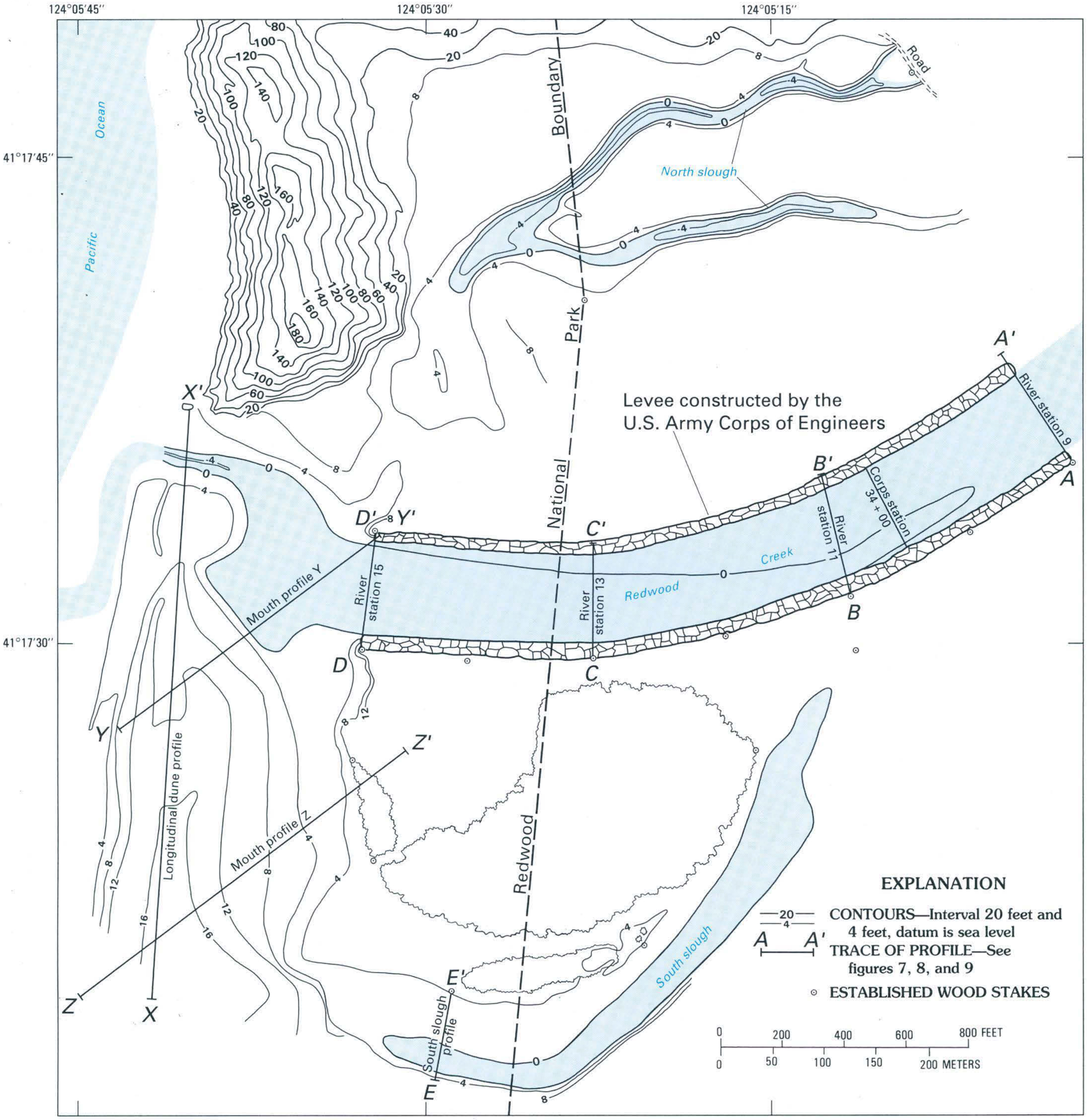

FIGURE 2.—Profile locations at the mouth of Redwood Creek.

Additional data came from historical photographs dating from 1931, interviews with local residents, streamflow gaging, and a flood deposit map compiled following the 1964 flood (McLaughlin and Harradine, 1965). The dates and magnitudes of pre-1949 floods on Redwood Creek have been inferred from regional precipitation and streamflow data as well as published accounts (chap. D, this volume; McGlashan and Briggs, 1939; Paulson, 1953; U.S. Army Corps of Engineers, 1961). After 1949, peak flood stages were measured by the Corps of Engineers on a staff gage at the Orick bridge, prior to establishment of the U.S. Geological Survey gaging station in October 1953.

Data on streambank erosion and migration of the last downstream meander, as well as on sedimentation adjacent to the embayment, were collected from vertical aerial photographs for the period 1936–68. Potential relations between high stream discharge and marine conditions were evaluated by plotting hydrographs for floods gaged at Orick against tide heights predicted for Humboldt Bay.

Sediment accumulation following levee construction was documented by comparing profiles surveyed by the Corps of Engineers in 1964 and 1966 with detailed topographic-bathymetric surveys conducted during summer 1980 and spring 1981.

Seasonal changes in mouth morphology and sedimentary structures of the mouth were documented repeatedly throughout the period of field observation from November 1979 to May 1982. The locations and approximate volumes of sediment mobilized during the 1980–81 winter season were obtained from successive topographic-bathymetric surveys. Fluvial sediment input was estimated from sediment transport, flow duration, and particle size plots for the U.S. Geological Survey gaging station at Orick, Calif.

Sieve analysis and heavy liquid separations of selected surface samples were used to delineate grain-size distribution and to distinguish among sediment sources by heavy-mineral variations. At the mouth, bottom material was sampled along profiles surveyed in summer 1980 and spring 1981. Where water depth prohibited scooping the upper 2 cm of sediment by hand, a gravity grab sampler was dropped from a row boat. Bottom material from streams and beaches adjacent to the mouth of Redwood Creek also was analyzed to identify lithologically distinct heavy-mineral sources.

The heavy-mineral fraction was separated from 56 samples of fine sand (0.250–0.125 mm) by gravity settling in tetrabromoethane (sp gr=2.96). Preliminary identification revealed that beach samples contained at least 20 percent strongly pleochroic blue-green hornblende, but the mineral was limited to only a few percent in Redwood Creek (Curt Peterson, School of Oceanography, Oregon State University, 1982, oral commun.). This indicator mineral and two other easily identifiable minerals, glaucophane and garnet, were used to facilitate rapid analysis of samples.

RESULTS

FLOOD-PLAIN MORPHOLOGY AND DENDROCHRONOLOGY

Below its confluence with Prairie Creek, Redwood Creek flows in a westerly direction through a widening valley to the ocean. Erosion scars on the lower flood plain indicate prehistoric flood overflow channels and stream channels (fig. 3). An arcuate patch of willows marks a former channel on the south side of the flood plain (fig. 1). Before channelization, several marshy areas and sloughs on the south flood plain drained into Strawberry Creek and the middle slough during overbank flows (fig. 1). On the north side of the flood plain, high flows occupied two channels that are now the fingers of the north slough.

Early photographs show that spruce (*Picea sitchensis*) once forested the Orick valley. The spruce grove near the mouth on the middle island (fig. 1) is relatively immature (fig. 4), suggesting that the trees became established following the floods in 1861–62 or 1890. The diversity in age distribution of the spruce may be the result of seedling establishment under conditions of periodic flooding. Spruce not located on higher elevation sites or not protected by accumulations of organic debris would have been destroyed by flooding. Although the maximum spruce age of 98 years suggests that the grove developed following the 1861–62 floods, it also could reflect an early unrecorded harvest or recovery from disease.

FLOOD HISTORY

Along the lower reaches of Redwood Creek, local residents recall severe flooding in the 1860's and in 1890 and 1927. At least as early as 1927, a short segment of the right bank downstream from Orick was protected by a low earthen structure called Chapman's dike (fig. 1). The 1927 flood breached the dike and flowed along the north side of the flood plain and into the north slough.

The late 1940's and early 1950's were prosperous years for the logging town of Orick. Many buildings were constructed along Redwood Creek in low marshy areas downstream from the Highway 101 bridge. This development led to local pressure for flood control after floods in 1953 and 1955. The California-Pacific Mill was established south of the last downstream meander in 1951 after Highway 101 was relocated in 1949 (fig. 1).

Since 1949, peak discharges for floods in Orick have been gaged at the Highway 101 bridge. Waananen and Crippen (1977) calculated a 16- to 17-year return period for the peak discharge of recent major floods (1,415 m^3/s; table 1). Coghlan (1984) discusses the effects of climatic patterns on flood frequencies, noting that it is not unreasonable to expect peaks on the order of 1,415 m^3/s

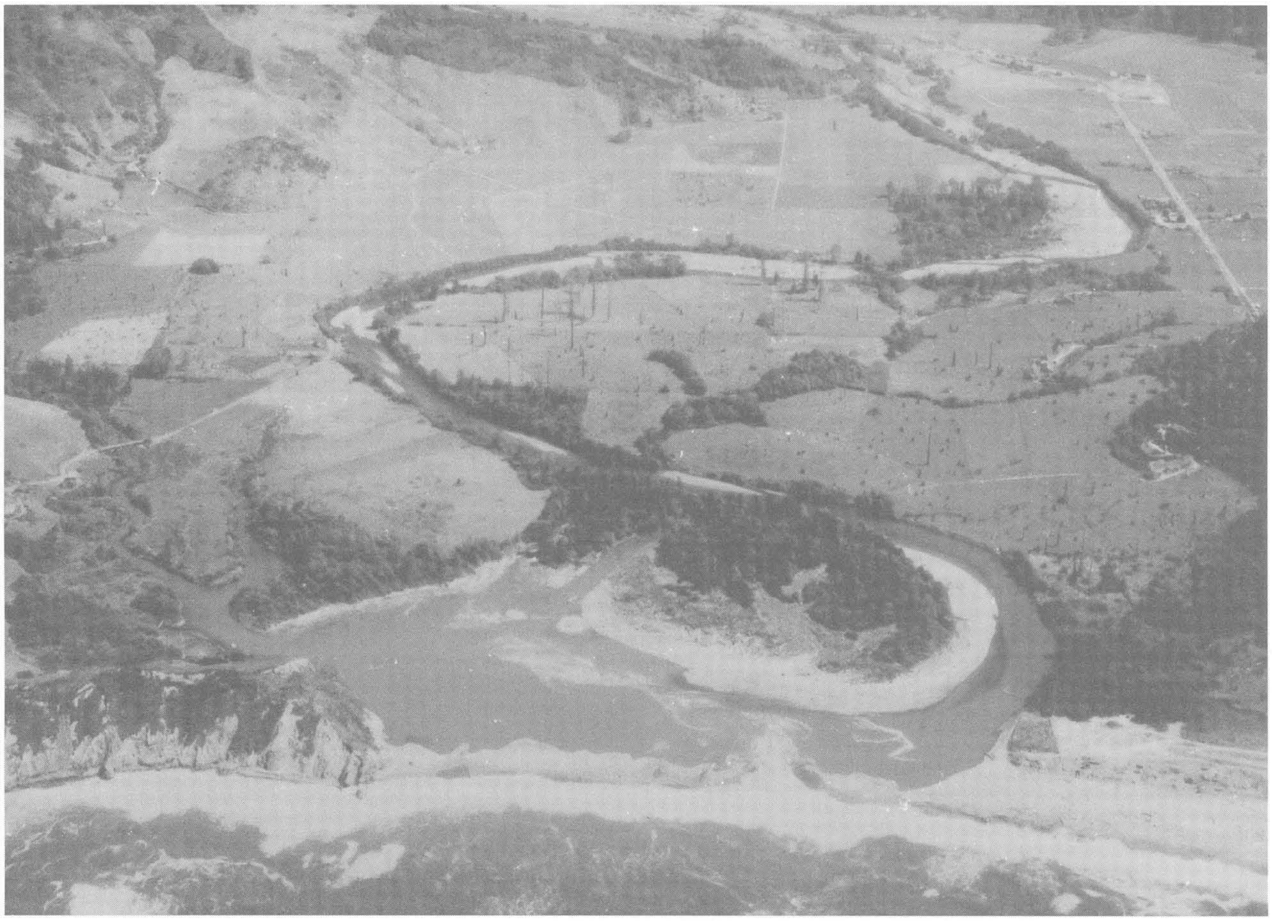

FIGURE 3.—Oblique aerial photograph of mouth of Redwood Creek, September 1948.

TABLE 1.—*Instantaneous peak discharge and storm runoff at Orick for recent major floods on Redwood Creek*

[Revised from Harden and others, 1978, p. 33. —, no data]

Storm dates	Instantaneous peak discharge (m^3/s)	Storm runoff (cm)
January 16–20, 1953 (peak, January 18)	1,415	—
December 15–23, 1955 (peak, December 22)	1,415	32.5
December 18–24, 1964 (peak, December 22)	1,430	[1]64.0
January 19–24, 1972 (peak, January 22)	1,285	28.7
March 1–4, 1972 (peak, March 3)	1,410	18.0
March 15–24, 1975 (peak, March 18)	1,420	28.2

[1] 64.0 cm is total runoff at Orick for the extended storm period December 18–30, 1964.

every 12 years. During more severe climatic periods such as that of 1953–75, a flood of this magnitude may occur every 3.5 years.

Local residents reported that the lower Redwood Creek channel was narrow and deep prior to the floods of 1953 and 1955. Aerial photographs of the lower flood plain show that the September 1954 channel appears wider and more aggraded than the June 1948 channel. The storm of January 16–20, 1953, was brief and intense and attained a peak discharge of 1,415 m^3/s (table 1). Downstream from the Highway 101 bridge (fig. 1), bank erosion removed sections of the county road. The Corps of Engineers placed emergency riprap along 600 m of the bank. Chapman's dike failed, leaving flood deposits in fields on the north side.

Precipitation during the storm of December 15–23, 1955, was more prolonged than in the 1953 storm. Following the 1955 flood, the Corps of Engineers provided bank protection along 460 m of the left bank downstream from Nielsen's log jam (fig. 1). On the north side, the Corps constructed a levee 1.5 m high at the site of the 550-m-long earthen dike, which had developed a 90-m breach.

The peak discharge of the December 18–24, 1964, flood was only slightly larger than for the floods of 1953 and 1955 (table 1), but the total flood volume and damage to streambanks and hillslopes was much greater (Janda and others, 1975). The thickness and texture of the 1964 flood deposits were mapped during a Humboldt County soil survey (McLaughlin and Harradine, 1965). Figure 1 depicts the mapped units and the configuration of the mouth 2 weeks after the 1964 flood. Flood deposits were thicker and coarser on the north side of the flood plain

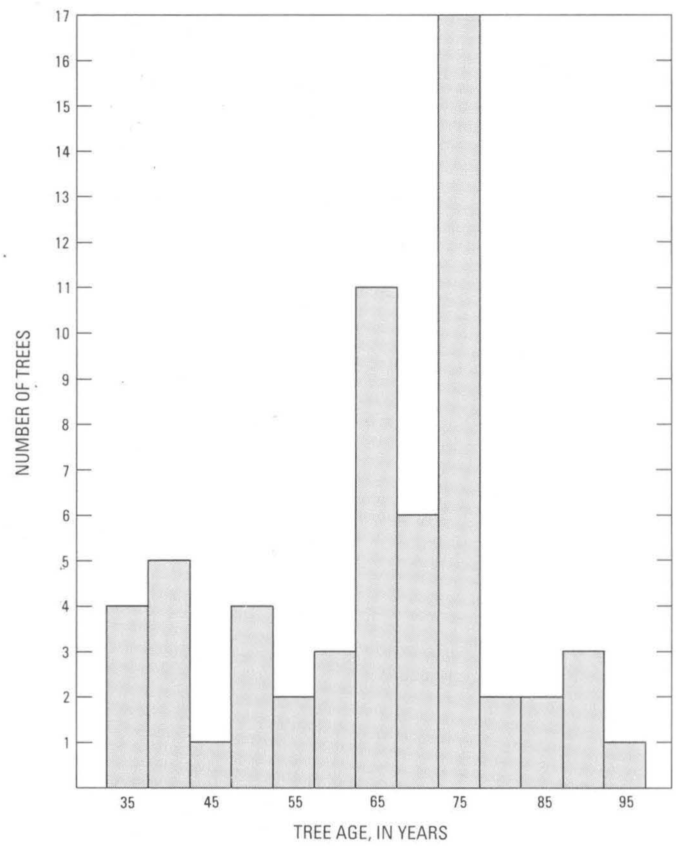

FIGURE 4.—Age distribution of *Picea sitchensis* (Sitka spruce) on the middle island, mouth of Redwood Creek.

than the south side. Catastrophic failure of the 1.5-m-high levee may have released higher velocity flows onto the north side.

Orick residents stated that the 1964 deposits were generally twice as thick as the 1955 deposits. Near the mouth, waves breaking against the middle island may have augmented deposition between the middle and north sloughs (fig. 1). Aerial photographs of the mouth taken between 1931 and 1967 show that the most extensive sediment storage site developed between the middle and north sloughs as a result of the 1964 flood. This event also eroded the beach berm from the north cliffs south to the California-Pacific Mill (fig. 1).

RATE OF STREAMBANK EROSION

The last downstream meander migrated progressively to the south from 1936 to 1967 at a rate of less than 2.1 m/yr (fig. 5). Significant episodes of streambank erosion were clearly associated with major floods (fig. 6) having peak discharges of at least 1,065 m^3/s.

However, the degree of migration of the last downstream meander differed during floods of similar magnitude in 1953, 1955, and 1964. Following a prolonged period of little or no streambank erosion (fig. 6), the concave bank had migrated considerably after the January 1953 flood (fig. 5). Although the December 1955 flood attained the same peak discharge as the 1953 flood (table 1), streambank erosion was not extensive (figs. 5, 6).

Nanson and Hicken (1983) proposed that differences in the degree of migration of stream meanders may be caused by processes that maintain an equilibrious channel width. When a convex bank is well defined and vegetated, migration occurs by erosion of the concave bank and is associated with channel widening. Successive floods of similar magnitude will not significantly erode the concave bank because velocity and boundary shear stress are reduced in a widened channel. The convex bank migrates by accretion and revegetation of a point bar until the equilibrious channel width is restored. The next major flood will again erode the concave bank of the confined channel.

In July 1957, the convex bank consisted of a wide point bar covered by organic debris that may have retarded erosion and aided revegetation of the bar. A well-vegetated insular bar had developed by August 1962, confining a narrower channel. Considerable concave bank erosion was again associated with the December 1964 flood.

The extent of streambank erosion also may depend on the duration and the rates of rise and recession of the major floods. Positive ground-water pore pressures in streambanks during flood recession may cause slumping of the bank (Keller, 1977). If this process was important along the last downstream meander, more extensive bank erosion probably would have occurred during the 1955 flood, when rapid recession coincided with ebbing tides.

EFFECTS OF CHANNELIZATION

During channelization and levee construction, the channel gradient was increased from 0.07 to 0.14 percent. This increase was due to removal of the last downstream meander and the excavation of the channel to a predetermined design slope. The combined effect of smoothing the roughness of the bed, increasing the hydraulic radius by shaping a trapezoidal channel, and increasing the slope increased the mean flow velocity. The resulting greater stream competence caused the bed material between the levees to be mobilized more frequently.

After channelization, sediment accumulated rapidly across the beach berm and in the downstream end of the abandoned meander, now the south slough (figs. 2, 7, 8). Along the north cliffs (fig. 1), water depths of at least 6 m apparently prevented the Corps of Engineers from surveying the neck of the north slough in 1964. By

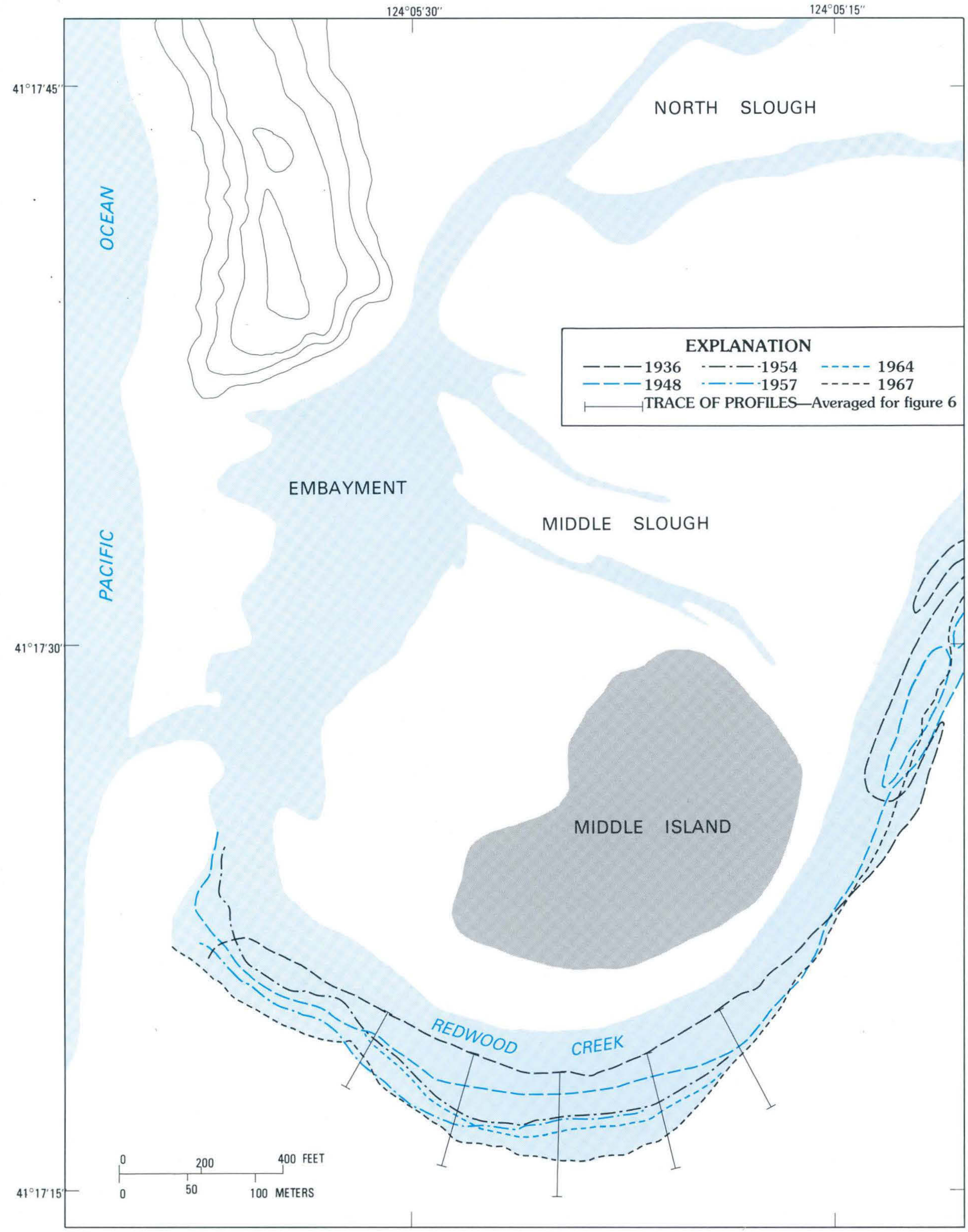

FIGURE 5.—Bank positions along the last downstream meander at the mouth of Redwood Creek, 1936 to 1967. The five cross-section lines through the streambank provided the bank erosion data for figure 6.

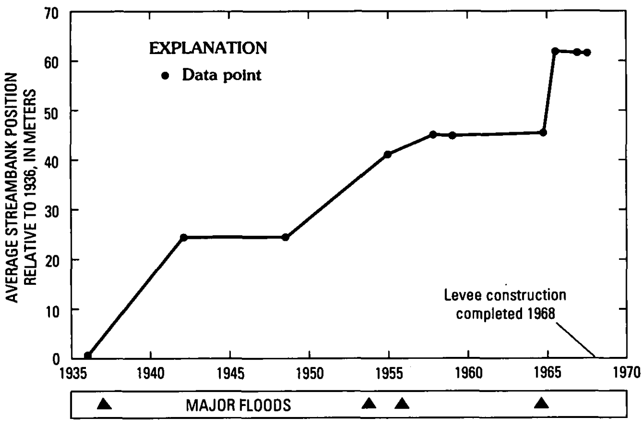

FIGURE 6.—Cumulative southward migration of the last downstream meander at the mouth of Redwood Creek, based on average erosion for the five cross-section lines shown in figure 5. Major floods have peak discharges of at least 1,065 m^3/s.

September 1974, a subaerial deposit had isolated the north slough from the main channel. Profiles at river stations 9, 11, 13, and 15 (fig. 9) illustrate the degree of aggradation between the levees since the design channel was excavated. Griggs and Paris (1982) observed that similar aggradation along the channelized lower portion of the San Lorenzo River, Calif., lowered the stream gradient toward the prechannelization equilibrium value. Aggradation also reduced the discharge capacity of the channelized reach. Along the lower reach of Redwood Creek, a stream gradient survey from approximately 2.3 km upstream of the mouth to the Highway 101 bridge showed a decrease from the 1966 design gradient (0.14 percent) to 0.11 percent in 1980 (M.A. Madej, written commun., 1982).

Since the Corps of Engineers surveys of 1964–66, 50 percent of the lower estuary (between 0 and 1.2 m above sea level) has filled with sediment or become isolated from the main channel. By confining the flow of Redwood Creek between levees, a trap for sediment was created in the sloughs. Minor flows from Strawberry and Sand Cache Creeks (fig. 1) provide the only circulation and flushing of sediment from the south slough and the north slough. The levees constrict the streamflow so efficiently that a very limited section of the beach berm is scoured by floods. The peak discharges for the December 1964 and March 1972 floods were very similar (table 1), but the extent of berm scour in 1972 was about 70 percent less with the channelized flow (fig. 10).

SEDIMENT SOURCES AND TRANSPORT PROCESSES

Redwood Creek transports 1,340,000 Mg of sediment as suspended load and 173,000 Mg as bedload past the Orick gaging station annually (table 2). The sand-sized

TABLE 2.—*Annual discharge of coarse-size fraction for Redwood Creek at Orick*

Size fraction[1]	Annual discharge (Mg)	Data base	Source
Suspended sediment.....	1,340,000	1954–80	J.R. Crippen, written commun., 1981.
....Do....	1,330,000–2,790,000	1978–80	USGS gaging station at Orick, Calif.
Bedload sediment	173,000	1954–80	J.R. Crippen, written commun. 1981.
....Do....	43,000–646,000	1974–76, 1978	USGS gaging station at Orick, Calif.
Suspended sand.........	860,000–1,130,000	1974–80	....Do....
Sand in bedload.........	62,000–96,000	1975–76, 1978, 1980	....Do....
Total sand..............	930,000–1,220,000	1974–80	....Do....
Sand and gravel	1,040,000–1,310,000	1974–80	....Do....

[1] Sand size=0.062–2.0 mm.

fraction (0.062–2.0 mm) of the total load ranges from 62 to 81 percent. The sand plus gravel fractions compose 69 to 86 percent of the total load. Assuming a sediment density of 1.92 g/cm^3, 544,000 to 680,000 m^3 of sand and gravel are supplied to the mouth of Redwood Creek annually. Most of this sediment is transported through the mouth to the nearshore environment. Gravelly sand and sandy gravel remain in the channel between the levees and throughout the embayment following winter flows.

The overwash slope is primarily composed of slightly gravelly, very coarse to medium-grained sand. Waves deposit sands of similar texture to the south of the north cliffs. In the necks of the sloughs, the limit of tidal current tractive transport is marked by an abrupt increase in water depth (fig. 2) and a change in bed material from muddy sand to sandy mud.

During summer months, thick deposits of mud and muddy sand may accumulate in the embayment at Redwood Creek. Boggs and Jones (1976) suggest a predominantly marine origin for sand and muddy sand layers deposited at the mouth of the Sixes River, Oreg., during summer months. Their suggestion is based on the presence of marine detritus in the deposit and the low suspended sediment load of the river. To evaluate the potential fluvial contribution, the volume of suspended sediment from Redwood Creek at the Orick gaging station was calculated for the period from early July to mid-October 1980. The summer fluvial input could not account for a major part of mud in the embayment, but

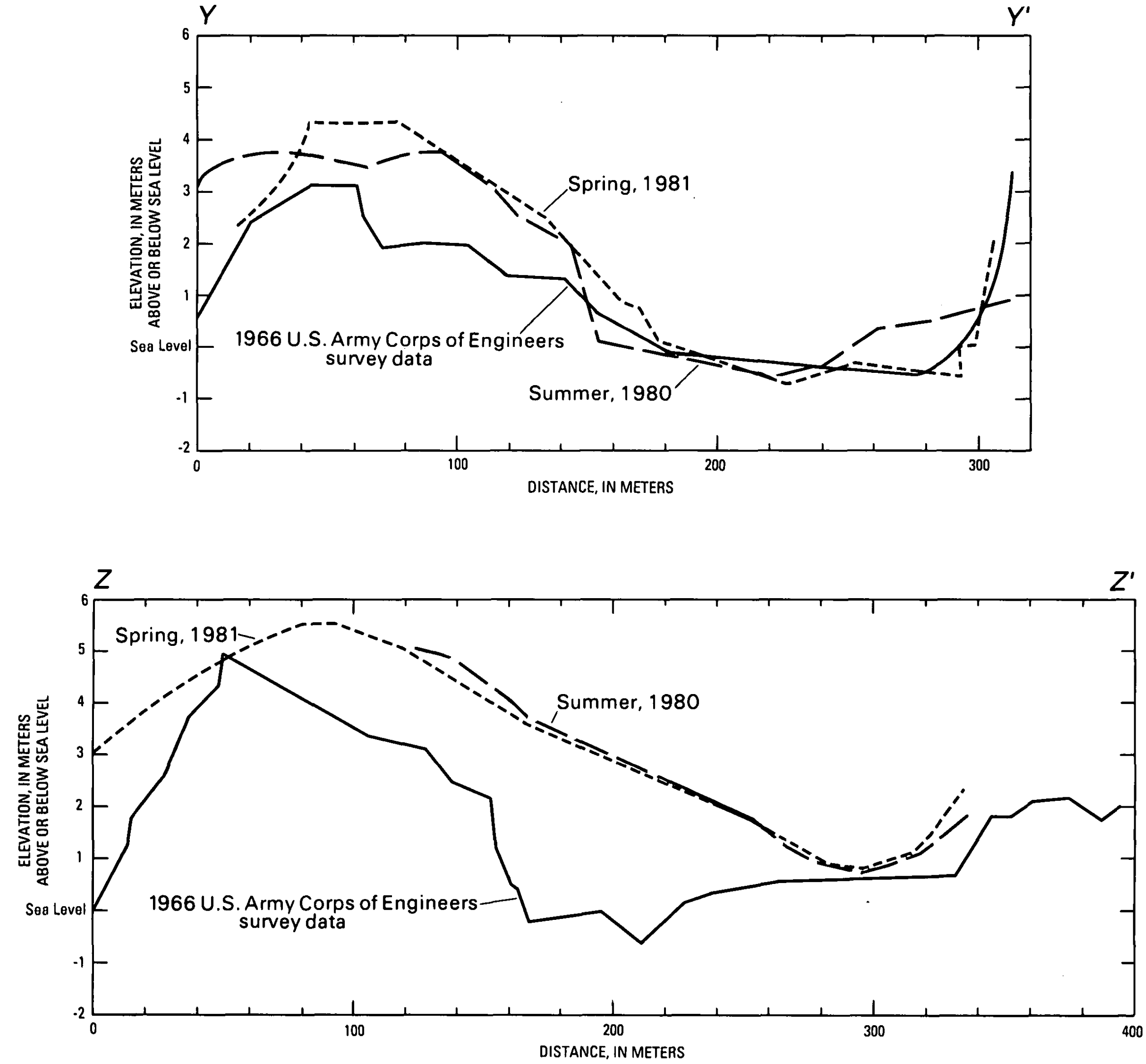

FIGURE 7.—Topographic profiles *Y–Y'* and *Z–Z'* across the mouth of Redwood Creek. Profile locations are shown in figure 2.

the volume data were not complete enough to allow evaluation of the actual contribution, if any.

Analyses of heavy minerals provide more substantial evidence of the relative contributions of marine and fluvial sediment to the Redwood Creek embayment and sloughs. Mineralogical analyses show that Redwood Creek sediment can be distinguished from marine contributions from northern and southern sources by the presence and (or) relative abundances of glaucophane and blue-green hornblende in the bottom sediment (fig. 11). The Klamath River to the north carries a large component of blue-green hornblende, whereas the Mad and Eel Rivers to the south are an abundant source of glaucophane (fig. 11). Samples of beach sand from 0.3 km south of the Klamath River to the mouth of Redwood Creek have 11 to 26 percent blue-green hornblende,

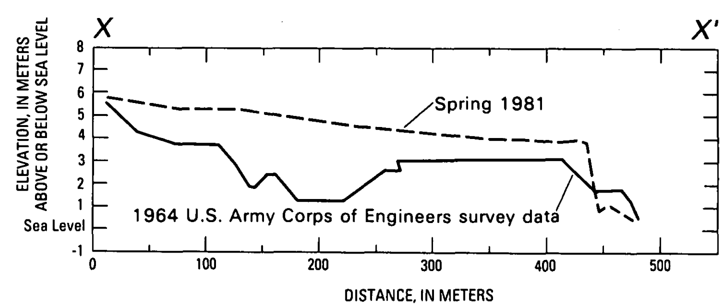

FIGURE 8.—Longitudinal dune profile *X–X'*, mouth of Redwood Creek. Dune profile location is shown in figure 2.

indicating southward longshore drift of Klamath-derived sands. Although Bodin (1982) postulated northward longshore drift between the Eel River mouth and Trini-

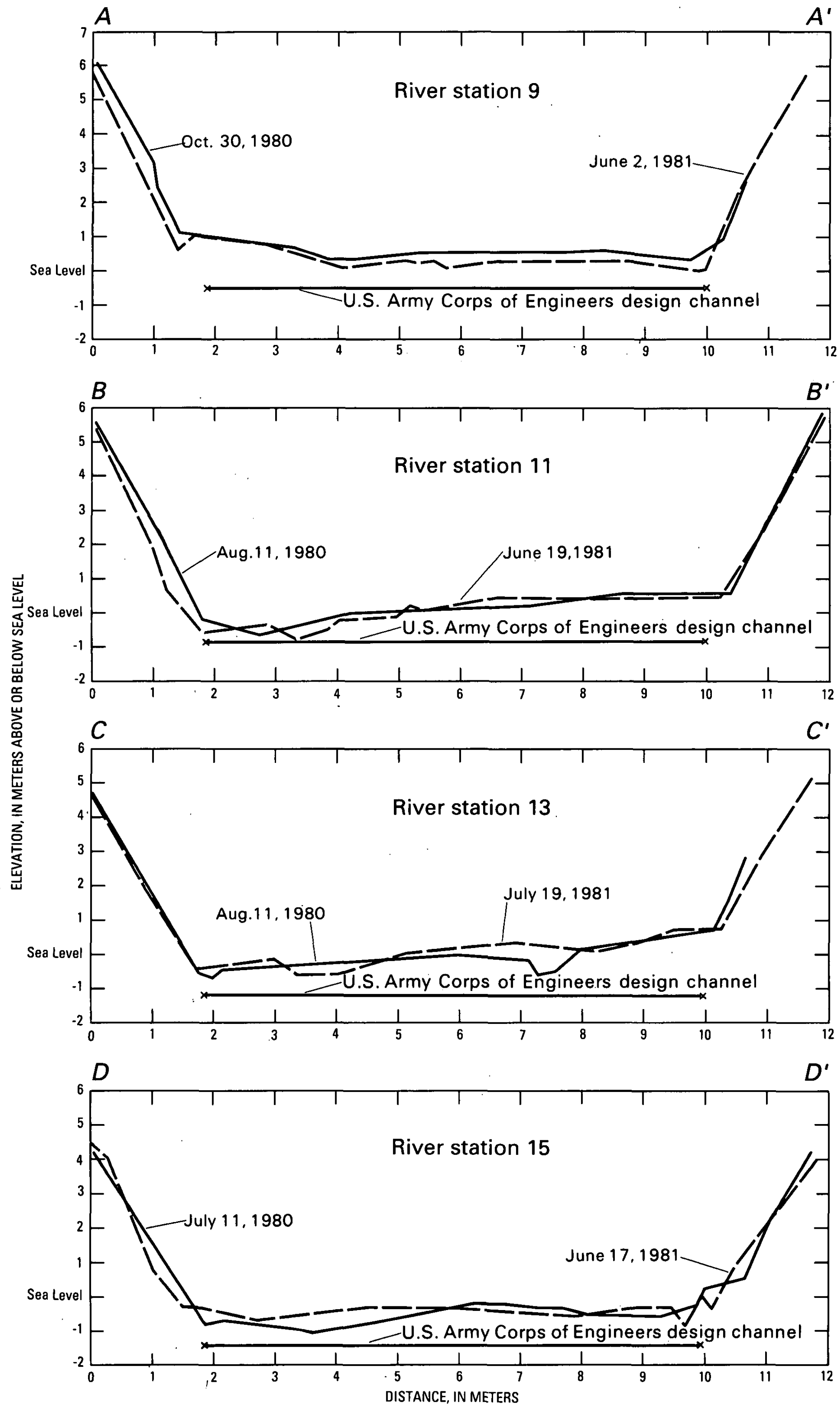

FIGURE 9.—River profiles *A–A'*, *B–B'*, *C–C'*, and *D–D'* along lower Redwood Creek. River station locations are shown in figure 2.

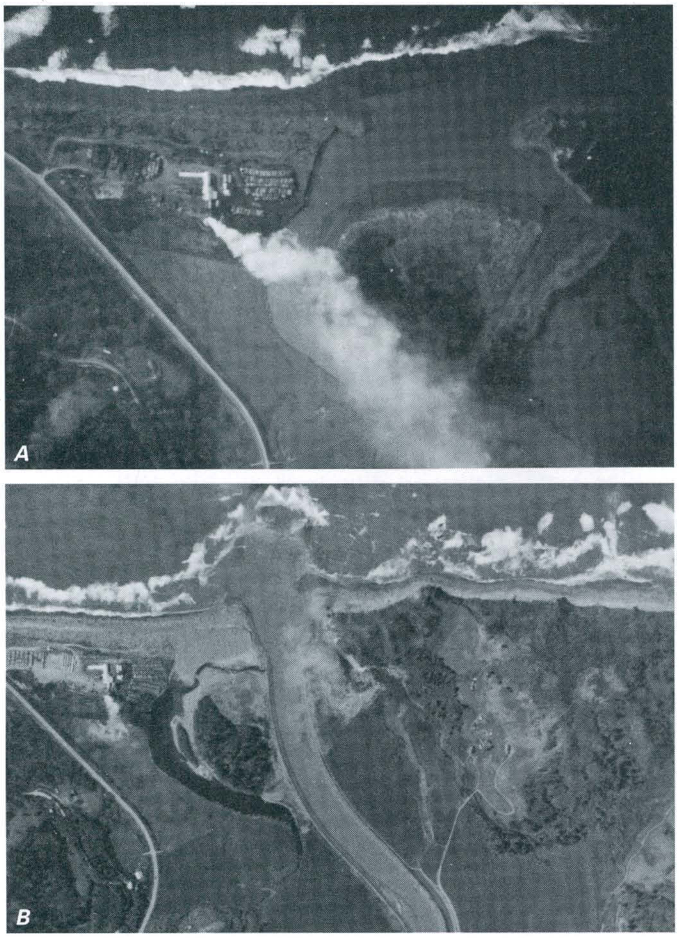

FIGURE 10.—Aerial photographs showing extent of scour of beach berm during major floods. *A*, January 13, 1965, following flood of December 18–24, 1964. *B*, March 7, 1972, following flood of March 1–4, 1972.

dad, no glaucophane-bearing sediment is found as far north as the mouth of Redwood Creek.

The heavy-mineral composition of fine sands at the mouth of Redwood Creek indicates that sediment is being transported from the beach environment into the embayment and the sloughs. The Redwood Creek basin does not contain blue-green hornblende, but at the mouth of Redwood Creek, mean values for blue-green hornblende from the north slough, south slough, and embayment are 23, 24, and 25 percent, respectively, slightly enriched relative to the beaches and extremely high relative to Redwood Creek. Upstream from the mouth of Redwood Creek, as far as the confluence with Prairie Creek (fig. 1), the blue-green hornblende content ranges from 2.2 to 9.0 percent. Prairie Creek contributes a minor amount of blue-green hornblende because it drains Plio-Pleistocene sediments deposited by the ancestral Klamath River (Kelsey, 1982). Upstream from Prairie Creek, sediment of the Redwood Creek channel contains

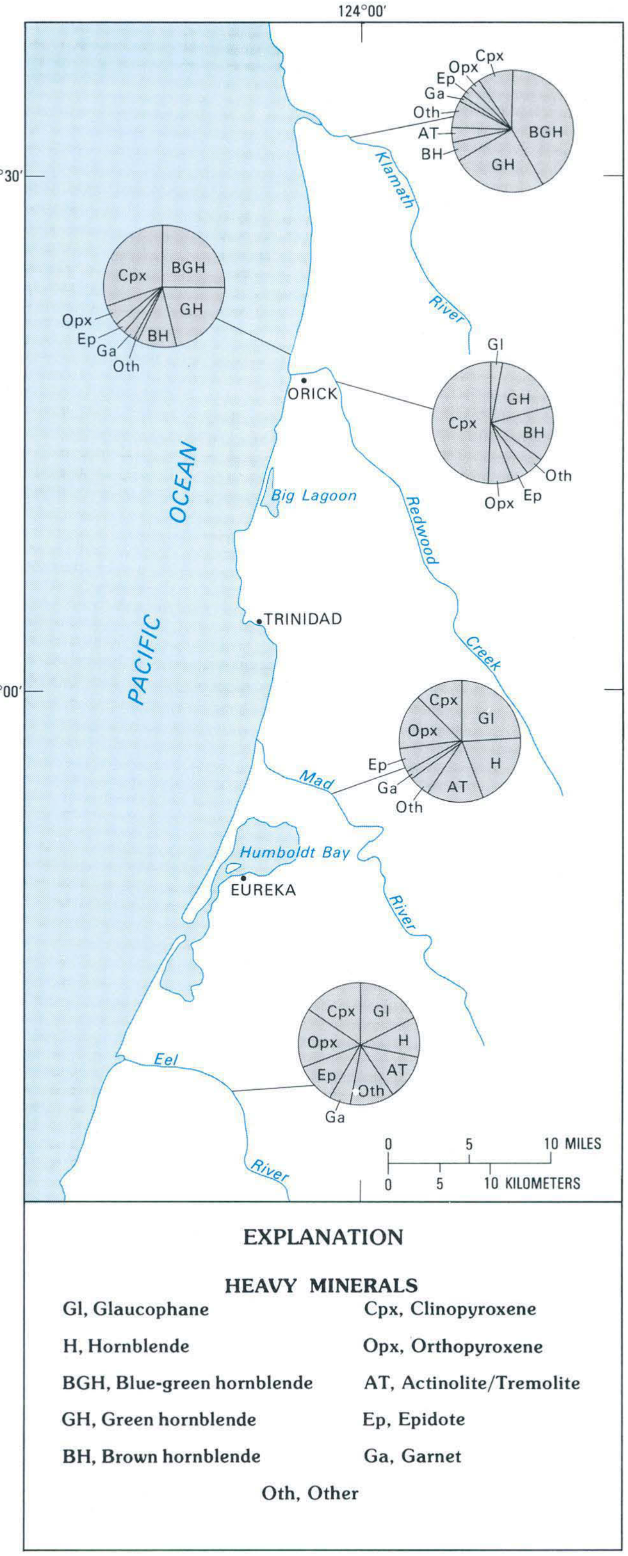

FIGURE 11.—Heavy-mineral analyses of northern California river sands and of the beach sand near the mouth of Redwood Creek. Klamath River data from Kulm and others (1968); Mad and Eel River data from Bodin (1982); and Redwood Creek and beach data from Curt Peterson (written commun., 1982).

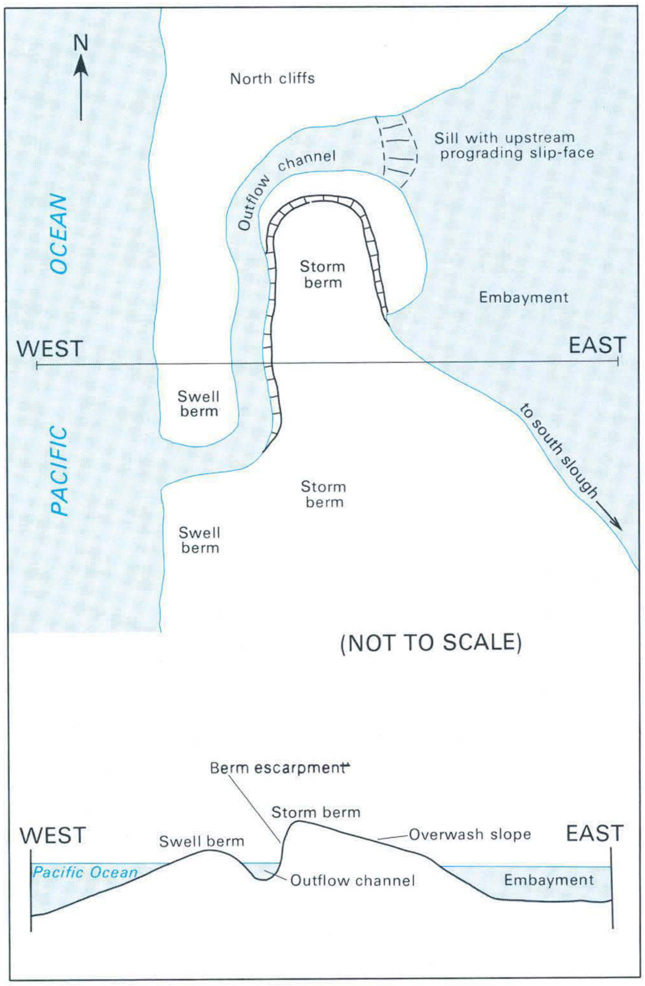

FIGURE 12.—Schematic diagram of typical summer morphological features at the mouth of Redwood Creek.

no blue-green hornblende. Heavy-mineral analyses therefore provide substantial evidence for an important contribution of marine sediment to lowermost Redwood Creek.

Overwash and tidal currents presently deposit most of the sediment in the sloughs and the embayment, with minor contributions from eolian transport and from landslides along sea cliffs. During winter storms in the years after channelization, wave overwash deposited a wide storm berm in the south slough (figs. 7, 8, 12). Overwash deposition rates were calculated for the overwash slope (fig. 12) for the area between mouth profiles *Y–Y′* and *Z–Z′* and between the storm berm crest and the middle of the south slough (figs. 2, 7). During the 1980–81 winter season, 4,200 m^3 of sediment were deposited by overwash. Between 1966, when levee construction began, and 1980, the average rate of overwash deposits was 3,400 m^3/yr. Deposition in the estuary during a winter storm bringing both high tides and high waves would be much greater than volumes cited for 1980 to 1982.

The subaerial deposit south of the north cliffs (fig. 1) is directly exposed to wave attack during storms arriving from the southwest to west-southwest. Sediment and organic debris are mobilized by tidal currents and redistributed in the north slough neck.

The neck of the south slough is protected from direct wave attack by the storm berm (fig. 12). Tidal currents deposited sand waves in the south slough near profile *E–E′* (fig. 2) at least twice from 1980 to 1982. The deposition by tidal currents was most extensive following peak discharges that scoured a wide mouth. Following a peak discharge, tidal currents deposited 63 m^3 of material as sand waves in the neck of the south slough (assuming deposition across an initially flat surface).

Prior to channelization, fluvial sediment probably did not accumulate in the embayment but was periodically flushed from the mouth. Fluvial sediment deposited in the nearshore environment is subject to resuspension and onshore transport during winter storms. Less than 1 percent of the annual sand and gravel load of Redwood Creek is washed back over the storm berm crest into the area between mouth profiles *Y–Y′* and *Z–Z′* (fig. 2).

The proportion of sediment in the beach and nearshore environments contributed by Redwood Creek is difficult to estimate. Intermediate values of blue-green hornblende, clinopyroxene, and brown hornblende in a sample from a beach near the mouth of Redwood Creek indicate mixing of Klamath River and Redwood Creek sources (fig. 11). Diverting streamflow directly to the ocean may have reduced the amount of Redwood Creek sediment in the beach and nearshore environments because the channelized stream may transport sediment beyond the nearshore zone, which is subject to wave resuspension.

SEASONAL PROGRESSION OF THE OUTFLOW CHANNEL

Generally, seasonal changes in the configuration of the outflow channel and in tidal current transport do not contribute to net sediment accumulation in the sloughs and the embayment. However, these seasonal features strongly influence the character of aquatic habitat by determining the distribution of substrate, quality of water, and volume of embayed water.

High discharge during the winter season typically erodes an escarpment in the storm berm and establishes a straight outflow channel (fig. 13*A*). As discharge decreases through the spring months, the straight outflow channel may be modified by incoming high waves and tidal currents. When the outflow channel is straight, diffraction of waves around the berm escarpment deposits a lobe (fig. 13*B*). During late spring and summer, the

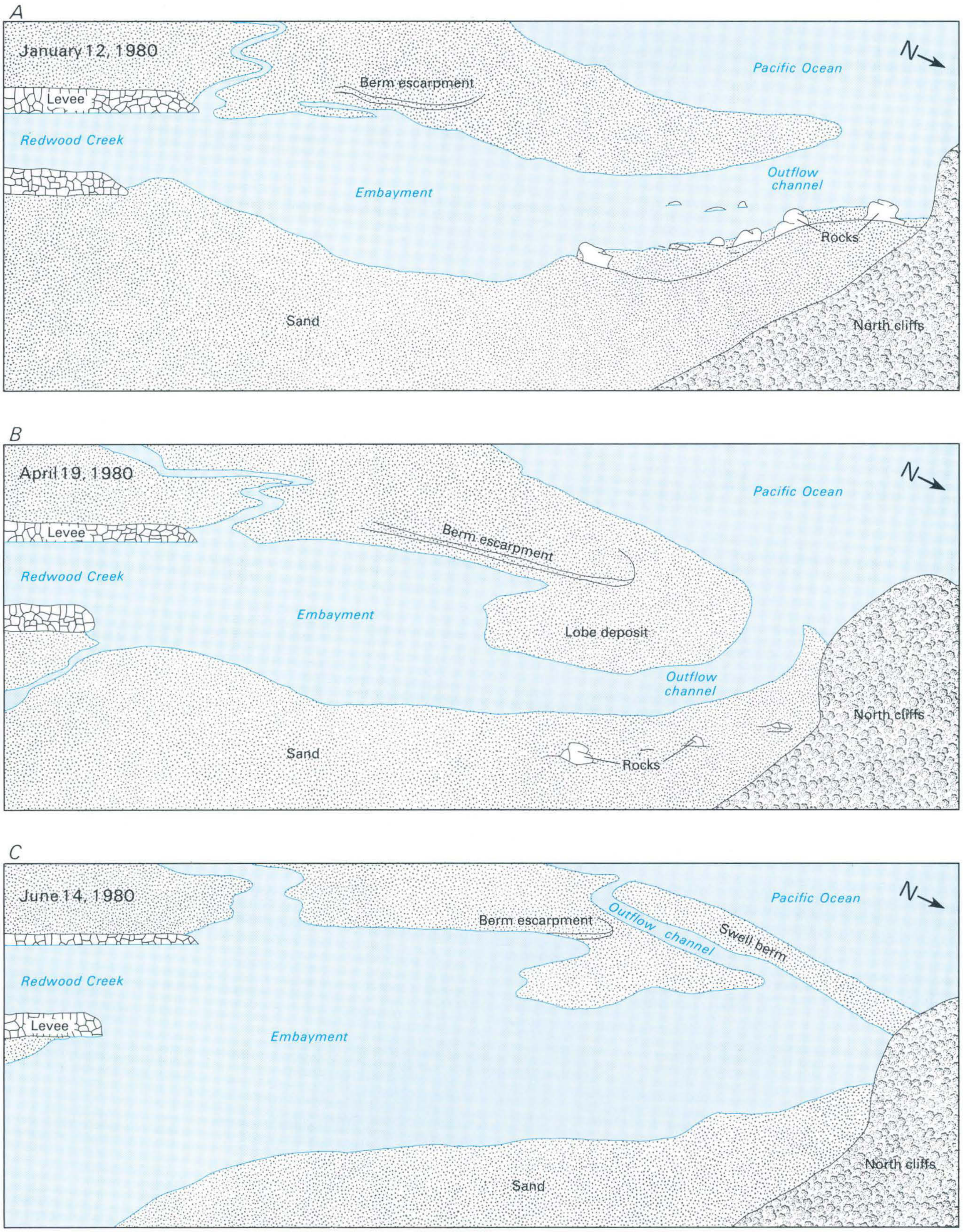

FIGURE 13.—Mouth of Redwood Creek—oblique views from the top of the north cliffs looking to the south.

outflow channel becomes narrower as discharge decreases and tidal currents transport sediment into the mouth. Incoming tidal currents slow upon reaching the wide embayment and deposit a sill at the upstream end of the outflow channel (Jones, 1972).

The sill builds above the low-tide level in the outflow channel and progrades upstream by accretion onto a steep slipface (Boggs and Jones, 1976). Clifton and others (1973) observed that sills alter the timing of the tides relative to the ocean and dampen the effective tidal range in small estuaries along the southern Oregon coast. In the upstream part of the outflow channel of the Sixes River mouth, Boggs and Jones (1976) measured bottom-current velocities that were commonly twice as fast on the floodtide as on the ebb. With the sill present, the highest velocity flood currents developed prior to the high tide in the ocean and moved through the deepest channel of the estuary (Boggs and Jones, 1976). This time-velocity asymmetry between flood and ebb currents is responsible for the net transport of marine sediment into the Sixes River estuary as well as into the Redwood Creek estuary.

The outflow channels of streams like Redwood Creek that have summer discharges ranging from 0.1 to 10 m^3/s commonly migrate alongshore (Clifton and others, 1973). During the period of field observation, the mouth of Redwood Creek migrated south when the discharge was as high as 6 m^3/s. The outflow channel migrates rapidly and episodically when prevailing north-northwest winds and high seas coincide with high tides. Waves deflect streamflow against the shoreward channel bank, eroding the bank while depositing a berm on the seaward side (swell berm on fig 13*C*). The outflow channel is located shoreward of the incipient swell berm and erodes into the storm berm (fig. 12).

When any part of the cross-sectional area of a tidal inlet is below sea level, the mouth is "functionally" open (Rice, 1974; see also Johnson, 1974). The ratio of wave energy to tidal energy per tidal cycle determines whether the mouth will close (O'Brien, 1971). Tidal energy depends on both the amplitude of the tide and the tidal prism. With a large tidal prism, the velocity of the ebb current is sufficient to erode the tidal inlet, preventing functional closure. At the mouth of Redwood Creek, stream discharge increases the velocity of the ebb current in the outflow channel. With decreasing discharge in the spring, a sill may build above sea level, thereby functionally closing the mouth. This process may presently occur more rapidly or earlier in the year than was the case prior to 1968. Due to the increased stream gradient of Redwood Creek from channelization and accumulation of sediment in the sloughs, the tidal prism has decreased by 50 percent below U.S. Army Corps of Engineers station 34+00 (fig. 2). Also, flow duration curves indicate a slight decrease in stream discharge during the summer months due to increased storm runoff (Janda and others, 1975).

As the sill builds above sea level, the effective tidal range is dampened. The velocity of the ebb current decreases, allowing the sill and outflow channel to build higher. The rate of outflow decreases, causing expansion of the water volume in the embayment because stream discharge is greater than the combined rates of outflow, seepage, and evaporation. Seepage rates through the sill and berm from the embayment to the ocean depend on the relative water levels, grain size, sorting, and area of the embayment in contact with the sill and berm (Clifton and others, 1973). Prior to deposition of the wide storm berm, water could seep along a steeper gradient through the swell berm from the embayment to the ocean (fig. 3). Presently, seepage is probably concentrated along a small part of the berm that is scoured during high discharge. Lower rates of seepage that result from the effects of channelization also could contribute to more rapid or earlier expansion of the embayment.

From 1980 to 1982, the natural sequence of longshore migration, functional closure, and total closure of the outflow channel was frequently interrupted by man-induced breaching of the berm. However, the outflow channel invariably closed completely as early as mid-July. Waves washing over the swell berm filled the migrated outflow channel in 1980 and 1982 and the straight perpendicular channel in 1981.

The configuration of the outflow channel determines both the degree of saltwater intrusion and the texture and distribution of sediments transported by flood tidal currents. Boggs and Jones (1976) show that flood currents do not dissipate as rapidly through a straight outflow channel as through a channel that has migrated alongshore. Through the straight outflow channel, sediment is transported farther up the estuary. Thus, breaching of longshore migration of the outflow channel, or lack of such migration, causes reworking of the embayment substrate. This reworking may be detrimental to benthic invertebrates.

CIRCULATION AND AQUATIC HABITAT

The immediate effects of channelization, as well as net accumulation of sediment over the last 30 years, have drastically changed circulation, water quality, substrate distribution, and the volume of aquatic habitat at the mouth of Redwood Creek.

Riparian vegetation, which supplies nutrients and streamside protection for fish and reduces water temperatures, was removed during levee construction. The pool-and-riffle structure that was destroyed during excavation of the trapezoidal channel has since reestablished itself. However, in the interest of flood control, the U.S. Army Corps of Engineers requires Humboldt County to periodically remove willows and other riparian species invading gravel bars between the levees. Since the high-gradient channel was constructed in 1968, the stream gradient in the lower reach has declined, although not to its former level. The stream gradient and lack of roughness result in higher mean velocities and more frequent mobilization of bed material. Seasonal colonization by benthic invertebrates and the species diversity among the invertebrates may still be affected by the instability of the substrate.

Circulation through the north and south sloughs is now more restricted because of overwash and tidal current deposition in the slough necks. During most of the year, the sloughs are isolated from the embayment. The embayment and sloughs may become connected during high stream discharge, during periods of high waves, floodtides, or when the outflow channel is functionally closed. Discharge from Sand Cache and Strawberry Creeks through the north and south sloughs is tidally dependent (fig. 1). When backwater develops, the sloughs function as ebb-flow channels, remaining stagnant until the floodtide and (or) high discharge recede.

Circulation from Sand Cache Creek into the north slough is further restricted at a road crossing. In the north slough, a chemocline 1.5 to 2.0 m below the water surface persists throughout the year (R. Gregory and J. Yuska, unpub. data, 1981). The bottom consists of mud, fine organic debris, and abundant pieces of woody debris. Floating woody debris covered most of the north slough until recently when the debris were removed after they floated onto adjacent pastures; at that time, a log boom was installed. Although woody debris accumulated in the north slough prior to channelization, larger deposits of debris may now be stored without being flushed from the slough during periods of high stream discharge. Except at the surface, the north slough is anoxic due to restricted circulation, decomposition of organic debris, and, until recently, floating debris that inhibited light penetration and macrophyte establishment (Gregory, 1982).

Unrestricted flow from Strawberry Creek, and the lower elevations at the slough neck, provides better circulation through the south slough than through the north slough. Winter flows from Strawberry Creek flush saltwater from the south slough. In the spring, when the south slough is isolated from Redwood Creek, oxygen concentrations decrease and temperatures increase. Macrophyte production during the summer generally increases the dissolved oxygen concentrations (Gregory, 1982).

Although there is no permanent saline layer in the embayment, when saltwater intrudes, it generally forms a stratified, salt-wedge estuary. During November 1980, saltwater was detected in the main channel of Redwood Creek 1.5 km upstream from the mouth (Gregory, 1982). The well-defined saltwater wedge intruded against a 2.8-m^3/s discharge on a 2.0-m tide with 5.9-m waves (Seymour and others, 1980). These waves caused mixing above and slightly below the north slough halocline and pushed woody debris and saltwater into the south slough as far as Strawberry Creek (Gregory, 1982). Later in the month, 3.3-m waves on a 2.3-m tide entered the mouth against a 1.2-m^3/s discharge and again carried saltwater 1.5 km upstream.

Saltwater intrusion into the embayment and sloughs occurs most frequently during high tides in the late spring and early summer months before the outflow channel becomes functionally closed. After the tide recedes, saltwater is left in small pockets that are much shallower than the 3- to 4.5-m depressions found at the Sixes River estuary (Boggs and Jones, 1976). As the outflow channel becomes functionally closed, tidal action is dampened, and stratification of the water column breaks down, as observed by Boggs and Jones (1976).

Unless the outflow channel functionally closes early in the summer, allowing the embayment to expand, the volume of aquatic habitat will be extremely limited. Due to sediment accumulation following channelization, the embayment fills more rapidly, and water rises over adjacent pastures more frequently than in the past. In January 1981, water was backed up by a berm 3.6 m above sea level, the highest backwater in the memory of local landowners. The encroachment of rushes (*Juncus* spp.) in pastures and of dead spruce adjacent to the north slough are signs of more frequent inundation.

Historically, the mouth of Redwood Creek has been breached by man almost every year for two purposes. First, eager fishermen open the mouth late in the season to provide access to the creek for upmigrating anadromous fish. This practice is now regulated by the California Department of Fish and Game due to incidents of illegal fishing methods and the lack of suitable spawning habitat upstream prior to the first winter rains. Second, the berm is breached to drain flooded pastures and, more recently, to prevent woody debris from floating into the fields. The trench through the berm is dug by shovel immediately following high tide. Water flows at a steep gradient through the new outflow channel during ebbtide and results in considerable lowering of the embayment water level. This type of catastrophic breach lowered the water level by 2.0 m in July 1980, isolating both sloughs and reducing by 75 percent the available aquatic habitat for 20,000 juvenile salmonids.

Following a breach, a partially mixed estuary may develop when saltwater intrudes against lower summer discharge. Breaching also changes the embayment substrate through erosion of mud layers and deposition of sand by tidal currents. Nutrients washed from adjacent pastures during a breach produce a heavy respiration demand for oxygen in the sloughs (Gregory, 1982).

Changes in substrate and water quality caused by the timing of embayment expansion and breaching influence the distribution and abundance of the dominant benthic invertebrate *Corophium* (Larson and others, 1981, 1982). The *Corophium* population and the volume of aquatic habitat also affect utilization of the embayment rearing habitat by juvenile steelhead trout (*Salmo gairdneri*) and chinook salmon (*Oncorhynchun tshawytsch*) (Larson and others, 1981, 1982) during the critical period of spring through the early fall months.

DISCUSSION AND CONCLUSIONS

Sites of sediment accumulation at the mouth of Redwood Creek have become more extensive since the early 1950's. Although an increase in the quantity of sediment transported from the drainage basin resulted in channel aggradation along the lower reach, the distribution of erosional and depositional sites at the mouth was altered more drastically by the effects of the channelization of Redwood Creek that took place from 1966 to 1968.

Channel widening, aggradation, and extensive overbank deposition along the lower flood plain resulted from floods in 1953, 1955, and 1964. Bank erosion associated with these major floods was not unusual along the last downstream meander. Prior to channelization, the last downstream meander migrated laterally southward from 1936 to 1967 at a rate of 2.1 m/yr. Considering the naturally high sediment load of Redwood Creek, this short-term migration rate reflects a relatively stable meander configuration.

Between 1936 and 1967, sediment accreted in the embayment mainly between the middle and north sloughs. Most of the material was deposited during the slow recession of the 1964 flood. Fluvial sediment deposited in the nearshore zone during the 1964 flood may have been transported onshore, accumulating in the embayment. During major floods, scour occurred in overflow channels and at the mouth, where the beach berm was eroded from the north cliffs south nearly to the California-Pacific Mill (fig. 10*A*).

After high flows were confined by the levees, only a limited part of the beach berm was scoured, and a high storm berm developed to the south. Since channelization, 50 percent of the lower estuary (between 0 and 1.2 m above sea level) has become filled with sediment or isolated from the embayment. The total sediment load of Redwood Creek is composed of 69 to 86 percent sand and gravel. However, during high to moderate streamflow, most of the sand and some gravel are flushed out of the mouth, leaving gravel in the channel. Presently, overwash and tidal current transport are the dominant processes of deposition in the embayment and sloughs.

Analyses of heavy minerals in fluvial and beach sands verify the presence of marine sediment in the embayment and sloughs. Blue-green hornblende, abundant in the Klamath River, is found along beaches at least as far south as Freshwater Lagoon (fig. 1). In the embayment, tidal currents deposit sands containing 20 to 31 percent blue-green hornblende on top of coarser stream sediment containing trace amounts of blue-green hornblende.

Overwash during periods of high waves and high tides builds the storm berm. Flood tidal currents deposit sediment in supratidal areas under similar conditions, particularly when discharge is low and the mouth is wide from recent scour during high discharge. As the berm builds and the sloughs fill, the rates of sediment deposition by overwash and tidal currents decrease. Overwash and tidal current deposition recorded during the study period probably represents a typical winter. During a winter storm with record waves and tides following a record stream discharge, deposition in the estuary would be much greater than volumes cited for water years 1980 to 1982.

The water volume subject to tidal fluctuations (tidal prism) has decreased due to sediment deposition in the necks of the sloughs and the steep stream gradient constructed during channelization. Freshwater and potential estuarine habitats are shallow, and circulation between the embayment and sloughs is restricted. With a smaller tidal prism, the outflow channel functionally closes earlier in the season, and the embayment fills more rapidly, allowing water to rise over adjacent pastures. To drain the pastures, local landowners historically have breached the beach berm, thereby reducing the volume of available aquatic habitat by as much as 75 percent. Thus, channelization has directly and indirectly altered the distribution of sediment and the quantity and quality of aquatic habitat at the mouth of Redwood Creek.

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Aquatic Biology of the Redwood Creek Basin, Redwood National Park, California

By ROBERT C. AVERETT *and* RICK T. IWATSUBO

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–R

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AQUATIC BIOLOGY OF THE REDWOOD CREEK BASIN, REDWOOD NATIONAL PARK, CALIFORNIA

By ROBERT C. AVERETT and RICK T. IWATSUBO

ABSTRACT

A study of the aquatic biota in Redwood Creek drainage basin of Redwood National Park, California, was conducted between 1973 and 1975. The study included an assessment of coliform bacteria, benthic invertebrates, fish, periphyton, and phytoplankton.

Coliform bacteria numbers were low except in Prairie Creek where a fish hatchery, State park, lumber mill, and residential area are located.

Benthic invertebrate communities were diverse, and the number per unit area varied greatly among sampling sites. Numbers and types of benthic invertebrates were directly related to the type of bed material. Following major winter storms, the numbers of invertebrates decreased rapidly, but usually returned to prestorm levels by autumn. Using the functional group categories of Cummins, most of the benthic invertebrates were in the collector category, followed by the predator category.

Seven species of fish representing those typically found in northern California coastal streams were captured. The most common were steelhead trout (*Oncorlynchus mykiss*).

Periphyton and phytoplankton communities were diverse, variable in density, and dominated by diatoms. Periphyton rates of accrual on acrylic strips were low because of shading from the dense forest canopy. The phytoplankton community was dominated by detached periphytic algae. Variability of periphyton and phytoplankton could not be directly related to differences in land use history of the basin.

Two decades have passed since the Redwood Creek study began. Resampling selected sites could be useful to determine if there have been changes in the biota since logging has stopped and the watershed has been allowed to revegetate.

INTRODUCTION

Aquatic flora and fauna are an integral part of any stream system. Not only do they influence the quality of the water in a stream, but they, themselves, are influenced by the quality of the stream water. Aquatic organisms have therefore been used as indicators of stream quality (Hynes, 1960). In Redwood Creek, the aquatic flora and fauna are important elements of Redwood National Park. Historically, Redwood Creek and its estuary have supported a varied flora and fauna, some, such as anadromous salmonids, being of economic value. Realizing the value of this native aquatic flora and fauna, the National Park Service and the U.S. Geological Survey initiated a study in September 1973, in part to study aquatic plants and animals in the Redwood Creek drainage basin with particular emphasis on their types, abundance, and distribution. The study concluded in September 1975, and the results were reported by Averett and Iwatsubo (1975) and Iwatsubo and Averett (1981).

Redwood National Park was formed on October 2, 1968, when Congress passed Public Law 90–545. When the Redwood Park study began in September 1973, only about 10 percent of the Redwood Creek drainage basin was within Redwood National Park. Since 1973, the national parkland has been expanded by the addition of 48,000 acres in the Redwood Creek drainage basin, including all basins upstream to Copper Creek and Devils Creek (fig. 1). Moreover, a 14,569-hm^2 park protection zone includes Coyote, Panther, and Lacks Creeks to help ensure that land use practices will not have detrimental effects on downstream park areas. When this study began in 1973, much of the land upstream from the present Redwood National Park was privately owned. This land contained virgin redwood (*Sequoia sempervirens*) and was commercially clearcut and removed by tractor-yarding. This logging practice resulted in landslides, mass movement, fluvial erosion and deposition of sediment, increased water temperature, and changes in water-quality constituents. These problems were most noticeable in the 0.8-km-wide, 11.3-km-long Redwood Creek corridor in which this biological study effort was concentrated. In April 1975, 65 percent of the Redwood Creek drainage basin was cutover timberland.

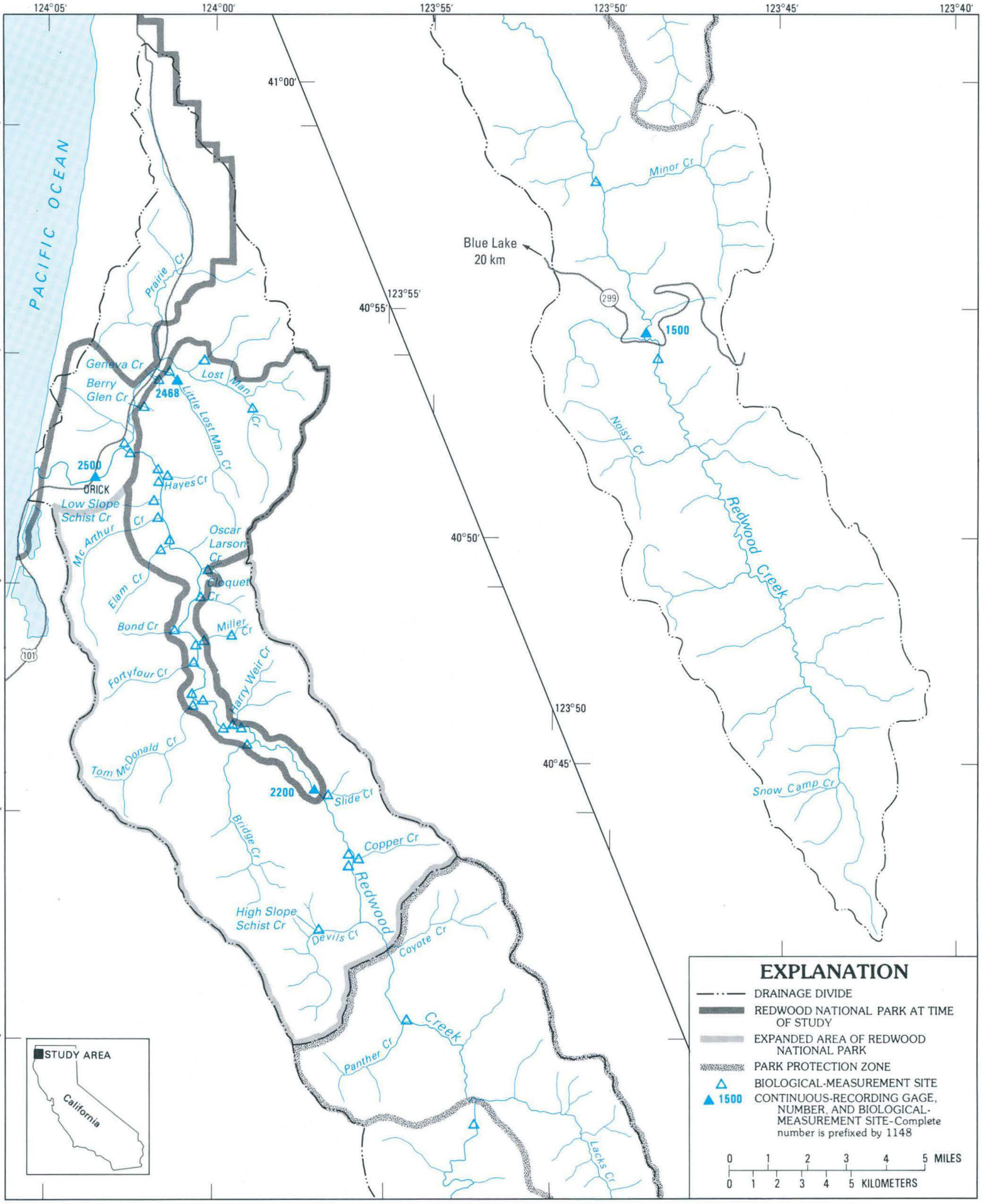

FIGURE 1.—Redwood Creek drainage basin showing main tributaries and sampling sites.

PURPOSE AND SCOPE

This paper summarizes the findings of the biological study as reported earlier by Averett and Iwatsubo (1975) and Iwatsubo and Averett (1981) and provides information that may be useful as the riparian vegetation in the Redwood Creek drainage basin matures, provides a medium for soil stabilization, and provides for more uniform flows in the main stem and tributary channels.

Bacteria, benthic invertebrates, fish, periphyton, and phytoplankton were the aquatic types included in the biological investigation. Most biological sampling was conducted during the receding flows of spring and during the low-flow periods of summer and early autumn in 1973, 1974, and 1975.

DESCRIPTION OF STUDY AREA

The Redwood Creek drainage basin covers 725 km^2 in the northern Coast Range of California. The basin has high relief, steep and unstable slopes, and narrow valleys and is elongated north-northwesterly. It is about 101 km long and 7.2 to 11.2 km wide. The overall drainage pattern is trellised, but some tributary drainage basins display a dendritic pattern. Altitude ranges from sea level at the mouth to 1,615 m at the upstream end. Relief is about 610 m in the north and greater than 900 m near the head of the basin. Average hillslope gradients range from 31 percent in the northern quarter to 34 percent in the southern quarter of the drainage basin. Flood plains along Redwood Creek are discontinuous and seldom exceed 60 m in width except for areas near Minor Creek, near the mouth of Lacks Creek, and near Orick (fig. 1).

Tributary channel gradients are steep, with average gradients ranging from 47 to 284 m/km. Streambed materials are extremely variable in size and range from large blocks of bedrock to fine sand and silt. However, pebbles and cobble gravel are the most prevalent materials. Small streamside slides and gullies are common. Numerous debris accumulations and large blocks of colluvium in the downstream end of many tributaries restricted the upstream migration of anadromous fish. Logging-related barriers to anadromous fish were uncommon, but in streams draining areas subject to recent timber harvest, coarse logging debris has accumulated on preexisting channel obstructions (Janda and others, 1975). Many tributaries are intermittent in their lower reaches during low-flow periods of summer and early autumn, restricting fish habitat to pooled areas. In the perennial streams, riffles and undercut banks provide additional habitat for fish.

Redwood Creek enters the Pacific Ocean 2.7 km west of Orick, Calif. At its mouth, the estuary is restricted by channelization (fig. 2). A small tributary enters the estuary from the north. During low-flow periods of summer and early autumn, the mouth of Redwood Creek is closed by an emergent sandbar. Anadromous fish are usually able to enter the stream only after the autumn freshets open the sandbar. In some years fishermen open the mouth of Redwood Creek, and in other years ranchers do so to reduce backwater flooding of pastures.

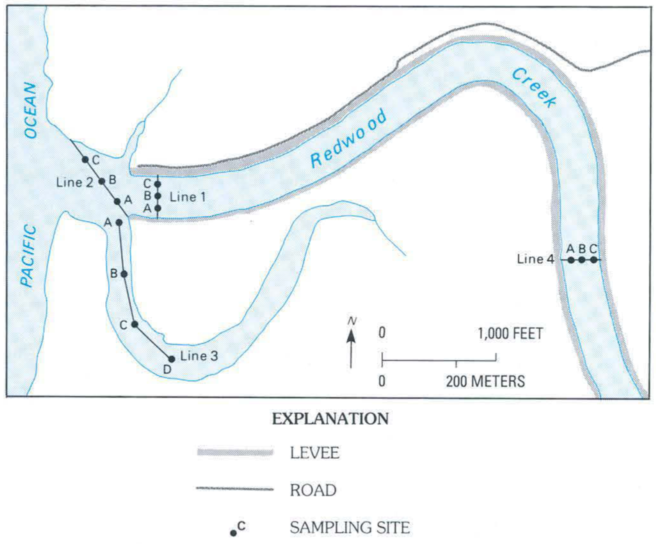

FIGURE 2.—Sampling stations on the Redwood Creek estuary.

The saltwater gradient of the Redwood Creek estuary has been described by Bradford and Iwatsubo (1978). Except during summer, the discharge of Redwood Creek is often sufficient to prevent saltwater from the Pacific Ocean from entering the estuary.

The dominant geologic unit of the Redwood Creek drainage basin is the Franciscan Complex (Strand, 1962, 1963), also considered as the Franciscan assemblage (Bailey and others, 1964). The eastern side of the Redwood Creek drainage basin, approximately upstream from Larry Damm Creek, is underlain by virtually unmetamorphosed Franciscan sedimentary rocks such as graywacke sandstone, mudstone, and conglomerate. The soil profile developed on this side of the drainage basin includes the Hugo, Kneeland, Melbourne, Mendocino, and Tyson soil series. On the west side of Redwood Creek, the drainage basin is underlain by mostly medium-gray, well-foliated quartz-mica schist, quartz-mica-feldspar schist, and quartz-graphite schist. These schists have weathered mostly to the Orick, Masterson, and Sites soil series (Iwatsubo and others, 1975). A transition zone exists between the unmetamorphosed sedimentary rocks of the east side of the drainage basin and the schists of the west side. Sheared rocks in this zone (Grogan, South Fork Mountain, and Bald Mountain faults and numerous small cross faults) are the parent material for the Atwell soil series, which is extremely unstable and susceptible to landslides.

Rantz (1969) estimated a basinwide precipitation total of 2,030 mm/yr. Average annual rainfall ranges from about 1,778 mm/yr at Orick to 2,540 or more near the head of the basin (Iwatsubo and others, 1975). Almost all of the precipitation in the drainage basin is rain. Air temperatures range from 15.6 °C in August to about 6.7 °C in January. In the southern part of the basin, air temperatures range from about 19.2 °C in July to about to 0 °C in January.

The highest flows in Redwood Creek occur between November and April, and lowest flows between August and October. Three continuous-recording streamflow gages are located on Redwood Creek. One is near Blue Lake (station 11481500), one at the South Park Boundary (station 11482200), and one at Orick (station 11482500). At the time of the study, Redwood Creek near Blue Lake, with 8 years of recorded data, had a maximum discharge of 346 m^3/s and a minimum of 0.08 m^3/s. Redwood Creek at South Park Boundary, with 5 years of recorded data, had maximum and minimum discharges of 935 and 0.13 m^3/s, respectively. Redwood Creek at Orick, with 24 years of recorded data, had maximum and minimum discharges of 1,430 and 0.26 m^3/s (U.S. Geological Survey, 1975).

Dissolved-solids concentrations in samples from Redwood Creek and tributaries ranged from 25 to 139 mg/L. Nitrogen and phosphorus concentrations were low but yet high enough to support modest algal production, especially in the main stem where insolation is high (Bradford and Iwatsubo, 1978).

SAMPLING STATIONS AND METHODS

SAMPLING STATIONS

Biological data were collected at 50 sampling sites in the Redwood Creek drainage basin. A brief description of the sampling stations and types of aquatic organisms collected was given in Iwatsubo and others (1976) and is repeated in brief form in table 1. Figure 1 shows the sampling sites along the Redwood Creek main stem, and figure 2 shows the sampling sites along the Redwood Creek estuary. The sampling sites were chosen on the basis of size of drainage area, location in reference to Redwood National Park, geology, and history of land use. The drainage basin of each sampling site had been categorized according to its history of land use or as a Redwood Creek main stem or estuary site; basin categories were (1) control (limited activities of man in the basin), (2) regenerating vegetation (after being logged), and (3) being logged in 1975.

METHODS

Biological assessments were made for fecal-coliform and fecal-streptococcal bacteria, benthic invertebrates, fish, periphyton and phytoplankton. Iwatsubo and Averett (1981) also reported on seston measurements. All techniques and methods used in the study conformed with those described by Slack and others (1973). Most of the aquatic organisms were collected during the receding-flow periods of spring and the low-flow periods of summer and early autumn. In winter, high streamflow limited biological sampling to the collection of bacteria. Water samples for bacterial determinations were collected in sterilized glass containers. The membrane-filter incubation method, using 0.45-μm pore-size membrane filters, was used to determine the densities of bacterial colonies.

Benthic invertebrates were collected with a Surber sampler in the stream or with an Ekman dredge in the Redwood Creek estuary. Benthic invertebrates from the 1973 samples were separated from detritus in the field by using forceps. Invertebrates from 1974 and 1975 samples were separated from detritus in the laboratory by the flotation technique described by Anderson (1959). Identification and enumeration of benthic invertebrates were made by using the following taxonomic references: Ross (1944); Gaufin and Tarzwell (1952); Pennak (1953); Usinger (1956); Edmondson (1959); Jewett (1960); Edmunds and others (1963); Johannsen (1969); Borror and DeLong (1971); Mason (1973); and Smith and Carlton (1975).

Fish were collected by using a 15.2-m seine with a 6.4-mm mesh opening, or a backpack electrofishing unit. Tricaine methanesulfonate was used to anesthetize salmonids prior to identification and determination of length and weight.

Periphyton were collected on artificial substrates made of clear acrylic strips measuring 102 mm by 457 mm. Substrates were usually given 8 to 10 weeks for periphyton colonization before removal. Identification and biomass analysis were done in the laboratory.

Water samples for phytoplankton analysis were collected in 1-L polyethylene bottles and preserved with Lugol's solution. Phytoplankton were identified and enumerated by the inverted microscope method (Slack and others, 1973).

BACTERIA

Sampling for bacteria was limited to fecal-coliform and fecal-streptococcal types. These two types of bacteria are recognized as indicators of the sanitary quality of water and so were measured in this study. Fecal-coliform and fecal-streptococcal bacterial densities were low except in Prairie Creek, a lower tributary to Redwood Creek. A State park, fish hatchery, lumber mill, and residential area are located above this sampling site and doubtless contributed to the higher bacterial counts of 220 and 750 colonies per 100 milliliters (col/100 mL).

Excluding Prairie Creek, the other tributaries to Redwood Creek that were sampled for bacteria had colony counts ranging from <1 to 30 col/100 mL for fecal-coliform bacteria and from <1 to 190 col/100 mL for fecal-streptococcal bacteria. In the Redwood Creek main stem, densities of fecal-coliform and fecal-streptococcal bacteria ranged from <1 to 47 and 1 to 280 col/100 mL of water, with mean densities of 13 and 35 col/100 mL, respectively. Additional counts and detailed results are given in Iwatsubo and Averett (1981).

BENTHIC INVERTEBRATES

The benthic invertebrate community was diverse in the Redwood Creek drainage basin and consisted of 144 taxa from the main stem and tributaries and 30 taxa from the estuary. Insects composed 68.6 percent of the benthic invertebrates collected in the Redwood Creek drainage basin (table 2). Diptera was the dominant order, constituting 22.0 percent of the benthic invertebrates, and was followed by Ephemeroptera (17.7 percent), Coleoptera (13.2 percent), Trichoptera (11.3 percent), Plecoptera (4.3 percent), and Collembola, Hymenoptera, Lepidoptera, Neuroptera, and Odonata (<0.1 percent for each order).

Representatives of the Phyla Mollusca (snails and clams), Nematoda (roundworms), and Platyhelminthes (flatworms) also were collected. Of these three phyla, Nematoda were the most abundant (especially in the estuary) but represented only 0.7 percent of the total invertebrates collected.

Water mites, Acari, were the only members of the Class Arachnoidea collected in the basin. Crustaceans (Class Crustacea) occurred primarily in samples from the Redwood Creek estuary. The estuarian scud *Corophium* was the dominant crustacean and represented 98.4 percent of the class in the Redwood Creek estuary. Minor numbers of *Anisogammarus* and *Stygobromus* (freshwater scuds), *Exosphaeroma* (aquatic sow bug), and an unidentified group also were collected. A complete taxanomic list for all benthic invertebrates in the Redwood Creek drainage basin to the generic level is given in Iwatsubo and Averett (1981).

The variations in the number of benthic invertebrates collected during the study reflected seasonal changes, but these variations were also greatly influenced by stream discharge and movement of the streambed. Data from the 1973 samples on benthic invertebrates should not be compared with the 1974 and 1975 data because the 1973 samples were sorted from sample detritus in the field, and the 1974 and 1975 samples were sorted in the laboratory. The field sorting resulted in a lower number of benthic invertebrates counted at each sampling site.

Along the Redwood Creek main stem, the number of benthic invertebrates collected during autumn 1973 ranged from 330 to 3,600 invertebrates per square meter (inverts/m^2) (table 3). The number of benthic invertebrates collected from Redwood Creek tributaries ranged from 90 to 4,400 inverts/m^2. Samples from Little Lost Man Creek ("control" land use class) had the largest number of benthic invertebrates (4,400 inverts/m^2), whereas the mouth of Miller Creek (logged drainage basin) had the smallest number (90 inverts/m^2).

On October 23, 1973, 157 mm of rain was recorded at the Orick-Prairie Creek precipitation station just north of Orick, Calif. (U.S. National Oceanic and Atmospheric Administration, 1973). Stream discharges at Redwood Creek near Blue Lake, at South Park Boundary, and at Orick peaked at 144, 305.8, and 459 m^3/s, respectively, on October 23, 1973 (U.S. Geological Survey, 1975). Because of increased water discharge, benthic invertebrate samples could not be collected from the Redwood Creek main-stem sites after the October 1973 storm; however, six tributaries—Harry Weir Creek, Tom McDonald Creek, Miller Creek at mouth, Miller Creek near Orick, Hayes Creek, Lost Man Creek, and Little Lost Man Creek—were resampled. The results indicated a marked decrease of benthic invertebrates in the samples collected after the storm (fig. 3).

Percentage decreases ranged from 20 at Hayes Creek to 93 at Little Lost Man Creek and averaged 62. Stream basins classified as "control" (Hayes Creek and Little Lost Man Creek) that were resampled after the October 23, 1973, storm had a mean decrease of 56 percent in the number of benthic invertebrates collected. Stream basins classified as "being logged" (Harry Weir Creek, Tom McDonald Creek, and Miller Creek at mouth) had a mean decrease of 60 percent. Lost Man Creek was the only stream basin classified as "regenerating vegetation" that was resampled following the storm, and it had an 81-percent decrease in the number of benthic invertebrates.

The variations in the number of benthic invertebrates collected from the Redwood Creek drainage basin in 1974 and 1975 were similar to the 1973 findings. Invertebrates in the spring samples represented individuals that were able to overwinter, as well as a few recently hatched individuals. In the autumn, when streamflows were lowest, samples of benthic invertebrates again were collected. The invertebrates collected in the autumn represented those organisms that had grown but had not emerged throughout the summer, as well as individuals

TABLE 1.—*Description of biological sampling sites, Redwood Creek drainage basin*

[From Iwatsubo and others (1976). B=bacteria; BI=benthic invertebrates; F=fish; P_1=phytoplankton; P_2=periphyton; S=seston; —, not determined]

Sampling sites	Drainage area (km^2)	Stream order	Streambed composition[1]	Canopy (estimated, in percent)[2]	Biological sampling	Basin classification[3]
Redwood Creek above Highway 299 bridge	171	5	Small cobbles, gravel, sand, and silt.	5	BI	Main stem
Redwood Creek near Blue Lake	175	5	....do....	30	B, BI, S	Do.
Redwood Creek at Redwood Valley Bridge, near Blue Lake	249	5	Cobbles, gravel, sand, and silt.	<1	B, BI, F, S	Do.
Redwood Creek at Lower End, Redwood valley	318.6	6	Small cobbles, mainly gravel, sand, and some silt.	5	BI	Do.
Redwood Creek above Panther Creek, near Orick	388.5	6	Cobbles, gravel, and sand.	10	B, BI, S	Do.
High Slope Schist Creek near Orick	1.37	2	Boulders, cobbles, some gravel, and sand.	98	BI, S	Control.
Redwood Creek above Copper Creek, near Orick	45.8	6	Cobbles, gravel, and sand.	<1	BI, F	Main stem.
Copper Creek near Orick	7.20	4	Cobbles, gravel, much sand, and silt.	<1	BI, F, S	Being logged in 1975.
Redwood Creek below Copper Creek, near Orick	466	6	Some boulders, mainly cobbles, gravel, and sand.	<1	BI	Main stem.
Slide Creek near Orick	3.00	3	Cobbles, gravel, sand, and silt.	95	BI	Being logged in 1975.
Redwood Creek at South Park Boundary, near Orick	479	6	Cobbles, some gravel, and sand.	5	B, BI, P_1, P_2, S	Main stem.
Bridge Creek near Orick	30.0	4	Cobbles, little gravel, sand, and silt.	3	BI, F, P_1, P_2, S	Being logged in 1975.
Redwood Creek above Harry Weir Creek, near Orick	523	6	Small cobbles, mainly gravel and sand, and some silt.	5	B, S	Main stem.
Harry Weir Creek near Orick	7.67	4	Cobbles, little gravel, sand, and silt.	95	B,BI, F, P_1, P_2, S	Being logged in 1975.
Redwood Creek below Harry Weir Creek, near Orick	531	6	Small cobbles, mainly gravel and sand, and some silt.	5	BI, F	Main stem.
Redwood Creek above Tom McDonald Creek, near Orick	534	6	Small cobbles, gravel, and sand.	5	BI	Main stem.
Tom McDonald Creek near Orick	17.8	4	Few boulders, cobbles, some gravel, sand, and silt.	50	BI, F, S	Being logged in 1975.
Redwood Creek below Tom McDonald Creek, near Orick	552	6	Cobbles and sand.	5	BI	Main stem.
Fortyfour Creek near Orick	8.00	3	—	—	S	Being logged in 1975.
Redwood Creek above Miller Creek, near Orick	565	6	Small cobbles and gravel, sand, and silt.	5	BI	Main stem.
Miller Creek near Orick	1.73	3	Small cobbles, gravel, sand, and silt.	70	B, BI, P_1, P_2, S	Being logged in 1975.
Miller Creek at mouth, near Orick	3.52	3	....do....	85	B, BI, F, P_1, P_2, S	Do.
Bond Creek near Orick	3.55	3	—	—	S	Do.
Cloquet Creek near Orick	2.95	2	Small cobbles, gravel, sand, and silt.	60	BI	Do.
Redwood Creek below Oscar Larson Creek, near Orick	583	6	Small cobbles, mainly gravel and sand, and silt.	5	BI	Main stem.
Elam Creek near Orick	6.45	3	Small cobbles, gravel, sand, heavily coated with oxidized material.	90	BI, S	Being logged in 1975.
Redwood Creek below Elam Creek, near Orick	593	6	Few cobbles, some gravel, mainly sand.	5	BI	Main stem.
McArthur Creek near Orick	9.66	3	—	—	S	Being logged in 1975.

TABLE 1.—*Description of biological sampling sites, Redwood Creek drainage basin*—Continued

[B=bacteria; BI=benthic invertebrates; F=fish; P_1=phytoplankton; P_2=periphyton; S=seston; —, not determined]

Sampling sites	Drainage area (km^2)	Stream order	Streambed composition[1]	Canopy (estimated, in percent)[2]	Biological sampling	Basin classification[3]
Low Slope Schist Creek near Orick	.49	2	—	—	S	Control.
Redwood Creek above Hayes Creek, near Orick	609	6	Large cobbles, gravel, and sand.	<1	BI, F, P_1	Main stem.
Hayes Creek near Orick	1.46	3	Cobbles, gravel, sand, and silt.	85	B, BI, P_1, P_2, S	Control.
Redwood Creek below Hayes Creek, near Orick	592	6	Cobbles, gravel, mainly sand.	<1	BI, F	Main stem.
Redwood Creek above Prairie Creek, near Orick	614	6	—	—	B	Do.
Prairie Creek near Orick	103	5	—	—	B	—
Lost Man Creek near Orick	10.3	4	Cobbles, little gravel, sand, and silt.	60	B, BI, P_1, P_2, S	Regenerating.
Larry Damm Creek near Orick	4.84	3	—	—	S	Do.
Little Lost Man Creek at site 2, near Orick	8.96	4	Cobbles, gravel, sand, and some silt.	60	B, BI, P_1, P_2, S	Control.
Little Lost Man Creek near Orick	9.45	4	Cobbles, gravel, sand, and silt.	40	BI, F, S	Do.
Geneva Creek near Orick	.20	2	Small cobbles, gravel, and sand.	95	BI, S	Regenerating.
Berry Glen Creek near Orick	1.03	2	—	—	S	Do.
Redwood Creek at Orick	720	6	—	<1	B, P_2, S	Main stem.
Redwood Creek estuary, site 1A, near Orick	730	6	Sand and silt.	<1	BI	estuary.
Redwood Creek estuary, site 1B, near Orick	730	6	....do....	<1	BI, P_2	Do.
Redwood Creek estuary, site 1C, near Orick	730	6	....do....	<1	BI	Do.
Redwood Creek estuary, site 2A, near Orick	730	6	....do....	<1	BI	Do.
Redwood Creek estuary, site 2B, near Orick	730	6	....do....	<1	BI, P_2	Do.
Redwood Creek estuary, site 2C, near Orick	730	6	....do....	<1	BI	Do.
Redwood Creek estuary, site 3A, near Orick	730	6	....do....	<1	BI	Do.
Redwood Creek estuary, site 3B, near Orick	730	6	....do....	<1	BI, P_2	Do.
Redwood Creek estuary, site 3C, near Orick	730	6	....do....	<1	BI	Do.

[1] Field observations not verified by laboratory analysis.

[2] Streambed exposure to direct sunlight at each station was influenced by deciduous riparian vegetation.

[3] The drainage basin of each sampling site is classified according to its history of land use or as a Redwood Creek main stem or estuary site. "Control" refers to areas of limited human activity and influence.

TABLE 2.—*Percentage taxonomic composition of benthic invertebrates collected from the Redwood Creek drainage basin*

[Taxonomic classification is by phylum, class, and order. The sum of the phylum percentages equaled 100 percent before rounding]

Taxonomic classification	Taxonomic composition, in percent		
	Main stem and tributaries	Estuary	Main stem, tributaries, and estuary
Annelida	1.2	0.6	1.0
Arthropoda	98.8	96.5	98.2
Arachnoidea	13.4	.4	10.1
Crustacea	.1	76.9	19.5
Insecta	85.3	19.2	68.6
Coleoptera	17.6	.2	13.2
Collembola	<.1	<.1	<.1
Diptera	23.1	18.9	22.0
Ephemeroptera	23.6	.1	17.7
Hymenoptera	<.1	.0	<.1
Lepidoptera	<.1	.0	<.1
Neuroptera	<.1	.0	<.1
Odonata	.1	.0	<.1
Plecoptera	5.7	.1	4.3
Trichoptera	15.1	.0	11.3
Mollusca	<.1	.0	<.1
Nematoda	<.1	2.9	.7
Platyhelminthes	<.1	<.1	<.1

from newly hatched eggs. At almost every sampling station, the autumn samples contained larger numbers of benthic invertebrates than did the spring samples.

Spatial variations in the number of benthic invertebrates collected from the Redwood Creek main stem (excluding the estuary) during spring 1974 and 1975 were low (table 3). There was little difference between the number of benthic invertebrates collected from the upstream and downstream reaches of Redwood Creek. In contrast, the autumn 1974 and 1975 samples showed wide variation in numbers of benthic invertebrates collected from the Redwood Creek main stem, ranging from 8,300 to 50,000 inverts/m^2.

In March 1975, a major storm in the study area resulted in flood discharges and attendant degradation and aggradation of the streambeds in the Redwood Creek drainage basin. The peak discharge for Redwood Creek at Orick of 1,422 m^3/s almost equaled the record flood peak discharge of 1,430 m^3/s on December 22, 1964. The number of benthic invertebrates collected in the samples during spring 1975 was low but somewhat similar to the number in the spring 1974 samples when the peak winter discharge reached 702 m^3/s. The benthic

TABLE 3.—*Number of benthic invertebrates per square meter in samples from the Redwood Creek drainage basin*

[–, not sampled]

Station name	1973		1974		1975	
	Autumn	After Oct. 23 storm	Spring	Autumn	Spring	Autumn
Redwood Creek above Highway 299	1,400	–	310	50,000	–	–
Redwood Creek near Blue Lake	1,900	–	250	22,000	590	33,000
Redwood Creek at Redwood Valley Bridge, near Blue Lake	3,200	–	280	34,000	–	–
Redwood Creek at lower end, Redwood Valley	830	–	190	15,000	–	–
Redwood Creek above Panther Creek, near Orick	3,600	–	370	35,000	–	–
High Slope Schist Creek near Orick	180	–	970	2,200	1,100	1,200
Redwood Creek above Copper Creek, near Orick	–	–	180	29,000	–	–
Copper Creek near Orick	1,800	–	1,500	38,000	1,200	51,000
Redwood Creek below Copper Creek	1,300	–	–	–	–	–
Slide Creek near Orick	610	–	1,400	7,700	–	–
Redwood Creek at South Park Boundary, near Orick	740	–	430	13,000	910	39,000
Bridge Creek near Orick	980	–	1,100	9,500	1,400	22
Harry Weir Creek near Orick	320	110	1,800	3,800	1,100	1,000
Redwood Creek below Harry Weir Creek, near Orick	450	–	430	17,000	–	–
Redwood Creek above Tom McDonald Creek, near Orick	–	–	420	15,000	560	19,000
Tom McDonald Creek near Orick	1,400	380	1,200	9,300	600	8,200
Redwood Creek below Tom McDonald Creek, near Orick	380	–	–	–	–	–
Redwood Creek above Miller Creek, near Orick	450	–	420	12,000	–	–
Miller Creek near Orick	–	200	4,400	5,500	6,000	13,000
Miller Creek at mouth, near Orick	90	52	580	2,300	1,200	4,500
Cloquet Creek near Orick	520	–	3,500	10,000	–	–
Redwood Creek below Oscar Larson Creek, near Orick	1,100	–	990	21,000	–	–
Elam Creek near Orick	440	–	1,000	1,300	–	–
Redwood Creek below Elam Creek, near Orick	330	–	670	15,000	1,100	8,400
Redwood Creek above Hayes Creek, near Orick	–	–	2,000	34,000	960	8,300
Hayes Creek near Orick	150	120	1,200	14,000	5,000	9,200
Redwood Creek below Hayes Creek, near Orick	720	–	–	–	–	–
Lost Man Creek near Orick	530	100	1,000	7,000	4,100	6,300
Little Lost Man Creek at site 2, near Orick	–	–	4,100	15,000	6,900	26,000
Little Lost Man Creek near Orick	4,400	290	4,200	–	–	–
Geneva Creek near Orick	–	–	1,800	–	–	–
Redwood Creek estuary, line 1A, near Orick[1]	–	–	2,800	–	–	–
Redwood Creek estuary, line 1B, near Orick[1]	–	–	2,300	79,000	–	–
Redwood Creek estuary, line 1C, near Orick[1]	–	–	1,700	–	–	–
Redwood Creek estuary, line 2A, near Orick[1]	–	–	15,000	–	–	–
Redwood Creek estuary, line 2B, near Orick[1]	–	–	1,900	68,000	–	–
Redwood Creek estuary, line 2C, near Orick[1]	–	–	1,100	–	–	–
Redwood Creek estuary, line 3A, near Orick[1]	–	–	11,000	–	–	–
Redwood Creek estuary, line 3B, near Orick[1]	–	–	2,900	45,000	–	–
Redwood Creek estuary, line 3C, near Orick[1]	–	–	26,000	–	–	–

[1] Estuary lines are shown in figure 2.

invertebrate density in Redwood Creek samples significantly increased in the autumn 1974 and 1975 samples. This increase is illustrated for eight sampling sites in figure 4. This dramatic increase in benthic invertebrates following major spring storms illustrates the ability of the benthic-invertebrate community to recolonize a stream. Benthic-invertebrate densities in the tributaries to Redwood Creek revealed a similar response in recolonization following the March 1975 flood. However, benthic-invertebrate densities in the tributary streams were more variable than in the Redwood Creek main stem.

Diversity indexes from the equation of Wilhm and Dorris (1968) and a similarity index derived by Sorenson (Odum, 1971) were calculated for use in a comparison of sampling stations (Iwatsubo and Averett, 1981). Diversity index values ranged from 1.00 to 4.09, with most between 2.50 and 3.50. There was no discernible pattern with the diversity index values, except that tributaries draining unlogged basins often had higher diversity index values than tributaries draining logged basins.

Most of the similarity index values were greater than 0.5 (the Sorenson index ranges from 0 to 1), and many were greater than 0.6. Similarity index values were not

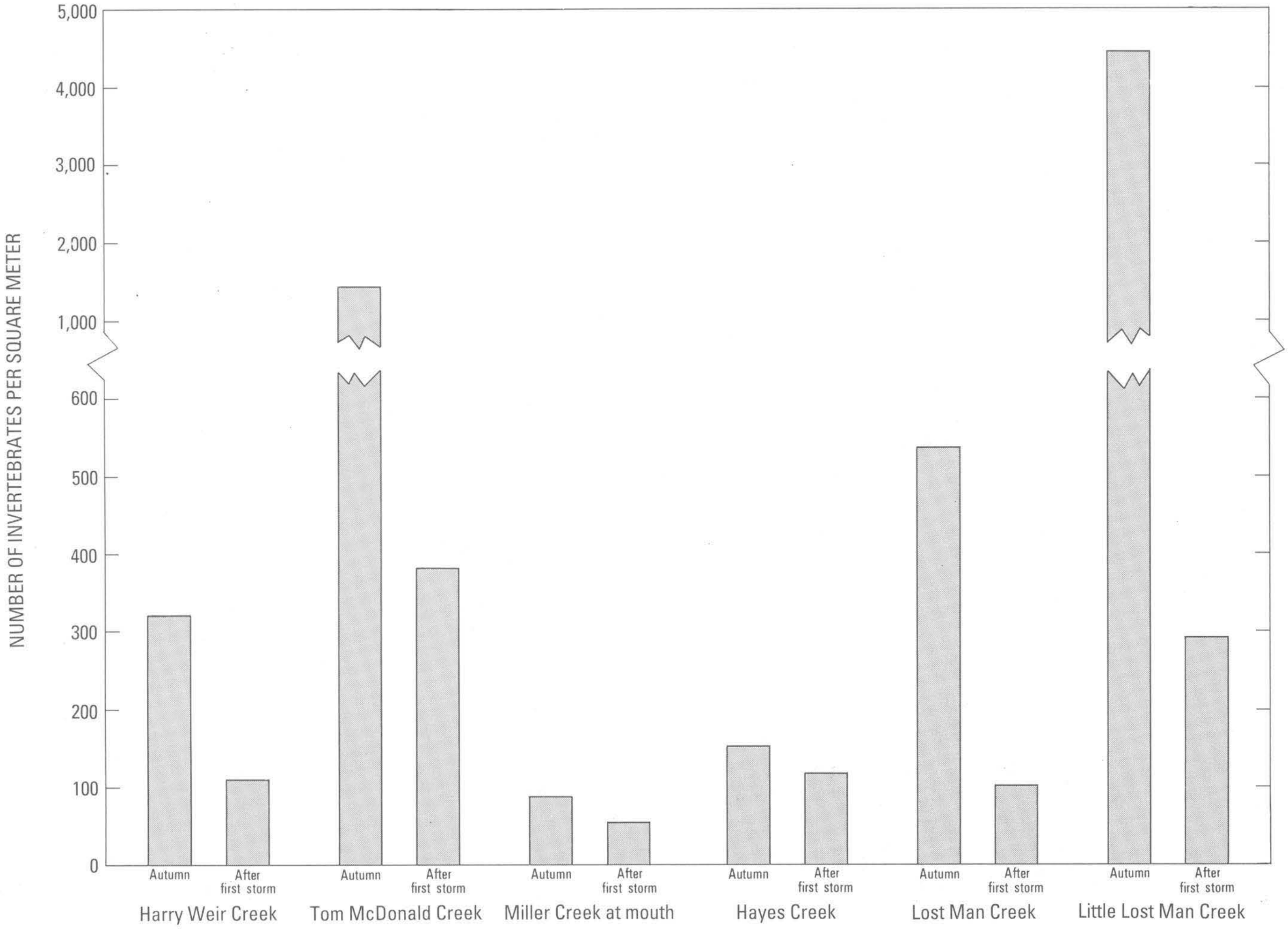

FIGURE 3.—Number of benthic invertebrates per square meter in six tributary streams to Redwood Creek in the autumn of 1973 and after the October 23, 1973, storm.

greatly altered following the October 1973 and March 1975 floods.

Cummins (1973) classified benthic invertebrates into four major functional groups based on feeding mechanisms: (1) shredders, which reduce coarse particulate organic matter (greater than 1 mm in diameter) such as leaves, twigs, bark, and flowers, into fine particulate organic matter (less than 1 mm in diameter); (2) collectors, which feed on this fine particulate organic matter; (3) grazers (scrapers), which feed on periphyton; and (4) predators, which feed on other animals in the stream. There are limitations to the functional group concept, mainly that some organisms occupy different functional groups at different life stages. Also, some organisms are difficult to place into a discrete functional group. Nevertheless, the functional group concept is useful in placing organisms into an "occupational" category and assessing the stream environment in terms of habitat stability for the benthic invertebrate community.

Iwatsubo and Averett (1981) listed nine functional group categories including the four listed above by Cummins (1973, 1974) and another five subcategories—micropredators, collector-grazers, collector-predators, collector-shredders, and grazer-shredders. Iwatsubo and Averett also presented a table showing the percentage of each type in the sample from each site. The predator and collector groups were by far the most numerous.

Table 4 is a compilation of the findings reported by Iwatsubo and Averett (1981). The representative sampling sites were from three control streams, two mainstem sites on Redwood Creek, one stream draining a regenerating forest, and three streams that were being logged in 1975 when the samples were collected.

The results indicate that the greatest percentage of organisms were in the collector category, followed by the predator category. Benthic organisms in the grazer category were third in percentage abundance, commonly less than 5 percent and never exceeding 30.8 percent.

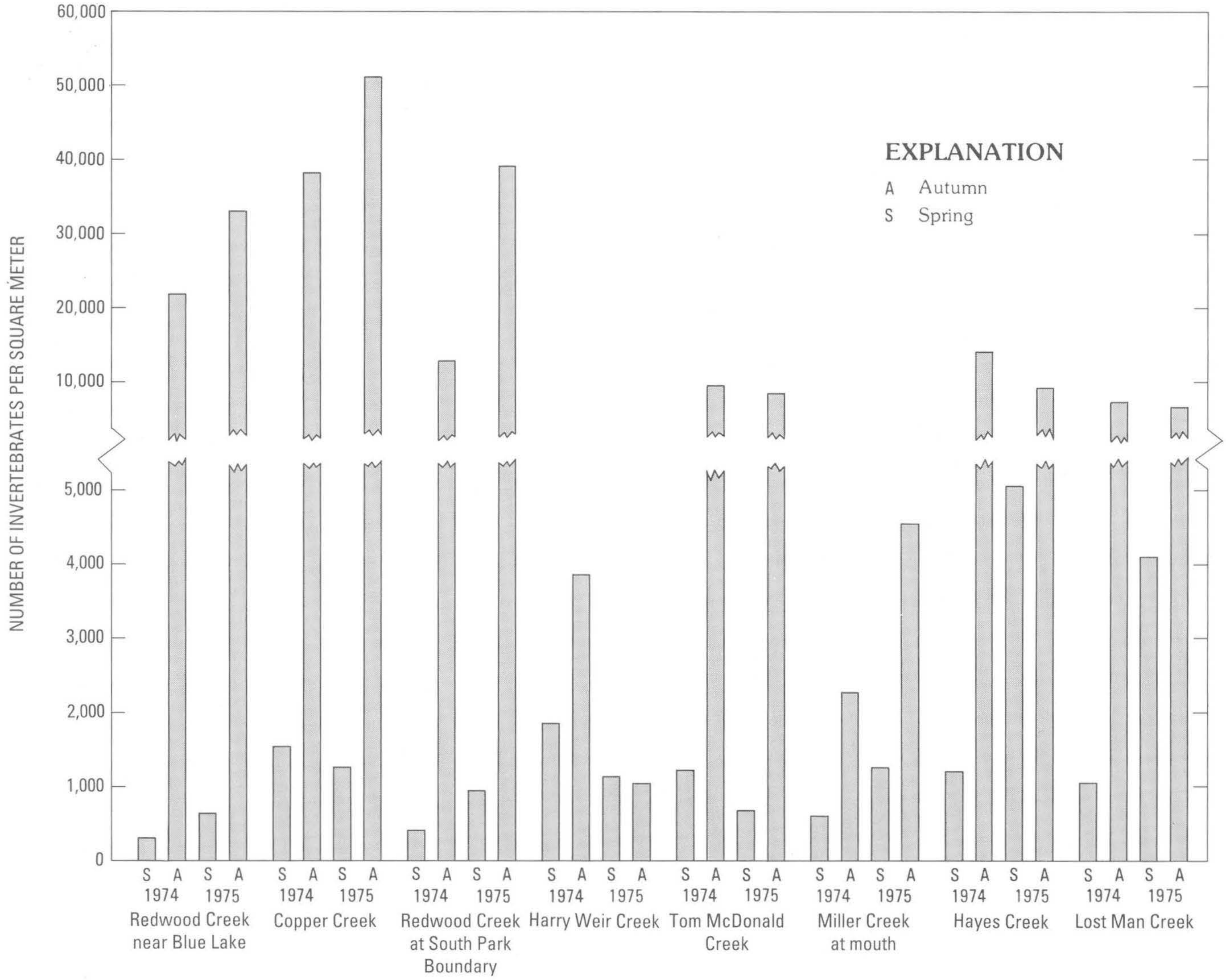

FIGURE 4.—Comparison of numbers of benthic invertebrates at eight sampling sites in the Redwood Creek drainage basin in the spring and autumn of 1974 and 1975.

The percentage of shredders in the samples was commonly less than 1.

The Redwood Creek drainage basin primarily contains coniferous trees. Thus, it is not surprising that collectors, those organisms that feed upon fine particulate organic matter, were the most abundant category in the samples. The dense canopy of the redwood forest reduces insolation and hence periphyton production, which limits the number of grazers in the samples. Predators were present in percentages ranging from 3.0 to 57.5. In only one instance was the predator percentage greater than 50 percent, an indication of community instability; however, these particular results could have been due to a sampling error. There were only small differences between percentage composition of the functional groups of benthic invertebrates collected from logged and unlogged tributary drainage basins.

FISH

The Pacific coastal streams, including Redwood Creek, have historically contained a varied and abundant fish fauna. Anadromous salmonids have received the greatest attention because of their size and their commercial and sport value. However, there are many resident fishes in the streams who do not seek saltwater for an ocean-growth period.

Of the 1,066 fish that were captured during the study, the species composition was steelhead trout, *Oncorlynchus mykiss* (69.6 percent); Humboldt sucker, *Catostomus humboldtianus* (10.6 percent); threespine stickle-

TABLE 4.—*Percentages of functional groups for benthic invertebrates from selected sampling stations in the Redwood Creek drainage basin*
[Modified from Iwatsubo and Averett (1981)]

Station name	Date	Basin classification[1]	Predator	Collector	Shredder	Grazer	Unknown	Individuals per square meter
High Slope Schist Creek near Orick	5–26–74	Control	39.1	60.4	0.5	0.0	0.0	970
	9–22–74		42.9	52.5	3.9	.0	.6	2,200
	5–30–75		43.4	53.3	3.4	.0	.0	1,100
	9–18–75		33.8	64.5	1.6	.1	.0	1,200
Hayes Creek near Orick	5–15–74	....do....	19.2	78.9	.9	.0	.0	1,200
	9–14–74		15.4	83.7	.3	.0	1.1	14,000
	5–29–75		19.3	80.1	.6	.0	.0	5,000
	9–20–75		19.2	80.8	.5	.2	.0	9,200
Little Lost Man Creek at site 2, near Orick.	5–10–74	....do....	17.6	81.4	.7	.3	.0	4,100
	9–14–74		27.9	66.8	3.0	.9	.0	15,000
	6–2–75		23.6	74.5	.4	1.6	.0	6,900
	9–20–75		16.8	78.0	1.1	3.3	.0	26,000
Redwood Creek near Blue Lake	5–8–74	Main stem	57.5	41.3	.0	.0	1.2	310
	9–18–74		12.6	86.5	.1	.8	.0	22,000
	5–27–75		33.3	66.2	.0	.5	.0	590
	9–14–75		10.4	88.8	.2	.7	.0	33,000
Redwood Creek above Hayes Creek, near Orick.	5–15–74	....do....	19.4	80.0	.3	.2	.2	2,000
	9–14–74		24.6	74.3	.1	1.0	.0	34,000
	5–28–75		30.9	61.5	.2	7.3	.0	960
	9–19–75		42.5	46.4	.1	11.0	.0	8,300
Lost Man Creek near Orick	5–10–74	Regenerating vegetation after logging.	20.2	79.8	.0	.0	.0	530
	9–15–74		24.6	70.3	1.0	3.0	1.1	7,000
	6–2–75		6.9	84.7	.0	8.4	.0	4,100
	9–17–75		18.3	50.4	.5	30.8	.0	6,300
Copper Creek near Orick	5–9–74	Being logged in 1975	12.9	86.7	.3	.0	.0	1,500
	9–19–74		18.0	80.3	.5	1.2	.0	38,000
	2–28–75		15.8	84.2	.0	.0	.0	1,200
	9–15–75		32.0	65.6	.4	2.0	.0	51,000
Harry Weir Creek near Orick	5–13–74	....do....	22.6	77.2	.2	.0	.0	1,800
	9–16–74		16.3	81.8	.0	1.0	.9	3,800
	6–1–75		23.0	77.0	.0	.0	.0	1,100
	9–16–75		25.1	73.0	.0	1.9	.0	1,000
Miller Creek near Orick	5–10–74	....do....	5.6	94.0	.4	.0	.0	4,400
	9–17–74		11.0	85.3	.3	2.6	.8	5,500
	5–31–75		3.5	95.3	.1	1.1	.0	6,000
	9–21–75		3.0	96.8	.0	.2	.0	13,000

[1] The drainage basin of each sampling station is classified according to its history of land use or as a Redwood Creek main stem or estuary station. "Control" refers to areas of limited human activity and influence.

back, *Gasterosteus aculeatus* (10.3 percent); coastrange sculpin, *Cottus aleuticus* (5.8 percent); coho salmon, *Oncorhynchus kisutch* (3.4 percent); and chinook salmon, *Oncorhynchus tshawytscha* (0.3 percent). The Pacific lamprey, adult and ammocete, *Entosphenus tridentatus*, was observed also.

Fish species reported to inhabit the Redwood Creek drainage basin but that were not captured during the study include resident rainbow trout, *Salmo gairdneri*; coastal cutthroat trout, *S. clarki clarki*; and eulachon, *Thaleichthys pacificus* (DeWitt, 1964). The steelhead trout is an anadromous rainbow trout, whereas the rainbow trout is a permanent freshwater resident.

A summary of fish inventories including length and length-weight relations in the Redwood Creek drainage basin is given in table 5. The seasonal percentage composition of fish captured in the basin revealed that steelhead trout were most abundant in the summer of 1974 and 1975 and the autumn of 1975. Steelhead trout and coho salmon were equally abundant in the spring of 1974 (fig. 5).

The effect of the March 18, 1975, flood on the fisheries resource of the Redwood Creek drainage basin is not known; however, the absence of salmon fry in the 1975 samples could be attributed to the flood. The spawning of chinook and coho salmon is usually completed by February (California Department of Water Resources, 1965). Absence of salmon fry during the 1975 fish-inventory survey could indicate a high mortality of salmon embryos developing in the spawning gravel during the flood.

TABLE 5.—*Summary of fish inventories, Redwood Creek drainage basin*

[—, not determined; $\bar{x}$=mean; n=number of measurements]

Sampling area	Date	Type of fish captured	Type composition (percent)	Fork length (cm)			Weight (g)		
				Range	$\bar{x}$	n	Range	$\bar{x}$	n
Redwood Creek near Redwood Valley Bridge....	8–2–74	Steelhead trout	51	2.6–14.5	6.7	109	0.2–37.1	5.1	109
		Humboldt sucker	18	—	—	24	—	—	—
		Threespine stickleback	.7	—	—	1	—	—	—
	7–25–75	Humboldt sucker	59	—	—	19	—	—	—
		Steelhead trout	41	4.3–5.8	4.9	13	—	—	—
	9–26–75	Steelhead trout	100	7.2–16.1	10.3	50	4.2–56.1	17.2	50
		Humboldt sucker[1]	—	—	—	—	—	—	—
		Pacific lamprey-ammocete[1]	—	—	—	—	—	—	—
Redwood Creek near mouth of Copper Creek....	7–24–75	Steelhead trout	100	2.8–5.6	4.4	11	—	—	—
		Humboldt sucker	74	—	—	14	—	—	—
		Steelhead trout	26	6.3–11.0	8.8	5	3.5–18.5	10.9	5
Copper Creek near mouth	7–24–75	Steelhead trout	100	2.5–9.4	3.8	42	—	—	—
	9–24–75	....do....	100	4.3–7.3	5.3	40	1.0–5.1	2.4	40
Bridge Creek near mouth......................	5–23–74	Coastrange sculpin	100	—	—	3	—	—	—
	7–17–75	Steelhead trout	100	2.5–13.5	6.0	16	—	—	—
	9–25–75	Steelhead trout	80	5.0–12.6	6.8	48	1.5–22.6	4.8	48
		Coastrange sculpin	18	—	—	11	—	—	—
		Humboldt sucker	1.7	—	—	1	—	—	—
Harry Weir Creek near mouth	5–23–74	Steelhead trout	75	3.9–11.3	8.1	3	<1–18.0	—	3
		Coastrange sculpin	25	—	—	1	—	—	—
	7–16–75	Steelhead trout	100	3.0–4.8	3.9	16	—	—	—
	9–25–75	Steelhead trout	93	4.1–11.7	5.3	50	.5–21.4	2.2	50
		Coastrange sculpin	5.6	—	—	3	—	—	—
		Humboldt sucker	1.8	—	—	1	—	—	—
Redwood Creek below Harry Weir Creek	7–30–74	Steelhead trout	58	4.2–9.3	6.0	60	.5–9.1	2.3	60
		Threespine stickleback	26	—	—	27	—	—	—
		Humboldt sucker	15	—	—	15	—	—	—
		Coastrange sculpin	.9	—	—	1	—	—	—
Tom McDonald Creek near mouth	5–24–74	Coho salmon	78.9	3.2–4.9	3.9	15	—	<1	15
		Coastrange sculpin	15.8	—	—	3	—	—	—
		Threespine stickleback	5.3	—	—	1	—	—	—
	7–21–75	Steelhead trout	64.7	2.8–17.3	5.7	44	—	—	—
		Coastrange sculpin	27.9	—	—	19	—	—	—
		Threespine stickleback	7.4	—	—	5	—	—	—
	9–25–75	Steelhead trout	89.3	5.1–15.8	6.9	50	.7–44.2	5.26	50
		Coastrange sculpin	10.7	—	—	6	—	—	—
		Pacific lamprey-ammocete[1]	—	—	—	—	—	—	—
Miller Creek near mouth	7–24–74	Steelhead trout	66.7	4.7–9.5	7.1	2	<1–8.0	—	2
		Coho salmon	33.3	—	3.9	1	—	<1	1
	7–22–75	Steelhead trout	70.0	4.1–11.2	7.6	7	—	—	—
		Coastrange sculpin	30.0	—	—	3	—	—	—
Redwood Creek near Hayes Creek	5–22–74	Coastrange sculpin	83.3	—	—	5	—	—	—
		Coho salmon	16.7	—	5.0	1	—	—	—
	5–29–74	Threespine stickleback	37.3	—	—	59	—	—	—
		Steelhead trout	29.1	4.9–14.6	8.2	46	.6–31.0	7.7	46
		Humboldt sucker	24.7	—	—	39	—	—	—
		Coho salmon	5.7	5.1–9.5	6.7	9	.9–10.5	3.5	9
		Chinook salmon	1.9	8.0–9.6	8.7	3	5.5–10.0	7.2	3
		Coastrange sculpin	1.3	—	—	2	—	—	—
Little Lost Man Creek near mouth	5–22–74	Steelhead trout	49.0	6.3–16.0	9.6	19	1.0–51.0	12.6	19
		Coho salmon	25.5	3.9–7.7	5.3	10	<1–4	—	10
		Threespine stickleback	25.5	—	—	10	—	—	—
	7–23–75	Steelhead trout	85.7	4.6–12.7	7.0	72	—	—	—
		Threespine stickleback[1]	8.3	—	—	7	—	—	—
		Coastrange sculpin	6.0	—	—	5	—	—	—
	9–24–75	Steelhead trout	100	6.0–23.6	8.6	39	1.4–147.3	11.7	39
		Threespine stickleback	—	—	—	—	—	—	—
		Pacific lamprey-ammocete[1]	—	—	—	—	—	—	—

[1] Observed only.

The effects of the March 18, 1975, flood on the steelhead trout population are somewhat different than the effects of that flood on the chinook and coho salmon populations. The total number of steelhead trout captured during the 1975 fish-inventory survey increased by 48 percent. The steelhead trout fry captured during the

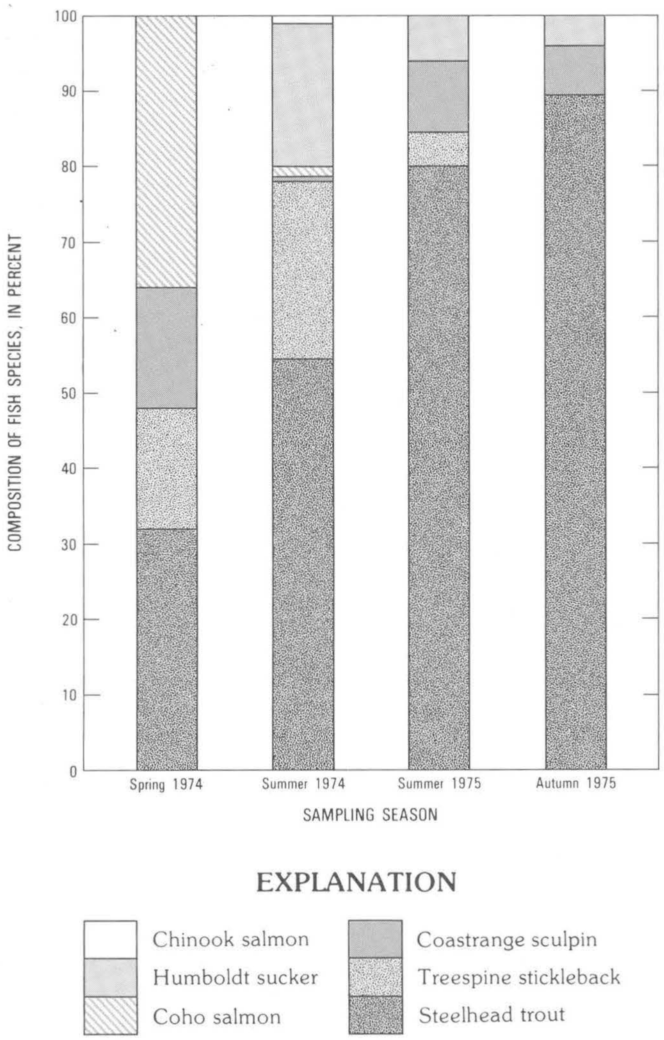

FIGURE 5.—Seasonal variations in percentage composition of fish species sampled in the Redwood Creek drainage basin.

July 1975 survey were probably the result of the spawning activity that occurred after the March 18, 1975, flood. This assumption was based on field observations of recent yolk-sac absorption of the steelhead trout fry and the notation that a large majority of the fry were captured within the depression of their redd. Survival of steelhead trout, chinook, and coho salmon fry from spawning activity prior to the March 18, 1975, flood is not known.

It is often useful to calculate a length-weight relation of fish and compare the findings to those for fish from other areas. The length-weight relations for steelhead trout were made by using the following equation (Lagler, 1969):

$$W = aL^b$$

where

W =weight in grams
L =length in centimeters
a =constant, and
b =slope of the regression line.

A least-squares regression was derived from the logarithmic transformation of the above equation. The values of a and b were determined empirically from the actual fork length and the weights of the salmonids captured. The slope of the regression line, b, can be used to indicate the extent of growth occurring in the salmonid fish captured; that is, the steeper the slope of the regression line, the more weight the fish is gaining per unit growth in length. Generally, when the slope of the regression is greater than 3, the fish are stout, and when the slope of the regression is less than 3, the fish are slim.

During the summer 1974, three areas along Redwood Creek main stem were sampled for fish. The slopes of the length-weight regression for the steelhead trout captured during this survey ranged from 3.06 to 3.61 with a mean slope of 3.38. During the autumn 1975 fish-inventory survey, both the Redwood Creek main stem and tributaries were surveyed. The slopes of the length-weight regression for steelhead trout captured from two Redwood Creek main-stem sites were 3.00 and 3.29 with a mean slope of 3.15; the slopes of the length-weight regression for steelhead trout captured from selected tributaries ranged from 2.71 to 3.18 with a mean slope of 2.90.

The length-weight relation, $W=0.017287L^{2.768}$, for the steelhead trout captured from the Redwood Creek drainage basin during the study was compared to the length-weight relation, $W=0.006237L^{3.063}$, for steelhead trout populations from small coastal California streams, as described by Calhoun (1966). Graphs of the compared length-weight relations are shown in figure 6. These equations indicate that the steelhead trout captured from the Redwood Creek drainage basin were substantially slimmer than the steelhead trout population representative of small California coastal streams.

PERIPHYTON

Periphyton is the assemblage of organisms that attach to or live on underwater substrates and includes algae, bacteria, fungi, protozoans, rotifers, and other small organisms. Insolation, streambed stability, sedimentation, plant nutrients, and water temperature have an effect on the abundance and diversity of the periphyton community.

The taxonomic classification and enumeration of periphyton collected from selected areas in the Redwood Creek drainage basin have been reported in Iwatsubo and others (1976). The composition of periphyton in the Redwood Creek drainage basin consisted of 50 taxa. Diatoms (Bacillariophyceae) were the most common group in each sample, and *Epithemia sorex*, *Achnanthes lanceolata*, and *Diatoma vulgare* occurred in the largest numbers. The percentage of green algae (Chlorophyta) was low for each periphyton sample with the exception of Bridge Creek in the spring of 1974 and Little Lost Man Creek at site 2 in the spring of 1975. *Chlamydomonas* sp., *Spirogyra* sp., and *Ulothrix* sp., were the most numerous green algae sampled from the Redwood Creek drainage basin.

Biomass of periphyton was determined for each sample collected during the study to obtain estimated daily rates of periphyton accrual, and organic and inorganic-material deposition (table 6). These rates were computed by simply dividing the weights of organic and inorganic materials deposited on the sampler by the number of days allowed for colonization. The results indicated that periphyton accrual was low in the Redwood Creek drainage area.

In the spring and summer 1974, the deposition of inorganic and organic material on the periphyton samplers was greater at the lower Miller Creek station than at the upper Miller Creek station (table 6). Excessive amounts of fine sediment were deposited on the periphyton sampler at the Miller Creek at mouth station. The input of sediment into Miller Creek probably was caused by the construction of a bridge located upstream and between the two sampling sites. The increases in organic material during these two sampling periods were not related to periphyton production but to the organic material that adhered to the sediment deposited on the substrates and to the inputs of fine organic debris directly into the stream during bridge construction. The increases that occurred during spring and autumn 1974 sampling as a result of bridge construction were, however, temporary, as no increases in deposition of organic or inorganic material on the periphyton samplers occurred between these two sites during spring 1975 sampling. The rate of accrual of periphyton increased from spring to summer 1974 for samples at Bridge Creek, Redwood Creek above Hayes Creek, and Lost Man Creek sites. Periphyton samplers installed at Little Lost Man Creek at site 2 were vandalized during spring 1974. During the 1975 sampling, the deposition of inorganic material on the periphyton samplers was greater in Bridge Creek and Harry Weir Creek than in the other streams sampled. Prior to the retrieval of the periphyton sampler installed at Bridge Creek, an input of sediment into the stream was caused by activities related to the removal of logging debris upstream from the sampling site. The cause of the increased deposition of inorganic material on the periphyton sampler installed at Harry

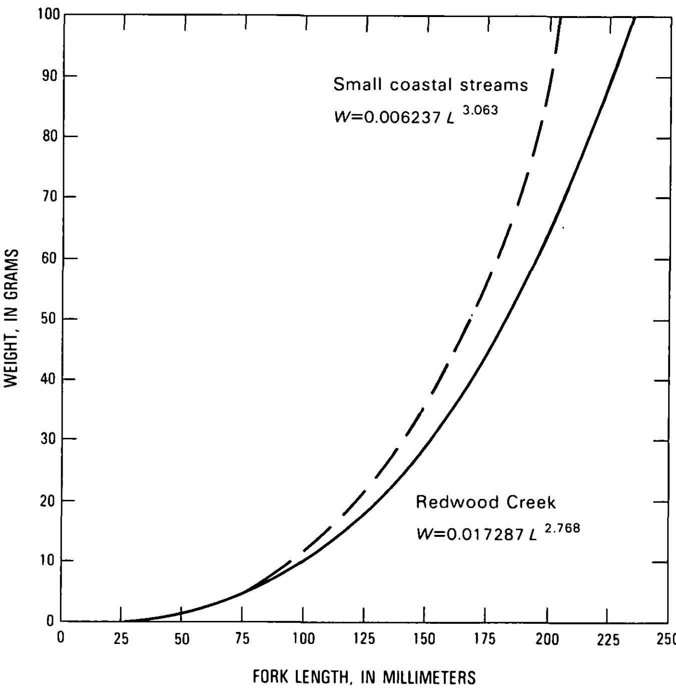

FIGURE 6.—Comparison of length-weight relations for steelhead trout. The length-weight relation for small coastal California streams is from Calhoun (1966).

Weir Creek may have been the construction of a road approach to an existing bridge.

The spring 1975 periphyton samplers installed at Redwood Creek at South Park Boundary and above Hayes Creek sites were lost. Periphyton was resampled at these two sites during summer 1975, and rates of accrual were similar to the rates of summer 1974 (table 6).

Diversity index was calculated for each periphyton sample collected during the study by using the equation of Wilhm and Dorris (1968). The periphyton samples have a wide variation in diversity-index values, which range from 0.00 to 2.76. Diversity indexes of periphyton samples collected within the Redwood Creek drainage basin ranged from 0.98 to 2.34 for main-stem sites and from 0.00 to 2.76 for tributary sites. Hayes Creek, a control basin, had the 0.00 diversity index, whereas Bridge Creek, a basin being logged in 1975, had the 2.76 diversity index.

Similarity indexes were calculated for selected periphyton samples on the basis of the Sorenson equation as given by Odum (1971). These indexes varied from sampling site to sampling site during the study and ranged from 0.12 to 0.80. There were no apparent similarities in periphyton communities that could be related directly to upstream land use activities. The variability in similarity indexes of periphyton primarily reflects the relatively small number of taxa present in each sample when

TABLE 6.—*Rates of accrual of periphyton at selected stations on Redwood Creek and tributaries*
[—, not determined; (g/m²)/d, grams per square meter per day]

Station name	Date sampler installed	Date sampler removed	Colonization period, in days	Weight of periphyton, in (g/m²)/d		
				Dry	Inorganic	Organic
Redwood Creek at South Park Boundary, near Orick	5–9–74	7–16–74	68	0.13	0.09	0.04
	7–16–74	9–13–74	59	.05	.02	.03
	Spring 1975	(1)	—	—	—	—
	7–30–75	9–5–75	37	.08	.05	.03
Bridge Creek near Orick	5–13–74	7–15–74	63	.02	.01	.01
	7–15–74	9–16–74	63	.43	.29	.14
	6–7–75	7–31–75	54	.59	.54	.05
Harry Weir Creek near Orick	5–13–74	7–15–74	63	.10	.07	.03
	7–15–74	9–16–74	63	.12	.09	.03
	6–1–75	7–31–75	60	.20	.18	.02
Miller Creek near Orick	5–10–74	7–16–74	67	.03	.02	.01
	7–16–74	9–17–74	63	.04	.03	.01
	5–31–75	7–28–75	58	.02	.02	.00
Miller Creek at mouth, near Orick	5–14–74	7–16–74	63	1.19	1.12	.07
	7–16–74	9–17–74	63	.92	.85	.07
	5–31–75	7–28–75	58	.03	.02	.01
Redwood Creek above Hayes Creek, near Orick	5–15–74	7–15–74	61	.11	.10	.01
	7–15–74	9–14–74	61	1.59	1.15	.44
	Spring 1975	(1)	—	—	—	—
	8–1–75	9–5–75	35	2.66	2.11	.55
Hayes Creek near Orick	5–15–74	7–15–74	61	.06	.06	.00
	7–15–74	9–14–74	61	.01	.01	.00
Lost Man Creek near Orick	5–10–74	7–15–74	66	.05	.03	.02
	7–15–74	9–15–74	62	.12	.08	.04
	6–2–75	7–27–75	55	.05	.03	.02
Little Lost Man Creek at site 2, near Orick	Spring 1975	(1)	—	—	—	—
	7–15–74	9–14–74	61	.46	.35	.11
	6–2–75	7–27–75	55	.01	.06	.04

[1] Samplers missing.

compared to the total number of taxa occurring in the periphyton community sample.

PHYTOPLANKTON

The taxonomic classification and enumeration of the phytoplankton (unattached algae) collected from selected areas in the Redwood Creek drainage basin have been reported in Iwatsubo and others (1976) and Iwatsubo and Averett (1981). Sixty phytoplankton taxa were identified from water samples collected from the Redwood Creek drainage basin upstream from the estuary, and 22 phytoplankton taxa were identified from samples collected from the Redwood Creek estuary.

Diatoms usually were the dominant phytoplankton group collected during the study; however, unknown flagellates and green algae were dominant at times. In the Redwood Creek drainage basin, exclusive of the estuary, unknown flagellates, *Gomphonema angustatum, Achnanthes lanceolata*, and *Coconeis placentula*, were the most numerous of the phytoplankton taxa collected. In Redwood Creek estuary, *Chlamydomonas* sp., unknown flagellates, *Cryptomonas* sp., and *Selenastrum minutum* were the most numerous phytoplankton.

The taxa *G. angustatum, A. lanceolata*, and *C. placentula* are not truly planktonic but are epiphytic (Smith, 1950). Analysis of the life histories of the remaining phytoplankton taxa (except the dominant taxa from Redwood Creek estuary) suggests that the majority of the phytoplankton were actually periphytic algae that had become dislodged from their substrate and were passively drifting downstream when sampled. In the Redwood Creek estuary, however, the dominant phytoplankton *Chlamydomonas* sp., *Cryptomonas* sp., and *Selenastrum minutum* are truly planktonic. The dominance of these truly planktonic forms in the Redwood Creek estuary can be related to an emergent sandbar that usually closes the mouth of Redwood Creek to the Pacific Ocean during low-flow periods. When this closing occurs, the Redwood Creek estuary becomes a ponded environment that favors production of planktonic phytoplankton.

Diversity-index calculations of phytoplankton ranged from 0.06 to 3.86. At the main-stem sites, diversity indexes ranged from 2.06 to 3.86, and they ranged from 1.37 to 3.18 at the tributary sites. In the estuary, the diversity indexes ranged from 1.03 to 2.43. Upstream from the estuary, diversity indexes of the phytoplankton samples were larger in the streams that received more insolation. Along the Redwood Creek main stem, a downstream increase in diversity indexes of phytoplankton occurred.

Phytoplankton samples collected at the estuary sites had smaller diversity indexes than did the samples collected at the upstream sites. The phytoplankton community in the estuary was primarily dominated by large numbers of *Chlamydomonas* sp. and *Cryptomonas* sp. Both of these genera have been related to organically enriched waters (Palmer, 1969). In addition, the presence of *Cryptomonas* in large numbers has been used to indicate the completion of organic-matter decomposition in the stream (Brinley, 1942).

Similarity index values were calculated for selected phytoplankton samples and ranged from 0.18 to 0.95. Comparisons between phytoplankton samples collected at Bridge Creek and the other areas sampled during summer 1975 showed low similarity indexes, ranging from 0.20 to 0.34. The phytoplankton community of Bridge Creek was dominated by green algae, whereas diatoms dominated the phytoplankton communities of the other sampling areas. Timber-harvest activities in the Bridge Creek basin were extensive, and removal of the streamside canopy resulted in increased insolation and green algal production. The types of green algae dominating the Bridge Creek phytoplankton community were actually dislodged filamentous periphyton such as *Ulothrix* sp., *Spirogyra* sp., and *Zygnema* sp.

Similarity indexes for phytoplankton collected from the Redwood Creek estuary were slightly variable between sampling sites. This variability probably was related to differences in salinity. The lowest similarity index occurred during midsummer 1974 when salinity values were highest in the estuary. At that time, the mouth of Redwood Creek was open to the ocean, and saltwater entered directly into the estuary during high-tide periods. In late summer 1974, the mouth of Redwood Creek was closed to the ocean by an emergent sandbar. Saltwater entered the estuary, but the volume was minimal because the inflow of seawater was subsurface and through the sandbar during high-tide periods. Salinity of the estuary was lower, and the similarity indexes were higher than those for the midsummer samples.

DISCUSSION AND CONCLUSIONS

Aquatic organisms have frequently been used to assess water quality (Hynes, 1960, 1964, and 1970). Coliform bacteria are indicators of direct fecal contamination by man and other animals. Periphyton and phytoplankton are short-term indicators of enrichment, and benthic invertebrates and fish are long-term integrators of changes in the aquatic environment.

In this study of the Redwood Creek drainage basin, an attempt was made to relate the biota to land use practices. Because few data were available, the design of the study was limited and thus resulted in some incomplete conclusions. Nevertheless, some definite conclusions are apparent from the data and deserve further comment.

Data on coliform bacteria indicated that fecal contamination was low. This finding was expected in an area having a low human population. There were, however, indications of fecal contamination at the Prairie Creek site.

The benthic invertebrates received the greatest emphasis in this study because of their importance as long-term integrators of water quality and because they are relatively easy to sample. In the Redwood Creek drainage basin, the size of streambed material and its stability were the major factors related to the distribution and abundance of benthic organisms.

There were striking differences between the number of benthic invertebrates collected before and after major storms. Many of these differences doubtless were related to streambed movement resulting from stream discharges. Most benthic organisms either cling to or hide beneath the larger streambed material. When this material is moved as a result of high discharges, these organisms are usually killed or moved downstream. Prolonged high discharges, which often occur after a major storm, result in the death of many benthic invertebrates.

Most benthic invertebrates are insect larvae, pupae, and nymphae (85.3 percent in the Redwood Creek main stem and tributaries). These organisms usually reach maturity in the spring and summer, emerge as sexually active winged adults, and lay their eggs over the water. The eggs usually hatch the same spring or in early summer. It was demonstrated in this study that reestablishment of benthic invertebrate populations in a stream can take place within one summer. Thus, while numbers of benthic invertebrates were low in the spring after the winter storms, they became high in the autumn after egg laying and when the streambed was stable. Recolonization of a stream with benthic invertebrates is thus rapid, and in streams having flow characteristics like those of Redwood Creek (winter floodflows ranging from 4,500 to 7,300 times greater than summer low flows), summer recolonization by surviving overwinter benthic organisms may be an evolutionary pattern. During the study period there were no samples collected in the spring following a low-flow winter. It would be instructive to have a sampling period following such a winter to determine if the spring counts of benthic invertebrates were in the same order of magnitude as the autumn counts.

On the basis of trophic-level categories defined by Cummins (1973, 1974) for insects, most of the aquatic insects in Redwood Creek drainage basin were in the collector category, followed by the predator category. Cummins developed his technique for Eastern streams, and there may be regional differences. Iwatsubo and Averett (1981) presented a list of species, and their functional group categories is based on Cummins' (1973) listing. The functional group concept is still new, however. As more is learned, some species on this list may be shifted to different categories. It was difficult at first to understand why more grazers and shredders were not found in the samples. Vannote and others (1980), however, indicated a predominance of collectors and predators in the middle lower reaches of streams. Our sample sites in the Redwood Creek drainage basin were located at the mouths of tributaries and in the Redwood Creek main stem. It is possible that grazers and shredders are found in the upper sections of the tributaries. The only conclusion that can be considered at this time is that much of the organic material that enters Redwood Creek is in the form of fine particulate organic matter.

While fish collections were made in Redwood Creek drainage basin, the goal of this study was primarily to determine species composition. No attempt was made to determine population numbers. It was surprising not to find cutthroat trout or resident rainbow trout. While the latter are sometimes difficult to distinguish from steelhead, the cutthroat trout are easy to identify. The lower (slimmer) condition of steelhead trout from Redwood Creek as compared to other coastal streams may be due to the low number of benthic organisms following the first major storms of winter. This supposition is certainly subject to experimental verification. Moreover, the results of Calhoun (1966) were from smaller coastal streams that may not have been subjected to extensive winter flooding. A more extensive fish study is needed before more definitive results can be forthcoming.

The findings on the periphyton and phytoplankton are inconclusive and probably are best suited for use in comparative future studies.

Studies of the Redwood Creek estuary did not reveal any unexpected findings. The data collected from the estuary could be useful, however, for future studies and comparisons.

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Compositional Variations with Season and Logging History in Streams of the Redwood Creek Basin, Redwood National Park, California

By WESLEY L. BRADFORD

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–S

Prepared in cooperation with the
National Park Service

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COMPOSITIONAL VARIATIONS WITH SEASON AND LOGGING HISTORY IN STREAMS OF THE REDWOOD CREEK BASIN, REDWOOD NATIONAL PARK, CALIFORNIA

By WESLEY L. BRADFORD

ABSTRACT

A 2-year study was made in the Redwood Creek drainage basin of Redwood National Park to determine existing chemical water-quality conditions and to identify the effects of logging on water quality in the main stem and tributaries.

Overall, the chemical water quality of the main stem and the tributaries is excellent, suitable for most beneficial uses. Dissolved-solids concentrations range from 25 milligrams per liter during the rainy season to 139 during the dry season. Water shifts from a mixed calcium-sodium bicarbonate-chloride type toward a calcium-bicarbonate type from the end of the wet season (about April) to the end of the dry season (about October). It shifts back toward a mixed calcium-sodium bicarbonate-chloride type from the end of the dry season to the end of the wet season. The pH shifts with the water type from a median value of 6.80 in the wet season to 7.37 in the dry season.

Evidence suggests that dissolved calcium and bicarbonate in stream water is produced by weathering of the Franciscan assemblage underlying the basins but that chlorides are transported inland from the ocean as dry fallout and spray and in rain. Exposure of the surface soils to the elements, either by logging or by natural causes such as sparse vegetation, seems to accelerate weathering, which leads to a calcium-bicarbonate water type. Logging accelerates weathering most in the tributary watersheds with regoliths derived from sandstone and least in those with regoliths derived from schist; however, the data suggest that the rate of weathering in a schistose watershed can increase dramatically if soil disruption is extensive.

Data collected during storms indicated that specific conductance and alkalinity were more likely to decrease at the discharge peak in logged watersheds than in forested ones. This suggests that overland flow, which contains lower concentrations of soil-derived dissolved solids than flow from other sources, is a larger component of peak flow in logged watersheds than in forested watersheds.

INTRODUCTION

BACKGROUND

The Redwood Creek drainage basin (fig. 1) is along the northern California coast where the moist, mild climate and seasonally heavy rainfall are suitable for growth of the coast redwood (*Sequoia sempervirens*) and associated vegetation. Prime examples of old-growth redwood forests are found here, particularly in Redwood National Park and neighboring State parks.

Redwood National Park was established by the U.S. Congress on October 2, 1968. The park includes downstream areas of the Redwood Creek basin and, by later acquisition, areas upslope of the park boundary. This study was completed before the later acquisitions, however. The National Park Service recognized the potential dangers to park resources from upslope logging and, soon after the creation of the park, began studies to assist in managing the park resources. On August 16, 1973, the National Park Service authorized a 3-year program of studies, and the U.S. Geological Survey began collecting data in September of that year.

Data and results of the studies have been presented in several reports. Janda and others (1975a) presented a comprehensive report on environmental conditions in the Redwood Creek drainage basin. Iwatsubo and others (1975, 1976) presented the water-quality, sediment-discharge, and biological data collected during the first 2 years of study. Janda and others (1975b), Lee and others (1975), Averett and Iwatsubo (1975), and Harden and others (1978) published interpretive reports of water and sediment discharge, rainfall-runoff relations, and aquatic biology. Results of water-quality studies were presented by Bradford and Iwatsubo (1978).

DESCRIPTION OF STUDY AREA

The Redwood Creek drainage basin consists of 725 km^2 of generally high-relief, geologically unstable terrain in California's northern Coast Ranges. Basin elevation ranges from sea level at the northern end near Orick to

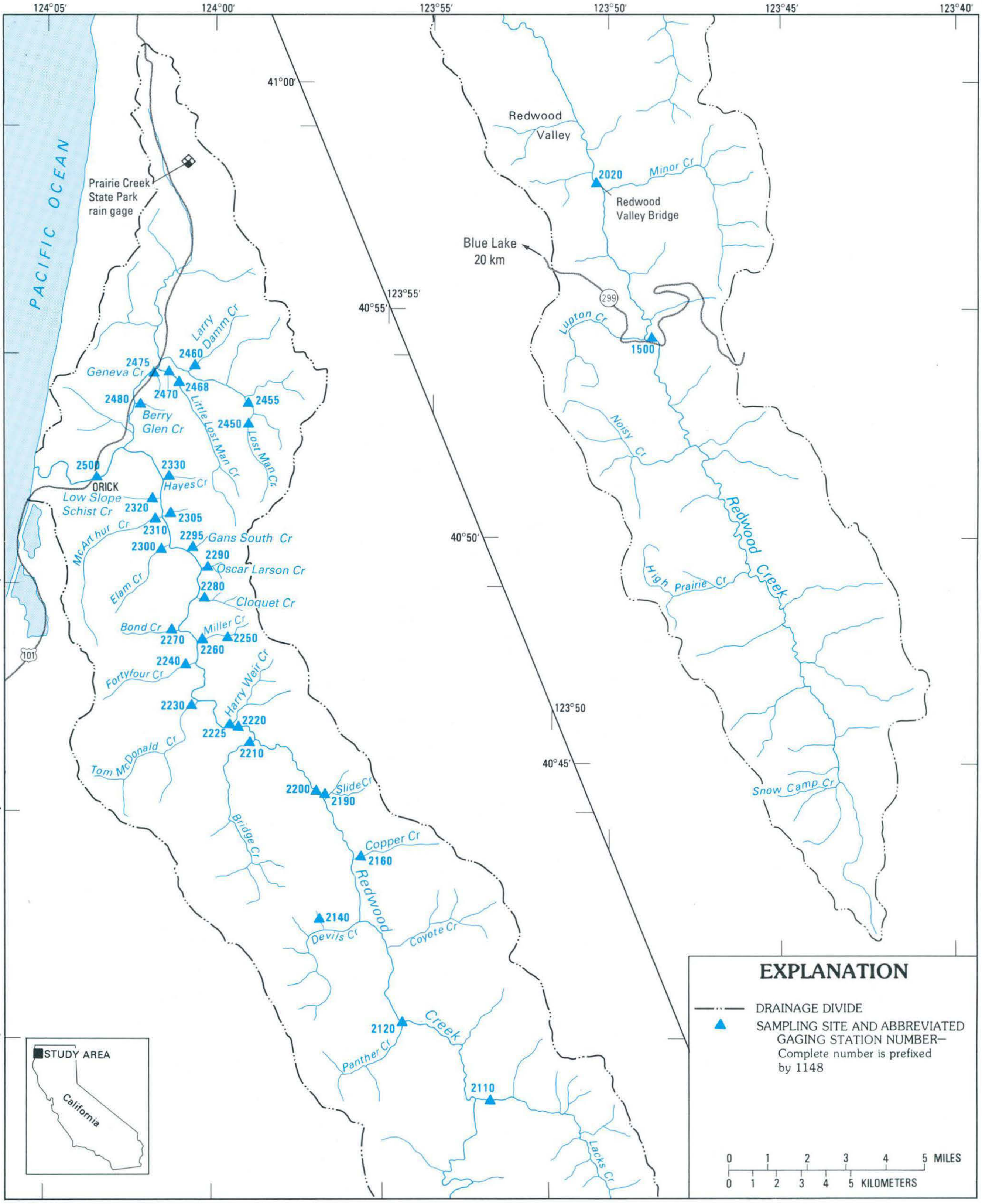

FIGURE 1.—Redwood Creek basin, showing location of sampling sites.

1,600 m in the southern end. The relief, in cross sections normal to the basin axis, ranges from 600 m in the northern end of the basin to 900 m in the southern end. Hillslope gradients range from an average of 31 percent in the northern quarter to 34 percent in the southern quarter of the drainage basin. Slope gradients steepen from the drainage-basin boundary to the stream channels and in several places are nearly vertical adjacent to the streams. Flood plains along Redwood Creek are discontinuous, and most are less than 60 m wide.

The climate in the northern part of the Redwood Creek drainage basin is influenced by the ocean. It is described as coastal Mediterranean and is characterized by high winter precipitation (1,780 to 2,290 mm/yr), mild temperatures, and short, dry summers having infrequent fog. Precipitation varies widely from year to year and is greatest at highest elevations. Most precipitation occurs as rain from large storm systems generated in the Pacific Ocean. Occasionally, snow falls at higher elevations; however, accumulations usually do not exceed 0.6 m. Near the coast, some precipitation also occurs as fog drip (Janda and others, 1975a, p. 89).

Through much previous work and numerous data on California coastal streams, it is known that the seasonal pattern of streamflow follows the seasonal pattern of precipitation in a well-established sequence. As the dry season gets underway, usually in April or May, water stored in ponded areas and channels drains off. As the dry season progresses, streams are fed at a low and gradually decreasing rate by base flow made up of ground water with a long residence time in the soil and underlying materials. Soil moisture is depleted, and water levels in the ground-water reservoir decline.

When the rainy season returns, usually in October or November, precipitation first replenishes the soil moisture, and there is little runoff. At times precipitation may be intense enough to exceed the infiltration rate and cause some runoff as overland flow, which makes little contact with the soil, or quick-return flow (Jamieson and Amerman, 1969), which has short-term contact with the soil (several minutes). As the rainy season progresses, soil-moisture needs are met; infiltration gradually replenishes the ground-water reservoir, causing an increase in base flow; and the soil becomes more saturated, causing overland flow to appear more quickly in response to precipitation than earlier in the season. Also, streamflow between storms increases, owing to delayed-return flow (Kennedy and Malcolm, 1978). Delayed-return flow is water that makes contact with the soil for several hours and reemerges as surface flow (Jamieson and Amerman, 1969).

Vegetation in the Redwood Creek basin varies with slope, elevation, microclimate, and several other factors. In the lower flood plain near Orick, the vegetation is a mixture of shrubs, grasses, pasture, and trees—predominantly Sitka spruce and shore pine. Redwood and Douglas-fir dominate the upland vegetation from the shore to about 15 km inland (Janda and others, 1975a, p. 102). Farther inland, redwoods grow only in the moist flood plain, terraces, and lower slopes adjacent to streams. On higher ground, Douglas-fir, tan oak, and mandrone become more abundant; on high ground toward the southern end of the basin, Douglas-fir, white fir, incense cedar, and black oak predominate.

The Redwood Creek basin is underlain by the indurated Franciscan assemblage, which shows varying degrees of metamorphism. The eastern side of the basin consists mostly of unmetamorphosed marine sedimentary rocks, largely graywacke and sandstone with lesser amounts of mudstone and conglomerate. By contrast, rocks on the western side are finer grained and consist of small, discontinuous bodies of greenstone, bedded radiolarian chert, and thick deposits of mudstone interbedded with sandstone (Janda and others, 1975a, p. 10–11). Schists, mostly light- to medium-gray quartz-mica-feldspar and quartz-mica, crop out throughout the western half of the basin.

The regoliths (the surface mantle of unconsolidated material produced by weathering and erosion) overlying unmetamorphosed sedimentary rocks range in thickness from about 0.5 m at higher elevations to about 4 m on lower slopes. The overlying soils have high infiltration capacity, good subsurface drainage, and moderate to high erosion potential.

Logging in the late 19th and early 20th centuries was limited largely to clearing flood plains and terraces in gentle terrain to provide pasture. By 1947 less than 5 percent of the Redwood Creek basin had been logged (Janda and others, 1975a, p. 114–122). The rugged topography upslope prevented large-scale timber harvesting until the early 1950's.

Intensive logging occurred in the upper part of the Redwood Creek basin in the early 1950's and in the lower part in the late 1950's. By 1973, only about 20 percent of the basin retained old-growth redwood forest. During the 1940's, the most common logging method was selective cutting of small timber plots, but in the 1950's the clearcutting of larger blocks and yarding (gathering for loading onto trucks) the logs downhill by tractor became popular. Soil disruption resulting from extensive logging probably increased erosion (Janda and others, 1975a, p. 164) and altered the hydrology of the basin (Lee and others, 1975).

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Arcata Redwood Co., Louisiana-Pacific Corp., Miller-Rellim Redwood Co., and Simpson Timber Co. allowed field teams general access to study stations on company properties.

STUDY DESIGN

Throughout this paper reference will be made to the Redwood Creek drainage basin, which encompasses several subbasins identified by the names of the creeks tributary to the main stem. To simplify terminology, the term "drainage basin" will be used to refer only to the entire Redwood Creek basin. The term "watershed" will be used to refer to the area drained by tributaries to Redwood Creek, and the name given to the watershed will be the name of the tributary creek.

WATERSHED CLASSIFICATION

The logging and regrowth of the Redwood Creek drainage basin has produced a complex mosaic of old growth, advanced secondary growth, and cutover forest areas. Table 1 shows the codes assigned to watersheds with regard to land use and regolith composition. Sampling stations (table 2; fig. 1) were selected to provide a data set representative of this broad range of land uses. More detailed descriptions of the regolith of watersheds upstream from the sampling stations are in Iwatsubo and others (1975, 1976).

STRATEGY OF DATA COLLECTION

Major effort was devoted to obtaining an overview of water-quality conditions at several stations (table 2) during several storms. In most of these synoptic studies, field measurements were made, and one to three samples were taken for laboratory analysis. Field measurements of alkalinity, specific conductance, pH, temperature, and dissolved oxygen were made at 2- to 6-hour intervals depending on the progress of the storm. Water samples for chemical analysis were taken at various times during each storm.

During two storms, November 6 to 8, 1974, and February 5 to 9, 1975, at Harry Weir Creek and at Little Lost Man Creek at site 2, samples for laboratory analysis were collected at 1-hour or longer intervals in an intensive study of the chemograph (time series of water-quality variations during storm runoff).

To determine the seasonal variations, water-quality measurements and samples were taken at all stations at regularly scheduled intervals. These data are referred to throughout this paper as nonsynoptic data.

TABLE 1.—*Codes designating watershed types with regard to land use and regolith composition*

Code	Description
	Land use
Main stem	Main-stem stations. (Not counted as a separate land use category.)
RF	Regrown, forested. Watershed first logged prior to establishing park (1968) and now substantially RF type. Not being logged during this study.
VL	Virgin timber, logged. Watershed first logged since 1968; in some cases watershed was being logged during this study.
RL	Regrown, being logged. Watersheds first logged well before 1968 and being logged of second growth during this study.
VF	Virgin timber, forested. Largely virgin timber with small and variable amounts of advanced second growth.
	Regolith
St	Schist. Watershed underlain predominantly by schist.
Sn	Sandstone. Watershed underlain predominantly by indurated sandstone, fractured in varying degrees, and some mudstone.
Mx	Mixture. Watershed underlain by a mixture of sandstone and schist or transitional rocks.

METHODS

The field measurements for alkalinity, specific conductance, pH, and dissolved oxygen and all laboratory analyses were made by methods described by Brown and others (1970) and the American Public Health Association and others (1971).

Water samples for the laboratory analyses were collected at approximately the middle centroid of flow of the stream (Guy and Norman, 1970) and were pretreated (as prescribed by Brown and others, 1970) before shipment to the U.S. Geological Survey's Central Laboratory in Salt Lake City, Utah (now known as the National Water Quality Laboratory and located in Arvada, Colo.). The samples for major constituent determinations (except carbonate and bicarbonate) were filtered through a 0.45-μm pore-size membrane filter and acidified to pH <2 with nitric acid. A separate sample for carbonate and bicarbonate analysis was unfiltered and unacidified.

RESULTS AND DISCUSSION

SYNOPTIC STUDIES DURING STORMFLOW

CHEMOGRAPH SYNOPTIC STUDIES

Detailed studies of the chemograph of several chemical constituents were made at station 11482225 on Harry Weir Creek (VL (virgin timber, logged) -type water-

TABLE 2.—*Selected data for individual sampling stations*

[Codes for watershed and regolith types are defined in table 1; "(S)" in front of station numbers indicates synoptic study sites; —, no data]

Station number and name	Average stream gradient (m/km)	History of land use (percentage of area)		Virgin and advanced second growth	Watershed classification	
		Logged since establishment of Redwood National Park	Logged prior to establishment of Redwood National Park		Land use type (percent of area)	Regolith type
11481500 Redwood Creek near Blue Lake	31.3	<5	>55	40	Main stem	—
11482020 Redwood Creek at Redwood Valley Bridge, near Blue Lake	26.9	<5	>60	35	Main stem	
11482110 Lacks Creek near Orick	57.2	10	40	50	RL	Sn
11482120 Redwood Creek above Panther Creek, near Orick	18.8	<5	>60	35	Main stem	—
11482140 High Slope Schist Creek near Orick	293.9	—	—	100	VF	St
11482160 Copper Creek near Orick	180.1	20	30	45	VL	Sn
11482190 Slide Creek near Orick	255.9	30	40	30	VL	Sn
(S)11482200 Redwood Creek at South Park Boundary, near Orick	18.6	<5	65	<30	Main stem	—
11482210 Bridge Creek near Orick	60.2	21	55	24	RL	St
11482220 Redwood Creek above Harry Weir Creek, near Orick	16.1	5	60	35	Main stem	—
11482225 Harry Weir Creek near Orick	145.1	40	—	60	VL	Mx[1]
11482230 Tom McDonald Creek near Orick	70.1	6	80	14	RL	St
11482240 Fortyfour Creek near Orick	104.5	20	75	5	RL	St
(S)11482250 Miller Creek near Orick	207.0	90	—	10	VL	Sn
(S)11482260 Miller Creek at mouth, near Orick	200.2	77	—	23	VL	Mx[1]
11482270 Bond Creek near Orick	137.7	27	55	18	RL	St
11482280 Cloquet Creek near Orick	219.9	55	—	45	VL	Mx
11482290 Oscar Larson Creek near Orick	283.3	23	—	77	VL[2]	Mx
11482295 Gans South Creek near Orick	271.8	—	—	100	VF	Mx
11482300 Elam Creek near Orick	89.8	40	30	30	VL	St
11482305 Gans West Creek near Orick	295.7	—	—	100	VF	Mx
11462310 McArthur Creek near Orick	47.2	30	45	25	VL	St
11482320 Low Slope Schist Creek near Orick	241.7	—	—	100	VF	St
(S)11482330 Hayes Creek near Orick	236.8	—	4	96	VF	Sn
(S)11482450 Lost Man Creek near Orick	103.6	—	87	13	RF	Sn
11482455 Lost Man Creek Tributary near Orick	243.9	—	—	100	VF	Sn
11482460 Larry Dam Creek near Orick	94.3	—	70	30	RF[3]	—
(S)11452468 Little Lost Man Creek at site 2, near Orick	75.4	0	6	94	VF	Sn
(S)11482470 Little Lost Man Creek near Orick	66.1	—	8	92	VF	Sn
(S)11482475 Geneva Creek near Orick	242.4	—	100	—	RF	Sn
11482480 Berry Glen Creek near Orick	261.2	—	100	—	RF	Mx
11482500 Redwood Creek at Orick	13.4	10	50	40	Main stem	—

[1] Regolith type does not agree with percentage of predominant soil type of parent material.
[2] Does not fit any land use category well.
[3] Watershed is overlain by a weakly consolidated layer.

shed, Mx (mixture) -based regolith) and at station 11482468 on Little Lost Man Creek at site 2 (VF (virgin timber, forested) -type watershed, Sn (sandstone) -based regolith). This study compared and contrasted the chemical characteristics of storm-associated flow from a heavily logged watershed (Harry Weir Creek) with that from a virgin forested watershed (Little Lost Man Creek) in greater detail than was possible for all the stations combined. The two were selected for special effort because of the sharp difference between them in land use.

The first such study was made during the storm of November 6 to 8, 1974, the second storm of the rainy season. The first storm of the rainy season, which passed through the area October 27 to 29, brought 76.0 mm of rain at the Prairie Creek State Park recording gage. By November 6, discharge in the two streams had returned to levels preceding the October storm. The storm of November 6 to 8 brought 25 mm of rain in 1 day, and a hydrograph of water discharge showed an easily identifiable rise, peak, and recession in both streams. The chemograph also varied considerably with discharge (fig. 2).

The peak discharge per unit area in Harry Weir Creek is higher and occurs earlier than in Little Lost Man Creek, suggesting that a larger fraction of runoff occurs as fast overland flow in Harry Weir Creek. The difference may be due partly to differences in slope and land cover. But the storm covered a broad area and dropped comparable amounts of precipitation on both watersheds so that differences in peak discharge per unit area (almost three times larger in Harry Weir Creek) cannot be attributed to small differences in either total rainfall or short-term intensity. Likewise, the differences in

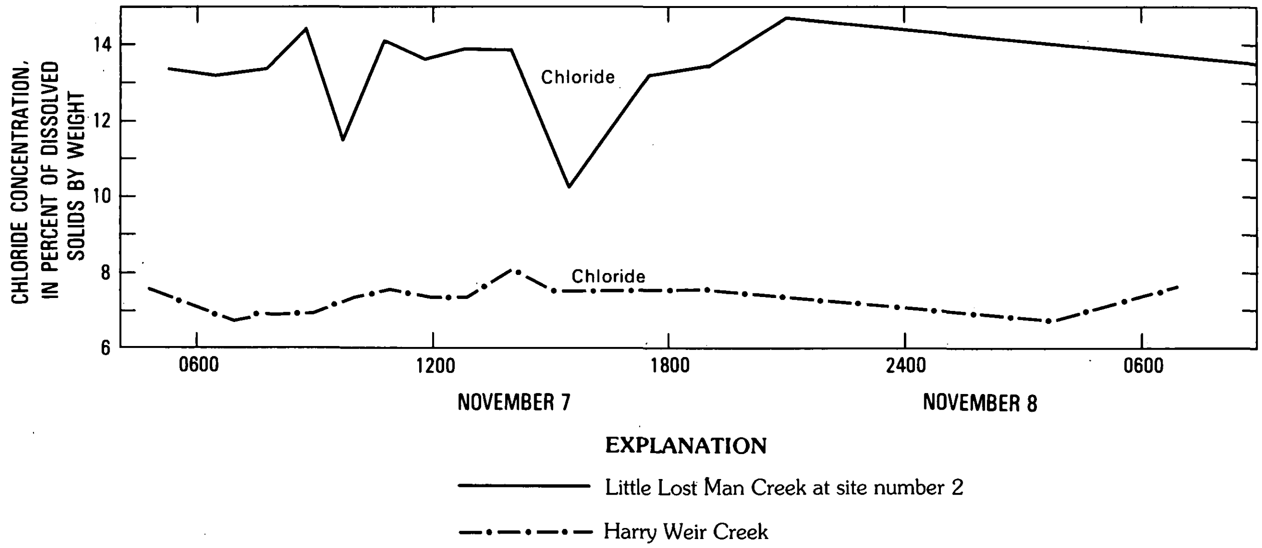

FIGURE 2.—Selected water-quality data from the synoptic study of November 6 to 8, 1974, Harry Weir Creek and Little Lost Man Creek at site 2. No data are shown for first day of the study.

timing of the two peak discharges (nearly 6 hours later in Little Lost Man Creek than in Harry Weir Creek) cannot be attributed to differences in the timing of precipitation (Janda and others, 1975b; K.M. Nolan, U.S. Geological Survey, oral commun., 1978).

The concentrations of the major constituents are higher and more variable with discharge in Harry Weir Creek than those in Little Lost Man Creek. This suggests that the rate of rock weathering to constituents soluble in water is greater in Harry Weir Creek. These soluble constituents probably were produced by weathering during the dry season and were dissolved easily in the early rains. The magnesium, sodium, and potassium lines are shown only for Little Lost Man Creek. There are slight but measurable differences between the lines for Little Lost Man Creek and Harry Weir Creek, but at the scale of figure 2, the differences cannot be resolved by eye.

The concentrations of calcium, bicarbonate, and sulfate in Harry Weir Creek all decrease steadily on the rise of the hydrograph, reach minima at or near peak discharge, and increase steadily on the recession. This suggests that, as discharge increases, an increasing fraction of that discharge comes from overland flow, which has had little contact with the soil and thus contains less dissolved solids than water from other sources. By contrast, data from Little Lost Man Creek show no discharge-related variations, suggesting that overland flow is not a major fraction of the discharge.

The concentrations of sodium and chloride are nearly equal to each other and are alike in both watersheds. Although the percentage chloride values as shown are different in the two watersheds, the chloride concentrations are approximately equal. This suggests that the source of chlorides is not rock weathering, which would have produced different concentrations in the two watersheds, as the dissolved-solids concentrations are different, but rather is sea salt either occurring as dry fallout during the summer or accompanying the rain. The latter situation probably is not the case, however, because if the chloride had been supplied at a constant concentration in rainfall, the time series of percentage chloride would have been the inverse of the time series for dissolved-solids concentration. Hence, the sodium and chloride in the runoff of the November 6 to 8, 1974, storm had probably accumulated in the soil through the summer from salt spray and fog drip.

The second storm studied occurred February 5 to 9, 1975. Since October 1974, 839 mm of rainfall had been recorded. A storm of February 1 to 5 caused 89 mm of rain. Measurements were made beginning February 5 because weather forecasts predicted that a major storm would begin sometime that day. This storm did not materialize, and daily rainfalls for February 5 to 8 were 11 mm, 13 mm, a trace, and 8 mm. Finally, 26 mm of rain fell February 9. Most of the samples taken during the study were in the period February 8 to 9.

The water discharge and concentrations of major constituents (fig. 3) are shown for the period February 8–9 only. Potassium values are not shown because they are uniformly less than 1.0 mg/L and do not show variations at this scale. Magnesium and sulfate concentrations are virtually identical at both stations.

Streamflows prior to this storm were about two orders of magnitude higher than the streamflows prior to the November storm, so that the hydrograph of the storm

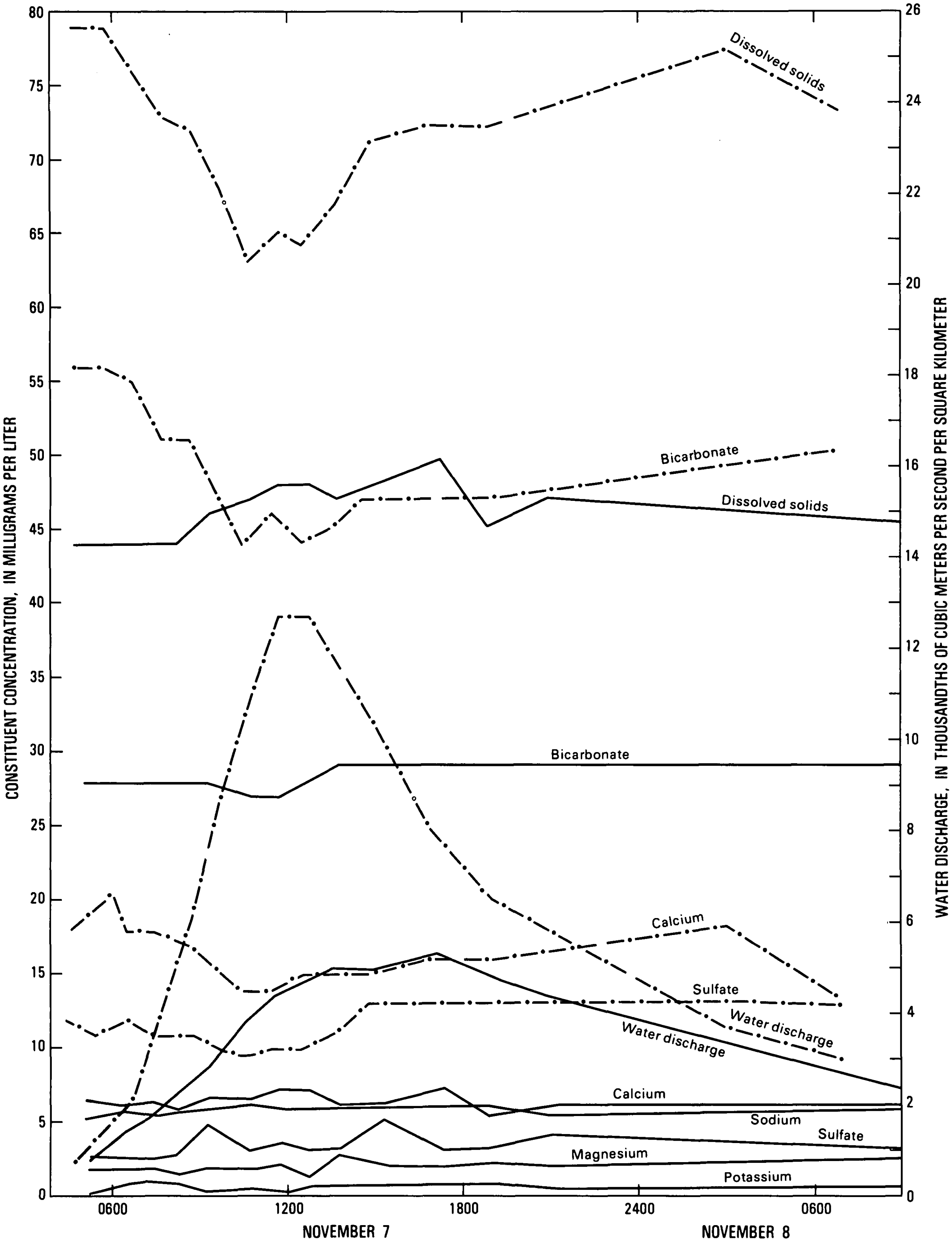

FIGURE 2.—Continued.

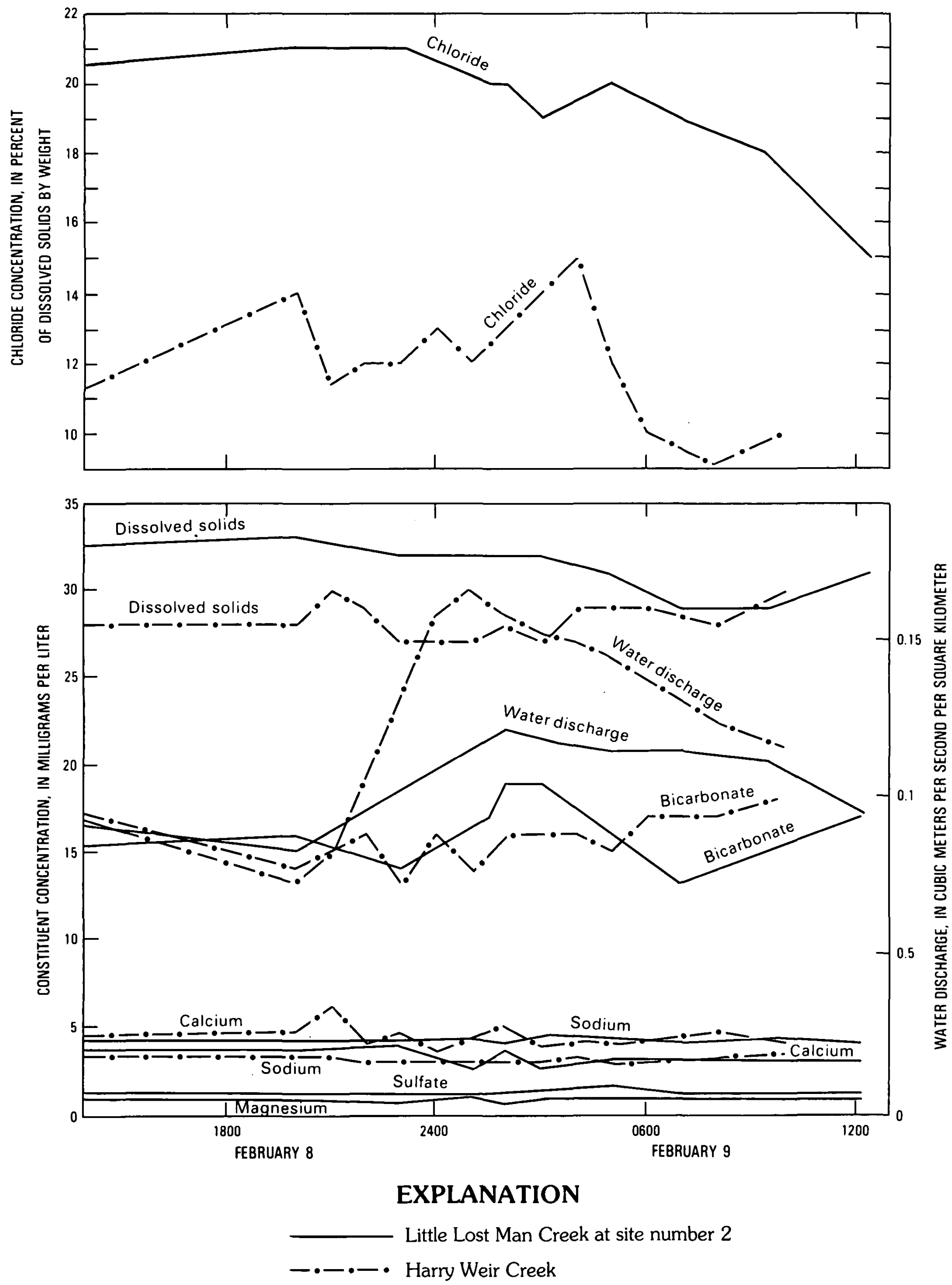

FIGURE 3.—Selected water-quality data from the synoptic study of February 5 to 9, 1975, Harry Weir Creek and Little Lost Man Creek at site 2. No data are shown for the first 3 days of the study.

discharge was superimposed on a much larger base flow in February than in November. As in the November synoptic study, the peak streamflow per unit area was greater and occurred earlier in Harry Weir Creek than in Little Lost Man Creek, suggesting that a greater fraction of the runoff in Harry Weir Creek was overland flow. Again, differences between watersheds in the peak discharge and in the time of the peak cannot be attributed to differences in total rainfall or the timing of rainfall (Janda and others, 1975b).

In the February study, the dissolved-solids concentrations in Harry Weir Creek and Little Lost Man Creek were nearly alike; in the November study, dissolved-solids concentration in Harry Weir Creek was much higher than in Little Lost Man Creek. Concentrations in both streams are substantially lower in February than in November, but more so in Harry Weir Creek. The general decrease in dissolved solids is probably due to higher discharges; that is, more water is present in both watersheds in February to dilute the soluble material available. The differences in magnitude of the decreases between Harry Weir Creek and Little Lost Man Creek suggest that in November more soluble material was available for dissolution in Harry Weir Creek. By the February storm, however, processes supplying soluble material were, apparently, operating alike in the two watersheds, as concentrations of individual constituents (except chloride) are alike.

The bicarbonate and dissolved-solids concentrations in Harry Weir Creek decreased slightly on the rise of the hydrograph (fig. 3), reached minima at or near the peak, and increased slightly on the recession, suggesting, as in the November storm, that overland flow was an important component of discharge. In Little Lost Man Creek, however, the peak bicarbonate concentration coincided with peak discharge, suggesting that much of the water constituting the peak discharge is not overland flow but is quick-return flow or water that enters the surface soil briefly and reemerges, thereby picking up more soluble salts than overland flow (Kennedy and Malcolm, 1978). This conclusion is supported by the relative shape of the two hydrographs, with Little Lost Man Creek experiencing slower rise, lower peak, and more sustained recession than Harry Weir Creek.

In Harry Weir Creek, the percentage of chloride seems to rise steadily through the discharge peak, then decreases through the recession. In Little Lost Man Creek, the percentage of chloride also decreases on the recession. In both streams, bicarbonate and dissolved-solids concentrations increase on the recession. This combination of observations suggests that, after the peak, an increasing fraction of the runoff is quick-return flow that contains higher concentrations of dissolved solids, except chloride. The chloride may be coming in primarily in rain, with little being added from the soil.

The percentage of chloride was higher in both watersheds in February than in November. In November the chloride concentrations were the same at both stations, but in February chloride was higher at Little Lost Man Creek. This suggests that chloride salts accumulated during the summer were the dominant source of chloride in November, but rainfall was the dominant source in February. The Little Lost Man Creek station may have had higher chloride concentrations in February because it is closer to the ocean and received more salt spray during the storm than did Harry Weir Creek.

From November to February, although calcium and bicarbonate continued to be important quantitatively, there was a general shift toward a sodium-chloride-type water at the expense of calcium and sulfate in Harry Weir Creek and at the expense of calcium, bicarbonate, and sulfate in Little Lost Man Creek (fig. 4). Little Lost Man Creek tended to be a more sodium-chloride-type water than Harry Weir Creek in both November and February but probably for different reasons. In November, both watersheds had accumulated roughly equal amounts of chloride salts per unit area. The first runoff of the rainy season would be expected to contain nearly equal concentrations of sodium and chloride in the two watersheds (as was seen), but because of higher concentrations of other salts, the water at Harry Weir Creek was less a sodium-chloride type than the water at Little Lost Man Creek. By February, the soluble material excess in Harry Weir Creek over that in Little Lost Man Creek that had been seen in November was gone. The processes supplying soluble solids in both watersheds were similar. But chloride in rain continued to appear in the runoff, thus causing a shift toward a sodium-chloride-type water. The chloride concentration in February was higher at Little Lost Man Creek than at Harry Weir Creek, probably because Little Lost Man Creek is closer to the ocean. Thus, in February also, Little Lost Man Creek water seems to have been a more sodium-chloride type than Harry Weir Creek water.

OTHER SYNOPTIC STUDIES

Synoptic field measurements of alkalinity, pH, temperature, dissolved oxygen, and specific conductance also were made at one station on the main stem (11482200) and at eight stations on tributaries of Redwood Creek during eight storms (table 2).

The time series of the synoptic field measurements proved to be of little value and are not presented. Other features of these data are discussed. Alkalinity and specific-conductance values occurring on the rise, peak, and recession proved to be suggestive of specific hydrologic processes. In table 3, the position of each value relative to the middle value of the measurements is shown at rise, peak, and recession. Hydrographs for the storms of February 28 to March 3, 1974, and February 5 to 9, 1975, showed poorly defined rise, peak, and recession portions at all stations and are excluded from this analysis.

Examination of the symbols (table 3) shows a preponderance of minus signs (indicating values below the middle of the three measurements) at the hydrograph peaks in all the VL-type (logged) watersheds—Harry Weir Creek, Miller Creek, and Miller Creek at mouth. Furthermore, in 18 alkalinity and in 17 specific-

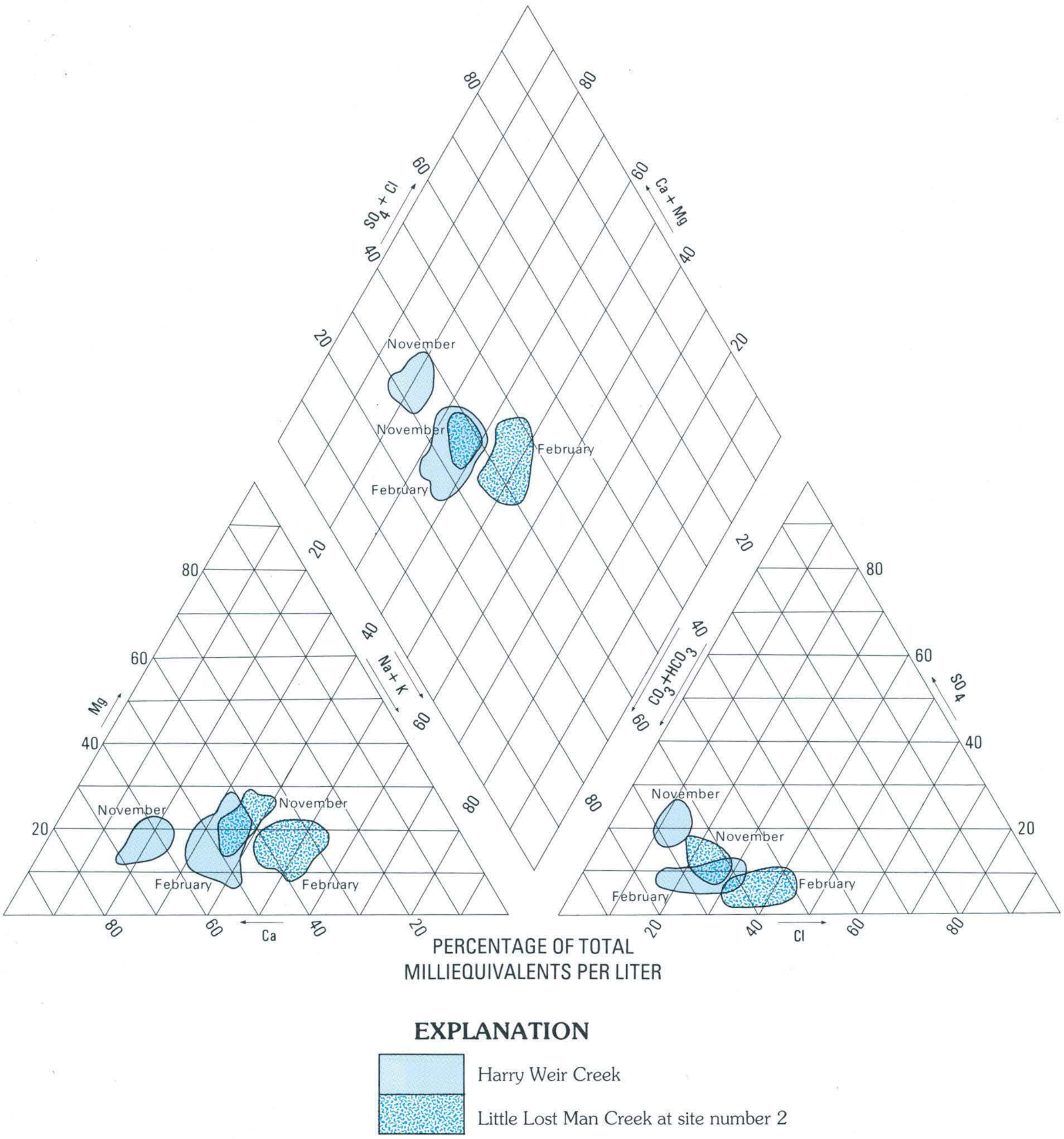

FIGURE 4.—Trilinear diagram showing major-ion composition for the chemograph synoptic studies, November 6 to 8, 1974, and February 5 to 9, 1975, Harry Weir Creek and Little Lost Man Creek at site 2. (Technique from Piper, 1944.)

conductance measurements at the peak discharge in the VL-type watersheds, no plus sign occurred. The probability of various combinations of plus and minus signs occurring at the discharge peak is given by the binomial distribution for n nonzero signs. From a table of the binomial distribution (Conover, 1971, table 3), one can see that, if plus and minus signs occurred with equal expectation (p=0.50) in 15 tries, between 3 and 11 plus signs would occur, with a 95 percent or greater confidence level. Since no plus signs occurred, it may be concluded that the expectation of plus and minus signs is not equal. Indeed, the lowest expectation at which at least one plus sign would occur at a 95 percent or greater confidence level is p=0.20. Considering specific conductance in VL-type watersheds, n=14, again all are minus signs. The conclusion regarding expectation is the same.

By contrast, VF- and RF (regrown, forested) -type watersheds (Hayes, Lost Man, Little Lost Man, and

TABLE 3.—*Relative magnitudes of alkalinity and of specific conductance values at the beginning of the rise, at the peak, and on the recession for synoptic events that produced hydrographs with definable features*

[Symbols ("+" and "−") represent the position of each value relative to the middle value of the measurements at rise, peak, and recession. The middle is always shown with a zero. Likewise, a zero also represents two equal values. Alkalinity values are considered equal if they are within 1.5 units of each other, and specific-conductance values are considered equal if they are within 3 units of each other. Both limits are judgments based on sensitivity of the measurements. Blanks mean no data]

Station number and name	November 7–9, 1973			January 11–13, 1974			February 20–22, 1974			November 6–8, 1974			November 20–22, 1974			February 12–14, 1975		
	Rise	Peak	Recession	Rise	Peak	Recession	Rise	Peak	Recession	Rise	Peak	Recession	Rise	Peak	Recession	Rise	Peak	Recession
Alkalinity, in milligrams per liter																		
11482200 Redwood Creek at South Park Boundary, near Orick.		−	+				0	−	0				+	−				
11482220 Redwood Creek above Harry Weir Creek, near Orick.										+	−	0	−	+				
11482225 Harry Weir Creek near Orick	+	0	0	+	−	0	+	−	0	+	−	0	+	−	0	−	+	
11482250 Miller Creek near Orick	0	0	+	+	−			−	+	+	−	0	+	−	0	+	−	0
11482260 Miller Creek at mouth, near Orick	0	−	0	+	−		0	−	0	+	−	0	+	−	0	−	0	0
11482330 Hayes Creek near Orick				+	−			0	0	+	0	−	+	−	0	0	0	0
11482450 Lost Man Creek near Orick		0	0	0	0		0	0	0	+	0	−	0	+	−	0	0	0
11482470 Little Lost Man Creek near Orick, sites 1 and 2.				0	0		+	0	0	0	0	0	+	−	0	0	0	0
11482475 Geneva Creek near Orick				0	0			0	0	0	+	−	+	0	−	0	0	0
Specific conductance, in micromhos per centimeter at 25 °C																		
11482200 Redwood Creek at South Park Boundary, near Orick.	+	0	0				0	−	0				+	−				
11482220 Redwood Creek above Harry Weir Creek, near Orick.										+	−	0	+	−				
11482225 Harry Weir Creek near Orick	+	−	0	0	−	0	0	−	+	0	−	0	+	−	0	+	−	0
11482250 Miller Creek near Orick	0	0	0	+	−		0	−	+	0	0	0	+	−	0	0	0	0
11482260 Miller Creek at mouth, near Orick	0	−	+	0	−	0	+	−	0	0	−	0	0	−	0			
11482330 Hayes Creek near Orick		0	0	0	0	0	0	−	+	0	+	−	0	−	+	−	0	+
11482450 Lost Man Creek near Orick		0	0	0	0		0	0	+	0	+	0	0	+	−	0	0	0
11482470 Little Lost Man Creek near Orick, sites 1 and 2.	+	0	0	0	0		0	0	0	0	0	0	0	0	−	0	0	0
11482475 Geneva Creek near Orick	+	0	0	0	0		0	0	0	+	−	0	+	0	0	0	0	0

Geneva Creeks) show a preponderance of zeros and small but approximately equal numbers of plus and minus signs at the peak for both alkalinity and specific conductance. This finding suggests that, in most cases, concentrations in VF- and RF-type watersheds at the peak discharge are not significantly or consistently diluted by overland flow, and the expectation of dilution occurring at the discharge peak cannot be shown to be different from $p=0.50$.

It may be concluded that peak alkalinity and specific conductance occur at peak storm discharge much less often in logged than in forested watersheds, probably because of increased occurrence of overland flow in logged watersheds.

The difference in the lag time of peak discharge between watershed types decreases from several hours in November to several minutes in February (Janda and others, 1975a, p. 6–20). This change may occur because as the soil becomes saturated it is less able to soak up new precipitation. Thus, overland flow should be more apparent in peak discharge in all watershed types late in the rainy season. In table 3, plus signs at the discharge peak occur only in VF and RF watersheds and only in the two storms studied in November 1974. This suggests that quick-return flow was a predominant part of peak discharge only in VF- and RF-type watersheds and only early in the rainy season, whereas late in the rainy season overland flow becomes important at the discharge peak in all types.

The significance of differences in water quality during storms between watersheds of different land use was evaluated by grouping the data from each synoptic study according to common land use type and calendar quarter (first quarter January through March, second quarter April through June, and so on). Calculations were made from data grouped by class interval (Sokal and Rohlf, 1969). Calculated values (table 4) are shown to one additional significant figure to avoid rounding error in subsequent statistical hypothesis testing. No mean or standard deviation is calculated for sets of less than 10 values because the sampling error of the mean and standard deviation are unduly large given only 10 values. The mean of each data set for the RF- and VL-type watersheds and the main stem was compared to the corresponding mean for the VF-type watersheds by using a student t-test (table 5).

Mean alkalinity and pH vary in the same direction and are mostly higher in VL-type watersheds than in

TABLE 4.—*Statistical summary of field-measurement data from synoptic studies, grouped by calendar quarter and watershed type*

[Means and standard deviations calculated from data grouped by class as follows: alkalinity, 1 mg/L; specific conductance, 5 μmho/cm at 25 °C; pH, 0.2 units; temperature, 0.5 °C; dissolved-oxygen saturation, 2 percent. Calculated values are shown to one additional significant figure to avoid rounding error in subsequent statistical hypothesis testing. —, no data]

Watershed types[1]	Fourth quarter 1973					First quarter 1974				
	Median	Range[2]	Mean	Standard deviation	Number of samples	Median	Range[2]	Mean	Standard deviation	Number of samples
Alkalinity, in milligrams per liter										
VF streams	13.0	12–15	—	—	3	14.8	7–24	14.7	2.2	49
RF streams	12.8	11–14	—	—	8	13.1	9–17	12.5	1.3	60
VL streams	14.1	11–18	13.9	1.5	23	14.9	10–21	15.1	2.4	73
Main-stream stations	28.0	27–34	—	—	3	29.5	26–32	28.9	1.6	11
Specific conductance, in micromhos at 25 °C										
VF streams	48.8	40–65	50.3	7.3	16	52.9	40–90	53.4	8.6	100
RL streams	42.9	30–55	43.1	5.4	16	42.6	20–55	41.7	5.1	94
VL streams	48.6	35–85	52.2	11.2	58	49.2	30–75	51.9	7.8	172
Main-stream stations	71.6	65–85	—	—	6	72.2	65–85	73.0	4.4	19
pH										
VF streams	6.95	6.8–7.6	—	—	3	7.00	5.8–7.8	6.92	.40	64
RL streams	6.16	5.6–7.0	6.17	.41	13	7.05	5.8–7.6	6.90	.36	71
VL streams	7.14	7.0–7.4	7.11	.11	40	7.07	6.2–7.6	7.04	.25	97
Main-stream stations	6.50	6.2–8.2	—	—	3	6.90	6.8–7.0	—	—	8
Temperature, in degrees Celsius										
VF streams	11.3	11.0–12.0	11.1	.2	18	8.3	6.5–9.5	7.9	.6	103
RF streams	11.9	11.0–13.5	11.7	.4	29	7.5	5.0–10.0	7.3	1.0	98
VL streams	12.3	11.5–13.0	12.0	.2	56	8.0	6.0–9.5	7.7	.7	159
Main-stream stations	12.6	12.0–13.0	—	—	6	7.6	6.0–8.5	7.2	.7	19
Dissolved oxygen, in percent saturation										
VF streams	96.7	88–102	95.9	3.3	16	97.0	84–104	95.8	3.9	57
RF streams	96.6	88–102	95.6	2.9	16	96.2	84–104	95.1	4.0	50
VL streams	99.8	98–102	99.4	1.2	17	98.3	92–104	97.9	2.1	73
Main-stream stations	99.0	96–100	—	—	3	97.5	92–100	—	—	9

Stream/station description	Fourth quarter 1974					First quarter 1975				
	Median	Range[2]	Mean	Standard deviation	Number of samples	Median	Range[2]	Mean	Standard deviation	Number of samples
Alkalinity, in milligrams per liter										
VF streams	24.2	20–38	26.9	5.4	67	12.7	9–17	13.0	1.3	57
RF streams	24.8	11–41	25.0	9.6	50	12.4	9–14	11.7	1.2	52
VL streams	31.4	17–52	32.5	8.1	62	14.3	10–18	13.7	1.4	65
Main-stream stations	70.0	54–94	72.1	10.7	12	26.9	13–47	28.0	7.1	10
Specific conductance, in micromhos at 25 °C										
VF streams	78.2	60–200	102.6	38.2	103	72.7	30–90	61.2	18.9	156
RL streams	93.8	60–150	87.4	16.8	81	41.2	30–65	42.6	6.8	152
VL streams	89.9	60–150	100.1	22.6	105	45.8	30–90	47.2	7.2	131
Main-stream stations	243.0	210–300	245.2	19.5	22	69.9	60–85	70.0	6.1	47
pH										
VF streams	7.38	6.4–8.6	7.36	.43	74	7.01	6.4–7.6	7.05	.23	125
RL streams	6.82	6.2–7.2	6.62	.20	50	7.19	6.4–7.6	7.06	.22	81
VL streams	7.48	6.8–8.0	7.35	.21	[3]56	7.16	6.0–7.6	7.14	.27	84
Main-stream stations	7.70	7.0–8.4	7.56	.37	11	7.04	6.2–8.0	7.04	.37	18
Temperature, in degrees Celsius										
VF streams	9.7	8.0–11.5	9.32	1.0	97	9.2	7.5–10.5	9.2	.6	154
RF streams	10.1	8.0–12.0	10.1	.8	77	8.6	6.5–10.1	8.7	.9	166
VL streams	9.8	8.5–12.5	9.6	.7	108	9.6	7.5–11.1	9.1	.8	129
Main-stream stations	11.1	9.0–12.5	10.6	.9	24	8.2	6.0–10.5	7.9	.9	42
Dissolved oxygen, in percent saturation										
VF streams	93.9	84–104	93.4	3.7	311	97.5	92–102	96.5	2.4	48
RF streams	88.1	80–96	87.2	3.8	32	96.9	88–104	96.4	2.6	46
VL streams	95.2	84–100	93.5	3.2	50	97.6	84–104	96.3	3.1	48
Main-stream stations	95.0	86–100	93.2	3.7	10	99.2	90–106	98.9	3.7	19

[1] Codes for watershed types (VL, RF, and so on) are defined in table 1.
[2] The range is the low end of the lowest class to the high end of the highest class.
[3] Seven pH values taken November 6 to 8, 1974, at Miller Creek at mouth are much lower than values determined simultaneously at Miller and Harry Weir Creeks and are not included in this calculation. Instrument malfunction was suspected at Miller Creek at mouth.

TABLE 5.—*Results of comparing the means of field measurements from RF, VL, and main-stem stations with means of field measurements from VF streams*

[The student *t*-test is used to test a null hypothesis that the means being compared are equal. Rejection of the null hypothesis with level of confidence in a one-tailed test implies that the difference shown (plus or minus) is significant at that confidence level. No data in the column indicates acceptance of the null hypothesis. N means no test was performed due to insufficient sample size. Relation of subject mean to the mean for VF streams is as follows: +, greater than; −, less than; 0, no difference]

Period	Description (land use code)[1]	Alkalinity (mg/L)		Specific conductance (μmho at 25 °C)		pH		Temperature (°C)		Dissolved oxygen (percent saturation)	
		Mean	Confidence level	Mean	Confidence level	Mean	Confidence level	Mean	Confidence level	Mean	Confidence level
Fourth quarter, 1973	RF	0	N	−	0.99	−	N	+	0.99	−	
	VL	+	N	+	+		N	+	.99	+	0.99
	Main stem	+	N	+	N	−	N	+	N	+	N
First quarter, 1974	RF	−	0.99	−	.99	−		−	.99	−	
	VL	+		−		+	0.95	−	.95	+	.99
	Main stem	+	.99	+	.99	−	N	−	.99	0	N
Fourth quarter, 1974	RF	−		−	.99	−	.99	+	.99	−	.99
	VL	+	.99	−		0		+	.95	0	
	Main stem	+	.99	−	.99	+		+	.99	0	
First quarter, 1975	RF	−		−	.99	0		−	.99	0	
	VL	+	.99	−	.99	+	.95	0		−	
	Main stem	+	.99	+	.99	0		−	.99	+	.95

[1] Codes are defined in table 1.

VF-type watersheds. Alkalinity and pH tend to be lower in RF-type watersheds than in VF-type watersheds. This difference may be due to different regoliths rather than different land uses, but lack of data prevents further analysis.

Mean temperatures in RF- and VL-type streams and in the main stem are significantly higher than in the VF-type streams in the fourth quarter of each year but are significantly lower in the first quarter of each year (table 5). This finding suggests a buffering of the VF-type streams against extremes of heat and cold. The amount of solar energy reaching the soil surface and the amount of energy radiating back to space would be expected to be greater in logged than in forested watersheds. Hence, streams draining logged watersheds should be warmer in summer and colder in winter than streams draining forested watersheds.

There is clear evidence that the main stem has significantly higher alkalinity and specific-conductance values than the VF-type streams, suggesting that the major dissolved-solids inputs to Redwood Creek occur upstream of the park.

Mean specific-conductance values are always significantly lower in RF-type streams than in the VF streams and are generally lower in the VL-type streams than in the VF-type streams. Lower mean values in VL-type streams may be due to a greater fraction of the runoff in these streams being from overland flow. Lower mean values in RF-type streams suggest a lower rate of regolith weathering than in VF-type streams.

Dissolved-oxygen saturation values show no pattern between watershed types.

SEASONAL VARIATIONS

Specific conductance, temperature, and alkalinity vary greatly with season. Because specific-conductance and alkalinity variations tend to be alike, alkalinity is not shown. Data used in this analysis consist of all the regularly gathered data from each station plus medians derived for the sites in each synoptic study.

Envelopes enclosing the range of values overlap considerably for VF- and RF-type watersheds (fig. 5); the envelope in VL-type watersheds has a greater range, and the values tend to be higher during the summer dry season. This difference between VL and the other types of watersheds suggests that logging accelerates normal weathering processes or initiates new processes altogether, leading to greater ranges of observed values at low flow. But the effect is apparently not uniform among VL-type watersheds; otherwise, the lower limit of the VL-type envelope would have shifted upward as did the upper limit in the dry season.

Temperatures vary too little between tributaries to be shown in this manner.

The time series of measurements at the main-stem stations above and below Harry Weir Creek, which approximately separates water of upstream origin from water affected by inpark tributary inflow, shows a different pattern (fig. 6). Water from upstream and water within the park are alike during the rainy months when specific conductance and temperature are both at minimum values, but water in the two areas differs considerably during the dry season. Main-stem water above the park is warmer and has a higher specific

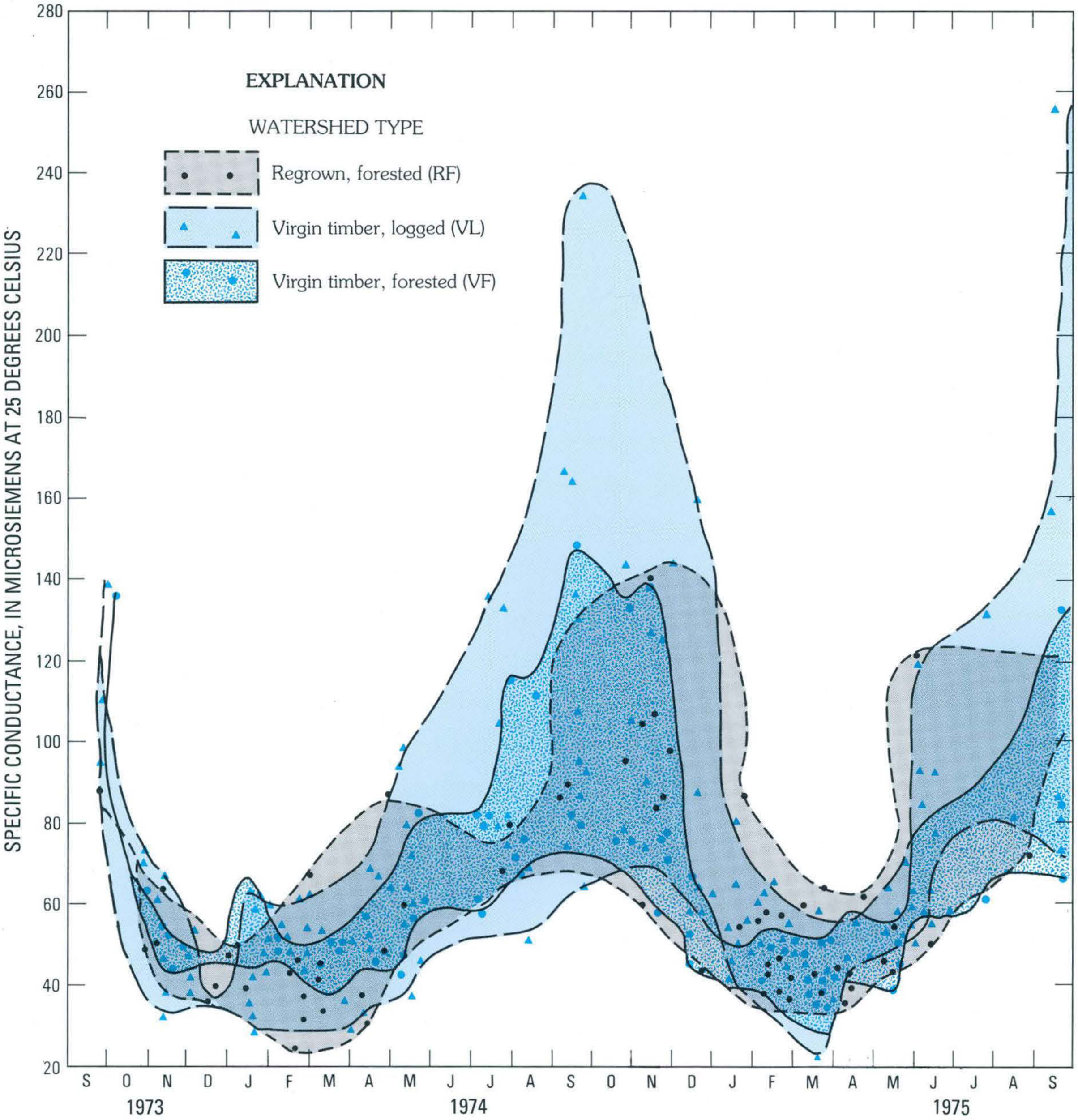

FIGURE 5.—Specific-conductance values for VF-, RF-, and VL-type watersheds.

conductance than main-stem water within the park, indicating that the main-stem water is diluted and cooled as it passes through the park, presumably from tributary inflow, influences of the marine climate, and shading.

Higher specific-conductance values upstream during the dry season suggest that the drainage basin upstream of the park is weathering faster than tributary watersheds within the park. Faster weathering may be partly related to slight differences in regoliths or to the intensity of logging activity (the drainage basin upstream of station 11482220 was 65 percent cutover as of 1973; table 2). It may also be related to exposure of the soil to the elements. According to Janda and others (1975a), vegetation in the upper basin grades upstream to prairie and sparse Douglas-fir, in contrast to the downstream part, which, in its pristine state, is covered by dense stands of redwood, Douglas-fir, and heavy undergrowth.

Differences related to regolith can be seen in the VL-type watersheds (fig. 7). During the dry season, streams with St-type regoliths seem to have the lowest specific-conductance values; streams with Sn-type regoliths have the highest values, and the Mx-type

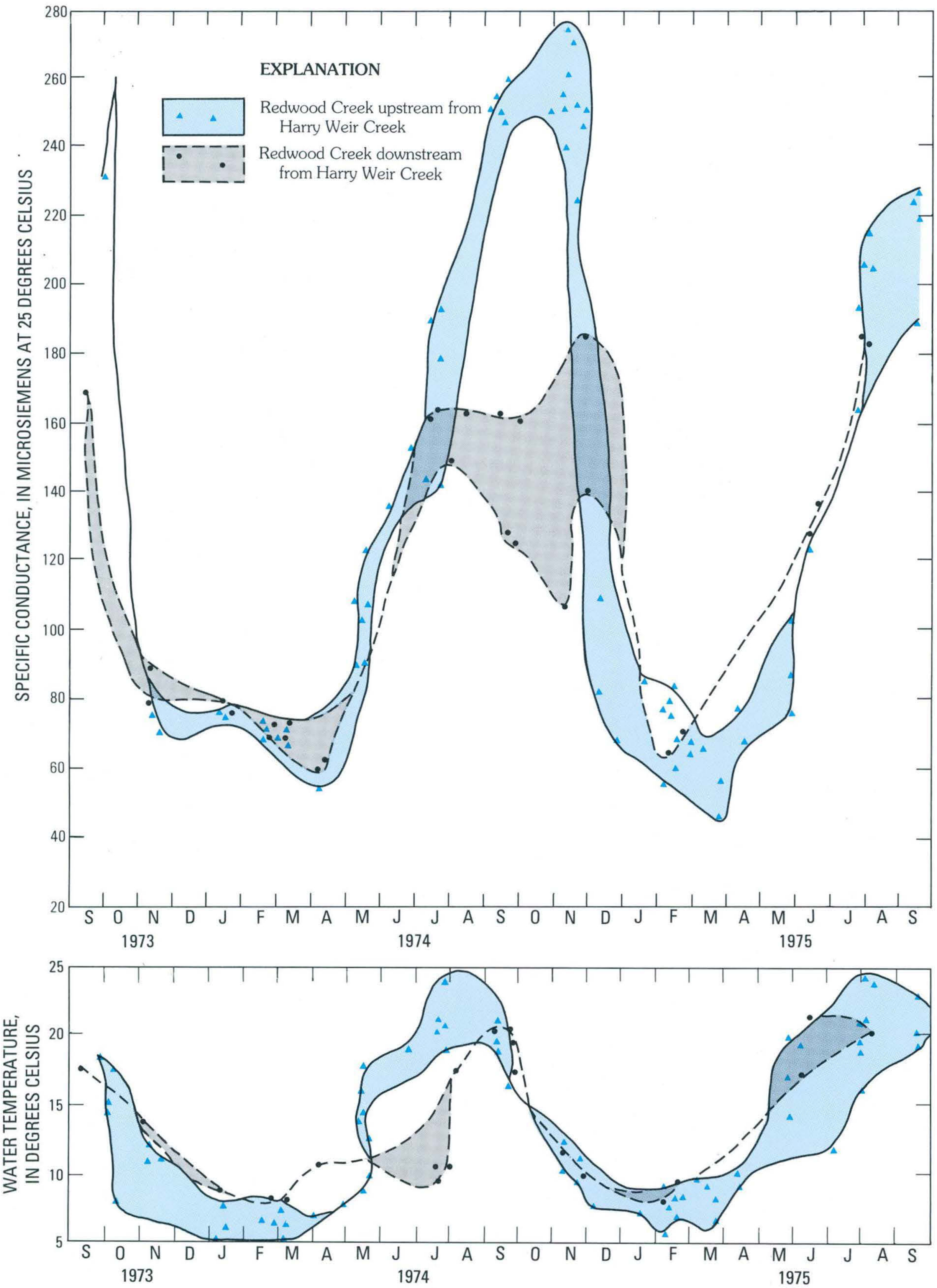

FIGURE 6.—Specific-conductance and water-temperature values for main-stem stations.

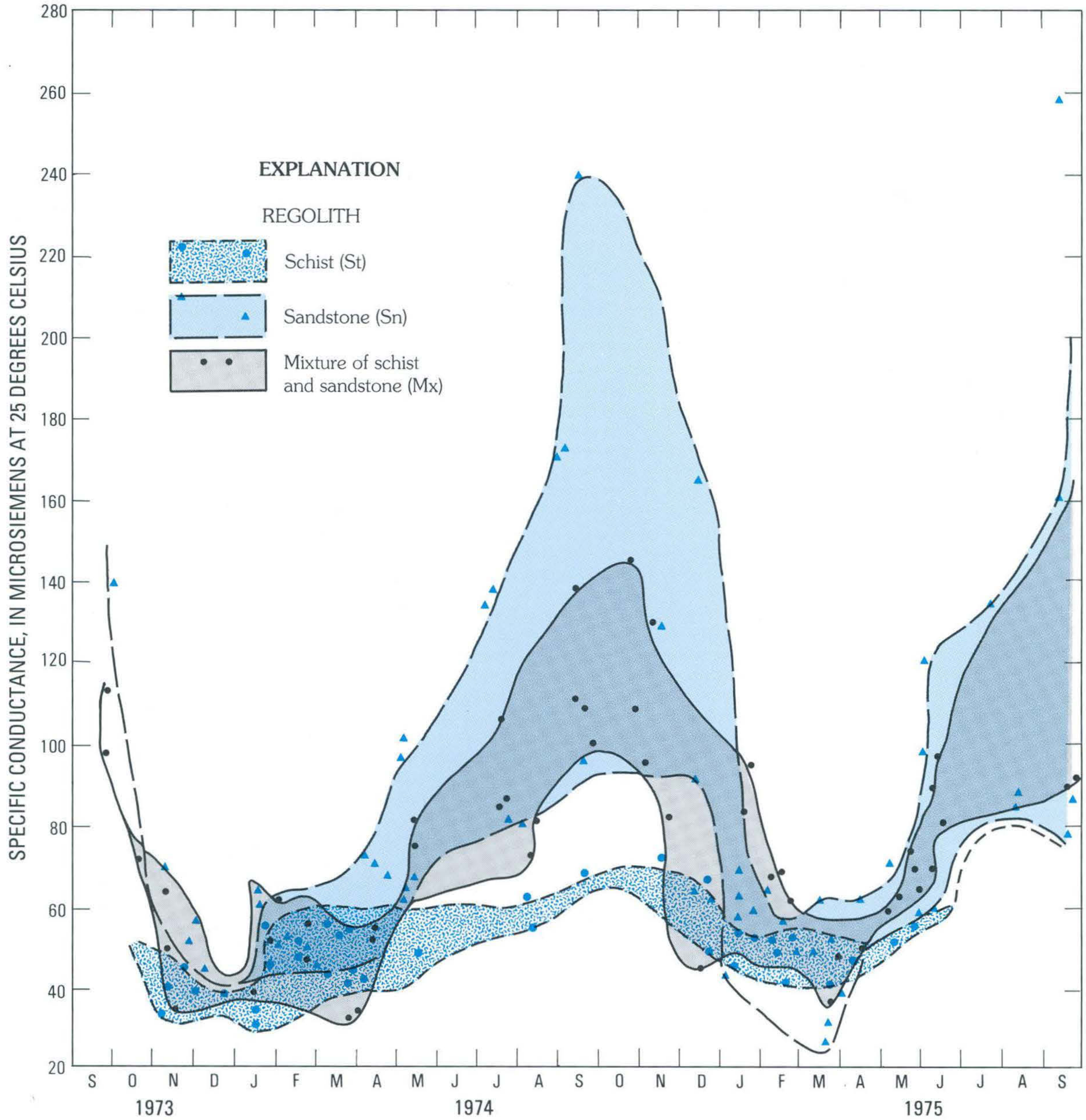

FIGURE 7.—Specific-conductance values for VL-type watersheds underlain by St-, Sn-, and Mx-based regoliths.

regoliths fall in between. This arrangement suggests that the sandstone-based (Sn) watersheds, when disturbed by logging, are more susceptible to weathering than are the schistose (St) watersheds. An examination of the data used in preparing figure 5 shows that the lower limit of specific conductance in VL-type watersheds during the dry season is defined by watersheds having a schistose regolith.

No differences in values related to regolith differences were found in the VF-type watersheds.

To examine further the characteristics of streams draining schistose regoliths, all data from St-based regoliths were analyzed in a similar manner (fig. 8). Envelopes enclosing data from VF-, VL-, and RL- (regrown, being logged) type watersheds generally overlap except for Bridge Creek (RL-type), which has much higher values of specific conductance than all other St-type streams. The Bridge Creek watershed is one of the steepest and most susceptible to erosion and landslumping in the Redwood Creek drainage basin.

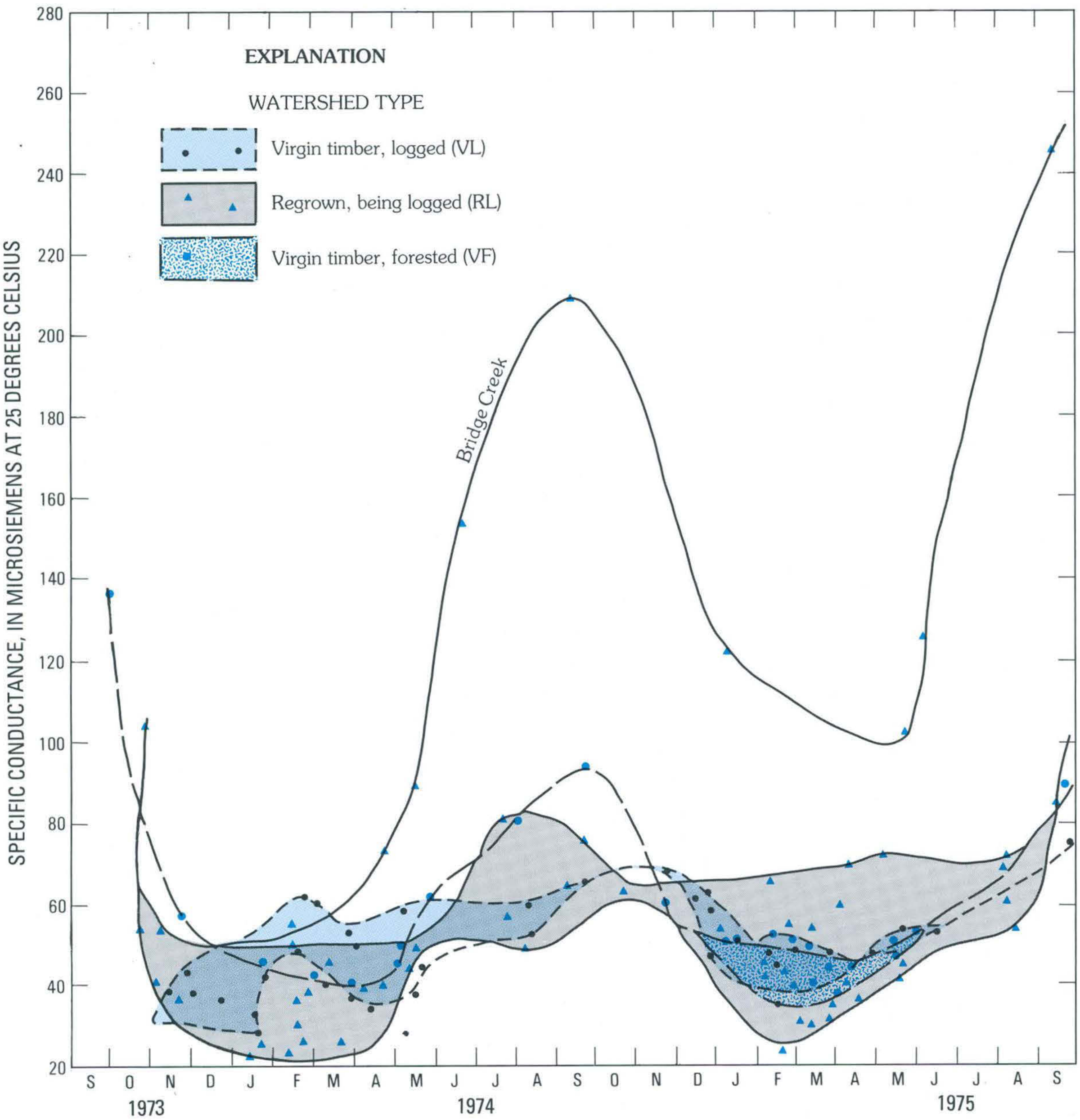

FIGURE 8.—Specific-conductance values for St-based regoliths in VL-, RL-, and VF-type watersheds.

Furthermore, it was logged intensively during this study. Because of the steepness of the slopes, logging caused considerably greater disruption of the surface soils there than in any other logged watershed (Deborah Harden, U.S. Geological Survey, oral commun., 1976). Perhaps intensive surface disruption has exposed deeper, less weathered soils to the elements, resulting in a greater rate of leaching of carbonate rocks.

In an analysis of water-type variations, preliminary evaluation indicated no differences between data sets collected in the first and fourth calendar quarters of both years. Data from these quarters were combined into one set representative of water quality during the rainy season. No regolith-related compositional differences could be found in the rainy-season data, but land-use-related differences are apparent (fig. 9).

The main-stem water is a calcium-bicarbonate type; water from unlogged areas (VF- and RF-type) is mixed sodium-calcium bicarbonate-chloride type. Water types from logged areas (VL-type) lie in between. The progression of water type from sodium chloride to calcium bicarbonate corresponds to increasing exposure of the

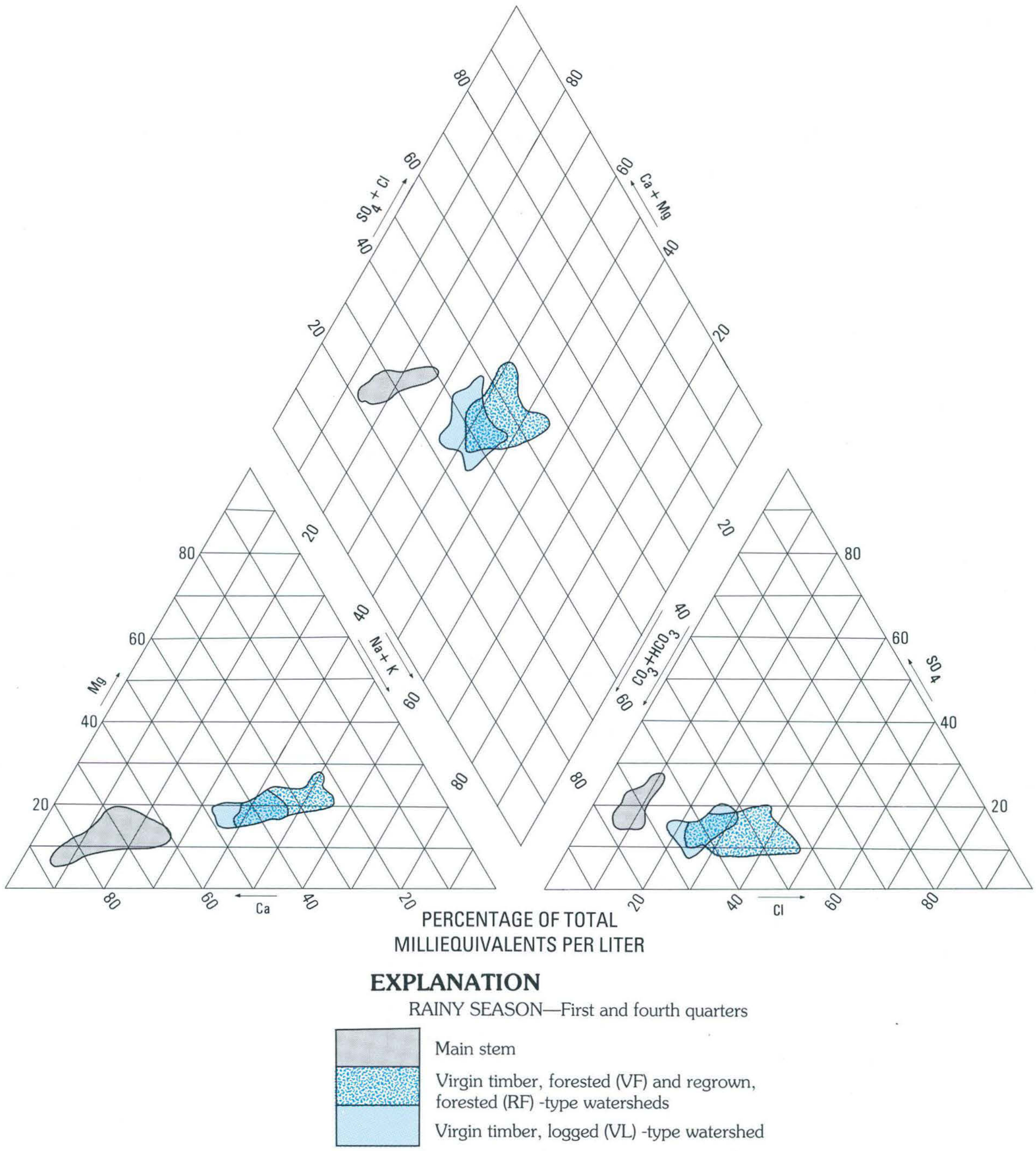

FIGURE 9.—Trilinear diagram showing major-ion composition in the fourth and first quarters, based on the nonsynoptic data, for VF-, RF-, and VL-type watersheds and main stem. (Technique from Piper, 1944.)

soil, either from logging activity or natural differences in vegetation.

Analysis of data from the second and third calendar quarters suggested that there are no compositional differences between sets from VF- and RF-type watersheds and no pattern of compositional differences due to differences in regolith in the combined VF- and RF-type sets. Differences attributable to regolith were observed in VL-type watersheds only.

Water from VF- and RF-type watersheds shifts from the second to the third quarter toward a calcium-bicarbonate type (fig. 10). Coincidentally, main-stem water, which is a single definable type in the second quarter, shifts to two types observable at South Park

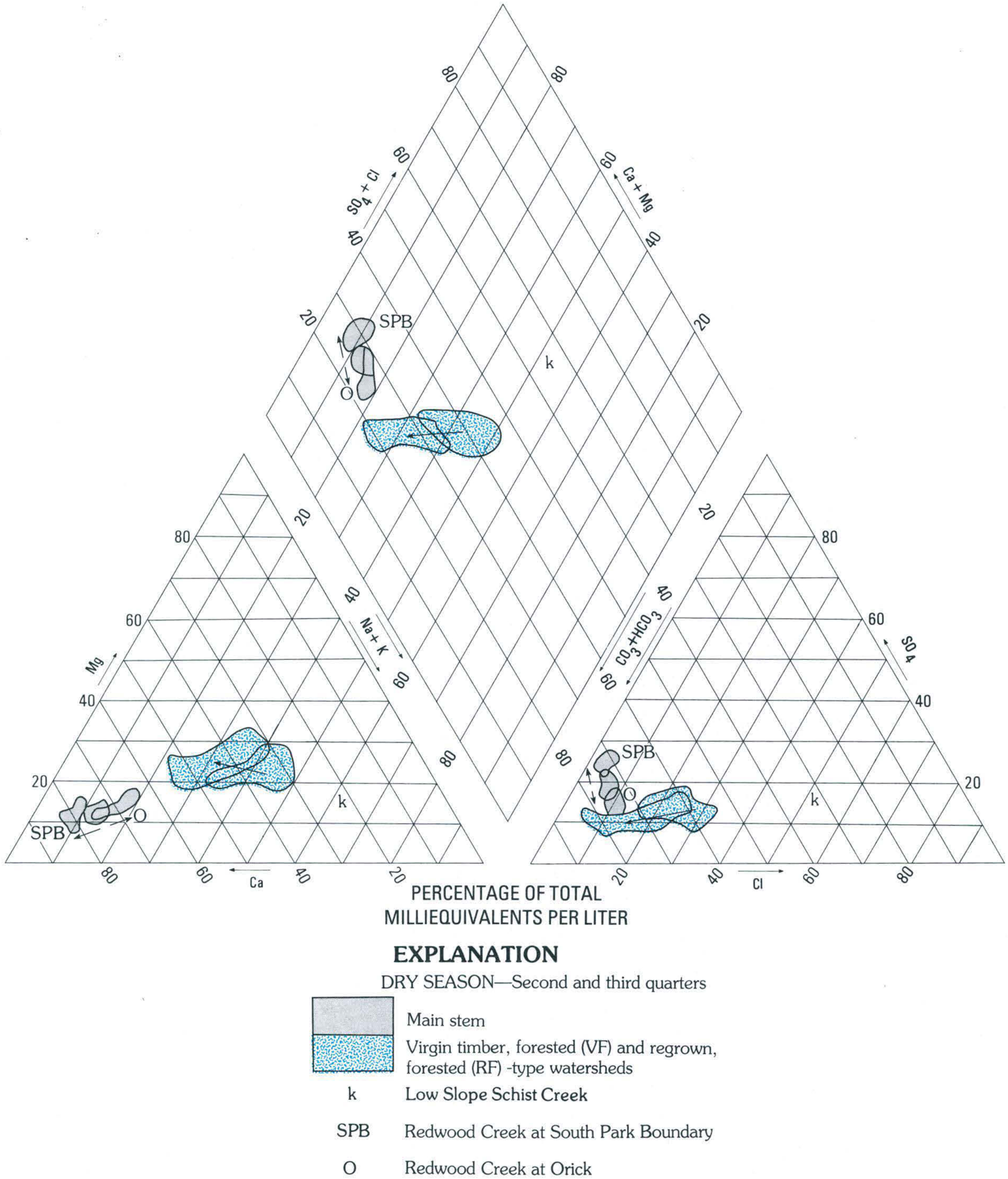

FIGURE 10.—Trilinear diagram showing major-ion composition in the second and third quarters, based on the regular data, for VF- and RF-type watersheds and main stem. Arrows indicate shifts in water types from the second to the third quarter. (Technique from Piper, 1944.)

Boundary (11482200) and at Orick (11482500). The water type at Orick shifts toward that of the park tributaries, indicating the effect of tributary inflow on main-stem water composition. Low Slope Schist Creek (VF-type, St-type watershed) stands out in figure 10 as a sodium-chloride-type water, suggesting very low weathering activity on the regolith of that watershed.

Compositional differences, apparently related to regolith differences, also exist between logged (VL- and RL-type) watersheds (fig. 11). This difference is most

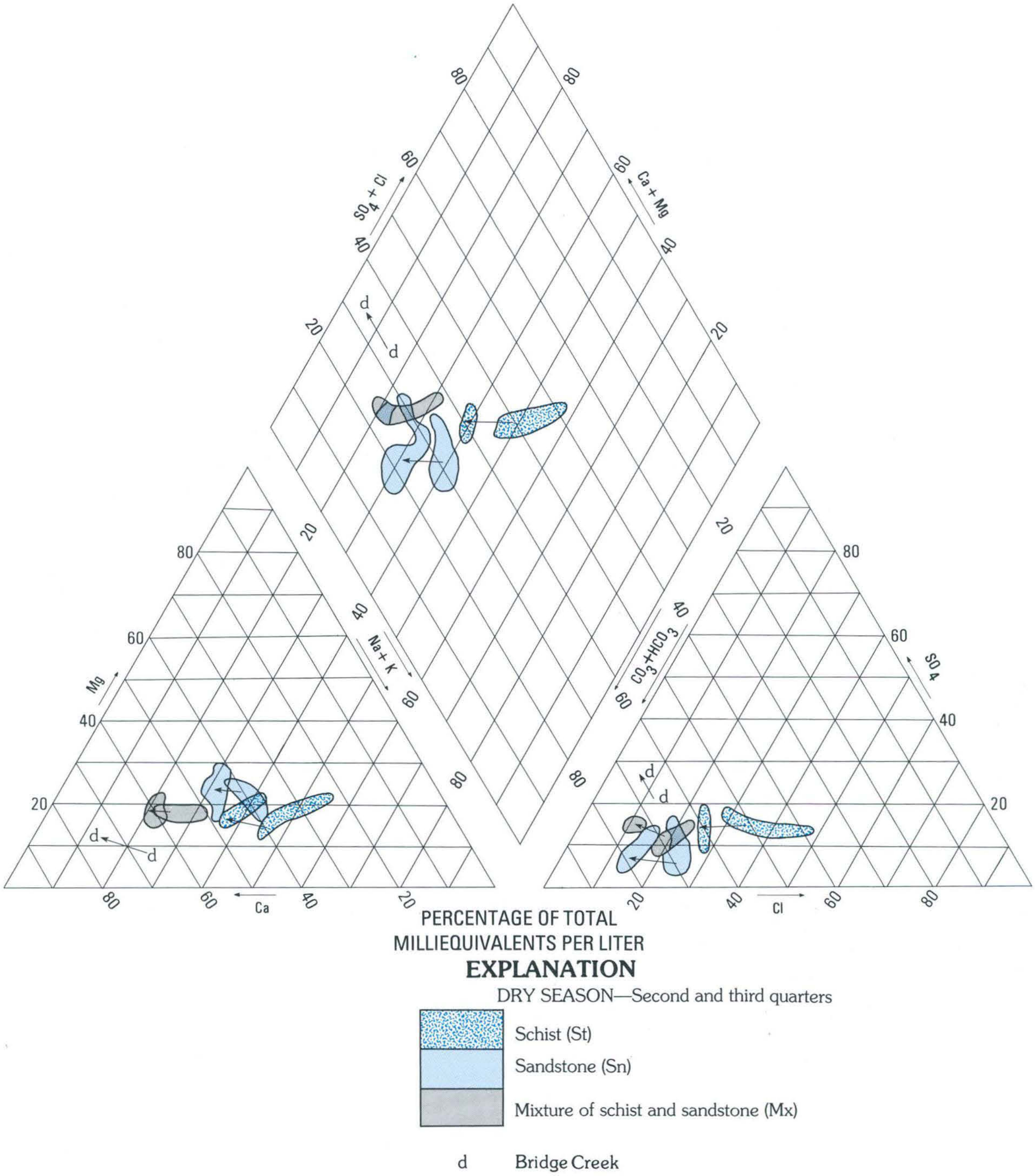

FIGURE 11.—Trilinear diagram showing major-ion composition in the second and third quarters, based on the regular data, for VL- and RL-type watersheds (St-, Sn-, and Mx-based regoliths). Arrows indicate shifts in water types from the second to the third quarter. (Technique from Piper, 1944.)

pronounced during the second quarter of the year. In the second quarter, St-type watersheds have a mixed sodium-chloride–bicarbonate-type water; Sn-type watersheds have a calcium–sodium-bicarbonate type. From the second to the third quarters, however, the water types in both St- and Sn-type watersheds shift toward calcium bicarbonate. Again, Bridge Creek (RL-type, St-type watershed) is unique among the St-type watersheds in having a calcium-bicarbonate-type water (see fig. 8).

In the second and third quarters, there is little difference in water type between the combined VF- and RF-type watersheds and the VL-type watersheds, as can be seen by comparing figures 10 and 11. If the schistose (St-type) watersheds are excluded from the set of VL-type watersheds, however, there is a tendency for the remaining VL-type watersheds to have water higher in calcium and bicarbonate than the water of the VF- and RF-type watersheds.

The weight of evidence suggests that schistose regoliths are generally more resistant to weathering than the other regolith types, which results in lower specific conductances and a more sodium-chloride-type water. But in cases of severe disruption (like Bridge Creek), the schistose watersheds can weather very rapidly, and this weathering results in high specific conductances and a calcium-bicarbonate-type water—the same characteristics seen in water from nonschistose watersheds that have been logged.

Data on pH and dissolved oxygen had no regular predictable dependence on time, so that handling the data by time series methods yielded little information. Changes with season and differences attributable to the land-use- or regolith-related watershed types were determined by statistical analysis of the grouped data.

No systematic variations in dissolved oxygen were observed either between calendar quarters or between the land-use- and regolith-related watershed types. Since physical turbulence is high in all streams studied, dissolved oxygen concentrations were all near saturation.

The mean pH of all streams studied appears to increase from 6.69 in the first quarter to 7.36 in the third and then decrease in the fourth quarter. The only systematic difference between land-use-related watershed types observed by a grouping analysis was that pH values for main-stem stations tended to be higher than those in tributary streams. Neither land use nor regolith type seemed to affect pH systematically between tributaries.

SUMMARY

HYDROLOGIC EFFECTS OF LOGGING

Overland flow makes only short-term contact with the soil before entering the stream. Thus it presumably contains fewer dissolved solids than the other components of stormflow. Dissolved-solids concentration or specific conductance and alkalinity decreased at peak storm discharge a significant number of times in the VL-type watersheds but only occasionally in the VF-type watersheds. This finding suggests that overland flow is an important part of peak discharge only in the watersheds that have been recently logged and is responsible for diluting the dissolved-solids concentrations. A statistical analysis suggests that peak specific conductances and alkalinities coincide with peak storm discharge with expectations of 50 percent in forested watersheds but at best only 20 percent in logged watersheds. Dilution at the peak occurs both early and late in the rainy season, suggesting that overland flow is an important part of the peak discharge in VL-type watersheds throughout the rainy season. Overland flow becomes more important in VF- and RF-type watersheds as the rainy season progresses but never occurs as frequently in them as in VL-type watersheds.

SYSTEMATIC VARIATIONS IN MAJOR-ION COMPOSITION WITH TIME

The most important changes in chemical composition with time are a regular shift in water type from season to season and accompanying changes in dissolved-solids concentrations. At the end of the dry season, streams tend to peak in specific conductance (hence, dissolved-solids concentration) and to be a calcium-bicarbonate type. As the rainy season progresses, the water type shifts steadily toward sodium chloride, and the specific conductance decreases, reaching a minimum in late March or early April. The change in water type through the rainy season is particularly evident from the chemograph data (fig. 4). Through the dry season, the water type shifts steadily back to calcium bicarbonate. This pattern is observed to about the same degree in all watersheds studied, although some distinction is evident between the land-use-related watershed types.

The probable mechanism for the changes in water type and dissolved-solids concentration is as follows. The first rains enter the soil and dissolve the soluble materials accumulated during the dry season, both products of weathering and salt spray from the ocean. A large part of this water probably percolates to the ground-water reservoir and later appears as base flow. The remainder of the water runs off, probably as quick-return and delayed-return flow. This process is repeated with each rain. As the soil becomes saturated and the water table rises, less water percolates and more appears as overland and quick-return flows. Repeated rains also leach the soils of soluble materials. Runoff from the early rains tends, therefore, to be of the same type and dissolved-solids concentration as the base flow except where the overland flow component is large. But as the rainy season progresses, available soluble materials decrease relative to the volume of runoff. Hence, runoff from rains later in the season contains less calcium and bicarbonate derived from the weathering of the Franciscan-based soils.

At the end of the rainy season, the water stored in the soil appears as base flow. Early in the dry season, the base flow consists largely of the water from the most recent rains. As the dry season progresses, and the water table falls, an increasing fraction of the base flow consists of water percolated to the water table at various times in the rainy season just concluded.

Because chloride salts are not produced in significant concentrations by the weathering of most rocks, the ocean is probably the source of those salts in runoff water. The chemograph studies suggested that chloride enters runoff water by different mechanisms early and late in the rainy season. Chloride concentrations were equal in both Harry Weir and Little Lost Man Creeks in November, and the time series of chloride concentrations were identical to the time series of other constituents. This similarity suggests that the predominant source of chlorides was the soil. Chloride salts were probably accumulated as dry fallout during the summer.

In February, the chloride concentration was higher in Little Lost Man Creek than in Harry Weir Creek and tended to remain constant through the discharge hydrographs of both streams. This observation suggests that late in the rainy season the predominant source of chloride was the rain itself. The chloride concentration was higher in Little Lost Man Creek probably because that creek is closer to the ocean than Harry Weir Creek and received more sea spray in the precipitation. The water type shifts toward sodium chloride as the rainy season progresses because other salts are derived from the soil and become scarce relative to the volume of runoff, whereas the chloride salts come with the rain.

VARIATIONS IN PHYSICAL CONDITIONS AND MAJOR-ION COMPOSITION BETWEEN LAND-USE-RELATED AND REGOLITH-RELATED WATERSHED TYPES

Stream temperatures are more variable in watersheds having more soil surface or stream surface exposed to the open sky. Mean temperatures in RF- and VL-type streams and in the main stem during stormflows are higher than mean temperatures in the VF-type streams in the fourth quarter and lower than in the VF-type streams in the first quarter (table 5). This pattern suggests that exposure of the soil leads to higher water temperatures in autumn and lower temperatures in winter during stormflow. This pattern is not seen in the data collected between storms in the dry season.

During the summer months, the main stem is significantly warmer above Harry Weir Creek than below it. This difference may be due to the greater exposure of the main stem above Harry Weir Creek, together with the cooling effect of water entering the main stem below Harry Weir Creek from tributaries in the park.

During low flow, watersheds having more exposure to weathering (VL- and RL-type) tend to have water with higher dissolved-solids (as indicated by specific conductance) concentrations than the forested (VF- and RF-type) watersheds. Also, the main stem above Harry Weir Creek has higher dissolved-solids concentrations at low flow than the main stem below Harry Weir Creek. The drainage basin above Harry Weir Creek is highly exposed both because of heavy logging and because the natural vegetation is sparser than in the drainage basin below the creek. Within the group of logged watersheds (VL), streams from the schistose regoliths (St) have the lowest dissolved-solids concentrations, and streams from the sandstone-based regoliths (Sn) have the highest concentrations. Within the group of schistose (St) watersheds, no differences in dissolved solids were discernible between watershed types, except that Bridge Creek, the watershed in the study area perhaps most heavily scarred by the various activities accompanying logging, has the highest dissolved-solids concentrations of any stream studied. Other factors not investigated here may contribute to high dissolved-solids concentrations in Bridge Creek. Thus, a firm cause-and-effect relationship cannot be established without further study.

Differences in water types also can be seen between land-use-related and regolith-related watershed types. During the rainy season, water types from the forested watersheds, logged watersheds, and the main stem form a regular progression from a mixed calcium-sodium bicarbonate-chloride type to a calcium-bicarbonate type. This progression corresponds to increasing exposure of the watershed to weathering due either to logging or to natural differences in vegetative cover. During the dry season, water from the group of VL- and RL-type watersheds (excluding the schistose watersheds) tends to be a more calcium-bicarbonate type than water from the VF- and RF-type watersheds.

The schistose (St-type) watersheds provide less consistent results. Generally, the water in this group of streams is a mixed calcium–sodium-bicarbonate–chloride type, regardless of the land-use-related watershed type, but Low-Slope Schist Creek (VF-type) has a distinctive sodium-chloride–bicarbonate-type water. In contrast, Bridge Creek (RL-type) has a calcium-bicarbonate-type water.

The results discussed above suggest that exposure of the land surface increases the rate of chemical weathering of the native regolith. The sandstone-based regoliths generally are most susceptible, and the schistose regoliths generally least susceptible to accelerated weathering, but extensive soil disruption in the schistose watersheds, as in Bridge Creek, may overwhelm the apparent natural resistance of the schistose regolith to weathering.

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Interchange of Surface and Intragravel Water in Redwood Creek, Redwood National Park, California

By PAUL F. WOODS

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–T

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INTERCHANGE OF SURFACE AND INTRAGRAVEL WATER IN REDWOOD CREEK, REDWOOD NATIONAL PARK, CALIFORNIA

By PAUL F. WOODS

ABSTRACT

The dissolved-oxygen concentrations of surface and intragravel water were sampled to investigate the interchange of surface and intragravel water in Redwood Creek, a major coastal stream that flows through Redwood National Park. Dissolved-oxygen concentrations were sampled weekly at three sites from June to November, 1974. In August 1974, streambed samples were taken at the three sites to determine the percentage composition of sediment particles, particularly those smaller than 0.833 millimeter.

There were no significant differences among the dissolved-oxygen concentrations of surface water at the three sampling sites. However, the intragravel water at the sampling site farthest downstream had significantly lower dissolved-oxygen concentrations than did the two upstream sampling sites. It was concluded, therefore, that the interchange of surface and intragravel water at the downstream sampling site was less efficient than at the two upstream sites.

The streambed samples revealed only slight differences in percentage composition of sediment particles smaller than 0.833 millimeter; thus, the data could not be used to explain the reduced interchange at the downstream sampling site. The reduced interchange at this sampling site was attributed to its smooth streambed surface, which was densely covered with periphytic algae.

INTRODUCTION

The commercial and sport fisheries of California's north coastal region rely on anadromous salmonid fish such as king salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), and steelhead rainbow trout (*O. mykiss*). Streambed gravels used by these fish for spawning have been affected adversely by deposition of sediment attributable to timber harvest operations, another principal industry of the region (Cordone and Kelly, 1961; Hall and Lantz, 1969; California State Water Resources Control Board, 1973).

Extensive research has been conducted on the relation of streambed sediment to survival of salmonid eggs spawned in the streambed. While in the streambed, the developing eggs and alevins (newly hatched juveniles) require an adequate interchange of surface and intragravel water to provide them with dissolved oxygen and to flush away their metabolic wastes. Reductions in interchange have been found to reduce the survival rate of salmonid eggs and alevins (Coble, 1961; Shumway and others, 1964). McNeil and Ahnell (1964) found that permeability was reduced as the percentage composition of sediment finer than 0.833 mm increased in the streambed. Increased sedimentation of streambeds, therefore, has the potential to reduce survival of salmonid eggs and alevins.

A major part of Redwood National Park lies within the Redwood Creek drainage basin (fig. 1). Redwood Creek is a major coastal stream accessible to anadromous salmonid fish via its mouth near Orick (fig. 1). Detailed descriptions of the Redwood Creek drainage basin and Redwood Creek are included in Janda and others (1975).

An assessment of the intragravel environment of Redwood Creek and some of its tributaries was included in a study of Redwood National Park. Intragravel water-quality conditions in the following three tributaries have been described by Woods (1980): tributary to Lost Man Creek, Little Lost Man Creek, and Panther Creek (fig. 1).

The study reported here was designed to collect data on intragravel water quality and to compare interchange of surface and intragravel water at three sampling sites on Redwood Creek. Samples were collected during 1974 and analyzed for dissolved-oxygen concentrations and temperatures of surface and intragravel water and the percentage composition of streambed sediment. The data were then used to assess interchange between surface and intragravel water.

METHODS

For this study, samples were collected in riffle areas at the following three sites on Redwood Creek: river mile

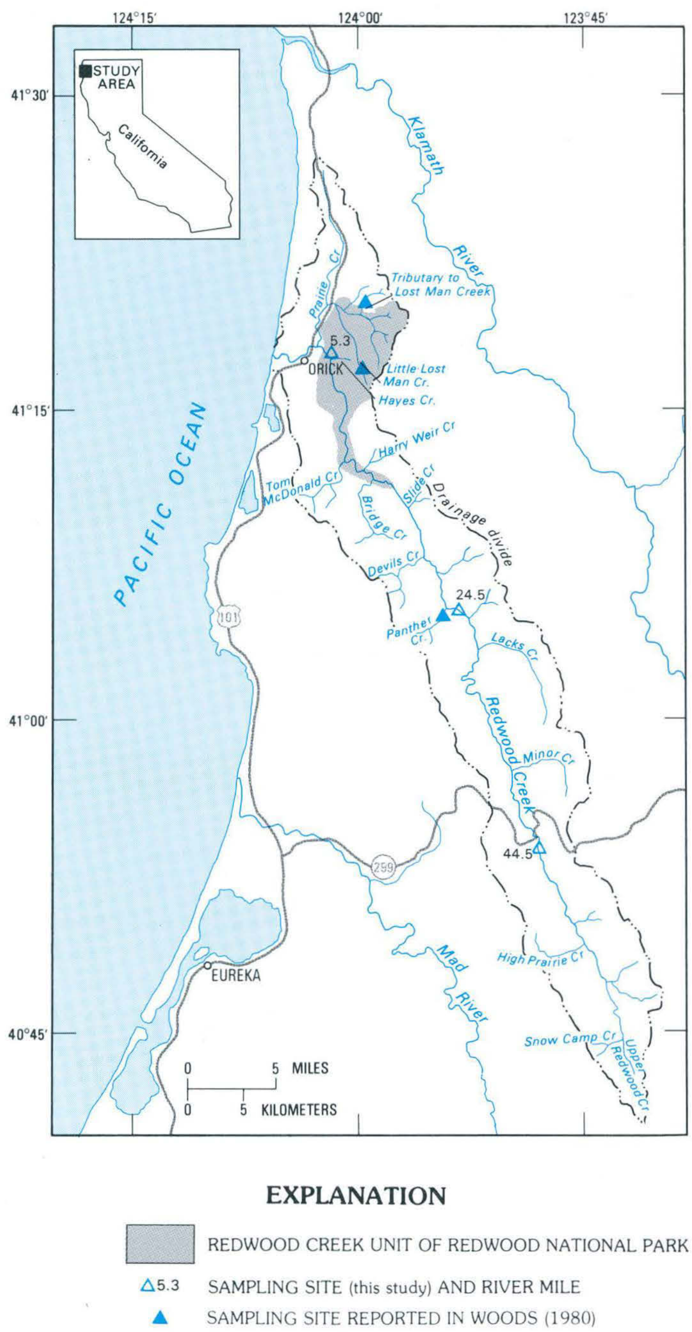

FIGURE 1.—Redwood Creek drainage basin showing locations of sampling sites.

5.3, downstream from the mouth of Hayes Creek; river mile 24.5, upstream from the mouth of Panther Creek; and river mile 44.5, adjacent to U.S. Geological Survey streamflow-measurement station number 11481500 (fig. 1). Samples were collected from June 26 to November 9, 1974. Large streamflow precluded sampling during the winter.

Dissolved-oxygen concentrations and temperatures of surface and intragravel water were sampled weekly. One middepth sample of surface water was taken because water depths did not exceed 610 mm. Intragravel water was sampled in place using polyvinyl chloride (PVC) plastic standpipes (fig. 2). The standpipes were modifications of those described by Terhune (1958), Gangmark and Bakkala (1958), and Coble (1961). In early June, five standpipes were randomly placed in riffle areas at each sampling site. Prior to sampling, one standpipe volume of water was gently pumped from each standpipe to ensure a fresh sample. Dissolved-oxygen concentrations and temperatures were measured with a dissolved-oxygen meter and thermister lowered into the standpipe. The meter was calibrated with the Alsterburg-Azide modification of the Winkler dissolved-oxygen test (Brown and others, 1970) before and after each sampling trip. The interchange of surface and intragravel water was expressed as a percentage with the following equation:

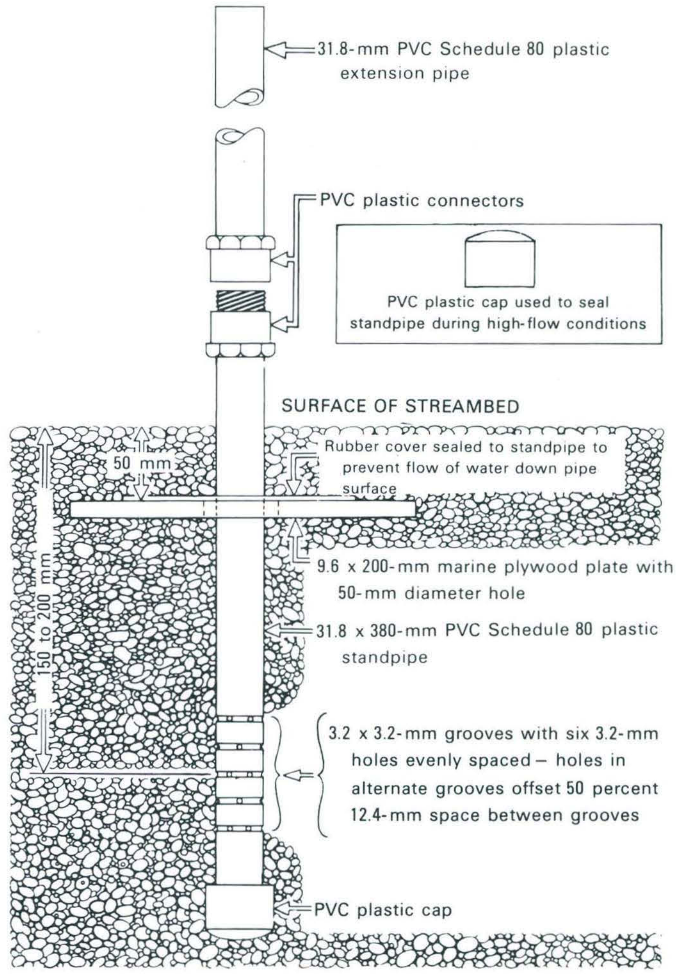

FIGURE 2.—Standpipe, extension, and sealing plate used to sample intragravel water for dissolved-oxygen concentration and temperature.

$$P=\frac{I}{S}\times 100.0$$

where:

P is interchange percentage,

I is mean dissolved-oxygen concentration of intragravel water, in milligrams per liter, and

S is dissolved-oxygen concentration of surface water, in milligrams per liter.

During August 1974, the percentage composition of streambed materials at each sampling site was estimated by using procedures and equipment described by McNeil and Ahnell (1964). A core of the streambed was separated into size classes with seven sieves that ranged in mesh from 26.67 to 0.104 mm. These sieves were chosen to conform to previously reported methods used in intragravel research. The contribution of each size class to the core sample was determined by wet volumetric displacement. Materials that passed the 0.104-mm mesh were measured in a graduated settling cone. Results of streambed sampling were biased because the core sampler excluded materials larger than 152.4 mm.

Nonparametric statistical analysis was used to test for and locate significant differences in all the data. The tests included the Kruskal-Wallis test (Sokal and Rohlf, 1969) and two multiple comparison tests, one for equal sample sizes (Zar, 1974) and one for unequal sample sizes (Dunn, 1964, as cited by Hollander and Wolfe, 1973).

RESULTS

The dissolved-oxygen concentrations of surface water ranged from 8.3 to 11.6 mg/L among the three sampling sites, whereas the mean dissolved-oxygen concentrations of intragravel water ranged from 4.1 to 11.3 mg/L (fig. 3). The three sampling sites did not differ significantly in their surface-water dissolved-oxygen concentrations, but the mean concentrations of dissolved oxygen in intragravel water were significantly lower ($p < 0.01$) at river mile 5.3 than those measured at the other two sampling sites. River miles 24.5 and 44.5 showed no significant differences in their mean concentrations of intragravel dissolved oxygen.

Interchange percentages at river mile 5.3 ranged from 44.5 to 61.5; they were never less than 86 percent at the other two sampling sites (fig. 4). There were no significant differences in interchange percentages between river miles 24.5 and 44.5; however, both had significantly larger ($p < 0.01$) interchange percentages than did river mile 5.3.

Surface-water temperatures ranged from 9.0 to 26.0 °C, and mean temperatures of intragravel water ranged from 9.0 to 26.0 °C among the three sampling sites (fig. 5). Surface-water temperatures did not differ significantly among sampling sites.

Mean temperatures of intragravel water at river miles 24.5 and 44.5 were significantly warmer ($p < 0.05$) than those at river mile 5.3. The temperatures of surface and intragravel water frequently were equal or within 0.5 °C at each of the two upstream sampling sites; however, such was not the case at river mile 5.3. Prior to mid-September, intragravel water at river mile 5.3 generally was cooler than surface water, but after mid-September intragravel-water temperatures exceeded surface-water temperatures by as much as 5 °C.

The percentage composition of streambed material at the three sampling sites is listed in table 1. An additional size class, finer than 0.833 mm, was added to the table because an inverse correlation between streambed permeability and this size class has been reported by McNeil and Ahnell (1964). No statistical tests were applied to the data in table 1 because of the small sample size. River mile 44.5 had a larger percentage of streambed material finer than 0.833 mm than either of the other two sampling sites. Visual observations of the streambed revealed that cobbles and gravels predominated at river miles 24.5 and 44.5; pebbles and sand predominated at river mile 5.3.

DISCUSSION

This study compared dissolved-oxygen concentrations of surface and intragravel water to determine the percentage of interchange between the two kinds of water. A complete evaluation of such interchange, insofar as it can be determined by measurement of dissolved-oxygen concentrations, would require in-depth study of the many physical, chemical, and biological processes that affect dissolved-oxygen concentrations of water. Only selected physical processes were studied in this project.

Within the streambed, dissolved oxygen is physically supplied by inflow of surface and ground waters. Interchange of surface and intragravel water is largely controlled by three characteristics of the streambed: configuration, thickness of permeable material, and permeability (Vaux, 1962, 1968). Surface water moves into the streambed where the bed has a convex configuration; intragravel water moves out of the streambed at concave configurations. Vaux also found that the movement of surface water into the streambed is promoted by an increase in the thickness of permeable material or an increase in streambed permeability in the direction of flow. None of the three streambed characteristics discussed by Vaux (1962, 1968) were quantified in this study. However, streambed configuration was qualitatively assessed, and indirect evidence for permeability was provided by data on percentage composition (by size) of streambed sediment.

The streambeds at the three sampling sites did not have distinct concave or convex configurations. The

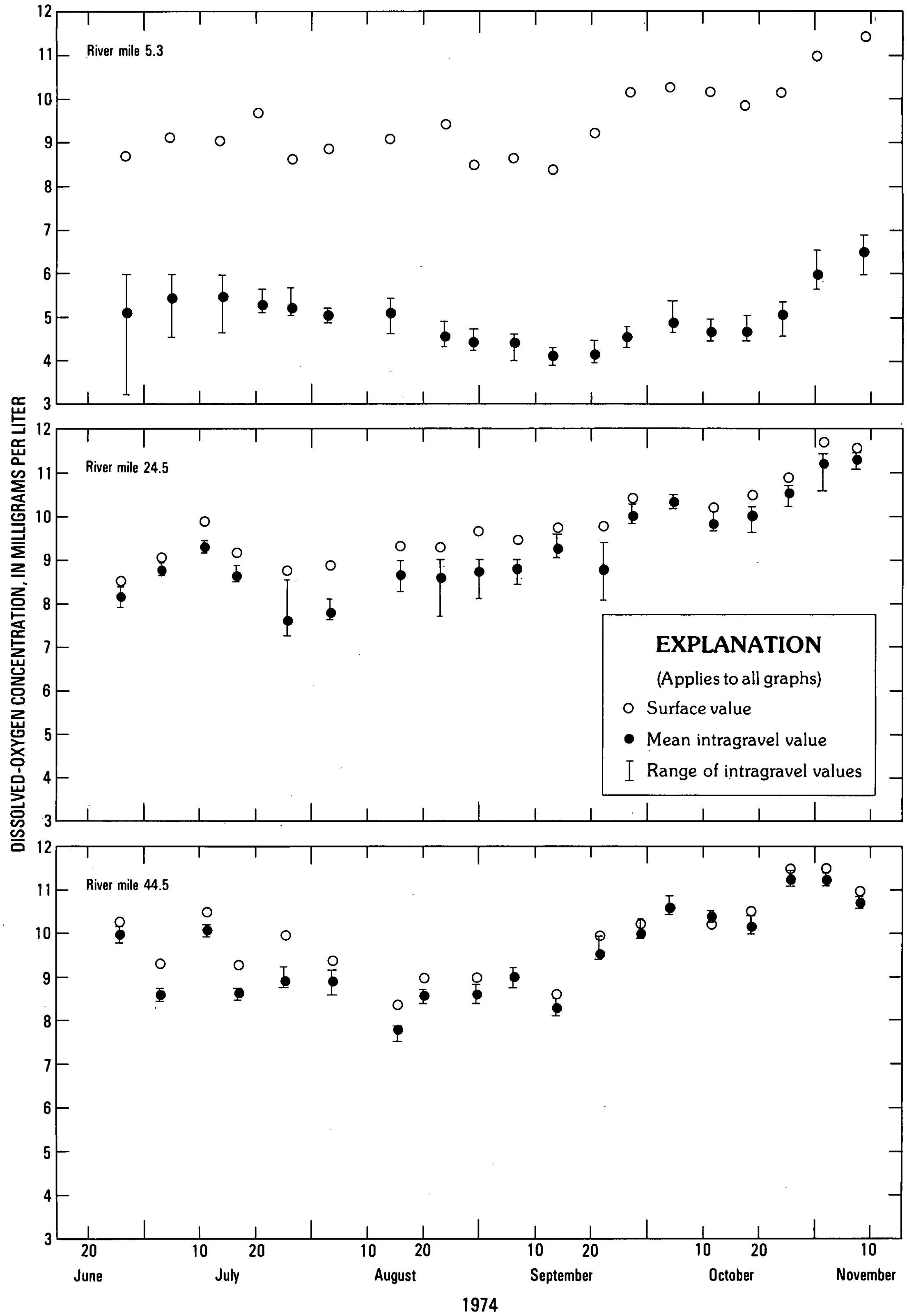

FIGURE 3.—Dissolved-oxygen concentrations of surface and intragravel water at three sampling sites.

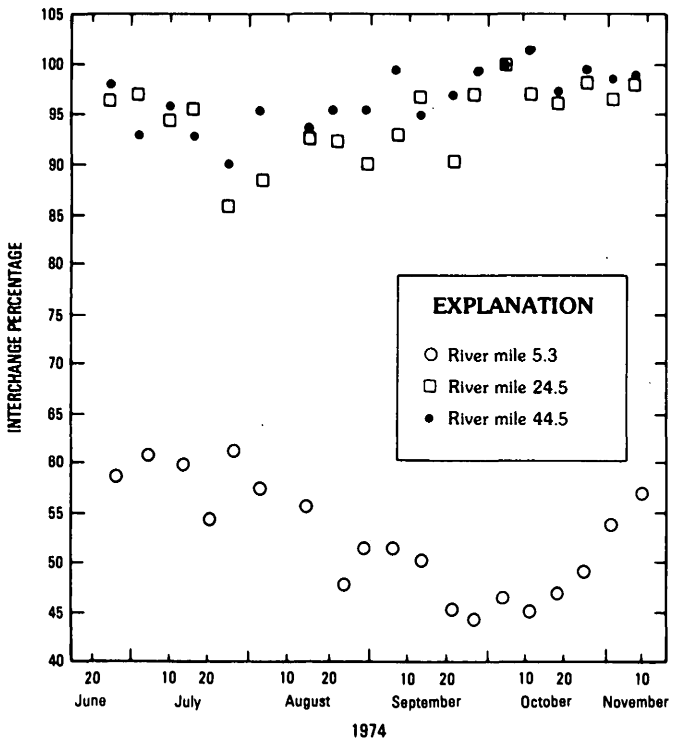

FIGURE 4.—Interchange percentages at the three sampling sites.

streambed surface at river mile 5.3 was relatively smooth, largely due to the predominance of pebbles and sand. Vaux (1962, 1968) determined experimentally that interchange would be minimized by a smooth streambed surface. The two upstream sampling sites had irregular streambed surfaces because they were predominated by cobbles and gravels. Cooper (1965) reported that irregularities at the streambed surface enhanced interchange.

Cooper (1965) found that streambed permeability could be reduced when sediments blocked interstices within the streambed. McNeil and Ahnell (1964) correlated reductions in interchange with increases in the percentage composition of streambed sediment finer than 0.833 mm. On the basis of these prior findings, one would expect the sampling site with the least interchange to possess the largest percentage of fine sediment. River mile 5.3 had the least interchange; however, it did not have the lowest percentage of streambed sediment finer than 0.833 mm. Therefore, the differences in interchange among the three sampling sites could not be explained by the inverse correlation between streambed permeability and the percentage of streambed sediment finer than 0.833 mm.

Interchange can also be impeded by mats of periphytic algae overlying the streambed (Sheridan, 1962). A mat of periphytic algae overlaid the sampling site at river mile 5.3 throughout the period of study and attained a maximum thickness of about 13 mm from mid-September until streamflow increased from a storm on October 27. River miles 24.5 and 44.5 also had mats of periphytic algae but to a much lesser degree than found at river mile 5.3. Because the five lowest values of interchange percentage at river mile 5.3 occurred during the period of maximum thickness of the periphyton mat, it appears that interchange may have been restricted by such mats.

Ground-water inflow was not directly measured at the three sampling sites, but water-temperature data provided some indirect evidence for such inflow at one site. The close correspondence in temperatures of surface and intragravel water at river miles 24.5 and 44.5 suggests that ground-water inflow was negligible. Such was not the case at river mile 5.3, however, where surface and intragravel water temperatures did not correspond and intragravel water temperatures did not respond to fluctuations in surface-water temperatures. This finding suggests that ground water, with less fluctuation in temperature than surface water, was flowing into the streambed at river mile 5.3.

The relatively low concentration of intragravel dissolved oxygen measured at river mile 5.3 may have been caused partly by inflow of oxygen-deficient ground water. This hypothesis cannot be tested because pertinent data were not collected during the study. However, shallow ground water in silty or clayey soils generally has a negligible dissolved-oxygen concentration (Freeze and Cherry, 1979). The soils of the Redwood Creek drainage basin typically are stony loams and stony-clay loams (Janda and others, 1975), and, therefore, ground water might be expected to be deficient in dissolved oxygen.

Once dissolved oxygen has physically entered the streambed, it can be consumed by respiring organisms and by oxidation of carbonaceous and nitrogenous materials. Because such chemical and biological processes were not measured in this study, the exact causes of the large differences in concentrations of intragravel dissolved oxygen between sites at river miles 24.5 and 44.5 and the site at river mile 5.3 cannot be determined. Any future investigators who propose to quantify the interchange of surface and intragravel waters would profit by collecting data applicable to evaluation of the chemical and biological, as well as the physical, processes that control dissolved-oxygen concentrations.

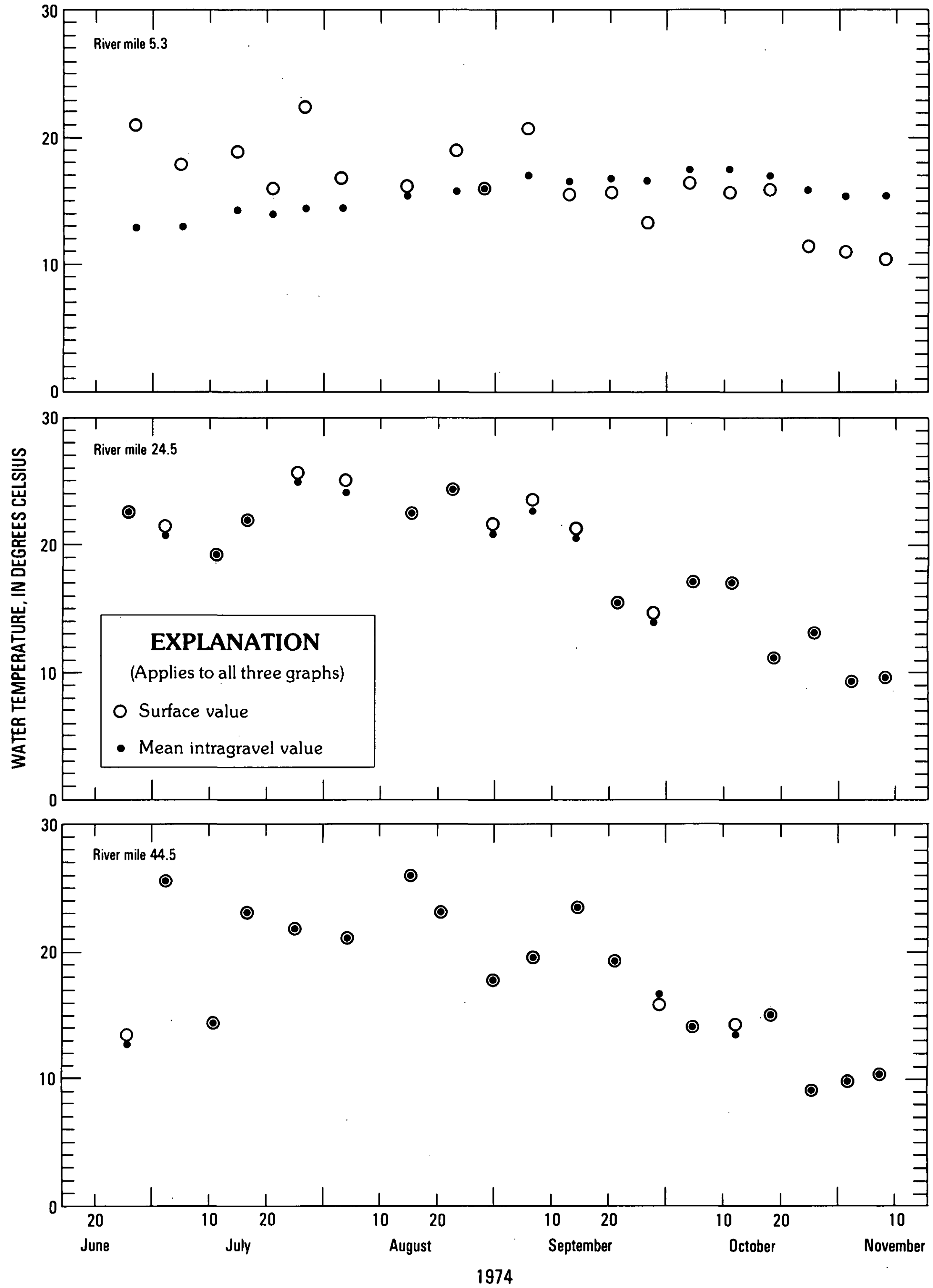

FIGURE 5.—Temperatures of surface and intragravel water at the three sampling sites.

TABLE 1.—*Percentage composition of streambed material at the three sampling sites*
[mm, millimeter; <, less than; five streambed cores were taken at each site]

Mesh size of sieve (mm)	River mile 5.3		River mile 24.5		River mile 44.5	
	Mean percent material retained	Standard deviation	Mean percent material retained	Standard deviation	Mean percent material retained	Standard deviation
26.67	4.5	3.6	13.0	4.7	22.5	8.1
13.50	14.8	6.0	15.5	2.4	12.8	2.8
6.73	20.6	4.0	16.5	2.0	12.2	2.1
3.33	18.7	5.7	12.9	1.9	10.8	2.3
1.70	13.6	4.2	11.9	1.0	11.8	1.6
.833	9.2	6.1	13.2	1.6	8.0	1.3
.104	14.3	1.7	9.4	1.9	11.9	2.0
<.104	4.3	2.5	7.6	1.6	10.0	2.8
[1]<.833	18.6	2.7	17.0	1.5	21.9	2.4

[1] McNeil and Ahnell (1964) found that permeability was reduced as the percentage composition of sediment finer than 0.833 mm increased.

CONCLUSIONS

Data for dissolved-oxygen concentrations and water temperatures revealed that the interchange of surface and intragravel water at river mile 5.3 was substantially less than at river miles 24.5 and 44.5. The presence at river mile 5.3 of a mat of periphytic algae on the streambed was a likely cause of the impeded interchange. The low concentrations of dissolved oxygen in intragravel water at river mile 5.3 may have resulted partly from inflow of oxygen-deficient ground water.

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Summer Cold Pools in Redwood Creek near Orick, California, and Their Relation to Anadromous Fish Habitat

By EDWARD A. KELLER, TERRENCE D. HOFSTRA, *and* CLARICE MOSES

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–U

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SUMMER COLD POOLS IN REDWOOD CREEK NEAR ORICK, CALIFORNIA, AND THEIR RELATION TO ANADROMOUS FISH HABITAT

By EDWARD A. KELLER,[1] TERRENCE D. HOFSTRA,[2] and CLARICE MOSES[1]

ABSTRACT

"Cold pools" in Redwood Creek, Calif., maintain summer water temperatures several degrees Celsius cooler than main-stream temperatures. The cold pools form where cool ground water, or main-stream water cooled by intragravel flow, seeps from the channel and does not rapidly mix with the warmer main-stream water. Mixing may be retarded by large organic debris, which also helps to create the pool by inducing scour during relatively high-flow events, or by midchannel or side-channel gravel bars. Thus, formation and maintenance of cold pools result from a variety of processes operating over a spectrum of flows ranging from winter floods, which scour pools and move large organic debris, to summer low flow, in which effluent subsurface water becomes significant.

Little is known about the hydrologic and fluvial geomorphic implications of effluent-influent subsurface water and streams. During the later summer, however, a larger portion of the base flow in Redwood Creek is probably produced from effluent ground water from point sources, such as the dry channel of Hayes Creek, rather than from more dispersed sources such as small springs that discharge along the valley margin from bedrock aquifers. Measurement of the summer low-flow discharge of Redwood Creek at the site of the Hayes Creek cold pool suggests that main-stream flow may be augmented locally by as much as 22 percent (of the main-stream flow upstream of Hayes Creek) by effluent subsurface flow. Furthermore, as streamflow in Redwood Creek decreases from early to late summer, the amount of subsurface water from the Hayes Creek catchment also decreases, but the amount of effluent subsurface flow as a percentage of the total streamflow increases. A limiting factor to anadromous fish productivity in many northern California streams is the summer pool environment. Cold pools in Redwood Creek, although few in number, provide high-quality summer habitat for juvenile and migratory adult anadromous fish relative to other pools. Formation of new cold pools in areas where cold subsurface water enters the stream would increase summer low-flow habitat for anadromous fish such as salmon and steelhead trout.

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INTRODUCTION

Interactions among geologic, hydrologic, and biologic processes in redwood forest areas influence channel form and process on a variety of scales. For example, large organic debris (woody material greater than 10 cm in diameter) in small steep tributary drainage basins of Redwood Creek largely controls local channel morphology (chap. P, this volume); geologic variability, however, tends to significantly control gross morphology of the long profile (Keller and Tally, 1979). On the other hand, in the lower 20 km of Redwood Creek, large organic debris has a lesser influence on channel morphology, while geology significantly influences the characteristic morphology of the valley sides through slope processes that deliver sediment to the main channel.

Large organic debris in the lower reaches of Redwood Creek is generally quite mobile because the stream, during high winter flows, is able to carry downstream even the largest redwood trunks. Occasionally, however, large redwood trunks may accumulate along the bank of Redwood Creek to form a log jam. Such locations tend to influence local scour and fill by inducing a turbulence that produces large pools. These pools in turn provide important aquatic habitat for anadromous fish and other animals such as river otter, beaver, various birds, and other fish. In a few of these pools, the stream environment is further modified by subtle relations between effluent ground water, intragravel flow of stream water, channel morphology, and large organic debris to produce summer pools having water temperatures several degrees Celsius cooler than main-stream temperatures. This paper documents the existence of some cold pools and discusses the processes by which such pools form and their significance to anadromous fish.

ACKNOWLEDGMENTS

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REDWOOD CREEK "COLD POOLS"

Cold pools that maintain summer water temperatures several degrees Celsius cooler than main-stream temperatures, through interaction with ground water that enters the stream or through interaction with intragravel stream water flowing through long gravel bars, were discovered in Redwood Creek near Orick, Calif. (fig. 1), during the summers of 1981 and 1982. Figure 2 shows the cold pool, as it existed in the summer of 1981, located at the junction of Hayes Creek and Redwood Creek approximately 4 km upstream from the town of Orick. Although the lower portion of Hayes Creek is dry in the summer, it contributes subsurface water (ground water and intragravel flow) to the main channel of Redwood Creek. The temperature of the subsurface water is approximately 11 to 12 °C, in marked contrast to the main-stream temperature of Redwood Creek, which, on warm afternoons, may exceed 20 °C. The cold subsurface water collected in a small trough, scoured by Hayes Creek where it joins Redwood Creek during winter flows, and slowly entered into the large downstream pool in Redwood Creek, which has formed or been modified by scour around several large redwood trunks. The cold water apparently was prevented from mixing with the warmer water in the main stem of Redwood Creek by both the organic debris and the midchannel bar shown on figure 2. Thus a plume of cold water lingered in the bottom of the pool, providing temperatures of 12 to 16 °C compared to 21 °C upstream and downstream of the pool. Reid (1961) speculated that cold springwater might produce a cold pool but thought that the cold water would enter the channel in the deep part of the pool rather than migrate there from streambank seeps, as in the Hayes Creek cold pool of Redwood Creek (fig. 1). Of course, other cold pools could form as Reid suggests.

Dissolved oxygen also was measured in the Hayes Creek cold pool. As cold ground water having assumed low dissolved-oxygen content slowly mixes with the warmer more oxygenated water of Redwood Creek, the oxygen concentration in the cold pool increases, as shown on figure 2.

Cold pools apparently persist during the summer low-flow period. Figure 3 shows thermograph data for two locations in the Hayes Creek cold pool (station 1 and 2, fig. 2) and maximum-minimum temperature data for one location in the main stream of Redwood Creek (station 3, fig. 2) from September 22 through September 25, 1981. Data were collected from two continuously recording thermographs placed near the bottom of the cold pool at stations 1 and 2 and from a maximum-minimum thermometer placed in the main stream of Redwood Creek (station 3). At no time during the 4 days was the water in the cold pool as warm as that in the main stream, and the differences in temperature varied

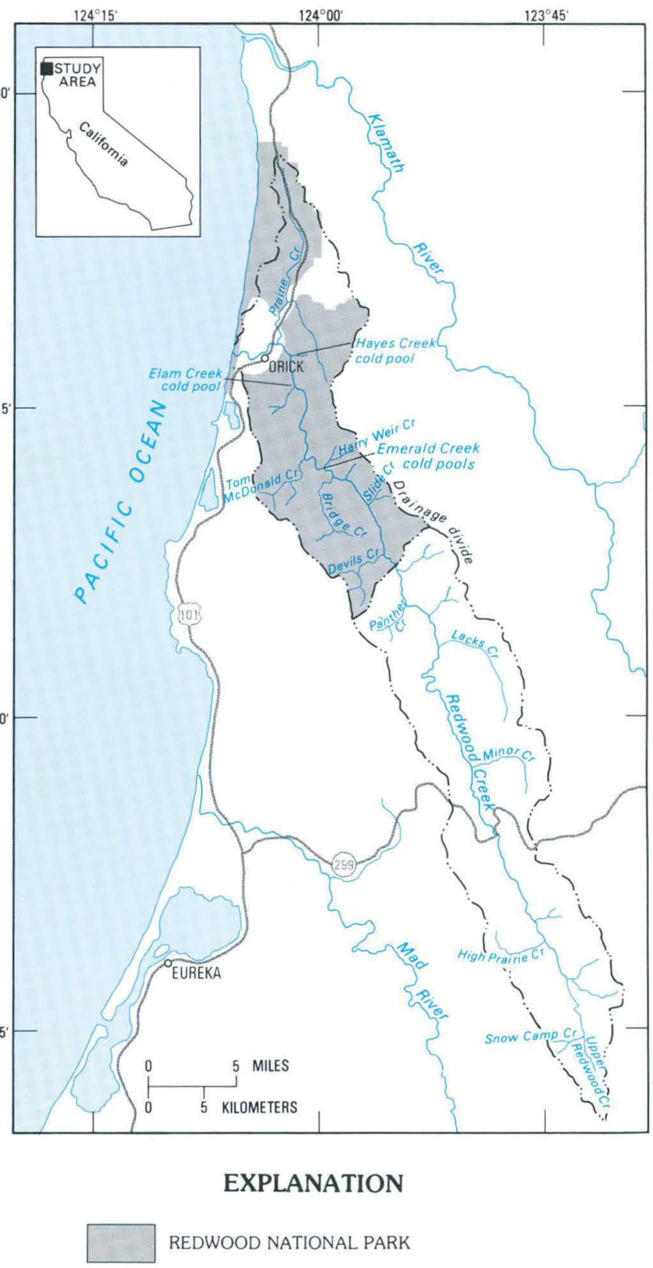

FIGURE 1.—Location of the three cold pools discussed in this paper.

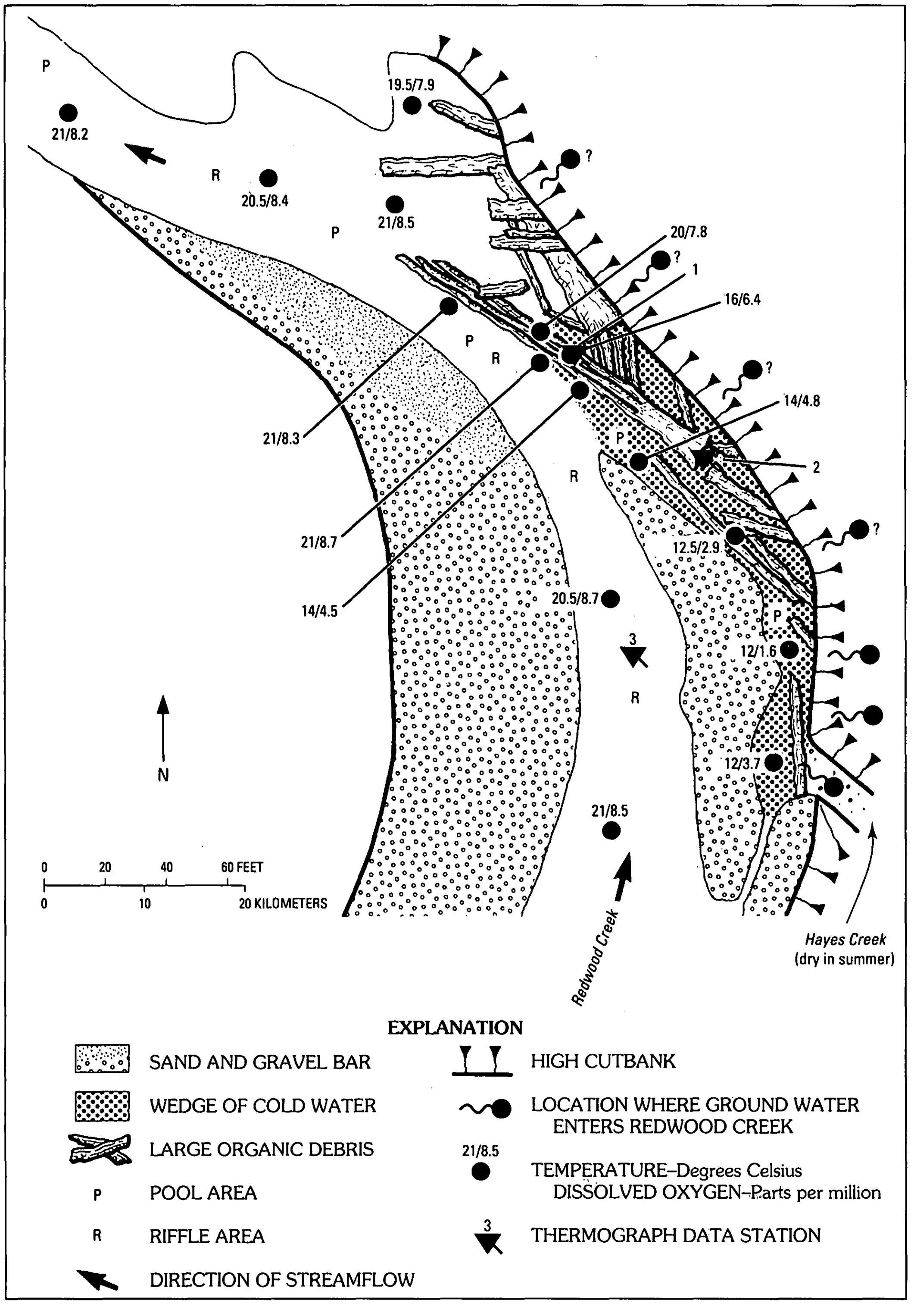

FIGURE 2.—Hayes Creek cold pool in Redwood Creek near Orick, Calif. Data collected on September 1, 1981 (10:30 a.m.–12:30 p.m.). Locations where continuous (station 1 and 2) and maximum-minimum (station 3) temperature data were recorded from September 22, 1981, to September 25, 1981, are indicated. Water depth in the cold pool at station 1 was about 1 m compared to about 0.2 m at station 3.

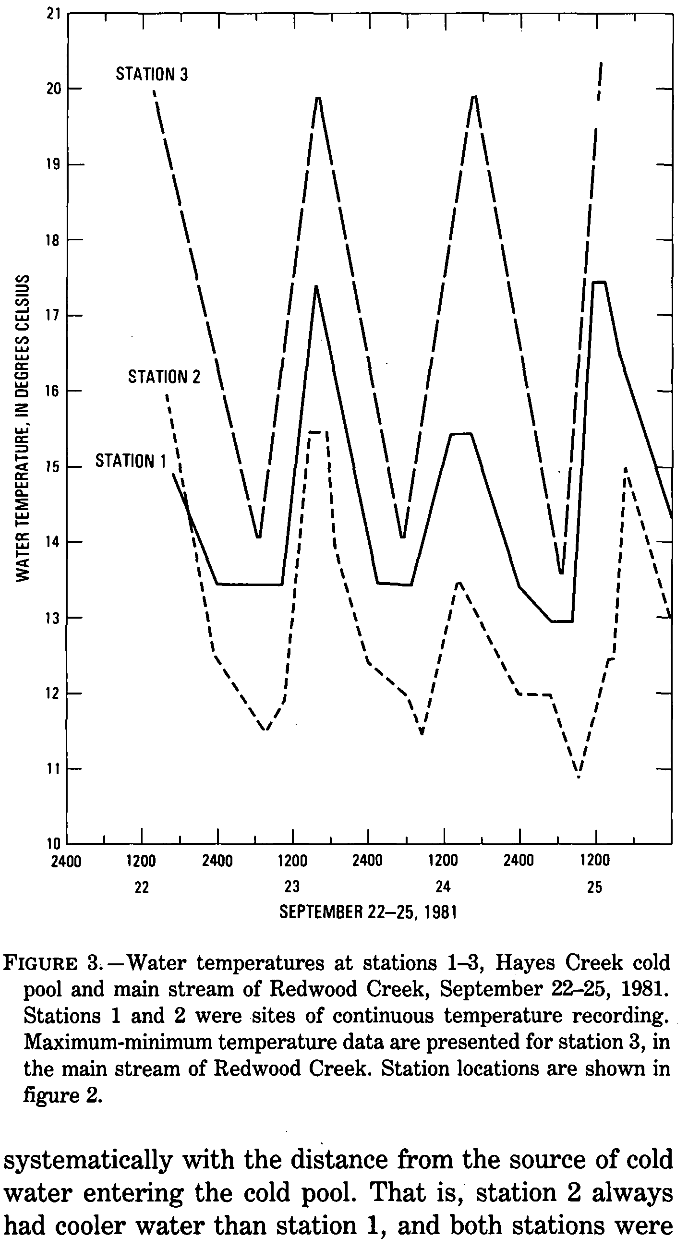

FIGURE 3.—Water temperatures at stations 1–3, Hayes Creek cold pool and main stream of Redwood Creek, September 22–25, 1981. Stations 1 and 2 were sites of continuous temperature recording. Maximum-minimum temperature data are presented for station 3, in the main stream of Redwood Creek. Station locations are shown in figure 2.

systematically with the distance from the source of cold water entering the cold pool. That is, station 2 always had cooler water than station 1, and both stations were always cooler than the main-stream temperatures. During warm afternoons, the temperature differences between the main stream of Redwood Creek and the cold pool were most pronounced, and during the early morning hours the differences were less (fig. 3). The reason for the horizontal portions seen on the graph station 1 is presumably related to a problem associated with the recorder.

Cold pools do not develop at all locations where cold ground water flows into the stream. Conditions favorable in Redwood Creek to the development of a cold pool include a concentrated source of cool ground water and a pool morphology that discourages mixing of the cold and warm water.

In Redwood Creek, large organic debris is apparently important in retarding mixing of the cold and warm water. Just downstream of the mouth of Hayes Creek, large redwood trunks, extending out into the pool and roughly parallel to the flow along with the midchannel gravel bar, trapped cold water and inhibited rapid mixing with the warmer water in Redwood Creek. These events explain the configuration of the plume of cold water shown on figure 2. If there is no barrier to inhibit mixing, cold pools may not develop even in places where inflow of ground water apparently is greater than such inflow at Hayes Creek.

During the winter of 1981–82, the Hayes Creek pool increased in area, depth, and volume. The midchannel gravel bar near the mouth of Hayes Creek, along with the large organic debris that physically isolated the cold effluent ground water, was removed, producing significant changes in the summer low-flow morphology (see figs. 2, 4). The gravel bar no longer isolated the effluent subsurface water, but the large organic debris did help retard complete mixing of the cold subsurface water with the warmer main-stream flow. Water temperature differences, however, were not as great as those observed during the summer of 1981, and a distinct wedge of cool water was not present.

Cold pools also may form during low-flow conditions when relatively warm main-stream water in Redwood Creek infiltrates into long gravel bars, then cools and emerges again downstream. Figure 5 shows two pools that are located approximately 0.4 km downstream of the Emerald Creek[1] confluence with Redwood Creek (not shown) and 2.4 km upstream from the Tall Trees Grove (not shown). The large cold pool on the west bank of the creek formed in a similar way to that of the Hayes Creek cold pool. The small pool on the east bank (at the downstream end of the dry channel) was only 1 °C cooler than the main stream and formed as a result of intragravel flow. Conditions that favored scour of the pools during the 1981–82 winter evidently ceased during the 1982–83 winter as most of the large cold pool on figure 5 filled with sediment, and the small pool completely disappeared.

Figure 6 shows a cold pool located 50 m downstream from the confluence of Elam Creek with Redwood Creek, approximately 5.5 km upstream from Orick. The cool water is from two sources: (1) Elam Creek surface and subsurface water that seeps through the large gravel bar on the west side of Redwood Creek and (2) springs discharging from rock fractures and landslides at the north end of the pool. Streamflow measured on September 9, 1982, indicates an increase in flow of Redwood

[1]Emerald Creek is shown as Harry Weir Creek on U.S. Geological Survey topographic maps. Locally the names are used interchangeably.

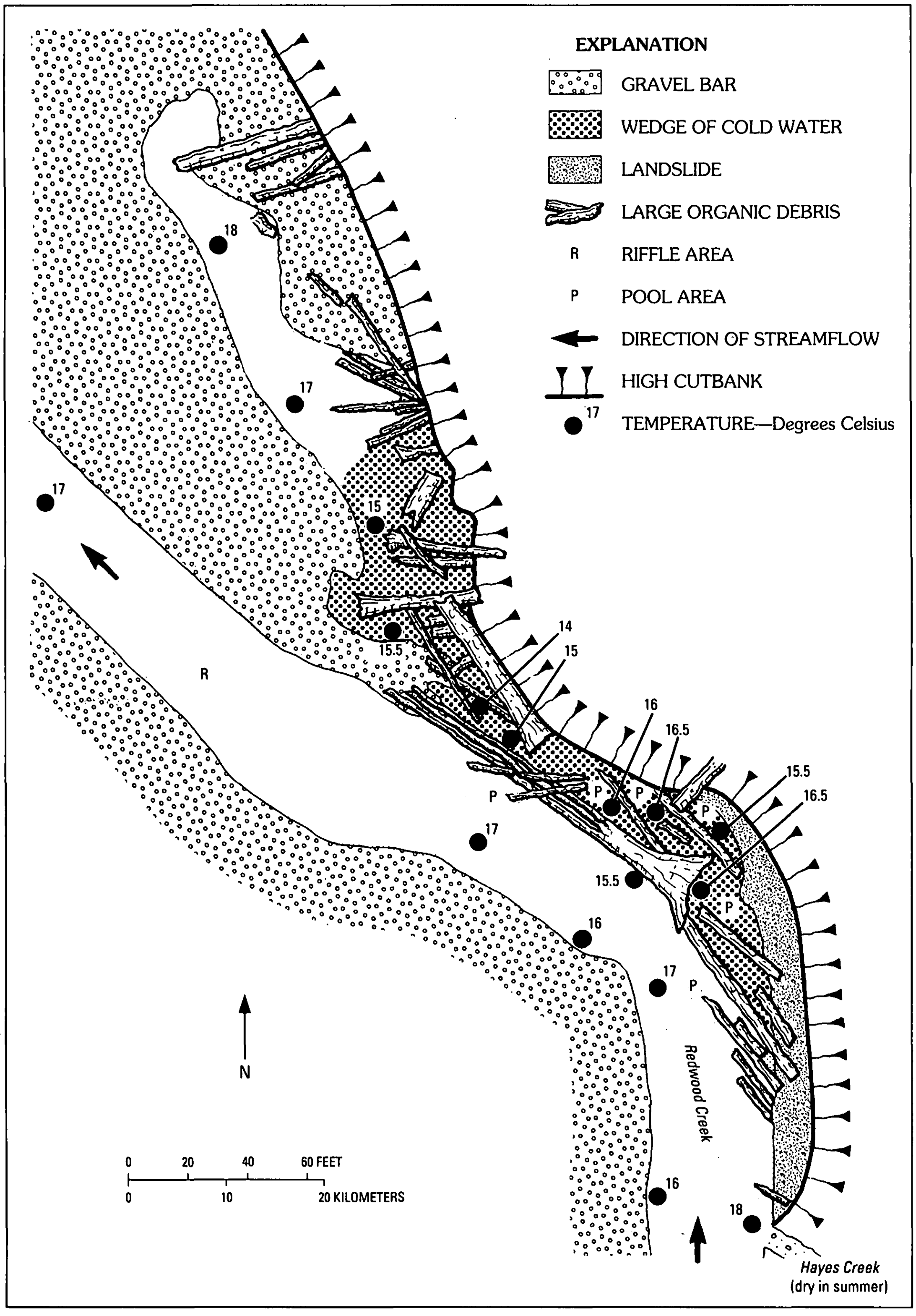

FIGURE 4.—Hayes Creek cold pool in Redwood Creek near Orick, Calif., mapped on September 1, 1982, at a streamflow of about 0.46 m^3/s. Temperature data were collected on September 16, 1982, at 2 p.m.

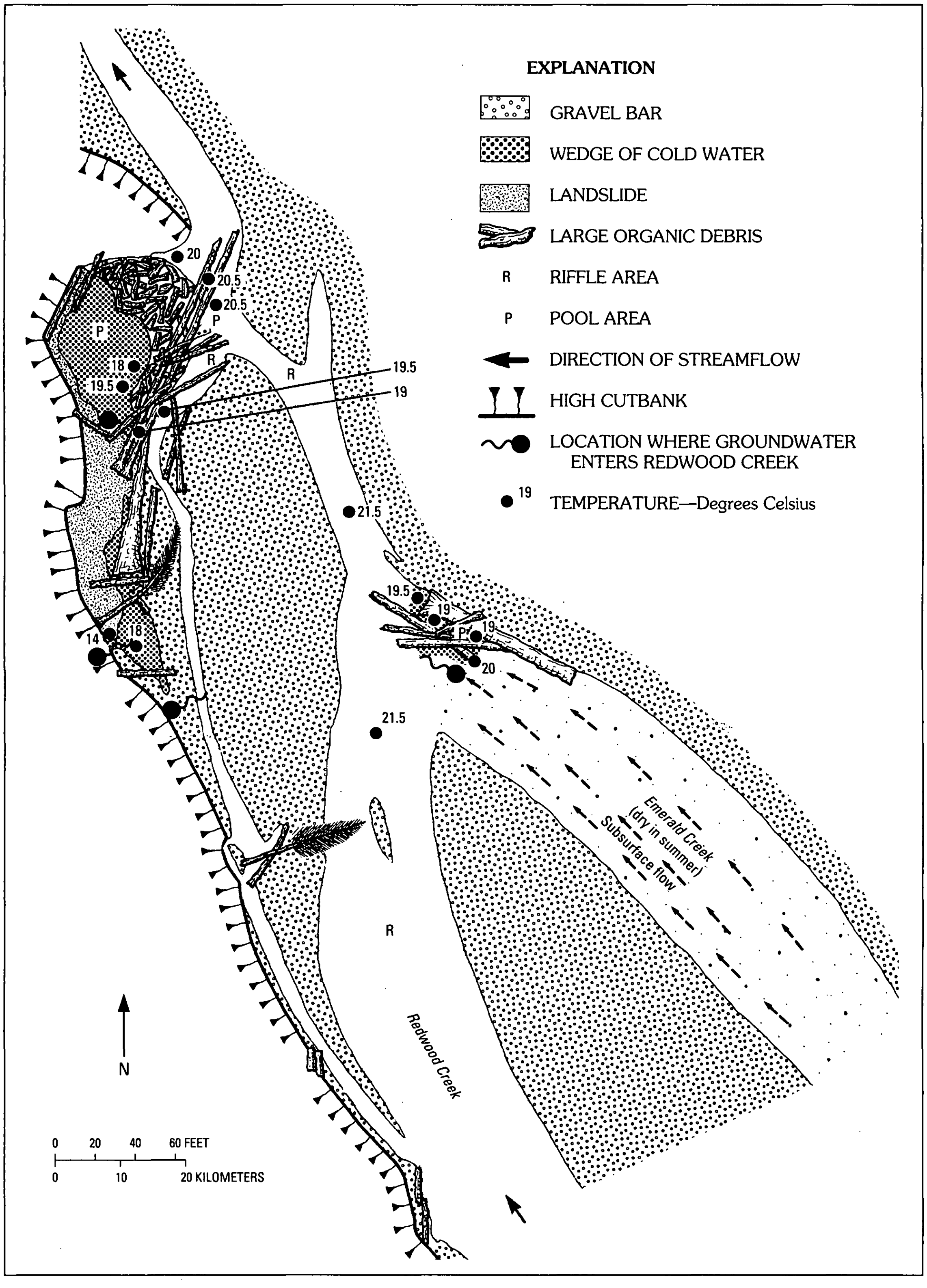

FIGURE 5.—Emerald Creek cold pools in Redwood Creek, mapped July 25, 1982, at a streamflow of 0.89 m^3/s. Temperature data were collected on August 11, 1982, at 2:10 p.m. The small cold pool on the east bank of Redwood Creek is due to cool intragravel water entering a small scour pool (produced at high flow) that is protected during low flow by large organic debris.

TABLE 1.—*Increase in streamflow of Redwood Creek due to effluent subsurface water at the Hayes Creek, Elam Creek, and Emerald Creek cold pools*

Cold pool name	Date measured	Upstream discharge (m^3/s)	Downstream discharge (m^3/s)	Increase (m^3/s)	Percent increase	Confidence in the percent increase (1=high, 4=low)[1]
Hayes Creek[2]	Sept. 4, 1981	0.40	0.49	0.09	22	1
Do	Aug. 10, 1982	.69	.82	.13	19	1
Do	July 9, 1982	1.77	1.97	.20	11	2
Elam Creek	Sept. 9, 1982	.32	.37	.05	14	2
Emerald Creek	Aug. 19, 1982	.47	.48	.01	2	4
Do	July 24, 1982	.87	.91	.04	5	3

[1] Reflects the fact that discharge can be measured only at ±5 to 10 percent. Thus while the increase in discharge at the Emerald Creek site is in the expected direction, the change is within potential experimental error of measurement.

[2] On August 23, 1982, the discharge upstream and downstream of the Hayes Creek cold pool remained nearly constant at 0.45 m^3/s.

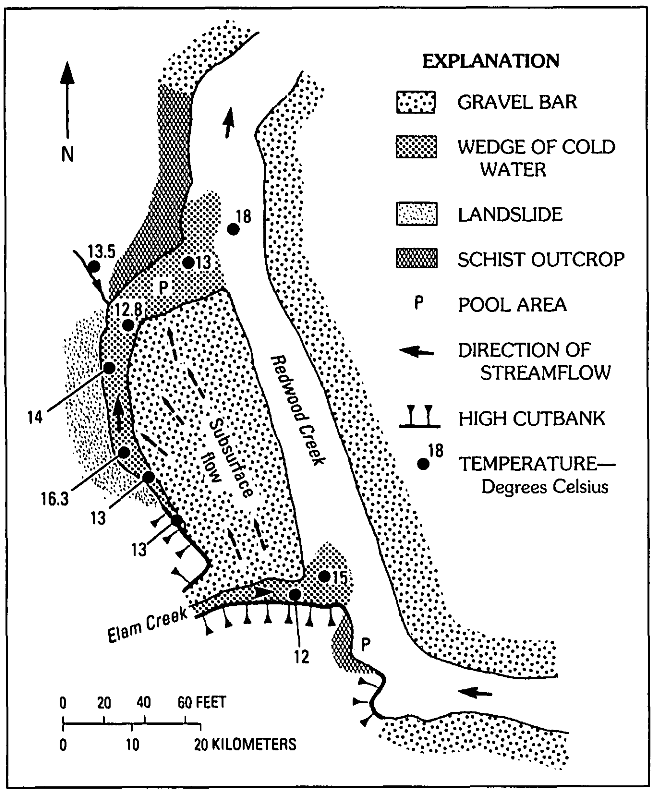

FIGURE 6.—Elam Creek cold pool in Redwood Creek, mapped September 9, 1982, at a discharge of 0.32 m^3/s upstream of the pool and 0.37 m^3/s downstream. Temperature data were collected on September 14, 1982, at 1 p.m.

Creek through the reach from 0.32 m^3/s (upstream) to 0.37 m^3/s (downstream). The relative proportion of cool water flow from the two sources is not known. The most important morphologic features in the formation and maintenance of the Elam Creek cold pool are (1) the scour channel along the west side of Redwood Creek, downstream of Elam Creek (fig. 6) that forms the deep part of the pool, (2) the large gravel bar that probably conveys cool subsurface water from Elam Creek to the pool while isolating the pool from the warmer water of Redwood Creek, and (3) the landslide and bedrock fractures along the west side of the pool, which allow additional cool water inflow to the system. This pool is also significant in its lack of large organic debris, which is present in both the Hayes Creek and Emerald Creek pools (figs. 2, 4, 5). Pools of the three creeks, however, have several features in common: (1) a source of cold water; (2) development of a scour pool, presumably during high flows of Redwood Creek; and (3) a barrier that reduces mixing of the cold water with warmer main-stream flow of Redwood Creek. Thus, as with many features of the fluvial system, the cold pools result from a variety of processes over a spectrum of flows ranging from winter floods to summer low flow.

HYDROLOGY OF COLD POOLS

Basic relations among influent and effluent ground-water flow, intragravel flow of water in the stream channel, and channel form and processes are nearly unexplored with regard to fluvial geomorphology. Observations of a small stream in Alaska by Harrison and Clayton (1970) suggest that both channel morphology and stream competency may be significantly affected by seepage of water into (effluent stream) or out of (influent stream) the channel. In Redwood Creek, as with many perennial streams, the summer flow or base flow is produced where ground water seeps into the channel. What is not known is the nature and extent of the processes that produce the observed base flow.

Measurements of relatively low summer streamflow in Redwood Creek during the summers of 1981 and 1982 (table 1) suggest (with one exception) that, over a distance of about 120 m, streamflow through the Hayes Creek cold pool increased by as much as 22 percent. (An increase of 10 percent is taken to be greater than error of measurement.) We were not able to determine how much of the increase was due to effluent intragravel flow versus effluent ground-water flow. The dissolved-oxygen-content data collected in 1981 (fig. 2), however, suggest a ground-water source. The data also suggest that, as streamflow decreases from early to late summer in Redwood Creek, the amount of subsurface water from the Hayes Creek basin entering Redwood Creek also decreases, but the amount of subsurface water as a percentage of total streamflow increases.

Measurements of streamflow above and below the Elam Creek and Emerald Creek cold pools are also shown on table 1. Streamflow above and below the Elam Creek cold pool in September of 1982 suggests an increase of 14 percent. Much of the increase may be due to intragravel flow of Elam Creek surface water rather than effluent ground water (fig. 6). The data from the Emerald Creek cold pool suggest a possible increase in streamflow, but the percent change is within the possible error of measurement. Nevertheless, cold ground water was observed entering the site by way of small springs along the west bank of Redwood Creek (fig. 5), and the flow was evidently sufficient to maintain, with shading and retardation of mixing by the organic debris, a cold pool environment until the winter of 1982–83 when the pool was filled by deposition of Redwood Creek sediment.

The data from the Hayes Creek and Elam Creek sites and field observations at other sites suggest that a good deal of the base flow of Redwood Creek may be supplied by point sources rather than by seepage from a more general ground-water source. Furthermore, once ground water enters Redwood Creek, most of it must become influent into streambed gravels. If the ground water did not become influent, late summer base flow of Redwood Creek would greatly exceed that observed.

The flow of Redwood Creek is relatively high during and after winter storms when surface flow from tributaries is high. Thus, the significance of subsurface water on the total flow of Redwood Creek during the wet winter months must be much reduced because only a small percentage of the total flow can be expected from subsurface sources. During the higher flows, however, the intragravel flow in the bed of Redwood Creek, especially in riffles, probably is important to anadromous fish (Vaux, 1962).

ANADROMOUS FISH HABITAT AND COLD POOLS

A limiting factor to anadromous fish productivity in many streams of northern California is the summer pool environment (Denton, 1974). Aggradation in Redwood Creek has impacted important nursery areas by decreasing pool volume. Pools also often have water temperatures too warm to maintain a healthy population of young fish. Decline of fish numbers in Redwood Creek is partly a function of availability of habitat, which has been degraded by certain land use practices, particularly timber harvesting, and by floods (National Park Service, 1981). Cold pools in Redwood Creek, although few in number and ephemeral, may in years of below-average summer flow support a disproportionate amount of the young anadromous fish. We observed in 1981 that hundreds of fish occupied the cold pools compared to tens of fish or none at all in adjacent pools having warmer water temperatures. The majority of these fish were smolt sized (greater than 8 cm). Cold pools may represent a refuge where young fish reside when water temperatures would otherwise limit optimum growth and development.

In August 1981, the lower 40 km of Redwood Creek was surveyed by trained swimmers and divers. The survey revealed a spotty distribution of juvenile fish; some deep pools were devoid of fish, while others contained many. The first cold pool was discovered subsequent to and independent of this survey. However, the second cold pool (near Emerald Creek) was located by referring to survey field notes and returning to a location where the number of juvenile fish observed was significantly greater than in other areas.

Both steelhead trout and coho salmon require a period of extended growth in freshwater before entering the ocean. In Redwood Creek, this period is from 2 to 4 years for steelhead trout and 1 full year for coho salmon. Studies of Redwood Creek tributaries (excluding Prairie Creek) have shown an abundance of young-of-the-year (<1 year old) steelhead (Anderson and Brown, 1982; Terrence D. Hofstra, written commun., 1982). Relatively few 1-year-old or older fish are encountered. The more restrictive habitat requirements of these larger fish apparently are not met in severely aggraded streams. In the Redwood Creek watershed, good quality summertime rearing habitat for 1-year-old or older fish exists only in cold pools or in an embayment that sometimes forms at the mouth of Redwood Creek (Hofstra, 1983; James P. Larson, written commun., 1982).

The distribution of young coho salmon is even more restricted (Anderson and Brown, 1982). No coho have been found rearing in the embayment or any of the tributaries (excluding Prairie Creek). Production of coho salmon in Redwood Creek may be closely tied to the cold pools.

It is apparent that, if there were more cold pools, there would be more summer habitat and perhaps greater fish production in Redwood Creek. As more is learned about the nature and extent of cold pools, it is expected that this information may significantly impact management of anadromous fish in streams of the Pacific Northwest. That is, managers may be able to take advantage of locations where cold water enters a stream and use it to enhance anadromous fish habitat. This approach will be particularly important where rearing habitat for juvenile fish is a limiting factor in fish production.

Redwood Creek, as well as other streams and rivers, including the Eel River and Klamath River, also supports a summer or spring run of steelhead trout. Adult, summer steelhead spend the summer in the river and spawn in the fall. These fish are intrinsically valuable, as they have a limited occurrence in California (Jones, 1980). Cold pools in the streams, associated with point-source ground-water effluence and channel morphology, undoubtedly provide refuge for migrating fish and holding sites for those waiting to spawn. In fact, fish migrating in the summer may move upstream from one cold pool to the next, thus avoiding high temperatures that exist during the day over most of the stream.

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Long-Term Effects of Clearcutting and Short-Term Impacts of Storms on Inorganic Nitrogen Uptake and Regeneration in a Small Stream at Summer Base Flow

By FRANK J. TRISKA, VANCE C. KENNEDY, RONALD J. AVANZINO, *and* KENT C. STANLEY

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454–V

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LONG-TERM EFFECTS OF CLEARCUTTING AND SHORT-TERM IMPACTS OF STORMS ON INORGANIC NITROGEN UPTAKE AND REGENERATION IN A SMALL STREAM AT SUMMER BASE FLOW

By FRANK J. TRISKA, VANCE C. KENNEDY, RONALD J. AVANZINO, and KENT C. STANLEY

ABSTRACT

Uptake and regeneration of dissolved inorganic nitrogen (DIN) in forest streams are controlled by factors operating on time scales of less than 1 day to greater than 80 years. Flux of inorganic nitrogen, primarily nitrate, was estimated in Little Lost Man Creek, Humboldt County, Calif., between 1974 and 1982 and in experimental channels during 1979. Studies were conducted during low flow (May–November) over an approximately 1,500-m reach of the stream flowing through an area clearcut in 1965. The study period coincided with the development of a riparian canopy, dominated by alder (*Alnus rubra*), a nitrogen-fixing species.

Studies in experimental channels indicated a large diel fluctuation in DIN concentration. Nitrate uptake rates decreased as the community aged. Uptake rates varied with canopy cover. Experimental short-term nitrate enrichment of the stream (200 μg/L NO_3-N) in 1975 (open canopy) and 1979 (closed canopy) confirmed reduced uptake under closed canopy conditions.

Background DIN chemistry surveyed weekly to biweekly during 1974 (prior to canopy closure) indicated a maximum uptake of 77 percent available nitrate (NO_3-N) at summer base flow. In 1976 maximum uptake was 87 percent of available NO_3-N under a similar sampling regime. Nitrate concentration at the upstream station (1975) was highest at night (18 μg/L NO_3-N) and lowest at midafternoon (8 μg/L NO_3-N). Nitrate concentrations downstream simultaneously ranged from 5 to 8 μg/L NO_3-N, indicating uptake within the reach. Four years later after canopy closure (1979), a diel study indicated regeneration (6–10 μg/L NO_3-N) rather than uptake in a 265-m section of the same reach. Regeneration was confirmed in June–November 1982.

Laboratory studies of stream sediments using an inhibitor of nitrite oxidation (sodium chlorate) indicated a potential for nitrate regeneration. Nitrate regeneration (measured by difference in upstream-downstream nitrate concentration) was also observed in a 92-percent-shaded experimental channel when the epilithon was senescent.

Development of the alder riparian zone is of long-term importance in nitrogen cycling of Little Lost Man Creek. We hypothesize gradual decline of instream production related to reduced synthesis of protein from inorganic nitrogen thus reducing passage of nitrogen to higher trophic levels. Biotic production will remain low until the canopy is reopened by natural mortality of riparian trees.

INTRODUCTION

Of the major dissolved elements in fluvial environments, nitrogen is especially valuable for studying biotic impacts on element transport. Nitrogen is useful as an indicator because most nitrogen chemistry is biologically mediated in nature, and nitrogen is rare in the mineral structure of sediments. In mountain streams, the biotic interface with solute chemistry is primarily associated with communities attached to benthic surfaces (epilithon). High gradients and current velocity, however, often prevent planktonic water-column communities from having a major impact on nutrient cycling. The instantaneous pool of dissolved elements in the surface water of a reach is usually insignificant; rather, the timing of nitrogen input determines the magnitude of potential chemical-biological interactions.

A myriad of factors, operating on different time scales, determines nitrogen uptake and transport properties of a stream under pristine conditions (table 1). Daylight uptake by photosynthetic algae can produce a diel fluctuation in nitrogen concentration during low flow. Small storms can reset the benthic community during the growing season by partially scouring sediment surfaces. Scouring is often followed by vigorous growth and rapid nitrogen uptake. Seasonal light and temperature fluctuations, due to such factors as spring leafout, bed stability, and fluctuations in discharge, introduce variability within a reach. Finally, canopy development in the riparian zone can control solar input to a reach (and thus uptake by photoautotrophs) for extended periods (Swanson and others, 1982).

This paper examines uptake and transport of dissolved inorganic nitrogen (DIN) from a variety of time perspectives. Biotic control of nitrate transport between storm-induced resets is examined daily and seasonally with

TABLE 1.—*Biological and physical factors that influence nitrate uptake on a stream reach over specified time scales*

<24 hours	1 to 30 days	30 days to 1 year	1 year to <100 years
Increase uptake (decrease transport)			
Diel photoperiod (daylight hours).	Epilithon in early successional stage (active growth).	Seasonal increase in daylight hours (spring-summer).	Canopy opening due to natural or storm-induced mortality.
Small storms that cause slight scour and elevate nitrogen concentration.	Moderate consumption of epilithon by grazing invertebrates.	Seasonal increase in temperature.	
Existing high bed roughness and porosity.		Seasonal discharge pattern: low base flow, high bed contact, high bed stability.	
Decrease uptake (increase transport)			
Diel photoperiod (hours of dark).	Epilithon in late successional stage (senescence).	Seasonal decrease in daylight hours (autumn, winter).	Canopy closure due to development of riparian vegetation.
	Extremely low or high consumption of epilithon by grazing invertebrates.	Seasonal decrease in temperature.	
	Major storms that cause high scour and high discharge.	Seasonal discharge pattern: high base flow, low bed contact, high bed disturbance.	
		Spring leafout of riparian canopy.	

respect to growth, maturity, and senescence of epilithon during summer low flow. The influence of canopy cover is examined in flumes in which shading, discharge, nutrient concentration, and channel geometry can be controlled. Observations from these controlled experiments are used to interpret long-term field variations in dissolved nitrogen (1974–82) during development of a riparian canopy.

STUDY SITE

The study was conducted at Little Lost Man Creek, a third-order pool-and-riffle stream located in Humboldt County in northwestern California (fig. 1). The site is approximately 5 km east of the Pacific Ocean. Soils on the watershed, derived from the rocks of the Franciscan assemblage (Bailey and others, 1964), are unstable, and numerous dormant landslides have been reported along the banks (Iwatsubo and others, 1975). The watershed is 9.4 km^2 and ranges in altitude from 24 to 695 m (387 m mean altitude). The channel gradient if 66 m/km (Iwatsubo and others, 1975; Iwatsubo and Averett, 1981). The area is characterized by cool, wet winters and warm, dry summers. Approximately 92 percent of the vegetation is old-growth, coastal redwood forest (*Sequoia sempervirens*) including associated Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga hetrophylla*). Between 1962 and 1965, and prior to incorporation into Redwood National Park, 8 percent of the watershed was clearcut at two sites. Following clearcutting, alder (*Alnus rubra*), a nitrogen-fixing species, has dominated the riparian vegetation.

Summer streamwater temperature typically varies between 14 and 20 °C. Summer background dissolved inorganic nitrogen and orthophosphate concentrations, which were determined colorimetrically with a Technicon II AutoAnalyzer, were approximately 20 to 40 μg N/L and 10 μg P/L. Summer and early autumn storms can increase DIN concentration to 150 to 175 μg N/L and orthophosphate concentration to 25 μg PO_4-P/L (Kennedy and Malcolm, 1977).

The summer epilithon community is dominated by diatoms including *Achnanthes lanceolata*, *Diatoma vulgare*, *Gomphonema angustatum*, and *Melosira varians*. (For a more complete species list, see Iwatsubo and others, 1976.) A full range of invertebrate functional groups (Cummins, 1973; Merritt and Cummins, 1978) is represented in the benthos with a predominance of collector organisms (Iwatsubo and Averett, 1981). Common fishes include steelhead trout (*Salmo gairdneri gairdneri*), coho salmon (*Oncorhynchus kisutch*), threespine stickelback (*Gasterosteus aculeatus*), and the coast-range sculpin (*Cottus aleuticus*) (Iwatsubo and Averett, 1981).

MATERIALS AND METHODS

FLUME STUDIES: SHORT-TERM NITROGEN UPTAKE AND REGENERATION

Determinations of short-term inorganic nitrogen uptake and regeneration were made in one set of six clear acrylic plastic channels, or flumes, between August 17 and September 20, 1979 (fig. 2; baseline water chemistry and channel characteristics are listed in tables 2 and 3). A header box with separate mixing chambers and separate V-notched weirs regulated flow (10 L/min) to each channel. Water was supplied through PVC (polyvinyl

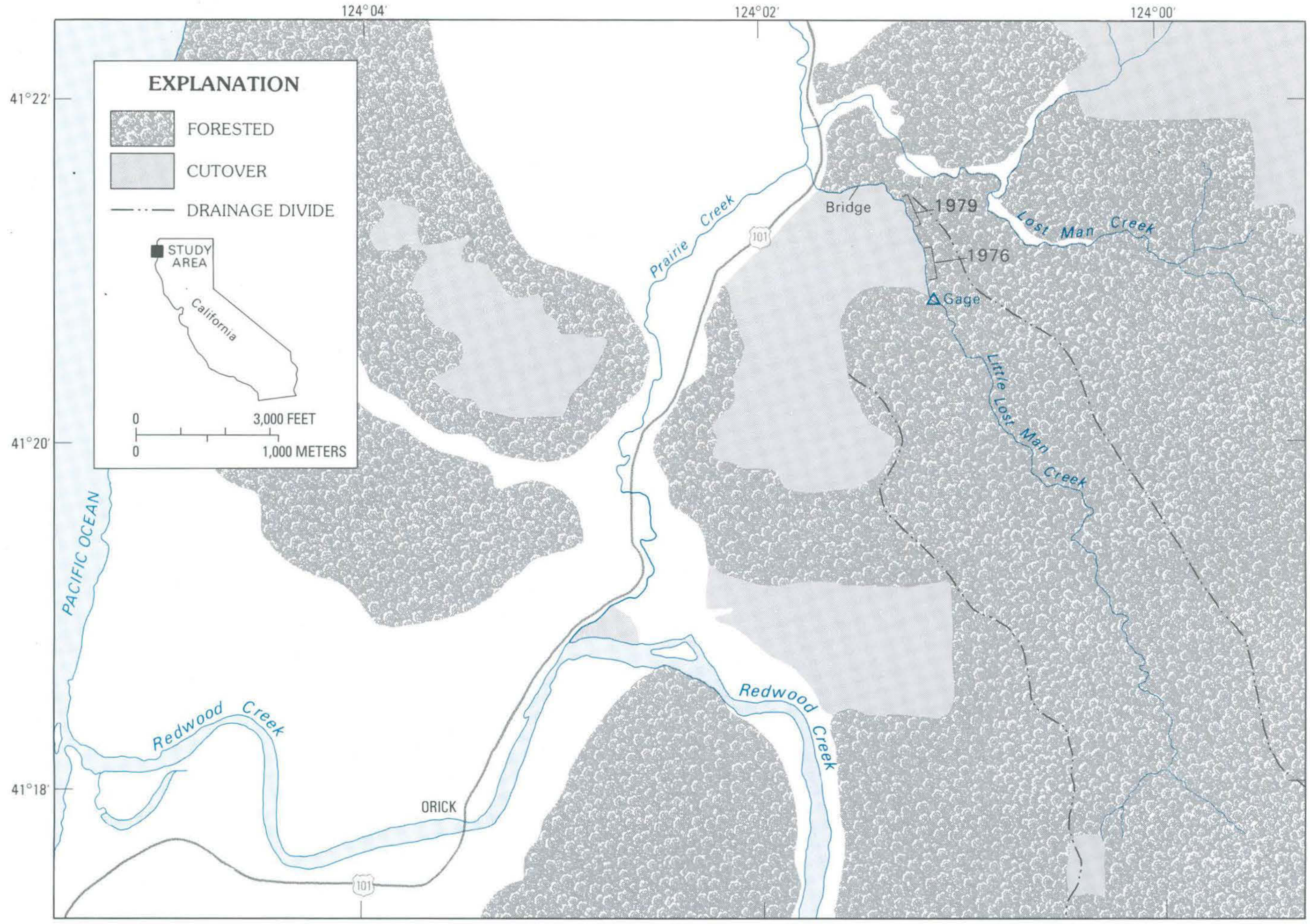


FIGURE 1.—Location of study area and sampling sites along Little Lost Man Creek. Most upstream-downstream dissolved inorganic nitrogen chemistry is compared between sites labeled "Gage" and "Bridge." Flume experiments occurred at the downstream end of the reach labeled "1979." Data from other upstream-downstream studies (1976, 1979) are labeled by year and indicate the approximate reach length. For all studies, the reach passed through an area clearcut on one bank in 1965.

chloride) pipe by gravity and passed through a 300-μm-pore-size filter. Nutrient solutions, when added, were pumped from a common source by using a separate pump for each channel. Nutrient enrichment was targeted at 100 μg/L NO_3-N and 25 μg/L PO_4-P except in the control channel. The nutrient concentrations in enriched channels were 2 to 3 times baseline concentrations (night) and typical of concentrations observed in summer and early autumn storms. Chloride was added with the nutrient solution at an accurately known flow rate and concentration. Since it is conservative with respect to biological uptake and sediment sorption, dilution of the added chloride after mixing was used as a measure of waterflow through the channel. Change in the ratio of chloride to nutrients during transport, which served as the measure of nitrogen flux, was calculated as follows:

$$\text{DIN uptake } (\mu g/h) = [N_o + (Cl_x - Cl_o \times N_T / Cl_T - N_x] \times Q$$

where:

N_o = DIN upstream concentration,
Cl_x = downstream flume concentration of chloride,
Cl_o = upstream flume concentration of chloride,
N_T = DIN concentration solute tank,
Cl_T = chloride concentration solute tank,
N_x = DIN concentration downstream, and
Q = discharge.

Discharge was determined daily from either daily injection pump rates and ΔCl or by using a calibrated bucket and stopwatch. Nutrient injection began August 24 and ended September 11, 1979.

Light input was estimated by a Licor 500 integrating light meter with a LI 190S sensor, which measured photosynthetically active radiation. Water temperature was measured by a continuous recording sensor placed in the stream.

TABLE 2.—*Channel properties and average background water chemistry (± standard deviation) in 1979 for the experimental acrylic plastic channels set in Little Lost Man Creek*

[DON=dissolved organic nitrogen; DOC=dissolved organic carbon]

Properties of the channel reach studied		Background water chemistry	
Length	9.75 m	DON	62.6±10.5 σ μg nitrogen per liter
Width	152.5 mm	NO_3	41.1±7.3 σ μg nitrogen per liter[1]
Depth	100.0 mm	NO_2	<3.0 μg nitrogen per liter
Volume	148.7 L	NH_4	<4.0 μg nitrogen per liter
Flow	9.5 L/min	PO_4	12.8±1.0 σ μg phosphorus per liter
Surface area (including slides).	12.4 m^2	DOC	1.1±.28 σ mg carbon per liter
Water surface area	1.48 m^2		
Water traveltime through reach.	15–20 min		

[1] Diel fluctuations in nitrate concentration were approximately 25 percent.

TABLE 3.—*Light and temperature data for selected sampling dates at Little Lost Man Creek*

[Light input was estimated by a Licor 500 integrating light meter with a LI 190S sensor that measures photosynthetically active radiation. Water temperature was measured by a continuous recording sensor placed in the stream]

Date (1979)	Temperature (°C)		Light [(μE/m^2)/s]
	Maximum	Minimum	24-hour average
Aug. 24–25	16.7	15.5	468
Aug. 28–29	16.9	15.6	317
Sept. 6–7	17.2	15.6	363
Sept. 12–13	17.2	16.7	372
Sept. 18–19	15.6	14.4	294

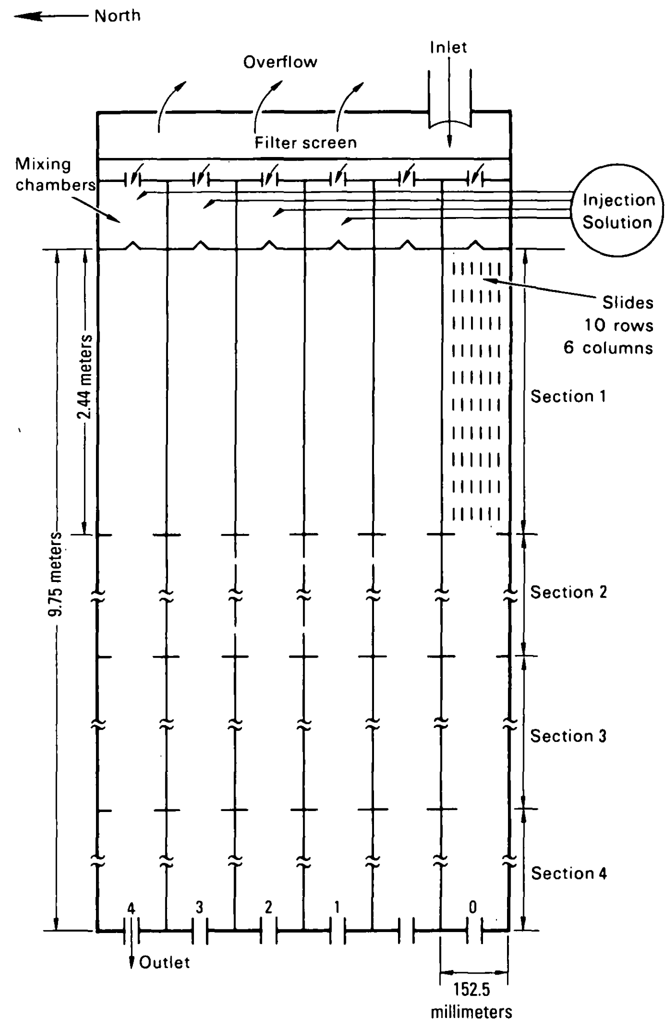


FIGURE 2.—Experimental flumes used to estimate short-term nitrogen flux by the epilithon community. Physical dimensions and arrangement of slides are illustrated.

Each experimental channel consisted of four successive longitudinal sections (fig. 2), and each section contained 10 rows of 102×152-mm clear plastic slides roughened by sandblasting and mounted perpendicular to the bottom. Each row contained six slides spaced 25 mm apart. Each channel contained 240 slides, and the total surface area of each flume was 12.4 m^2. Potential access to nutrients by epilithon was identical in each channel. Slides were placed in various streambed habitats 5 days before mounting in the channels, then acclimated 4 additional days prior to nutrient enrichment. Experimental treatments with regard to nutrient enrichment and canopy were as follows: channel 0 (control)—background nutrient, full sunlight; channel 1—nutrient amendment, full sunlight; channel 2—nutrient amendment, 30 percent shade; channel 3—nutrient amendment, 66 percent shade; channel 4—nutrient amendment, 92 percent shade. Shading was provided by woven nylon greenhouse screen of variable mesh size to produce the respective shade treatments. On each sampling date, 18 slides (6 percent of channel surface area) were randomly removed from each channel, and no location was sampled more than once. Slides were placed in individual plastic bags and returned to a field laboratory where epilithon was harvested by scraping, placed in plastic bags, and frozen. Each sample yielded four subsamples. Scraped slides were returned to the channels. A detailed description of sampling procedures is presented elsewhere (Triska and others, 1983).

At the conclusion of the experiments, chlorophyll α was determined on one sample chosen from each section of each channel on each sampling date. (Three samples were collected per channel.) Chlorophyll α was determined by extraction of algae in 90 percent acetone shaken with magnesium carbonate. Absorbance was read at 665 nm for chlorophyll α and 750 nm to correct for turbidity. Readings were made before and after acidification to correct for phaeopigments (Wetzel and Westlake, 1974). Results were extrapolated from the known surface area of the sample (slide) to the total surface area of the plastic channel.

Biomass was determined by oven drying duplicate nonextracted samples at 50 °C. Ash content was estimated by ignition at 500 °C for 4 hours. From the amount of ash from the acetone-extracted sample and known percent ash from the unextracted samples, biomass was estimated for the acetone-extracted sample. Epilithon transported from the flume or deposited on the bottom was not included. The carbon:nitrogen ratio of epilithon was determined on a Carlo-Erba CHN analyzer at the laboratory of Dr. Wayne Minshall, Idaho State University.

Water was sampled five times daily for background concentrations of NO_3+NO_2, NH_4, PO_4, and Cl and for nutrient concentrations at the outlet of each flume. Samples were collected before sunrise (approximately 6:00 a.m.) and at 10:00 a.m. and 2:00, 6:00, and 10:00 p.m. After collection, samples were filtered (0.45 μm) at streamside. Samples for nitrogen and phosphorus were frozen (−20 °C) until the day of analysis, and samples for chloride were refrigerated. Analyses were made on a Technicon AutoAnalyzer II with a precision for NO_3-N+NO_2-N and NO_2-N of ±1 μg/L below 100 μg/L and ±1 percent above (Technicon Industrial Method no. 158–71W, December 1972). Analytical precision for orthophosphate was ±1 μg/L (Technicon Industrial Method no. 155–71W, January 1973). Analytical precision for chloride was ±1 percent at 5 mg/L and above (Technicon Industrial Method no. 99–70W/B, revised February 1976; O'Brien, 1962). Water samples frozen for extended periods did not show significant loss of nutrients compared to samples analyzed immediately. Nitrite and ammonium were always at or below the limits of detection; thus nitrate and DIN are essentially synonymous.

FIELD STUDIES: LONG-TERM NITROGEN UPTAKE AND REGENERATION

Field studies consisted of both daily and weekly to biweekly surveys of DIN. Samples were taken at midafternoon. When water was sampled more than once the same day, the samples collected closest to 2:00 p.m. were used for comparison. Weekly to biweekly surveys were made at low flow in 1974, 1976, and 1982. Water samples were taken at two sites: Gage, at a gaging station, and Bridge, downstream near the base of the clearcut. Diel fluctuations in chemical constituents were measured in 1975, 1979, and 1982. Diel sampling was conducted at Gage and Bridge and at two subreaches within the clearcut area (designated "1976" and "1979" in fig. 1).

Nitrification potential was estimated from bankside sediments collected at two sites in the clearcut area and at one site in the old-growth forest. Following the method of Belser and Mays (1980), sodium chlorate (10 m*M* final concentration) was added to shaken slurries of stream sediments (20 g fresh weight). Slurries were incubated at room temperature (23 °C) for 48 h. Chlorate inhibits enzymatic oxidation of nitrite to nitrate. Nitrification was estimated by comparing accumulations of nitrite in treated sediment slurries to untreated controls. Organic carbon content of sediments was determined on a Leco carbon analyzer by subtraction of inorganic carbon from total carbon.

RESULTS AND DISCUSSION

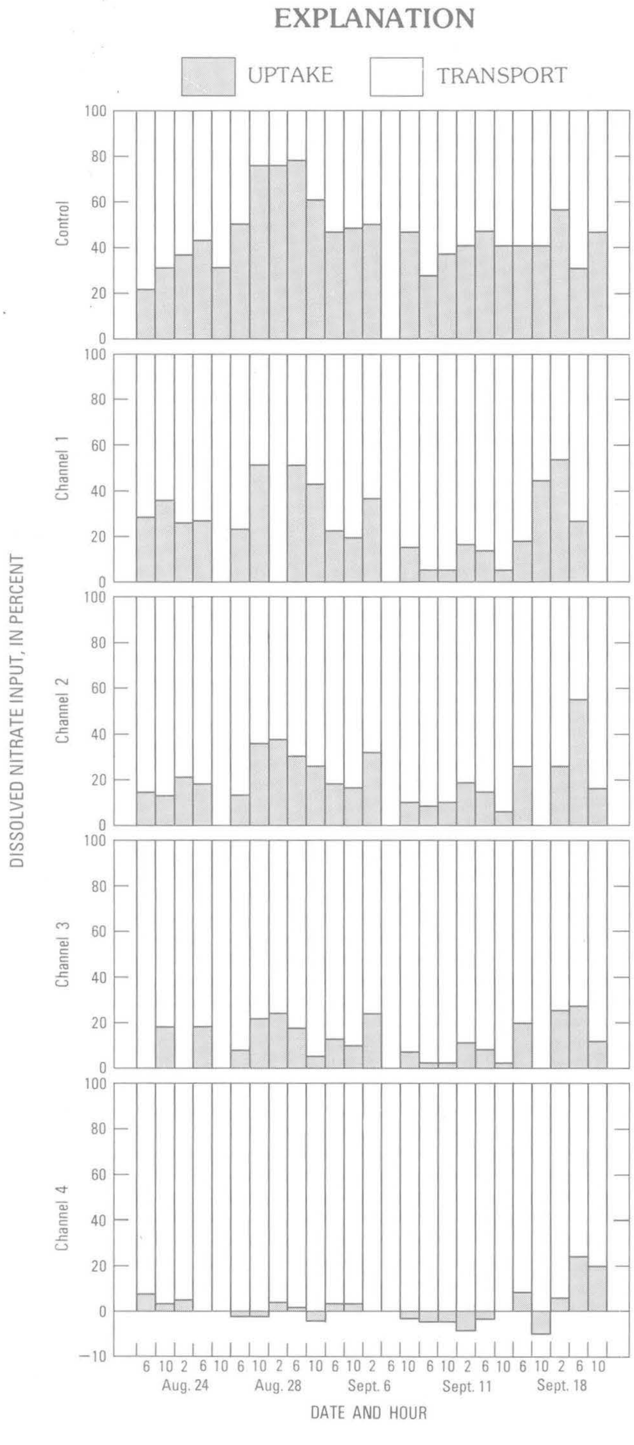
FLUME STUDIES: SHORT-TERM NITROGEN UPTAKE AND REGENERATION

Light and temperatures were regulated by climate, geomorphology, and vegetation of the watershed. Little Lost Man Creek flows through a long narrow valley that has steep slopes that reduce light intensity part of the day. Incident radiation input on sampling days varied from 294 to 468 ($\mu E/m^2$)/s (table 3). Between August 28 and September 12, day length (light input) to the flumes was decreased by morning fog. Fog also helped to moderate temperature. The diel variation in water temperature was about 2 °C. Temperature throughout the experiment ranged between 14.4 and 17.2 °C.

Nitrate uptake, the difference between input and output (transport) concentrations in the channels, varied (fig. 3). Uptake was greatest in midafternoon and least after dark. The magnitude of fluctuation depended on nutrient concentration, shading, and the maturity of the biological community.

Nitrate uptake rates in the control channel and in channel 1 were similar prior to nutrient addition (fig. 4; 6:00 and 10:00 a.m., August 24). Once injection of nutrients began, nitrate uptake immediately increased in channel 1 (fig. 4; 2:00 p.m. and 6:00 p.m. samples, August 24). High rates of uptake continued through August 28, as the community grew rapidly. In the control channel, nitrogen uptake increased by 5 to 10 mg/h during daylight hours through August 28 but by an additional 20 to 30 mg/h in channel 1 as a result of nutrient amendment. Differences between the channels decreased as the community matured (September 11). On September 19, 1 week after the end of nutrient amendment, diel uptake patterns were similar in both channels.

Nitrogen uptake in the nutrient-amended channels was also controlled by shading (figs. 3, 5). Over the full experiment, algal uptake on an areal basis was linearly related (r^2=0.95) to shading in the nutrient-amended



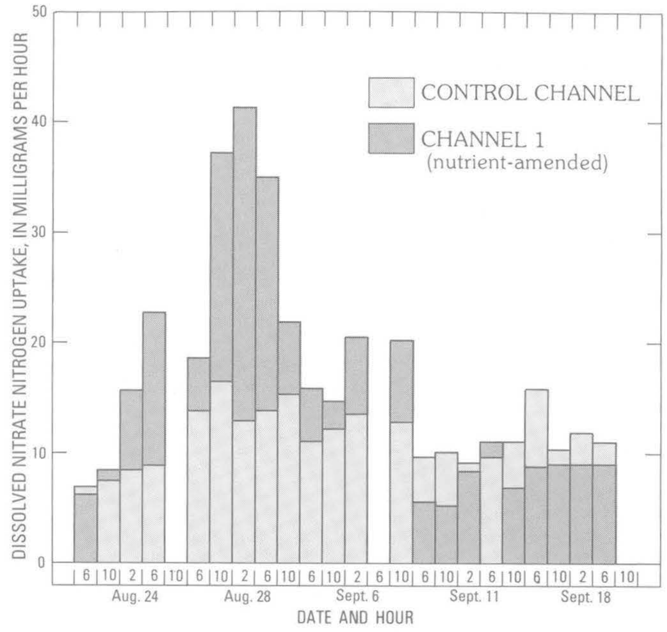


FIGURE 4.—Nitrate uptake in two channels exposed to full sunlight. The control channel had background nutrient concentrations, while nitrate and phosphate were added to channel 1.

◄ FIGURE 3.—Diel uptake versus transport as a percent of instantaneously available nitrate on five sampling dates during a 28-day experiment. Uptake is input minus output, and transport is equivalent to output. Nutrient concentration and shading were manipulated as follows: Control—background nutrients, full sunlight; channel 1—nutrient amendment, full sunlight; channel 2—nutrient amendment, 30 percent shade; channel 3—nutrient amendment, 66 percent shade; channel 4—nutrient amendment, 92 percent shade. Negative uptake indicates samples in which dissolved inorganic nitrogen concentration was higher in output than in input water. Nutrient amendment was 100 μg NO_3-N/L and 25 μg ortho PO_4-P/L. Nutrient amendment was cut off on September 12.

channels. Uptake was greatest in channel 1 (0.73 g N/m^2) and least in channel 4 (0.002 g N/m^2).

Transport, nitrate not removed biologically as uptake, was also linearly related (r^2=0.97) to percent shading over the total experiment. In the nutrient-amended flumes, average transport varied between 75 percent (channel 1) to more than 99 percent (channel 4) (fig. 3). In the control, transport was approximately 55 percent of input nitrate (fig. 3). Considering the short flume length (<10 m), small surface area (12.4 m), and continuous input of nitrate, a very short cycling distance under natural conditions is suggested.

Nitrate uptake also was related to community senescence. In both control and nutrient-amended channels, uptake of amended nitrate decreased as the community aged (fig. 3). Maximum nitrate uptake occurred when

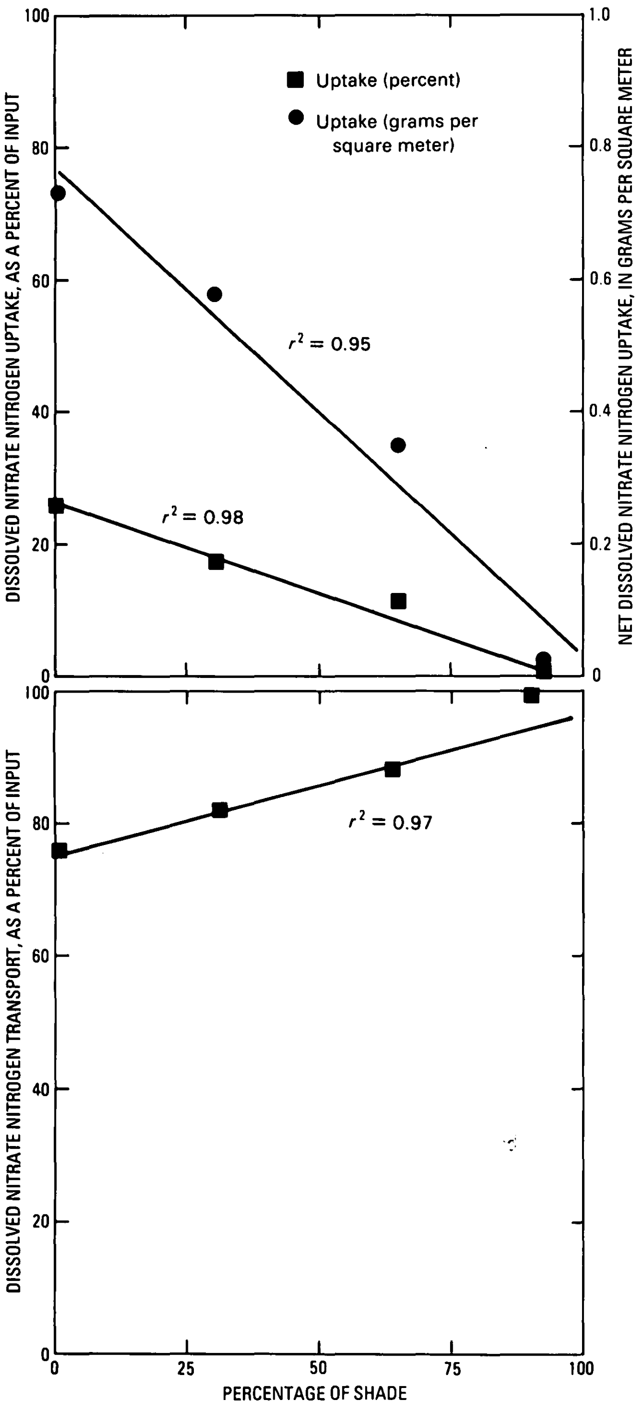


FIGURE 5.—Cumulative nitrogen uptake and transport for the full experiment in response to controlled levels of shading after 28 days of continuous nutrient amendment.

growth rate was greatest (August 28–31). After August 28, midafternoon uptake gradually declined at all levels of shading. By September 11, nitrate uptake in the nutrient-amended channels was less than at the beginning of the experiment, although epilithon biomass was maximum. On September 12, nutrient addition was cut off, thus the higher percentage uptake September 18 is of background nitrate. Net community primary production also declined as the community aged (Triska and others, 1983). Pryfogle and Lowe (1979) report that dead cells can constitute between 20 and 50 percent of the biomass in natural epilithon communities. Thus, dead and senescent tissue can represent a high proportion of organic matter that is physiologically inert to nutrient uptake.

In channel 4 (92 percent shade), many samples had higher output than input of nitrate concentration. Regeneration, 105 to 110 percent of input, is shown as negative uptake on figure 3. Regeneration occurred almost continually from September 6 to 12 (data shown for September 11 only) and is attributed to remineralization of organic detritus. By the end of the experiment, regeneration nearly equaled earlier uptake, explaining the low net uptake for all channels (fig. 5). This regeneration is considered in detail in Triska and others (1985). The influence of nitrate regeneration in flume experiments will be considered later in the discussion of field studies that examine the long-term influence of canopy development.

The relation of nitrate uptake to three measurements, biomass, chlorophyll, and carbon:nitrogen ratio, was also examined. When nutrient enrichment commenced, epilithon biomass (ash free) ranged from 2.43±0.5 to 7.77±0.68 g/channel (table 4). After 4 days of nutrient enrichment, the heavily shaded channel 4 (92 percent) had little biomass accumulation. Biomass in this channel thereafter remained significantly lower than that in channel 1 (student's *t*-test, $p < 0.01$). Two weeks after the nutrient amendment began, channel 1 was significantly higher ($p < 0.05$) in biomass than either the 30-percent-shaded or the 66-percent-shaded channels. On September 11, 19 days after nutrient addition began, biomass in all shaded channels was significantly lower than that in channel 1; (channel 2, $p < 0.05$; channel 3, $p < 0.01$). On September 12, nutrient addition ended, and nutrient concentration in all treated channels returned to background levels. Immediately before cutoff, both fully lighted channels supported nearly equal biomass (52.2±7.0 g/channel for the control channel vs. 49.0±2.3 g/channel for channel 1). After cutoff, biomass declined equally in both channels (17.6±2.6 g vs. 16.8±0.3 g biomass remaining, respectively, for channel 0 and channel 1).

Although the accumulation of biomass was nearly identical in the control and in channel 1, chlorophyll α content of the control channel at nutrient cutoff was less than half that of channel 1 (table 4). From a base of 31 mg, chlorophyll α increased to 182 mg/channel in the control. In channel 1, however, chlorophyll α rose from a base of 22 mg to a maximum of 403 mg/channel. Channel 2 (30 percent shade) produced slightly more chlorophyll α

TABLE 4.—*Biotic characteristics of the epilithon in the experimental flumes*

Date		Aug. 24	Aug. 28	Sept. 6	Sept. 11	Sept. 20
Channel treatment		Biomass, in grams ash-free dry weight (± standard deviation)[1]				
0	Control	7.77±0.68	13.34±0.60	31.27±4.53	52.15±6.99	17.63±2.64
1	0 shade	5.13±.55	14.82±2.36	40.50±2.94	49.02±2.34	16.83±.31
2	30 percent shade	4.76±.66	11.62±1.63	23.25±1.43	39.59±1.01	23.91±2.93
3	66 percent shade	3.71±1.23	9.72±1.08	21.33±2.80	28.18±4.70	25.53±3.36
4	92 percent shade	2.43±.50	3.27±.48	3.94±1.43	7.45±2.42	4.54±2.00
Channel treatment		Chlorophyll α in milligrams [2]				
0	Control	30.98	63.47	167.42	181.86	64.77
1	0 shade	21.59	135.20	270.87	402.52	104.34
2	30 percent shade	20.64	134.74	332.65	410.34	170.68
3	66 percent shade	20.10	132.85	178.32	278.05	130.06
4	92 percent shade	14.60	54.51	59.42	92.77	51.78
Channel treatment		Carbon:nitrogen[3] (± standard deviation)				
0	Control	11.58±0.67	14.06±0.26	10.56±0.62	8.11±0.21	7.18±0.07
1	0 shade	12.76±.29	8.21±.15	7.39±.22	7.79±.07	7.49±.02
2	30 percent shade	11.13±.48	9.15±.71	7.35±.55	6.83±.31	6.91±.01
3	66 percent shade	9.22±.14	7.74±.17	7.30±.07	7.47±.06	7.39±.06
4	92 percent shade	9.72±.11	9.19±.62	6.92±.06	8.47±.30	8.08±.06

[1] Biomass estimates for the total channel.
[2] Chlorophyll α in the total channel.
[3] Carbon:nitrogen is determined from samples taken at midflume.

than channel 1 but had approximately 20 percent less biomass, possibly indicating shade adaptation (Meeks, 1974; Lyford and Gregory, 1975). Chlorophyll α was lower in the 66-percent-shaded and 92-percent-shaded channels.

Carbon:nitrogen ratios varied between 9.2 and 12.8 when the experiment began (table 4). C:N was lower in most nutrient-amended flumes than in the control channel. Nutrient amendment resulted in reduction of C:N by August 28, and C:N generally continued to decline throughout the experiment. In the control flume, however, C:N increased when community growth was most rapid, indicating potential nitrogen limitation. By September 20, C:N was similar in all flumes.

After 1 week, the cumulative nitrate uptake in channel 1 (0.358 g NO_3-N/m^2) was 1.8 times higher than that of the control (0.198 g NO_3-N/m^2). This cumulative nitrate uptake is consistent with the observed lowering of C:N. Cuker (1983) reported an increase in chlorophyll α levels in the epilithic algal community of an arctic lake after addition of nutrients. Chlorophyll α may partially serve as a reservoir of nitrogen, because the chlorophyll molecule contains significant nitrogen. This possibility is also consistent with our own observations of chlorophyll α enhancement as a result of nutrient amendment. Rhee (1978) observed that protein was the major storage pool of cellular nitrogen. Protein also serves an important function in the structural arrangement of chlorophyll in chloroplasts. Wherever the intracellular location of nitrogen, however, the decline in C:N and high cumulative uptake indicate a rapid epilithon response to increased nitrate.

Although the highest rates of nitrate uptake occurred in midafternoon, indicating a primarily algal response, significant uptake also was observed afterdark. Afterdark uptake varied by shade treatment and was greatest during the period of most active epilithon growth, August 24 to 28. Afterdark uptake was maximum in the control channel at about two-thirds the uptake of daylight, possibly indicating nitrogen limitation. Eppley and others (1971) reported afterdark uptake of nitrate in nitrogen-limited chemostat cultures of two marine phytoplankton. Grant and Turner (1969) observed afterdark uptake but found light uptake was 23 times greater. This observation was presumably due to the fact that nitrate uptake and reduction by algae are energetically linked to photosynthesis (Eppley and Coatsworth, 1968; Eppley and others, 1971; Healy, 1973; Cloern, 1977), possibly through the reversible inactivation of nitrate reductase during light-dark cycles (Hodler and others, 1972; Griffiths, 1979). Nitrate reductase activity rapidly increases in *Chlorella* sp. cultures during the light period and may begin to fall even before the dark period begins. The rapid response following illumination may result from conversion of a preformed macromolecule into an active enzyme (Tischner and Hutterman, 1978). These previous studies on *Chlorella* sp. in chemostats used pure and synchronous algal cultures. Because afterdark uptake was proportionally higher in our field experiments, significant nitrogen flux also may occur through bacteria and fungi in natural epilithon.

The channel experiments illustrate how biological uptake can regulate the distance that a nitrate ion travels downstream. Temporally, uptake was controlled on a daily basis by irradiance and on a week-to-week basis by physiological senescence that reduced uptake at all levels of shading. In natural channels, physical factors, including sloughing, animal grazing, and small summer and early autumn storms, reset the community and partially mitigate the effect of senescence. Tissue removal, whether directly by consumption or indirectly by sloughing or scouring, may enhance both nitrogen passage to higher trophic levels and the DIN uptake per unit area.

Spatially, canopy cover (percent shading) controlled the overall magnitude of uptake. Under natural conditions canopy cover is a function of stream order, with almost complete coverage in lower order streams and less coverage downstream.

FIELD STUDIES: LONG-TERM NITROGEN UPTAKE AND REGENERATION

In this section, we will apply conclusions from the flume studies to longer term DIN chemistry by comparing years when the riparian canopy was open, 1974 to 1976, to years when it was largely closed, 1979 to 1982. We will approach canopy effects on inorganic nitrogen transport from a diel and seasonal perspective, as in the flume studies, and briefly speculate about the long-term impact of canopy closure on the structure of biological communities.

Diel nitrate patterns in September 1974 and 1982 are compared in figure 6 for two stations, Gage and Bridge. The Gage site was at the head of the clearcut area and indicates dissolved inorganic nitrogen input from the upstream virgin forest. The Bridge site was located about 1,500 m downstream near the base of the clearcut area and upstream of the junction of Little Lost Man Creek and Prairie Creek (fig. 1). Diel variation in background nitrate concentration at Gage was typically 10 to 20 μg NO_3-N/L in both 1974 and 1982 but was higher in 1982. The diel pattern of nitrate concentration at Gage was similar to the pattern seen in our experimental channels (highest after dark and lowest between noon and 4:00 p.m.). In 1974 (fig. 6), the riparian canopy was open, and full sunlight reached the stream. At the Bridge site, nitrate concentration was typically reduced to between 5 and 8 μg NO_3-N/L due to biological uptake. Absence of a diel pattern at Bridge is attributed to continuous biotic uptake. Uptake of approximately 77 percent of transported nitrate occurred between the two stations in 1974. Opposite results were observed at the same sites in 1982 (fig. 6). Rather than a reduction in nitrate concentration, a threefold increase in nitrate was observed at the downstream site. The canopy was nearly closed in 1982, except for a few large pool reaches that allowed light infiltration.

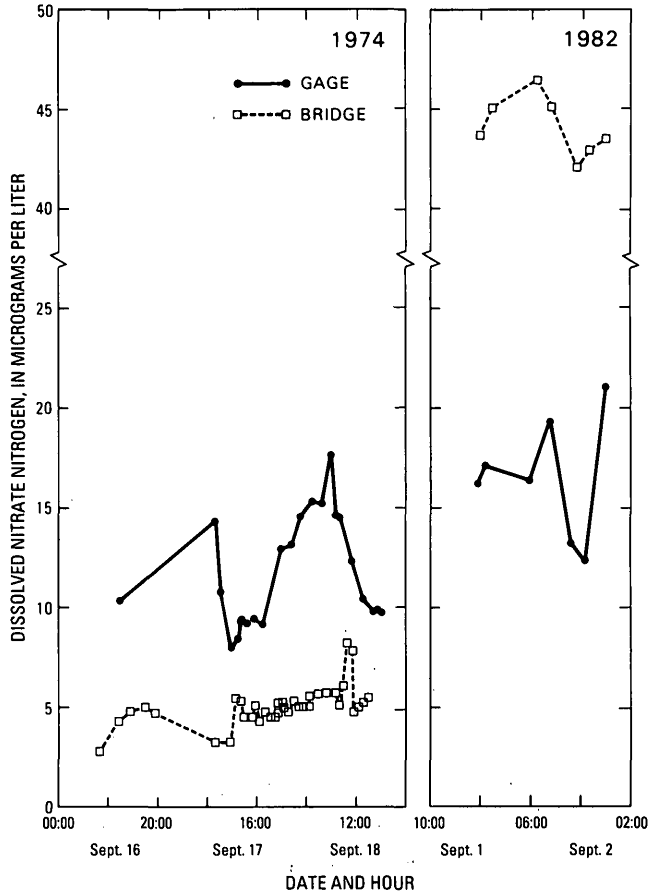


FIGURE 6.—Diel difference in NO_3-N concentrations during late summer between an upstream (Gage) and a downstream (Bridge) study site. Concentration differences prior to canopy closure (September 16–18, 1974) are indicated on the left, and differences after canopy closure (September 1–2, 1982) are indicated on the right. Location of the Gage and Bridge study sites is shown in figure 1.

By 1982, nitrate regeneration was observed over the whole summer-autumn period of declining discharge (fig. 7). Except for the mid-August sample, the pattern of background nitrate concentration at the Gage site was similar in both 1974 and 1982; DIN concentration was low during early summer (June and July), usually between 10 and 15 μg N/L in 1974 and 5 and 10 μg N/L in 1982. Maximum midday nitrate concentration at the Gage site was approximately 40 μg N/L during 1974 (mid-August sample) but less than 20 μg N/L during 1982. Concentrations at the Gage site during 1976 were intermediate, but as in 1974, the Gage site samples had a higher concentration in late summer. Comparison of data from the Bridge and Gage sites indicates nitrate disappearance during the late spring and summer in 1974 and 1976 but nitrate regeneration throughout the summer of 1982.

During the low-flow period, uptake in the reach was greatest during July in 1974 and in mid-July and early

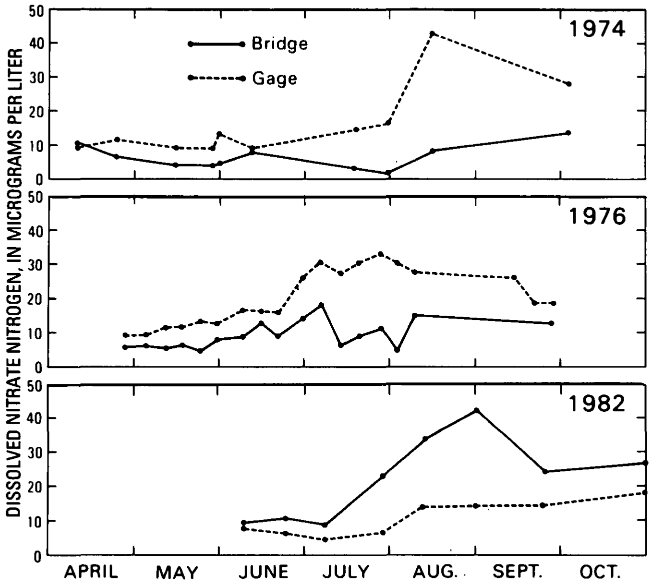


FIGURE 7.—Seasonal differences in midday NO_3-N concentration between an upstream study site (Gage) and a downstream study site (Bridge). The riparian canopy was open above the stream during 1974 and 1976 and closed by 1982. Study site locations are shown on figure 1.

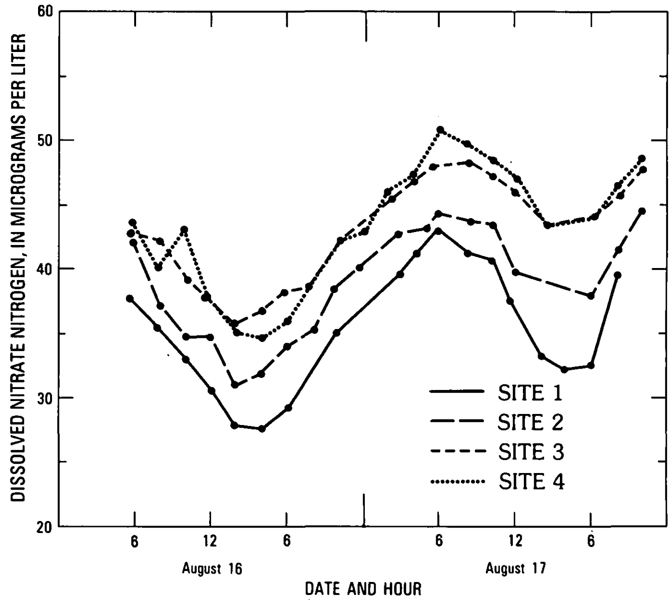


FIGURE 8.—Diel change in background NO_3-N concentration at four stations within a 265-m reach of Little Lost Man Creek under low-flow conditions, August 16 to 17, 1979. Distance between sites 1 and 2 is 64 m; between sites 2 and 3 is 58 m; and between sites 3 and 4 is 143 m. This 265-m reach is labeled "1979" on figure 1.

August in 1976. Differences between study sites were less in early summer, presumably because higher discharge and increased velocity shortened traveltime and lessened contact with the epilithon. Nitrogen uptake declined in September and October. Declines in uptake, despite low flow, may indicate community senescence as observed in the experimental channels. Possible causes of senescence include emergence of many grazer invertebrates by late summer and extremely low flows, which allow metabolites to accumulate and minimize physical sloughing. Nitrate regeneration also declined by mid-September in 1982.

The nitrate regeneration currently observed at Little Lost Man Creek is not uniform throughout the reach. A diel study at four sites in a 265-m section of the clearcut reach (labeled "1979" in fig. 1) indicated significant increase in nitrate concentration within short distances (fig. 8). For example, the distance between sites 1 and 2 was 64 m and between sites 2 and 3, 58 m. The greatest observed increase in nitrate concentration occurred between sites 1 and 3. The distance between sites 3 and 4 was 143 m but was characterized by net nitrate uptake during daylight and by slight nitrate regeneration after dark and until noon the next day. This reach contained one unshaded riffle and two long unshaded pools.

The flume studies indicate two potential sources of nitrate increase in 1979 and 1982: (1) regeneration within the bed and (2) decrease of algal uptake of nitrate from inflowing ground water as a result of canopy development (increase in shading). To test the hypothesis that nitrification was actually occurring in stream sediments, we collected submerged bankside soils at three sites along the stream: (1) adjacent to an alder stand where nitrogen-fixing nodules were not observed on roots, (2) adjacent to an alder tree where roots were definitely nodulated, and (3) adjacent to an old-growth maple tree. Nitrification potentials were measured as an increase in nitrite by inhibition of the enzyme that facilitates the final oxidation of nitrite to nitrate. Samples from all three sites indicated nitrification potential when compared to uninhibited controls (fig. 9). In conjunction with our observations in the experimental channels, this preliminary survey of bankside sediments indicates a biological potential for nitrate regeneration.

A second hypothesis for the observed nitrate increase is absence of nitrate uptake from inflowing ground water. If ground water is higher in NO_3-N than stream water due to upstream removal of NO_3-N during transit, then an apparent increase in NO_3-N in the shaded clearcut areas may result from lack of uptake from newly contributed ground water rather than from actual nitrification. To test this hypothesis, two experiments involving passage of a 3-hour midmorning pulse of nitrate in two reaches were compared between 1976 when the canopy was open and 1979 when it was closed (for location see fig. 1). Calculated nitrate uptake relative to nitrate concentration (based on chloride as a conservative tracer) is presented in figure 10. The results indicate

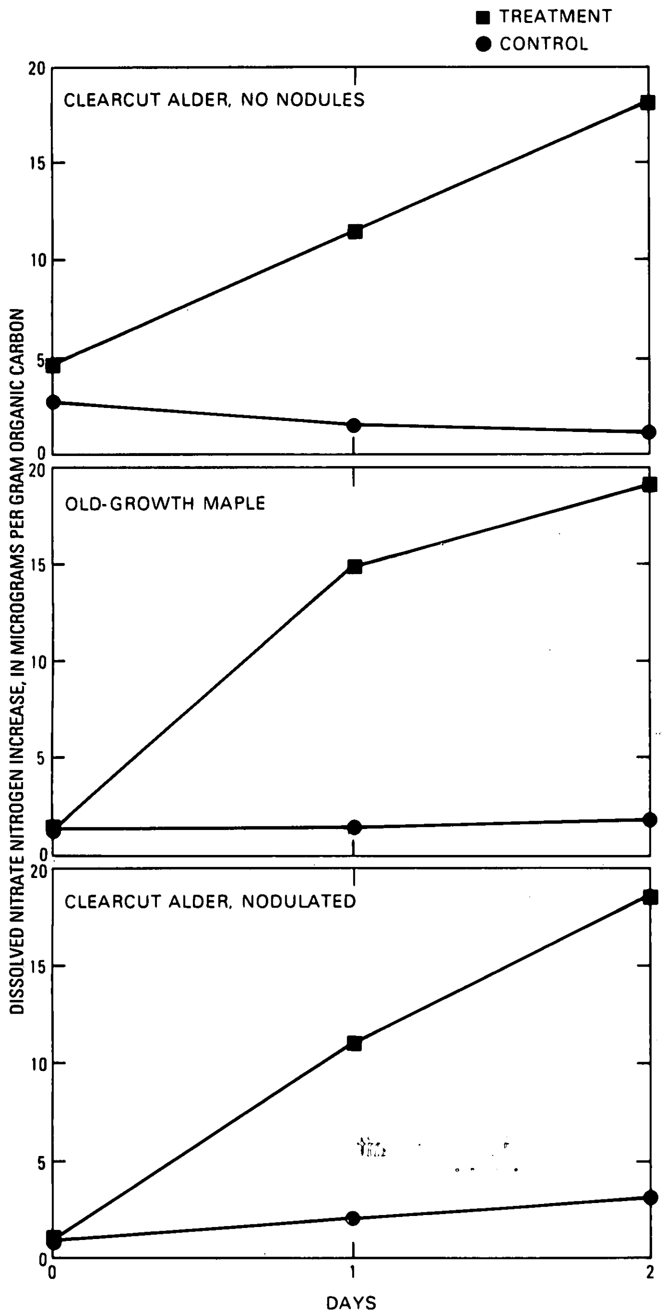


FIGURE 9.—Nitrification potential along Little Lost Man Creek, August 1981, measured by chlorate inhibition. Bankside sediments were collected adjacent to an alder tree where nitrogen-fixing nodules were not observed, adjacent to an old-growth maple, and adjacent to an alder tree where nitrogen-fixing nodules were observed on the roots.

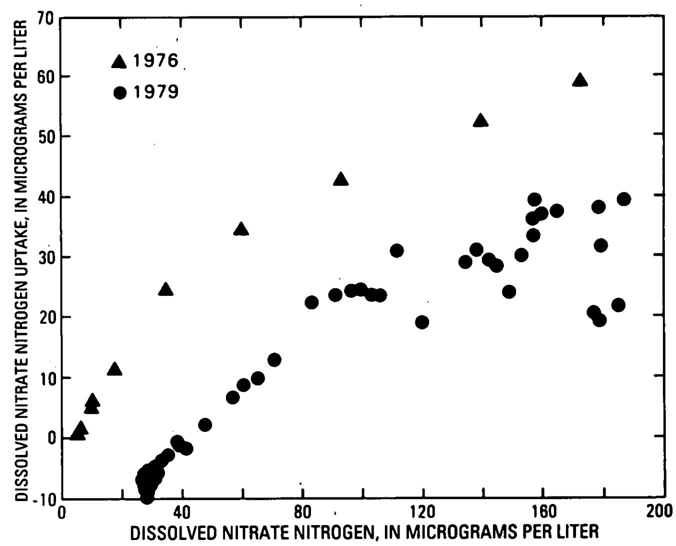


FIGURE 10.—Nitrate uptake at concentrations between 5 and 200 μg NO_3-N/L after passage through two reaches of Little Lost Man Creek (labeled "1976" and "1979" on fig. 1). Experimental injections of nitrate were conducted during 1976 when the riparian canopy was open and during 1979 after canopy closure. Concentration was varied by passage of a nitrate pulse down the channel; chloride was used as a conservative tracer to correct for dilution.

less nitrate uptake at all concentrations between approximately 30 and 180 μg NO_3-N in 1979. The negative uptake observed in 1979 around 30 μg NO_3-N/L is due to regeneration. Decreased uptake was observed in 1979 despite the fact that the minimum traveltime was shorter in 1976 (2.2 hours compared to 7 hours in 1979). The longer traveltime should have enhanced contact with periphyton in 1979. Even with better contact, less nitrate uptake after canopy closure indicates significantly reduced capacity for nitrogen uptake by biota. Thus both mechanisms, nitrification in the bed and reduced uptake by the epilithon, contribute to the current increase in DIN transport from the watershed.

At Little Lost Man Creek, the atomic N:P ratio (NO_3-N+NO_2-N)/ortho PO_4-P) was extremely low in 1974 (approx 1.75) but rose to approximately 7.8 by 1979. Although N:P has risen due to less nitrogen uptake and greater regeneration, both ratios indicate potential nitrogen limitation relative to phosphorus (Redfield and others, 1963; Rhee, 1978). Under the former (1974–76) conditions of high light input and nitrogen limitation, nitrate regeneration would have been difficult to observe in place, because nitrogen-limited algae can remove nitrogen both night and day (Conway and Whitledge, 1979; Triska and others, 1983; Sebetich and others, 1984), obscuring any potential contribution of nitrate regeneration. Since 1979, however, canopy shading has limited light infiltration, thereby lowering algal growth and nutrient uptake. At the same time, enhanced input of particulate organic matter (for example, alder leaf litter and decomposing root tissue) provides an additional source of organic nitrogen for regeneration. Dense shading also optimizes conditions for nitrate regeneration because nitrifying bacteria are inhibited by light (Olson, 1981; Ward and others, 1982). The result has been a change within the reach from a net loss of nitrogen in transit to a net gain.

SUMMARY AND CONCLUSIONS

The channel and stream studies in combination indicate that uptake and regeneration of inorganic nitrogen can be regulated on variable time scales in the stream. In experimental control, midafternoon nitrate uptake was up to 75 percent during the period of most active growth and approximately 40 percent by senescent communities under full sunlight. In the stream, maximum diel uptake was greater than 75 percent of the available nitrogen (77 percent in 1974, 87 percent in 1976) in an approximately 1,500-m open reach of Little Lost Man Creek. These levels of uptake indicate the potential of the biotic community to control diel nitrate transport under low-flow conditions.

Within longer term resetting periods (such as between storms), the epilithon community varied in its ability to influence nitrate transport in experimental channels. In an unshaded, nutrient-amended channel, the major factor controlling uptake was the maturity of the algal community. Actively growing epilithon had high nitrogen uptake per unit biomass compared to senescent films, under identical solute nitrogen concentration and channel discharge. In the control, a high C:N of periphyton during active growth presumably reflected nitrogen limitation. In the absence of periphyton removal, nitrogen uptake and C:N of periphyton generally decreased as the community aged. Under natural conditions of full sunlight in the stream, uptake increased from May through August. As discharge fell, background nitrogen concentrations rose, but nitrogen was effectively removed through most of the low-flow period. Toward late August and September, uptake declined although discharge was at its annual low. Community senescence was a possible cause.

Reduction in canopy density, such as from lower to higher order streams or through time as a result of canopy development, also influenced nitrate transport. The canopy increased solute nitrogen concentrations by at least two mechanisms: (1) by promoting nitrification in bankside sediments and (2) by decreasing algal uptake due to light limitation. In our experimental flumes, nitrate regeneration presumably occurred as benthic communities became senescent. However, the process could be verified only under highly darkened conditions, perhaps conditions simulating intragravel sites having high organic matter mineralization. Historically, nitrate regeneration did not produce an observable impact at Little Lost Man Creek until 14 years after clearcutting, when closure of the riparian canopy was nearly complete. The impact of nitrate regeneration was slight early in the growing season but increased throughout the summer to a peak in early September. Regeneration declined in late September, although discharge remained constant. The role of other sources and sinks, such as nitrogen fixed by riparian vegetation or lost via denitrification, is not known.

Experimental shading in the flume studies reinforced our conclusion that development of the riparian zone is of long-term importance in nitrogen cycling at Little Lost Man Creek and similar creeks. Our results suggest that canopy development will result in a long-term decline in epilithon production because of limitation of the synthesis of algal protein. Epilithon production is a major interface between DIN and the passage of nitrogen to higher trophic levels. Heterotrophic processes such as the decomposition of leaf litter will gain in importance due to greater litter input. However, nutrient flux associated with these heterotrophic processes is slow compared to nutrient flux associated with epilithic communities. As a result, animal species dependent on epilithic films are likely to decline in abundance. Other species that filter sloughed tissue from the water column or consume it as organic detritus are also likely to be affected. Decrease in protein synthesis low in the food chain may even extend to higher level carnivores such as fishes. Murphy (1979), who surveyed 20 small streams in Oregon, found trout biomass (g/m^2) to be lowest in streams covered by dense second-growth riparian cover, highest in open streams, and intermediate in the mixed canopy cover of old-growth forests. Thus the net result of lower DIN flux may be a large decline in biotic production until natural mortality in the riparian zone reopens the canopy (Triska and others, 1982). Development of an alder canopy is a typical response to clearcutting in coastal watersheds of northern California and the Pacific Northwest. As a result, more long-term data are needed for clearcut reaches like Little Lost Man Creek, to adequately assay the long-term impacts of current land management practices.

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