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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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WATERSHED CONDITIONS IN THE DRAINAGE BASIN OF REDWOOD CREEK, HUMBOLDT COUNTY, CALIFORNIA AS OF 1973

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Prepared in cooperation with the National Park Service

U.S. Geological Survey

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This report has not been reviewed for conformity with Geological Survey stratigraphic nomenclature

Menlo Park California
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INTRODUCTION

The drainage basin of Redwood Creek is located a short distance northeast of Eureka, California (fig. 1), and comprised of about 280 square miles (725 square kilometers) of some of the most rapidly eroding non-glaciated terrane in North America. High rates of erosion reflect a combination of rock types, geologic history, climate, and land use that exists throughout vast areas of northwestern California and southwestern Oregon. Early vertical aerial photographs and geological investigations indicate that the pristine Redwood Creek basin, even though it was about 85 percent mantled with a dense coniferous forest, was subjected to episodic vigorous mass movement and stream channel erosion.

The forests of this basin are a major source of both commercial wood fiber and public enjoyment. As of 1973 about 65 percent of the Redwood Creek basin was cutover forest land much of which displayed actively eroding gullies and landslides that were clearly related to timber harvest and associated road construction. Nearly all the timber harvesting occurred in the last 25 years. Of about 20 percent of the basin that still bears old growth forest, nearly two-thirds has been set aside as public parks in the redwood (Sequoia sempervirens) - dominated forests of the downstream portion of the basin.

The parkland of lower Redwood Creek is included within Redwood National Park which was established on October 2, 1968, when the U.S. Congress enacted Public Law 90-545 in order "to preserve significant

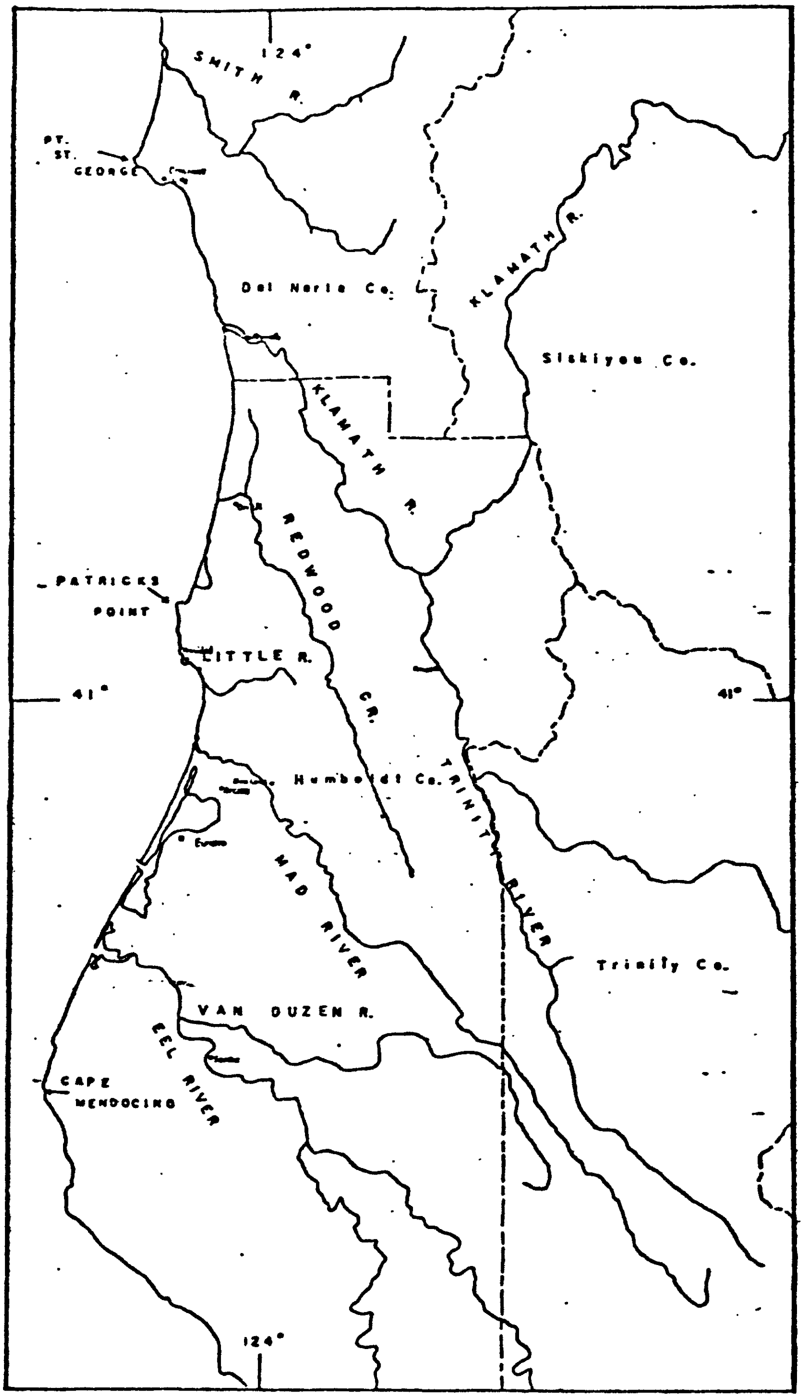


Figure 1. Location map--small scale.

examples of the primeval coastal redwood (Sequoia sempervirens) forests and the streams and seashores with which they are associated for purposes of public inspiration, enjoyment, and scientific study,...". The southernmost portion of this park is a seven-mile-long, half mile-wide appendage that straddles Redwood Creek and that contains some of the park's most magnificent redwood groves (fig. 2).

The Congress apparently foresaw potential problems in preserving park values in the downstream end of an intensively logged, and highly erosive drainage basin, as they provided the Secretary of the Interior with statutory authority to engage in special actions designed to protect park resources. The relevant sections of the Act of establishment are as follows:

> Section 2a "...The Secretary of the Interior...may from time to time, with a view to carrying out the purpose of this Act and with particular attention to minimizing siltation of the streams, damage to the timber, and assuring the preservation of the scenery within the boundaries of the national park as depicted on said maps, modify said boundaries...".
>
> Section 3e "In order to afford as full protection as is reasonably possible to the timber, soil, and streams within the boundaries of the park, the Secretary is authorized, by any of the means set out in subsections (a) and (c) of this section, to acquire interests in land from, and to enter into contracts and cooperative agreements with, the owners of land on the periphery of the park and on watersheds tributary to streams within the park designed to assure that the consequences of forestry management, timbering, land use, and soil conservation practices conducted thereon, or of the lack of such practices, will not adversely affect the timber, soil, and streams within the park...".

Public Law 90-545, however, also restricts the total acreage of the park to 58,000 acres and limits expenditure of public funds for land acquisition to 92 million dollars, so that an apparently impressive array of discretionary authority is actually rather limited.

Shortly after the creation of Redwood National Park, the Secretary of the Interior and the National Park Service initiated a series of studies designed to assist them in understanding the various options for protecting and managing the timber, soil, streams, and scenery within the park. The first of these studies (Stone and others, 1969) described "potentially destructive inputs into the park," and the impact of land-management activities on the magnitude of those impacts. This report went on to recommend specific restrictions to be applied to timber harvest and other management activity within 800 feet (244 metres) of the park boundary and urged creation of a voluntary Redwood Creek land management association to address itself to stabilizing the actively eroding upper Redwood Creek watershed. The possible need for additional Federal action to protect the Redwood Creek unit of Redwood National Park was reviewed again starting in March of 1972 by a University of California-Federal interagency task force under the leadership of Dr. Richard C. Curry. This task force (Curry, 1973) identified channel instability as the greatest potential threat to park resources and went on to recommend that increased efforts be made to influence management actions in areas well beyond the 800-foot buffer zone proposed by Stone and others (1969). Understanding of the interactions between various geomorphic processes and the terrestrial and aquatic ecosystems that inhabit the Redwood Creek basin was so incomplete, however, that the Curry task force did not feel comfortable in making final action recommendations, but suggested that the National Park Service in cooperation with the U.S. Geological Survey initiate studies to provide data needed in formulating management activities that would assure, to as great a degree as possible, the preservation of park resources. Thus, on August 16, 1973, the National Park Service requested and formally authorized the Geological Survey to initiate a three-year study designed (1) to delineate and to describe particular portions of the terrestrial and aquatic ecosystems within Redwood National Park that are directly or indirectly threatened by recent changes in the intensity of erosion and sedimentation, (2) to define more precisely the magnitude, frequency of occurrence, and duration of the processes that pose the most imminent threats, and (3) to assess the impact of recent road construction and timber harvest on those processes.

PURPOSE AND SCOPE

The two major purposes of this report are to describe the physical condition of the drainage basin of Redwood Creek as of 1973, and to attempt to identify processes that are modifying or are threatening to modify the ecosystem that inhabits Redwood National Park. In attempting to fulfill these goals, major uncertainties and inadequacies in the available data base have been identified and are now being studied as part of our continuing research in the drainage basin. Considerable public debate has focused on possible timber harvest-induced changes in the hydrologic and sedimentation regimes of Redwood Creek and the potential impact of those changes on the resources of Redwood National Park. This report addresses itself to those issues at considerable length, but attempts more to isolate specific questions than to provide answers. Interim and final reports of our continuing studies will attempt to answer some of those questions. The present report is composed mostly of a description of both the physical setting of the drainage basin of Redwood Creek and some of the physical processes that influence the terrestrial and aquatic ecosystems that inhabit the basin. The description is based primarily on a compilation and interpretation of numerical, descriptive, and photographic information that was available at the end of 1973, prior to the initiation of intensive data collection by the Geological Survey. The report attempts to bring information from various germane scientific disciplines together into one unified body of data so that interrelationships between different processes and between processes and organisms become more readily apparent. Most of the numerical computations, statistical and graphical analyses, and interpretations of data presented here were completed after December 1973. While this report was in preparation, the data base was constantly expanding. If new data either contradict or clarify relationships suggested by the older data, the new data are briefly discussed in passing, but not discussed in detail. For example, the report contains physiographic data including erosion process information gleaned from interpretations of published 15-minute topographic quadrangle maps and historical sequences of aerial photographs, but it does not present data discernible only on detailed topographic maps and aerial photographs obtained after December 1973. The intent was to describe the condition of the basin at a point in time--late 1973--and to suggest how it got that way. Therefore, the interpretations in this report should be considered preliminary and subject to revision as more definitive information becomes available.

Acknowledgments

We would like to thank Stephen D. Veirs and Richard C. Curry of the National Park Service for helpful discussions of new ideas in the field. Veirs also reviewed early drafts of some chapters of this report. Edward Helley and Clyde Wahrhaftig, U.S. Geological Survey, have served as sounding boards for new ideas in the office. Robert C. Averett and Rick T. Iwatsubo of the Geological Survey have given us an introduction to the complexities of the aquatic community. We would also like to acknowledge Ted Hatzimanolis of the National Park Service for the use of his invaluable 1936 aerial photographs of the Redwood Creek basin. Most of the illustrations in the report were drafted by Christine G. Janda.

The Forestry staffs of Arcata Redwood Co., Louisiana Pacific Corp., and Simpson Timber Co., and members of the Curry task force team provided valuable information and insights during discussions in the field.

Numerous professional colleagues and personal friends whose schedules have been disrupted by our participation in this study have provided valuable assistance, understanding, and inspiration. We hope that this report will recall for them past discussions of various aspects of the study and help them realize our gratitude for their contributions.

GEOLOGIC SETTING AND REGOLITH

The lithologic and structural properties of the rocks of the Redwood Creek basin make them highly susceptible to chemical decomposition and erosion. Geologically recent uplift may also have influenced present rates and processes of erosion. The geologic setting and history of this basin, however, are poorly understood because the spatial distribution of rock units for most of the basin is known only from reconnaissance mapping (Strand, 1962, 1963 and references therein), and the nature of the geologic contacts has been studied only cursorily. Evidence concerning the evolution of the topography during Neogene and Quaternary time is particularly meager.

ROCK TYPES AND ASSOCIATED REGOLITH

The entire basin upstream from the mouth of Prairie Creek is underlain by the strongly indurated Franciscan assemblage of rocks (fig. 3) whose origin, metamorphism, and subsequent tectonic deformation are related to sea-floor spreading and subduction of the Pacific Ocean floor beneath the western edge of North America (Blake and Jones, 1974). These rocks show varying degrees of metamorphism with texture zones 1, 2, and 3 of Blake and others (1967) all being present. Marine sedimentary and metasedimentary rocks are far more abundant than volcanic and metavolcanic rocks. No fossils have been found within the Franciscan assemblage in the Redwood Creek basin, but petrographically similar rocks can be traced southeastward where fossils and radiometric dating suggest that these rocks are of Late Jurassic and Early Cretaceous age (Blake and others, 1967).

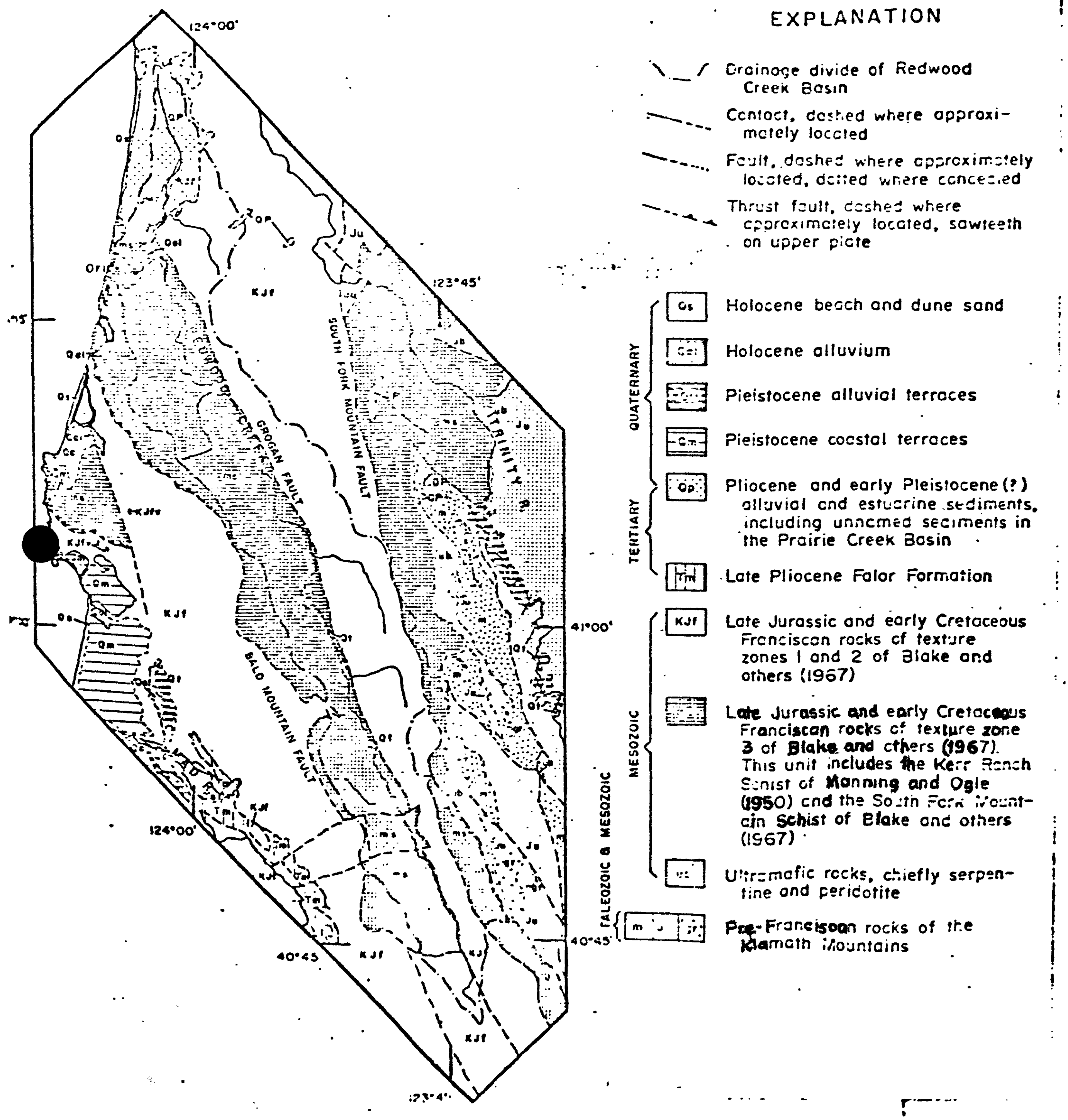


Figure 3. Geologic setting of Redwood Creek basin from Strand (1962, 1963).

The rocks underlying the northwestern Lost Man Creek basin and the upper Prairie Creek basin, in contrast, are unnamed, weakly indurated coastal plain sediments. These unnamed sediments contain Pliocene or younger plant fossils and interfinger with the marine Pliocene St. George Formation (Moore and Silver, 1968).

Essentially unmetamorphosed Franciscan sedimentary rocks underlie most of the eastern side of the basin. Most of the rocks labelled "KJF" in Figure 3 are texture zone 1 rocks (Blake and others, 1967). Graywacke sandstone (lithic and arkosic wacke, according to Williams and others, 1958, page 259) is the most abundant rock in this zone. Lesser amounts of mudstone and conglomerate are present. Some of the conglomerate is composed solely of subangular to subrounded granules and fine pebbles of unmetamorphosed mudstone in a sand matrix. Most of the conglomerate, however, shows pebbles derived predominantly from rocks resistant to chemical weathering such as chert, fine-grained metavolcanic rocks, quartzite, and quartz porphyry. A few clasts of fine-grained plutonic rocks are present, but clasts derived from rocks resembling schists of texture zone 3 are absent. Bedding, although often obscure, is mostly from 4 to 120 inches (0.1 to 3 meters) thick. Graded bedding and other internal sedimentary structures indicative of deep water, turbidite deposition are common.

The western part of texture zone 1 rocks in the Redwood Creek basin are finer grained, lithologically more diverse, and structurally more complex than rocks in the eastern part. Small discontinuous bodies of greenstone and bedded radiolarian chert are present. Mudstone units that are several tens of feet thick are interbedded with the sandstones; less conglomerate is present than in the eastern part. Sheared and closely fractured rocks are also far more prevalent in the western part than in the eastern part of texture zone 1. Throughout most of the basin, earthflows and other forms of mass movement are particularly common in the area immediately east of the main channel of Redwood Creek (Colman, 1973)--an area with many sheared mudstone units. The general appearance of the western part of texture zone 1 in the Redwood Creek basin generally resembles that associated with some of the extensive tracts of Franciscan melange farther south in the Coast Ranges, except that exotic blocks ("knockers") of amphibolite and metavolcanic rocks are absent.

Texture zone 2 rocks, which in the Redwood Creek basin are composed primarily of phyllite and stretch-pebble conglomerate, represent a transition between the essentially unmetamorphosed sedimentary rocks of texture zone 1 and the schists of texture zone 3. Mudstones typically have partially recrystallized and display a weak cleavage and a micaceous "sheen" but no pronounced mineral segregation or foliation. Sandstones and conglomerates of texture zone 2 have not recrystallized but cataclastic rotation and flattening of grains in these rocks have produced an aligned fabric that is clearly discernible in the field.

Within the Redwood Creek basin, rocks of texture zone 2 crop out principally in close proximity to Redwood Creek in a narrow belt at the western edge of the belt of rocks labelled as "KJf" in figure 3. Texture zone 2 throughout most of the basin is 1,000 to 3,000 feet

(305 to 914 meters) thick which is comparable to or slightly thinner than texture zone 2 in the Black Butte-North Yolla Bolly area where such rocks form a complete unfaulted transition between unmetamorphosed sandstone and schist (Blake and others, 1967). Locally within the Redwood Creek basin, texture zones 1 and 3 are in sharp contact with no intervening zone 2 present.

Naturally-occurring bedrock outcrops are scarce in areas away from the major stream channels in the Redwood Creek basin because of a nearly ubiquitous mantle of colluvium and (or) residual soil which supports dense vegetation. Distinguishing between residual soil, and colluvium derived from deep residual soil and saprolite is often difficult, so we apply the term regolith to the entire surficial mantle of unconsolidated materials produced by both hillslope erosion processes and mechanical and chemical weathering. Regolith includes saprolite, colluvium, and residual soil.

The rocks of texture zones 1 and 2 bear quite similar regoliths. The thickness of the regolith is highly variable ranging from less than 2 feet (less than 0.6 meters) along many hilltops and divides in the southern part of the basin, to more than 13 feet (more than 4 meters) on some broad divides in the northern part of the basin, in some landslides, and on many other mid-slope and lower-slope sites. The average thickness, however, is probably less than 6.6 feet (less than 2 meters). The colluvium is mostly stony loam and stony-clay loam that appears to represent eroded saprolite and residual soil. Some open-worked angular rubble on steep sandstone slopes in the eastern parts of the Lacks Creek and Minor Creek basins, and at the margins of large isolated "knocker"-like outcrops of sandstone and greenstone in zone 2 and the western part of zone 1 is rockfall talus derived from relatively fresh rock materials; some talus has been displaced downslope by creep. Most of the residual soils in the Redwood Creek basin have formed on stabilized colluvium rather than on in situ bedrock.

Type and degree of soil profile development, as indicated on 1:31,680 scale soil-vegetation surveys (Alexander and others, 1959-62) are virtually the same on rocks in texture zones 1 and 2 with common soil series including Hugo, Melbourne, Mendocino, Atwell, Kneeland, and Tyson. A few small patches of strongly developed soils resembling the Josephine soil series are found in association with the Hugo and Melbourne soil series on midslope positions in the northern part of the basin. Parent materials for the Hugo soil series appear less deeply weathered and less cohesive in the southern part of the basin than in the north. The Kneeland and Tyson soil series are grassland soils; the others are all forest soils. The Hugo soil series is more abundant than all the other soil series developed from texture zones 1 and 2 combined (Iwatsubo and others, 1975, tables 2 and 3).

The grain-size distribution and ped structure of all these soils give them high infiltration capacities and generally good subsurface drainage. However, their surface horizons are dominantly loams and stony loams with little cohesion, so that when surface runoff does occur, the erosion hazard is moderate to very high (Alexander and others, 1959-62).

Most of these soils, even though they are often developed from deeply decomposed and leached parent materials, show only meager soil profile development and are classified as inceptisols. The more strongly developed Melbourne, Mendocino, and Josephine soils are ultisols. The inceptisols and ultisols both show decreasing pH and (where laboratory analyses are available) base saturation with increasing depth. The concentration of organic matter in surface horizons and the higher base saturation of the surface horizons relative to those at depth suggest that the reservoir of available essential plant nutrients is concentrated in the surface and near-surface soil horizons, and that the fertility of these soils is strongly dependent upon nutrient recycling by plants (Buol and others, 1973, p. 278). The physical removal of the surface horizons of these types of soils by, for example, earth-moving equipment or erosion, thus would result in a significant loss in the potential site productivity.

The Atwell soil series is developed from pervasively sheared rocks within the western part of texture zones 1 and 2 and along the north-northwest-trending faults in the basin. The Atwell soil series is not significantly more susceptible to surface fluvial erosion than other soil series in the basin (Alexander and others, 1959-62), but parent materials for this soil series are particularly susceptible to repeated mass movement failures (Stone and others, 1969). The soil parent are, therefore, relatively unweathered rock and colluvium. These soils commonly have more clay, and higher pH and base saturation values than soils developed from less sheared rocks within texture zones 1 and 2. Their pH and base saturation do not necessarily decrease with increasing depth. The Atwell soil series is, therefore, variously classified as either an alfisol or an ultisol depending upon the results of laboratory studies of individual soil profiles.

Rocks of texture zone 3, which have previously been mapped as the Kerr Ranch Schist of Manning and Ogle (1950), consist mostly of light to medium gray, well foliated quartz-mica-feldspar schist and quartz-mica schist. The schist has recrystallized to form alternating individual laminae, a few millimeters in thickness, that are either predominantly mica, or predominantly quartz or quartz and feldspar. Other common rocks within texture zone 3 are quartz-mica-graphite schist, phyllite, both massive and foliated greenish-gray metavolcanic rocks, amphibolite, and metachert.

Lens-like and vein-like quartz segregations are abundant throughout texture zone 3. Petrographic examination of thin sections (Manning and Ogle, 1950) and hand specimens suggest that this unit contains rocks from both the greenschist and the glaucophane schist facies of regional metamorphism (Turner and Verhoogen, 1960). The metasedimentary rocks appear to have been derived from a suite of sedimentary rocks that was predominantly finer grained than most of texture zone 1 in the Redwood Creek basin. In most localities the foliation is well developed, steeply dipping, and intricately deformed.

Rocks of texture zone 3 crop out throughout the western half of the Redwood Creek basin and in a separate north-northwest trending belt in the southeastern corner of the basin (fig. 3).

The unnamed weakly indurated Pliocene coastal plain sediments that underlie most of the Prairie Creek basin (Diller, 1902; Strand, 1962, 1963; Moore and Silver, 1968) are several hundred feet thick and in part auriferous. Diller (1902) interprets these rocks as being deposited in an ancient mouth of the Klamath River. The unit, however, has not been studied in detail and some littoral and (or) estuarine deposits crop out in the southern part of this unit. Multiple cycles of deposition may be recorded.

Where schist and sandstone crop out in close proximity to one another, as in the drainage basin of Harry Wier Creek, regolith derived from the schist is generally deeper, redder, finer grained, and more cohesive than that derived from sandstone. These differences reflect the fact that the schist usually mechanically breaks down into finer, more weatherable fragments than the sandstone. The small size of the schist fragments, in turn, results from the schist laminae being many times thinner than the sandstone beds, and from the more abundant, closely spaced joints and faults of small displacement in the schist. Clay is more abundant because the metamorphic minerals are more labile with respect to chemical weathering than the primary minerals in the sandstone and shale.

The most common soil series developed on texture zone 3 schists are, in order of increasing degree of soil profile development, Masterson, Orick and Sites (Alexander and others, 1959-62). The Masterson soil series underlies about 22 percent of the entire basin, making it the most abundant soil series in this basin (Iwatsubo and others, 1975, Tables 2 and 3). This soil series is an inceptisol with infiltration capacity, subsurface drainage, and susceptibility to surface fluvial erosion comparable to those associated with the Hugo soil series. The Orick and Sites soil series are ultisols that also have high infiltration capacities and generally good subsurface drainage. However, these soils are somewhat more clayey and cohesive than either the Masterson soils or the soils derived from sandstone and mudstone. When surface runoff does occur, the Orick and Sites soil series, therefore, are only moderately susceptible to surface fluvial erosion (Alexander and others, 1959-62). As in the case of soils derived from sandstone and mudstone, the available plant nutrients are concentrated in the surface and near surface soil horizons of the schist-derived soils. Atwell soils are mapped on pervasively sheared schist as well as sandstone; the pervasive shearing apparently determines the dominant profile characteristics despite profound differences in primary mineralogy.

The youngest stratigraphic documentation of the geologic history of the Redwood Creek basin is provided by remnants of alluvial strath terraces along the main channel. These are preserved primarily on relatively stable drainage divides of tributary basins, and even there the upper terrace surfaces are often drastically modified by erosion or burial by colluvium. These terrace remnants, except for the area between highway 299 and Lacks Creek, are for the most part less than 10 acres (4 hectares) in size. The alluvial terrace veneer consists of coarse gravelly alluvium no more than 33 feet (10 metres) thick, which is a thickness comparable to or only slightly greater than the thickness of presently active alluvium along the main channel. No evidence for thick alluvial fill caused by landslide dams, sea level oscillations, or persistent major changes in load-discharge relationships has been found. The stream terraces along Redwood Creek, therefore, most likely reflect progressive downcutting.

The alluvial terraces along Redwood Creek contain no fossils and can be dated only by comparing the degree and type of soil profile development, stone-weathering characteristics, and erosional modification that they display with that displayed by better dated, lithologically similar sediments under comparable vegetal and climatic conditions. Provisional ages have been assigned to the alluvial terrace sediments of Redwood Creek primarily on the basis of comparisons between these sediments and the glacial till and outwash in nearby areas of north-western California (Davis, 1958; Sharp, 1960), and a sequence of highly fossiliferous coastal deposits near Cape Blanco, Oregon (fig. 1) (Janda, 1970). These comparisons suggest that eroded patches of alluvium as high as 490 feet (150 metres) above the present channel of Redwood Creek are mid-Pleistocene or younger, and that terraces as high as 90 feet (27 metres) above the present stream are at least as old as the more than 20-thousand year-old Tahoe (early Wisconsin) Glacier, but no older than the prominent low coastal terraces thought to be about 120,000 years old (Birkeland and others, 1971).

FAULTING

All contacts between unmetamorphosed Franciscan sedimentary rocks and schist within the Redwood Creek basin have previously been mapped as high angle faults (Manning and Ogle, 1950; Strand, 1962, 1963). These units are separated by the north-northwest trending South Fork Mountain, Grogan and Bald Mountain Faults and numerous smaller cross faults (fig. 3). These large north-northwest trending faults, however, were mapped prior to recognition of the transitional texture zone 2 rocks. Moreover, the geometry of the proposed faults, and their sense and history of movement are accurately known at a few localities. Recent mapping in the Willow Creek Quadrangle (Young, in press) suggests that the thrust-related metamorphic gradation proposed for the South Fork Mountain Fault in the North Yola Bolly area may also apply to the South Fork Mountain and Grogan Faults in the southeastern part of the Redwood Creek basin. However, the Grogan Fault, which is closely followed by the main channel of Redwood Creek for many miles, appears to be quite complex. At some localities the metamorphic gradation appears incomplete or even nonexistent. Intensively sheared rocks and serpentine are locally associated with this proposed fault. Whatever the tectonic nature of the South Fork Mountain and Grogan Faults, many mass movement failures occur in the disrupted rocks along their traces (Colman, 1973; Young, in press). The Bald Mountain Fault in the vicinity of Lord Ellis Summit appears not to be associated with any texture zone 2 rocks (Harvey M. Kelsey, written communication, 1975).

Some areas of pervasively sheared rock occur within the belts of schist and sandstone, as well as at their margins. Some of these areas appear to line up with one another, and with alined topographic features to define north-northwest trending shear zones or faults. The two most prominent examples are lineaments defined by linear reaches of Minor Creek and Lacks Creek, and by linear reaches of Bridge Creek, Devils Creek, and tributaries to Panther Creek. Patches of the Atwell soil series (Alexander and others, 1959-62) and numerous recent landslides (Colman, 1972) are mapped along these two lineaments.

The north-northwest trending faults in the southern part of the Redwood Creek basin are apparently not active at the present time. At least two of these faults, the Grogan and Bald Mountain Faults, are offset by high angle, east-northeast trending faults which also offset the fault-bounded trough of Fallor Formation along the northeastern side of the Mad River valley (Manning and Ogle, 1950). The Fallor Formation consists of more than 2300 feet (more than 700 meters) of marine, estaurine, and fluvial sediments containing abundant late Pliocene molluscan fossils (Addicott, 1974).

In the northern part of the basin the Grogan Fault apparently has moved in post-Pliocene time as it offsets the unnamed beds of probable Pliocene age that underlie much of the Prairie Creek basin (J. C. Young, oral communication, 1972). Additionally, Franciscan sandstones appear to have been thrust over the same unnamed beds in the northern Lost Man Creek basin (J. C. Young, oral communication, 1972).

No historic earthquake epicenters have been recorded in the Redwood Creek basin. Earthquakes, however, commonly do occur along a line extending eastward from near Cape Mendocino, in the Eel River embayment, and off the present shoreline. Ground vibrations from these nearby earthquakes are felt in the Redwood Creek basin. Seismically-induced stresses, therefore, should be included in considerations of hillslope stability in this area.

REGIONAL SUBSIDENCE AND UPLIFT

A sequence of lagoons and alluviated coastal valleys between Big Lagoon and Orick attest to recent submergence. Holocene rise of sea-level probably accounts for most of this submergence, but some may reflect tectonically-induced subsidence. Sea cliff exposures at Gold Bluffs and between Patricks Point and Big Lagoon show continental sediments of Pliocene or Pleistocene age warped below sea-level (Moore and Silver, 1968). Offshore, these rocks appear to be folded into northwest-trending folds with dips of generally less than ten degrees and an average wavelength of about 3 miles (5 kilometers) (Moore and Silver, 1968).

Late Cenozoic tectonic uplift of the inland portion of the drainage basins of Redwood Creek and surrounding streams profoundly influenced topographic development and present erosional processes in these basins by causing deep incision into rocks that had been intensively fractured and sheared by earlier tectonic activity. Progressive channel incision is recorded by ridge-capping stream gravels immediately east of the Bald Hills (Strand, 1963), the "Second and Third Cycle" auriferous gravels of the Trinity River (Diller, 1910), the strath terraces along Redwood Creek, and similar terraces along the Mad and Van Duzen Rivers (Harvey Kelsey, written communication, 1975). This uplift, at least locally, extends westward to the present coast, as documented by the sequence of coastal terraces that between McKinleyville and Patricks Point extends up to an altitude of at least 1,280 feet (390 meters). These coastal terraces are probably entirely of Pleistocene age as they are cut, in part, across sediments containing mid-Pleistocene molluscs and mammals (W. O. Addicott and Charles Repenning, oral communication, 1973). Moreover, even the highest of these terraces displays a degree of soil profile development comparable to that shown by fossiliferous mid-Pleistocene surficial terrace sediments in southwestern Oregon. The occurrence of the strongly developed Sites and Josephine soil series on and near some broad, gently sloping drainage divides, in contrast to the occurrence of the less strongly developed Orick, Masterson, and Sheetiron series on adjacent lower hillslopes may provide additional evidence of recent incision in areas without geologic deposits (Zinke and Colwell, 1965).

NATURAL RATES OF EROSION

The distribution of certain Pliocene and Quaternary sediments, landforms, and soils allows limits to be placed upon natural long-term average rates of erosion in parts of northwestern California and southwestern Oregon (Wahrhaftig and Curry, 1967; Janda, 1971, 1972). The volumes of rock eroded from beneath coastal landforms that are thinly mantled with fossiliferous marine sediments and that range in age from about 80,000 to 10 million years, suggest an average long-term erosional lowering of the landscape of less than 0.5 foot (0.15 meter) per thousand years. Franciscan rocks or rocks of the lithologically and structurally similar Otter Point and Rocky Point Formations accounted for all of the eroded volume except for that associated with the surficial veneer of late Cenozoic sediments.

Four aspects of the geologically computed average rates of landscape lowering must be stressed. First, these rates are an upper limit on the long-term average in the areas for which they were computed. Whenever any uncertainty existed concerning either the age or the volume of eroded material, the assumption that maximized the erosion rate was chosen. Second, expressing erosion rates as the average lowering of an entire drainage basin is misleading because erosion is concentrated along stream channels and landslides with relatively little erosion occurring along drainage divides; nonetheless, this procedure does allow for convenient comparisons between different drainage basins. Third, these long-term rates are the average of periods of slow erosion and periods of rapid erosion. Rates may have increased through time in response to increases in local relief and surface area caused by progressive stream incision; rates may also have responded to Quaternary climatic fluctuations, eustatic changes in sea level, and tectonic events. Fourth, average rates of landscape lowering cannot be computed for areas where erosion has been so severe that reconstruction of the original landform is no longer possible. The degree to which the first and fourth items counteract one another is not known.

A geologic check on the reasonableness of the long-term erosion rates based upon volumes of eroded rock is provided by the long-term rate of sedimentation in the deep ocean and the continental margin. Recent geophysical work summarized by Silver (1969), indicates that rivers and seacliff erosion provided the ocean off northern California and southern Oregon with not more than 81.4 x 10^{13} cubic feet (69 x 10^{12} cubic meters) of sediment during the last 5 million years. This would require erosion of about 61.4 x 10^{13} cubic feet (52 x 10^{12} cubic meters) of rock and suggests a long-term average rate of erosion of 0.9 foot (0.26 meter) per thousand years. Silver (oral commun., July, 1972) stresses that the sediment volume presented in his thesis is an upper limit on the actual volume; the actual volume may be only 60 percent of this limiting value. Silver also indicates that some of the sediment included in computing that volume may have been derived from the Columbia River rather than from drainage areas immediately onshore. Obviously, then, the rates of erosion derived from the estimated volume of sediment deposited during the last 5 million years should be considered an upper limit on the actual rate. The second and third items of concern in the preceding paragraph also apply to this rate.

Reconstruction of an old landscape that can serve as a satisfactory reference in computing long-term rates of landscape lowering in the Redwood Creek basin is not possible because the preserved patches of terrace gravels and old soils are too small and widely scattered. Moreover, lithologic diversity of the bedrock probably always resulted in a complicated landscape of moderate relief.

An upper limit on the long-term average rate of erosional lowering of the Redwood Creek basin can be calculated, based on the assumption that during late Pleistocene and Holocene time the main channel of Redwood Creek was lowered more rapidly than the drainage basin as a whole. This assumption seems justified in light of available physiographic and pedologic evidence. As discussed in the physiography section of this report, cross-valley profiles of the Redwood Creek basin show irregularly, convex-upward hillslopes with the steepest slopes being adjacent to Redwood Creek and its more deeply-incised tributaries. Hillslopes adjacent to these channels show thinner, less strongly developed soil profiles and more active mass movement than hillslopes farther away from the channels. Bedrock outcrops are common in and adjacent to the creek, whereas they are uncommon elsewhere. The overall impression is that hillslopes adjacent to the creek have been oversteepened by active channel incision. The extensive mid-slope and upper slope areas of strongly developed Sites, Orick, Josephine, and Melbourne soil series, on the other hand, attest to much slower rates of erosion. Well-drained ultisols with strong brown or reddish-brown colors, and well-developed textural B-horizons are found only on sediments and landforms that are at least several tens of thousands of years old and that are usually more than 100 thousand years old (Birkeland and others, 1971). Fully developed ultisols with brownish-red and red colors and extremely argillic B-horizons, such as the Sites and Josephone soil series, are found only on early and middle Pleistocene landforms that are at least several hundred thousand years old (Trimble, 1963; Crandell and others, 1965; Balster and Parsons, 1968; Janda, 1971). These soils could not persist if erosion was vigorous as the sites where they are preserved.

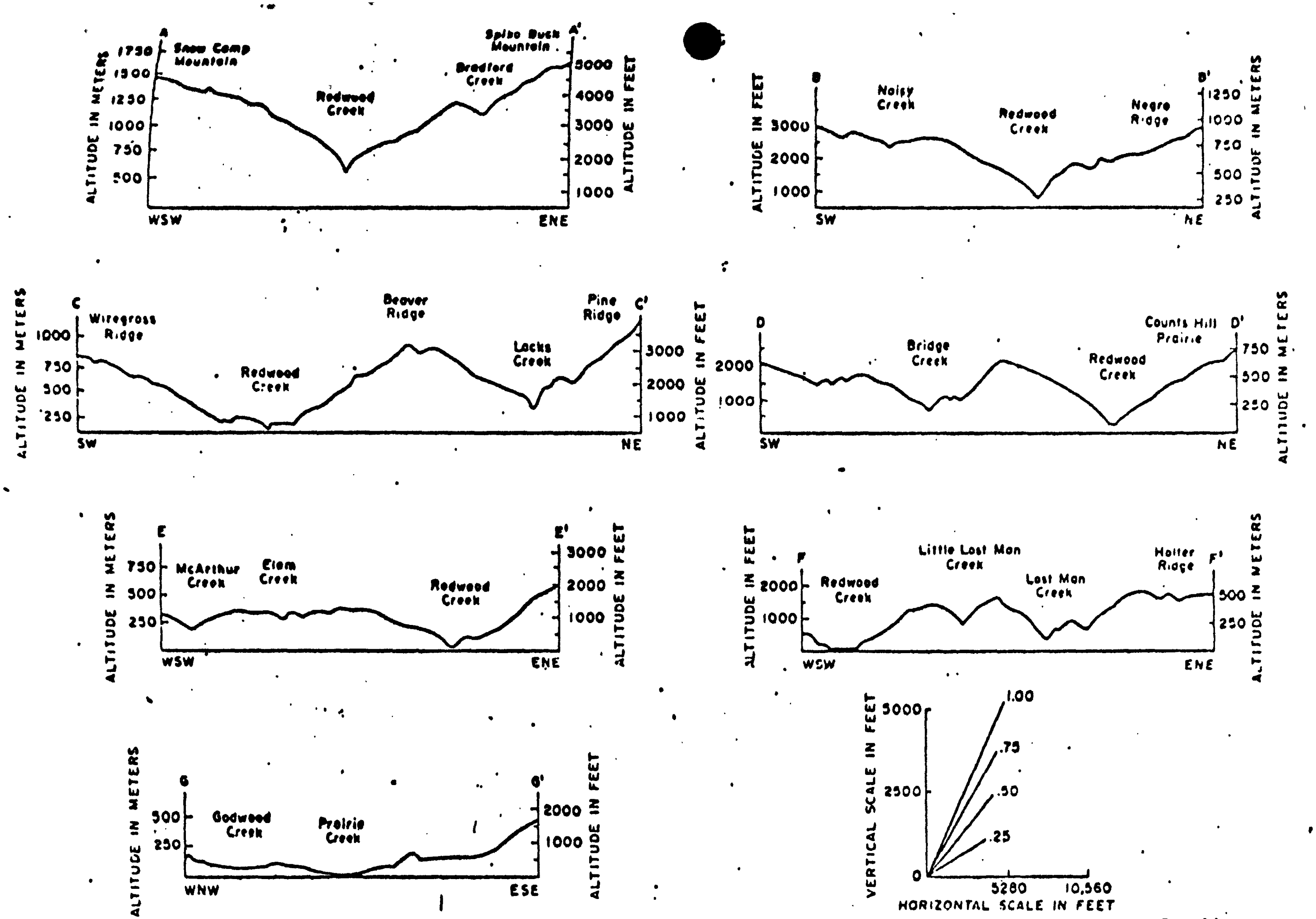
Soil stratigraphic correlations discussed earlier indicate that river terraces up to 90 feet (27 metres) above Redwood Creek appear to be less than 120,000 years old but more than 20,000 years old. However, the highest of these terraces is probably at least 60,000 years old. The maximum possible average rate of incision is, thus, about 4.5 feet per thousand years. Because the 90 feet (27 metres) terrace is probably more than 60,000 years old, a more realistic upper limit on the rate of incision is about 1.5 feet per thousand years. Therefore, during late Pleistocene and Holocene time, the average rate of erosional lowering of the Redwood Creek basin could not have been more than 1.5 feet per thousand years, and was probably much less.

PHYSIOGRAPHY

GENERAL

The drainage basin of Redwood Creek (fig. 1) is composed of about 280 square miles (725 square kilometres) of rugged terrane within the North Coast Ranges of California. The creek flows into the Pacific Ocean about 17.5 miles (28 kilometres) south of the mouth of the Klamath River and 37.5 miles (60 kilometres) north of the mouth of Humboldt Bay. The midpoint in the basin is about 24 miles (39 kilometres) northeast of Eureka. The basin is strongly elongated in a north-northwesterly direction and is about 56 miles (90 kilometres) long, and 4.5 to 6.9 miles (7.2 to 11.1 kilometres) wide throughout most of the basin. The elongation ratio for the basin is 0.34.

The intricately dissected drainage basin is characterized by high relief, moderately steep to steep unstable hillslopes, and narrow valley bottoms. Hillslope steepness and instability, however, are not particularly excessive in the Redwood Creek basin relative to most other drainage basins in north coastal California. The drainage density for streams indicated by blue lines or inflections of contour lines on 1:62,500 topographic maps is about 7.7 miles per square mile (4.8 kilometres per square kilometre) for the basin as a whole with the headwaters showing a slightly greater density than downstream areas (Iwatsubo, and others, 1975). The total basin relief is about 5300 feet (1615 metres). Cross-sectional relief normal to the basin axis ranges from about 200 feet (610 metres) in the north, and more than 3000 feet (914 metres) near the head of the basin



Reference Hillslope Gradients

Figure 4. Exaggerated cross-basin topographic profiles for the Redwood Creek basin.

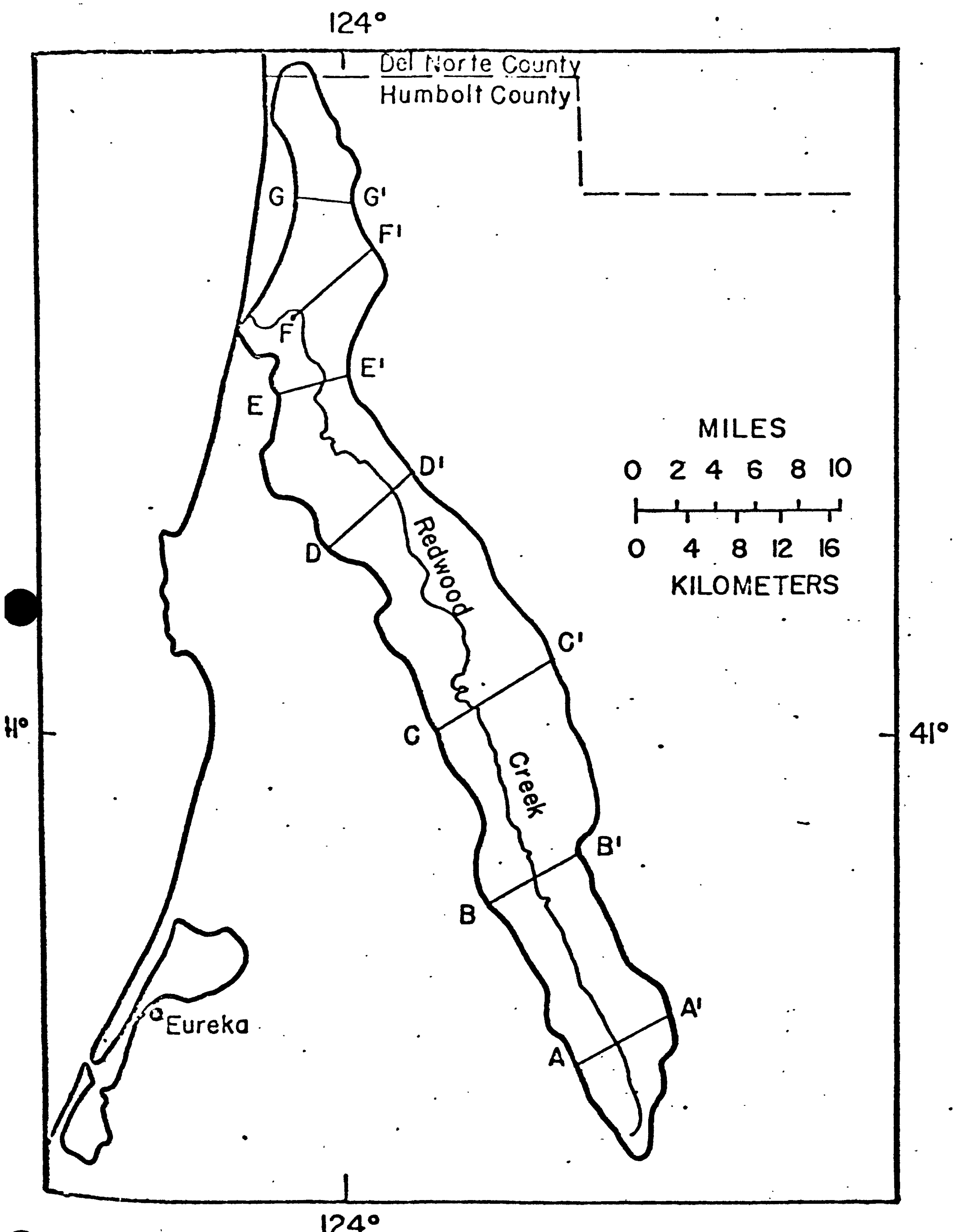


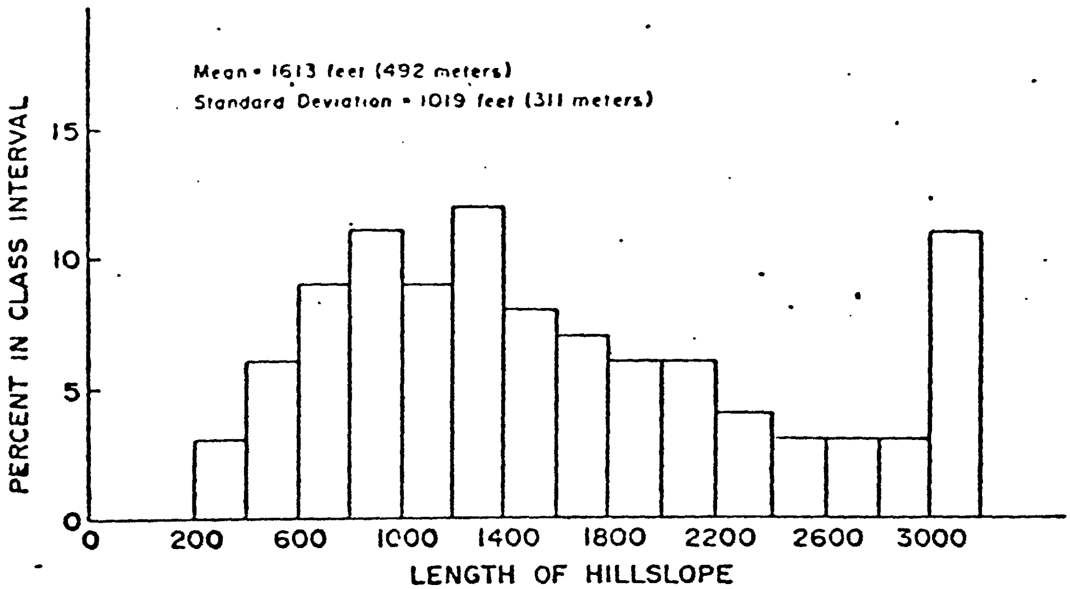
Figure 5. Map showing locations of the cross-basin topographic profiles shown in Figure 4.

(fig. 4). Throughout the entire basin the eastern drainage divide stands higher than the western divide (fig. 4). The relief within individual tributary basins ranges from 1320 feet (402 meters) to 3880 feet (1183 meters) with all values less than 2000 feet (610 meters) being restricted to small northern tributary basins. The highest peaks and greatest local topographic relief occur in the southeastern part of the basin near Spike Buck Mountain. The average hillslope gradient for the entire basin, as determined by the Wentworth (1930) technique, is about 0.26 (14.4 degrees). More than half of the individual hillslopes steeper than 0.05, however, display average gradients in excess of 0.35 (19.3 degrees) (fig. 6). The eastern sides of Minor and Lacks Creek display the steepest hillslopes in the entire basin. Flood plains are discontinuous and narrow with widths in excess of 200 feet (61 meters) being uncommon except for areas between Minor Creek and Mill Creek, near the mouth of Lacks Creek, and near Orick. The paucity of flood plains means the active stream channels often abut directly against the hillslopes. From several vantage points within the basin, an inner valley appears to be incised into an older landscape with considerably less relief than the present landscape (Diller, 1902).

HILLSLOPES

Geometric Properties

Hillslope length, steepness, and shape provide important indications of the relative susceptibility of hillslopes to various erosional processes (Carson and Kirby, 1972). These properties were determined at 473 points on a rectangular grid superimposed on a 1:62,500 topographic map of that portion of the basin that lies upstream from the mouth of



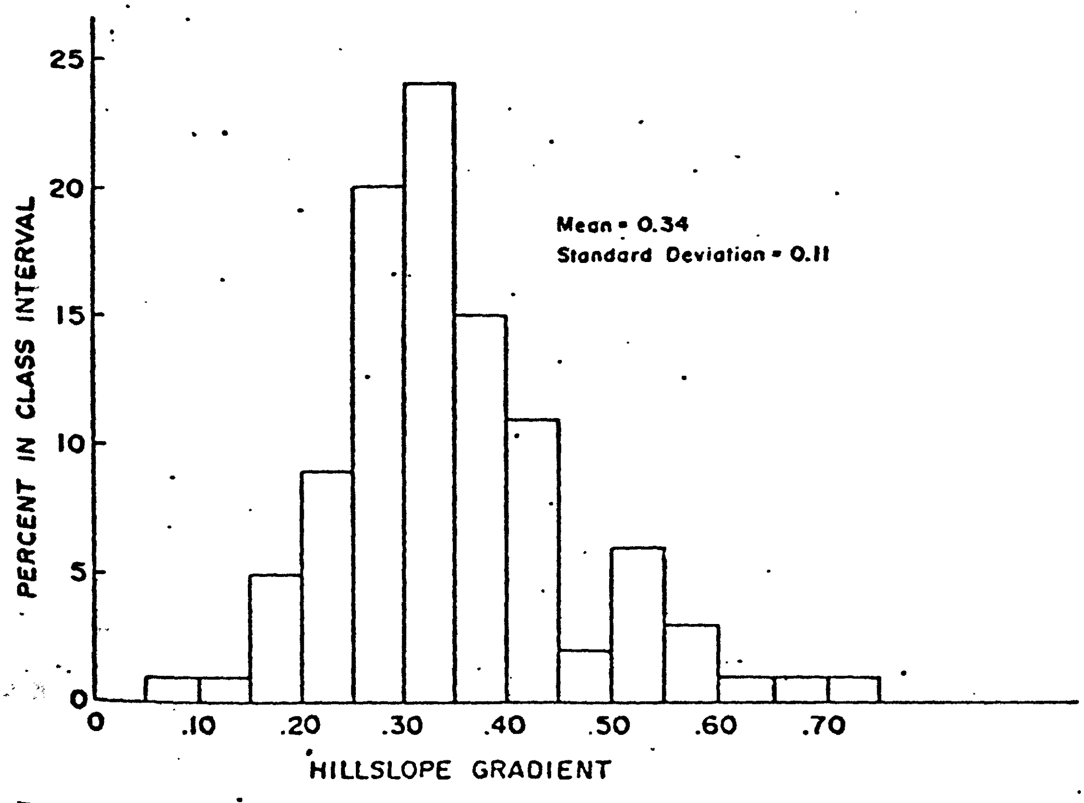


Figure 6. Histograms showing the distribution of length and steepness (i.e., gradient) of 398 randomly selected, individual hillsides that display gradients steeper than 0.05 and that are located within the Redwood Creek basin upstream from the mouth of Prairie Creek.

Prairie Creek. The drainage basin of Prairie Creek was excluded because of gross differences between the erosional resistance of the bedrock there and in the upstream portion of the basin. Measurements were made at each grid point along a line drawn normal to the contour lines and extended from the nearest divide to the nearest valley. Many of these divides and valleys were defined by rather subtle contour inflections.

Seventy-five of these points on the sampling grid were located on flat drainage divides, alluvial terraces, or flood plains with gradients of less than 0.05. Most of these points are located on or near the western drainage divide. Because hillslope characteristics could not be adequately determined for these sites with existing topographic maps, these points were excluded from the analysis. The topographic map measurements at the points with gradients in excess of 0.05 are summarized in figure 6.

Hillslopes steeper than 0.05 are highly variable in length. The mean length is about 1600 feet (488 meters) but the standard deviation is about 63 percent of the mean. More than 36 percent of the measured slopes are longer than 2000 feet (610 meters). Although hillslope gradients also show a wide range of values, they are much less variable than lengths. The mean gradient of hillslopes steeper than 0.05 is 0.34 (18.8 degrees), and the standard deviation is about 32 percent of the mean. Twenty-five percent of the measured hillslopes have gradients steeper than 0.40 (21.8 degrees). The angle of internal friction for most colluvium in the Redwood Creek basin appears to be at least 0.50 (26.6 degrees) as debris slides and avalanches are restricted to hillslopes steeper than this; twelve percent of the measured hillslope gradients are steeper than 0.50.

The steeper hillslopes are most abundant along the more deeply incised streams. Moreover, the streamside segments of the individual hillslopes throughout the basin are generally steeper than segments near the drainage divide. Fully 75 percent of the sampled hillslopes steeper than 0.05 have lower ends that are as steep as, or steeper than, their upper ends. For example, 284 Abney level determinations of hillslope gradients immediately adjacent to Redwood Creek between Rodiscroft Road (about two miles above Snow Camp Creek) and the mouth of Hayes Creek (Colman, 1973) have a mean of 0.60 (31 degrees) (Standard deviation, 0.08) which is nearly twice as steep as the mean of the hillslope gradients determined from topographic maps.

Mass Movement-Related Landforms

Many hillslopes in the Redwood Creek basin are unstable and highly susceptible to mass movement failure because of the steepness of the terrane and the low shear strength of many of the underlying rocks and soils. At least 36.4 percent of the basin upstream from Prairie Creek shows landforms suggestive of former mass movement failures (Colman, 1973). Several other areas in addition to those shown on Colman's (1973) maps appear to have been eroded by mass movement. Steep, straight, colluvium-veneered hillslopes, such as those in the drainage basin of Lacks Creek and Lost Man Creek, are sculptured by infrequent large shallow debris slides and avalanches. The smooth convex-upward hillslopes, such as the northeast - and east-northeast - facing slope immediately upstream from the mouth of Bridge Creek appear to result primarily from creep (Gilbert, 1909). The steep lower segments of the creep-sculptured hillslopes show numerous small scale descrete failures involving both rotational and translational movement. The deeply incised amphitheater-shaped drainage basins of Colman (1973) and perhaps some of the large scale hillslope irregularities and drainage anomalies upstream from highway 299 result partly from old, stream-modified, deep seated mass movement. Evidence of old deep-seated mass movement in the Redwood Creek basin, however, is not as prominent as in many nearby drainage basins.

Complex associations of slumping[1/] and flowing movement classified as earthflows are the most visually obvious forms of mass movement in the Redwood Creek basin because the earthflows usually bear grass, grass-bracken fern, or grass-oak vegetation that stands in marked contrast to the mature coniferous forest or cutover land adjacent to more stable slopes. These are large-scale landforms with dimensions measured in terms of hundreds and thousands of feet. These features underlie about 13 percent of the drainage basin upstream from the mouth of Prairie Creek (Colman, 1973). Earthflows all show prominant scarps, flats, and hummocky and lobate microtopography. Some have clearly defined margins but others gradually merge with areas of

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1/ Slumps are intact blocks of soil and rock that have moved with a backward rotation, primarily along concave-upward failure surfaces or zones. Pure slumps are uncommon in the Redwood Creek basin.

active soil creep. Earthflows commonly become increasingly active downslope. The more active portions of these features show unvegetated or partly vegetated scarps, open lateral and transverse cracks, closed depressions, areas of bare mineral soil and discontinuous gullies. Depths of movement probably range from a few feet to several tens of feet. Field examination of surficial morphology and comparison of sequential aerial photography suggest that most of the ground disruption is caused by differential movement and that rates of surficial movement on most flows within the Redwood Creek basin are usually less than a few feet per year. Several of the more active flows may move a few tens of feet per year. These earthflows are, thus, much less active than similar features in the nearby Eel (Dwyer and others, 1971) and Van Duzen (Harvey Kelsey, written communication, 1975) drainage basins. Although they presently appear to be eroding more rapidly than the adjacent hillslopes, the earthflows in the Redwood Creek basin are for the most part not deeply incised into the slopes.

Figure 7 shows Counts Hill Prairie, a typical large compound earthflow on the eastern border of Redwood National Park. Detailed views of various parts of this earthflow are contained in photo essay prepared by Earth Satellite Corporation (1972, figs. 50, 52, 53, 54, and 71). Other earthflows are shown in figure 13 and 15 in this report and in figure 61 of the Earth Satellite Corporation (1972) report.

The colluvium in earthflows within the Redwood Creek basin is mostly stony sandy loam; large blocks of bedrock are not common. Some

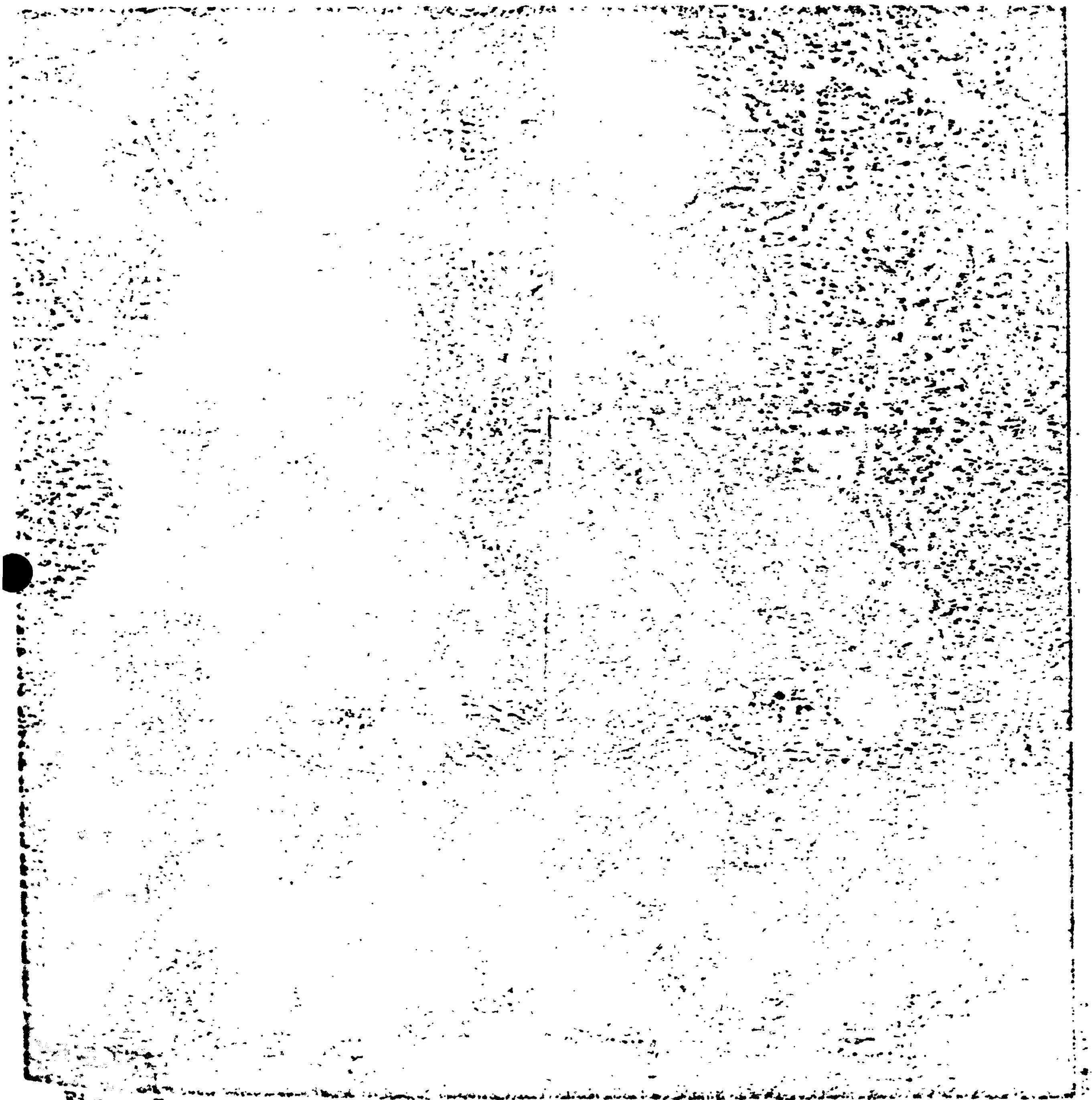


Figure 7.-
Stereogram of Counts Hill Prairie, a large compound earthflow adjacent to Redwood National Park.

earthflows merely move colluvium into temporary storage farther downslope, but others deliver significant quantities of sediment to Redwood Creek and its major tributaries. Sediment delivery is effected by sloughing directly into major stream channels or into well developed shallow gullies within the earthflows. Thus, much of the earthflow-derived sediment in the main channels is delivered by small scale fluvial processes rather than directly by mass movement. Most of the material delivered to the streams is sand-sized or finer and capable of being transported in suspension; probably less than 30 percent of the earthflow-derived sediment is transported principally as bed load.

Rock and debris slides are another visually obvious form of mass movement within the drainage basin of Redwood Creek. These features underlie only slightly more than one percent of the total area but they are concentrated along the channels of Redwood Creek and its major tributaries where they locally are a dominant landscape feature. Slides are generally smaller than earthflows with their surficial dimensions measured in hundreds of feet. Lengths rarely exceed 1000 feet (305 metres) and are usually two to five times larger than the width. Depths again range from a few feet to a few tens of feet.

Slides are characterized by dominantly translational movement of varying amounts of rock and regolith along a reasonably planar failure surface or zone that is essentially parallel to the hillslope. The material in the slide block is usually completely removed from its original location leaving behind an unvegetated scar with sharply defined margins. Although the initial movement involves little internal disruption, most of these blocks have little cohesion and commonly become intensely disrupted as movement progresses. Typical streamside slids are shown in figures 11, 15, and 18 in this report and in figures 57, 59, 60, and 64 in the Earth Satellite Corporation report (1972).

Most slides within the Redwood Creek basin have moved repeatedly. Many recently active slides occur within larger areas with morphologic and (or) vegetal evidence suggesting former failures. Individual episodes of movement that produce large unvegetated scars take place in a relatively short time (seconds to minutes). Beyond the margins of the raw slide scar, however, tilted trees and open tension cracks frequently attest to prolonged slow movement that both preceded and continued after the principal failure. Slides commonly grow upslope because of the removal of lateral support. Some mid-slope slides also enlarge downslope by overloading the lower hillslope with slide debris. Some midslope failures involve minor rotational slumping as well as translational sliding.

The lower segments of hillslopes within the Redwood Creek basin have thicker regolith, steeper gradients, wetter soil moisture regimes, and greater susceptibility to sliding than upslope segments. The susceptibility to sliding is enhanced at streamside sites by lateral channel erosion removing lateral support from the bases of these slopes. However, not all the streamside slides in the Redwood Creek basin result from undercutting. Many slides have failed, particularly those with toes buffered by rock outcrops or areas of overbank deposition, because of excessively high-pore pressures and seepage forces generated during major rain storms or because of changes in slope configuration and moisture regime brought about by road construction and timber harvest.

The sediment transported by slides in the Redwood Creek basin show very poorly sorted grain-size distributions. Cobble-size and larger sediment is generally more abundant in slides than in earthflows. Slides are major sources of actively transported stream bedload and large bedrock blocks that accumulate as lag concentrates along some channels. Most slide-related sediment is delivered to streams by large-scale failures triggered during major storms; minor sloughing and gullying after the principal failure contributes lesser amount of sediment.

Debris avalanches, flows and torrents, a transitional series involving successively greater water content and lower viscosity, are also much in evidence in the Redwood Creek basin. These phenomena all involve chaotic rapid downslope movement of soil, colluvium and associated organic debris along relatively narrow, well-defined tracks. The tracks often follow natural drainage ways or man-induced gullies. Avalanche deposits tend to be completely chaotic in grain-size distribution, surface morphology, and internal structure. Debris flows, in contrast, show surficial concentrations of coarse material, levees, and lobate surface form. Debris torrents are indicated by scoured gully walls and floors, and often lead into severely agraded stream channels. Although numerous debris avalanches, flows, and torrents occur in the Redwood Creek basin, they underlie less than one percent of the total area upstream from Prairie Creek (Colman, 1973). Nonetheless, these phenomena do move sediment directly into stream channels and are a major source of both bedload and suspended sediment.

Debris avalanches, flows and torrents are more prevalent along roads and in recent timber harvest units than in undisturbed forests. These shallow-seated failures, however, are apparently more common in some other logging-impact-study areas than in Redwood Creek (Swanston, 1971; Swanson and Dyrness, 1975). The lower incidence in Redwood Creek probably reflects lower hillslope gradients, different timber types, and different forms of ground disturbance here.

Small-Scale Fluvial Landforms

Despite the presence of dense vegetation and highly permeable regolith, actively eroding rills and shallow gullies are surprisingly common in even the virgin forests of the Redwood Creek basin. These features are generally more abundant on the lower hillslope segments than near major drainage divides. Some rills are initiated by springs that emerge from shallow pits formed by wind-toppled trees. Others appear merely to reflect local irregularities in the depth and permeability of the regolith. The geometry and direction of flow of these rills and shallow gullies are controlled closely by roots, standing trees, and fallen limbs and trunks, as well as by hillslope gradients and colluvium. The width and depth of these features are extremely variable, but they are usually less than two feet (0.6 meters) wide and six inches (15 centimeters) deep. Some of the smaller features are only several-hundred feet long and end in small alluvial cones. Others flow through to higher order channels.

Trunks and large limbs of wind- and slide-toppled trees often divert water from established shallow drainage ways. The diverted water results in locally accelerated erosion by causing other established drainages to enlarge their cross-sectional area or by eroding entirely new drainages.

In many recent logging units within the Redwood Creek basin, particularly in large tractor-yarded clearcuts[1/] of old growth redwood, roads, skid trails, layouts, and concentrations of slash have obliterated the natural, small-scale hillslope drainage characteristics. Mid-slope roads often have been constructed with a smaller number of culverts than there are streams so that the natural drainage is intercepted and concentrated. This concentrated runoff then erodes roadside ditches, culvert outlets, and discharge channels. The erosional impact of concentrated and redistributed runoff may be augmented by increases in the total amount of runoff. Evidence concerning such increases, however, is presently not conclusive. (Available evidence is discussed later in this report.) The net effect of this man-caused baring of mineral soil and modification of natural surface runoff has been to produce visually apparent increases in the size and abundance of erosional landforms produced by fluvial processes in recently cutover land relative to comparable virgin terrain. In general, recent logging in most parts of the Redwood Creek basin has accelerated fluvial erosion far more than mass movement.

1/ Various silvicultural and yarding systems employed in the Redwood Creek basin are described later in this report.

Lithologic and Aspect Control of Hillslope Characteristics

The paucity of detailed geologic maps of the Redwood Creek basin makes the correlation of hillslope characteristics with lithology tenuous. Nonetheless, the heterogeneous group of rocks within textural zones 1 and 2 do appear as a group to show slightly steeper average hillslope gradients than those of textural zone 3. The difference between an average gradient of 0.37 on textural zone 1 and zone 2 rocks versus 0.32 on textural zone 3 rocks is statistically significant at the 99.5 percent level. The lithologic control of hillslope gradients, although obvious throughout the basin, is more pronounced in the southern half of the basin than in the north. Reconnaissance observations suggest that those parts of textural zones 1 and 2, with abundant mudstone or tectonic shearing, show gentler hillslope gradients and more abundant earthflows and slides than the unit as a whole.

At least forty-five cross-sections of tributary valleys display opposing valley sides with markedly different hillslope gradients. Asymmetry is shown by tributaries draining all the prominent lithologic types in the basin. The northerly-facing hillslopes in all but eight of the 45 most priminent examples of valley asymmetry have steeper gradients than the southerly-facing hillslope. This asymmetry cannot be satisfactorily explained by Coriolis force or bedrock lithology and structure because the asymmetry occurs on both easterly and westerly flowing streams and is at a high angle to the general trend of geologic structure. Hillslope aspect (orientation) control of microclimate and vegetation does appear partly responsible for the asymmetry in gradient. North- and east-facing hillslopes throughout the basin tend to show more arboreal vegetation and(or) a greater overall vegetation density than their south- and west-facing counterparts. These vegetation differences probably reflect the fact that the north- and east-facing hillslopes receive less insolation during the heat of the day and are, therefore, cooler and moister than opposing south- and west-facing hillslopes. The extreme lateral variability in lithology and structure apparently obscures any systematic basin-wide slope aspect control of gradients of isolated hillslopes because no statistically significant correlation between hillslope orientation and gradient or length could be detected even when the data were classified into broad lithologic units. Nonetheless, the basin-wide distribution of types of hillslope erosion processes does appear to relate to hillslope aspect. For example, on south- and west-facing hillslopes, earthflows are more prevalent and small scale fluvial landforms less prevalent than on north- and east-facing hill-slopes. An important corollary of these observations is that if reasonably subtle hillslope aspect controlled differences in vegetation and microclimate have influenced hillslope form and process, man-induced modification of the natural vegetation may well alter rates and processes of hillslope erosion.

STREAM CHANNELS

Redwood Creek

Redwood Creek during low and moderate discharges flows within an unvegetated, gravelly "inner flood plain" (fig. 8) that is typically two and a half to seven times as wide as the low water channel. The channel within this gravel plain displays alternating meandering and braided channel patterns with braided patterns being somewhat more prevalent. The width of the unvegetated inner flood plain allows considerable insolation to reach the surface of the low water channel, except where the inner canyon is particularly narrow or the riparian vegetation is particularly tall. High insolation results in generally warm ($20^{\circ}C \pm 5^{\circ}C$) average summer water temperatures along Redwood Creek.

In most reaches, as discussed previously, rock and hillslope colluvium abut directly against the active inner flood plain, but elsewhere a narrow, densely forested "upper flood plain" (fig. 8) underlain by 5 to 15 feet (2 meters to 5 meters) of unweathered fine sandy loam and silt loam is present. More than one unweathered upper flood plain is present at many cross-sections. Some of the most magnificent redwood groves within Redwood National Park are on these upper flood plains.

The lower flood plain of Redwood Creek is completely inundated several times during the course of a normal winter storm season. The upper flood plain, in contrast, is apparently completely inundated only by major floods that usually occur not more than once or twice in any given decade. At sections with more than one upper flood plain surface,

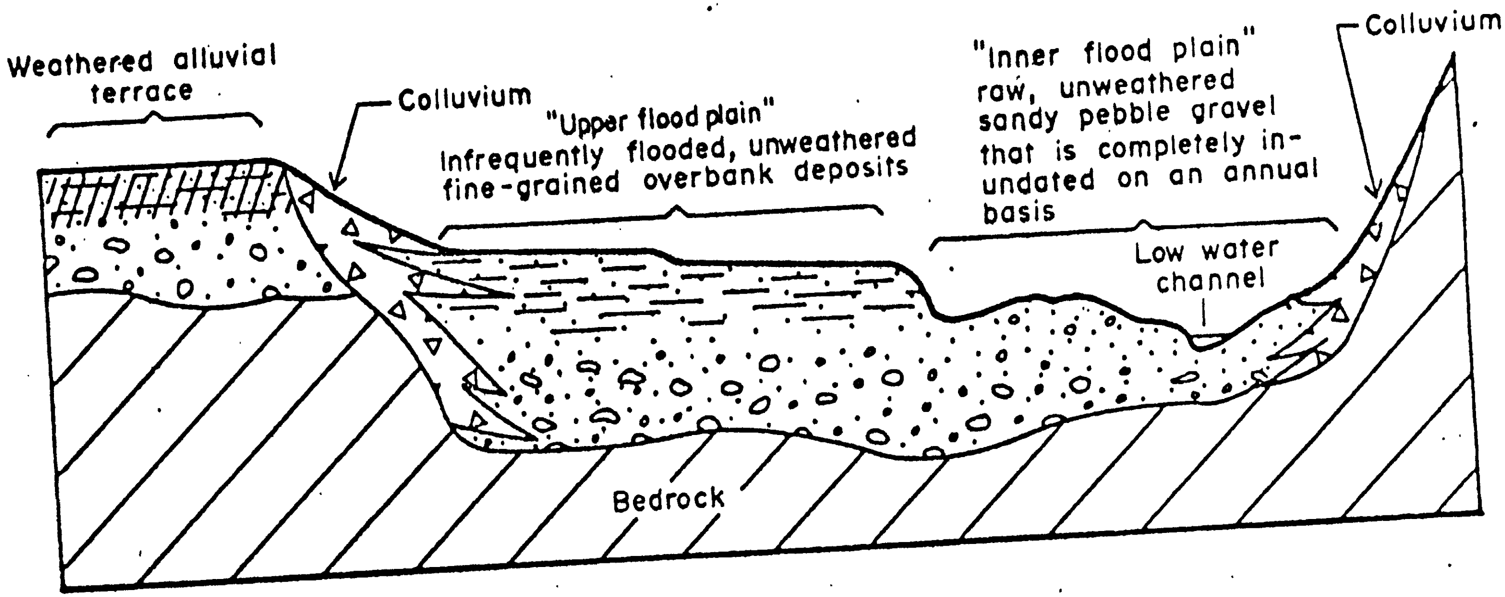


Figure 8. Schematic representation of a typical cross-section of the flood plain, of Redwood Creek.

the floods of January and March 1972 inundated only the lowest one or two surfaces. Furthermore, not all sections showing only one upper flood plain were subjected to overbank flooding in 1972. While this report was in preparation, a similar pattern of inundation was associated with the major flood of March 18, 1975. The frequency of overbank flooding, therefore, varies from section to section and definition of a geomorphically significant "bankfull discharge" (Leopold and others, 1964, pp. 319-322) is difficult.

The origin of the multiple upper flood plain surfaces is poorly understood, but at least three, not mutually exclusive, processes may account for them. First, multiple surfaces could result from channel incision caused by geologically recent uplift; this suggestion is compatible with the sequences of alluvial strath terraces found throughout the basin that suggest that such processes were operating during at least late Pleistocene and early Holocene time. Secondly, the multiple surfaces may record rapid deposition associated with major floods of different magnitudes (Helley and LaMarche, 1973); apparently even-aged stands of trees on some upper flood plain surfaces suggest that this is true at least locally. Thirdly, historical observations and depositional sequences exposed in cut-banks suggest that the principal areas of overbank deposition along Redwood Creek, unlike "normal" flood plains described by Wolman and Leopold (1957), commonly receive depositional increments about 1.0 ± 0.5 feet (0.3 ± 0.15 meter) thick during a single flood event. Such rapid overbank deposition may allow the upper flood plain surface to build up to the point that the frequency of overbank flooding is drastically reduced.

During high discharge periods when the creek occupies the entire area between its banks, only a few large mid-channel bars are emergent and the creek displays a single sinuous channel. During these high flows the thalweg wanders back and forth over the entire inner flood plain causing considerable cut and fill (for example, see cross-section 17 on figure 17). The inherent instability of the streambed material and the paucity of pools suitable for low-water rearing of fish appear to drastically limit aquatic ~~aquatic~~ productivity.

For the purpose of discussing present channel characteristics and processes, Redwood Creek can be conveniently divided into seven distinctive reaches on the basis of field and aerial photograph observations of stream-bank stability, bed material, channel obstructions, and fluvial erosion and deposition.

Reach 7

The 4½ miles (7 kilometers) of Redwood Creek upstream from Snow Camp Creek (reach 7, fig. 9) is characterized by steep gradients, alluvial deposits of large grain sizes, abundant log and debris jams, and extensive streamside sliding (Colman, 1973). Channel gradients range from 125 to 1000 feet per mile (20 to 190 meters per kilometer) with an average slope of 550 feet per mile (110 meters per kilometer). During late summer and early autumn much of this reach is dry and intermittent.

Throughout most of this reach no upper flood plain is present and the active lower flood plain abuts directly against colluvial hillslopes. Stream banks and adjacent hillslopes are extremely unstable and abundant

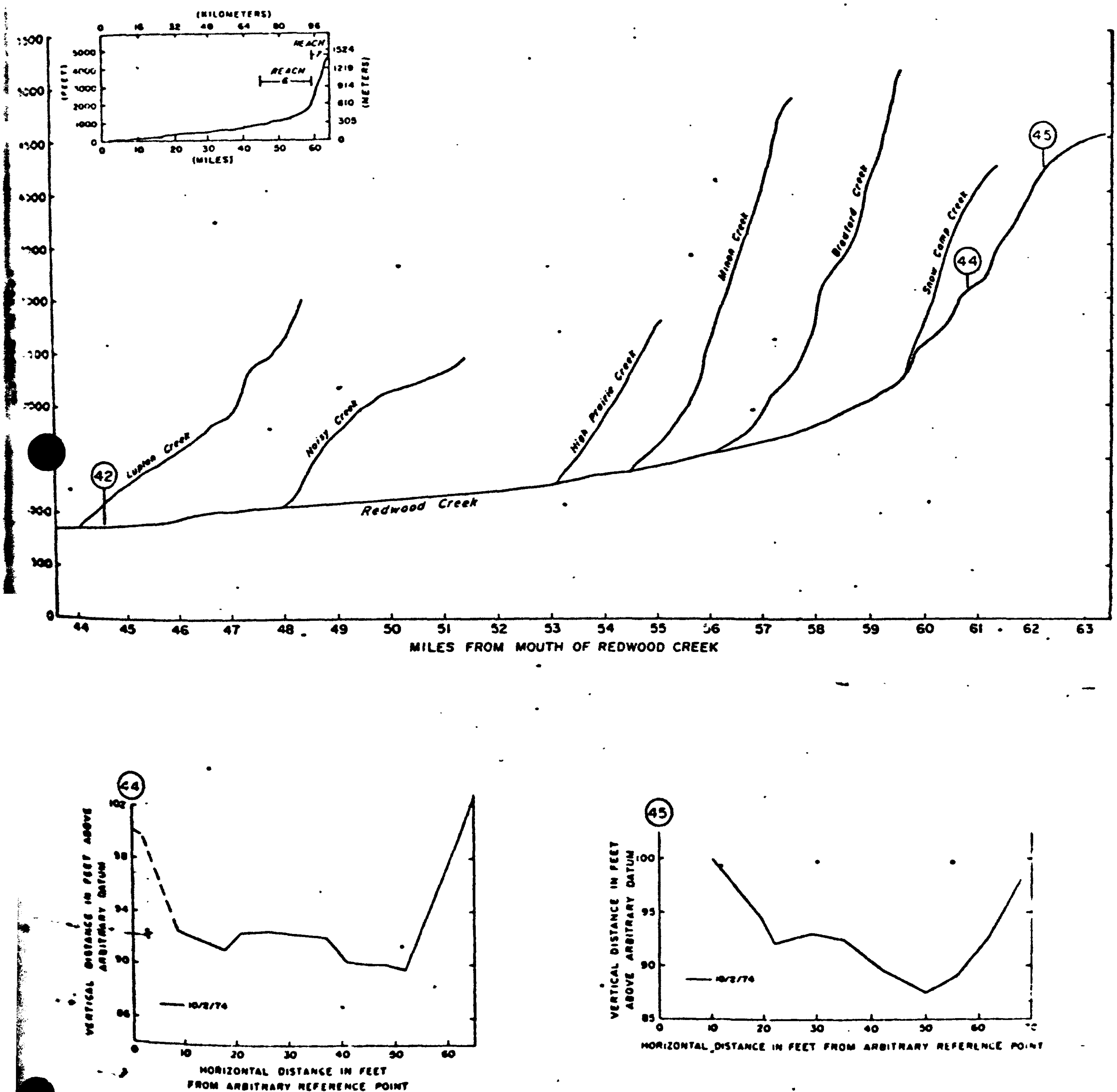


Figure 9. Vertically exaggerated stream profiles and channel cross-sections for reaches 6 and 7 of Redwood Creek.

colluvium is found in the channel bottom during low-flow periods. Approximately 64 percent of the stream banks in this reach display signs of active erosion. Tractor logging of old growth Douglas-fir forests during the late 1950's and early 1960's has clearly accelerated hillslope and stream-bank erosion. Despite the introduction of prodigious quantities of coarse sediment from streamside slides and old cutover land, the stream typically shows a single meandering channel, indicating that velocities are sufficient to transport most of the sediment presently supplied to the channel.

About 30 log and debris jams have obstructed stream flow in the upper reach and have acted as bed-load sediment traps. The storage capacity of these traps has now been completely consumed. Streambed elevations commonly fall 50 to 100 feet (15 to 30 meters) on the downstream ends of the jams, probably indicating the amount of upstream aggradation. This trapped sediment forms the only alluviated sections in this reach.

Streambed material consists predominantly of subangular to subrounded cobbles and boulders; angular bedrock blocks several tens of feet in diameter are abundant in non-alluviated sections. Bed material in this upper reach shows the largest average grain size of Redwood Creek. Some culverts and logging cables have been incorporated into the alluvium.

Near the downstream end of this reach a steep cascade underlain by an accumulation of angular blocks of sandstone several tens of feet in diameter forms a natural barrier to upstream migration of anadromous fish. Figure 9 shows two monumented stream channel cross sections in this reach.

Reach 6

The most dramatic examples of large-scale streamside instability in the entire Redwood Creek basin occur along the fourteen-and-a-half-mile (23 kilometer) reach between Snow Camp Creek and highway 299 (Colman, 1973) (reach 6, fig. 9). Flow is perennial throughout this and all downstream reaches. Channel gradients range from 34 to 500 feet per mile, averaging 83 feet per mile. Wide alluvial reaches are more prevalent than in reach ~~seven~~ 7. Culverts, logging cables, and truck tires are occasionally found in the alluvium. Approximately 18 large accumulations of logs and wooden debris occur in this reach but only one is sufficiently voluminous to act as an efficient sediment trap. Other debris accumulations, however, are large enough to deflect the current against streamside accumulations of colluvium. Approximately 62 percent of the stream banks on this reach are actively eroding. Streamside slides occur on the outside of nearly all of the channel bends and are generally larger than the slides in the headwaters. As in reach 7, erosion and stability of stream banks and streamside hillslopes has been adversely impacted ~~upon~~ by logging carried out well before the creation of Redwood National Park.

Extensive flat-topped gravel berms have been deposited in this reach on the insides of channel bends and in areas of abruptly increased width or decreased gradient. Two distinct levels of berms are present.

top of the upper berms is approximately 15 to 20 feet (5 to 6 meters) above the present thalweg, and a lower, less prominent, berm occurs 6 to 8 feet (2 to 2.5meters) above the thelweg. The upper berms bear young alders, madrone, cedar, and Douglas fir seedlings that during the summer of 1974 were no more than 10 years old; thus, the upper berm may have been deposited by the 1964 flood. The lower berm bears only a sparse cover of young alders and herbaceous plants and probably reflects the 1972 flood. Many large upright conifers showing more than 200 annual rings have been buried and killed by the upper berm deposits.

Despite large amounts of post-1964 alluviation, Redwood Creek maintains a single predominantly meandering low-flow channel pattern throughout this reach. Grain size of bed material is substantially smaller than in reach 7, with cobble gravel composing most of the bed material and colluvium being less abundant. Pools suitable for rearing young fish are few; those that are present are associated with turbulent eddies caused by large blocks of rock or accumulations of organic debris.

Figure 10 shows a mommented cross section near the downstream end of this reach; figure 11 provides photographic documentation of geomorphic conditions along this reach.

Reach 5

In the 16-mile-long (26 kilometers) reach between highway 299 and the mouth of Lacks Creek (reach 5, fig. 10), the channel of Redwood Creek is quite variable in character but in general it becomes wider and less

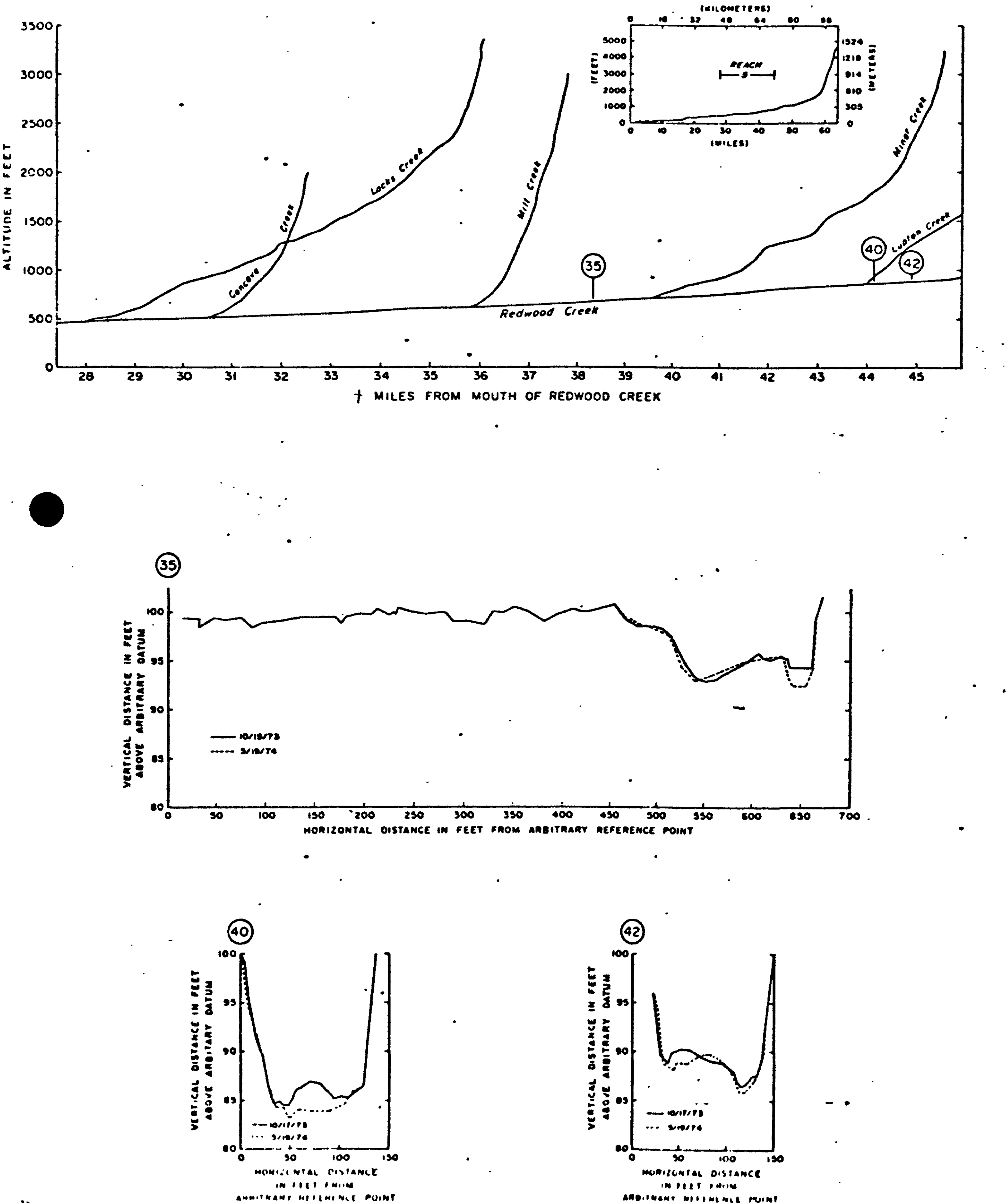


Figure 10. Vertically exaggerated stream profiles and channel cross-sections for reach 5 of Redwood Creek.

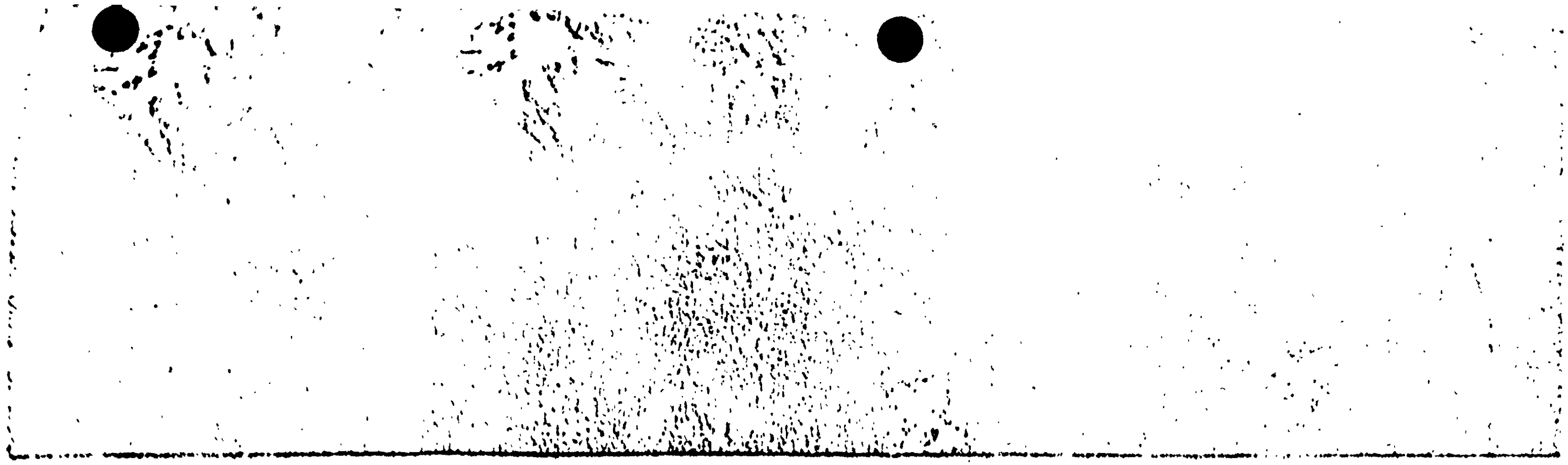
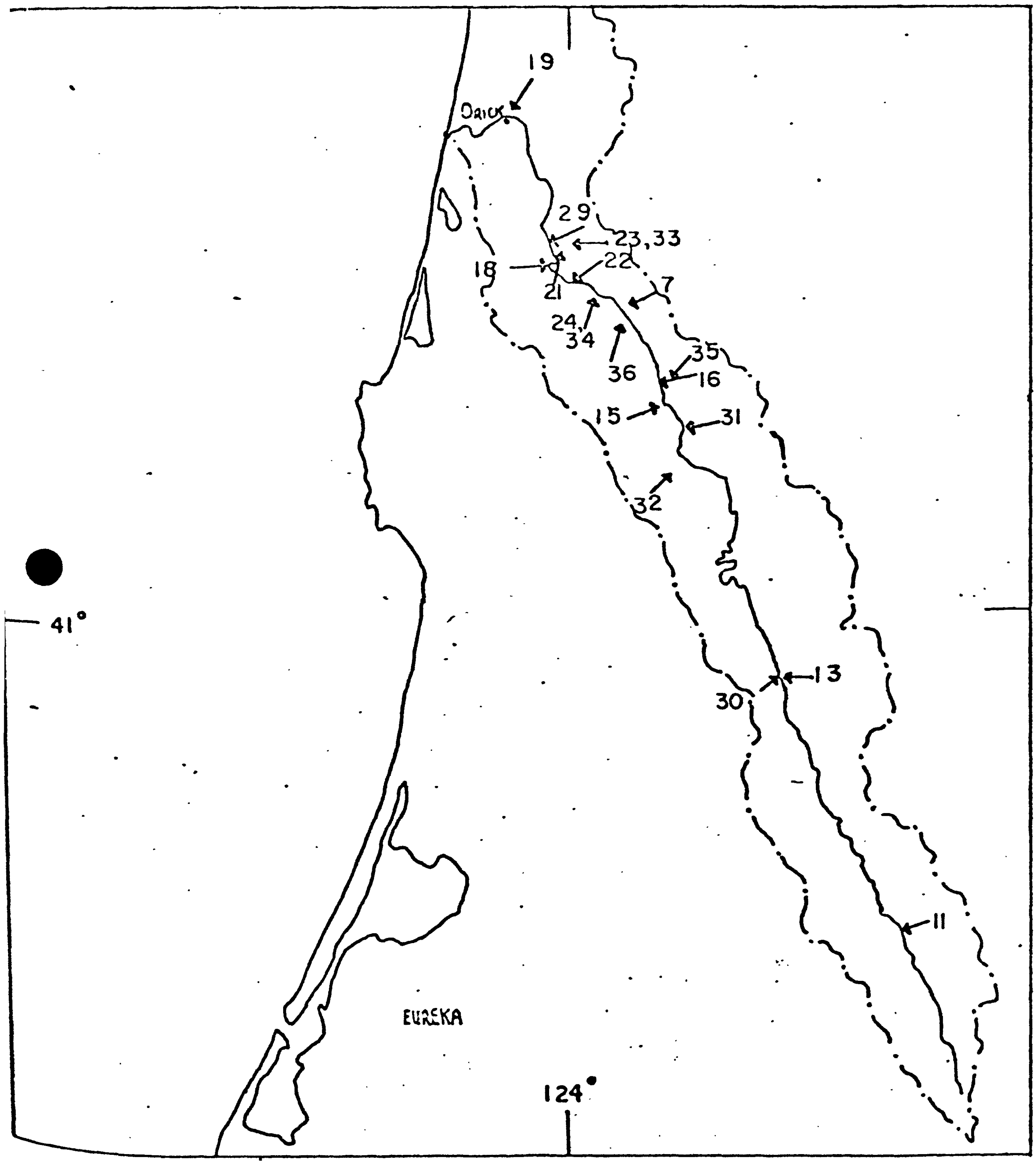


Figure 11A. 1947 conditions

Figure 11B. 1973 conditions

Figure 11. Stereograms showing channel and hillslope conditions in reach 6 of Redwood Creek in 1947(A) and 1973(B). Location of these photographs is shown on figure 12.



gure 12. Location of photo illustrations. Numbers on map refer to text figures.

steep than reach 6. The typical channel pattern in this reach is also more braided than in upstream areas. The average gradient for the entire reach is 24 feet per mile (5 meters per kilometer), with the gradient of the upper third being 32 feet per mile (6 meters per kilometer), and that of the lower two-thirds being only 21 feet per mile (4 meters per kilometer). Numerous compound earthflows along the right valley wall in the steep segment of this reach above Minor Creek contribute large volumes of sediment directly to the creek. Streamside translational slides and debris slides, although smaller and much less abundant than along reach 6, are common on both sides of the creek. The decreased abundance of streamside mass movement failures is partly the result of increased width and frequency of occurrence of upper flood plains and low alluvial terraces which buffer potentially unstable hillslopes from the scouring action of flood flows. Logging of riparian vegetation has had less direct effect on the channel in this reach than in upstream areas. However, cattle grazing, sewage disposal, and construction of low-flow recreational ponds have altered the physical and chemical characteristics of the creek. Approximately 56 percent of the streambanks in this reach are actively eroding.

The increased channel width is most noteworthy in the upstream-most 13 miles (21 kilometers) of this reach. Several broad alluvial reaches with active lower flood plains as much as 650 feet (198 meters) wide occur in the Redwood Valley part of this reach. Those parts of these wide areas that are not persistently inundated by normal winter storms display a several-feet-thick gravel veneer implaced by the 1972 flood; this gravel veneer is the upstream-most evidence of major deposition associated with 1972 flooding. Recent aggradation in some of these alluviated areas has nearly obliterated the streambanks that separate the lower and upper flood plains.

The downstream end of this reach displays a series of tight meanders incised 150 to 200 feet (46 to 61 meters) into Pleistocene terrace gravels and underlying bedrock. These meanders have amplitudes of 3000 to 4500 feet (914 to 1372 meters) and stand in marked contrast to the less sinuous course of Redwood Creek in upstream and downstream reaches. The degree to which the occurrence and morphology of these meanders reflects localized vagaries in geologic structure is not known.

Cobbles and boulders in the alluvium of this reach are less abundant, smaller in diameter, and more rounded than in upstream areas. Moreover, increasing amounts of fine pebbles and sand are mixed in with the streambed materials. In fact, the surface of some of the gravel is strongly impregnated by fine sediment. Several large accumulations of logs and other wooden debris occur in this reach but they do not appear to have dammed the stream or even to have caused major deflection of its thalweg. Metal artifacts, including culverts, logging cables, and automobile parts are more abundant in this reach than any other. Some large pools suitable for rearing young fish occur in the steep rocky section above Minor Creek and in the incised meanders. In the intervening section pools are nearly nonexistant.

Figure 10 shows two monumented stream-channel cross sections in this reach; figure 13 provides photographic documentation of geomorphic conditions along this reach.

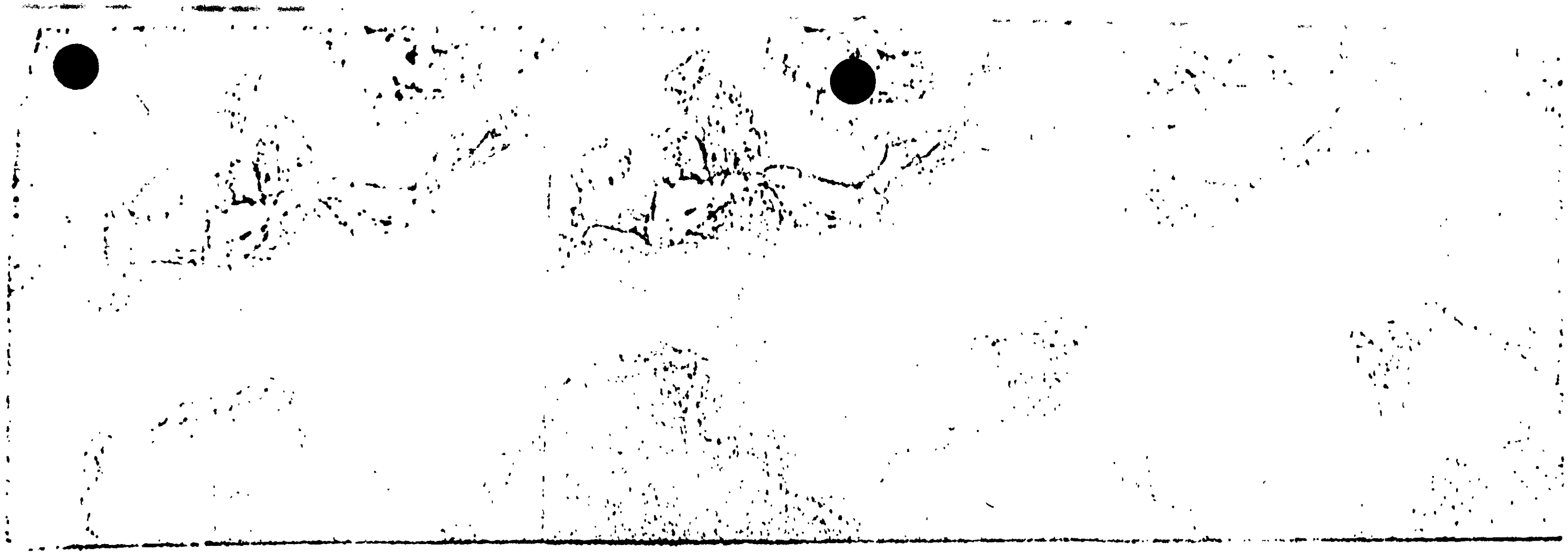


Figure 13A

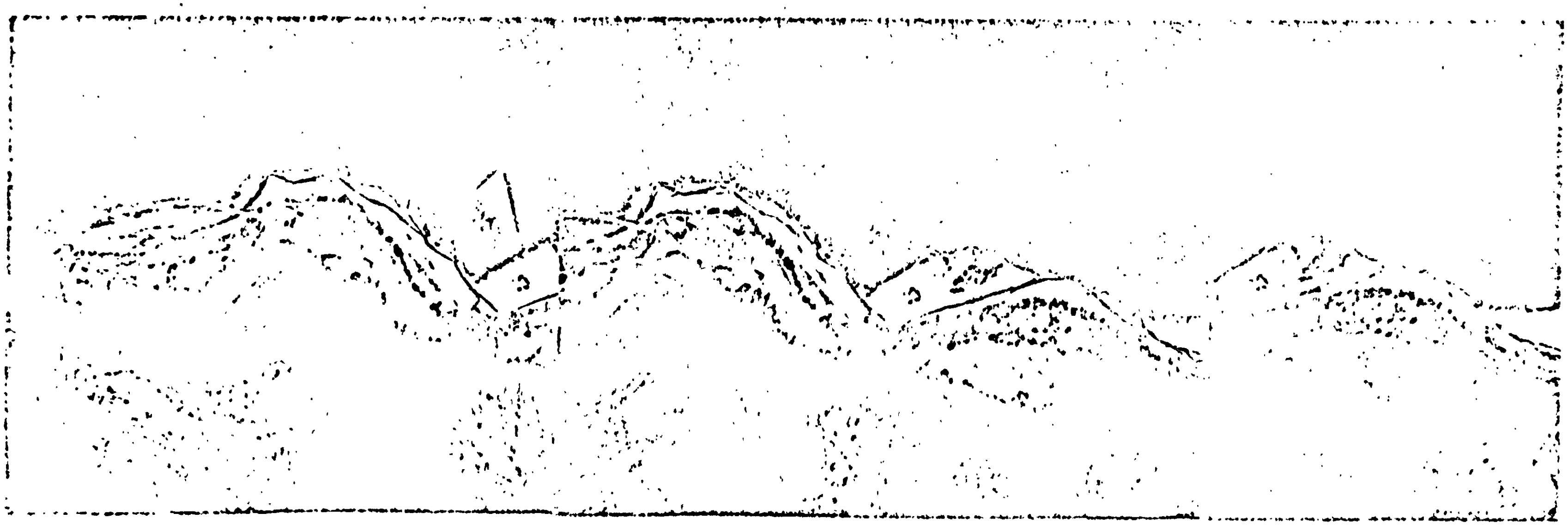


Figure 13B

Figure 13.- Stereograms showing channel and hillslope conditions in a part of reach 5 of Redwood Creek in 1947(A) and 1973(B). Locations of stereograms shown in figure 12.

Reach 4

The 8.8-mile-long (14 kilometer) reach between Lacks Creek and Copper Creek (reach 4, fig. 14) is characterized by a single sinuous rocky channel completely lacking upper flood plains and alluvial terraces. Channel gradients range from 19 to 30 feet per mile (4 to 6 meters per kilometer) and average 22 feet per mile (4 meters per kilometer). About 52 percent of the streambanks are actively eroding. Hillslopes adjacent to the channel again show abundant and varied mass movement that delivers large quantities of sediment directly to Redwood Creek. The grain size of the bed material is larger in this reach than in the Redwood Valley reach (reach 5). Alluvium here consists of a mixture of frequently transported, rounded cobble and boulder gravel, and a lag component consisting of large angular blocks of local bed rock. Mass pools capable of supporting young anadromous fish during low flows are associated with the bedrock blocks. Large amounts of wooden debris, including sawed logs, get introduced to the creek in this reach. However, considering the rough, irregular character of the channel, accumulations of this debris are surprisingly small and few in number. Moreover, debris accumulations that are present do not appear to have significantly modified stream processes. Flood-related depositional features are also scarce. Despite the lack of obvious depositional features, metal objects are nearly as abundant in this reach as in the Redwood Valley area. Flood lines here are generally lower than those in upstream and downstream reaches. Prior flood flows along this reach apparently were accommodated by increasing velocities more than by increasing depths.

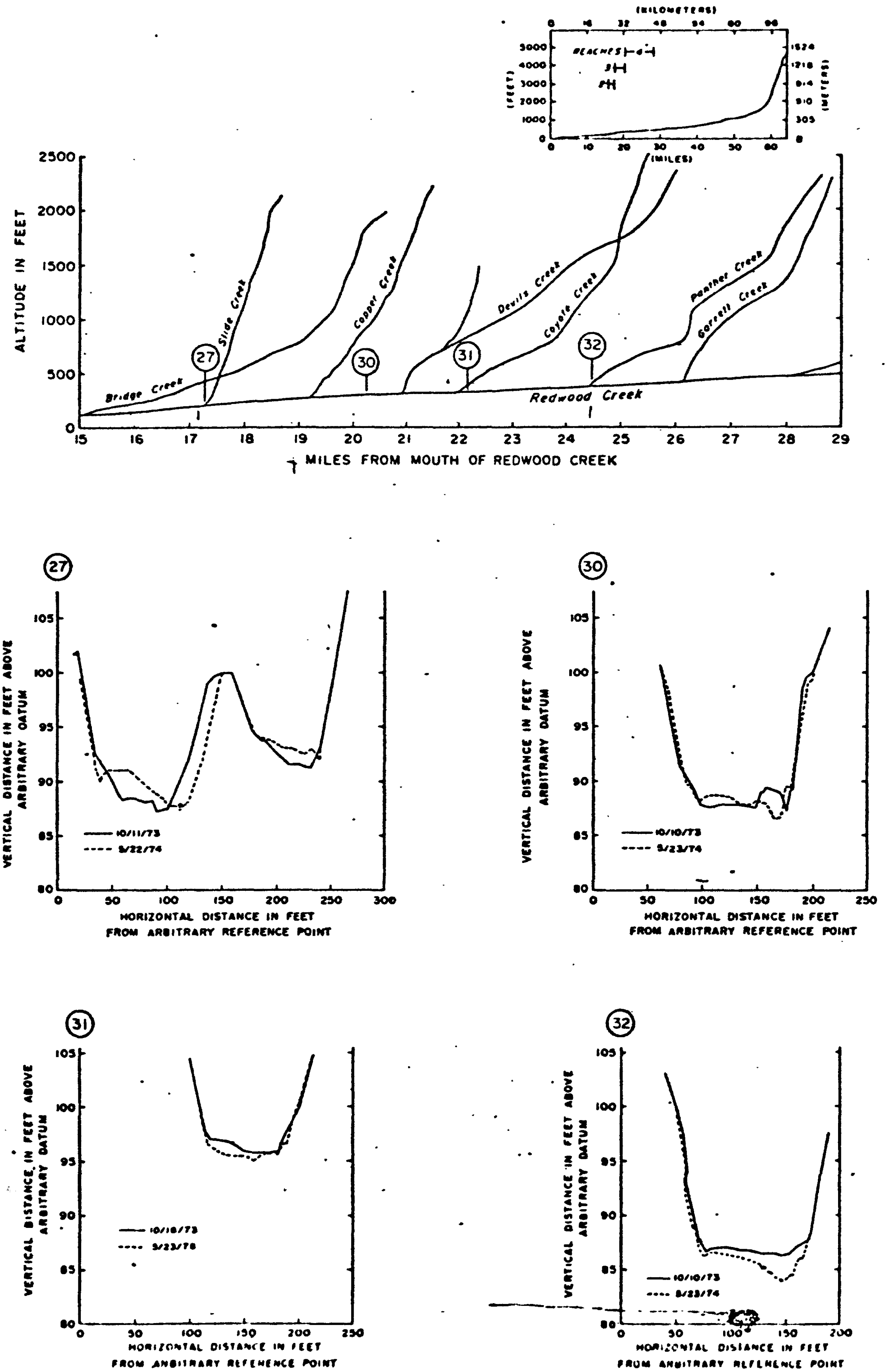


Figure 14. Vertically exaggerated stream profiles and channel cross-sections for reaches 2, 3, and 4 of Redwood Creek.

The natural stability of the steep streamside hillslopes in this reach apparently has been adversely impacted by construction of logging roads and skid trails. In fact, since 1968 the direct impact of logging on stream environments has been greater in this reach than in any other along Redwood Creek.

Figure 14 shows three monumented stream-channel cross sections along this reach; figure 15 provides photographic documentation of geomorphic conditions along this reach.

Reach 3

Along the two-mile-long reach (3 kilometres) between Copper Creek and the southern boundary of Redwood National Park (Reach 3, fig. 14), the channel becomes noticeably wider and steeper and shows a renewed tendency toward braiding. Gradients range from 31 to 38 feet per mile (6 to 7 metres per kilometre) and average 35 feet per mile (6.7 metres per kilometre). A few small upper flood plains and low terraces are present at the upstream end of this reach. Sixty-eight percent of the stream banks are actively eroding. Streamside hillslopes also show considerable natural instability (Colman, 1973); stability here, however, has not yet been as directly affected by logging as in the reach above Copper Creek. Actively transported alluvium in this reach consists mostly of pebble and cobble gravel. A lag component of large bedrock blocks is present but not as prominent as in the adjacent reaches. Rearing ponds are again associated with these blocks. Several large accumulations of logs and other debris have collected on a few of these blocks and have deflected the current against the adjacent stream banks thereby accelerating bank erosion.

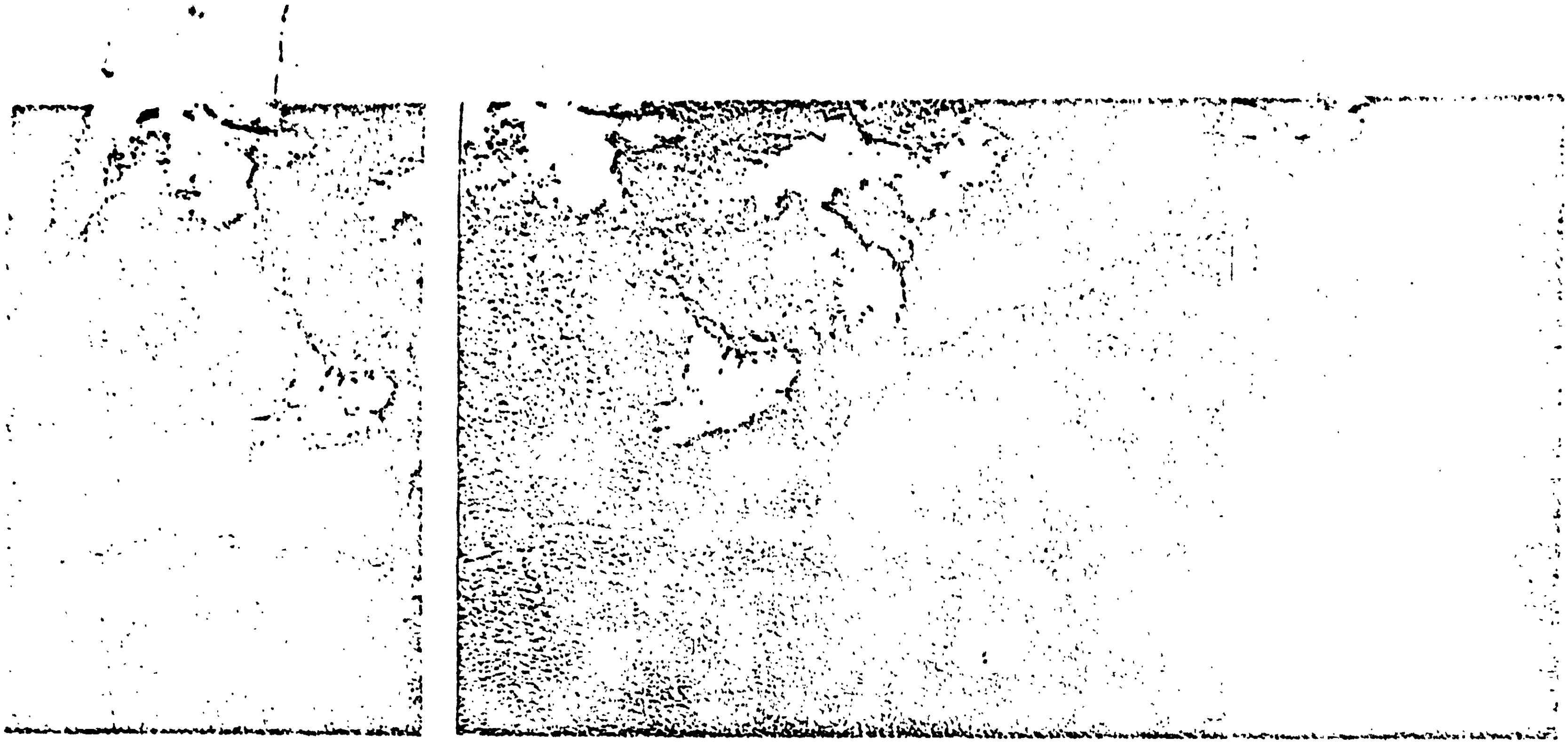


Figure 15A.

Figure 15.- Stereograms showing channel and hillslope conditions in part of reach 2 of Redwood Creek in 1936(a), 1968(B), and 1973(C). Location of stereograms is shown in figure 12/ The 1968 photographs are included to indicate conditions at the time Redwood National Park was established.

Figure 15 B.

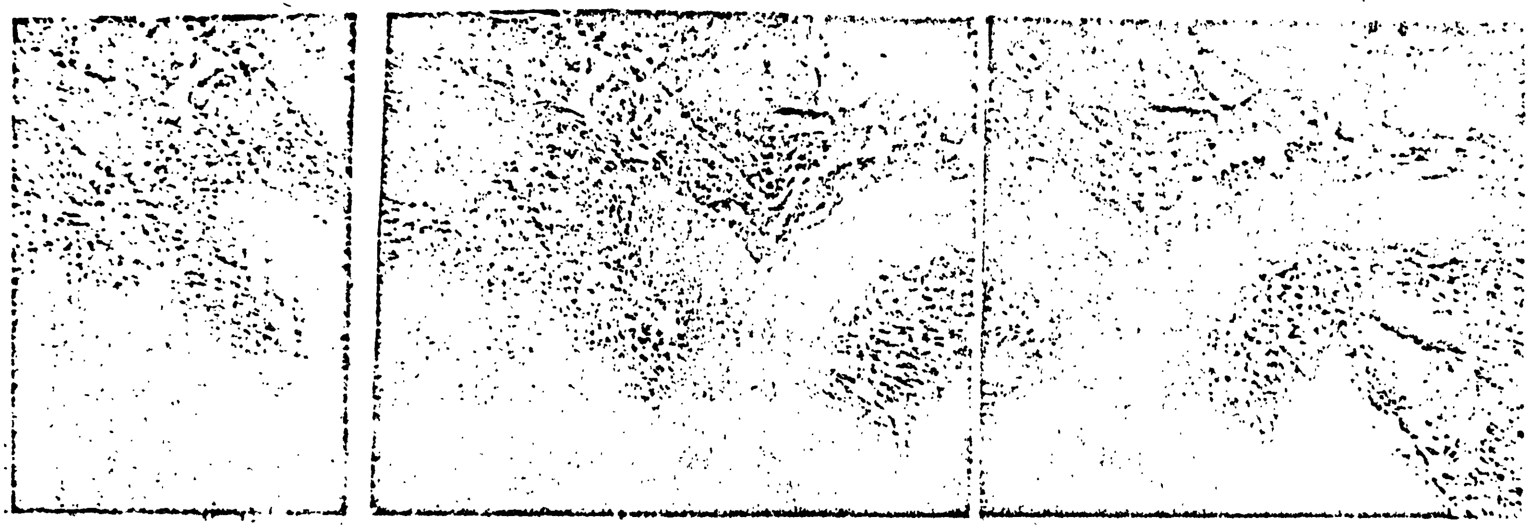


Figure 15C.

Figure 15. Stereogram showing channel and hillslope conditions in a part of reach ? of Redwood Creek in 1936(A), 1968(B), and 1973(C). Location of stereogram is shown in figure 12. The 1968 photographs are included to indicate conditions at the time Redwood National Park was established.

Prominent, sparsely vegetated, flood deposited berms similar to those described by Stewart and LaMarche (1967), and Helley and LaMarche (1973) occur at several points in this reach. These berms rose 5 to 10 feet (1.5 to 3.0 metres) above the low-water channel. Berms at the upstream end of the channel appear related to the 1964 flood, whereas those at the downstream end are related to the 1972 floods. During the floods of January and March 1972, more than 15 feet (5 metres) of gravel was deposited on the orifice line for the U.S. Geological Survey stream gaging station at the sourthern boundary of Redwood National Park.

Figure 14 shows a monumented stream-channel cross section near the downstream end of this reach; figure 16 provides photographic documentation of geomorphic conditions along this reach.

Reach 2

For about one mile downstream from the southern boundary of Redwood National Park, Redwood Creek flows through a steep narrow rocky gorge (Reach 2, fig. 14). Many large blocks of bedrock have accumulated in this reach, but they are not large enough or abundant enough to impede upstream migration of anadromous fish. The gradient is highly irregular in detail but averages about 47 feet per mile (9 metres per kilometre). Well over half of the stream banks in this reach are actively eroding; non-eroding banks appear to be protected by large bedrock blocks implaced by a variety of mass movement processes. Indeed, the streamside hillslopes display some of the most active mass movement in the entire Redwood Creek basin (Colman, 1973). The west valley wall which is underlain by

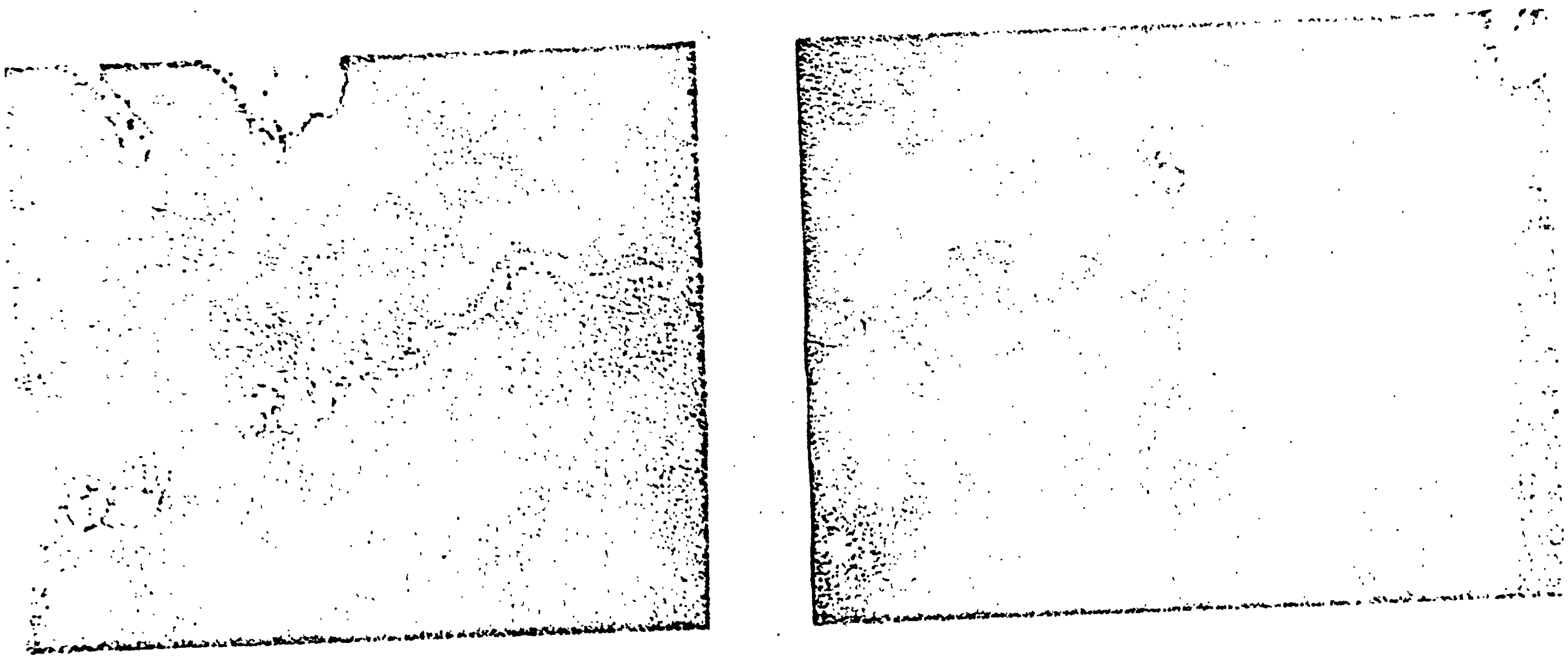


Figure 16A. 1936 conditions

Figure 16. Stereograms showing channel and hillslope conditions in a part of reach 3 of Redwood Creek in 1936(a(, 1968(b) and 1973(C). Location of these photographs is shown in figure 12. The 1968 photographs are included to indicate conditions at the time Redwood National Park was established.

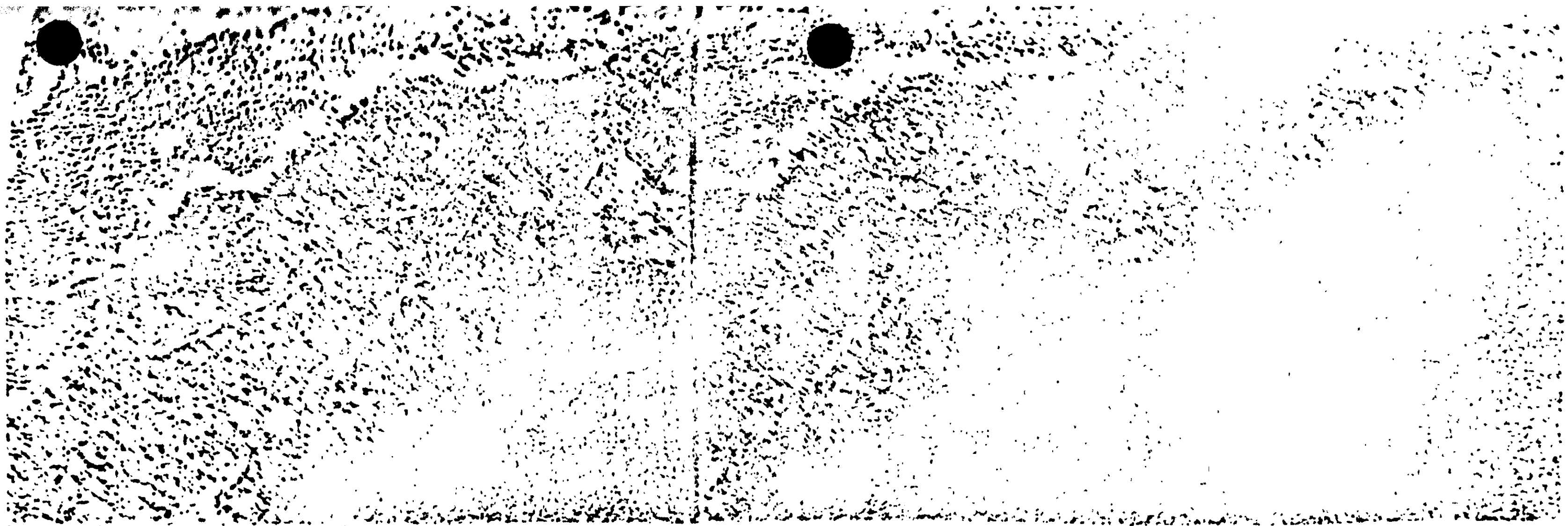


Figure 16B. 1968 conditions

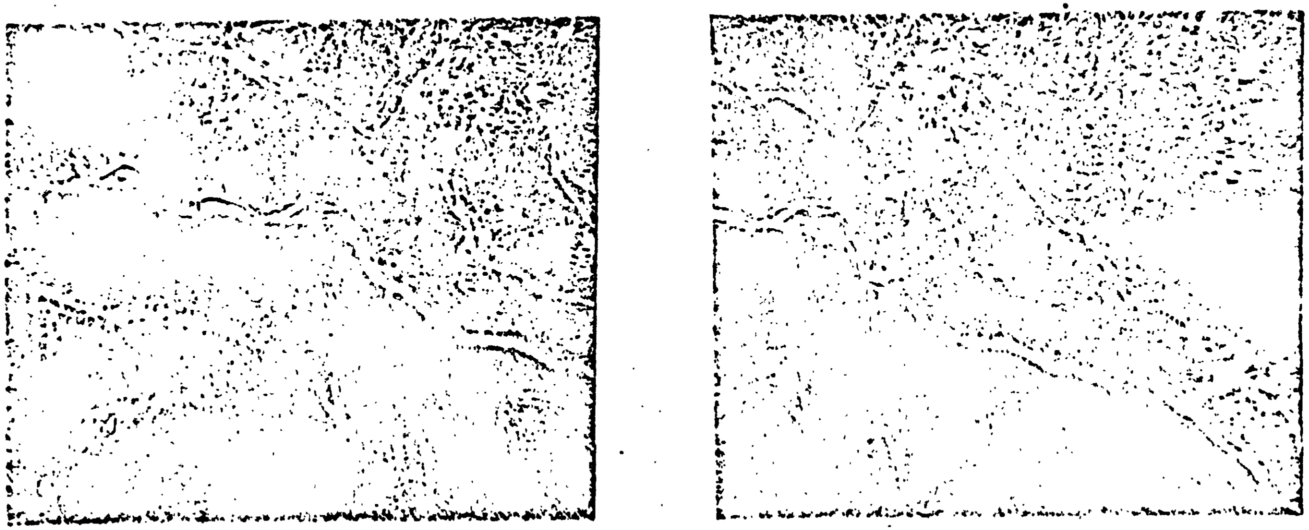


Figure 16C. 1973 conditions

Figure 16. Stereograms showing channel and hillslope conditions in a part of reach 3 of Redwood Creek in 1936(A), 1968(B), and 1973(C). Location of these photographs is shown in Figure 12. The 1968 photographs are included to indicate conditions at the time Redwood National Park was established.

schists of textural zone 3 appears to be sculptured by exceptionally active creep with some translational slides at the toe of the slope. The east valley wall which us underlain by fractured and sheared Franciscan sandstone and siltstone appears to be eroded by several large discreet translational slides and a large compound earth flow (Counts Hill Prairie, fig. 7). This vigorous mass movement accounts for the lag of large angular blocks within the channel. Large pools associated with these blocks serve as low water rearing areas for young fish. Between these blocks the streambed material consists mostly of sandy pebble and cobble gravel. Flood-related berms and normal upper flood plains are lacking in this reach.

Reach 1

Along the 16 miles (26 kilometres) of channel below the mouth of the narrow rocky gorge (Reach 1, fig. 17), Redwood Creek is characterized by a braided channel set in a broad, active lower flood plain. At many localities one or more narrow upper flood plains separate the active lower flood plain from the adjacent hillslope. Some terrace gravels are present but they are not associated with prominent landforms. Channel gradients range from eight to forty feet per mile (1.5 to 8 metres per kilometre) and average about 11 feet per mile (1 metre per kilometre). The lower four miles (six kilometres) of channel are lined with rock levies designed to protect the broad flood plain in the vicinity of Orick. About 41 percent of the unlined streambanks along this reach are actively eroding. The lower flood plain is actively widening at many localities, but his process is most in evidence in the area between MacArthur Creek and Prairie Creek (cross section 3, fig. 17). Streamside slides are smaller and less abundant in this reach than in any other reach along Redwood Creek (Colman, 1973). Summertime

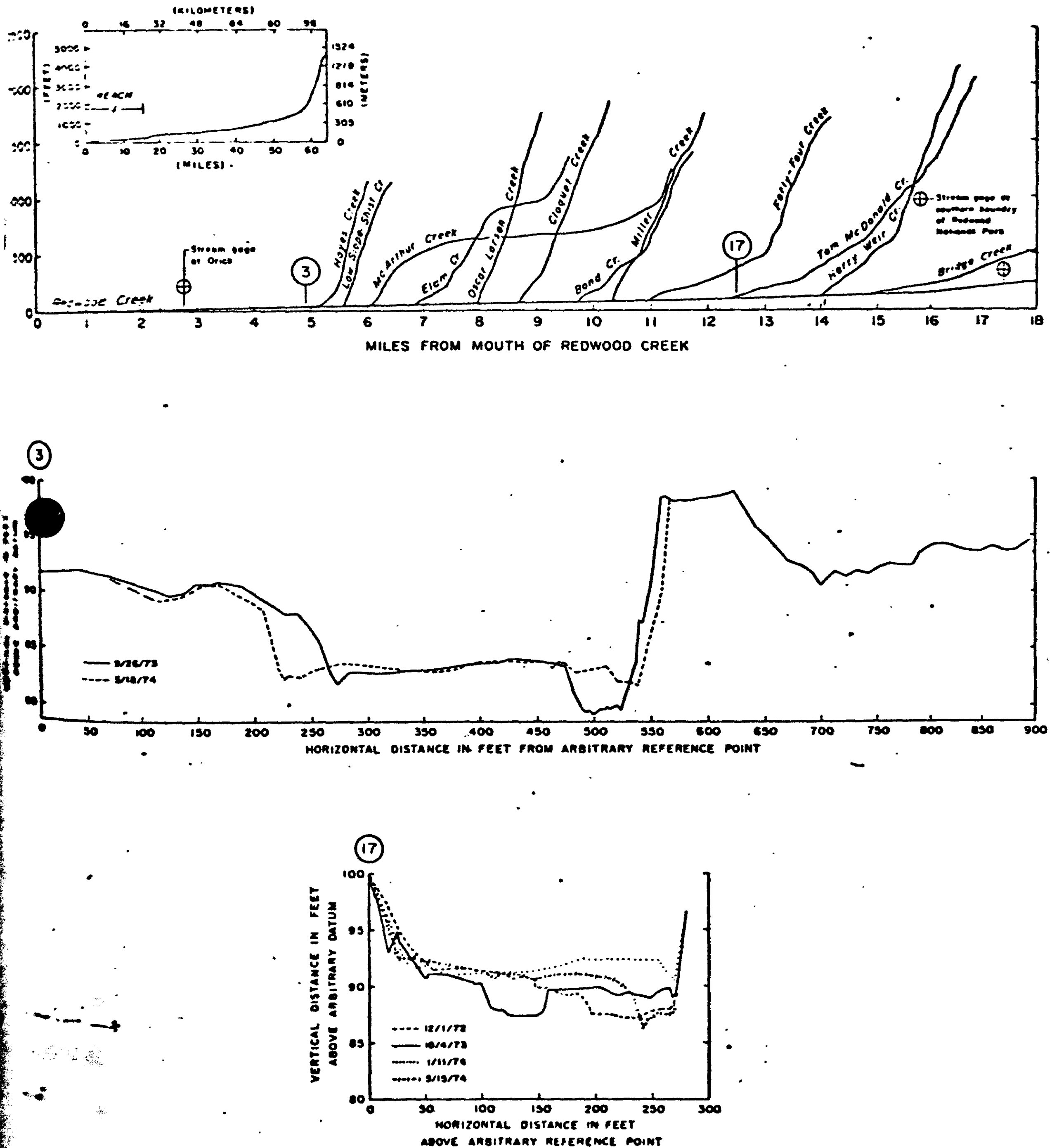


Figure 17. Vertically exaggerated stream profiles and channel cross-sections for reach 1 of Redwood Creek.

maximum water temperatures are somewhat less here than in upstream areas because taller, more abundant riparian vegetation and more persistent summer fog result in substantially less insolation reaching the surface of the low water channel here than along upstream reaches.

The stream bed, which consists mostly of pebbly sand and sandy pebble gravel, is actively agrading in the area between Bridge Creek and Elam Creek. Pools suitable for rearing young fish are sparse because deep water occurs only in association with turbulent eddies caused by rocks and fallen trees, or where recent stream deposits have restricted the low water channel and increased stream velocity. Flood-deposited berms of coarse pebble and cobble gravel are prevalent immediately below the mouth of the gorge and on the inside of many stream bends down to the mouth of Elam Creek. Some of these berms have been deposited on the outer edges of upper flood plains and have killed young tanoaks, maples, Douglas-firs, and redwoods. The berms in this reach all appear to have been emplaced or at least to have had their upper surfaces modified by the 1972 floods. Many of the dead trees were killed prior to 1972, so that the 1972 flood deposits in some localities may be only a veneer over older, perhaps 1964, berms. Even in some areas without prominent berms, sandy gravel is being deposited at sites that formerly received only fine grained, overbank sediments. Some small tributary valleys have been dammed by recent gravel aggradation. Many other tributaries have been severely aggraded by back-water effects. Metal objects and tires are not as abundant as in some upstream reaches, but at least nine of these artifacts were clearly visible on the inner flood plain between Bridge Creek and Prairie Creek during the summer of 1974.

Figure 17 shows two monumented stream channel cross sections in this reach. Figures 18 and 19 provide photographic documentation of geomorphic conditions along this reach.

Tributary Channels

The main channel and tributary channels within the 278-square-mile (720-square-kilometre) drainage basin of Redwood Creek upstream from the stream gage at Orick show a pronounced trellised drainage pattern with an overall drainage density of about 7.7 miles per square mile (4.8 kilometres per square kilometre). This pattern is comprised primarily of a large number of relatively short individual tributaries that drain relatively small areas. Only two tributaries, Prairie Creek and Lacks Creek, drain more than five percent of the total area. The drainage areas of the 28 tributaries shown on figures 9, 10, 14, and 17 range from 0.2 to 17 square miles (0.5 to 44 square kilometres).

Prairie Creek, which is the largest and downstream-most of Redwood Creek's major tributaries, drains about 40 square miles (104 square kilometres) and enters the main creek about one mile (1.6 kilometres) north of Orick(fig. 2). The drainage basin of Prairie Creek upstream from the mouth of Lostman Creek is underlain primarily by unnamed weakly indurated sedimentary rocks and is characterized by average hillslope and stream channel gradients that are less steep than elsewhere in the Redwood Creek basin. The southern part of

Figure 18A. 1936 conditions.

Figure 18.- Stereograms showing channel and hillslope conditions in reach 1 of Redwood Creek near the Tall Trees Grove in 1936(A), 1968(B), and 1973(C). Location of these photographs is shown in figure 12. The 1968 photographs are included to show conditions at the time Redwood National Park was established.

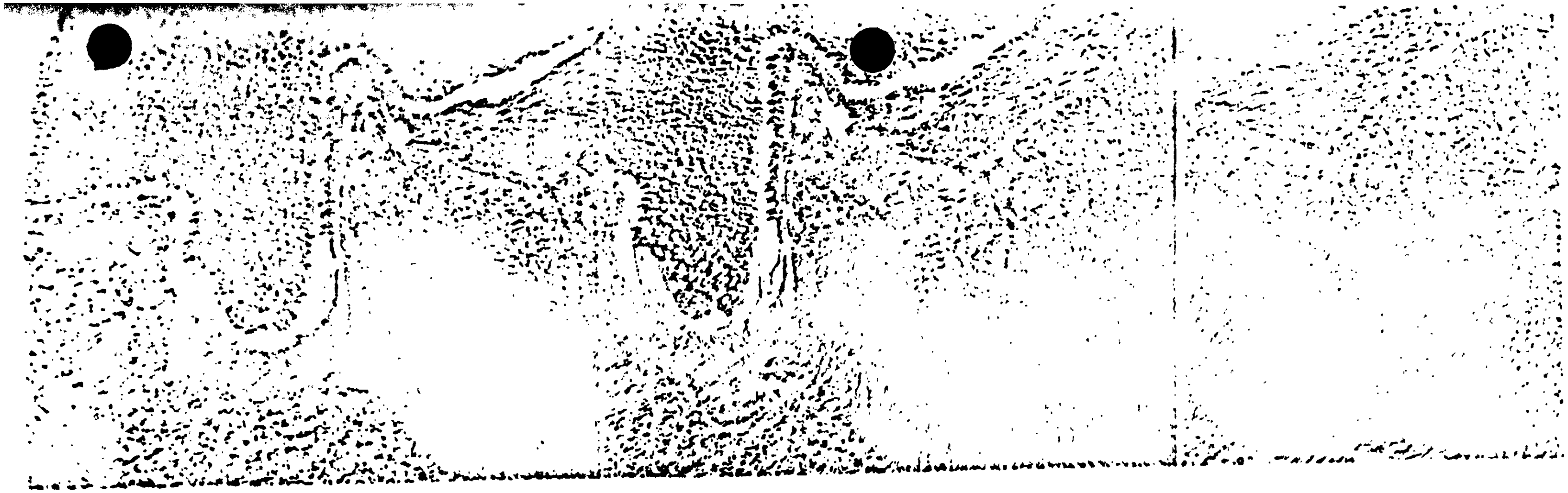


Figure 18B. 1968 conditions

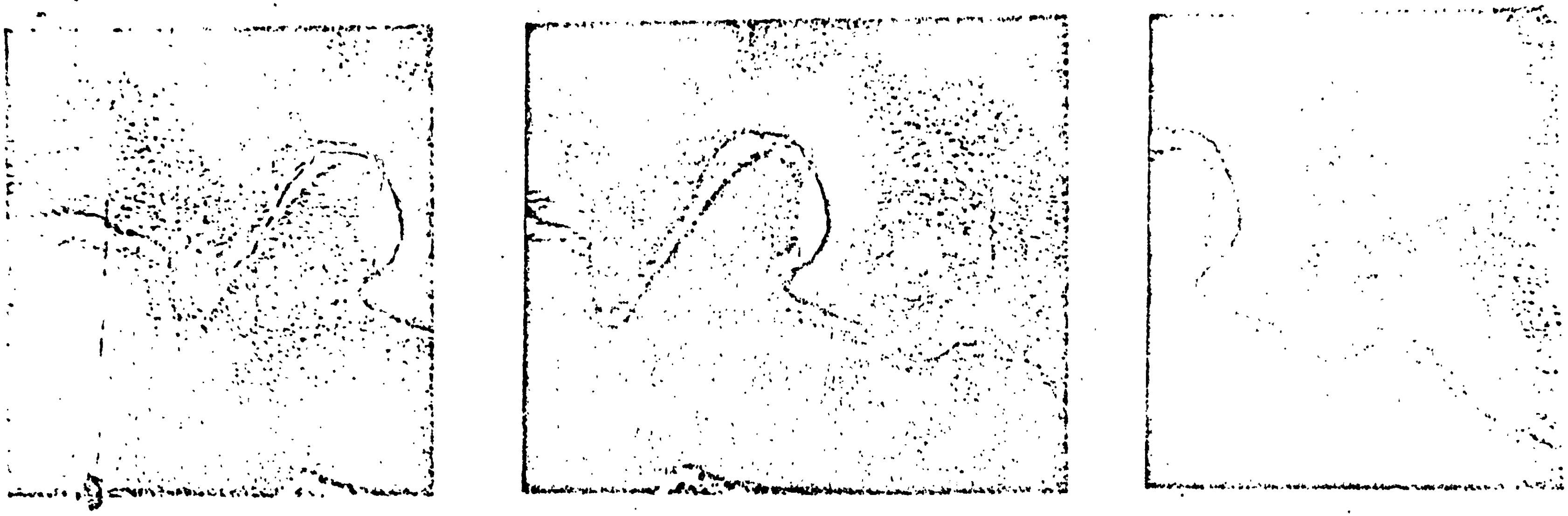


Figure 18C. 1973 conditions

Figure 18. Stereograms showing channel and hillslope conditions in reach 1 of Redwood Creek near the Tall Trees Grove in 1936(A), 1968(B), and 1973(C). Location of these photographs is shown on figure 12. The 1968 photographs are included to indicate conditions at the time Redwood National Park was established.

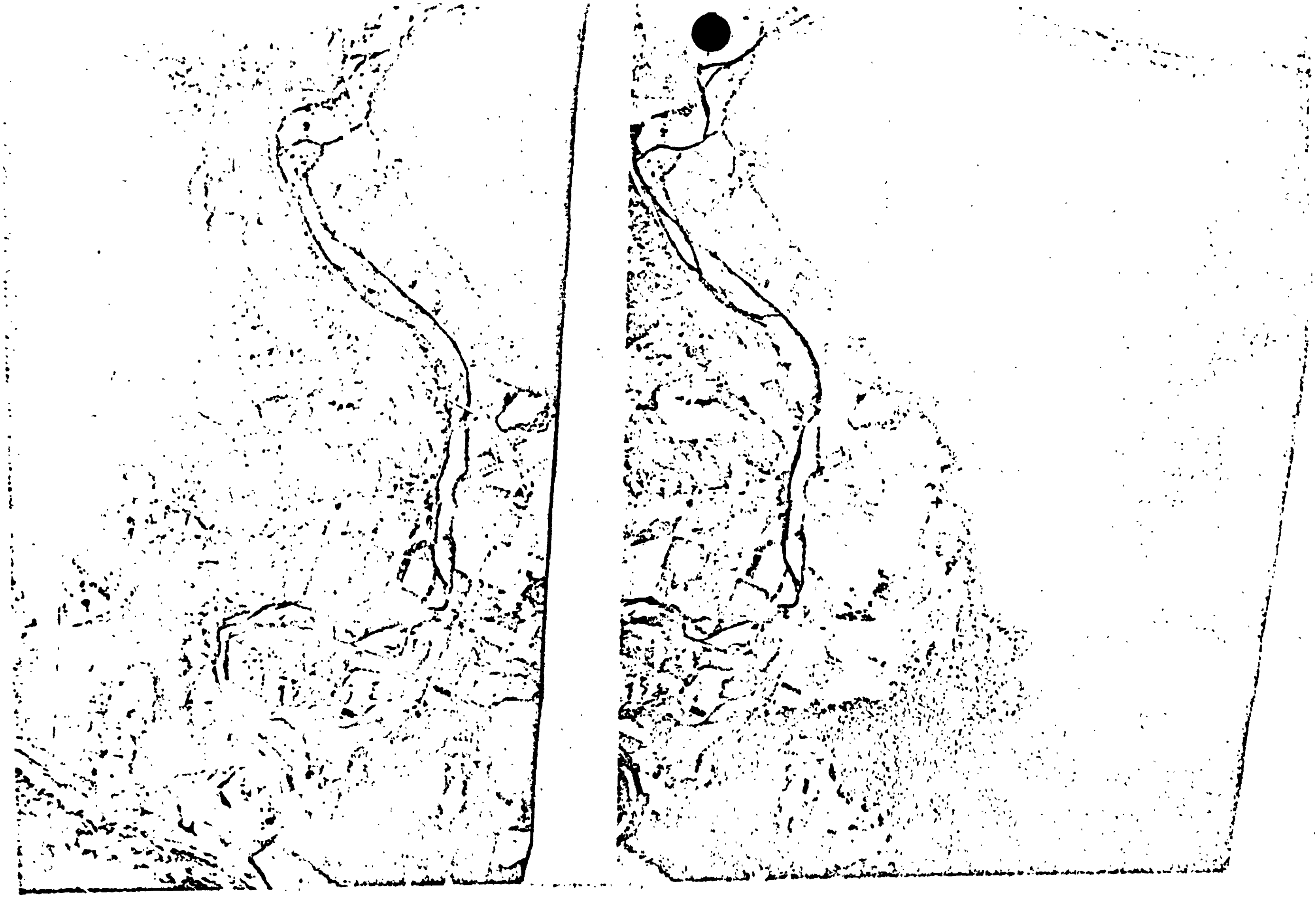


Figure 19A. 1936 conditions

Figure 19.- Stereograms showing channel and hillslope conditions in reach 1 of Redwood Creek in the vicinity of Prairie Creek and McArthur Creek in 1936(A), 1968(B), and 1973(C). Location of these photographs is shown in figure 12. The 1968 photographs are included to indicate conditions at the time Redwood Creek National Park was established.

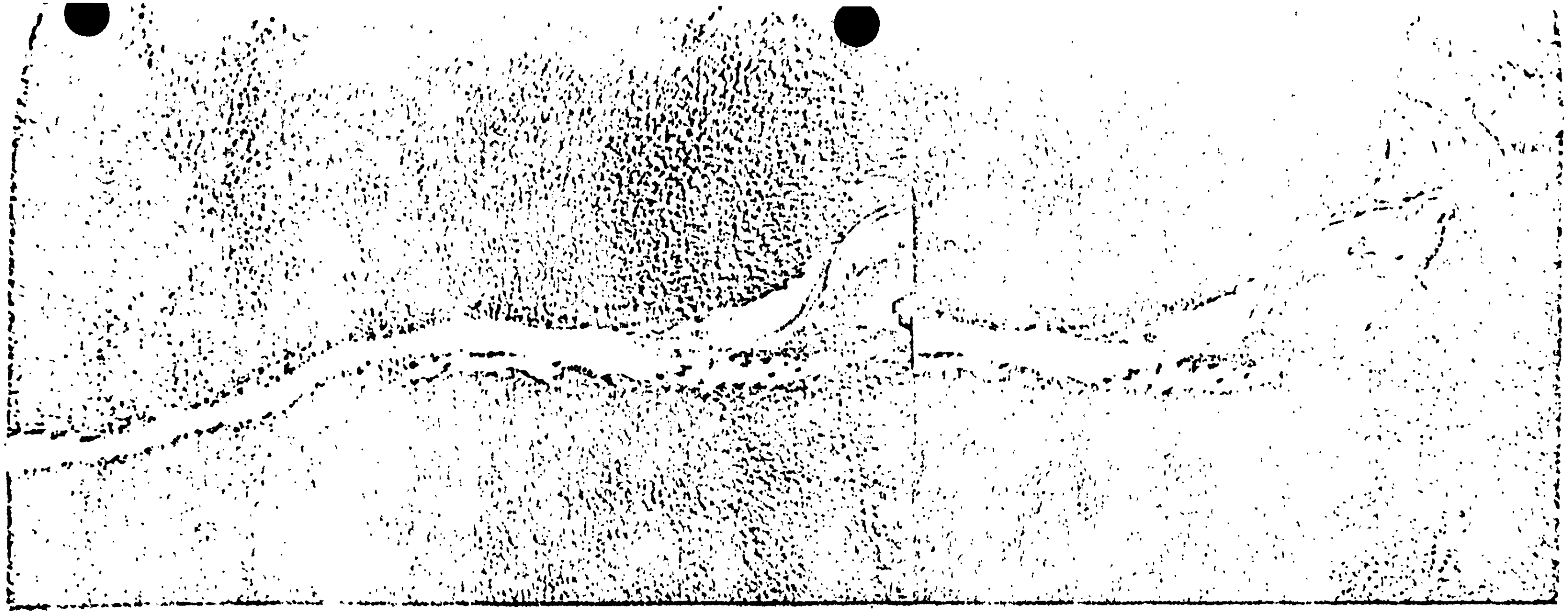


Figure 19B. 1968 conditions.

Figure 19C. 1973 conditions

Figure 19. Stereograms showing channel and hillslope conditions in reach 1 of Redwood Creek in the vicinity of Prairie Creek and McArthur Creek in 1936(A), 1968(B), and 1973(C). Location of these photographs is shown on figure 12. The 1968 photographs are included to indicate conditions at the time Redwood National Park was established.

the Prairie Creek basin, including the drainage basins of Lost Man, Little Lost Man, Geneva, Berry Glenn, and Skunk Cabbage Creeks, is underlain by the Franciscan assemblage of rocks and has physiography that is more comparable to that found upstream from the mouth of Prairie Creek (Iwatsubo and others, 1975, tables 1 and 3).

Prairie Creek has a single clearly defined channel that even during low flow occupies most of a narrow inner flood plain and displays a slightly sinuous to meandering course. Throughout most of its length, this channel is separated from wide upper flood plain areas of overbank deposition by clearly defined banks. The longitudinal profiles of Prairie Creek and its major tributaries are shown in figure 20. The average channel gradient is about 64 feet per mile (12 metres per kilometre), but the downstream half of the channel below the headquarters of Prairie Creek State Park has an average gradient of only 19 feet per mile (4 metres per kilometre). Streambed material is predominantly sandy-fine pebble gravel. Accumulations of coarse organic debris are sparse and do not appear to have seriously impacted upon channel behavior or fish migration.

Redwood Creek's tributaries, including those in the southern portions of the Prairie Creek basin, typically show channel characteristics comparable to those of main channel reach 7 in that they have straight to slightly sinuous courses, steep gradients, infrequent areas of overbank deposition, heterogeneous bed material, and abundant natural obstructions caused by wind-toppled trees, debris slides, and rock falls. The longitudinal profiles of 28 major tributaries to Redwood Creek are shown

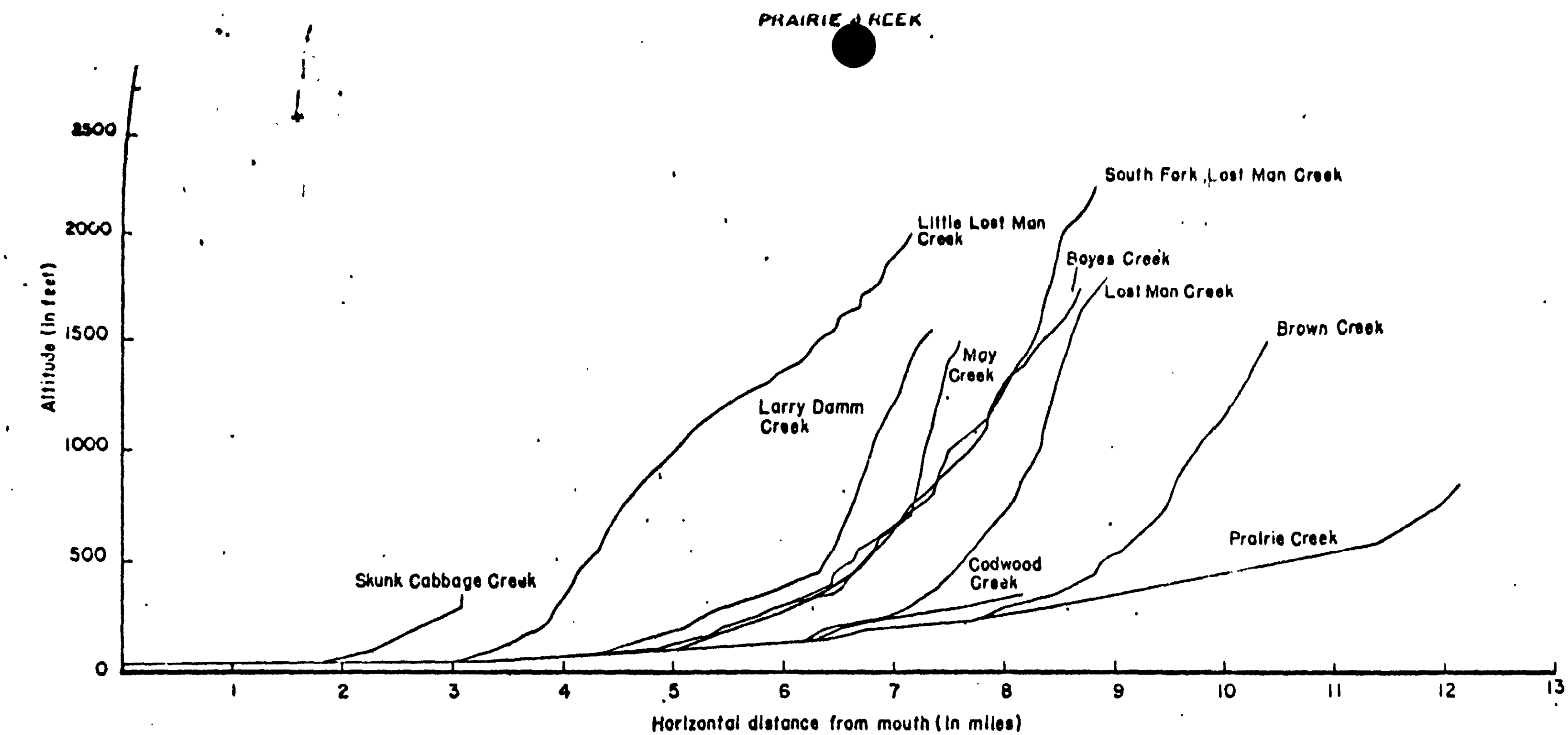


Figure 23. Vertically exaggerated stream profiles for Prairie Creek and its major tributaries.

in figures 9, 10, 14, and 17. Average channel gradients of individual tributaries range from about 250 to 1500 feet per mile (48 to 286 metres per kilometre). Lacks Creek, Bridge Creek, Tom McDonald Creek, and MacArthur Creek are the only tributaries upstream from Prairie Creek to have average gradients of less than 400 feet per mile (76 metres per kilometre). The channel gradients, however, are highly irregular in detail and reflect lithologic and structural properties of the underlying bedrock as well as obstructions caused by recent landslides and accumulations of toppled riparian vegetation. Some low gradient reaches near the western drainage divide of Redwood Creek, such as in the headwaters of High Prairie, Noisy, Lupton, Bridge and MacArthur Creeks, may be associated with remnants of an old erosion surface.

Alluvial streambanks and areas of overbank deposition are uncommon along tributaries except immediately upstream from prominent obstructions and in "backwater areas" influenced by flood flows along Redwood Creek. Streambed materials are highly variable in grain size and sorting characteristics, but subrounded to subangular, pebble and cobble gravel is most prevalent. Flood-deposited, flat-topped gravel berms comparable to those found along the main channel are uncommon in the tributary basins.

Dense riparian vegetation severely restricts the amount of insolation reaching unlogged portions of tributary streams. Light levels are so low along some tributaries that they limit aquatic productivity. Reaches of tributaries flowing through natural breaks in the vegetal canopy show more periphyton and benthic invertebrates than do adjacent reaches.

Small streamside slides and gullies are common along the downstream reaches of essentially all of the deeply incised tributaries. Examples of such instability are particularly prevalent, however, in the sheared contact zone between the schist and sandstone, and along long north-northwest trending linear channel segments, such as those along Bridge Creek and Lacks Creek. These tributary channels actively interact with these streamside areas of instability because of the scarcity of floodplains. Even relatively minor channel shifts frequently erode the bases of hillslopes and thereby trigger slides that deliver large volumes of sediment directly to the stream channels.

Most of the colluvium introduced into the streams by various hillslope erosion processes is transported downstream, but a prominent lag component of angular blocks of colluvium is generally present in all but the most strongly alluviated reaches. This lag is an important element of the natural aquatic habitat. Most of the pools that persist through the summer low-flow period are associated with large blocks of colluvium. These blocks also serve as stable nitches for benthic invertebrates. On the other hand, excessively large and abundant blocks of colluvium make many tributary reaches unsuitable for spawning by anadromous or resident fish.

Fallen trees and streamside rock and debris slides along the tributaries often completely dam the tributary streams and give them a distinctive stepped profile. These obstructions serve as check dams and energy dissipators and thereby mitigate storm damages (Heede, 1972); however, those obstructions that are more than five or six feet high (1.5 or 2 metres) form effective barriers to fish migration (Gibbons and Sulo, 1973). All of Redwood Creek's tributaries upstream from Prairie Creek have a series of such barriers that naturally limit anadromous fish to the main channel and the lowermost reaches of the tributaries. Some of the larger tributaries, however, do support resident fish populations in reaches between these barriers. Even those channel obstructions that merely deflect the tributary channels from their established courses accentuate bank erosion and, thereby, commonly trigger other landslides.

Many of the landslides and fallen trees that locally obstruct the tributary channels are clearly antecedent to recent landuse changes. Decaying tree trunks in some debris accumulations serve as nurse logs for conifers that appear to be at least several decades old. Other trunks have been polished and sculptured into bizarre free-flowing shapes by long-repeated contact with sediment-laden flood discharges. Additionally, much of the streamside slide debris bears mature conifers and dense mats of moss, ferns, and various herbaceous plants. The natural esthetic characteristics of the tributaries to Redwood Creek are closely tied to various channel obstructions and the lag of large angular blocks of colluvium (fig. 21 and 22).

Many tributaries within and immediately downstream from areas that have recently undergone extensive timber harvest have some major characteristics that differ drastically from those in comparable virgin watersheds. Streams draining recently tree-harvested areas frequently are plugged with

Figure 21. Ground photograph- natural channel

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Figure 22. Ground photograph- natural channel

excessive quantities of coarse organic debris including sawed logs. Although much of this debris is scattered at random along these channels, most appears to have accumulated on pre-existing channel obstructions. Relatively few logging-related debris barriers in the Redwood Creek basin bar anadromous fish from natural spawning areas along tributary streams; logging-related barriers near the mouths of Minor Creek, Panther Creek, Tom MacDonald Creek, the south fork of Lost Man Creek, and several tributaries above Highway 299, however, had had this effect.

Extensive channel aggradation is commonly observed along tributaries in and immediately downstream from some of the more massive recent timber harvest units. The aggraded streambeds have filled pools and buried the lag of bedrock blocks. These aggraded streambeds usually are composed of finer-grained bed material than that on the initial streambed. Rusting culverts and cables, as well as sawed logs, are common in the alluvium (fig. 23 & 24). Many unfilled pools show a veneer of brownish silt and fine sand. The decreased grain size increases the inherent instability of the streambed and degrades the intra-gravel environment for benthic invertebrates and spawning fish. Bank erosion and streamside sliding appear more prevalent in these aggraded reaches. Removal of riparian vegetation increases the amount of insolation received on the stream surfaces and apparently results in elevated stream temperatures and locally lush growth of filamentous algae.

The large-scale natural roughness elements along the tributary channels act as small check dams that attenuate rapidly the impact

Figure 23.- Cutover channel.

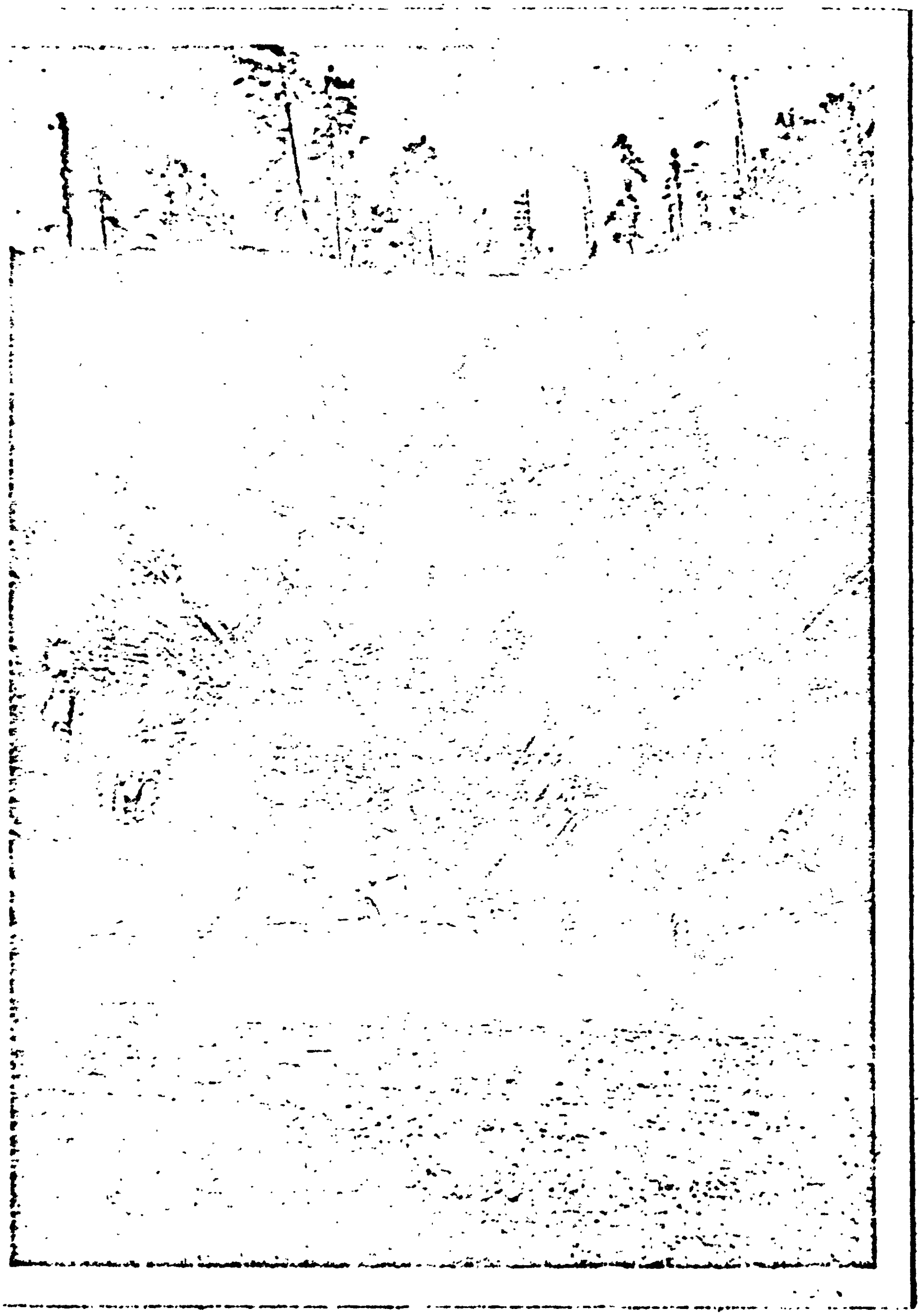

Figure 24.- Cutover channel.

associated with the coarse organic debris and streambed material introduced from recently cut-over forest land. The rate of attenuation, however, depends upon the degree to which channel aggradation accelerates stream bank erosion and streamside landsliding. If these interrelated processes cross an, as yet, undefined critical threshold, they may trigger self-reinforcing feedback mechanisms that could completely devastate downstream aquatic and riparian environments. Moreover, even when the magnitude of the channel changes wrought by logging operations diminish rapidly away from the site of disturbance, those changes may persist for many decades. This persistence would allow the effects of separate upstream disturbances to become cumulative. Dense shade along tributaries downstream from recently cut-over land allows water temperatures to cool relatively rapidly during the summer months.

Estuary

The estuary at the mouth of Redwood Creek is relatively small and follows a generally sinuous course. Under all but the most extremely high tides, tidal influence on river stage extends upstream only about 1.6 miles and water quality influence somewhat less. Smaller tributary arms extend north and south at its downstream most end. Prior to the installation of flood levees in 1968, the estuary covered approximately twice its present area. At that time, the main flow through the southern channel, which has become a back water slough since channelization of the creek. The main flow of the creek now continues approximately 400 feet beyond the end of the levees to its mouth. The outlet of the estuary shifts north and south as tidal circulation and littoral processes build up a river mouth sand bar.

The river mouth bar periodically becomes emergent and dams the creek during low flow periods of summer, when the flow is insufficient to keep pace with the sand deposition. The emergent bar forms a barrier to anadromous fish seeking to enter the estuary during this time.

The first autumn freshet usually breaks through the bar, allowing Salmonids to enter the creek for spawning. According to Reimers (1973), river mouth estuaries are also important rearing areas for juvenile salmon before their entry into ocean waters.

The reduction of the estuarine area by channelization may thus have had a significant impact on the Salmonid population of the creek.

CLIMATE

NORMAL CLIMATIC CONDITIONS

The moist mild climate of the northern California Coast Ranges reflects their middle latitude location on a steep mountainous coast on the lee side of the Pacific Ocean and in the path of numerous winter polar-front cyclones. The climate of Redwood Creek is typical of most of the surrounding region. The northern half of the Redwood Creek basin, according to the Koeppen classification of climates (Critchfield, 1966), has a coastal Mediterranean climate with mild winters and short warm dry summers with frequent fog (a Csbn climate). The marine influence is less profound in the southern half of the basin which has an interior Mediterranean climate with mild winters and hot dry summers with infrequent fog (a Csan climate). The mean annual precipitation within the Redwood Creek basin, however, is somewhat greater than that associated with most Mediterranean climates.

The full spectrum of climatic variability within the basin is not known quantitatively because few long-term climatological data have been collected from within the basin. Moreover, the data that have been collected are representative of a limited number of orographic situations. This paucity of precise climatological data is typical of most mountain watersheds, but it is, nonetheless, worthy of mention because it is a major source of ambiguity in assessing the recent geomorphic history of the basin.

The most usable body of climatic data for the Redwood Creek basin is the daily records of precipitation and temperature that have been collected continuously at Orick-Prairie Creek State Park since 1937. This station provides the only air-temperature record available for the entire basin. Various government agencies have collected partial precipitation records from time to time near Board Camp Mountain, near the old Highway 299 crossing of Redwood Creek, and at Orick. The U. S. Geological Survey installed in the 1974 water year 16 precipitation gages in the environs of Redwood National Park (Iwatsubo and others, 1974). Private individuals have also collected partial rainfall records at a variety of ranches, vacation homesites, and logging operations. The description that follows is based not only upon this intra-basin data but also upon extrapolation of data collected from climatological stations in nearby drainage basins, climatological implications of stream-discharge records, and assessments of probable orographic influence on precipitation and temperature by climatologists and hydrologists with several government agencies, notably the National Weather Service (formerly U. S. Weather Bureau; see USWB 1953-65; 1964).

The entire Redwood Creek basin is characterized by generally mild air temperatures throughout the year because seasonal temperature extremes are moderated by the proximity of the Pacific Ocean. The seasonal pattern of mean monthly temperatures for Orick-Prairie Creek State Park is shown in figure 25. The more inland southern part of the basin, nonetheless, has hotter summers and colder winters than the northern more maritime part. Temperature gradients are steeper in summer than in winter. Mean maximum temperatures in July range from about 69°F to 95°F (20.5°C to 34.6°C), and mean minimum temperatures in January range from about 32°F to 37°F (0°C to 2.7°C). For all but the highest most inland

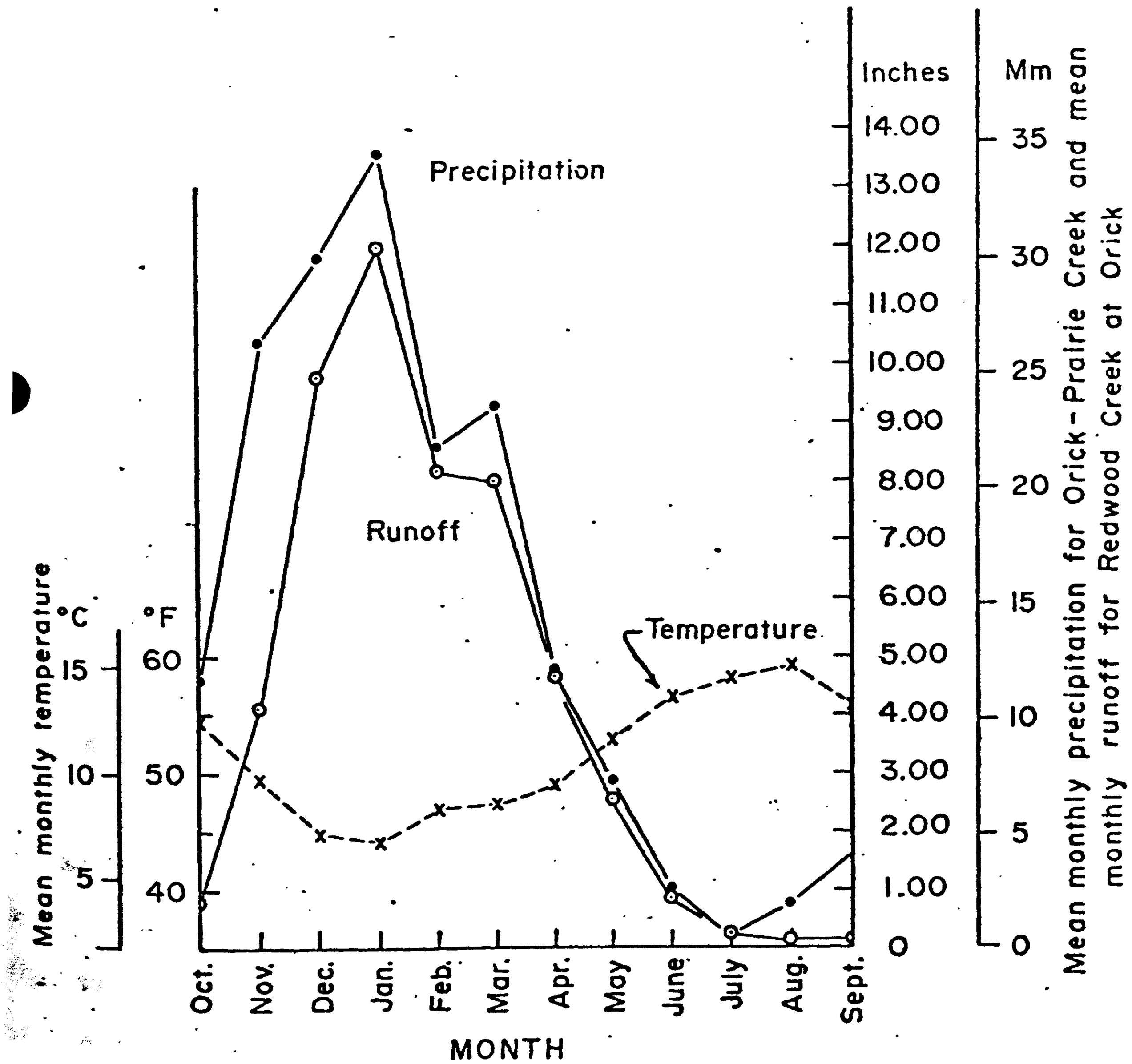

Figure 25. Mean monthly precipitation and temperature for Orick-Prairie Creek Park and mean monthly runoff for Redwood Creek at Orick for water years 1954-1972.

parts of the basin, the frost-free period is usually from mid-April to early November and lasts 200 to 250 days. During the frosty period, most of the basin is characterized by frequent diel freeze-thaw cycles rather than persistently frozen ground. Pipkrake (needle ice) is observed more frequently in cutover land than in the adjacent uncut forest so that the frequency of freeze-thaw cycles may be increased by vegetation removal.

The estimated mean annual basin-wide precipitation for the Redwood Creek basin is 80 inches (2032 mm.) (Rantz, 1964), but altitude, proximity to the ocean, and slope aspect profoundly influence the amount of precipitation at any given location (Rantz, 1969). Commonly the mean annual precipitation varies by as much as ten inches per 1000 feet (305 m) of altitude. Differences in annual rainfall totals reflect differences in amount of rain contributed by individual storms more than differences in the total number of storms.

The mean annual precipitation at Prairie Creek State Park (36 years of record, 1938 to 1973) is 69.81 inches (1773 mm.), computed on a water year basis (October through September). However, this annual amount is highly variable with a standard deviation of 11.62 inches (295 mm.) or 17 percent of the mean. The largest amount of rain to accumulate during any water year in this period was 93.18 inches (2367 mm.) in 1938 and the lowest amount was 50.33 inches (1278 mm.) in 1939. During the period of stream gaging records for Redwood Creek, water years 1954 through 1973, the mean annual precipitation at Prairie Creek State Park was 69.41 inches (1763 mm.), the standard deviation was 10.80 inches (274 mm.) or 16 percent of the mean, and the actual values ranged from 89.96 inches (2285 mm.) in 1956 to 53.88 inches (1369 mm.) in 1973.

Even rather subtle differences in physiography can result in significant differences in precipitation. Three stations along the lower valley of Prairie Creek (Orick-Prairie Creek State Park; Orick-Arcata Redwood, and Orick 3 NNE) are located within 3.3 miles (5.3 km.) of one another at altitudes between 50 and 150 feet (15.2 and 45.7 m.) above sea level and yet their annual rainfall accumulations usually differ from one another by 10 to 20 percent.

Available data indicate that the higher parts of the Redwood Creek basin in general do get more rain than the area near Orick, but that orographic influences cause extreme local variations in precipitation amounts. The eastern and western drainage divides of Redwood Creek near the southern boundary of Redwood National Park received between November 1973 and April 1974 between 25 and 30 percent more rain than Prairie Creek State Park (Iwatsubo and others, 1975). The average annual accumulation in a storage precipitation gage maintained by the California Department of Water Resources near Board Camp Mountain was 103.37 inches (2626 mm.) (standard deviation of 24 inches (610 mm.) or about 23 percent of the mean accumulation) during a 9-year period between 1964 and 1972. These data suggest that Board Camp Mountain receives about 1.5 times as much precipitation as Prairie Creek State Park. Orographically induced vagaries in precipitation amounts are well illustrated by records from the stream gaging site on Redwood Creek near Blue Lake (O'Kane). Partial precipitation records collected since 1956 by the California Department of Water Resources (Calif. Dept. Water Res., 1956-1973; National Weather Service, 1974) suggest that this site receives only about 92 percent as much rain as Prairie Creek State Park.

The seasonal distribution of precipitation within the Redwood Creek basin is characterized by a winter rainfall maximum and a pronounced summer drought (fig. 25). About 77 percent of the annual precipitation at Orick-Prairie Creek State Park during water years 1954 through 1973 fell between November and March whereas only about 5.2 percent fell between June and September (fig. 25). The mean monthly precipitation figures at this station indicate that some rain has fallen in every month. The figures for the summer months, however, are strongly weighted by a few unusual storms. In fact nearly every summer is characterized by a completely rain-free period or periods of more than 30 days' duration.

Some moisture is added to the soil in the northern third of the Redwood Creek basin during rainfree-periods in summer by light drizzle and dripping condensation associated with persistent coastal fog. The amount of moisture delivered to the forest floor by fog drip is highly variable from place to place. Between July 4 and September 15, 1970 fog drip produced about 0.12 inches (3 mm) of moisture at the 1200-foot (365.8 metre) level, only a trace of moisture at the 1000 foot (304.8 metre) level, and no moisture at all at the 800-foot (243.8 meter) level on the forested hillside south of Berry Glen (Freeman, 1971). In contrast, quite substantial amounts of moisture have been produced from Pacific coastal fog drip in areas north and south of Redwood Creek (Ruth, 1954; Parsons, 1960). Even when the direct contribution of moisture to the forest floor by fog drip is small, fog does lessen summer soil-moisture stress by reducing the total radiation and by causing the radiation that is received to evaporate surficial moisture on vegetation surfaces before inducing evapotranspiration (Black, 1967). Summer-moisture conditions on the higher ridges in the northern third of the basin and throughout most of the southern two-thirds of the basin are not directly influenced by the fog.

Thunderstorms occur infrequently and are associated more with the passage of cold fronts in late summer and autumn than with mid-summer thermal convection cells. Many of the thunderstorms in the environs of Redwood Creek are associated with little or no rain. The critical dry season with respect to fire hazard and moisture stresses on vegetation is immediately prior to the start of major autumn storms, when warm daytime temperatures persist but coastal fog occurs less frequently than during the summer months.

Nearly all of the precipitation in the Redwood Creek basin is rain because of the prevailing mild temperatures (fig. 25). Moreover, most runoff-generating storms in this basin, especially storms producing major floods, are associated with warm air masses (Rantz, 1959; Hofmann and Rantz, 1963; Waananen and others, 1971; Wagner, 1972; Dickson, 1972). Coastal areas do occasionally experience light snowfall but in most years snow falls only above an altitude of 1750 feet (533.4 m.) and persists only above an altitude of 3500 feet. Snow accumulations usually do not exceed two feet. Snow storage and melt, thus, have only a minor impact upon runoff in Redwood Creek because typically less than 25 percent of the drainage basin has a significant snow pack, and because the snow pack contains relatively little water relative to the amount of rain associated with warm, flood-producing storms.

The large amounts of annual precipitation received by the Redwood Creek basin primarily reflect a large number of regional storms of light to moderate intensity. During the interval encompassing the 1954 through 1973 water years, the annual average number of rainy days at Orick-Prairie Creek State Park was about 122; about 23 days each year had more than an inch of rain and only about 6 days each year had more than two inches (51 mm.) of rain (fig. 26). The intensities of short duration (one-hour or less) rainfalls are low, but the intensities of 6-hour and longer rainfalls are moderately high compared to the nation as a whole (Hershfield, 1961). Once every two years rainfalls with durations of six hours and 24 hours can be expected to produce within the Redwood Creek basin at least 2.0 to 2.6 inches (51 to 66 mm.) and 4.5 and 6.0 inches (114 to 152 mm.) of rain respectively. Likewise, once every 10 years rainfalls

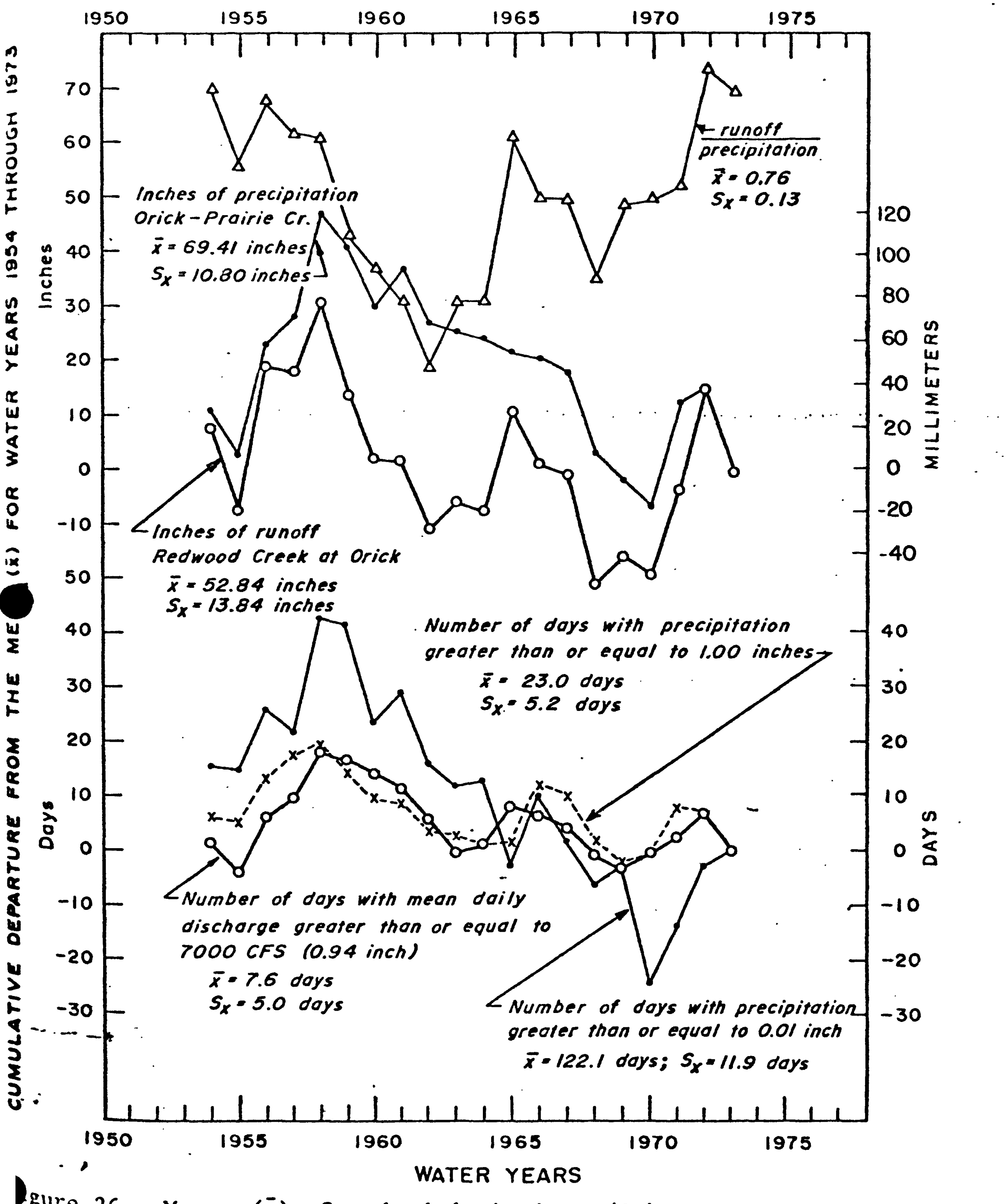

Figure 26. Means ($\bar{x}$), Standard deviations (S_x) and cumulative departures from the mean for selected rainfall and runoff parameters measured at Orick-Prairie Creek Park and Redwood Creek at Orick for water years 1954 through 1973.

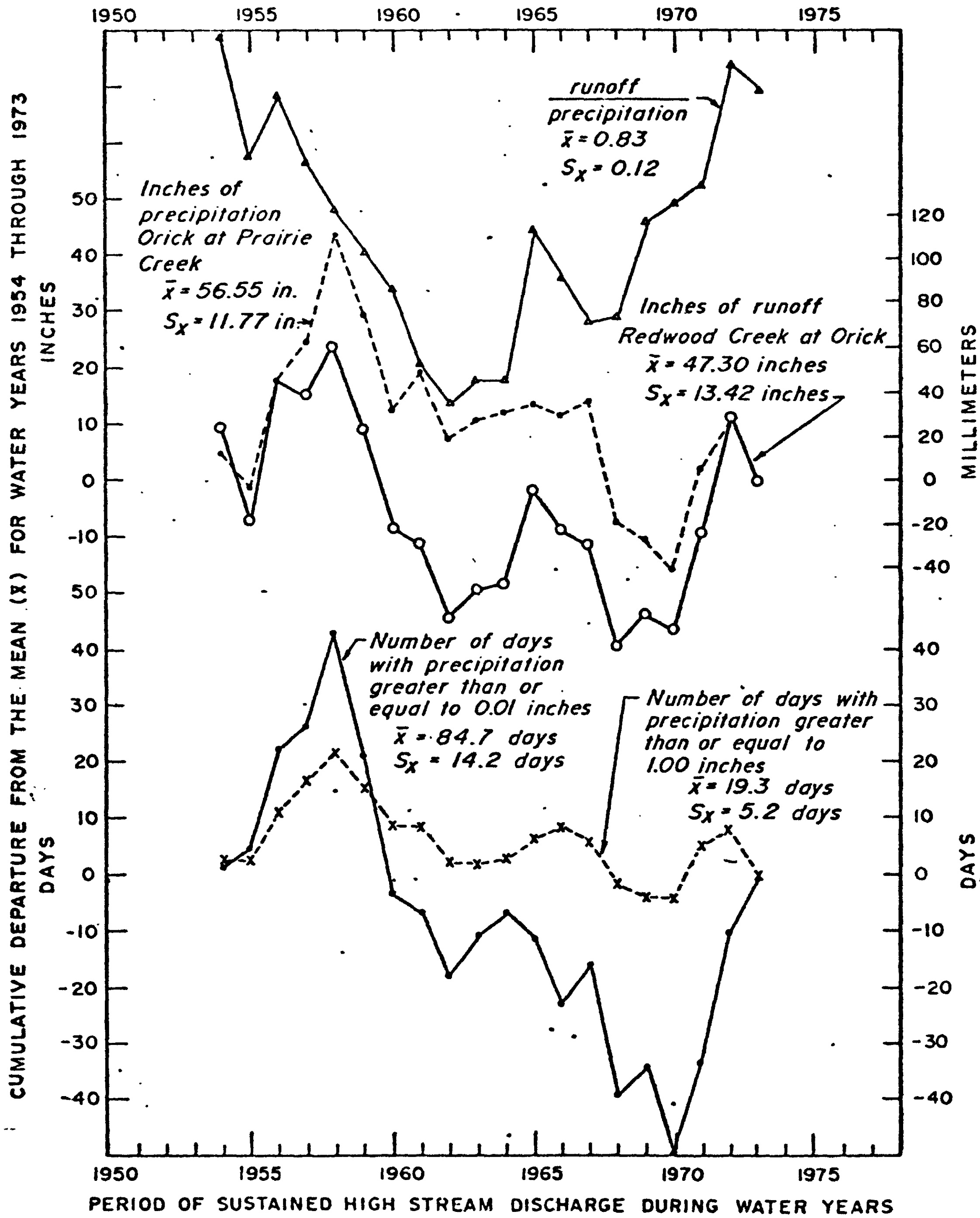

Figure 27. Means ($\bar{x}$), Standard deviations (S_x) and cumulative departures from the mean for selected rainfall and runoff parameters measured at Orick, Prairie Creek Park and Redwood Creek at Orick for periods of sustained high stream discharge during water years 1954 through 1973.

with durations of six hours and 24 hours will produce 2.8 to 3.4 inches (71 to 86 mm.) and 7.0 to 8.0 inches (178 to 203 mm.) of rain respectively (Miller and others, 1973). The most intense rainfall occurs in areas with the largest mean annual precipitation. Similarly, the rainfall patterns of most major winter storms rather closely reproduce the gross features of the mean annual pattern (Gilman, 1964). Individual storms, nonetheless, display their own individual characteristics. For example, the flood-producing rains of December 1955 and December 1964 appear to have been most intense in the interior part of the Redwood Creek basin, whereas the flood-producing rains of January 1953 and March 1972 appear to have been most intense in the coastal areas.

Wind speed exerts a major influence on evapotranspiration, and additionally has a strong impact on many biologic and erosional mechanisms operating within the Redwood Creek basin because redwood trees are readily damaged and toppled by high winds (Stone and others, 1969). Wind damage on the average accounts for about 54 percent of the annual mortality of growing stock and saw timber on commercial forest land in Humboldt County (Oswald, 1968). The pits and mounds associated with the root masses of the wind-toppled trees represent a discrete process of downslope soil creep (Denny and Goodlet, 1956). The exposed mineral soil in these scars serves as a good seed bed for new redwood and Douglas-fir (Stone and Vasey, 1967).

Wind-toppled trees also occasionally influence fluvial erosion processes by diverting or blocking existing drainage channels, and generating ephemeral seeps that erode rills or shallow gullies. Despite the economic, ecologic, and geomorphic significance of high winds, wind direction and speed have not been measured within the Redwood Creek basin in part because these parameters are influenced to such an extreme degree by topography.

The nearest quantitative wind data are collected on the coastal plain at Eureka where orographic influences are minimal. Average winds at Eureka are light although strong winds occasionally accompany severe storms. Winds at Eureka during a three-and-a-half-year study were calm about 22 percent of the time, from the north or northwest about 29 percent of the time, and from the southeast or south about 19 percent of the time; southeast winds were most prevalent during November through March, whereas north and northwest winds were most prevalent from April through October. The Eureka data led to the suggestion that areas that are neither protected nor unusually exposed can expect winds of 40 to 50 miles per hour (64 to 80 kilometres per hour) about once every two years and winds of 80 to 90 miles per hour (129 to 145 kilometres per hour) about once every century (National Weather Service, 1974). The strongest, most damaging winds are from the southerly quarter and are associated with the approach of cyclonic storms. Particularly damaging winds accompanied major storms in 1955, 1962, and 1964.

Wind patterns within the Redwood Creek basin and other mountain areas are more complex than those on the Eureka coastal plain. During periods of calm, diel heating and cooling of the air creates density differences that lead to upslope and upvalley winds during the day, and downslope and downvalley winds during the night. During windier periods, the diel downvalley-upvalley circulation is less prominent, but the wind patterns are still quite complex. Topographic irregularities locally concentrate the flow of air and create turbulence. Turbulence intensities are generally greatest on the immediate lee side of ridges and on the middle portion of both the lee and windward hillslopes (Stone and others, 1969). Breaks in vegetation such as occur at the edges of clearcut blocks can also accentuate wind turbulence (Stone and others, 1969). Although the wind patterns within the Redwood Creek basin are poorly documented, the greatest concentration of wind-toppled trees appears to be in areas of unstable regolith in topographic situations exposed to relatively high wind velocities. Wind-toppled trees are not abundant on exposed sites underlain by stable regolith.

RECENT FLUCTUATIONS IN RAINFALL AMOUNT AND INTENSITY

In order to place recent rainfall patterns into a long-term historical perspective, we have plotted graphs of cumulative annual departures from the mean annual precipitation (fig. 28) for the total length of record for Orick-Prairie Creek State Park and several nearby weather stations with records going back to the late nineteenth century. The records included in this comparison are Eureka, a combined record from Crescent City 7ENE, Crescent City 8 NE, and Crescent City 1N, and a combined record from Fort

Gaston and Hoopa. The Eureka record is probably the most reliable standard for comparison as the other records involve rather complicated station histories. Different stations collected data for different intervals of time, so in order to generate comparable departures, means computed for the twenty-year period 1954 through 1973 were used in this analysis. Cumulative departures from the mean rather than moving averages were used to show historic trends in precipitation because no evidence exists to show that annual precipitation totals in this area are serially correlated, and because moving averages build in time dependence over and above that already present (Dawdy and Matalas, 1964). The slope of a graph of cumulative departures from the mean (fig. 26, 27, and 28) conveys significant information. An upward slope indicates greater than average precipitation,

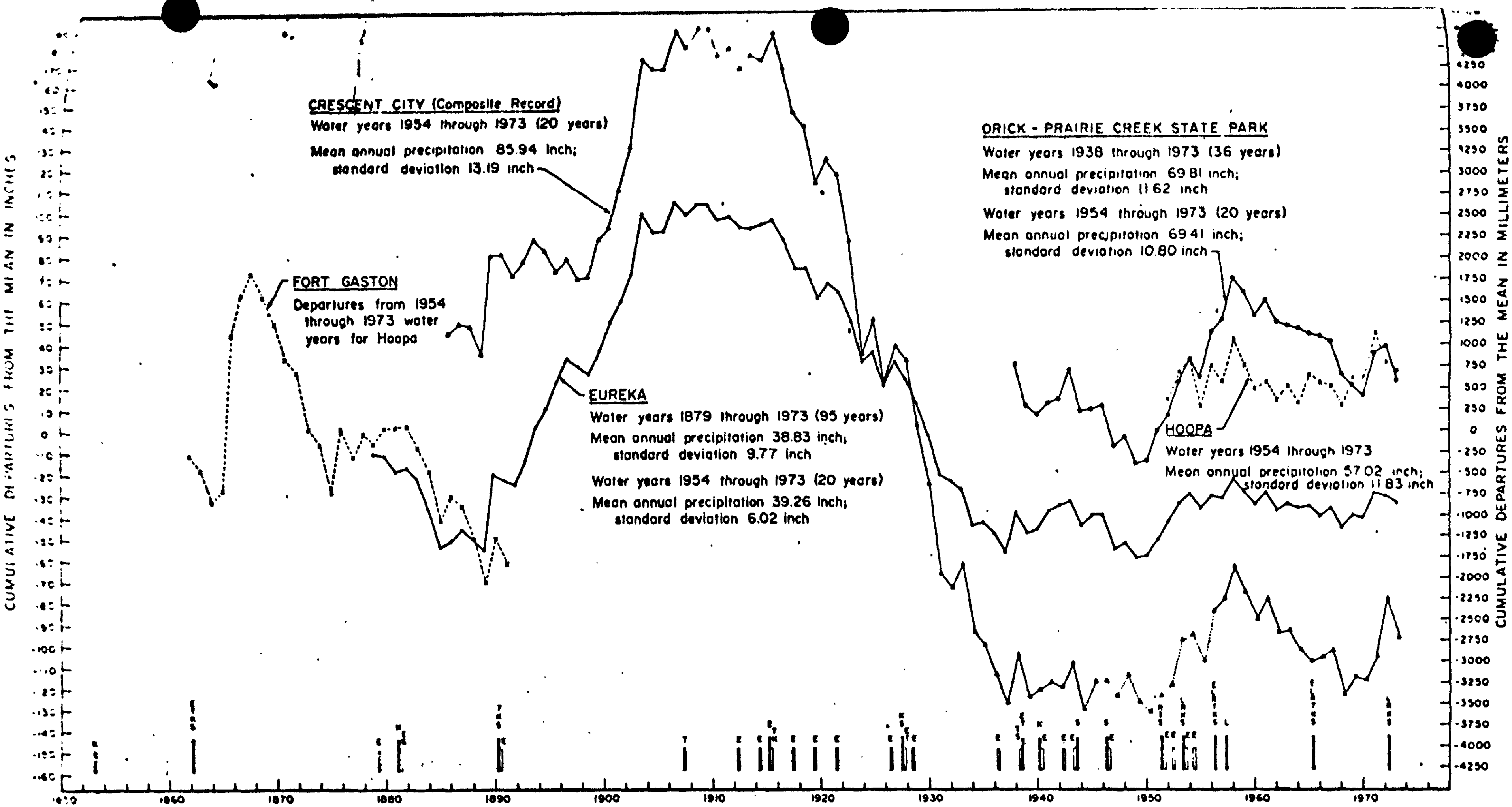

Figure 28. Historical record of annual rainfall and major floods for northwestern California. Graphs of cumulative annual departures from the mean annual rainfall are shown for Fort Gaston-Hoopa, Crescent City, Eureka, and Orick-Prairie Creek Park. All means are computed for the common interval, 1954 through 1973. Flood producing storms are shown in relation to the flood of December 1964. Solid bars indicate floods at least 40 percent as large as that of 1964, and open bars indicate floods at least 20 percent as large as that of 1964. Rivers are indicated as follows: S, Smith River; K, Klamath River; T, Trinity River; R, Redwood Creek; L, Little River; and E, Eel River.

whereas a downward slope indicates less than average precipitation. The actual plotted points for any given year, however, are of little significance on such graphs.

The entire Orick-Prairie Creek State Park precipitation record displays a pattern of cumulative departures from the mean that closely resemble that displayed by records collected in the surrounding area, even though those records were collected in grossly different physiographic situations.[1/] Assuming that this similarity in behavior has characterized the entire period of precipitation record collection in northwestern California (1861 to present), figure 23 can be used to imply periods of generally greater than average precipitation and periods of generally less than average precipitation in the Redwood Creek basin. Generally wet periods include 1865 through 1868, 1900 through 1904, and 19[illegible] through 1958, and exceptionally wet individual years include 1866, 1876, 1890, and 1904. Generally dry periods include 1869 through 1875, 1882 through 1889 and 1917 through 1937. Periods characterized by generally erratic fluctuations about the mean include 1876 through 1882, 1890 through 1899, 1905 through 1916, and 1938 through 1950. The period 1959 through 1968 generally was characterized by average or less than average

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1/ These physiographic differences probably account for the fact that absolute precipitation amounts for individual years and storm periods at the different weather stations correlate in only a general way. Regression relations between mean annual precipitation at Orick-Prairie Creek State Park and mean annual precipitation at Eureka, at Crescent City, and at Hoopa for water years 1954 through 1973 are as follows:

$(OP) = 8.21 + 0.45\ (EK);\ r^2 = 0.65$ r^2 = Coefficient of determination

$(OP) = 4.45 + 0.76\ (HP);\ r^2 = 0.48$ All values in inches

$(OP) = -11.70 = 1.14\ (CEC\ IN);\ r^2 = 0.70$

$(OP) = 11.32 = 1.08\ (CEC\ 7ENE);\ r^2 = 0.78$

(OP) = Orick-Prairie Creek, EK - Eureka, HP = Hooper

CEC IN = Crescent City IN, CEC 7ENE = Crescent City 7ENE precipitation, and the period 1969 through 1971 was generally wet. The 1972 water year in northern and coastal parts of this area was also wet. The 1973 water year, in contrast, was dry throughout northwestern California. Given the added perspective provided by the fact that the 1974 water year was one of the wettest on record, the most characteristic feature of the precipitation records in the period since 1968 appears to be the extreme variability of annual rainfall.

Annual fluctuations in both the total number of rainy days and the number of days with more than one inch of rain during the 1954 through 1973 period at Orick-Prairie Creek State Park show patterns that closely mimic that shown by the total amount of annual precipitation (fig. 26). The occurrence of major flood-producing storms, nonetheless, is not restricted to the generally wet periods. In fact, only the regional floods of October 1950, January 1953, and December 1955, and the March 1957 flood in the Little River basin occurred during these wet periods. The flood of December 1964, the largest well-documented flood to occur during the entire period of historic observation throughout most of northwestern California, occurred during a year of average or even slightly less than average precipitation.

Except for unusually variable annual rainfall amounts, rainfall patterns during the last 25 years do not appear to have been significantly different from those that prevailed earlier in the record. Considerations of watershed conditions visible on 1936 and 1947 aerial photographs of the Redwood Creek basin, as well as remarks by area residents concerning the "exceptional" severity and frequency of storms since 1950 must be carefully weighed in light of the unusually long period of relatively dry, and storm-free conditions that prevailed prior to these observations.

VEGETATION

The productive soils, moderate temperatures, and seasonally abundant moisture of the Redwood Creek drainage basin support a naturally dense and complete mantle of forest, woodland, and prairie vegetation. Most of the undisturbed forest and woodland sites within this basin have dense understory vegetation as well as trees. Mineral soil is exposed under natural conditions only where the vegetal cover is disrupted by various forms of mass movement or lateral corrosion.

The natural vegetation in the drainage basin has been extensively modified by man. As of April 1975 about 65 percent of the drainage basin was cutover forest land. Most of the logging occurred during the last 25 years and the dominant silvicultural methods have been clearcutting and seed-tree-leave logging. Virgin forests cover about 20 percent of the basin, and prairies, woodland, and brush cover the remaining 15 percent.

The individual plant species in the Redwood Creek basin tend to occur in distinctive groups or communities that appear to reflect both regional climatic gradients and local site conditions such as altitude, proximity to the ocean, slope aspect, topographic position, and slope stability. The overall distribution of plants within the basin resembles that found throughout coastal northern California and southwestern Oregon. In fact, the vegetation communities, except the redwood-dominated forest in the downstream end of the basin, can be reasonably compared with vegetation communities in the Picea sitchensis, Tsuga heterophylla, Interior Valley, Mixed-Evergreen, and Mixed-Conifer Zones of Franklin and Dyrness (1969). The species composition of the vegetation of most of the Redwood Creek basin is shown on 1:31,680 maps prepared by California Cooperative Soil-Vegetation Survey (1959-1962). Moreover detailed 1:24,000 timber-type maps were prepared by Hammon, Jensen and Wallen (1967) for that part of the basin within and adjacent to Redwood National Park. A generalized 1:760,320 map of "Vegetal Cover Types" is included in the U.S. Department of Agriculture's (1970) report on the water, land, and related resources of north coastal California.

Before the forests on the lower flood plain of Redwood Creek near Orick were cleared for pasture, sitka spruce (*Picea sitchensis*) dominated the vegetation. The remaining spruce appears to tolerate the salt spray and high water table. On particularly windy sites near the estuary, shore pine (*Pinus contorta*) is also present. On more mesic sites and and where the influence of wind-borne salt is reduced, redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*) are the dominant flood plain conifers and sitka spruce becomes an associate.

Redwood with its common associate Douglas-fir dominates the upland vegetation of the basin from near the Pacific shore to approximately ten miles (16 kilometers) inland.

Farther inland, redwood-dominated vegetation is restricted to relatively moist flood plains, low stream terraces, and lower hillslopes adjacent to the main channel and its principal tributaries in the downstream half of the basin. Isolated redwood trees occur adjacent to the main channel as far upstream as the mouth of Snow Camp Creek, but the upstream-most groves of redwood-dominated vegetation are on the flood plain of Redwood Creek near Stover Ranch, and on north-facing hillslopes in the lower Lacks Creek basin. Natural environmental controls on the vegetation mosaic within the redwood-dominated vegetation are discussed in detail by Waring and Major (1964) and Becking (1967).

Although nearly pure stands of redwood are the essence of the layman's vision of the primordial redwood forest, such stands are extremely limited in nature. Some Douglas-fir is almost always associated with the redwood; hemlock (Tsuga heterophylla), grand fir (Abies grandies), and tanoak (Lithocarpus densiflora) are also common. Port Orford cedar (Chamaecyparis lawsoniana) and madrone (Arbutus menziesii) occur locally within the redwood-dominated vegetation. Black cottonwood (Populus trichocarpa), big leaf maple (Acer macrophyllum), California bay (Umbellularia californica), hazel (Corylus cornutta), large red alders (Alnus rubra),and willows (Salix spp.) occur on riparian sites. Thickets of young alders occur in a variety of moist localities but are particularly characteristic of areas where mineral soil has been exposed by recent overbank stream deposition, mass movement, timber harvest, and road construction. Thickets of tanoak and (or) red alder have locally retarded coniferous regeneration in some cutover land within the basin. Red alder also appears to the dominant pioneer plant on recent flood berms of sand and gravel, although lupine (Lupinus, spp.), Douglas-fir, and tanoak are additionally present on young berms in the downstream half of the basin. The alders and tanoak are probably seral stages in these situations because some stream gravel deposits and landslide scars that are on the order of 50 to 200 years old bear dense, apparently even-aged, pure stands of young Douglas-fir.

Slope-aspect control of the size and abundance of individual redwood trees in the forests of the lower Redwood Creek basin is readily apparent on vertical aerial photographs and in the field (fig. 29). With regard to the redwood-dominated forest immediately adjacent to the main channel of Redwood Creek, Stone and others (1969, p. 17) noted, "The vegetative cover on the two sides of the creek differs significantly. On the south side, stand density is greater, the percentage of redwood in the stands is higher, and the average age of the trees is older. On the north side there are relatively few windfall trees on the ground. In contrast, on the south side there are several places where 20 percent or more are down." These differences probably reflect slope-aspect control of microclimate, rather than differences in soil parent materials as these differences in vegetation can be observed when the same parent material is present on both sides of the creek. Furthermore, comparable slope-aspect controlled differences in redwood-dominated vegetation can be observed in tributary basins draining a single rock type. In the tributaries, north- and east-facing hillslopes bear more and larger redwoods than south- and west-facing hillslopes. These differences can be observed in both sandstone terrane and schist terrane.

The seed mixtures utilized to restock some recently cutover land in and adjacent to Redwood National Park could conceivably have at least a temporary impact upon the successional status of adjacent redwood-

Figure 29

Figure 29. 1936 Aerial photograph showing hillslope aspect control of the size and abundance of individual redwood trees in the lower part the drainage basins of Fortyfour Creek, Miller Creek, and Bond Creek. North is toward the top of the photograph. Location is shown of figure 12.

dominated vegetation within the park. For a variety of silvicultural and economic reasons, the proportion of Douglas-fir and sometimes sitka spruce is much larger in these seed mixtures than in the origihal forest. Stone and others (1969, p. 67) suggested that, from the point of view of protecting park resources, redwood should be the favored species in the initial restocking of cutover lands adjacent to the park. Redwood second growth would lessen the potential for insect invasion and fire hazards as well as minimize problems associated with restocking following subsequent cutting cycles.

At least two exotic large plants are present in the downstream half of the Redwood Creek basin. Monterey pine (Pinus radiata) has been used by timber companies working east and southwest of Redwood National Park to stabilize actively eroding cut banks and fill slopes. A few of these pines are in cutover land near Berry Glenn within the park. Pampas grass (Cortaderia selloana) occurs sporadically along some roads in cutover land on the western side of the basin. Some occurs along the trail to the Tall Trees Flat.

On slightly drier sites farther upslope and farther inland, redwood becomes smaller and less abundant. As a corollary, the species composition of the forest trees becomes more varied. Douglas-fir, hemlock, tanoak, and madrone are the first trees to become more abundant. Throughout most of the Redwood Creek basin, Douglas-fir is the dominant conifer.

In the still higher more continental southern and southwestern parts of the Redwood Creek basin, Douglas-fir remains a prominant part of the forest vegetation, but the associated trees are quite different from those that are prevalent in the more maritime parts of the basin. Redwood, western hemlock, Port Orford cedar, and grand fir are not present. Instead the common associates of Douglas-fir are white fir (Abies concolor), incense cedar (Libocedrus decurrens), and black oak (Quercus kelloggii). A few isolated Pacific yew (Taxus brevifolia) occur in riparian sites. Giant chinquapin (Castanopsis chrysophylla), canyon live oak (Quercus chrysolepsis), vine maple (Acer circinatum) and poison oak (Rhus diversiloba) are locally abundant especially on dry and (or) stony sites. Recent flood berms of sand and gravel are being colonized by incense cedar, madrone, and Douglas-fir.

The non-canopy vegetation, although not of any direct commercial value, does play a role commensurate with that played by the canopy trees in intercepting rainfall and physically holding the mineral soil in place. The understory and ground-covering vegetation is usually quite dense and varied in composition at most forested sites within the basin, except in extraordinary dark conditions in some old-growth redwood groves, and in some parts of the inland Douglas fir - white fir - incense cedar forest. Moreover, the noncommercial, nonarboreal plants exert great influence on the visual characteristics of the firest.

Under the darkest conditions associated with some flood plain and lower hillslope groves of redwood, the understory is limited to a sparse cover of oxalis (Oxalis oregana) and sword fern (Polystichum munitum).

Under more open conditions associated with stands of mixed species composition on mid-slope and upper slopes sites, the understory and ground-covering vegetation is more dense and varied. Common plants, in addition to oxalis and sword fern, include rhododendron (Rhododendron macrophyllum), black huckleberry (Vaccinium ovatum), red huckleberry (Vaccinium parvifloium), salal (Gaultheria shallon), azalea (Rhododendron occidentale), hazel (Corylus cornuta var. californica), dogwood (Cornus nuttallii), Oregon grape (Berberis, sp.), and several types of berries (Rubus spp. and Ribes spp.). A variety of small ferns and flowering herbaceous plants also occur commonly at moist sites, especially in association with fallen trees and stream banks. Vine maple (Acer circinatum), chinquapin (Castanopsis chrysophylla), blueblossom (Ceanothus thyrsiflorus), manzanita (Arctostaphylus spp.), and poison oak (Rhus spectabilis) become more abundant in the inland forest. In general the forest understory at inland sites is not as lush as that at sites nearer the coast.

Areas of natural prairie and woodland vegetation are intimately associated with forested areas throughout most of the basin. Nonforest vegetation occurs, however, more commonly (1) on sedimentary rocks than on metamorphic rocks, and (2) in inland parts of the basin than near the coast. Furthermore, areas bearing these vegetation communities are larger and more abundant on south- and west-facing hillslopes than on north- and east-facing hillslopes. Likewise, these vegetation communities are more common on ridge crests than on lower hillslopes. Even in these nonforested areas the vegetal cover usually effectively protects the underlying mineral soil from erosion except where that soil has been exposed by recent mass movement, road construction, or over-grazing.

The most common communities of nonforest vegetation are grass prairies, grass-bracken fern (Pteris aquilina) prairies, oak (both Quercus garryana and Q. kelloggii) - grass woodland, oak-poison oak - grass woodland, and oak-madrone - brush woodland. The native bunch grass-herb flora has been largely replaced by introduced annual grasses and weeds that are more tolerant of heavy grazing (Munz and Keck, 1968). By far the most common elements of the brush flora are various species of Ceanothus and Arctostaphylos. Coyote brush (Baccharis pilularis), wild rose (Rosa, sp.) and birchleaf-mountain mahogany (Cerocarpus betuloides) are also present. Isolated individual Douglas-fir trees are scattered throughout the expansive brush areas, and groves of Douglas-fir are common on north-facing hillslopes within these areas (fig. 11 & 30). Brush has heavily invaded some cutover land that formerly bore Douglas-fir forest of the basin. Ceanothus is a major component on particularly dry sites in the southeastern part of the invading brush.

Although dense growth of alders and Ceanothus have retarded coniferous regeneration in some cutover land within the Redwood Creek basin, this seral invasion by noncommercial plants does have some associated benefits. These plants become established rapidly and retard surface erosion. Moreover, nitrogen-fixing bacteria in root nodules of these plants put considerable nitrogen in the soil in a form that can be readily utilized in the growth of subsequent commercial conifers.

Figure 30 Hillslope aspect- control of 1936 vegetation patterns near the mouth of Minor Creek. Douglas fir dominated forests are concentrated on the north-facing hillslope. Location is shown on figure 12.

The origins of the grass and grass-bracken fern prairies are obscure. ss movement (Colman, 1973), natural and Indian-set fires (Lewis, 1973) d lateral variability in soil parent materials (Zinke, 1966) have obably all played a role. Persistence of the grasslands can reasonably e attributed to plant-microclimate interactions and grazing by elk, er, and domestic cattle. Nonetheless, most of the prairies display border of oak-brush woodland and (or) young Douglas-fir suggesting at the grasslands were formerly more extensive (fig.7,15,31). This ggestion in turn raises the possibility that the present distribution of airies may partly be a function of Holocene climatic fluctuations and n-induced fire-control measures.

Considerable public interest focusses on some particularly tall dividual trees as well as upon the overall vegetation mosaic in the dwood Creek basin (Zahl, 1964; Becking, 1967). Particularly noteworthy a redwood growing on the upper flood plain of Redwood Creek opposite e mouth of Tam McDonald Creek. This tree was 367.8 feet (112.1 meters) ll in 1964 and said to be the world's tallest living thing (Zahl, 1964). ree other exceptionally tall redwoods were measured at the same time. eir heights of 367.4 feet (112.0 meters), 364.3 feet (111.0 meters), d 352.3 feet (107.4 meters) ranked them as the second, third, and sixth llest trees in the world. The second tallest tree is in a flood-plain ve opposite the mouth of Fortyfour Creek, while the third and sixth llest trees are in the same grove as the tallest. Becking (1967) mentions

Figure 31 1936 vegetation pattern in the drainage basin of Cayote Creek. Forest are denser on north facing hillslopes. Prairies are more abundant on south and west, facing hillslopes and on ridgetops. Most prairies are rimmed with brush and (or) thickets of young Douglas firs. Location is shown in figure 12.

other tall redwoods as well as some exceptionally tall Douglas-fir, grand fir, and hemlock trees in flood-plain groves along lower Redwood Creek. Perhaps too much emphasis is placed upon the measured heights of these trees, because growth, storm damage to their crowns, and deposition of alluvium at their bases cause frequent changes in height. At any rate, an exceptionally large number of redwoods and associated conifers on flood plains along Redwood Creek have grown to remarkable heights.

RESOURCE UTILIZATION AND RELATED LANDSCAPE CHANGES

GENERAL

The forested landscape of the lower Redwood Creek basin with its magnificent trees, complex vegetation mosaic, and free-flowing streams has been recognized as a valuable park resource and some downstream parts of the basin have been set aside in Prairie Creek State Park and Redwood National Park for the purpose of public inspiration, enjoyment, and scientific study. The timber, grazing land, fish, and stream gravel of the basin, however, are resources of more clearly definable economic value. Utilization of some of these economic resources has occasionally caused adverse impacts on downstream park resources.

TIMBER

The timber of the Redwood Creek basin is unquestionably its resource of greatest economic value. Harvesting of this resource requires construction of timber access roads, and the falling, yarding[1/] and physical removal of the forest trees. In the past, these activities have frequently been carried out in a manner that leads to accelerated erosion, which in turn poses a direct threat to the soil resources at the site of timber harvest and an indirect threat to many downstream resources, including park resources.

The rugged topography of the Redwood Creek basin and its remote location relative to early lumber mills and centers of population effectively placed the basin's timber in a reserve status until the 1930's. Logging in the late nineteenth and early twentieth centuries mostly involved clearing of the forest from flood plains, low terraces, and areas adjacent to natural prairies in order to create more grazing land. The most striking example of commercial timber harvest visible on aerial photographs taken in 1936 is an active or recently completed cable yarded clearcut involving more than 3000 acres of the headwaters of Devils Creek and Panther Creek (fig. 32) ~~and an even larger area in~~ ~~the adjacent basins of Little River and Maple Creek.~~ A small portion

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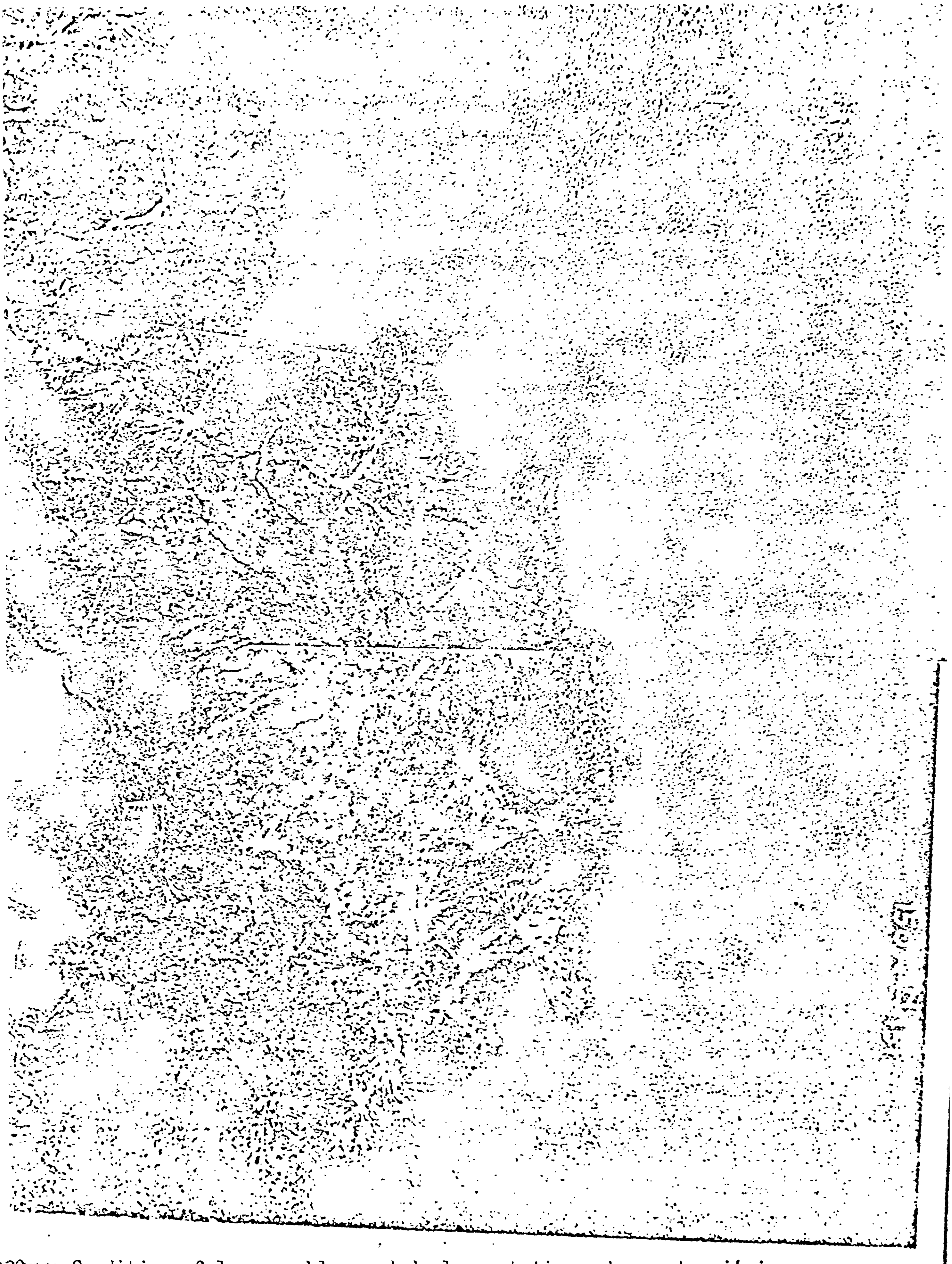
1/ Yarding is the transporting of fallen logs, usually by dragging, to storage areas from which they may subsequently be transported by truck.



re 32a.--Condition of large cable-yarded clearcut timber-harvest unit in drainage basins of Devils Creek and Panther Creek in 193?, shortly after logging.

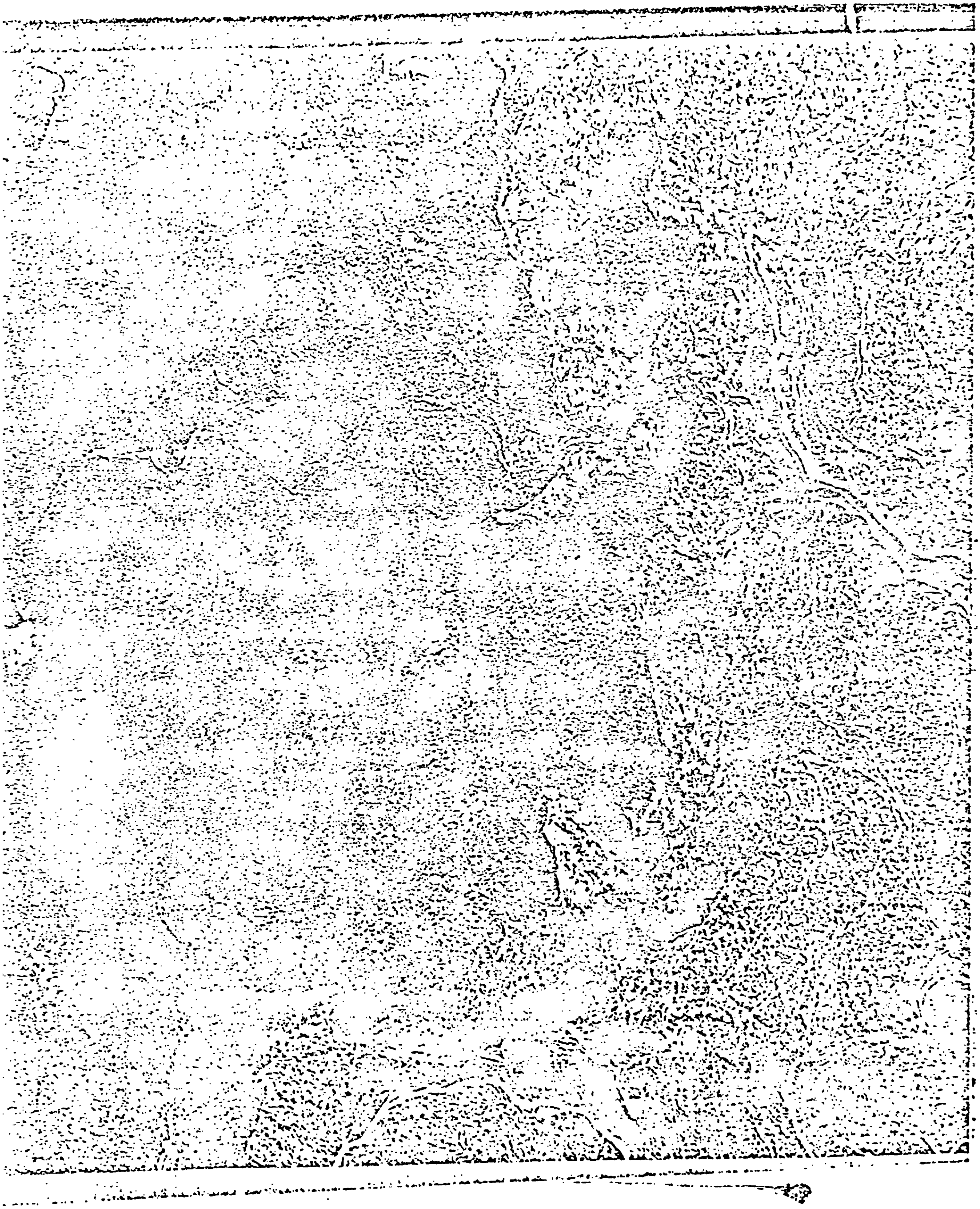


Figure 32b.- Condition of large cable-yarded clearcut timber-harvest unit in the drainage basin of Devils Creek and Panther Creek in 1975.

of the timber removed from this cut was yarded downhill by skidding the logs with tractors. Other pre-1936 timber harvest units within the Redwood Creek basin include a several hundred acre clearcut in the headwaters of Pardee Creek north of Snow Camp Lake and several hundred acres of selective logging above the Redwood Valley Road southwest of the mouth of Minor Creek. All told less than three percent of the total basin appears to have been logged prior to 1936.

Aerial photographs of the Redwood Creek basin, and ground photographs of nearby areas assembled by the California Division of Forestry (1972)[1/] indicate that these early timber harvest activities were associated with large clearcut units, heavy concentrations of slash, and intense localized ground disruption around landings and primary cable ways (skid trails). Large tracts of mineral soil were exposed by the yarding operations and subsequent slash burning. However, except at localized sites of concentrated disturbance, the surface drainage pattern and the general configuration of the land surface were modified much less drastically in these early timber harvest units than in the large scale tractor yarded clearcuts of the 1960's and early 1970's (Earth Satelite Corp., 1972; fig. 33, 34, and 35).

A comparison of the 1936 aerial photographs with similar photographs obtained during the summer of 1947 indicates that timber harvest was continuing at a moderate rate. Several hundred acres of forest on the northwest side of the Devils Creek basin were apparently selectively logged early in the intervening period. Several other blocks of timber, all of them less than a few hundred acres in size, apparently were harvested late in this period in the headwaters of High Prairie Creek, Lupton Creek, and Minor Creek, as well as on the east-facing slope between Wiregrass Ridge-Lord Ellis Summit and Redwood Creek. The dominant

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1/ Alfred Merril of Louisiana-Pacific Corporation has shown the present authors comparable photographs of the lower Little River basin near Crannel taken immediately following logging and again in the early 1970's.

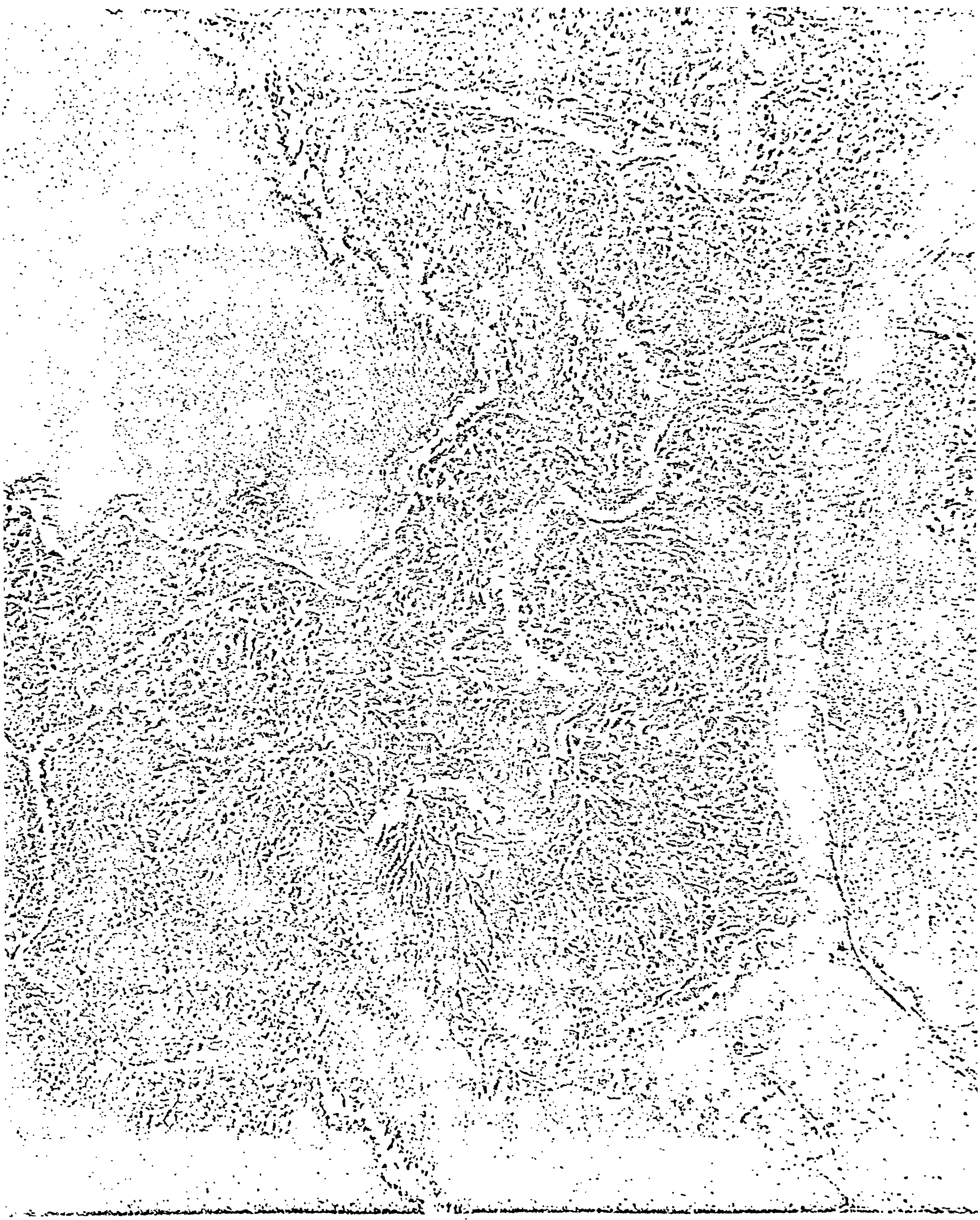
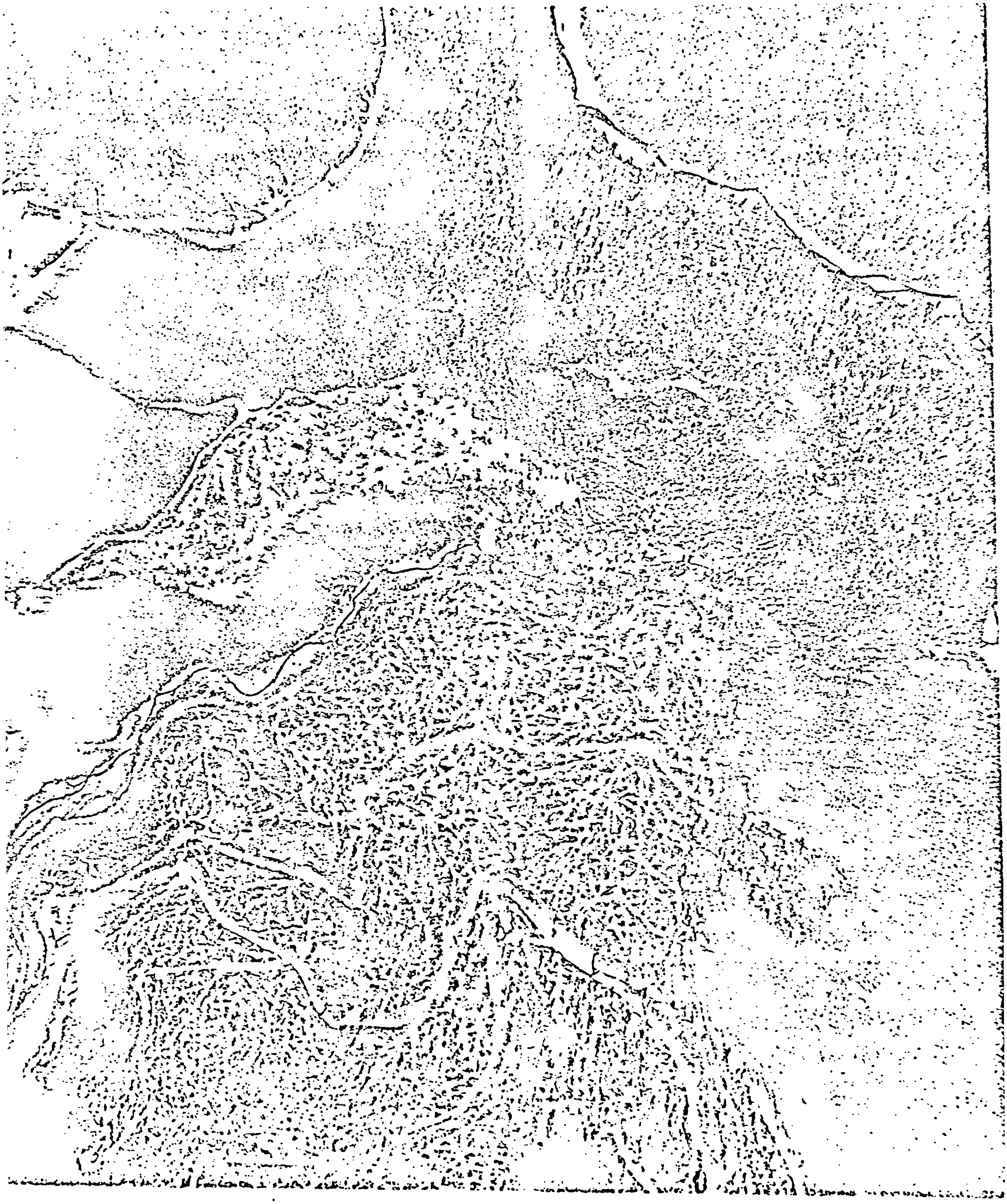


Figure 33. Tractor- yarded clearcut timber harvest in the headwaters of Miller Creek



iqure 34. Tractor- yarded clearcut timber harvest in the lower part of the Bridge Creek basin

Figure 35. Tractor- yarded clearcut timber harvest in the drainage basin of Copper Creek

harvesting procedures appear to have been selective cutting or a seed-tree-leave (modified shelterwood) system coupled with downhill yarding using track-laying tractors. Well less than five percent of the total Redwood Creek basin had been logged by 1947. The first large-scale, tractor-yarded clearcut in the vicinity of Redwood Creek, consisting of a few thousand acres in the headwaters of the north fork of Maple Creek immediately west of the headwaters of Bridge Creek, was discernible on the 1947 aerial photographs.

The cable yarded clearcut in the headwaters of Panther Creek and Devils Creek was, for the most part, well vegetated in 1947 and the streams draining the cutover area did not display excessive aggradation or an extraordinary number of streamside landslides. Some of the regenerating vegetation apparently consisted of thickets of hardwoods, rather than coniferous trees. The main haul roads, landings, cable ways, and skid trails were still unvegetated.

Intensive timber harvest began during the early 1950's in the upstream part of the Redwood Creek basin and during the late 1950's in the downstream part. As of 1973 only about twenty percent of the basin still bears old growth forest. In the upstream part of the basin, sizeable uncut blocks of old growth timber remain principally within Six Rivers National Forest. More expansive areas of uncut old growth forest exist in the lower portion of the basin, especially within Redwood National Park, on the steep west-facing slope of the Redwood Creek valley immediately adjacent to the park, and within the drainage basins of Bridge Creek, Devils Creek, and Lacks Creek.

During the late 1950's and early 1960's, timber harvesting procedures evolved toward using larger cutting blocks, use of bulldozer-constructed layouts (that is smooth "beds" into which trees are felled), and increased reliance on tractor yarding and clearcutting. The expansive tracts of recently harvested land reflect the combination of large annual harvest units and the sequential harvest of adjoining blocks of timber. Increased demand for redwood products led to an increase in the size of annual timber harvest units. Adjoining blocks of timber were harvested in successive years so as to minimize the costs associated with construction of roads through uncut timber to reach advanced cutting blocks.

Increased reliance on track-laying tractors in constructing layouts and in yarding logs to landings in part reflects the development of larger more powerful tractors, but other factors are involved. In the early logging of redwoods, trees were felled either without layouts or into layouts constructed from limbs and brush; this procedure did not protect the trees from the breaking and splitting to which they are susceptible because of their large size and the brittleness of the wood. Bulldozer-constructed layouts have been far more effective in preventing such breakage, and are now utilized throughout the redwood region.

Large track-laying tractors became the dominant form of yarding equipment in the redwood forests of northwestern California during the 1950's when selective cutting and natural reseeding were the most prevalent silvicultural systems used in harvesting and regenerating redwood forests. Large tractors proved to be versatile and effective tools for selectively cutting old-growth redwood forests. During that period the timber companies built up their inventories of large track-laying tractors and equipment capable of yarding massive redwood logs; these companies also acquired considerable experience and confidence in the operation of this type of equipment. Thus, it is not surprising that when in the 1960's the timber companies reverted back to clearcutting and even-age silvicultural management, they continued to rely on tractor yarding rather than acquiring new modern cable yarding equipment. Additional reasons given by the companies for preferring tractor yarding over cable yarding include the following:

1) Tractors (bulldozers) are needed anyway for construction of layouts, landings, and roads.
2) Excessively large redwoods are too bulky and heavy to be handled by all but the largest and most expensive cable systems.

3) Tractor yarding is more versatile than cable yarding in terms of terrain and property configuration.
4) More stem breakage is associated with cable yarding than with tractor yarding.
5) The operation of large yarding tractors is cheaper, faster, and safer than the operation of high lead or slack line cable yarding equipment.

The forestry staffs of the timber companies operating in the environs of Redwood National Park have discussed with the present authors an impressive number of silvicultural, practical, and economic reasons for using clearcutting in the harvest of the old growth redwood and Douglas-fir forests of the Redwood Creek basin. Most of these reasons have been presented in recent papers prepared by the California Division of Forestry (1972), and Arcata Redwood Company (1973). Basically, selective logging of old growth redwood and redwood-Douglas-fir forests in northwestern California was abandoned when industry and government foresters noted that the residual trees did not experience the rapid release of growth that was anticipated following thinning of the original stand. In fact, many of the residual trees sustained severe stem breakage or were toppled by wind storms. Furthermore, the residual trees did not always prove to be as reliable a seed source as was anticipated. Additional reasons given by timber industry spokesmen for utilizing clearcutting in the harvest of old growth redwood include the following:

1) Clearcutting is an extension of the population dynamics of the natural forest. Approximately even-aged stands of redwood and Douglas-fir occur naturally and appear to result from such natural catastrophes as floods, landslides, and fires.
2) Redwood and Douglas-fir seedlings can be more successfully established in bare mineral soil than in forest humus; Douglas-fir seedlings do well in sunny locations, but poorly in shady locations.

3) Without utilizing clearcut logging or fire as a management tool, forest succession over the next several centuries could cause hardwoods and other conifers to become the dominant trees in some presently redwood-dominated forests (Stone and others, 1969).
4) Many trees are inadvertently killed or damaged during selective logging. Moreover, breakage of felled trees is more prevalent during selective logging than during clearcutting.
5) Clearcutting minimizes road construction and maintenance.
6) Timber stands in Humboldt and Del Norte Counties are taxed at full value until seventy percent of the stand has been removed. If a stand of redwoods is thinned to this degree, the remaining trees are highly susceptible to wind throw and stem breakage.
7) Any deleterious impact on the environment is short-lived and readily reversible.
8) Selective logging requires the land to be subjected to repeated trauma rather than to a single trauma as in the case in clearcutting. Ground disturbances associated with relogging operations often damage or kill regenerating forest trees and accelerate erosion.
9) The composition of the regenerated forest can be controlled by planting and aerial seeding to provide the most economically desirable mix of species.
10) Regenerating even-aged, second-growth forests are better wildlife habitats than virgin forests because second-growth forests are more open and provide more browse.
11) Managed even-aged, second-growth forests are less susceptible to fire, insects, and disease than uneven-aged, virgin forests.
12) Vigorous young growth redwood forests are growing today on sites that were clearcut and repeatedly burned in the late nineteenth and early twentieth centuries.

13) Conversion to an even-aged stand involves the generation of smaller trees of more uniform size that can be harvested with smaller equipment than old growth forests. Smaller equipment causes less ground disturbance and less accelerated erosion.

The basis for the first, third, and seventh of these reasons is inconclusive. Natural catastrophes, like those cited in reason one, have indeed resulted in approximately even-aged stands within redwood and redwood-Douglas-fir forests. These even-aged stands, however, typically occupy widely separated sites that are not more than a few hundred acres in size. Most are only several tens of acres in size. With regard to reason three, on-going research by Stephen Veirs (1972) indicates that at most hillslope sites the redwood trees are of mixed ages, although the associated trees often represent an event-related, uniform age class. Veirs further believes that redwood can continue to dominate the forest vegetation even when few seedlings and young trees occur in the understory because of the greater longevity of individual redwood trees relative to that of the associated trees; the great longevity of the redwoods allows them to be replaced more-or-less on a one-for-one basis. Detailed logging impact studies (Fredriksen, 1970; Brown and Krygier, 1971) that serve as the principal justification for reason seven documented the impacts associated with smaller cutting units, and considerably less ground disruption than that associated with the recent conversion of old growth redwood to even-age silviculture. The types of environmental impact associated with large scale, tractor-yarded clearcut harvest of old growth redwood, as well as the magnitude and persistence of those impacts, remain to be established, and provide the central theme for our on-going studies in the Redwood Creek basin.

Although some valid silvicultural and economic justifications for the present reliance on large clearcut blocks and the use of large tractors for layout construction and yarding can be presented, the basic fact remains that the type and amount of ground surface disruption associated with this combination of forest practices leaves the landscape more susceptible to accelerated erosion than any combination of practices previously used to harvest redwood timber (Curry, 1973). Three examples of recent tractor yarded clearcut timber harvest units in close proximity to the Redwood Creek unit of Redwood National Park are shown in figures 33, 34, and 35. Glimpses of this mode of logging are shown on other photographs included in this report. Detailed photographic documentation of ground-surface conditions in these units is contained in the photo essay prepared by Earth Satelite Corporation (1972). Downhill tractor yarding requires construction of roads and landings at mid-slope and lower slope locations which tend to be less stable than upper slope locations because of steeper hillslope gradients, more soil water seepage, and thicker accumulations of colluvium associated with the lower parts of these hillslopes. Parts of skid trails and associated layouts are frequently cut to depths in excess of three feet, and cause some water that had previously infiltrated the forest floor to reappear as surface runoff. The tractor skid trails tend to be laid out in fan-shaped patterns that converge downhill at landings and concentrate surface runoff. After completion of timber harvest, low berms of soil and associated ditches ("water bars") are placed across the skid trails in order to divert water on to the adjacent forest floor and thereby to impede erosion by concentrated runoff. Some skid trails, however, have been carved too deeply to allow for effective construction of water diversion structures. Moreover, even when skid trails have been carved to relatively shallow depths, water deflecting berms and associated ditches are often of insufficient height and number to be effective.

The total amount of ground disturbance from logging operations is impressive; interpretations of recent aerial photographs with the aid of direct ground observations indicate that in a sample of six typical timber harvest units that were logged between 1968 and 1973 and that involve a total area of 5000 acres upslope from the Redwood Creek unit of Redwood National Park, about 81 percent of the total ground surface has been disrupted (the range for individual cutblocks is 80 to 85 percent), and about 41 percent of the area is covered with roads, skid trails, layouts, and landings (the range for individual cutblocks is 35 to 50 percent). The net effect is to obliterate completely the fine details of the natural drainage pattern and to create an artificial ~~microtopography of mounds~~ and trenches that often displays relief in excess of five feet.

Considerable effort is expended by timber companies to utilize as much of the wood fibre produced by the forest as possible. Nonetheless, a considerable volume of smashed or rotten logs, tree tops, limbs, and broken brush remain on the ground following logging. These logging residues together with the surface litter and near surface roots provide some protection for surface soil from sheet wash and rill erosion. However, residue concentrations are a serious fire hazard and occupy space that could be occupied by new forest trees; thus, the residues are usually burned. Surface erosion is often accelerated following burning of logging residues by destruction of organic debris that serves as small check dams for fluvially transported sediment (Fredriksen, 1970) and by creating water repellent layers that increase surface runoff (Rice and others, 1972).

The amount of time required for the cutover land to become revegetated is a function of the orientation (aspect) of the hillslope, the amount of original ground disturbance, the procedures used in restocking the forest, and the sequence of climatic events during the recovery period. For example, if exceptionally intense rainstorms initiate gullies and debris slides during the recovery period, revegetation will take longer than under more nearly "normal" conditions. In general, however, the ground surface in cable yarded areas and between skid trails in tractor yarded areas usually has a nearly complete cover of herbaceous vegetation and new forest shrubs and trees within four to six years of the burning of the logging residues. More deeply disturbed and (or) compacted areas, such as landings, layouts, and tractor skid trails often remain unvegetated and actively eroding for more than ten years following burning. Even after the crown cover of the regenerating forest appears reasonably complete on aerial photographs, field traverses show persistent areas of bare mineral soil and some actively eroding shallow gullies.

The amount of ground disruption associated with the harvest of the second growth forest should be significantly less than that associated with harvest of the old growth forest because the trees would be cut when they are of a smaller and more uniform size that can be handled with smaller yarding equipment. However, the extreme amount of primary mechanical and secondary erosional modification of the land-surface resulting from tractor yarded clearcut harvest of old growth redwood may at many sites hamper the effective use of conventional yarding equipment during harvest of the second growth forest. The irregular ground surface would accentuate the amount of earth that would have to be moved in order to provide yarding equipment with effective access to proposed harvest sites away from maintained roads. The irregularities would also increase the amount of soil disturbance associated with yarding operations. The amount of ground disruption, although significantly less than that associated with the old growth harvest would probably still be substantial during harvest of the second growth forest.

The timber companies operating on the border of the Redwood Creek unit of Redwood National Park in cooperation with the National Park Service initiated in 1973 some modifications of their timber harvest practices that were designed to mitigate the impact of on-going logging on park resources. These modifications focused on an 800-foot-wide, so-called buffer adjacent to the park boundary, 75-foot-wide strips adjacent to designated streambanks, and areas with recently active mass movement1/. More effort is now taken to minimize ground and vegetation disturbance at the park boundary and in the designated streamside areas. Within the buffer at the park boundary, harvest units are restricted to an average size of about 20 acres, separated from one another by uncut blocks of timber and, for the most part, yarded by cable systems that apply some lift to the logs. The uncut blocks are not to be harvested for at least years following slash burning in the adjacent cut block. An example of 1973-1974 timber harvest within the buffer at the southwestern end of Redwood National Park is shown in figure 36. Timber companies also have recently utilized cable yarding

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1/ In the unsigned cooperative agreements between the timber companies and the National Park Service, restrictions were also placed on road construction and maintenance in that part of the Redwood Creek basin that extends upstream to and includes the drainage basin of Lacks Creek.

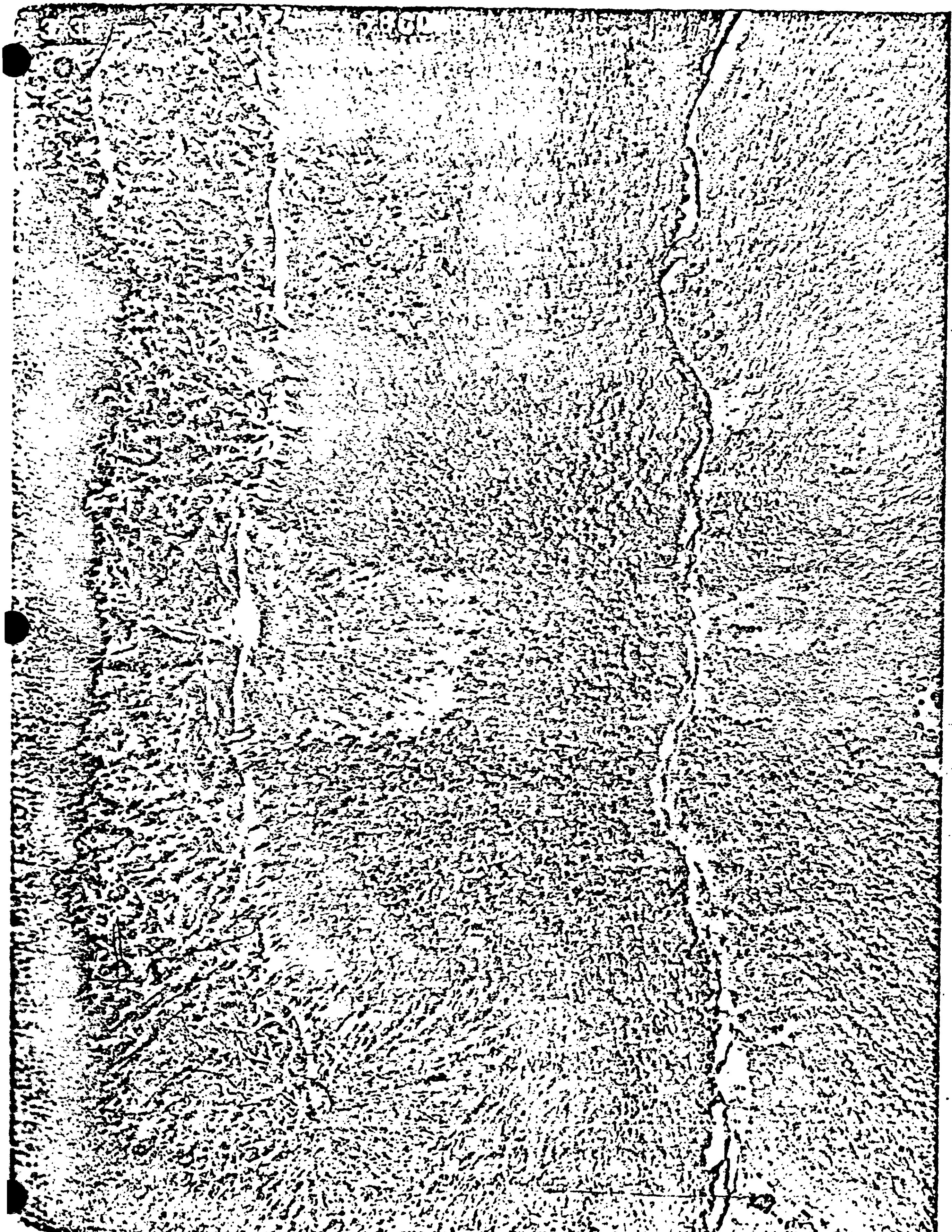


Figure 36 Combination of large scale tractor- yarded clearcut timber harvest and small scale cable-yarded clearcut timber harvest on the southwestern boundary of Redwood National Park

in timber harvest operations within 400 feet of designated streambanks and within critical areas so designated by the National Park Service because of a prior history of mass movement. Cable yarding results in an upslope-converging fan-like pattern of shallow cable ways (skid trails) that tend to disperse surface runoff. When the terrain is reasonably steep and not too irregular, cable yarding tends to alter the ground-surface configuration and the amount and pattern of surface runoff much less than tractor yarding. In 1973, away from the areas specifically mentioned in the unsigned cooperative agreements between the National Park Service and the neighboring timber companies, the dominant mode of timber harvest remained tractor yarded clearcutting of harvest units several times larger than those in the buffer. The degree of protection afforded park values by the recent modification of timber harvest procedures in parts of the lower Redwood Creek basin remains to be evaluated.

ROADS

The more than 1000 miles of roads within the Redwood Creek basin are associated with major erosion problems but they provide access needed to protect and fully utilize the economic, recreational, and scientific resources of the basin. The roads are, thus, an important resource in their own right. The recently relocated State Highway 299 is the only major avenue of regional commerce to cross the Redwood Creek basin upstream from the mouth of Prairie Creek. The only other paved roads in the basin are the Bald Hills Road, the Redwood Valley Road, Chezem Road (old State Highway 299) and a part of the Snow Camp Road. All these roads, except Chezem Road, were designed to provide access to ranches and logging operations within the basin. State Highway 299 is a major transportation link between the Sacramento Valley and the coastal cities of northwestern California. The Redwood Valley Road and Chezem Road provide access to established residences and recreational home sites. However, the other paved and unpaved roads in the Redwood Creek basin are designed and maintained primarily to provide access to commercial stands of timber or electrical transmission lines, and only incidentally provide access to grazing areas or potential recreation sites. When timber harvest in an area is completed, many access roads cease to be maintained, and erosion and (or) encroachment of vegetation soon make them impassable. The esthetic and physical impacts of the more than 3000 miles of tractor skid trails throughout the basin are similar to those of other unpaved roads.

Construction of some of the roads in the Redwood Creek basin has locally accelerated erosion by both mass movement and fluvial processes, thereby caused long lasting adverse impacts upon other resources. Roads accelerate mass movement by removing lateral support from the toes of potential landslides, by intensifying downslope-directed components of gravity and seepage forces in existing or potential slide areas, and by creating new slide-prone materials such as sidecast spoil and fill. Within the Redwood Creek basin, road-related debris avalanches are a common form of mass movement. Roads accelerate fluvial erosion by exposing materials readily eroded by sheet and gully erosion, by increasing surface runoff, and by diverting and concentrating surface runoff.

The location, size, and design of these roads appear to strongly influence the degree to which they accelerate erosion. The lower two thirds of the hillslopes in the Redwood Creek basin have steeper gradients, thicker accumulations of colluvium and more frequent and voluminous seepage of soil water than the ridge or the upper third of the hillslopes. Moreover, roads on the lower portion of these hillslopes require more cuts and fills and cross more streams and landslides than roads on the upper hillslopes. Thus, roads on the lower two thirds of these hillslopes are much more likely to accelerate erosion than comparable roads on the upper hillslope. The Redwood Creek basin has a particularly large number of roads on the middle and lower parts of its hillslopes, because of the reliance on downhill tractor yarding in most logging operations in this basin.

Erosion is most likely to be accelerated when road prisms are adjacent to stream channels or within active or recently stabilized landslides. The common practice of sidecasting road spoil directly into stream channels leads directly to accelerated erosion and destroys riparian vegetation, thus affecting aquatic biota and habitats in the streams involved Another common example of undesirable road-stream interactions is the erosional failure of fill and culvert crossings of small streams. Many failures result from the downstream end of the culvert discharging directly onto unprotected fill. Moreover, these culverts are often plugged with debris which causes an upstream impoundment of water. The fill then may fail by over-topping and subsequent gullying and (or) by saturation and slumping. The massive amounts of sediment introduced to streams by direct sidecasting and (or) by erosional failures of fill and culvert crossings may cause intensive local aggradation that is rapidly attenuated downstream along gently sloping streams. In contrast, the introduction of such massive amounts of sediment into more steeply sloping streams may generate highly erosive debris torrents that scour downstream reaches of the affected streams, and possibly initiate downstream streambank landslides.

Initial slope failures at sites where roads cross active landslides usually result from removal of support and increased seepage on cutbanks or overloaded lower fill slopes. Although such initial failures are often quite small, they can further adversely change the distribution of stresses in the affected landslides and lead to progressive failure of more massive slides.

Much of the erosion damage associated with forest roads takes place after timber harvest when road maintenance is often neglected. Following logging the majority of the roads in cutover land are used infrequently or not at all; maintenance operations are concentrated on the most frequently used roads. Under these circumstances plugged culverts and obstructed ditches become more common and cause new drainage adjustments which once again lead to accelerated erosion. Therefore, roads that are not needed for fire protection or active management of the regenerating forest should be returned to a nearly natural condition.

Careful planning, construction, and maintenance could mitigate much of the damage caused by erosion related to timber access and haul roads (Bullard, 1965; Packer 1967; Hicks and Collins, 1970, Lantz, 1971; Larse, 1971; Burrough and others, 1973).

OTHER RESOURCES

The Indian population considered the fish of Redwood Creek as a valuable food resource and established sizeable fishing villages at the mouth of the creek and in Redwood Valley. Early white settlers also utilized the fish for food. Present utilization relates primarily to sport fishing; the California Department of Fish and Game (1965) estimates that 150 salmon and 500 steelhead are caught annually in Redwood Creek. Department personnel and local residents say that this represents a drastic decline in the annual total of fish caught and the number of fish caught per angler day. The estimated average annual spawning escapement of chinook and coho salmon in Redwood Creek is about 7000 which is only about 2.5 percent of the total salmon escapement for California coastal streams north of Humboldt Bay (U.S. Fish and Wildlife Service, 1960). Thus, the salmon of Redwood Creek probably make only a relatively minor contribution to the local ocean-going commercial salmon fleet.

During the late 19th and early 20th Centuries, the natural browse associated with the grass, and grass-bracken fern prairies was the resource of primary interest to the white settlers in the Redwood Creek basin. Some attempts were made to cut and burn the forest on the borders of the natural prairies and to convert them to rangeland. Most of the attempts at land conversion were only partly successful and much of the converted land is now covered with brush and (or) second growth forest. Aerial photographs taken in 1936 show that the prairies between Redwood Creek and the Bald Hills road, at the mouth of Lacks Creek, in Redwood Valley, and on the ridge between High Prairie Creek and Lake Prairie were being actively utilized as rangeland, and small orchards were associated with most of the individual homesteads. These same areas as well as some smaller natural prairies are still utilized for grazing by ~~sheep and~~ cattle. Range management and road maintenance in the hillside prairies (especially in their downstream portions) is difficult because of naturally occurring landslides. The turf in most of the grazing areas appears to be in good condition, and gullying and landsliding do not appear to have been accelerated by grazing.

Sources of durable road metal for paved and gravel surfaced roads are not common in the Redwood Creek basin because of deep weathering and intense fracturing of the bedrock. Greenstones within the Franciscan assembledge of rocks are probably the most durable rocks available for road metal. Stream gravel, and massive parts of the Franciscan sandstones in the eastern part of the basin, however, are more readily available. Small borrow pits and quarries have from time to time been operated near State Highway 299 and near various logging operations in the Redwood Creek basin. Most of these excavations were designed with little thought to minimizing erosion, and many, therefore, remain as active sources of sediment long after the borrow operation has ceased. Excavating gravel directly from the bed of a stream is disruptive of the local aquatic habitat and can increase downstream turbidity; thus, this practice is closely regulated by the California Department of Fish and Game. Procedures used to mitigate the impact of these gravel operations include dikes to prevent downstream increases in turbidity and the use of bypasses to allow for free passage of migrating fish. During 1972, relatively large quantities of gravel were excavated from the bed of Redwood Creek near the mouth of Prairie Creek, and smaller quantities were removed near the old U.S. Highway 299 bridge and near the mouth of Panther Creek. Prior to the establishment of Redwood National Park, Georgia-Pacific Corporation (now Louisiana-Pacific Corporation) excavated gravel from the sidestream alluvial fan of Tom McDonald Creek; their excavations may have impeded the growth of the fan, and minimized its tendency to deflect the main stream current against the Tall Trees Flat.

STREAMFLOW

STREAMFLOW CHARACTERISTICS

The dominant runoff characteristics of the Redwood Creek basin are a large but highly variable annual amount of runoff, a pronounced seasonal concentration of runoff, and a high runoff-precipitation ratio (fig. 25). These characteristics result primarily from (1) the large but variable amount of annual precipitation, (2) the fact that most of the precipitation is concentrated in a short period when soil moisture is high and evapotranspiration losses are minimal, (3) the relatively thin regolith overlying impervious rock, and (4) the rapid delivery of runoff to the main channel by numerous short steep tributaries.

Prolonged low flows and high flood flows are part of the natural flow regime of Redwood Creek; nonetheless, both extremes are sources of environmental concern. Low flows of summer greatly restrict the living area available to aquatic organisms, make the streams prone to excessive heating, and allow development of a continuous subaerial river mouth bar that prevents migration of anadromous fish. Flood flows drastically modify stream channels and riparian hillslopes, transport enormous quantities of sediment, and damage works-of-man and esthetic values. Recent changes in land use particularly large-scale, tractor-yarded, clear-cut timber harvest and associated road construction apparently have affected the runoff extremes of Redwood Creek. The degree to which land-use changes have affected runoff from individual storms remains uncertain. Even when land-use-related changes in runoff are only modest, those changes can modify stream channel geometry and alter the natural erosion processes (U.S. Dept. Agr. River Basin Planning Staff, 1970).

The present runoff characteristics of the Redwood Creek basin are reasonably well documented by continuously recording stream gages on Redwood Creek near the old highway 299 bridge crossing (Redwood Creek near Blue Lake, drainage area 67.6 square miles or 175 square kilometres), at the southern boundary of Redwood National Park (drainage area 185 square miles or 479 square kilometres), and at Orick (drainage area 278 square miles or 720 square kilometres) and by periodic discharge measurements made at three other sites along Redwood Creek and at 20 localities on tributaries downstream from the mouth of Coyote Creek. The types of data collected and the period of record for the three recording stream gages on Redwood Creek are presented in Table 1. Because streamflow records from within the Redwood Creek basin are of relatively short duration, historical trends in runoff characteristics of this basin have to be evaluated in part from extrapolations of streamflow records from nearby basins and qualitative observations of long-time residents concerning historic flood marks, depths and persistence of snowfall, and summer low flow. Systematic periodic discharge measurements at nonrecording sites within the basin were not initiated until the 1974 water year.

The average annual streamflow of Redwood Creek at Orick for the twenty-year period encompassing water years 1954 through 1973 is 783,800 acre feet or 52.86 inches which accounts for about 66 percent of the estimated mean annual basin-wide precipitation (Rantz, 1964). The annual

Table 4. Period, frequency, and type of data collection at recording stream gaging stations along Redwood Creek, Humboldt County, California. The frequency of collection is indicated by the following symbols: C for continuous records, D for samples collected at least once a day with more frequent samples collected during storm periods, P for periodic samples collected throughout a wide range of hydrologic conditions, and F for collection only during times of potential flooding. Periods of collection are listed by water years.

Station name and number	Drainage Area (sq.mi.)	Types of Data: Water Discharge	Water Temperature	Suspended Sediment Load	Total Sediment Load	Other chemical and biological indices of water quality
Redwood Creek near Blue Lake (11481500)	67.5	C 1954-1958 1973- F 1959-1972	C 1974-	D 1973-	P 1974-	P 1974-
Redwood Creek at southern park boundary near Orick (11482200)	183	C 1971-	P 1971-1973 C 1974-	P 1971-	P 1974-	P 1971-
Redwood Creek at Orick (11482500)	278	C 1912-1913 1954-	P 1962-1964 C 1965-	D 1971-	P 1974-	P 1962-

Table 2. Annual Runoff at Recording Stream Gages Along Redwood Creek During Periods of Concurrent Records. Values are given in acre feet and , in parentheses, inches.

Year	Redwood Creek near Blue Lake	Redwood Creek at South Park Boundary	Redwood Creek at Orick
1954	902,200 (60.8)		199,000 (55.2)
1955	552,300 (37.2)		114,000 (31.6)
1956	1,174,000 (79.2)		307,100 (85.2)
1957	767,200 (51.7)		182,800 (50.7)
1958	982,200 (66.2)		285,600 (79.2)
1971	1,021,000 (68.9)	658,200 (66.7)	
1972	1,064,000 (71.8)	704,500 (71.4)	
1973	559,000 (37.7)	387,600 (39.3)	139,400 (38.7)

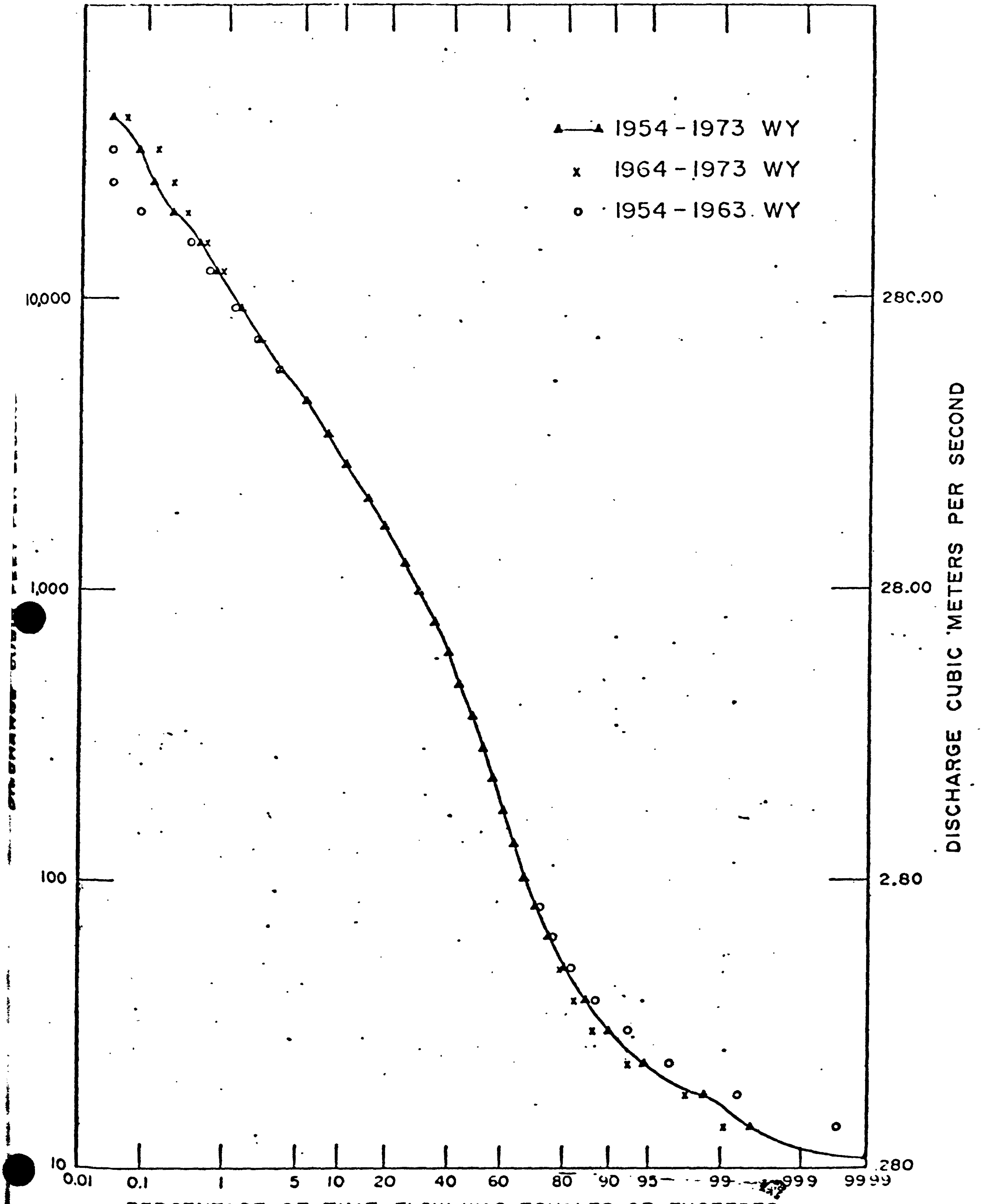


Figure 37. Flow duration curve for daily discharges for Redwood Creek at Orick.

runoff, however, is highly variable (fig. 26, Table 2) with a standard deviation of 204,900 acre feet or 13.82 inches which is about 26 percent of the mean. The recorded annual runoff at Orick was ranged from 482,000 acre feet (79.12 inches) in the 1968 water year to 1,174,000 acre feet (79.18 inches) in the 1956 water year (Table 2).

The daily discharges during any given year at Redwood Creek at Orick can be expected to fluctuate through a range of five thousand fold about a median discharge of 325 cubic feet per second (fig. 37). Mean daily flood discharges in excess of 7000 cubic feet per second, and mean daily low discharges of less than 23 cubic feet per second have occurred during every year of record (Table 3).

The seasonal pattern of mean monthly runoff closely follows the seasonal pattern of mean monthly precipitation (fig. 25). The seasonal runoff-precipitation relationships shown by these mean monthly values are similar to that shown by typical storms during the course of the water year, but individual storms may differ drastically from this pattern. Most of the late summer and early autumn rains that end the prolonged summer drought have relatively little impact upon stream discharge. As the storm season progresses, soil moisture and ground water reservoirs become recharged and an increased proportion of precipitation appears as direct runoff. Most storms throughout the winter are associated with warm air masses so that nearly all the precipitation is rain. Usually little water is stored as snow and the amount of snowmelt is insufficient to cause any major freshet. Nonetheless, a few flood discharges, including that of December 1964, have been augmented by rapid snowmelt induced by warm rain. Late winter and

Table 3. DURATION TABLE OF DAILY DISCHARGE

REDWOOD CREEK AT ORICK CALIF

NUMBER OF DAYS IN CLASS

CLASS / Water YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	CFS_DAYS
1954					4	1	18	32	25	16	14	10	30	17	10	9	9	19	25	17	19	15	17	12	14	12	3	2	3	1	2	1				454816.0
1955				25	6	16	27	16	19	12	13	8	11	16	12	12	19	26	36	19	25	14	16	8	3	3	1	1			1					278427.0
1956				11	15	22	24	19	17	11	18	7	19	11	10	11	17	15	22	10	18	7	13	8	16	18	9	5	5	3	3	1		1		592109.0
1957				10	12	15	11	19	12	8	7	16	20	13	18	36	22	16	26	22	20	11	11	11	6	9	3	8	2		1					386830.0
1958				6	12	17	17	14	9	14	15	18	9	25	21	24	14	12	12	12	21	16	18	19	14	7	3	5	5	6						495234.0
1959		1	22	22	14	19	17	16	13	16	30	19	14	15	13	16	15	12	11	16	19	8	13	7	3	5	3	4	2							268873.0
1960				9	30	35	28	21	16	12	14	13	13	5	8	12	7	22	28	25	16	16	10	9	6	4	2	2	1		2					305575.0
1961				5	22	25	19	20	13	10	9	11	9	14	14	23	9	16	21	23	27	14	18	8	12	12	6	3	2							395303.0
1962				5	13	27	25	17	22	19	17	11	10	13	16	18	28	19	19	11	18	12	18	9	11	4	1	1	1							282347.0
1963					20	17	12	13	10	11	11	10	10	20	24	19	26	24	17	12	21	18	17	9	16	9	16	1	1		1					446083.0
1964				6	19	16	8	7	15	10	17	15	18	15	20	18	27	26	14	23	20	14	16	11	9	3	5	1	1	3			1			383759.0
1965		4	19	25	14	22	19	12	7	11	10	15	7	19	29	20	19	10	8	7	14	9	13	11	13	6	6	5	4	1	2	1	1	1	1	535431.0
1966		1	3	47	20	19	14	8	5	19	18	24	15	8	15	14	13	12	16	25	16	13	15	9	5	4	1	2	1	1	1			1		320296.0
1967				19	39	15	7	9	11	11	12	12	8	7	13	13	19	23	17	22	35	20	19	11	8	4	6	2	1	2						381693.0
1968				13	15	13	25	34	21	15	13	16	31	21	15	16	14	10	14	15	20	16	12	5	4	3	2	2		1						243019.0
1969				5	28	20	15	12	16	12	12	14	15	5	7	12	9	20	25	34	23	15	8	21	13	12	7	3	1	1						434122.0
1970		4	7	24	24	8	11	19	18	16	17	16	7	24	17	21	15	17	22	13	14	8	14	7	3	4	4	2	4	1	2	2				365955.0
1971		17	1	3	5	10	21	14	18	9	9	16	17	9	12	11	10	21	21	15	27	18	18	21	11	11	10	1	6		3					514592.0
1972			4	18	13	14	12	25	14	18	19	16	10	5	12	11	10	25	20	16	18	21	18	7	14	10	4	2	4	1	1	1	1	1	1	536199.0
1973		8	16	19	28	14	12	14	9	11	14	13	18	17	19	14	11	12	15	14	27	19	17	9	3	8	3	1								281803.0

CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT
0	0.00	0	7305	100.0	9	80.00	269	5255	71.9	18	750.0	389	2534	34.7	27	7000	53	152	2.0
1	11.00	35	7305	100.0	10	100.00	289	4986	68.3	19	960.0	351	2145	29.4	28	9000	44	99	1.3
2	14.00	72	7270	99.5	11	130.00	288	4697	64.3	20	1200.0	418	1794	24.6	29	12000	21	55	.7
3	18.00	272	7198	98.5	12	170.00	291	4409	60.4	21	1600.0	284	1376	18.8	30	15000	19	34	.4
4	23.00	353	6926	94.8	13	220.00	279	4118	56.4	22	2000.0	301	1092	14.9	31	19000	6	15	.2
5	30.00	345	6573	90.0	14	280.00	305	3839	52.6	23	2600.0	212	791	10.8	32	24000	3	9	.1
6	38.00	342	6228	85.3	15	360.00	330	3534	48.4	24	3300.0	184	579	7.9	33	31000	4	6	.0
7	49.00	341	5886	80.6	16	460.00	313	3204	43.9	25	4300.0	148	395	5.4	34	40000	2	2	.0
8	63.00	290	5545	75.9	17	590.00	357	2891	39.6	26	5500.0	95	247	3.4					

spring snowmelt may also result in minor diel fluctuations in discharge and help sustain flow at the end of the storm season. Stream discharges gradually decline during the course of the summer with the lowest discharges commonly occurring after the end of a mid-summer rain-free period, but before onset of major autumn storms.

The magnitude, persistence, and frequency of occurrence of environmentally restrictive, extremely high and low streamflow for Redwood Creek at Orick are presented in tables 3, 4, and 5, and figure 3. Daily discharges at the Orick gaging station are less than 49 cubic feet per second about 19.4 percent of the time (Table 3). During these periods of low flow, many tributaries with drainage areas of less than one square mile are dry or intermittent. Log-Pearson type III frequency analyses (Water Resources Council, 1967)[1/] suggest that in any given year there is an even chance that for periods of one day, 14 days, and 30 days, daily flows at Orick will be less than 18, 21, and 25 cubic feet per second, respectively (Table 4). The chance in any given year of the minimum daily discharge of Redwood Creek at Orick not exceeding 10 cubic feet per second is about one percent.

In contrast, daily discharges for Redwood Creek at Orick exceed 2000 cubic feet per second about 14.9 percent of the time (Table 3). Log-Pearson type III frequency analyses suggest that in any given year there is an even chance that for an instantaneous peak discharge to exceed

[1/] This reference deals primarily with the frequency analysis of annual-series flood discharges, but these techniques can be used for frequency analyses of any hydrologic variable whose population may be assumed to follow a log-Pearson type III distribution.

Table 4. Log-Pearson Type III Frequency Analysis of Daily Low Flows for Redwood Creek at Orick.

Probability that the mean daily discharges for any period of the specified length of time will not equal or exceed the indicated discharge during any given water year	The recurrence interval (in years) of low flows of this magnitude	One-day low flow (CFS)	14-day low flow (CFS)	30-day low flow (CFS)
0.010	100	10	11	12
0.050	20	12	13	15
0.100	10	13	15	17
0.200	5	15	16	19
0.500	2	18	21	25
0.800	1.25	23	27	33
0.900	1.11	27	31	38
0.960	1.04	31	36	44
0.980	1.02	34	39	49
0.990	1.01	37	43	54
0.995	1.01	41	46	59

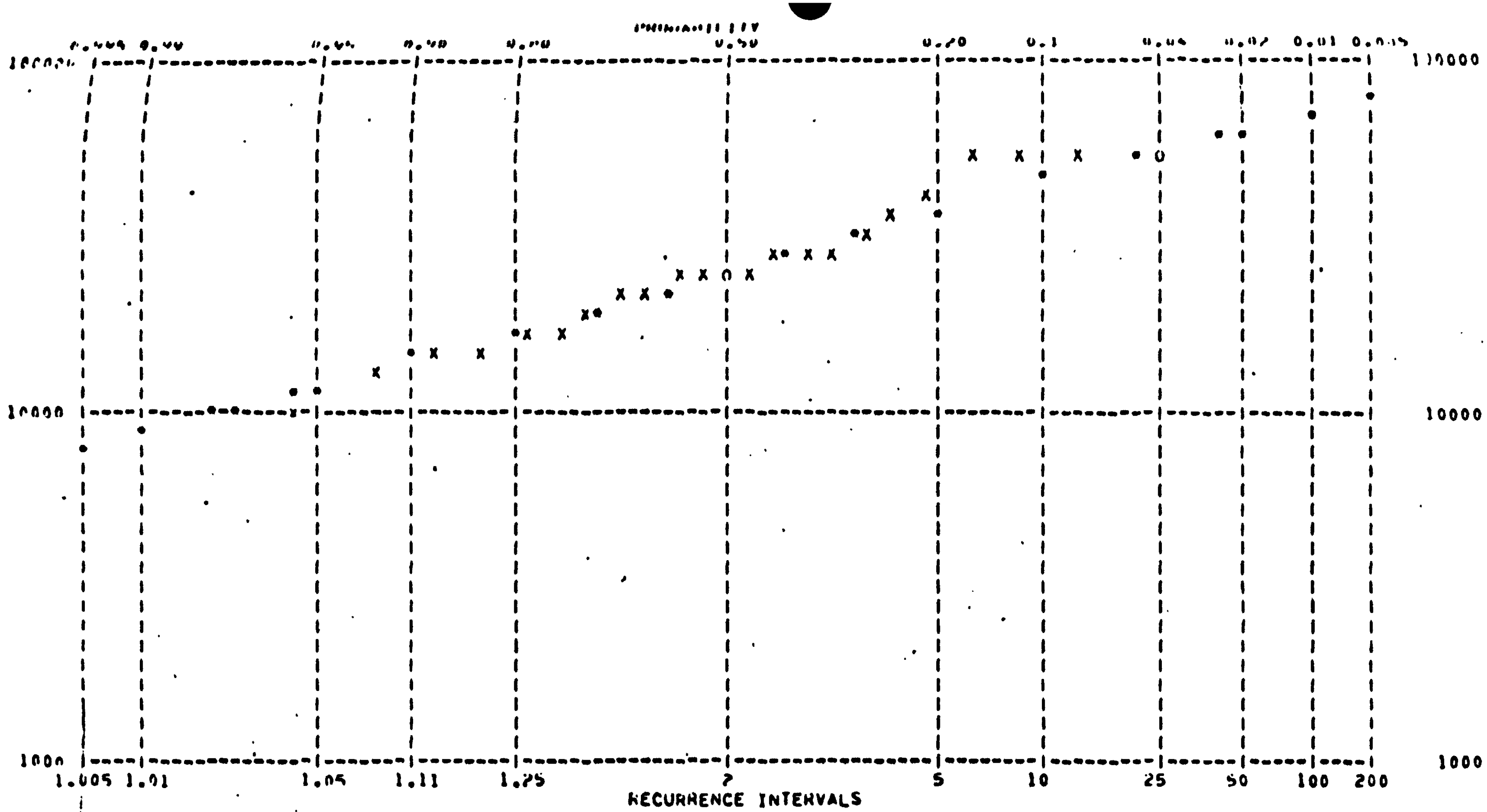
Table 5. Log Pearson Type III Frequency Analysis of Daily and Instantaneous High Flows for Redwood Creek at Orick.

Probability that the instantaneous peak discharge or the mean daily discharge for any period of the specified length of time will equal or exceed the indicated discharge during any given water year	The recurrence interval (in years) of high flows of this magnitude	Instantaneous Peak Discharge (CFS)	One-day high flow (CFS)	Three-day high flow (CFS)	Seven-day high flow (CFS)
0.990	1.01	8,500	6.900	5,200	4,100
0.950	1.05	11,800	8,700	6,500	4,900
0.900	1.11	14,000	10,000	7,400	5,400
0.800	1.25	17,200	11,900	8,800	6,300
0.500	2.00	25,400	17,300	12,600	8,600
0.200	5.00	37,200	26,500	12,100	12,700
0.100	10.00	45,300	33,900	24,100	15,900
0.040	25.00	55,700	44,600	31,500	20,800
0.020	50.00	63,600	53,800	37,800	25,000
0.010	100.00	71,500	64,100	44,700	29,700
0.005	200.00	79,600	75,600	52,500	35,100

25,400 cubic feet per second (Table 5, fig. 38) and for periods of one day, three days, and seven days, daily flows will exceed 17,300, 12,600, and 8,600 cubic feet per second, respectively (Table 5).

During the last 20 years, five flood peaks in excess of 45,000 cubic feet per second (162 cubic feet per second per square mile) have occurred at Orick, with the largest being 50,500 cubic feet per second (182 cubic feet per second per square mile) on December 22, 1964 and the smallest being 45,300 cubic feet per second on January 22, 1972. The winter of the 1972 water year was exceptionally stormy and another major flood with a peak discharge of 49,700 cubic feet per second occurred on March 3, 1972. Two floods with discharges of 50,000 cubic feet per second occurred on January 18, 1953 and December 22, 1955. All five of these Redwood Creek floods were associated with high antecedent moisture conditions, warm storms of regional extent, and prolonged rainfall of relatively moderate hourly intensity (Paulsen, 1953; Rantz, 1959; Hofmann and Rantz, 1963; Waananen and others, 1971). Some perspective on the relative magnitude of the peak water discharge associated with these floods can be gained by comparing them with peak discharges of two highly publicized recent floods.

Although these five flood peak discharges on Redwood Creek were quite similar, the individual flood events differed greatly in duration, volume, and damage (Table 6). The 1964 flood throughout most of north-



THE FOLLOWING SYMBOLS MAY APPEAR IN THE PLOT
X = AN INPUT DATA VALUE
• = A CALCULATED VALUE
O = A CALCULATED VALUE AND ONE DATA VALUE AT SAME POSITION.
2 = TWO INPUT DATA VALUES PLOTTED AT SAME POSITION
3 = THREE INPUT DATA VALUES PLOTTED AT SAME POSITION
A = A CALCULATED VALUE AND TWO DATA VALUES AT THE SAME POSITION
B = A CALCULATED VALUE AND THREE DATA VALUES AT THE SAME POSITION

Figure 38. Log-Pearson type III frequency curve for instantaneous peak discharges for Redwood Creek at Orick.

western California appears to have been the greatest flood since 1852 (Hofmann and Rantz, 1963). In Redwood Creek, the peak discharge of the 1964 flood was only slightly larger than peak discharges associated with the 1953 and 1955 floods, but total flood volumes and damages in 1964 were significantly greater than those associated with the earlier floods. Residents and timber operators within the basin suggest that the increased property damage in 1964 reflects both increased capital investment by timber companies and small land owners, and increased sedimentation at sites inundated by previous flood. More streamside slides were triggered by this flood than by the previous floods (Colman, 1973); possible reasons for the increased sliding are discussed later in this report.

The October 1950 storm is included in Table 6 in order to emphasize some of the factors that control flood magnitudes in this basin, even though log-Pearson type III flood frequency analysis (Table 5) suggests that a flood peak of the magnitude of the 1950 flood, estimated to be 23,000 cubic feet per second (Rantz, 1959), has a better than even chance of occurring in any given year. The rainstorm associated with the 1950 flood was exceptionally intense (Paulsen, 1953), but did not generate exceptional runoff in Redwood Creek because antecedent moisture conditions were low and because the intense rains were apparently limited to the coastal part of the basin. The fact that the forested hillslopes in the downstream end of the basin were virtually unlogged at the time of this flood may also have moderated the 1950 flood peak.

Table 6. Recent Major Flood History for Redwood Creek at Orick, California

Date of Flood Peak	Flood Peak (CFS)	Length of time between initial rise and return to discharge less than 3000 CFS or recession is interrupted by another storm (days)	Total flow during 10 days following initial rise (acre-feet)	Max. calendar day rainfall at Orick Prairie Creek (inches)	Total storm rainfall at Orick-Prairie Cr.	Total storm damage in Redwood Creek basin(dollars)
October 29 or 30, 1950	23,000[1/]	6 - 8	-	11.50	21.24 inch in 8 days	624,500 in all of NW Calif.
January 18, 1953	50,000	approx. 5	-	5.19	19.02 inch in 10 days	1,062,500
December 22, 1955	50,000	15	224,473	2.36	14.39 inch in 11 days	597,100
December 22, 1964	50,500	15	377,091	3.00	14.28 inch in 12 days	1,300,000
January 22, 1972	45,300	11	214,612	5.07	12.44 inch in 8 days	2/
March 3, 1972	49,700	9	231,997	4.00	6.49 inch in 4 days	2/

1/ Estimated from flood marks, and the stage-discharge relation developed after to gage was established in 1953 (Rantz, 1959).

2/ Although no formal damage survey was compiled for the 1972 floods, damage was substantial. Orick was protected by newly constructed levies, but the levies themselves sustained some damage. Damage to public roads was comparable to that sustained during earlier floods, and timber company roads were more severely damaged than previously.

The major floods in this area, even though they are of regional extent, were characterized by highly variable unit runoff which reflects variations in rainfall intensity as well as differences in drainage basin characteristics. Regional patterns of rainfall intensity display gross differences from storm to storm with the details of any given pattern showing close orographic control. Isohyetal maps for the storms causing the 1950, 1953, 1955 and 1964 floods are included in the reports by Paulsen (1953), Rantz (1959), Hofmann and Rantz (1963) and Waananen and others (1971). Regional precipitation patterns and runoff records from Redwood Creek (Table 7) and adjacent basins suggest that unit runoff in the Redwood Creek basin during the floods of October 1950, January 1953, and January 1972 was greatest in the downstream part of the basin. Indeed the two highest recent flood peaks in the neighboring Little River basin were the floods of January 1953 and January 1972. Similar data suggest that unit runoff for the December 1955 flood was nearly uniform throughout the basin, and that unit runoff for the floods of December 1964 and March 1972 was greatest in the high inland parts of the basin. An important corollary of these observations is that some downstream tributaries of Redwood Creek (including those within Redwood National Park) may have experienced greater flood discharges in 1950, 1953, and 1972 than they experienced in 1955 or 1964.

Table 7. Unit Runoff for Notable Recent Flood Peaks in the Drainage Basins of Redwood Creek and Little River, Humboldt County, California. Discharges are in cubic feet per second per square mile.

Date	Redwood Creek near Blue Lake (67.6 sq.mi.)	Redwood Creek at Orick (278 sq.mi.)	Little River near Trinidad (44.4 sq.mi.)
January 18, 1953	1/	180	2/
December 22, 1955	179	180	191
March 11, 1957	87	87	209
February 8, 1960	-	90	191
January 20, 1964	-	136	179
December 22, 1964	243 3/	182	186
January 4, 1966	-	142	187
January 23, 1970	-	88	185
November 24, 1970	-	110	199
January 22, 1972	102 4/	163	219
March 3, 1972	203 4/	179	214

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

2/ Flood marks for the flood were at a stage of 15.7 feet, whereas flood marks for the flood of 1955 were at a stage of only 9.63 feet. No discharge value was assigned to the 1953 flood peak (Hofmann and Rantz, 1963).

3/ Discharge was estimated from flood marks and stage-discharge relations in effect when operation of station was discontinued.

If any channel aggradation occurred in the interval between the discontinuation of the record and the 1964 flood peak as seems to be the case, the estimated discharge would be high.

4/ 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 re-established stage-discharge station.

Available data, although meager, suggest that runoff characteristics for the entire Redwood Creek watershed are generally similar to those at Orick (fig. 39, Tables 3, 8, and 9), except that the upper basin may be characterized by slightly larger average annual unit runoff. This difference, however, is not great and varies considerably from year to year (Table 8). The larger average total annual unit runoff probably reflects larger annual precipitation in the headwaters than in coastal areas. Unit runoff differences are discernible at both high and low discharges (fig. 39). Higher unit discharges during storm periods are documented not only by flow duration analysis, but also by the fact that annual instantaneous unit peak discharges at the Blue Lake station in all of the eight years of reliable documentation were equal to or larger than those at Orick (Table 7). In four of these years the unit peak discharge at Blue Lake was more than 25 percent larger than that at Orick. Only the more notable of these floods are summarized in Table 7. High unit flood runoff determined for the gage near Blue Lake probably results primarily from the smaller drainage area and steeper channel gradients in the upper basin than in areas downstream from the gaging station near Blue Lake. Secondary influences are related to more intense storm precipitation, thinner regolith, less channel storage and, apparently, a large amount of tractor-yarded clear-cut logging in the upper basin.

The higher sustained low flows observed at the gage on Redwood Creek near Blue Lake relative to those observed at downstream gages (fig. 39) are somewhat surprising given

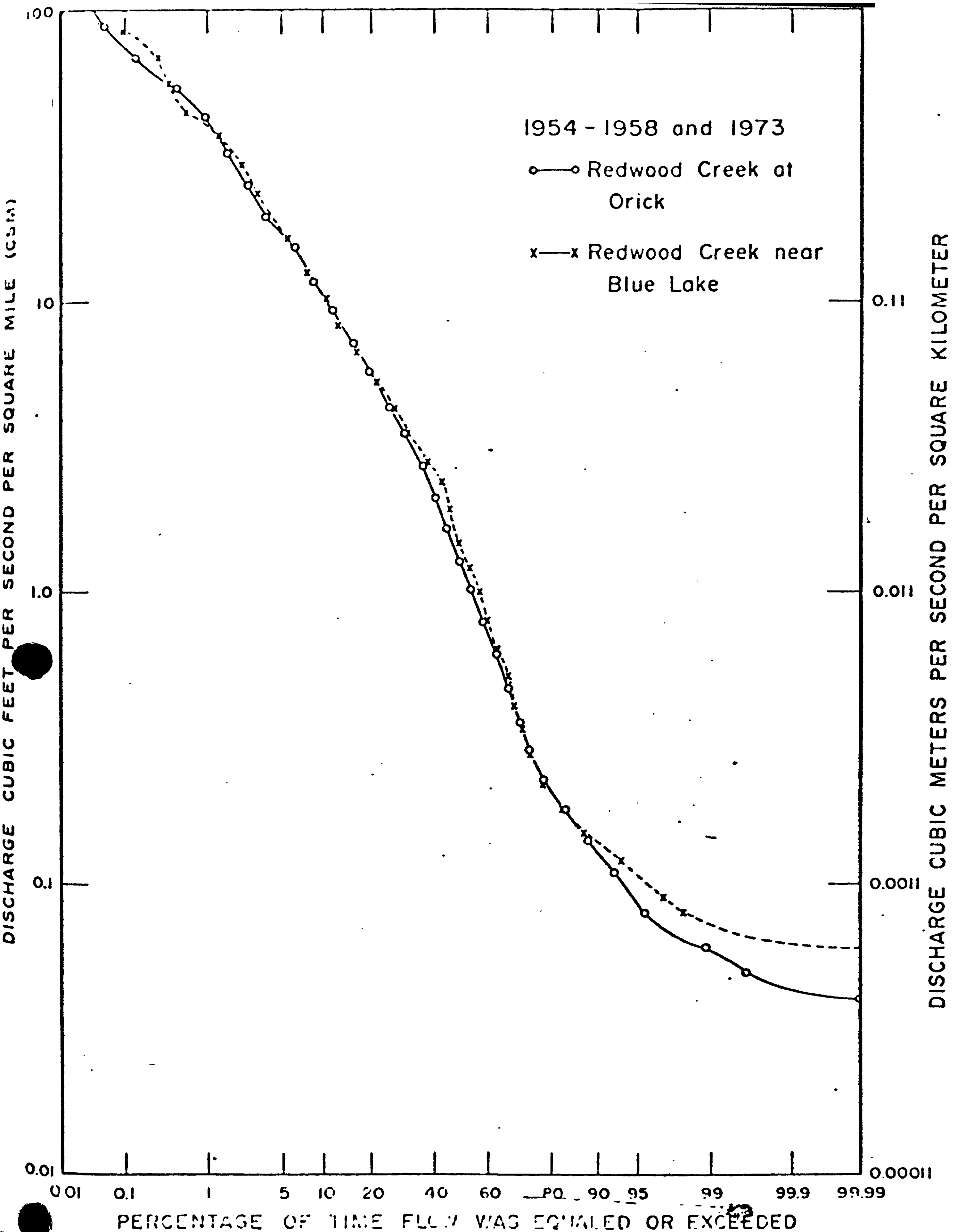


Figure 39. Comparison of flow duration curves for daily discharges at Redwood Creek near Blue Lake and Redwood Creek at Orick. The six year average runoff was 55.44 inches at Redwood Creek at Orick and 56.79 inches at Redwood Creek near Blue Lake.

STATION NUMBER 11481000

DURATION TABLE OF DAILY DISCHARGE FOR YEAR ENDING SEPTEMBER 30

REDWOOD CREEK NEAR BLUE LAKE CALIF

NUMBER OF DAYS IN CLASS

CLASS / YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	CFS_DAYS
1954					2	22	39	23	12	12	8	18	18	13	12	8	9	9	17	26	23	21	16	15	8	12	10	3	2	1	5			1		100313.9
1955				9	20	26	31	10	14	6	8	15	8	12	10	8	21	23	36	36	23	25	16	2	1	2		1			1	1				57554.9
1956					36	20	28	23	10	10	12	4	5	11	7	7	7	4	19	25	25	28	9	9	15	15	7	4	5	6	6	3	2	2	2	154829.9
1957				4	20	17	17	10	14	14	15	17	14	12	18	14	12	19	25	32	13	14	18	8	10	5	7	5	5	1	5					92140.6
1958			2	7	27	13	14	8	13	7	11	15	8	10	19	14	22	12	17	11	6	9	24	19	16	17	10	16	3	5	8	1		1		144097.0
1973		24	26	6	21	14	12	5	6	7	7	12	19	15	20	12	13	12	15	16	17	19	25	19	11	2	5	2	3							70243.7

CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT
0	0.00	0	2191	100.0	9	22.00	56	1586	72.4	18	160.0	129	931	42.5	27	1200	31	100	4.5
1	3.60	24	2191	100.0	10	27.00	61	1530	69.8	19	200.0	146	802	36.6	28	1500	18	69	3.1
2	4.50	28	2167	98.9	11	34.00	81	1469	67.0	20	250.0	107	656	29.9	29	1900	13	51	2.3
3	5.60	26	2139	97.6	12	42.00	72	1388	63.4	21	310.0	116	549	25.1	30	2300	25	38	1.7
4	7.00	126	2113	96.4	13	53.00	73	1316	60.1	22	390.0	108	433	19.8	31	2900	5	13	.5
5	8.80	112	1987	90.7	14	66.00	86	1243	56.7	23	490.0	72	325	14.8	32	3700	2	8	.3
6	11.00	141	1875	85.6	15	82.00	63	1157	52.8	24	610.0	61	253	11.5	33	4600	4	6	.2
7	14.00	79	1734	79.1	16	100.00	84	1094	49.9	25	770.0	53	192	8.8	34	5700	2	2	.0
8	17.00	69	1655	75.5	17	130.00	79	1010	46.1	26	960.0	39	139	6.3					

Table 8a. Flow Duration Table for Redwood Creek near Blue Lake.

STATION [illegible] 11482500

DURATION TABLE OF DAILY DISCHARGE FOR YEAR ENDING SEPTEMBER 30

REDWOOD CREEK AT SOUTH PARK BOUNDARY NR ORICK CALIF

NUMBER OF DAYS IN CLASS

CLASS / YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	CFS_DAYS
1971		17		1	1	9	15	27	13	12	9	12	11	13	15	12	10	22	21	18	22	17	18	27	10	7	7	5	5	5	3	1				331825.7
1972					20	10	19	24	14	16	20	21	13	8	10	10	11	7	19	25	18	18	16	23	9	14	7	3	2	3	2		2		2	355170.0
1973			6	13	15	19	30	13	15	8	21	7	13	17	25	7	12	9	13	16	14	29	24	20	6	4	7	1	1							195399.5

CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT
0	0.00	0	1096	100.0	9	45.00	36	815	74.4	18	420.0	53	464	42.3	27	3900	9	35	3.1
1	5.10	17	1096	100.0	10	57.00	50	779	71.1	19	540.0	59	411	37.5	28	5000	8	26	2.3
2	7.80	6	1079	98.4	11	73.00	40	729	66.5	20	690.0	54	352	32.1	29	6400	8	18	1.6
3	10.00	14	1073	97.9	12	94.00	37	689	62.9	21	880.0	64	298	27.2	30	8200	5	10	.9
4	13.00	36	1059	96.6	13	120.00	38	652	59.5	22	1100.0	58	234	21.4	31	11000	1	5	.4
5	16.00	38	1023	93.3	14	150.00	50	614	56.0	23	1400.0	70	176	16.1	32	14000	2	4	.3
6	21.00	64	985	89.9	15	200.00	29	564	51.5	24	1900.0	25	106	9.7	33	17000		2	.1
7	27.00	64	921	84.0	16	250.00	33	535	48.8	25	2400.0	25	81	7.4	34	22000	2	2	.1
8	35.00	42	857	78.2	17	330.00	38	502	45.8	26	3100.0	21	56	5.1					

Table 8b. Flow Duration Table for Redwood Creek at South Park Boundary

the thin regolith, steep hillslopes and channels, and warm, fog-free summers that are prevalent in the upper basin. Perhaps the lower density of forest vegetation in the upper basin reduces evapotranspiration-induced moisture losses to the extent that physical and climatic factors are outweighed. Any difference in vegetation-induced evapotranspiration would be accentuated by the fact that during the period of concurrent stream-gaging records the proportion of recently cutover land in the basin above the gaging station near Blue Lake was far greater than in the basin as a whole. Another explanation for the apparently greater low flow at the upstream site is that the much narrower and thinner alluvial fill at that site provides less opportunity for intragravel flow than at Orick. The difference in valley-bottom configuration probably account for most of observed difference in low flow.

Tributaries draining predominantly schist terrane, other factors being equal, appear to show slower responses to storm precipitation, lower peak discharges, and higher sustained low flow than tributaries underlain predominantly by less metamorphosed rocks of texture zones one and two. Only a limited number of discharge measurements have been made on tributary streams (Iwatsubo and others, 1975) so that these differences in hydrologic regime must be inferred primarily from qualitative observations.

RECENT RUNOFF TRENDS

Fluctuations in annual runoff for Redwood Creek at Orick during water years 1954 through 1973 are generally similar to fluctuations in precipitation for Orick-Prairie Creek State Park, but some intriguing discrepancies in this pattern are discernible (fig. 26). Three periods of water years characterized by greater than average annual runoff for Redwood Creek at Orick, are apparent in graphs of cumulative departures from the mean (fig. 26); these periods are water years 1956 through 1958, 1963 through 1965, and 1971 through 1972. The first and third of these periods coincide with periods of greater than average annual precipitation at Orick-Prairie Creek State Park, whereas the second period coincides with a period of average or slightly less than average precipitation at Orick-Prairie Creek State Park. Because the amount, as well as the intensity, of streamflow strongly influences erosion processes, it is important to seek explanations for the apparently increased percentage of annual streamflow at Orick.

Runoff-precipitation relationships may not have been constant over the entire 20 years of stream records at Orick. Flow-duration curves (fig. 37) suggest that average total annual runoff has become greater and that both exceptionally high flows and exceptionally low flows occurred more frequently during water years 1964 through 1973 than during the preceding ten years. Curves of cumulative departures from the mean (fig. 26) also suggest that in about 1962 Redwood Creek at Orick started a trend toward higher annual runoff and higher runoff-precipitation ratios; major departures from this trend occurred only in 1966, 1968, and 1973. The trend toward larger runoff-precipitation ratios at a time of apparently decreasing annual precipitation is particularly intriguing because in a humid climate evapotranspiration losses vary little from year to year so that annual runoff-precipitation ratios normally vary directly with total annual precipitation. These apparent changes are most discernible on the graph dealing only with periods of sustained high stream discharges (fig. 27).

These apparent changes in runoff relationships cannot be satisfactorily explained solely in terms of changes in precipitation amounts or intensity at Orick-Prairie Creek State Park. For example, during water years 1954 through 1963, about 7,746,100 acre feet of water flowed past the Orick gage and the total rainfall at Orick-Prairie Creek State Park was 719.51 inches. On the other hand, during water years 1964 through 1973 about two percent more water, 7,928,600 acre feet, flowed past the Orick gage even though the total rainfall at Orick-Prairie State Park was 668.65 inches or about 93 percent of the rainfall during the preceding ten years. This increased runoff apparently cannot be satisfactorily explained by increased rainfall intensities at Prairie Creek State Park. At that station, 24 fewer days with precipitation of more than 0.01 inch, 5 fewer days with precipitation of more than one inch, and 17 fewer days with precipitation of more than 2 inches occurred between water years 1964 and 1973 than during the preceding 10 years. More satisfactory explanations of the apparent changes in runoff relationships at Orick may be related to changes in regional precipitation patterns and land use.

Given the natural variation in storm tracks and the complex physiography of the Redwood Creek basin and its environs, large variations in regional precipitation patterns appear to be part of the variability inherent in the present climate. Annual precipitation records at Crescent City, Hoopa, Eureka and Board Camp Mountain (fig. 28) do indeed suggest that some of the variation in annual precipitation-runoff relationships at Orick may reflect variations in regional annual rainfall patterns. That is to say that under some circumstances precipitation at Orick-Prairie Creek State Park may be a rather poor index of basinwide precipitation.

Regional variation in rainfall patterns (fig. 23 seem partly to explain anomalously low runoff in 1957 and anomalously high runoff in 1963, 1965 and 1969. However, the positive departures from mean precipitation at all of these weather stations are much smaller than the coeval positive departures from mean runoff at Orick.

Additional factors that could account for part of the recent apparent increase in the percentage of annual rainfall that appears as streamflow in Redwood Creek at Orick include changes in land use and change in the time sequence of storms in relation to each other and to seasons of the year. Both types of changes can influence streamflow by modifying evapotranspiration losses, interception, and antecedent soil moisture conditions. Logging and road construction can further modify streamflow by reducing infiltration and by intercepting subsurface flow along roads and skid trails. Our interpretation of data related to the possible importance of time sequences of storms and changes in land use on increasing streamflow in Redwood Creek are not completed. However, a preliminary rainfall-runoff model of streamflow data collected at Orick and rainfall data collected at Orick-Prairie Creek State Park (D. R. Dawdy, K. W. Lee, and G. W. Kapple, written communication, 1975) suggests that rainfall-runoff relations have changed and that the increased runoff can not be explained by seasonal effects or antecedent moisture. Because of considerable public concern about the possible impact of timber harvest on the streamflow regime of Redwood Creek, we summarize in the following paragraphs our preliminary findings and interpretations in light of published studies on logging-induced streamflow modifications.

TIMBER HARVEST AND STREAMFLOW

Although data presented in this report are insufficient to prove quantitatively any land-use induced changes in the runoff characteristics of the Redwood Creek basin, we have noted the coincidence that intensive timber harvest and associated road construction in the Redwood Creek basin were initiated at or immediately prior to the apparent change in runoff characteristics. Moreover, initial measurements of storm precipitation and runoff in some tributaries in the lower basin (Iwatsubo and others, 1975) suggest that recent changes in land use, especially intensive timber harvest, have increased annual runoff; runoff from small and moderate storms appears to have been increased more than that from major storms. The preliminary Redwood Creek findings are compatible with more detailed studies at experimental watersheds with climate and vegetation not greatly different from those of Redwood Creek (Anderson and Hobba, 1959; Rothacher, 1965, 1970; Black, 1967; Hibbert, 1967; Harper, 1969 and Hsieh, 1970 quoted in Brown and Kryger, 1971; Harris, 1971).

Most analyses of the impact of logging on stream runoff in the literature cited above suggest (1) that logging increases total annual runoff, (2) that the increases in runoff are most pronounced during early autumn storms and the biologically critical summer dought, (3) that impacts upon major flood flows are less than upon low and moderate stream discharges, and

(4) that any increase in flow persists for relatively few years. These changes in runoff patterns are summarized in schematic flow duration curves shown in figure 40.

If the recent increase in the frequency of both extremely low flows and extremely high flows on Redwood Creek at Orick (fig. 37) partly reflects logging of old growth Redwood and Douglas-fir forests, a comparison of figures 37 and 40 suggests that the logging-induced changes in the runoff regime of Redwood Creek are somewhat different than those observed at experimental basins in northwestern California and southwestern Oregon. These differences may reflect larger cutting units, greater ground disturbance, and more pronounced summer drought in the Redwood Creek basin than in the experimental basins. Increased ground disturbance associated with recent logging of old growth redwood compared with that associated with Douglas-fir-dominated logging in most experimental watersheds in the Pacific Northwest results from the greater use of tractor yarding in the redwood region. Also the large size and brittle nature of redwood timber often require bulldozer-construction of layouts. Forest practices in the redwood region are discussed in more detail in the section on resource utilization.

Increases in runoff following logging have usually been explained in the previously cited references primarily in terms of (1) decreased interception of rainfall and direct evaporation from canopy vegetation, (2) soil compaction leading to decreased infiltration rates and soil moisture storage, and (3) decreased depletion of soil moisture by evapotranspiration. Loudermilk (1966) has expanded slightly upon infiltration-

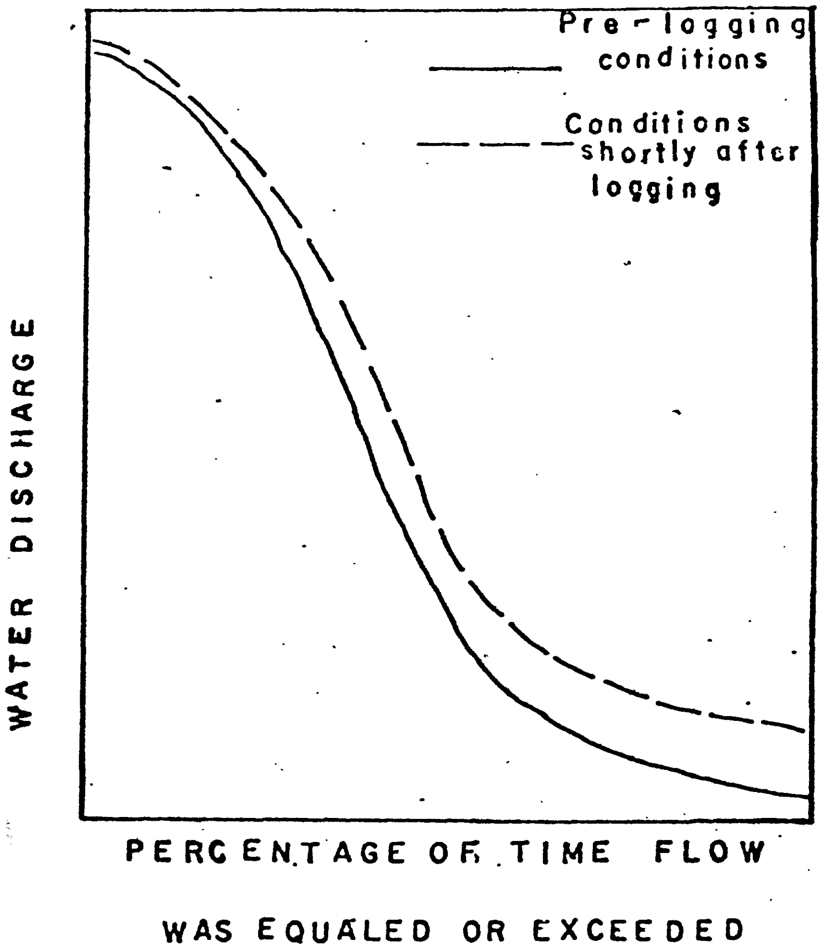


Figure 40. Schematic representation of typical change in flow frequency curves following timber harvest as suggested by paired basin studies previously reported in the literature.

oriented explanations of increased runoff by suggesting that theory and limited experimental data indicate that highly turbid waters draining recently denuded land will infiltrate any given soil profile much more slowly than clean water draining well-vegetated land. All four of these processes have probably influenced stream runoff from cutover land in the Redwood Creek basin. However, the type and degree of mechanical disruption of the soil within tractor-yarded cutover land brings still other runoff-generating processes into play.

The role of increased mechanical disruption of the ground in increasing runoff can be understood best in terms of a partial area (Dunne and Black, 1970a, 1970b) or variable source (Hewlett and Hibbert, 1967) model of storm runoff generation. Subsurface seepage from cutbanks along roads and skid trails, as described by Megahan (1972), appears to be a major (perhaps even dominant) process in generating overland flow in the Redwood Creek basin. The conversion of subsurface flow to surface flow greatly increases the total area within a basin that consists of either saturated soil or actual free-water surfaces. Rain falling on these areas is converted entirely to surface runoff and leads to greatly increased volumes and rates of storm runoff.

The different geometric patterns of skid trails resulting from different yarding procedures can also influence storm runoff (Stone and others, 1969). Cable yarding systems result in fan-shaped patterns of shallow skid trails ("cable ways") that converge upslope and tend to disperse overland flow. In contrast, tractor yarding ("cat logging") results in dendritic patterns of skid trails that are commonly several feet deep and converge downslope and tend to concentrate surface runoff. In most experimental watersheds in the Pacific Northwest high lead or sky-line cable systems were used to yard the logs, whereas tractor yarding has been the dominant style of logging in the Redwood Creek basin.

Some controversy about the impact of logging upon flood discharges still exists. Anderson and Hobba (1959) suggest that logging can increase unit discharge of high as well as low and moderate flood flows. Similarly, Black (1966) suggests that the increased frequency and magnitude of flooding in the Eel River basin is directly related to logging. In contrast, Rantz (1965) believes that peak discharges of the devastating 1964 flood in northwestern California were not influenced by logging. Hewlett and Helvey (1970) indicate that, even when peak discharges are little affected by timber harvest, the total volume of storm runoff is increased significantly, and this increased volume could result in increased downstream flooding. The spatial distribution as well as the size and number of recently cutover areas within a basin influence peak discharges (Stone and others, 1969). The papers cited above have relied on completely different analytical techniques and only limited data. The present authors believe that the impact of recent timber harvest upon the magnitude of major floods in the redwood region is an urgent question that still cannot be definitively answered.

Considerable historical information (McGlashan and Briggs, 1939; Paulsen, 1953; Hofmann and Rantz, 1963; Rantz, 1965), as well as geological and botanical evidence (Zinke, 1966; Stewart and La Marche, 1967; Helley and La Marche, 1973) indicates that destructive, high magnitude floods occurred repeatedly throughout northwestern California long before the initiation of any major changes in landuse. Historical observations on the Smith, Klamath, Trinity, and Eel Rivers(fig.28) suggest that the Redwood Creek basin probably experienced floods in 1862 and 1890 that were comparable in magnitude to those of 1953, 1955, 1964, and 1972. Helley and La Marche (1973) have used radiocarbon and tree-ring dating to assign ages to prehistoric flood deposits at several localities in northwestern California. These workers conclude that a flood larger than that of December 1964 occurred about the year 1600 and that floods closely comparable to that of 1964 have occurred several times since then.

At several localities within the Redwood Creek basin we have observed flood plain stratigraphy comparable to that described by Zinke (1966) and pre-historic Holocene gravel deposits bearing apparently a single young age class of conifers comparable to those studied by Helley and La Marche (1973). So far we have attempted to date these features only by counting annual rings on stumps. Even these limited data, however, suggest that a flood-related depositional event comparable to that of 1964 had not occurred in the headwater reaches of Redwood Creek during the preceding 300 years, whereas gravel deposition comparable to that of December 1964 did occur at least once in the late nineteenth century in the reach between highway 299 and Redwood Valley. More systematic sampling of these ancient flood deposits would undoubtedly provide a clearer understanding of the magnitude and recurrence interval of major floods.

STREAM AND WATER QUALITY

The overall water quality of Redwood Creek and its major tributaries, like that of most other streams of northwestern California, is good in that its water generally meets the objectives of the California North Coast Regional Water Quality Control Board (1974). Moreover, these streams support an interesting and diverse aquatic ecosystem comprising a rather limited number of individuals. At present the problems relating to water quality of these streams are principally streambed instability and high suspended-sediment concentrations during late autumn and winter storm periods. The observed combination of high water temperature and low dissolved-oxygen concentration along the main channel and some low-gradient tributaries during low-flow periods of late summer and early autumn is also undesirable. Accruing data further suggest that high concentrations of essential plant nutrients, locally excessive periphyton, and coliform bacteria may occasionally cause water-quality problems in some parts of the basin. The degree to which these water-quality problems result from man's modification of the natural environment is not obvious; this is particularly true in the case of the seasonally high stream sediment loads (Janda, 1972).

SEDIMENT DISCHARGE

Suspended-sediment discharge

The sediment regimen of Redwood Creek is comparable to that of other large streams in northwestern California in that the creek transports an exceptionally large annual suspended-sediment load and that most of the sediment is transported in a rather brief period of time. Indeed suspended-sediment discharge records suggest that northwestern California is the most rapidly eroding region within the conterminous United States (Judson and Ritter, 1964); at least 18 northwestern California stream-gaging stations that monitor drainage basins in excess of 100 square miles are characterized by average annual suspended-sediment yields in excess of 2000 tons per square mile (Janda, 1972). Recent reports on the high sediment loads of individual northwestern California rivers include Ritter and Brown (1971), Brown and Ritter (1971), Knott (1971, 1974), Ritter (1972), and Brown (1973).

Even in this environment, however, the suspended-sediment load of Redwood Creek appears to be noteworthy. In fact, during the first three years of complete sediment records (water years 1971 through 1973) the average annual suspended-sediment yield of about 8,100 tons per square mile for Redwood Creek at Orick was, on a per square mile basis, nearly two times greater than that of the Eel River at Scotia (Table 9)--a basin credited with the highest suspended-sediment yield of any comparably sized river in the conterminous United States (Brown and Ritter, 1971). During this time, however, the suspended-sediment load of the Eel River, in all but one year, was far below the 16-year average load (Table 9) because the major sediment-transporting storms were not as intense in the Eel River basin as in the Redwood Creek basin.

A common method of studying the sediment-transport characteristics of rivers is to define relations between water discharge and suspended-sediment discharge. In this report we shall refer to the graphical representation of such relations as sediment-transport curves. Sediment-transport curves for stations along Redwood Creek are presented in figures 41, 42, 43, and 44. Curves for stations at Orick and near

Station name and number	Drainage Area (square miles)	Period of water records (years)	Period of sediment records (years)	WY 1971 Water discharge (acre-feet and percent of mean) of record	WY 1971 Suspended sediment discharge (tons and percent of mean) of record	WY 1972 Water discharge (acre-feet and percent of mean) of record	WY 1972 Suspended sediment discharge (tons and percent of mean) of record	WY 1973 Water discharge (acre-feet and percent of mean) of record	WY 1973 Suspended sediment discharge (tons and percent of mean) of record	Mean sediment [illegible] for period [illegible] through WY 1973 (tons sq. mi.)
Eel River at Scotia, Calif. 114770.00	3,113	63	16	7,737,000 (147)	27,374,000 (103)	4,506,000 (86)	5,29[illegible],000 (20)	[illegible] (112)	[illegible] (31)	[illegible]
Mad River near Arcata, Calif. 114810.00	485	26	16	1,377,000 (125)	2,758,000 (104)	1,166,000 (106)	3,145,000 (119)	[illegible] (73)	1,130,000 (43)	4,900
Redwood Creek at Orick, Calif. 114825.00	278	22	3	1,019,000 (131)	2,178,000 1/	1,062,000 (136)	3,800,000 1/	554,000 (72)	758,000 1/	8,100
Trinity River at Hoopa, Calif. 115300.00	2,854	46	17	5,131,100 (132)	6,011,000 (109)	3,563,000 (91)	4,361,000 (79)	2,544,000 (75)	1,350,000 (24)	1,400

1/ Duration of record is insufficient to compute a significant mean.

Table 10. Maximum mean daily suspended sediment concentrations for selected stream gaging stations in northwestern California.

Station name and number	Period of record prior to October 1973 (years)	Maximum of record (mg/l)	Maximum during WY 1972 (mg/l)
Eel River at Scotia, Calif. 114770.00	16	33,000	3,360
Mad River near Arcata, Calif. 114810.00	16	21,900	6,330
Redwood Creek at Orick, Calif. 114825.00	3	-	8,840
Trinity River at Hoopa, Calif. 115300.00	17	20,400	3,370

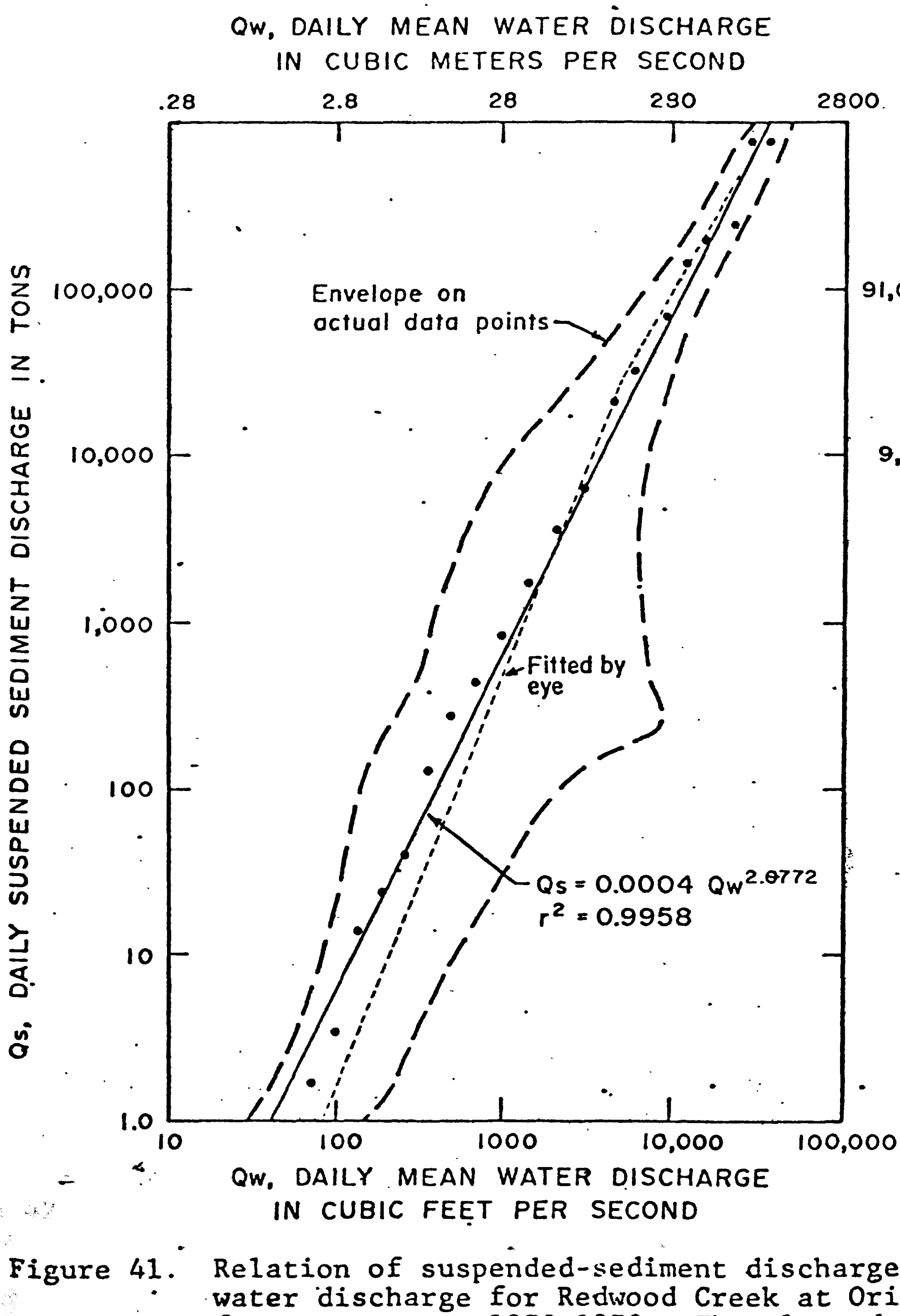


Figure 41. Relation of suspended-sediment discharge to water discharge for Redwood Creek at Orick for water years 1970-1973. The plotted points represent average values of suspended-sediment discharge for selected intervals of water discharge. The regression equation was developed from only these average points.

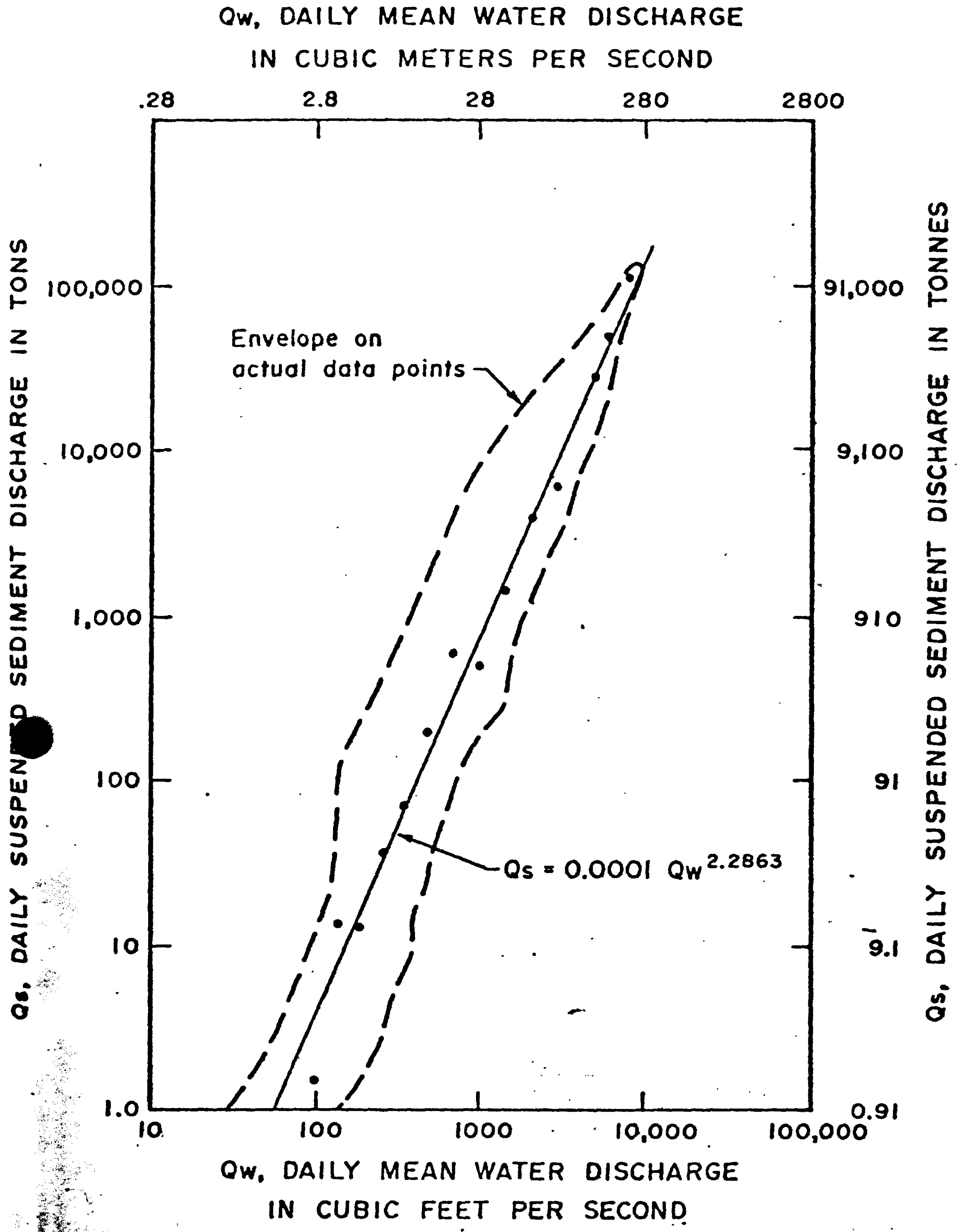


Figure 42. Relation of suspended-sediment discharge to water discharge for Redwood Creek at Orick for 1973 water year. The plotted points represent average values of suspended-sediment discharge for selected intervals of water discharge. The regression equation was developed from only these average points.

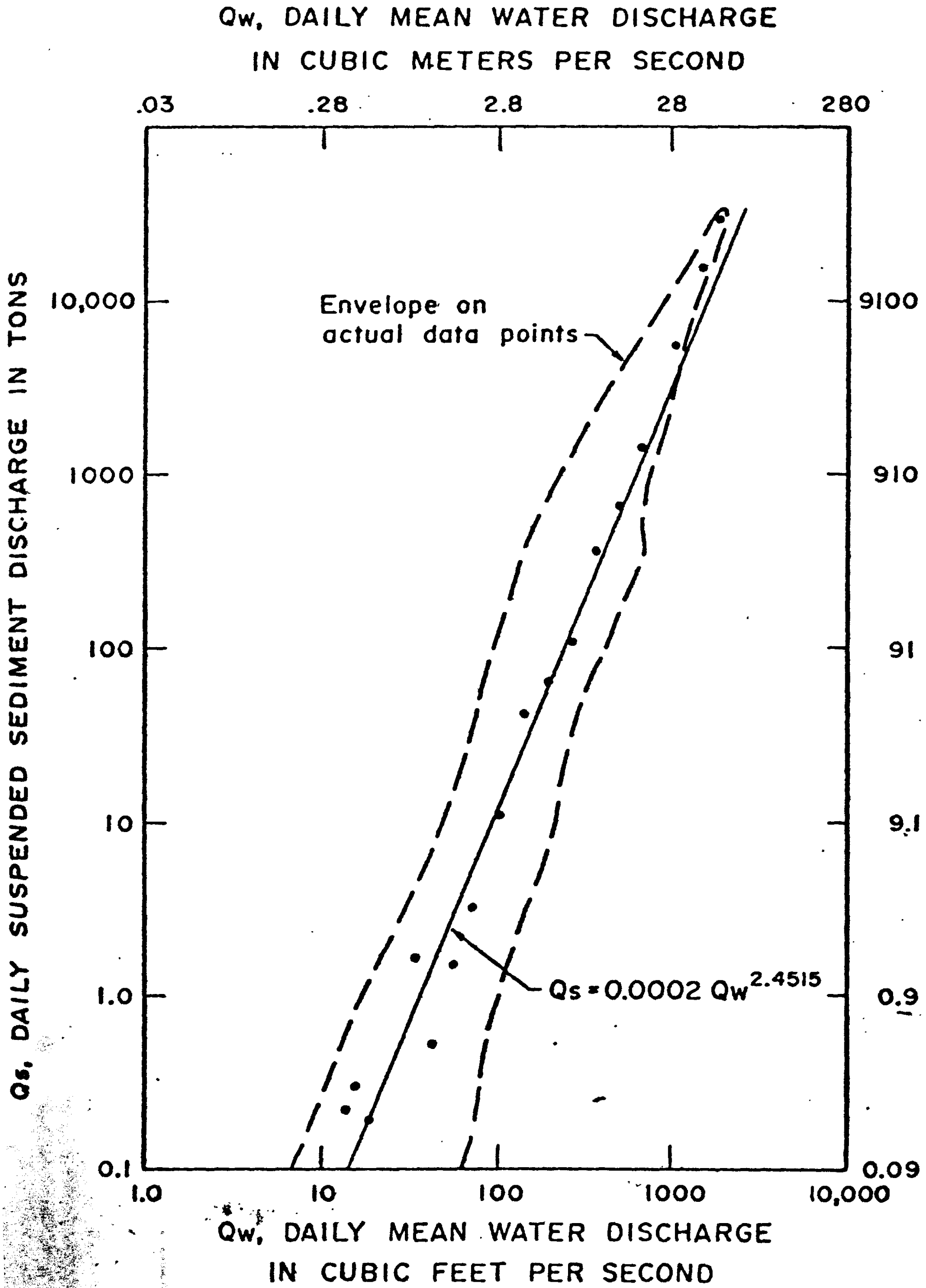


Figure 43. Relation of suspended-sediment discharge to water discharge for Redwood Creek near Blue Lake for 1973 water year. The plotted points represent average values of suspended-sediment discharge for selected intervals of water discharge. The regression equation was developed from only these average points.

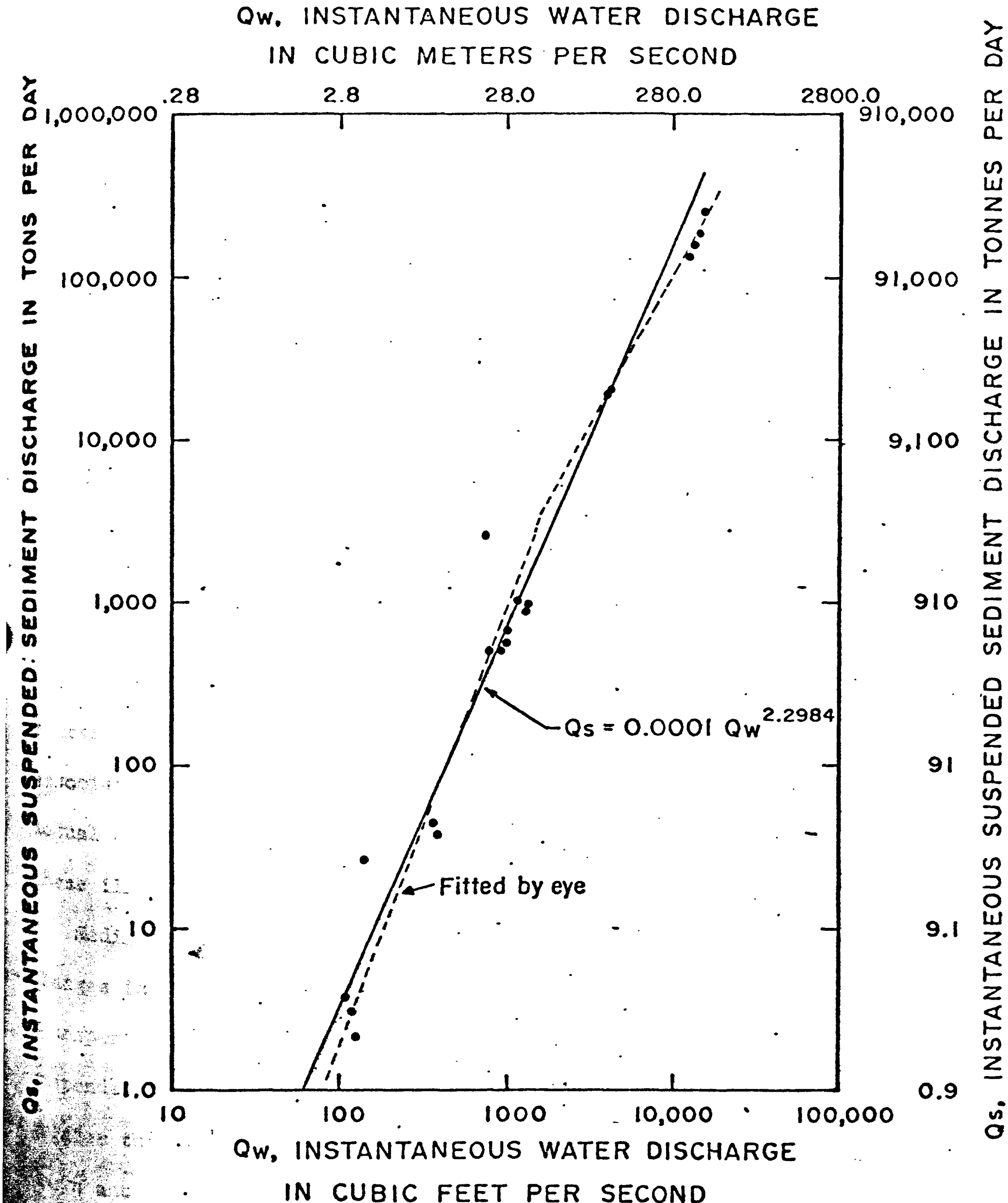


Figure 44. Relation of suspended-sediment discharge to water discharge for Redwood Creek at South Park boundary near Orick for water years 1971-1973. Plotted points are actual instantaneous values.

Blue Lake, where suspended-sediment data are collected on a regular daily basis, are plotted in terms of average daily values of water and sediment discharge. The plotted points on these curves represent average values of suspended-sediment discharge for selected intervals of water discharge; these values were derived from a computer program described by Brown and Ritter (1971, p. 23-24). The regression lines were developed from only these average points.[1/] In contrast, the curve for the station at the southern boundary of Redwood National Park, where sediment data are collected on only a periodic basis, is plotted in terms of instantaneous values of water and sediment discharge.

The infrequent events represented by the high values on these curves are responsible for most of the sediment transport. Thus, it is imperative to define the upper parts of these curves as precisely as possible. Curves fitted by eye to the actual data points often have a gentler slope at high discharges than at low discharges (figure 41 and 44). Thus, simple linear regression lines may over estimate the actual suspended sediment discharge associated with high water discharge. Envelope curves around all the actual data points used in the averaging computations are also shown on these illustrated sediment-transport curves.

Sediment-transport curves often change in response to major floods and changes in land use. Following the 1964 floods, for example, sediment-transport curves for many northern California streams indicated that suspended-sediment loads for a given stream discharge were two to five times greater than they were immediately prior to the flood (Anderson, 1970; Brown and Ritter, 1971; Brown, 1973; Knott, 1971, 1974). Since the 1964 flood, sediment-transport curves have gradually shifted back toward those reflecting pre-flood conditions (Knott, 1971, 1974; Brown, 1973). Although pre-1972 sediment-transport relations for Redwood Creek at Orick are poorly defined, the floods of January and March, 1972, may have caused a slight upward shift in the sediment-transport curve (compare figures 41 and 42. In nearby drainage basins with gaging stations where suspended-sediment data are collected, the magnitude and duration of 1972 floods were not large enough to alter their sediment-transport curves.

1/ The coefficients of determination (Hewlett-Packard, 1974, p. 54-55) for these regression lines are all high because of this averaging procedure and because the water discharge (Q_w) is a factor in determining the suspended-sediment discharge (Q_s). Thus, the coefficients have no physical significance and they are not listed.

When compared with other rivers with high suspended-sediment yields (Leopold and Maddock, 1953, Appendix B; Judson and Ritter, 1964; Holeman, 1968), the high suspended-sediment loads of northwestern California's rivers appear unusual in that the loads are the product of high stream discharge and relatively modest concentrations of suspended sediment (Table 10). For example, during the three years of record for Redwood Creek at Orick the mean daily concentration of suspended sediment has been in excess of 1000 mg/l on only 94 days and in excess of 5000 mg/l on only five days. The average concentrations of suspended sediment associated with the average daily discharge (1220cfs) and the daily discharge with a recurrence interval of two years (17,300 cfs) for Redwood Creek at Orick during this interval were about 300 mg/l and 5400 mg/l, respectively. Storm runoff on many streams in the southwestern United States and in agricultural land in the midcontinent is generally characterized by considerably higher concentrations of suspended sediment than streams in northwestern California. In those areas, average suspended-sediment concentration is commonly greater than 2000 mg/l and storm runoff commonly has concentrations of several tens of thousands of milligrams per liter (Leopold and Maddock, 1953, Appendix B; Rainwater, 1962).

Gaging Station	Drainage Area: Sq. mi.	Drainage Area: Percent (of total)	Water Discharge (acre feet)	Suspended Sediment Discharge (tons)	Concentration of Suspended Sediment (mg/l)	Suspended Sediment Yield (tons/sq.mi.)	Percent of Discharge at Orick: Water	Percent of Discharge at Orick: Suspended Sediment
Redwood Creek near Blue Lake	67.6	24	139,400	184,700 1/	970	2730	25	24
Intervening Drainage Area	117.4	42	247,800	>64,000		>550	44	>8
Redwood Creek at South Park Boundary	185	67	387,600	>249,000 2/3/	>470	>1360	69	>33
Intervening Drainage Area	93	33	171,100	<514,000		<5410	31	<67
Redwood Creek at Orick	278	100	559,000	757,600 1/ >522,000 3/4/ Between 745,000 and 971,000 5/	1,000	2725 >1880 Between 2680 and 3490	100	100

1/ Computed on the basis of daily sediment sampling (Porterfield, 1978). These values are more reliable than those computed from flow duration curves. Computations based upon flow duration and sediment-transfer curves are included (see footnotes 4 and 5) for comparative purposes. This comparison indicates the general level of uncertainty associated with the value for South Park Boundary.

2/ Estimated from the relation between water discharge (Qw in CFS-days) and suspended sediment discharge (Qs in tons per day) for the period including water years 1971 through 1973 ($Qs = 0.0001\ Qw^{2.2984}$; $r^2 = 0.9744$), and the flow duration curve for WY 1973. Estimate was based upon computed values of Qs for mid-points of each discharge increment in Table [illegible]. Insufficient data are available to compute a water discharge-suspended sediment discharge relation from only WY 1973 data.

3/ Because of the logarithmic relation between discharge and suspended-sediment concentration (or load), more sediment is transported in the upper part of each discharge increment than in the lower part; thus, sediment loads computed using the mid-points are lower limits on the actual loads.

4/ Estimated from the relation between water discharge and suspended sediment discharge for the period including water years 1970 through 1973 ($Qs = 0.0004\ Qw^{2.0772}$; $r^2 = 0.9958$) and the flow duration curve for WY 1973. Estimate was based upon computed values of Qs for mid-points of each discharge increment in Table 3.

5/ Estimated from the relation between water discharge and suspended sediment discharge ($Qs = 0.001\ Qw^{2.2603}$; $r^2 = 0.9909$) and the flow duration curve (Table 3) for only WY 1973. The lower limit on the suspended sediment discharge was computed from values corresponding to the mid-points of the discharge class intervals in Table 3, whereas the upper limit on the suspended sediment discharge was computed from the upper limits of these [illegible]

Even though concentrations of suspended sediment in Redwood Creek are not exceptionally high, moderate concentrations persist throughout much of the winter storm season and impart to the creek a distinctive gray color. Average daily concentrations in excess of 300 mg/l commonly persist for several days at Orick; nine such periods persisted for more than 10 days during water years 1971 through 1973. These periods occur at the time when anadromous fish are spawning and their fry emerging (Holmberg, 1972). Prolonged exposure to concentrations of suspended sediment in excess of 300 mg/l are considered by some authors lethal to fish (Gibbons and Salo, 1973). These concentrations are also sufficiently high to cause local degradation of intra-gravel environments by partially impregnating streambed materials. The interactions between aquatic organisms and stream-sediment loads are discussed in more detail later in this report.

In attempting to interpret existing suspended-sediment records for Redwood Creek and in designing the collection of future suspended-sediment data, the episodic nature of sediment transport along Redwood Creek, and northwestern California streams in general, must be fully appreciated. In any given year, nearly all the stream sediment is transported during a few short intense storm periods. Data documenting the episodic character of sediment transport on Redwood Creek at Orick are summarized in figure 45; the dashed line on this figure is used to indicate that during the water years 1971 through 1973 stream discharges that were equalled or exceeded only five percent of the

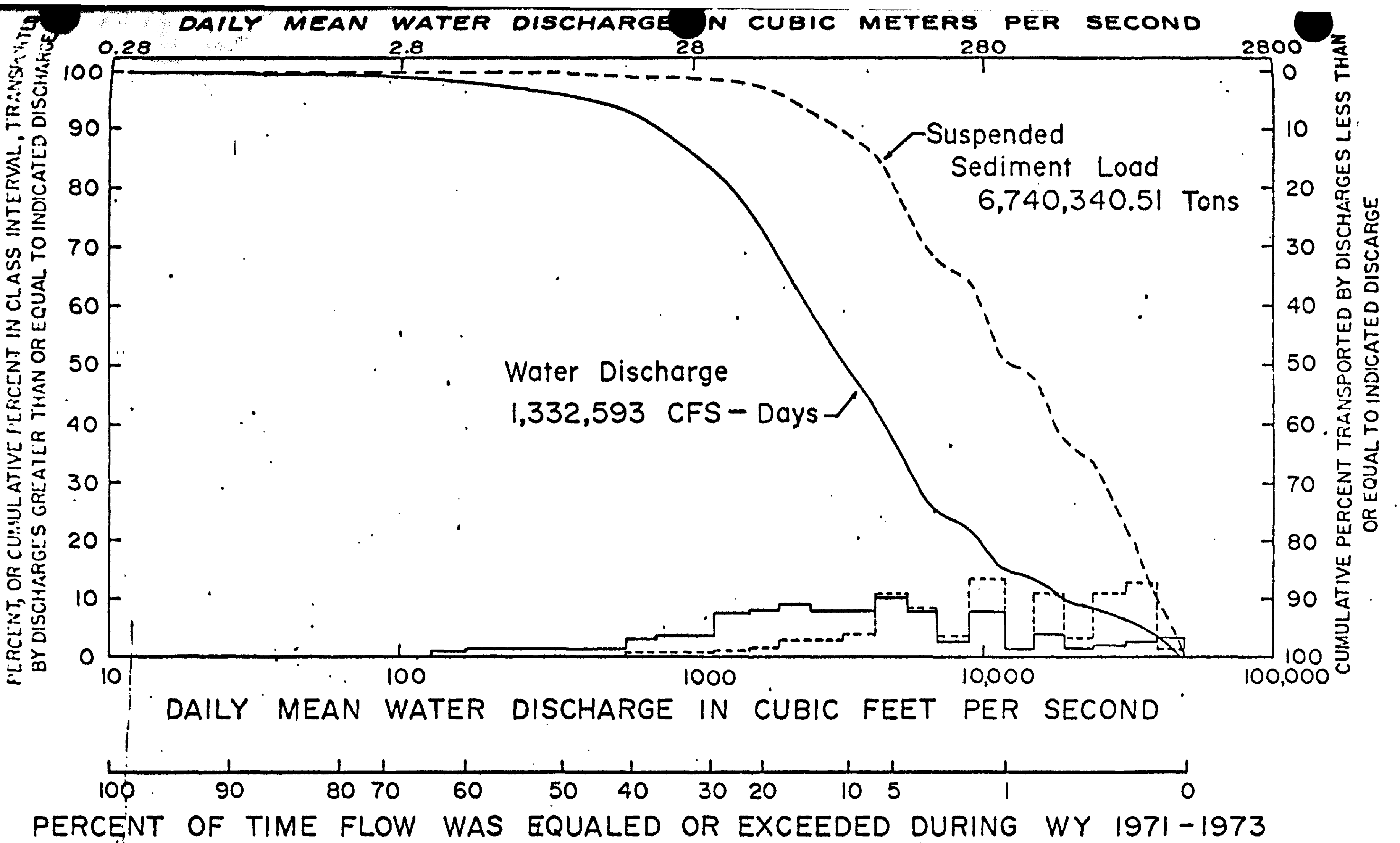


Figure 45. Cumulative curves and histograms of water discharge and suspended-sediment load for selected increments and frequencies of occurrence of water discharge for Redwood Creek at Orick during water years 1971 through 1973.

time accounted for about 37 percent of the total water discharge and transported about 80 percent of the total suspended-sediment load. Similarly, stream discharges that were equalled or exceeded only 1 percent of the time during water years 1971 through 1973 accounted for about 15 percent of the total water discharge and transported about half the total suspended-sediment load. The episodic, storm-related nature of suspended-sediment transport for Redwood Creek at Orick is illustrated further in figures 46 and 47. Only about 11 percent of the total suspended-sediment load transported by Redwood Creek during water years 1971 through 1973 was transported during water year 1973 (fig. 46). Moreover, about 80 percent of the total water year 1973 suspended load for Redwood Creek stations at Orick and near Blue Lake was transported during two brief storm periods between the middle of December and the middle of January (fig. 47). A more striking example of the importance of storm runoff in determining the sediment load of Redwood Creek is provided by the storms of March 1972; about 28 percent of the suspended-sediment load transported at Orick during water years 1971 through 1973 did so during March 1972. Thus, a year with low total runoff but a few major storms can result in a far greater sediment yield than a year with high sustained flow, but no major storms.

Suspended-sediment concentrations and load per unit area for Redwood Creek near Blue Lake are apparently about equal to those at Orick (Table 11). Comparative sediment-transport curves plotted in terms of sediment load per unit area for stream-gaging stations along Redwood Creek near Blue Lake, at the southern boundary of Redwood National Park, and at Orick show rather similar relationships (fig. 48). However, at high discharges that are responsible for most of the sediment transport, the sediment discharge per unit of drainage area appears to decrease slightly between the station near Blue Lake and the southern Park boundary, and then to increase between there and Orick.

Downstream increases in suspended-sediment contributions from streambank erosion and from recently logged areas apparently make up for downstream decreases in suspended-sediment contributions from earthflows and streamside landslides. Independent interpretations of aerial photographs

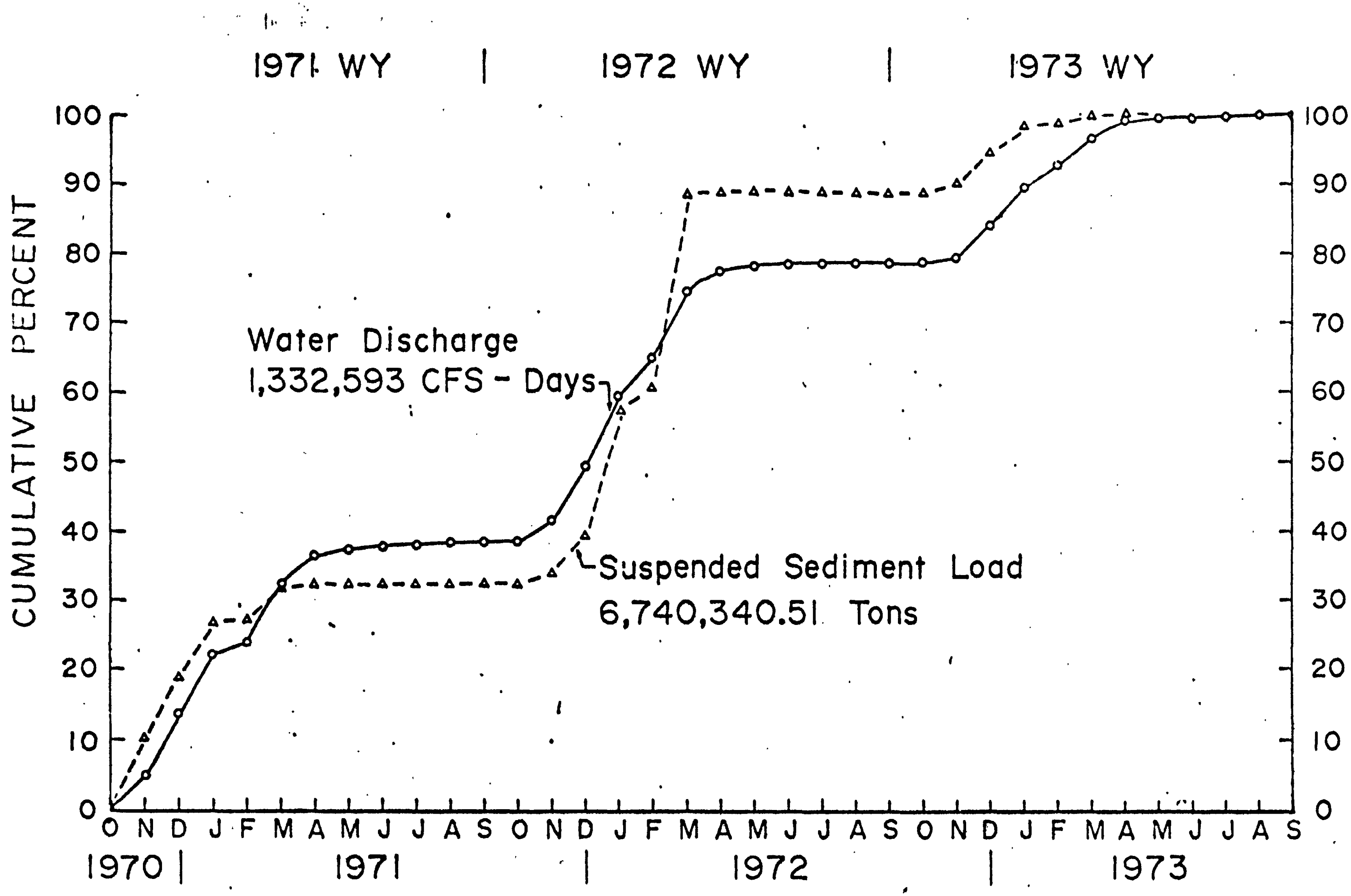


Figure 46. Cumulative curves for water discharge and suspended-sediment load for Redwood Creek at Orick for water years 1971 through 1973.

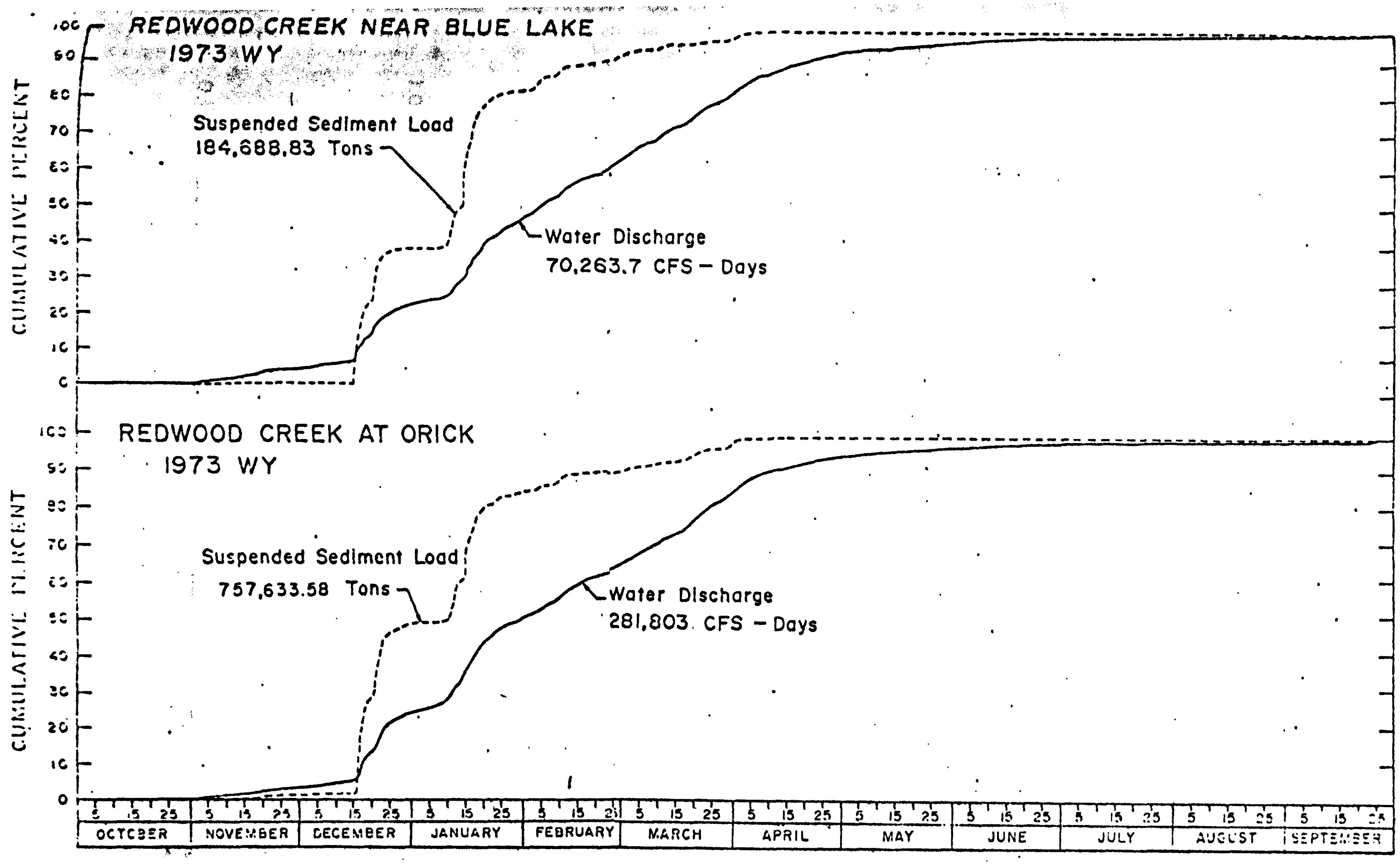


Figure 47. Cumulative curves for water discharge and suspended-sediment load for Redwood Creek near Blue Lake and Redwood Creek at Orick for water year 1973.

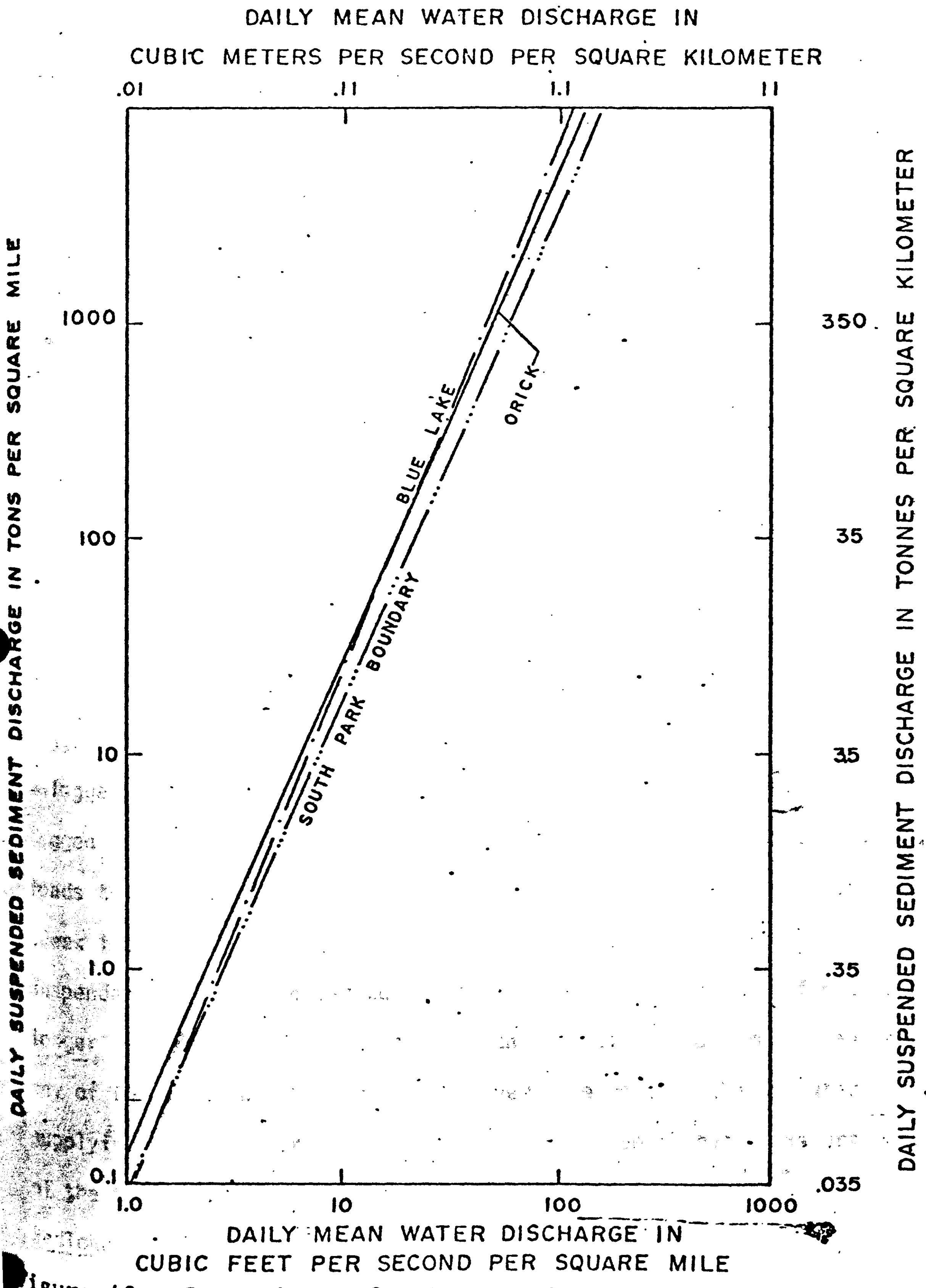


Figure 48. Comparison of relations between water discharge and suspended-sediment discharge for Redwood Creek near Blue Lake, at south park boundary, and at Orick.

and field inspection at different times by the U.S. Department of Agriculture's River Basin Planning Staff (1970) and the U. S. Geological Survey (Curry, 1973) suggest that the area between the gaging station near Blue Lake and the southern boundary of Redwood National Park may be the most rapidly eroding part of the basin; available fluvial-sediment data (Table 11) appear to contradict this observation but they are insufficient to test fully this hypothesis.

Observations throughout the Redwood Creek basin and initial measurements in the downstream third of the basin (Iwatsubo and others, 1975) suggest that during observed storms of low to moderate intensity tributaries draining extensive tracts of recent timber harvest have higher suspended-sediment concentrations and loads per unit of drainage area than do tributaries draining only unlogged forests and revegetated older logging units. The suspended sediment from the more recently logged tributary basins also appears to be browner in color than that from unlogged basins. However, during the observed storms even the most heavily logged tributaries appear to have suspended-sediment concentrations and loads that even on a per-square-mile basis are lower than those of Redwood Creek itself (Winzler and Kelley, 1975; Iwatsubo and others, 1975). Suspended-sediment induced turbidity also appears to persist for a much longer period of time along the main channel of Redwood Creek than in any of the studied tributaries. However, the role of the tributaries in supplying sediment during the extreme runoff events that transport most of the total suspended sediment load remains to be evaluated.

Bedload

Recent major changes in stream-channel geometry throughout the Redwood Creek basin attest to occasionally high rates of bedload transport.

Knowledge of the absolute quantities of bedload and the relations between bedload and water discharge is scant because generally acceptable procedures for sampling and computing bedload are still being developed. Periodic direct measurements of bedload utilizing the Helley-Smith (1971) sampler, however, were started along Redwood Creek during water year 1974 (Iwatsubo and others, 1975). Initial data collected at six sites along Redwood Creek as well as data from similar nearby streams (Brown and Ritter, 1971; Knott, 1971, 1974) suggest that bedload probably accounts for 15 to 35 percent of the total sediment load of Redwood Creek.

The percentage of sediment transported as bedload by Redwood Creek appears to decrease in a downstream direction. The absolute quantity of bedload moved past Orick appears to be significantly less than the quantity moved past the southern boundary of Redwood National Park. Channel aggradation along the reaches of Redwood Creek within the Park, as documented by repetitive surveys of monumented stream-channel cross sections in 1973 and 1974, (Iwatsubo and others, 1975), probably accounts for much of this decrease in bedload.

The mechanical disintegration of streambed material, however, provides an alternative explanation for the downstream decrease in bedload. Anderson (1971) has postulated that this mechanism accounts for part of the downstream increase in suspended load that accompanies the downstream decrease in bedload along the Eel River. Mechanical disintegration of bed material is a plausible process along Redwood Creek as bed materials observed during low flow contain a large number of cracked and partly decomposed clasts of sandstone, siltstone, and schist that would abrade and fracture quickly in transit. The proportion of mechanically unstable clasts appears to decrease in a downstream direction. If mechanical disintegration is a prominent process, the downstream decrease in bedload should be accompanied by a downstream decrease in grain size of the bedload and a comparable downstream increase in suspended load. These conditions do exist along Redwood Creek, but present data are insufficient to decide to what degree those conditions reflect aggradation, mechanical disintegration, selective hydraulic sorting, and introduction of new sediment from bank erosion and downstream tributaries. Data documenting the relative importance of each of these processes is needed to plan for the passage of present and anticipated sediment loads through the park lands of lower Redwood Creek.

The characteristics of streambed materials, the frequency and duration of bedload movement and the pool and riffle configuration in heavily-logged tributary basins along Redwood Creek are strikingly different from those in uncut basins. Increased rates and frequencies of bedload transport in logged versus unlogged tributaries are suggested by qualitative observations throughout the basin and measurements in the lower third of the basin (Iwatsubo and others, 1975). The streambeds in heavily logged basins, moreover, display more poorly sorted sandy pebble gravel than streambeds in uncut areas. The poorly sorted sandy pebble gravel appears to be derived primarily from erosion of roadside ditches, gullied skid trails, and sidecast road spoil in recently logged areas. The abundance and grain size of this gravel apparently decreases progressively downstream away from recent logging units because of the natural sediment-retention capacity of rock pools and low-gradient stream reaches above natural check dams created by streamside slides and fallen trees. This retention would attenuate the immediate impact of logging-related bed load on downstream reaches, where the most visible initial modification of the streambed materials is usually increased quantities of brownish "mud" (silt and fine sand) in pools.

The environmental price of this attenuation, however, is high. The filling of pools and the burial of previously stable wooden-debris jams and rock riffles, along with a general smoothing and fining of the streambed, result in less living area for swimming organisms and less stable substrates for benthic invertebrates and periphyton. Observations along Oregon streams that are physiographically similar to tributaries along Redwood Creek suggest that the introduced bed material normally works its way slowly downstream as a diffusely-defined slug, unless exceptionally intense rainfall leads to the generation of a scouring debris torrent like those described by Fredricksen (1963) and Swanston (1971). As the introduced bedload moves through unlogged downstream reaches, self-reinforcing feedback mechanisms are occasionally initiated. Local aggradation, deflection, and increased channel widths may cause erosion of streambanks and previously stable colluvium. This, in turn, may trigger streamside slides and additional aggradation.

Long-term implications of stream-sediment loads

The consequence of the high stream-sediment loads measured along Redwood Creek and other northwestern California ~~rivers for the~~ existing aquatic and riparian ecosystems are reasonably clear and are discussed elsewhere in this report. The implications of these loads for the long-term evolution of the landscape, however, are more obscure. The principal sources of uncertainty are the shortness of existing sediment records, the impact of recent major floods, and uncertainties regarding future climatic fluctuations and man's land-management decisions. Nonetheless, it is important to realize that if these high sediment loads persist for long, they are a source for immense practical concern (Wallis, 1965; Wahrhaftig and Curry, 1967; Janda, 1972). This concern lies in the fact that the stream-sediment loads are derived from the forest soils that support the commercial and parkland timber resources of northwestern California. Observations of types and degrees of soil-profile development on landforms of widely differing ages in northern California and southwestern Oregon suggest that the dominant timber-supporting soils in the Redwood Creek basin have developed over tens and even hundreds of millenia and partly under climatic conditions different from those of the present. Thus, over socially meaningful spans of time, these forest soils are a nonrenewable resource and should be managed accordingly.

Erosion rates computed from existing stream-sediment records suggest that the entire regolith could be eroded away in only a few millenia, even if the computed rates overestimate the actual long-term erosion rates by a factor of two. Erosion rates computed from suspended-sediment records for Redwood Creek at Orick for 1970–73, for example, imply a rate of erosion of about 0.35 feet of rock or 0.7 foot of soil per century, expressed in terms of an average lowering of the land surfaces. This rate is more than twice as fast as the geologically computed, upper limit on the long-term average rate of erosion for this basin as discussed earlier. Similar estimates of long-term erosion rates based on suspended-sediment loads of nearby streams are presented in Judson and Ritter (1964), Wahrhaftig and Curry (1967), and Janda (1972); the present erosion rates of these streams also appear to be several times more rapid than the geologically computed long-term average rate of erosion. The erosion rates estimated from suspended-sediment loads would obviously be significantly higher if they included bedload and dissolved load. Large areas, however, will be characterized by rates of soil erosion that are considerably less than the average rate because stream-channel erosion and landsliding, the dominant erosion processes in these basins, operate over only rather small parts of the total landscape. Conversely, some parts of the landscape that presently bear mature coniferous forest could be stripped of their soil mantle in a few decades.

The degree to which these high rates of erosion reflect an aberration resulting from natural climatic events as opposed to recent intensive logging is unresolved at present; both factors appear to have significantly increased these rates. However, even when deliberate attempts (Knott, 1971, Table 5; Brown and Ritter, 1971, p. 34) are made to subtract out the bias introduced by recent floods, or this is done by chance (Hawley and Jones, 1968), sediment-discharge rates remain high. For example, J. M. Knott and G. D. Glysson (written communication, 1975) indicate that the "long-term" average annual suspended-sediment yield, calculated from the 1973-1975 sediment-transport curve and the 1954-1975 flow-duration curve, for Redwood Creek at Orick is about 5900 tons per square mile, or more than 1.7 times the rate implied by the geologically computed upper limit on the erosional lowering of the basin. Moreover, the long-term productivity of the land is strongly dependent upon the balance between soil-profile development and soil erosion irrespective of the reasons for that balance. Indeed, from the point of view of forest management, the long-term consequences are most serious if the present apparently excessive soil erosion reflects primarily natural factors. In that case active erosion control is far more complex than if erosion results directly from the activities of man.

The Impact of Man on Stream Sediment Loads

The long-term natural erosion rates in the Redwood Creek basin and surrounding terrain, as discussed previously, have apparently been exceptionally rapid relative to erosion rates reported from many other mountain areas. They are, nonetheless, several times less rapid than the present rate of erosion implied by measured stream sediment loads in the Redwood Creek basin. This discrepancy undoubtedly reflects, in part, geologically youthful channel incision, recent major floods, and perhaps other natural phenomena, but massive changes in land use over the last four decades have also contributed to increased erosion.

No direct measurements of stream-sediment loads were made on Redwood Creek or comparable large nearby rivers prior to intensive timber harvest, grazing, and road construction. Direct quantitative assessments of the impact of changed land use upon stream sediment loads are, therefore, not possible.

Three types of qualitative and semiquantitative information, when taken as a unit, do indicate that recent large-scale timber harvest and associated road construction within the Redwood Creek basin have substantially accelerated erosion, and thereby increased suspended-sediment concentrations and total sediment loads. These types of information include (1) visual comparison of the types, abundance, and scale of erosional landforms in virgin timber and comparable terrain that has recently been logged, as previously described, (2) initial rect measurements of concurrent sediment loads in comparable uncut and recently logged tributary basins (Iwatsubo and others, 1975), and (3) a general review of the literature on the impact of timber harvest and associated road construction on reasonably similar drainage basins. Only qualitative observations are available to suggest that the erosional impact of highway construction, early grazing, and conversion of forest to range in the Redwood Creek basin have been comparable to that associated with timber harvest. In the paragraphs that follow we discuss only the impact associated with timber harvest--an activity that has been carried out in about 65 percent of the Redwood Creek basin during the last 40 years.

Recent reviews of the extensive literature documenting examples of the direct impact of logging and related activities on stream-sediment loads have been prepared by authors representing a broad spectrum of opinion (Dyrness, 1967; Packer, 1967; Curry, 1971a, 1971b, 1973; American Forest Institute, 1972; Rice and others, 1972; Brown, 1973; Gibbons and Salo, 1973; Jones and Stokes Assoc., 1973). In the following discussion we have tried to summarize our observations concerning the impact of timber harvest on the sediment loads of Redwood Creek, and to extract from the literature only those data and opinions that help clarify our observations along Redwood Creek. With one exception, we have purposely avoided trying to generalize, so as to avoid drawing unwarranted conclusions based upon the impact of different styles of logging in different types of terrane.

The one generality that we glean from the recent literature is that it is now widely accepted that the harvest of wood fiber is comparable to the harvest of food crops, overgrazing, wild fire, strip mining, and construction of housing tracts and highways in that all activities that destroy the vegetative mat that protects the underlying mineral soil, lead to accelerated erosion. Considerable uncertainty and controversy, however, still surround the magnitude, duration, and ecological consequences of the accelerated erosion that follows timber harvest. Much of the uncertainty reflects the fact that the erosional impact of relatively few combinations of logging systems and terrane types have been adequately documented. Much of the controversy appears related to over-generalization from a few carefully controlled experiments. A related source of uncertainty and controversy is the fact that conditions and activities in many of these controlled experiments differ strikingly from conditions and activities that characterize typical forest practices (Leopold, 1972).

The number of individual variables and combinations of variables that can influence the magnitude of the direct impact of logging operations on stream-sediment loads are enormous. Thus, the magnitude of that impact is highly variable. In some areas, such as the Cedar River watershed of western Washington, with a combination of resilient terrain and exceptionally careful forest management the impact of timber harvest on sediment loads can be reduced to a barely detectable minimum (Cole and others, 1973) Conversely, in some areas, such as the Bull Creek watershed of northwestern California, with a combination of unstable terrane, poorly managed logging, and extreme floods, accelerated erosion and stream deposition following timber harvest can completely devastate downstream aquatic and riparian habitats (Zinke, 1966). In the drainage basin of Redwood Creek, as well as most forested drainage basins in northwestern California and southwestern Oregon, the combination of variables is such that the impact of logging on stream-sediment loads lies somewhere between these extremes. An important corollary of these observations is that meaningful assessment of the potential impact of proposed timber harvest should include detailed study of the interactions among the individual forest practices involved in the proposed operation (for example, road construction and maintenance, felling, yarding, slash disposal and restocking) with specific environmental factors (for example, hillslope and stream-channel gradients, rock and soil types, proximity of streams and landslides, and downstream and downslope resources) at the actual site of the proposed activity. While much can be learned from experiences on other hillslopes and in other drainage basins, such experiences alone should not be used to assess the potential impact of any proposed activity.

The two most definitive studies of the impact of timber harvest on stream-sediment loads in western coniferous forests have been carried out in the Alsea River basin in the coast ranges of western Oregon (Brown and Krygier, 1971), and in the H. J. Andrews Experimental Forest in the central Oregon Cascades (Fredriksen, 1970). These studies involved cable yarding of steep, clearcut units no larger than 237 acres. Results of these studies indicate that suspended-sediment loads following logging are significantly increased, but that under favorable circumstances those increases may be small, persist for only a few years, and be difficult to distinguish from natural variations imposed by flood events. Road construction and slash burning accounted for much of the increased stream-sediment loads observed in the Alsea and Andrews experiments.

A comparable paired basin study is in progress in well-bedded, coastal belt Franciscan sedimentary rocks near Fort Bragg, California (Krammes and Burns, 1973). Following construction of 4.2 miles of road and removal of 47 acres of advanced second-growth redwood along the road right-of-way, the suspended-sediment discharge and debris-basin deposition from the 1,047 acre South Fork of Casper Creek basin increased significantly.
The increase persisted for at least four years. The magnitude and persistence of the impact, however, reflected failure of a splash dam constructed during the initial timber harvest in the 1880's, as well as the present cycle of road construction and right-of-way logging. Results of the selective cutting of about two thirds of the South Fork basin's timber that started in 1972 have not yet been published.

The sedimentation regime of the drainage basin of Redwood Creek is rather different from that in these experimental watersheds. Suspended-sediment concentrations and loads are many times greater in Redwood Creek and its major tributaries (Iwatsubo and others, 1975) than in streams within these experimental watersheds. Moreover, most of the logging that has been done in the Redwood Creek basin involves larger cutting units, greater ground disturbance and less rapid recovery of ground-covering vegetation than logging in the Alsea and Andrews study areas. Additionally, in Redwood Creek logging-induced changes in the character of streambed materials and increases in the frequency and intensity of bedload movement appear to have had a more devastating and persistent impact upon aquatic environments than increases in suspended-sediment concentration and load. Bedload data from experimental watersheds are incomplete, but major increases in bedload movement were associated with road-related landslides in the Andrews Forest (Fredrikson, 1970). Thus, the results of the Alsea, Andrews, and Casper Creek experiments are applicable to conditions along Redwood Creek only in that they probably suggest a lower limit on the magnitude of man's impact on stream-sediment loads.

Most of the commercial old-growth redwood timber remaining in the Redwood Creek basin is on steep and (or) unstable terrain in close proximity to major stream channels. Thus, even though only a rather small amount of old growth remains, the harvesting of those trees should be carried out in a most careful manner in order to prevent a sizeable increase in stream-sediment loads. Increased sediment loads at this time would be particularly deleterious in that many reaches of Redwood Creek and its tributaries have not yet fully recovered from the increased sediment loads and changes in channel geometry wrought by recent floods and earlier logging activities.

Logging-induced erosional landforms in redwood-dominated forests of the lower Redwood Creek basin are in general not as obvious on aerial photographs as in the Douglas-fir-dominated forests of the upper basin. Massive landslides in streamside cutover land, and road and culvert failures are larger and more prevalent in the upper basin than in the lower basin (Colman, 1973). This difference probably partly reflects more deeply weathered and cohesive soil parent materials, and increased hillslope protection afforded by more abundant upper flood plains in the lower basin. Additionally, because of sprouting and slow decay of redwood roots and stumps, soil shear strength associated with tree roots is not decreased as much following redwood logging as following Douglas-fir logging. Most of the apparent difference in frequency of post-logging mass movement, however, is probably an artifact of the interaction of recent storms and logging rather than a reflection of major differences in inherent slope stability. Most massive slope failures in the upper basin occurred on the wet, steep, lower parts of hillslopes adjacent to major stream channels; examples of logging on this type of terrane in the lower basin are not common. Moreover, the examples that are present represent recent logging done subsequent to the major storms that triggered most of the slides in the upper basin. Some massive road failures have also been prevented by generally higher standards for road design and maintenance in the lower basin.

In contrast to mass movement small-scale fluvial erosion features such as gullied skid trails, roadside ditches, and enlarged stream channels appear more prevalent in recently tractor-yarded clearcut timber-harvest units of the lower Redwood Creek basin than in the older logging units of the upper basin. This difference in erosion activity reflects, in part, the reestablishment of a reasonably stable drainage net in many of the tributary basins in the upper third of the basin.

Concurrent measurements of stream-sediment loads for Redwood Creek and some of its tributaries that are in differing phases of the timber harvest-regeneration cycle are available for the 1973-1974 storm season (Winzler and Kelly, 1975; Iwatsubo and others, 1975). Preliminary interpretations of these data suggest that during storms of moderate intensity, streams draining tributary to basins that have been subjected to recent intensive timber harvest, transport significantly more sediment than streams draining basins that remain virtually uncut or that were harvested 10 to 12 years previously. The increased frequency and intensity of bedload transport appears more pronounced than the increase in suspended load. However, during these moderately intense storms, even those tributaries that have been subjected to exceptionally intensive timber harvest transport, on a per unit of drainage area basis, less sediment than Redwood Creek.

In addition to directly affecting stream-sediment loads, timber harvest may also have an indirect effect. Sequential aerial photographs and repeated surveys of monumented stream channel cross-sections indicate that streambank erosion is widespread throughout the Redwood Creek basin and that this erosion is not balanced by concomitant streambank deposition (U.S. Dept. of Agriculture, 1970; Iwatsubo and others, 1975). Because natural stream channel geometry is adjusted to runoff volumes, and amount and type of sediment load (Leopold and

Maddock, 1955), increased storm runoff and bedload transport from recent timber-harvest units may accelerate downstream streambank erosion (U.S. Dept. of Agriculture, 1970, p. 57). In stream reaches lacking upper flood plains, streambank erosion frequently triggers streamside landslides. The sediment added by these slides may then cause further adjustments in channel morphology. The whole process displays a built-in self-reinforcing feedback loop which is discussed in more detail in the section on recent changes in channel morphology.

Organic Debris

Stream and riparian environments along Redwood Creek are strongly influenced by stream-transported organic debris including fine debris that is transported in suspension and larger pieces of bark, limbs, and tree trunks that are transported partly in suspension and partly as bed load. As discussed in the section on physiography, fallen trees and large limbs often serve as check dams, energy dissipators, and stable niches for aquatic organisms. This coarse debris, however, can have a destructive as well as a stabilizing influence on the aquatic environment. Particularly large accumulations of coarse debris may form barriers to fish migration. Others may deflect the current and thereby cause erosion of previously stable streambanks. This erosion, in turn, may topple riparian vegetation and (or) trigger landslides. Trunks and logs borne by flood waters severely batter and even topple some streamside trees, including young redwoods. The battered trees commonly have large areas of bark knocked off. The resulting scars then can serve as paths of entry for heart rot and other diseases. Furthermore, tree trunks, limbs, and logs are usually the most massive and destructive objects transported by scouring debris torrents, because the closely fractured bedrock limits the size of rock detritus.

The coarse organic debris in most Redwood Creek tributaries, including all the tributaries within the Park, results mostly from natural causes such as wind-toppled trees and streambank landslides. Many recent timber-harvest operations have introduced logs, pieces of bark, limbs, and other slash into the tributaries. To date, however, the natural roughness elements along the tributary streams appear to have been quite effective in trapping logging-induced coarse organic debris close to the site of introduction. Although stream-deposited accumulations of coarse wooden debris frequently contain rooted trees, the framework of the majority of the accumulations observed along Redwood Creek between Rodiscroft Road and the mouth of Prairie Creek during the summer of 1974 consisted largely of tree trunks with sawed ends, cable scars or other indications of logging. Practically all the large accumulations contained some logs. Thus, considerable quantities of coarse logging debris have recently been introduced to the main channel of Redwood Creek. Given the apparently high trapping efficiency of most tributaries, this debris is probably derived mostly from logging operations on eroding hillslopes in close proximity to the main channel. Accumulations of these materials are most prevalent in and immediately downstream from such operations.

Organic debris, especially some finer particles, further influence the environment by exerting a strong biochemical oxygen demand on the water with which it comes in contact. This oxygen demand can, in turn, lower the dissolved-oxygen concentration of water in pools and in the interstices of the stream gravel (Hall and Lantz, 1969; Ponce, 1974). Similarly, deposition of excessive amounts of organic debris on and around riparian vegetation can reduce the amount of oxygen available for root respiration (Zinke, 1966; Stone, 1966). Locally, organic debris appears to be somewhat more abundant on recently inundated surfaces along Redwood Creek than in older overbank deposits exposed in stream cutbanks. However, recent floods have deposited mostly alluvium that is rather low in organic content.

Enormous quantities of fine organic debris are produced in undisturbed old-growth forest; the degree to which timber harvest influences the amount of fine debris that is introduced to the streams is not known.

WATER TEMPERATURE

Water temperatures in inland parts of the Redwood Creek basin in late summer are close to or even exceed lethal temperature thresholds of some resident aquatic organisms (Committee on Water Quality Criteria, 1972); however, low water temperatures do not appear to place restrictions on the aquatic organisms that inhabit this basin. A continuously recording thermograph was installed on Redwood Creek at Orick in 1968; similar thermographs were installed at gaging stations at the southern Park boundary and near Blue Lake in the summer of 1973. These water—temperature records are published annually in Water Resources Data for California - Part 2, Water Quality. Temperature data for tributary streams and miscellaneous sites consist of instantaneous observations by field personnel and maximum-minimum thermometers left in place for periods of four to seven days. Some of these auxiliary temperature data are presented in Iwatsubo and others (1975).

The average monthly water temperatures for Redwood Creek at Orick have an annual range of about 15°C; the lowest recorded temperature was 1°C on December 14, 1967 and the highest recorded temperature was 23°C on September 18, 1970. We have not made a frequency analysis of the temperature data but inspection of the data suggests that water temperatures are rarely lower than 5°C; residents at Orick report that prominent ice occurs in the margins of the channel only several times in a decade and that the creek has not frozen over completely in recent memory. Summertime water temperature range at Orick is usually between 11 and 20°C. The diel variation of water temperature at Orick is moderated by coastal fog and normally is about 3°C.

Geographic differences in water—temperature regimen in the Redwood Creek basin are more profound in summer than in water. Summer water temperatures at inland parts of the Redwood Creek basin are generally warmer than in coastal parts of the basin because of more direct insolation and warmer air temperatures. Greater insolation results from less freqeunt summer fog and more destruction of riparian vegetation by recent floods and logging in those inland areas. Within the Redwood Creek corridor of Redwood National Park, late summer daily maximum water temperatures in Redwood Creek and Bridge Creek commonly exceed 21.5°C and diel variation is often about 7°C. In contrast water temperatures in other tributaries in the Park rarely exceed 16°C. Diel variations are usually not more than 1.5°C. Upstream reaches of Redwood Creek and its tributaries often have daily maximum temperatures in excess of 25°C. Even though mid-day water temperatures in the reach between Highway 299 and Lacks Creek are often 27°C to 28°C, which is reportedly higher than the lethal temperature threshold for sticklebacks and juvenile salmonids (Committee on Water Quality Criteria, 1972), large active schools of these fishes are frequently observed there.

CHEMICAL QUALITY

Major Dissolved Constituents

In terms of major dissolved mineral constituents and essential plant nutrients, the water quality of Redwood Creek is apparently quite good and suitable for most purposes. Nearly all of the detailed chemical analyses, however, have been obtained at the gaging station at Orick (U. S. Geological Survey, 1959-1966; California Department of Water Resources, 1962-1973).

The water of Redwood Creek at Orick is a dilute, neutral to slightly alkaline solution characterized by a predominance of calcium and bicarbonate ions. These waters meet or exceed the water quality objectives of the California Water Resources Control Board,

(1974) for specific conductance, dissolved solids, essential plant nutrients, and pH. The total alkalinity and buffering capacity of this stream are low. Additions of small amounts of acid or basic solutions to the stream could, therefore, rapidly alter its pH. The altered pH in turn could have undesirable effects on the stream biota.

The average annual dissolved load of Redwood Creek at Orick during water years 1971 through 1973 (the period of suspended-sediment records) was apparently not more than 62,460 tons (56,660 tonnes) or 225 tons per square mile (78.8 tonnes per square kilometer) which was only about 3% as large as the suspended-sediment load. This load is computed from (1) the relation between specific conductance and stream discharge for water years 1970 through 1973 (fig. 49), (2) the relation between dissolved

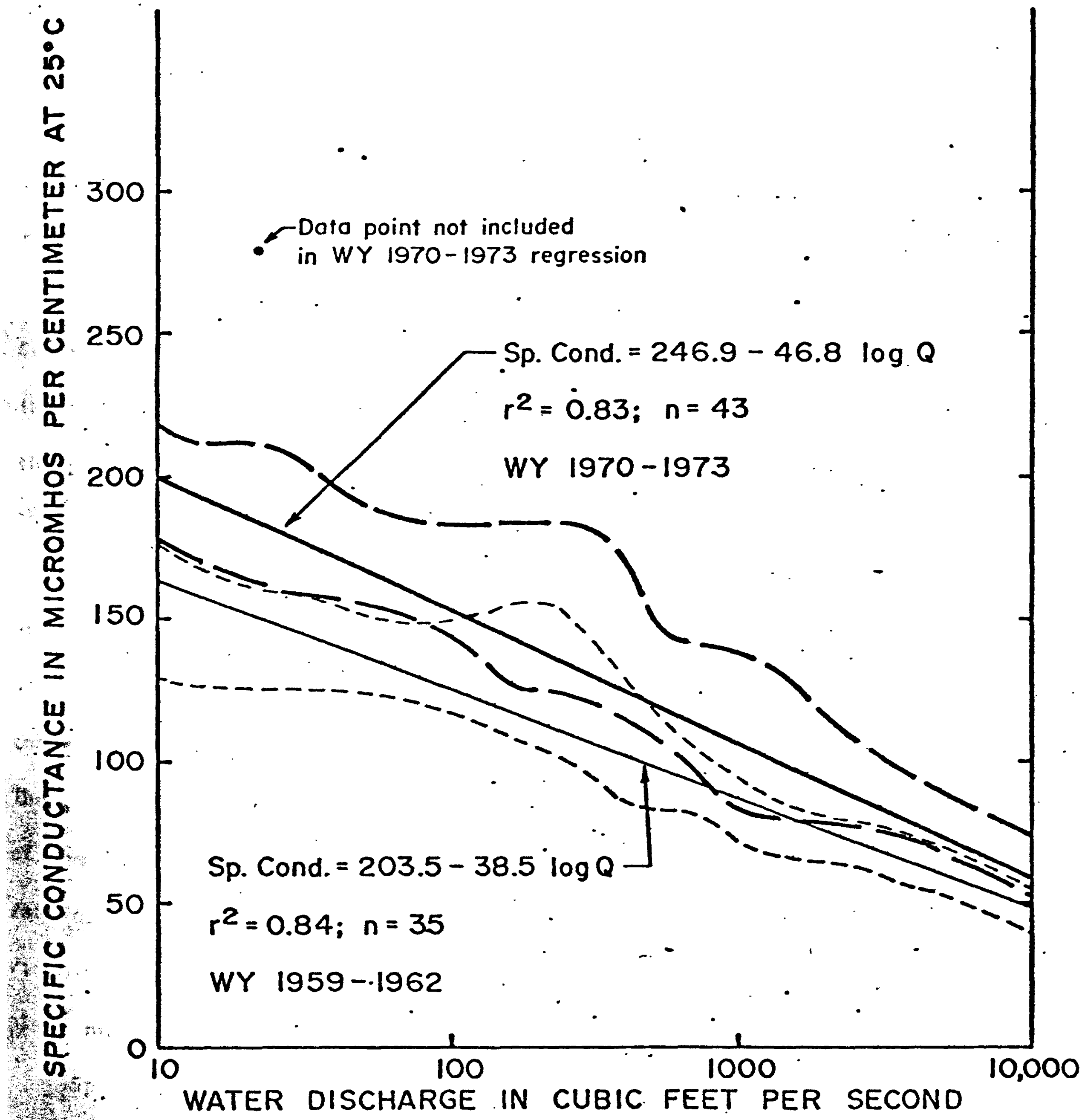


Figure 49. Relations of specific conductance and water discharge for Redwood Creek at Orick. Solid lines are regression lines; dashed lines are envelope curves on data points. Heavy lines show the 1970-1973 relation; light lines show the 1959-1962 relation. r^2 is the coefficient of determination for the regression line. n is the number of data points.

solids and specific conductance for water years 1959 through 1973 (fig. 50), and (3) the flow-duration table for water years 1970 through 1973 (Table 3). This computed dissolved load probably places an upper limit on the actual load because the only three points representing analysis of samples collected during water years 1970 through 1973 plot on the low side of the ~~total~~ dissolved solids-specific conductance relation (fig. 50).

Typically more than half of the total dissolved load of Redwood Creek is composed of bicarbonate, sulfate, chloride, and nitrate (number of samples 36, mean value 55%, standard deviation 4.9%). Given the paucity of carbonate, sulfate, and chloride minerals in the formations underlying the Redwood Creek basin, many of these anions are probably derived either directly from the atmosphere or from atmosphere-biosphere interactions, rather than from chemical weathering of bedrock (Janda, 1971). Additionally some constituents may be derived from cyclic ocean salts washed from the air. Thus, under existing watershed conditions, the average rate of lowering of the land surface by chemical processes is negligible relative to the rate of lowering by mechanical erosion. The implications of the dissolved load for rates of chemical weathering and budgets of essential plant nutrients in this basin remain to be evaluated.

Specific conductance, hence concentration of dissolved substances, for any given stream discharge is apparently greater at present than during the initial period of data collection at Orick. The increase in

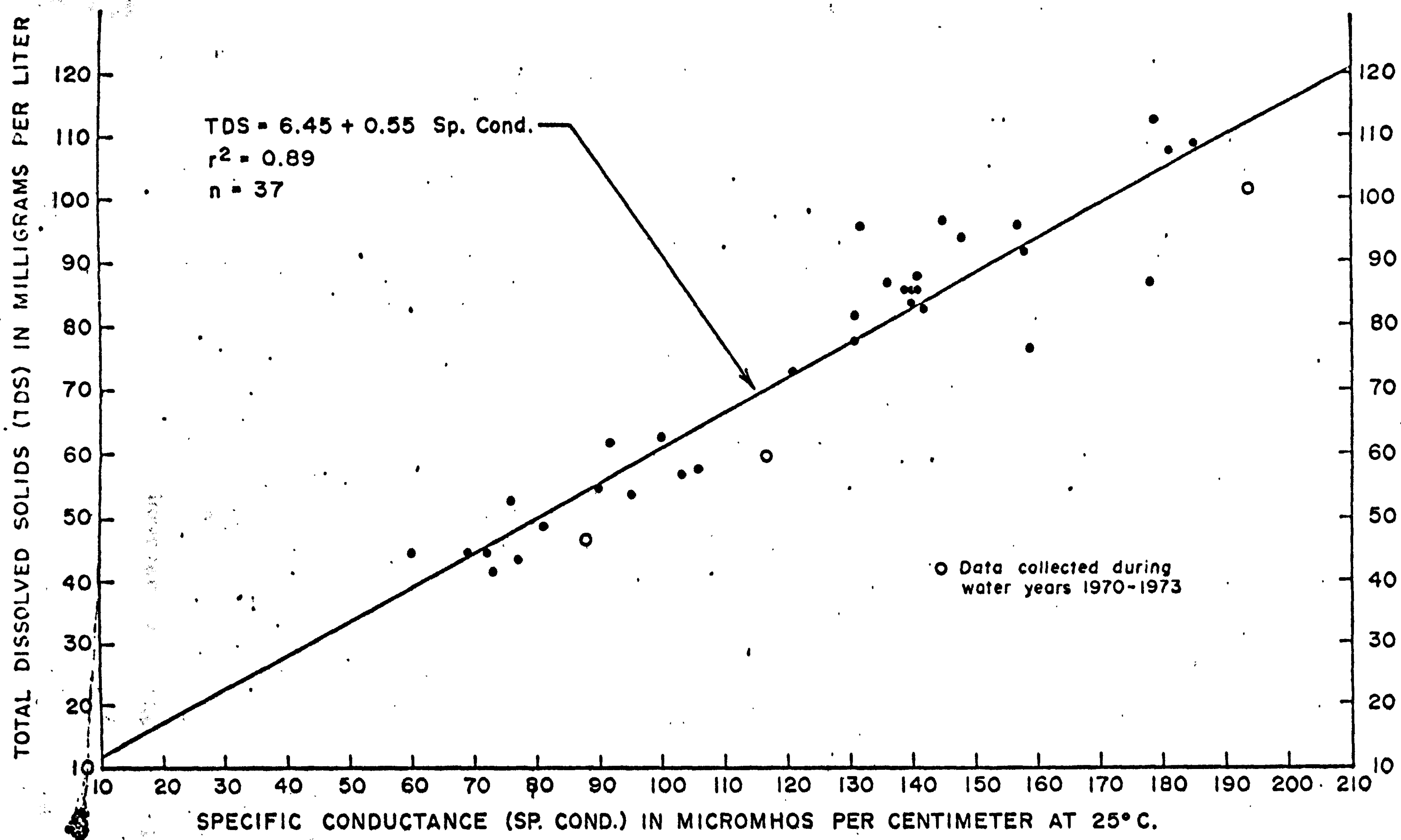


Figure 50. Relation between total dissolved solids and specific conductance for water years 1959 through 1973 for Redwood Creek at Orick.

conductance is most noticeable for low discharges. This increase is suggested by comparison of relations between stream discharge and specific conductance for the last four years, water years 1970 through 1973, and the first four years, water years 1959 through 1962, of chemical-quality records for Redwood Creek at Orick (fig. 49). Two possible explanations for the observed increase in conductance come readily to mind--(1) increased contact with relatively fine-grained alluvium and colluvium deposited in valley bottoms during recent major floods and (2) accelerated leaching of soils following vegetation removal and slash burning. Photographic records and observations of residents and workmen in the basin demonstrated the importance of the first possibility. The importance of the second possibility, however, remains to be evaluated. Such an evaluation would be valuable considering the implications for the long-term productivity of the forest soils of this basin and the controversy that presently exists considering the impacts of forest practices on essential plant-nutrient budgets (Gessle and Cole, 1965; Fredricksen, 1971; American Forest Institute, 1971; Pierce and others, 1972; Curry, 1973; Bateridge, 1974).

Limited chemical data available from tributary streams and upstream reaches of Redwood Creek indicate that specific-conductance values associated with any given stream discharge are generally higher for Redwood Creek at South Park boundary than for Redwood Creek at Orick (U. S. Geological Survey, 1971-1973). However, with the exception of chloride which is more abundant at Orick, the relative proportions of various chemical constituents are about the same at Orick and the South Park boundary. Data in Iwatsubo and others (1975) suggest that the in-park tributaries are more dilute than the main stem of Redwood Creek.

Dissolved Oxygen

The entire drainage net of Redwood Creek is characterized by steep stream channels with frequent riffles and, in the case of most tributaries, cascades and waterfalls, which generally keep the surface waters of Redwood Creek well oxygenated. This is particularly true during the winter storm season when dissolved-oxygen levels are generally at or above saturation throughout the Redwood Creek basin (fig. 51). During summer low flow, however, high water temperatures and biochemical oxygen demand associated with decaying organic debris and periphyton locally depress dissolved oxygen to levels that may be deleterious to resident aquatic organisms (fig. 52). Those values are lower than both the California State Water Resources Control Board (1974) water-quality objectives and the recommendations of the Committee on Water Quality (1972). Even relatively pristine streams such as Little Lost-Man Creek and Hayes Creek have summer dissolved-oxygen levels that are less than saturation.

Dissolved-oxygen values presented in figures 51 and 52 were collected by us with the assistance of S. D. Veirs, Jr., of the National Park Service; all determinations were made at the collection site using prepackaged chemical

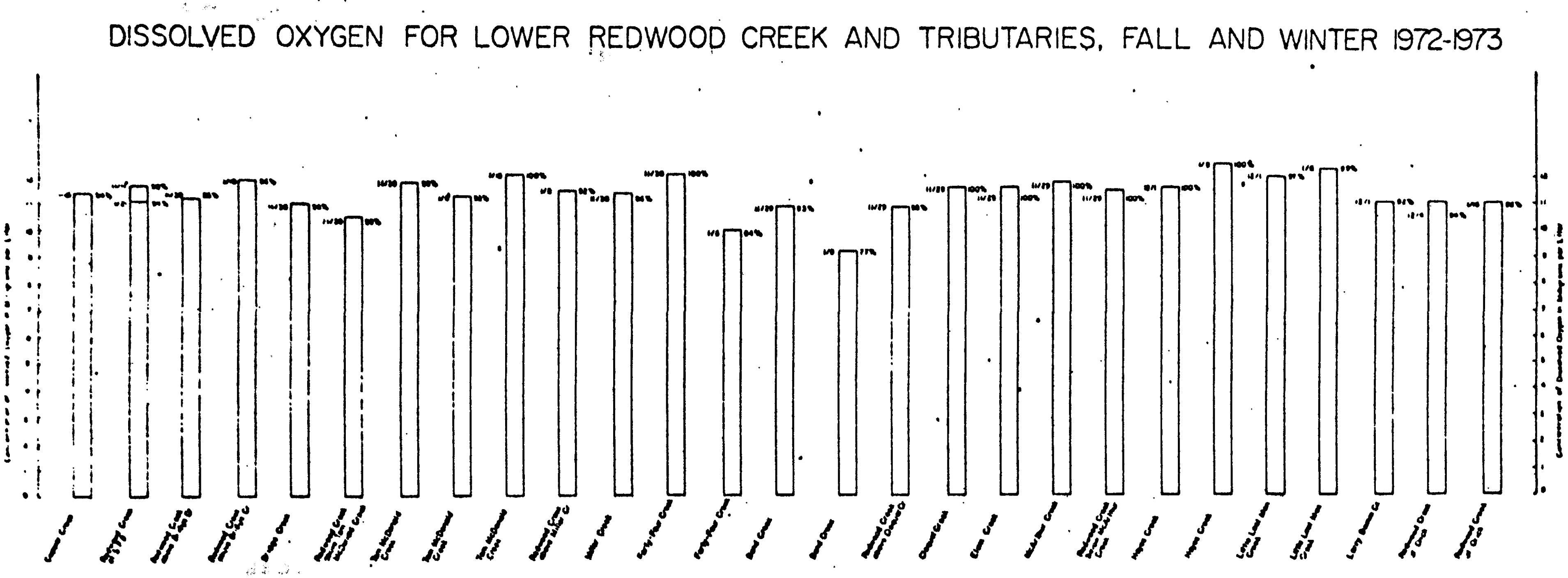


Figure 51. Dissolved oxygen data for Redwood Creek and selected tributaries during 1972-1973 storm season.

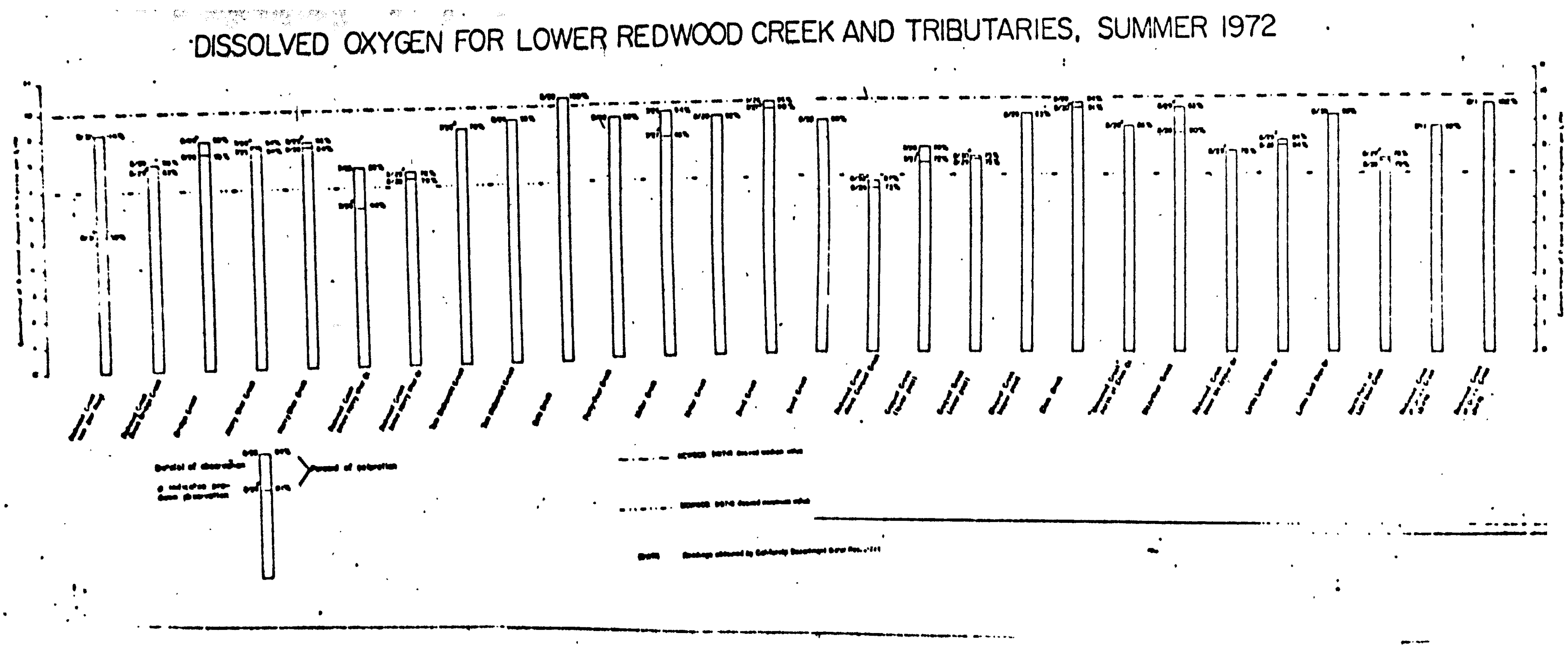


Figure 52. Dissolved oxygen data for Redwood Creek and selected tributaries during the summer of 1972.

reagents and the modified Winklèr technique. Other data have been collected periodically at Orick by the California Department of Water Resources (1963-1972) and at the southern Park boundary by the Geological Survey (1971-1973), Dissolved-oxygen data for Park tributaries during the 1973-1974 storm season are included in Iwatsubo and others (1975).

Diel variations in concentration of dissolved oxygen at many sites are large during summer. The greatest diel variation is observed on clear days in stream reaches with abundant periphyton. Dissolved-oxygen levels at many sites along Redwood Creek range from super-saturated to less than 60 percent saturated within a single day. Most low values of dissolved oxygen, that is values less than 7 milligrams per liter, are associated with nighttime and pre-dawn observations. These low values have been observed in pools throughout the Redwood Creek basin in late summer. Daytime values as low as 5.5 milligrams per liter are found in intermittent reaches associated with log jams above Snow Camp Creek and with the aggraded lower ends of parkland tributaries. In general summer dissolved oxygen levels are higher in tributaries than in the main stream. Although even the lowest observed dissolved-oxygen concentrations are not in themselves lethal to the organisms that inhabit Redwood Creek, any reduction in natural dissolved-oxygen levels is deleterious to fish and sensitive benthic invertebrates (Committee on Water Quality Criteria, 1972). Increased water temperatures lead to increased metabolic rates and increased oxygen demand; thus, the persistent combination of high water temperature and low dissolved-oxygen concentration is particularly burdensome for many of the native aquatic organisms that inhabit Redwood Creek. The relatively cool and well oxygenated water introduced to Redwood Creek by its major tributaries during summer, therefore, may be important in sustaining some organisms in the main creek.

In winter dissolved oxygen-concentrations and levels of saturation throughout the Redwood Creek basin are higher than in summer (fig. 51). Autumn-leaf fall from riparian alders and maples does not seriously influence dissolved-oxygen concentration of surface waters; the November and December observations in figure 51 were collected when most of the leaves had fallen and had started to decay, but prior to any flushing action by early winter storms.

AQUATIC ORGANISMS

The diverse aquatic ecosystem characteristic of Park reaches of Redwood Creek and its tributaries is a valuable and interesting resource that is frequently overlooked because of the magnificence of the adjoining forest. The types and numbers of aquatic organisms that inhabit this basin appear closely controlled by the stream's sedimentation regimen and the amount of light reaching the stream surface.

Attached diatoms and filamentous algae (periphyton), commonly considered the basic trophic level of the aquatic ecosystem, are not abundant at most sites in the Redwood Creek basin. Rooted aquatic plants are scarcely represented. During the storm-runoff season few stable substrates exist, and even those are subjected to severe abrasion by stream-sediment loads. Dense, tall riparian vegetation coupled with frequent fog and cloudiness restrict the amount of light reaching the water surface in many narrow stream reaches especially in the northern part of the basin. The species composition and biomass of the aquatic plants in these streams have not been determined. Along unlogged tributaries, periphyton are commonly concentrated at sites where the canopy vegetation has been disturbed by recent wind damage or landslides. More pronounced accumulations of algae are commonly observed during low discharge periods in some slack water pools and inactive anabranchs along wide aggraded reaches of the main channel, and in shallow streams flowing through recently cutover land. Particularly lush growth of filamentous algae appears to be associated with abundant decaying organic debris. The sparcity of aquatic plants throughout much of the basin suggests that terrestrial plant detritus must be an important food source for the aquatic insects that inhabit these streams. Elsewhere in the basin, low-water concentrations of periphyton are sufficient to cause marked diel fluctuations in the concentration of dissolved oxygen. Some pools and shallow riffles that support lush algal growth go dry in years of exceptionally flow, such as 1973, and leave behind unsightly, foul-smelling mats of decaying algae.

The aquatic insects and other benthic invertebrates that inhabit the streams of the Redwood Creek basin are an important source of food for amphibians and fish. Direct visual observations and forty-two Surber sampler collections (each composed of three one-square-foot samples) from Redwood Creek and its major tributaries downstream from Devils Creek were made during the summer and winter of 1972 (Tables 12 and 13). After taking each sample, the entire contents of the collection bag (including bed material and organic debris) were placed in wide-mouth glass jars, covered with isopropyl alcohol, and mailed to J. Brocksen for separation, identification and counting. Similar collections were made in the summer of 1973, but only two sample jars were not broken in transit (Table 14). More comprehensive collections and analyses of benthic invertebrates living in the Redwood Creek basin during the autumn of 1973 are presented in Iwatsubo and others (1975, Table 13).

	[illegible] Creek pool 7-1-72	[illegible] Creek riffle, run 7-1-72	[illegible] Creek riffle 7-1-72	[illegible] Creek pool 7-1-72	[illegible] Creek riffle 8-28-72	[illegible] Creek pool 8-28-72	[illegible] Creek riffle 7-2-72	[illegible] Creek pool 7-2-72	[illegible] Creek riffle 8-29-72	[illegible] Creek pool 8-29-72	[illegible] Creek riffle 7-2-72	[illegible] Creek riffle 7-2-72
Diptera (True Flies - Midges)												
Tendipedidae (Chironomidae)			14 larva	28 larva	27 larva	13 larva				1 larva	1 larva	1 larva
Simuliidae			4 larva		166 larva	2 larva			1 larva			
Heleidae		1 larva									1 larva	
Tipulidae					1 larva							
Unknown												
Ceratopogonidae												
Stratiomyidae												
Ephemeroptera (May Flies)												
Baetidae		1 nymph	18 nymphs	4 nymphs	12 nymphs	5 nymphs	26 larva	3 nymphs	1 nymph	5 nymphs		13 nymphs
Heptageniidae	1 nymph	1 nymph				1 nymph		2 nymphs	5 nymphs	4 nymphs		1 nymph
Coleoptera (Beetles)												
Elmidae	2 adults	(1 larva (1 adult			(2 larva (2 adults		(3 larva (3 adults	1 larva		9 larva	2 adults	
Dytiscidae				4 larva								
Psephenidae								1 larva		2 larva		
Hydrophilidae												
Trichoptera (Caddis Flies)												
Limnephilidae												
Psychomyiidae							1 larva	1 larva				
Rhyacophilidae			1 larva		1 larva		4 larva	2 larva	20 larva	1 larva		
Goeridae												
Hydropsychidae					2 larva							
Leptoceridae						3 larva						
Hydroptilidae						5 larva						
Lepidostomatidae										5 larva		
Gastropoda (Snails)												
Viviparidae	3 adults							4 adults				
Plecoptera (Stone Flies)												
Perlodidae									2 nymphs	1 nymph		
Perlidae					18 nymphs		4 nymphs					
exoskeletons					many							
Hemiptera (True Bugs)												
Corixidae				3 adults								
Gerridae												
Amphipoda												
Gammaridae												
Annelida, Oligocheata (worms)												
Number of orders	3	3	3	4	5	3	4	4	4	5	2	2
Number of forms	3	4	4	4	8	6	5	7	5	8	3	3
Number of individuals	6	5	37	39	231	29	41	14	29	28	4	15

Table 12 Cont. BENTHIC INVERTEBRATE FAUNA OF REDWOOD CREEK UNIT OF REDWOOD NATIONAL PARK, SUMMER 1972.
Collections of 3 sq. ft. samples by R. J. Janda and S. Colman;
Identifications and counts by J. Brockaen

	Tom MacDonald Creek pool 7-2-72	Cloquet ~~Arcata N.~~ Creek riffle 7-26-72	Cloquet ~~Arcata N.~~ Creek pool 7-26-72	Bond Creek riffle 7-26-72	Bond Creek pool 7-26-72	Miller ~~Arcata S.~~ Creek pool 7-26-72	Miller ~~Arcata S.~~ Creek pool upper station 7-26-72	Miller ~~Arcata S.~~ Creek riffle 8-29-72	Miller ~~Arcata S.~~ Creek pool 8-29-72	MacArthur Creek riffle 8-25-72	MacArthur Creek pool 8-25-72
Diptera (True Flies - Midges)											
Tendipedidae (Chironomidae)	2 larva	2 larva	12 larva				1 larva		2 larva	5 larva	1 larva
Simuliidae		1 larva									
Heleidae											
Tipulidae											
Unknown		2 adults									
Ceratopogonidae											1 larva
Stratiomyiidae											
Ephemeroptera (May Flies)											
Baetidae	3 nymphs	10 nymphs	2 nymphs	1 nymph		1 nymph					
Heptageniidae	5 nymphs	3 nymphs		1 nymph	1 nymph					1 nymph	
Coleoptera (Beetles)											
Elmidae		{10 adults, 4 larva	2 larva	2 adults							1 larva
Dytiscidae					1 larva						
Psephenidae											
Hydrophilidae		2 larva									
Tricoptera (Caddis Flies)											
Philopotamidae											
Psychomyiidae		3 larva	1 larva							1 larva	
Rhyacophilidae											
Goeridae											
Hydropsychidae				3 larva							
Leptoceridae											
Hydroptilidae											
Lepidostomatidae											
Gastropoda (Snails)											
Viviparidae											
Plecoptera (Stone Flies)											
Perlodidae		2 nymphs	6 nymphs		1 nymph					2 nymphs	
Perlidae		6 nymphs	3 nymphs		1 nymph			1 nymph			
exoskeletons											
Hemiptera (True Bugs)											
Corixidae											
Gerridae		1 adult	2 adults			1 adult	3 adults	1 adult			
Amphipoda											
Gammaroidae			1								
Annelida, Oligochaeta (worms)											1
Number of orders	2	6	6	3	3	2	2	2	1	4	3
Number of forms	3	11	7	4	4	2	2	2	1	4	4
Number of individuals	10	46	28	7	4	2	4	2	2	9	4

	[illegible] Man Creek riffle 7-3-72	[illegible] Man Creek pool 7-3-72	[illegible] Man Creek riffle 8-30-72	[illegible] Man Creek pool 8-30-72	[illegible] Creek riffle 7-3-72	[illegible] Creek pool 7-3-72
Diptera (True Flies & Midges)						
Tendipedidae (Chironomidae)	92 larva		40 larva	9 larva	17 larva	7 larva
Simuliidae	1 larva		7 larva			
Heleidae						
Tipulidae			45 larva	4 larva		
Unknown						
Ceratopogonidae						
Stratiomyiidae			1 larva			
Ephemeroptera (May Flies)						
Baetidae	53 nymphs	3 nymphs	37 nymphs	13 nymphs	30 nymphs	14 nymphs
Heptageniidae	2 nymphs		9 nymphs	10 nymphs	11 nymphs	10 nymphs
Coleoptera (Beetles)						
Elmidae	{26 adults, 5 larva}	2 larva	{8 larva, 5 adults}	18 larva		4 larva {2 adults, 2 larva}
Dytiscidae						
Psephenidae						
Hydrophilidae						
Tricoptera (Caddis Flies)						
Limnephilidae	2 larva		9 larva	13 larva		2 larva
Psychomyiidae	4 larva		6 larva	1 larva		1 larva
Rhyacophilidae	1 larva		4 larva		5 larva	
Corixidae		3 larva				
Hydropsychidae			17 larva			
Leptoceridae						
Hydroptilidae			7 larva			
Lepidostomatidae				3 larva		
Gastropoda (Snails)						
Viviparidae	1 adult			9 adults		
Plecoptera (Stone Flies)						
Perlodidae			4 nymphs			
Perlidae	9 nymphs	1 nymph	8 nymphs		6 nymphs	3 nymphs
exoskeletons						
Hemiptera (True Bugs)						
Corixidae						
Gerridae						
Amphipoda						
Gammeridae					1 adult	
Annelida, Oligocheata (worms)						
Number of orders	6	4	5	5	5	5
Number of forms	10	4	14	9	6	8
Number of individuals	196	9	207	80	70	45

	Gopher Creek riffle 1-10-73	Gopher Creek pool 1-10-73	Bridge Creek riffle 1-10-73	Tom MacDonald Creek riffle 1-9-73	Tom MacDonald Creek pool 1-9-73	Bond Creek riffle 1-9-73	Bond Creek pool 1-9-73	[illegible] Creek riffle 1-8-73	[illegible] Creek pool 1-8-73	N.B. Creek riffle 1-8-73	N.B. Creek pool 1-8-73
Diptera (True Flies - Midges)											
Tendipedidae (Chironomidae)	1 adult									2 larvae, 1 pupae	
Simuliidae									1 larvae		1 larvae
Heleidae											
Tipulidae										2 larvae	
Blephariceridae											
Empididae											1 larvae
Ephemeroptera (May Flies)											
Baetidae				1 nymph		8 nymphs	1 nymph		9 nymphs	1 nymph	1 nymph
Heptageniidae						8 nymphs				7 nymphs	1 nymph
Coleoptera (Beetles)											
Elmidae											
Tricoptera (Caddis Flies)											
Psychomyiidae											
Hydropsychidae	1 larvae			1 larvae		4 larvae					
Rhyacophilidae										1 larvae	
Limnephilidae		1 larvae									
Leptoceridae											
Philopotamidae						1 larvae					
Plecoptera (Stone Flies)											
Nemouridae				1 nymph					1 nymph	1 nymph	
Perlidae											
Chloroperlidae											
Collembola											
Sminthuridae										1	
Poduridae										1	
Homoptera											
Aphididae											1 adult
Amphipoda											
Gammaridae									2		
Haustoriidae									1		
Annelida											
Lumbricidae										1	
Lepidoptera (moths)											
Terrestrial								1 larvae			
Number of orders	2	1	0	3	0	3	1	1	4	6	3
Number of forms	2	1	0	3	0	4	1	1	5	9	5
Number of individuals	2	1	0	3	0	21	1	1	14	18	5

Table 13 cont

BENTHIC INVERTEBRATE FAUNA OF REDWOOD CREEK UNIT OF REDWOOD NATIONAL PARK, WINTER 1972-1973
Collections of 3 sq. ft. samples by R. J. Janda
Identifications and counts by S. S. Hahn and H. E. Jeavons

	Little Lost Man Creek riffle 1-10-73	Little Lost Man Creek pool 1-10-73
Diptera (True Flies - Midges)		
Tendipedidae (Chironomidae)	25 larvae	{35 larvae {1 pupae {1 adult
Simuliidae		1 larvae
Heleidae	1 larvae	
Tipulidae	6 larvae	12 larvae
Blephariceridae	1 larvae	
Empididae		
Ephemeroptera (May Flies)		
Baetidae	72 nymphs	64 nymphs
Heptageniidae	12 nymphs	6 nymphs
Coleoptera (Beetles)		
Elmidae	3 larvae	{1 larvae {1 adult
Tricoptera (Caddis Flies)		
Psychomyiidae	8 larvae	1 larvae
Hydropsychidae	3 larvae	
Rhyacophilidae	4 larvae	{2 larvae {1 cases
Limnephilidae		{5 larvae {2 cases
Leptoceridae		1 cases
Philopotamidae		
Plecoptera (Stone Flies)		
Nemouridae	7 nymphs	1 nymph
Perlidae	2 nymphs	2 nymphs
Chloroperlidae		2 nymphs
Collembola		
Sminthuridae		
Poduridae		
Homoptera		
Aphididae		
Amphipoda		
Gammaridae		
Haustoriidae		
Annelida		
Lumbricidae		
Lepidoptera (moths)		
Terrestrial		
Number of orders	5	5
Number of forms	12	13
Number of individuals	144	139

Table 14.--BENTHIC SAMPLE ANALYSIS
U.S. Geological Survey, Menlo Park
August 15, 1973

	Miller Creek pool nr. mouth 7-21-73 11:30 A.M.	Cloquet Creet nr. mouth riffle 7-21-73 1:15 P.M.
Tricoptera		
Limnephilidae	1 larva	
Lepidostomatidae: <u>Lepidostoma</u>	2 larvae	
Philopotamidae: <u>Wormaidia</u>	2 larvae	
	1 pupa	
Diptera		
Tendipedidae	1 larva	
	1 pupa	
Dolichopodidae	1 larva	
Plecoptera		
Perlidae	1 nymph	
Arthropoda		
Diplopoda	3 millipedes	
Coleoptera		
Dytiscidae	1 adult	
Arthropoda		
Diplopoda		2 millipedes
Tricoptera		
Hydropsychidae: <u>Parapsyche</u>		2 larvae
Hydroptilidae		3 larvae
Limnophilidae		9 larvae

Table 14 (contd)

	Miller Creek pool nr. mouth 7-21-13 11:30 A.M.	Cloquet Creek nr. mouth riffle 7-21-73 1:15 P.M.
Plecoptera		
Perlidae; <u>Acroneuria</u>	4 nymphs	
Ephemeroptera		
Dactidae: Ephemerellinae; <u>Ephemerella hecaba</u>	6 nymphs	
Gastropoda		
Ctenobranchiata; Pleuroceridae	6	

Insects, such as may flies (Ephemeroptera) and caddis flies (Tricoptera) that are particularly sensitive to temperature, dissolved oxygen, and pH have been found in all streams sampled in the Redwood Creek basin, although often in only limited numbers. The 1972 data suggest that following the major floods of January and March of 1972, the benthic invertebrate fauna of the tributaries was larger and more diverse than that of the main stream (Table 12). Winter benthic invertebrate faunas in tributaries were much more limited than those of summer (Table 13). The 1973 data (Table 14; Iwatsubo and others, 1975, Table 13), in contrast, indicate that following the moderate and low flows that prevailed throughout the 1973 water year (Table 3), the number of organisms per sample were generally higher and more diverse than in 1972, and that profound difference in the sample densities no longer existed between the main channel and its tributaries.

Available data suggest that the grain size and relative stability of the stream bed, sunlight (insolation), and perhaps water temperature are major factors controlling the abundance of benthic organisms in the Redwood Creek basin. Organisms are most abundant and diverse in open reaches of cool streams, like Little Lost Man Creek, with stable cobble riffles, and little mud in either the pools or gravel interstices. Organisms appear least abundant and diverse in those streams, like Miller Creek, that display stream beds with abundant silt, sand, and fine gravel that are set in motion during many winter storms. The nearly complete absence of benthic invertebrates in lower Miller Creek in the summer of 1972 is perplexing because it stands in such marked contrast to nearby streams, such as Hayes, Cloquet, and Wier Creeks, that displayed at the time of sampling similar water temperatures, concentrations of dissolved oxygen, and indications of stream-bed instability. However, at that time, bars of poorly sorted fine gravel with a muddy matrix, mud layers in pools, and raw eroding stream banks were somewhat more apparent in park reaches of Miller Creek than in similar reaches of neighboring streams. The abundance of these phenomena suggests that the bed of Miller Creek was altered more by the January and March 1972 storms than those of its neighbors. Although the increased alteration was apparently not great, it may have been sufficient to cause the stream to cross a biologically critical threshold.

In order to check on potential chemical toxicity as an explanation for the paucity of benthic organisms in Miller Creek in 1972, two sediment samples were collected in the fall of 1972. These samples contained no detectable toxic chemicals other than trace amounts of diazinon (Leon S. Hughes, written commun., 1972). Diazinon is not a chemical that is normally used in forest management; thus, the trace amounts may represent sample contamination. However, during the five and a half months separating the time of sampling from the most likely time of introduction, during the winter and spring storms, the toxic substance(s) could have been flushed from the system or chemically altered.

The benthic invertebrate fauna in the Miller Creek samples during the summer of 1973 increased markedly relative to the summer of 1972 (Table 14; Iwatsubo and others, 1975, Table 13), but remained somewhat less than in samples from neighboring streams.

Comparisons between the benthic faunas in recently logged and unlogged tributaries in the Redwood Creek basin[1] and similar data from the Casper Creek study near Fort Bragg, California (Hess, 1969) suggest that following logging the number of different types of benthic invertebrates in a drainage basin is commonly reduced more than the total abundance (biomass) of organisms. In some cases, the total biomass of benthic invertebrates increases or remains constant following logging. Nonetheless, any change in the composition of the benthic inveterbrate fauna can have a serious impact upon higher organisms by forcing changes in their feeding habits (Hynes, 1970, p. 209-210, 444-445). For example, burrowing insects, such as midge larvae (Diptera) that live in sand or mud streambeds are not as available to fish as may flies, caddis flies, and stone flies that live in gravel streambeds (Phillips, 1971).

An interesting and diverse amphibian fauna occupies a trophic level intermediate between benthic invertebrates and fish in the Redwood Creek basin. To the best of our knowledge, however, a systematic survey of this basin's amphibia has not been made. Some of the more commonly observed salamanders and frogs along these streams and in adjacent moist riparian sites display striking color patterns; others display coloration that blends in well with their surroundings. Professor Rudolf Becking of the California State University at Humboldt reports (oral comm., April 1973)

1/ The amount of recent timber harvest in all of the sampled drainage basins is indicated in Iwatsubo and others (1975, Tables 2 and 3).

that he and his associates observed ten species of Amphibia on a single day field trip along the lower reaches of Harry Wier Creek. The wide ranging but uncommon tailed frog (*Ascaphus truei*) is of particular interest to naturalists because of questions raised by its trans-Pacific distribution in relation to dispersal patterns. Professor Becking and his associates believe that Amphibia tadpoles, especially those of *Ascaphus truei*, may be intolerant of increases in turbidity or streambed instability. Other work (Burry, 1968), however, suggests that *Ascaphus* population are controlled largely by water temperature and that in maritime areas of coastal Humboldt County, *Ascaphus* is reasonably tolerant of timber harvest. Moreover, we have observed abundant tadpoles of unknown species in what would appear to be particularly undesirable habitat niches with extreme diel fluctuations in temperature and dissolved-oxygen concentrations. Tadpoles are often the only animals observed in algae-choked pools along severely aggraded, debris-clogged streams in recent clearcut timber-harvest units. The amphibian fauna will apparently have to be inventoried, and the environmental tolerances of the individual species ascertained, before the potential impact of various land-use changes on these organisms can be effectively evaluated.

A , limited number of fish species inhabit Redwood Creek and other coastal streams of the redwood region (DeWitt, 1964). The fish most commonly observed along the main channel of Redwood Creek during the summer of 1973 were small schools of sticklebacks (*Gasterosteus* sp.) Most of Redwood Creek's fish species, however, are

Same P

anadromous with steelhead trout (Salmo gairdneri), chinook (or king) salmon (Oncorhyncus tshawytscha), and coho (or silver) salmon (Oncorhyncus kisutch) being the economically valuable species.

Coho salmon tend to spawn in streams with finer gravel than those in which chinook salmon spawn. Redwood Creek and its tributaries transport mostly fine gravel because intensely and pervasively fractured bedrock occurs throughout the basin; thus, the grain-size distribution of the stream gravel makes many of the potential spawning areas in the Redwood Creek basin more desirable for silver salmon than for chinook salmon. The California Department of Fish and Game (1965) estimated that in 1965 within the Redwood Creek basin there were 112 miles of potential spawning habitat suitable for steelhead trout, 110 miles suitable for silver salmon, and only 69 miles suitable for chinook salmon.

The combination of 1972 floods and recent intensive timber harvest had by 1973 reduced the amount of potential spawning and rearing habitat for anadromous fish along Redwood Creek relative to what it was in 1965. This reduction in habitat resulted from (1) aggradation, with attendant filling of pools and decreased grain-size of bed material (see section on recent changes in channel geometry), (2) increased frequency and intensity of bedload transport, and (3) increased deposition of fine sediment (very fine sand, silt, clay) and organic debris within and on stream gravels during the waning stages of freshets. The impact of stream sedimentation on spawning gravels is discussed by Hall and Lantz (1969) and Phillips (1971).

Excessive amounts of fine sediment have an indurating effect on the gravel that seriously impedes construction of redds by spawning fish and the emergence of fry. Additionally, the fine sediment reduces the permeability of the gravel and impedes the exchange of intragravel water with well-oxygenated surface water. The organic debris deposited along with the fine sediment causes a high biochemical oxygen demand when it decays. The combination of increased oxygen demand and decreased exchange of wate can lead to low concentrations of dissolved oxygen in the intragravel water and consequent mortality of eggs and fry.

Semiquantitative estimates of spawning escapement (U.S. Fish and Wildlife Service, 1960) and general observations by the California Department of Fish and Game and local residents indicate that in the Redwood Creek basin the steelhead trout population is considerably larger than the combined salmon population, and that chinook salmon are much more abundant than silver salmon. Thus, the relative abundances of the two different salmon species is presently contrary to what one would anticipate given the fine-grained character of the available spawning gravel. Perhaps the abundance of different fish partly reflects different times of spawning relative to likely times of gravel-transporting floods. Chinook salmon usually start to spawn in northern California streams earlier in the fall than coho salmon (Holmberg, 1972; Calif. Dept. Water Resources, 1965). After spawning, salmon eggs require 50 to 60 days to hatch depending upon water temperature; another 20 to 30 days are required for the alevins to wriggle up through the gravel and become free-swimming fry

(Holmberg, 1972, p. 2). Thus, for a period of 70 to 90 days, while the young salmon are in the stream gravel, vigorous bed-load transport, such as occurs along Redwood Creek during most major winter storms, can kill large numbers of young fish. Because of the extreme shifting of streambed material, the chance for successful spawning and emergence is better for early fall-spawning chinook, and late winter and early spring-spawning steelhead than for late-spawning chinook and coho. Given the paucity of suitable low-water rearing pools in Redwood Creek, the larger estimated spawning escapement of chinook salmon than of coho salmon for Redwood Creek may also relate, in part, to the fact that coho remain in fresh water for a year or more, whereas young chinook migrate to the ocean in their first few months of life (Holmberg, 1972, p. 2).

Observations by the California Department of Fish and Game and local residents suggest that Redwood Creek historically supported a significantly larger run of anadromous fish than at present (Calif. Dept. Fish and Game, 1965), and that coho formerly made up a larger proportion of the salmon. A stream survey by E. A. Caldwell and A. E. Burghduff in the 1930's[1/] indicated that at that time Redwood Creek "gets a very heavy run of steelhead and silver salmon." In considering potential implications of these observations, one should recall that they were made following a long period of modest annual rainfall and few floods.

1/ This report was given to the Geological Survey by Don Lolloch, Chief of Branch of Environmental Services, Calif. Dept. Fish and Game on August 7, 1975. The precise date of Caldwell and Burghduff's survey is not known.

Other anadromous fish in the Redwood Creek basin include sea-run cutthroat trout (*Salmo clarki clarki*), candlefish or migratory eulachon (*Thaleichthys pacificus*), and Pacific lamprey (*Entosphenus tridentatus*) (De Witt, 1964). The sea-run cutthroat trout is a small but popular game fish. The candlefish is a popular food fish of the smelt family that is caught by seining. The size and time of occurrence of candlefish runs are less predictable than the runs of salmon and steelhead. In mid to late April 1973, "millions" of candlefish were observed by the California Department of Fish and Game[1/] in the downstream-most 15 miles of Redwood Creek; no candlefish were seen in the tributaries. Another large run of candlefish in Redwood Creek occurred in 1967. Limited numbers of lampreys are observed spawning in lower Redwood Creek in the spring. Lampreys were a popular food of the indians, but are presently not much valued as a food fish.

Many miles of the headwaters of Redwood Creek and some of its major tributaries, although not accessible to anadromous fish because of obstructions formed by naturally occurring landslides and windfalls, are suitable habitat for the spawning and rearing of limited numbers of resident fish. Small resident cutthroat trout (*Salmo clarki clarki*) and rainbow trout (*Salmo gairdneri*) live in pools above these obstructions. Cutthroat trout are more abundant than rainbow trout.

1/ Field note by Dave Rogers given to the Geological Survey by Don Lolloch, Chief of Branch of Environmental Services, Calif. Dept. of Fish and Game on August 7, 1975.

The total population of resident cutthroat trout along any individual stream is so limited that it could be completely eliminated by overfishing or by logging-induced accelerated sedimentation. Other resident fish species are found along the lower reaches of Redwood Creek and include the Humboldt sucker (*Catastomus humboldtianus*), sculpins (*Cottus*, sp.), and stickleback (*Gasterosteus* sp.) (De Witt, 1964).

RECENT CHANGES IN HILLSLOPE EROSION

Landforms produced by various types of hillslope erosion processes in the Redwood Creek basin became more numerous and more active between 1936 and 1973. A few earthflows and slides were more active in 1947 than in 1973. The overall increase in activity can be well documented by sequences of available vertical aerial photographs[1/]. The distribution of mass movement phenomena in the Redwood Creek basin in 1947 and 1972 is shown on 1:62,500 maps prepared by Colman (1973). The most visually obvious change in erosional activity is the increased

1/ The following sets of black and white aerial photographs were examined as part of this study:

Date	Scale	Coverage	Ownership
1936	1:30,000	north 2/3 basin	T. Hatzimanolis, National Park Service, Crescent City, CA.
1947	1:45,000	south 3/4 basin	U. S. Geological Survey, Menlo Park, CA.
1958	1:10,000	entire basin	Humboldt County, Timber Assessor's Office
1962	1:10,000	entire basin	"
1966	1:10,000	entire basin	"
1968		north 1/2 basin	National Park Service, Crescent City, CA.
1970-71	1:10,000	entire basin	Humboldt County, Timber Assessor's Office
1972	1:36,000	entire basin	National Park Service, Crescent City, CA.
1973	1:10,000	entire basin up to and including the drainage basin of Lacks Creek	U. S. Geological Survey, Menlo Park, CA.

number of streamside rock and debris slides along the main channel of Redwood Creek and its major tributaries. Thirty slides adjacent to the main channel show on 1947 photographs, whereas 341 such slides appear on 1973 photographs. A large increase in debris avalanches also occurred between 1947 and 1973. Only nine debris avalanches with lengths of at least 200 feet (61 meters) show on 1936 and 1947 photographs, whereas 91 such features appear on 1973 photographs. A great many smaller debris avalanches are also present. New debris avalanches are mostly associated with roads. A few of the large compound earthflows show recent gullies and increased ground disruption. For the most part, however, the earthflows appear to have maintained a more or less constant average rate of movement. The recent gullies in the earthflows are mostly associated with ranch and logging roads. The recent large-scale timber harvest in the Redwood Creek basin appears in general to have directly impacted far more upon fluvial erosion than upon mass movement. As discussed previously, however, timber harvest may indirectly impact upon hillslope stability; streambank erosion caused by increased storm runoff or aggradation can trigger streamside slides.

The combination of four major flood events and the initiation of intensive timber harvest and road construction during this interval has undoubtedly been responsible for accelerated erosion. The relative importance of these two factors is difficult to assess quantitatively owing to their contemporaneous occurrence and complex interaction with each other and with geomorphic processes. However, timber harvest has clearly increased the erosional impact of the floods over what it would have been if the basin had not been logged.

The number of new streamside slides along Redwood Creek discernible on aerial photography for years of available coverage is shown in Table 15. Slides are separated into those occurring in areas which showed previous instability and those which were stable in 1947. This separation was made because in this type of terrain slides tend to occur repeatedly at the same locality. Areas were also categorized as logged or unlogged at the site of failure in order to see to what degree timber harvest and associated road construction have altered hillslope stability.

A major problem with the comparison of sliding history in logged and unlogged areas is that the likelihood of a new slide occurring in an unlogged area decreases through time with the progressive increase in cutover area. In order to reduce this inherent bias, the number of new slides in each category was weighted by the number of streambank miles included in that grouping for each interval (Table 16). The number of slides per mile was then computed on a per-year basis to compensate for the difference in length of time between photo coverage. However, this procedure may be somewhat misleading as slide occurrence was probably somewhat clustered about the major flood events of 1953, 1955, 1964, and 1972.

Another major drawback in these comparisons is that no allowance is made for the impact of logging upslope from sites. Thus, although a new slide is shown to occur in an unlogged area, it may actually have been triggered by increased runoff, pore pressure, or seepage force caused by uphill logging operations (Hicks and Collins, 1970).

Table 15. Initiation of streamside slides along the channel of Redwood Creek. The plus figures with the brackets indicate slides that occurred between 1958 and 1966; resolution on the 1962 photographs was not sufficient to decide whether or not the slides were present at that time.

	Year	Number of [1/] slides in previously stable areas		Number of [1/] slides in previously unstable areas		Total	
Number of slides in logged areas	47	0		0		0	
	58	13		10		23	
	62	14	+4	8	+6	22	+10
	66	35		8		43	
	70	18		4		22	
	72	8		3		11	
	73	8		5		13	
Number of slides in unlogged areas	47	0		27		27	
	58	36		42		78	
	62	25	+1	17	+2	42	+3
	66	21		14		35	
	70	5		2		7	
	72	4		1		5	
	73	0		0		0	
Total	47	0		27		27	
	58	49		52		101	
	62	39	+5	25	+8	64	+13
	66	56		22		78	
	70	23		6		29	
	72	12		4		16	
	73	8		5		13	
		192		149		341	

1/ As defined by 1947 conditions.

Table 16. Initiation of streamside slides per mile of sampled streambanks in logged and unlogged areas adjacent to Redwood Creek.

	Slides/channel mile in logged areas	Slides/mile/year in logged areas
1947	.00	–
1958	1.07	.10
1962	.89	.22
1966	.81	.20
1970	.34	.09
1972	.15	.08
1973	.18	.18
	Slides/channel mile in unlogged areas	**Slides/mile/year in unlogged areas**
1947	.26	–
1958	.97	.09
1962	1.01	.25
1966	.86	.22
1970	.19	.05
1972	.17	.09
1973	.00	.00
	Total slides/channel mile	**Total slides/mile/year**
1947	.27	–
1958	.99	.09
1962	.63	.16
1966	.77	.19
1970	.29	.07
1972	.16	.08
1973	.13	.13

Unfortunately, Tables 15 and 16 list only slides where movement was initiated in a given interval. Many existing slides may have increased in size or activity during a particular interval. We adopted this procedure because not all photographs were available for simultaneous comparisons at the time when we had access to the 1962 photographs. Thus, another bias may have been generated, in that the number of channel miles without existing active slides is continually decreasing. For example, by 1972 most of the streamside areas that were prone to sliding (outsides of streambeds, old slides, and so forth) had already experienced recent slope failures. As a result the floods of 1972 triggered not more than 16 new slides along Redwood Creek, but caused nearly 100 existing slides to increase in size or activity (Colman, 1973, fig. 25, p. 110).

The greatest number of new slides per mile of streambank occurred during the 1947-1958 interval (Table 16). This may reflect either the occurrence of the 1953 and 1955 flood events or the long period between photo coverage. It would be reasonable to expect the first of the series of major floods since the late 19th century to do the greatest amount of damage to riparian hillslopes and to remove large quantities of colluvium that had accumulated during the interval.

Although the shortcomings associated with the numbers in Tables 15 and 16 do not permit quantitative assessment of the erosional impact of floods and logging on stream sediment loads, those numbers do suggest that it may be unwise to try to isolate either one of these factors as the dominant cause of streamside sliding. For example, they indicate that almost as much sliding occurred during the 1958-1962 interval, when no major flood events occurred as during the 1962-1966 period which included the 1964 flood. Furthermore, on a per-mile basis slightly more sliding was initiated in unlogged areas than in logged areas during the 1958-1962, 1962-1966, and 1970-1972 intervals. From 1972 to 1973 all new slides occurred in logged areas. This may indicate that the impact of the 1972 flood was felt most in these areas, but the sample size is probably too small for definite conclusions.

The total volume of material contributed directly to Redwood Creek by streamside slides in recent years was estimated by Colman (1973, Appendix I) to be about 1,396,400 cubic yards (1,067,700 cubic metres). Assuming that the slide debris has an average bulk density of about 92 pounds per cubic foot (1474 kilograms per cubic metre), the total mass of this slide debris would be about 1,734,400 tons (1,573,400 tonnes). Most of this material was eroded between 1964 and 1973. The total quantity of sediment provided by these visually obvious features over a nine-year period is, thus, not more than 80 percent of the average annual quantity of suspended sediment to move past the gage at Orick during 1971-1973. Therefore, although the streamside slides along Redwood Creek do contribute substantial quantities of sediment directly to the channel and alter local channel geometry, they should not be considered a dominant sediment source. Interpretation of aerial photographs led the U.S. Department of Agriculture (1970) to suggest that between 1941 and 1965 all slides (not just streamside slides) in the Redwood Creek basin accounted for not more than 27 percent of the total stream-sediment load.

The approximately 1100 miles (1770 kilometres) of roads and 3000 miles (4825 kilometres) of skid trails that exist in the Redwood Creek basin have seriously impacted upon hillslope erosion. Except for 12 miles of recently relocated State Highway 299, most of the roads that have aggravated erosion were constructed since 1947 primarily to provide access to ranches and timber-harvest units. At least 37 streamside slides along

Redwood Creek were caused in part by road construction. Numerous small failures occur along most roads, and although these slides and gullies may be individually insignificant, the sum of their impact is substantial.

Road construction is associated with numerous small slumps and slides in cutbanks and road fill. Most road-related debris avalanches are triggered by these types of failures. Two additional forms of hillslope erosion are triggered by road construction--deep gullying and sliding of water-saturated colluvium. Deep gullies commonly form when runoff is concentrated into small drainages whose capacity is exceeded during storms (fig. 7). Road-concentrated drainage also may increase the period of duration of oversaturated soil conditions to cause failure of already unstable slopes by sliding or slumping.

The headwater reaches of Redwood Creek show a series of streamside slides whose head scarps are aligned along old logging roads. Indeed, in some cases the impact of these roads may be as important as removal of toe support by the stream. Another example of road-related streamside sliding and gullying is found along the Redwood Creek trail above the Tall Trees Flat; the old M-line logging road has failed in several places to produce a line of slides and deep gullies.

A more detailed discussion of recent changes in mass movement activity is contained in Colman (1973).

RECENT CHANGES IN CHANNEL CHARACTERISTICS ALONG REDWOOD CREEK

In response to the recent major floods and intensification of timber harvest, described in previous sections, the channel characteristics and sedimentation processes of Redwood Creek have changed drastically in recent decades. The major changes appear to be (1) channel aggradation and gravel-berm deposition associated with major floods, (2) increased numbers of braided reaches, (3) increased channel width, and (4) decreased average size of streambed material. Many of these changes can be seen in the mounted stereo pairs of aerial photographs in figures 11, 13, 15, 16, 18, and 19. Attendant to these changes in visual characteristics is an increased frequency and intensity of bedload transport. During this same time interval, comparable channel-geometry changes have occurred on the Middle Fork Eel River (Knott, 1971; J. C. Fraser, written communication, 1975), Trinity River (Knott, 1974), and Van Duzen River (Harvey Kelsey, written communication, 1975).

Time-sequential aerial photography, stream-gaging records, streambank stratigraphy, historic land surveys, and interviews with long-term residents have been utilized in an effort to document these changes. Monumented stream-channel cross sections established in 1972 and 1973 (Iwatsubo and others, 1975) have been used for references and to interpret short-term history.

1936 AND 1947 CHANNEL

In 1947, Redwood Creek, above State Highway 299, was characterized by a narrow sinuous channel (fig. 11). A closed vegetation canopy existed along much of this reach. The canopy was broken only locally by a streamside slide or wide alluviated reach.

In 1947 and 1936 Redwood Creek between Highway 299 and Lacks Creek was predominantly a sinuous stream moderately incised into a wide alluvial flood plain (fig. 13). Many areas of this flood plain contained abundant vegetation with many 10- to 20-feet (30 to 61 meters) tall conifers.[1] Conifer growth was not restricted to the edges of alluviated areas but also lined the narrower active channel. Below Lacks Creek the channel and flood plain became narrower. (fig. 15); braided channels were virtually absent from Lacks Creek to Cooper Creek.

In general, the flood-plain morphology exhibited in 1936 and 1947 above Cooper Creek resulted from moderate channel incision into a wider upper flood plain, the morphology of which may reflect geomorphic processes operating during major flood events in the late nineteenth century. The period of 1891 to 1953 was a time of moderate peak flows in the Redwood Creek basin and environs.

Below Copper Creek the channel and flood plain of Redwood Creek became wider (fig. 16), then abruptly narrowed in the "gorge" area (fig. 7), and finally broadened into the wide alluvial reach above Bridge Cree. From Bridge Creek to the mouth of Redwood Creek, the 1936 channel displayed a predominantly braided channel on an inner flood plain generally devoid of vegation (figs. 18 and 19). Some patches of alders and shrub

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1/ The heights of these conifers were estimated during stereoscopic examination of aerial photographs by comparison with the height of an adjacent building still standing in the Minor Creek area.

vegetation were present on midchannel bars near the Tall Trees Flat and on abandoned parts of the lower 4 miles of channel where the width is great and braiding is predominant. Land surveys by Harry Weir and Oscar Larson in 1946, 1947, and 1951 show a 90-foot lateral migration of the main channel indicating inherent channel instability during this five-year period (fig. 19), even though no major floods occurred.

CHANNEL CHANGES

Recollections of residents and workmen, sequences of aerial photographs, and stream-gaging records suggest that beginning in the mid-1950's the active-gravel inner flood plain of Redwood Creek started to aggrade, to erode its banks actively, and to shift across wider areas of its former flood plain. This change in channel characteristics is manifested in increased channel width, increases in mean stream-bed and thalweg elevations, deposition of large gravel berms, and a large increase in streamside land sliding.

CHANGES IN STREAMBED ELEVATION

Stereoscopic examination of 1936, 1947, 1968, and 1974 aerial photographs, gaging-station records, and stratigraphic evidence indicates that, except for areas near Orick and between Lacks Creek and the mouth of the gorge above Bridge Creek (reaches 4, 3 and 2), the channel of Redwood Creek has aggraded considerably since 1936. Major periods of aggradation were associated with the flood events of 1964 and 1972. Some seasonal aggradation occurs during moderate high flows and is followed by channel scour during the spring and summer months in a normal water year.

The scale and quality of the 1936 and 1947 aerial photographs limit photo interpretation of channel degradation or aggradation to empirical qualitative observations. Comparison of these photos with those of the 1973 channel suggests a severe reduction of bank heights in some upstream reaches. Stereoscopic examination of figure 13 provides some indication of decreased bank height and lessened channel incision.

In places between Snow Camp Creek and Minor Creek recent gravel deposition has completely filled the former stream channel and spilled out onto extensive areas of the former upper flood plain, thereby killing many flood-plain trees (principally Douglas-fir). Flood-plain stumps in this area with diameters comparable to those of the standing dead trees mostly display 200 to 300 annual rings. The gravel supported many alder, madr[illegible], incense cedar, and Douglas-fir seedlings that during the summer of 1974 were more than two but less than 10 years old. These seedlings suggest that the gravel was deposited during the 1964 flood. Redwood Creek has locally incised an entirely new channel through these gravel deposits. As a result, isolated groups of standing dead trees are often surrounded by the abandoned gravel-filled former channel, and the new active channel. In general, Redwood Creek appears still to be flowing at a higher level than prior to the 1964 period. Some gravel deposition appears to have accompanied the 1972 floods in these headwater reaches of Redwood Creek but such deposition here was not nearly as voluminous as during the 1964 period.

These empirical, photo-interpretive observations are supported in semiquantitative fashion by the history of the gaging station on Redwood

Creek near Blue Lake and by observations by residents and workmen. As a by-product of normal stream-flow measurements, channel cross sections are produced in reference to the gage datum. Mean streambed elevations and thalweg elevations for all measurements made within 20 feet of the Blue Lake gage cable section are shown in figure 53 and selected stream-channel cross sections are illustrated in figure 54. The short-terms perturbations in channel elevation resulting from normal variations in stream flow as well as long-term, net changes can be seen in both figures 53 and 54.

Both mean streambed and thalweg elevations increased appreciably through the period of record at the station near Blue Lake.[1/] The streambed elevation at the start of the record may have been recently elevated by aggradation associated with the 1953 flood; in the nearby Van Duzen River basin separate episodes of aggradation accompanied the 1953, 1955, and 1964 floods (Harvey Kelsey, written communication, 1975). The mean bed elevation for Redwood Creek near Blue Lake has risen approximately 3 feet and the thalweg of the November 13, 1973 cross section is over 4 feet above that of January 15, 1958. The major floods of December 1964 and January and March 1972 occurred during the non-operational period of the station; local residents and U.S. Geological Survey engineers indicate that most of the aggradation was associated with these floods.

Conversations with residents and county road crews in the O'Kane and Redwood Valley areas further suggest that the amount of aggradation documented by the discontinuous stream-gaging record for Redwood Creek near Blue Lake probably does not represent the full amount of aggradation

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1/ The stream gage record was re-established in 1973 utilizing the same datum as during the 1954 to 1958 period of record.

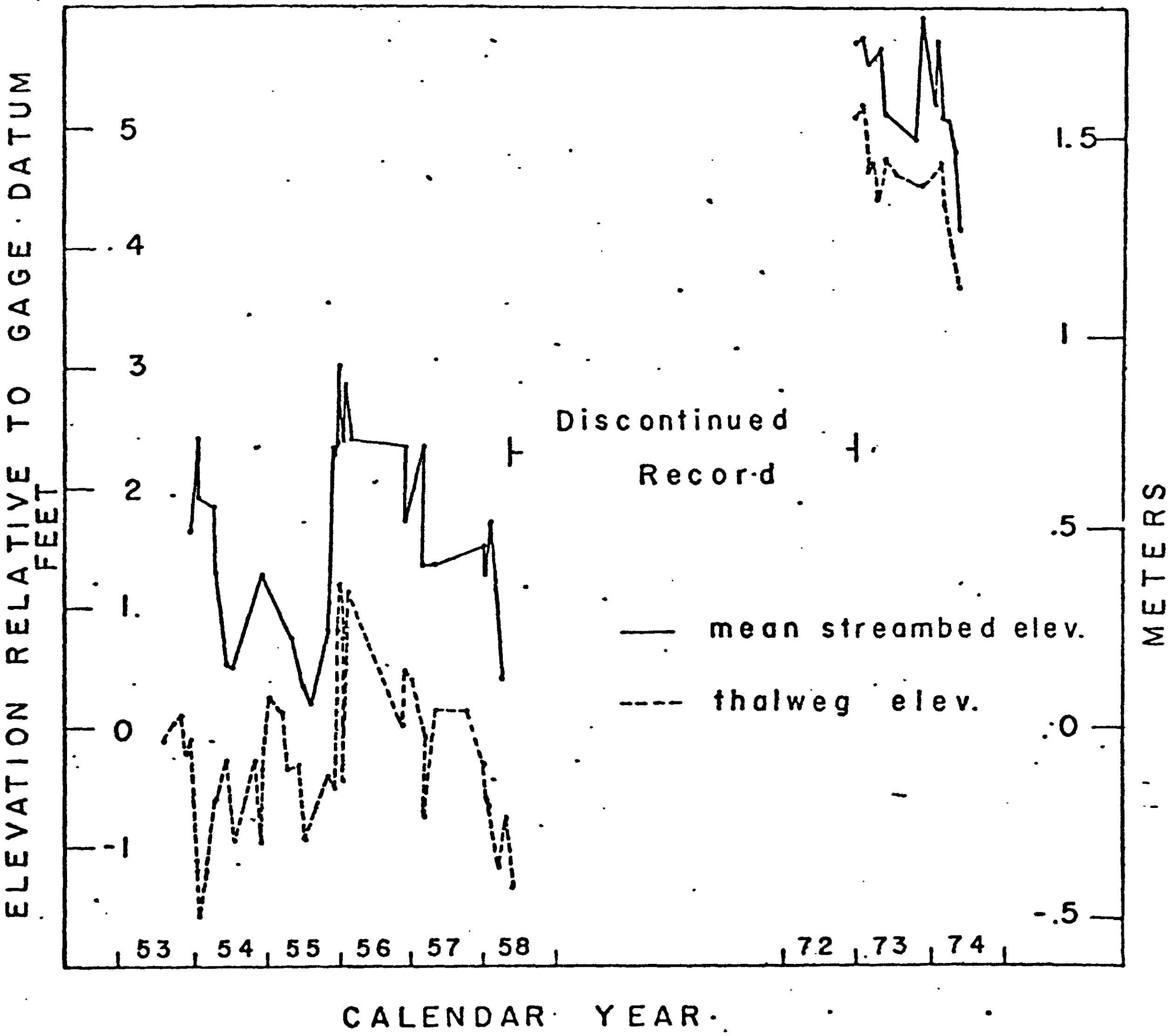

Figure 53. Variations in thalweg and mean streambed elevation for Redwood Creek at gaging station near Blue Lake.

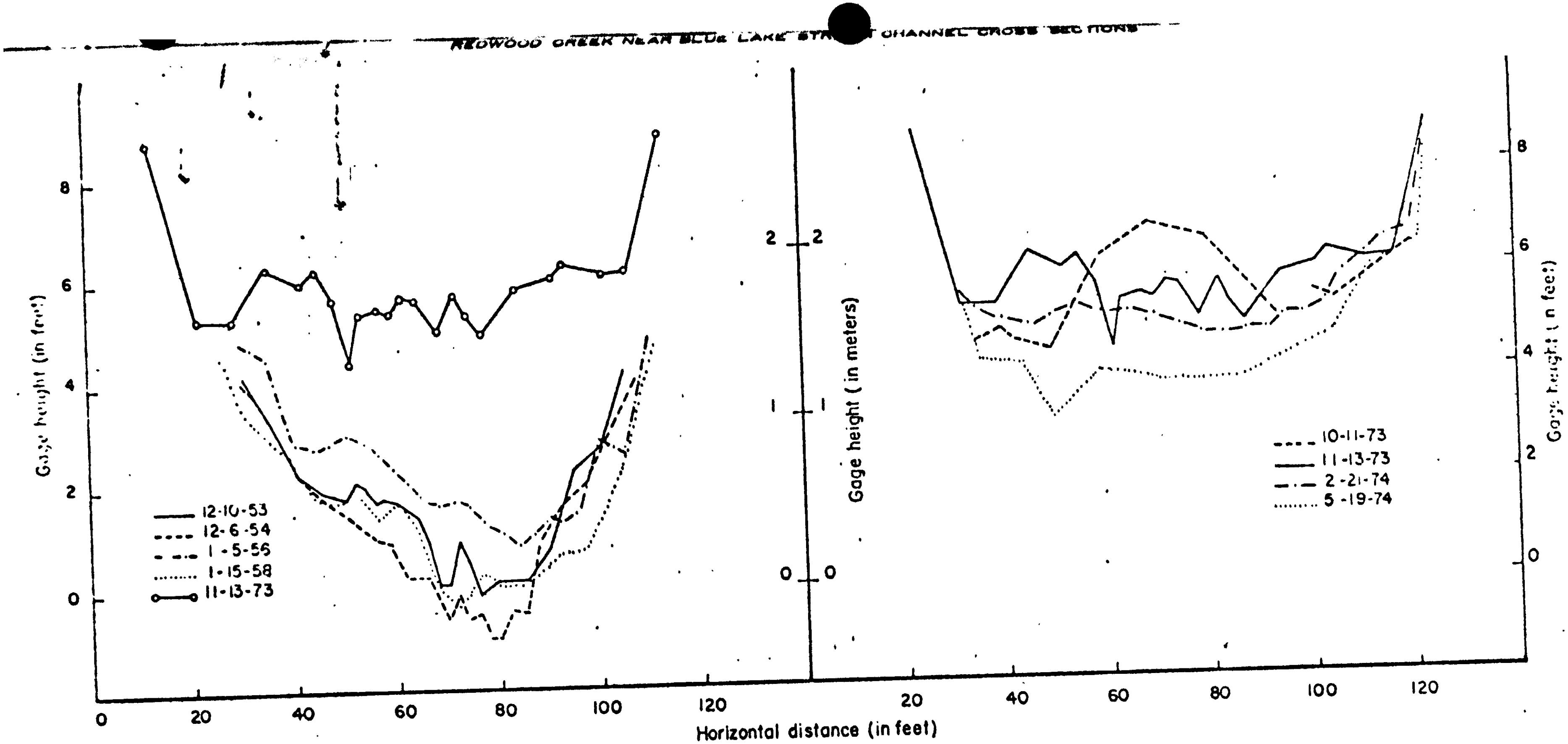

Figure 54. Redwood Creek near Blue Lake stream channel cross sections.

caused by the 1964 flood. By the time the gage record was re-established many of the large bedrock blocks that were buried by the 1964 flood deposits had started to reappear. Prior to the 1972 floods the channel throughout the sixteen mile (26 kilometer)-long reach 5 (figs. 10 and 13) between Highway 299 and Lacks Creek had incised itself into the 1964 flood deposits to a level somewhat lower than the 1973 level. The 1972 floods then caused another episode of aggradation, but the channel did not fill up to its 1964 level.

The stream bed elevation of Redwood Creek at two sites in this area is known to have aggraded at least 15 feet (4.6 metres) during the 1964 flood. One site is at a natural swimming hole on the ranch of Oren B. Frankie about half way between Minor Creek and O'Kane; this hole had a rock with a diving board attached 15 feet (4.6 metres) above the low water surface. The hole and rock are now completely buried. The other site is at the bridge on the Redwood Valley road where several residents report that following the 1964 flood, gravel had been deposited up to the level of the beams supporing the bridge deck. In 1973, the channel was 15 to 18 feet (4.6 to 6.1 metres) below the road deck but still at a higher level than prior to 1964.

Changes in streambed elevation, comparable to those in the upper Redwood Creek Basin, recently occurred elsewhere in northwestern California. Hickey (1969) in reviewing the history of low-water streambed elevations at 51 stream-gaging stations in this area found that (1) 41 stations showed recent fill, (2) 10 of those stations experienced three or more feet of fill, and (3) most of the fill was deposited by the flood of December 1964. Pronounced aggradation has occurred in the relatively pristine upper Van Duzen River basin (Harvey Kelsey, written communication, 1975) and the upper Middle Fork Eel River basin in and immediately downstream from the Yolla Bolly Wilderness Area (J.C. Fraser, written communication, 1975).

Extensive unvegetated gravel inner flood plains, such as those that characterize the channel between Snow Camp Creek and Lacks Creek, were not present in 1973 between Lacks Creek and the mouth of the gorge downstream from the southern park boundary in reaches 4, 3 and 2 (figures 14, 15 and 16). Here, large angular bedrock blocks commonly protrude through alluvium in the active channel. Prominent flood-related gravel berms, however, are locally present along some unusually wide reaches and on some stream bends such as below Copper Creek and near the southern park boundary. Timber-company employees indicate that some of these berms are erosional remnants of berms that were much more extensive following the 1964 flood. Other berms appear to have been deposited by the 1972 floods; for example, the orifice tube at the gaging station at the southern boundary of Redwood National Park had more than 15 feet (4.6 metres) of alluvium deposited on it during the 1972 floods (Gerald LaRue, oral communication, March 1972). The amount, type, and age of vegetation observed on these berms in 1974 suggest that most either originiated or had additional sediment deposited upon them in 1972.

Within the reaches of Redwood Creek in the Park, considerable photographic, botanical, morphologic and stratigraphic evidence suggests that recently the Creek has significantly aggradated. Sequences of aerial photographs suggest reductions in bank heights. Coarse sandy gravel channel deposits are commonly found lying upon thick sections of silt loam and fine sandy loam overbank deposits. Locally, between the mouth of the gorge and the prominent bend immediately upstream from the Tall Trees Flat recent deposition of coarse-grained deposits has killed groves of alder, maple, tonoak, Douglas-fir, and redwood trees at the streamside edges of upper flood plains. Downstream from the Tall Trees Flat only isolated individual trees appear to have been killed by recent deposition of coarse-grained alluvium. The upper surfaces of nearly all of the recently deposited coarse-grained channel deposits and berms bear only sparse young vegetation that appears to have been established subsequent to the 1972 floods. Nonetheless, many of the trees that appear to have been killed by recent deposition were dead prior to 1972, so that the January and March 1972 floods may merely have deposited a relatively thin veneer upon alluvium laid down principally in 1964. Streambanks are clearly defined at most sections in this reach, and even where recently aggraded channel deposits have spilled onto upper flood plains, only the outer edges of the flood plains have been affected.

The bulk and height of flood-deposited gravel berms, as well as the vertical separation between the channel of Redwood Creek and its upper flood plain, suggest that the amount of recent aggradation in reaches of Redwood Creek within the park as of 1973 was greatest between the mouth of the gorge and Harry Weir Creek. The amount decreased downstream, so that by Hayes Creek, streambank heights along Redwood Creek were comparable to what they were during the early 1950's.