SUMMARY OF WATERSHED CONDITIONS IN THE VICINITY OF REDWOOD NATIONAL PARK, CALIFORNIA

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ABSTRACT

The Redwood Creek Unit of Redwood National Park is located in the downstream end of an exceptionally rapidly eroding drainage basin. Spatial distribution and types of erosional landforms, observed in the field and on time-sequential aerial photographs, measured sediment loads, and the lithologic heterogeneity of streambed materials indicate (1) that sediment discharges reflect a complex suite of natural and man-induced mass movement and fluvial erosion processes operating on a geologically heterogeneous, naturally unstable terrain, and (2) that although infrequent exceptionally intense storms control the timing and general magnitude of major erosion events, the loci, types, and amounts of erosion occurring during those events are substantially influenced by land use. Erosional impacts of past timber harvest in the Redwood Creek basin reflect primarily the cumulative impact of many small erosion problems caused not so much by removal of standing timber as by the intensity and pattern of ground surface disruption accompanying removal.

Recently modified riparian and aquatic environments reflect stream channel adjustments to recently increased water and sediment discharges, and are classified by the National Park Service as damaged resources because the modifications reflect, in part, unnatural causes.

Newly strengthened State regulations and cooperative review procedures result in proposed timber harvest plans being tailored to specific site conditions, as well as smaller, more dispersed harvest units and more sophisticated attempts at minimizing ground-surface disruption than those used in most previous timber harvesting in this

basin. However, application of improved timber harvest technology alone will not assure protection of park resources. Much remaining intact and residual commercial old-growth timber is on hillslopes that are steeper, wetter, more susceptible to landsliding, and more nearly adjacent to major stream channels than most of the previously harvested hillslopes in the lower Redwood Creek basin. Moreover, natural debris barriers along streams flowing through remaining old-growth forest have temporarily stored substantial quantities of sediment introduced into streams by recent storms and upstream land-use changes. Removal of merchantable timber from these barriers may destroy their stability and cause rapid release of stored sediment. Additionally, massive erosion in some recently harvested areas suggest that they are so erosionally sensitive that following rehabilitation and reforestation, they should not be reharvested. Thus, in order to maintain site productivity and to protect downstream park resources, some erosionally critical areas may have to be maintained as perpetual timber reserves dedicated to watershed protection. Selective Federal acquisition of just erosionally critical acreage would create ownership patterns that would make management of both parklands and commercial timber lands exceedingly difficult.

INTRODUCTION

On October 5, 1977, Senator James Abourezk, Chairman of the Senate Subcommittee on Parks and Recreation, requested that Assistant Secretary of Interior Robert L. Herbst follow through on his offer to have the Geological Survey submit a written statement for the record *** "summarizing its recent findings and refuting the contradictory claims made by industry consultants." This statement has been prepared in close consultation with my colleagues K. M. Nolan and D. R. Harden as a response to Senator Abourezk's request.

I am presently, and have been since 1962, employed as a geologist by the Water Resources Division (WRD) of the U.S. Geological Survey in Menlo Park, California. I am a Registered Geologist (Certificate 2941) in the State of California. Since the autumn of 1973 I have served as the project chief for an intensive study of the various geomorphic processes operating in the drainage basin of Redwood Creek, the impact of man upon those processes, and the impact of those processes upon the resources of Redwood National Park.

I am a geomorphologist by training having received a B.S. in 1960 from the Department of Geology and Mineralogy of the Pennsylvania State University, and a Ph. D. in 1966 from the Department of Geology and Geophysics of the University of California at Berkeley. In the course of my employment with the Geological Survey, I have worked extensively in diverse forested terrains in California, Oregon, Washington, and Hawaii, but my intensive studies have been limited to the western flank of the central Sierra Nevada and to the Coast Ranges of northern California and southern Oregon. I have been the author or co-author of 39 professional publications. In addition to my employment with the Geological

Survey, I have also served as a Visiting Associate Professor of Geomorphology at the Pennsylvania State University (autumn 1971) and the University of California at Santa Cruz (spring 1975, spring 1976). I was elected to the Geomorphology Panel of the Geological Society of America (1971-72), and appointed to the Temperate Region Subcommission of the Present Day Geomorphic Processes Commission of the International Geographic Union (1973). I presently serve as a member of the standing Research Advisory Committee to the California State Board of Forestry, and the National Advisory Committee to the H. J. Andrews Experimental Forest.

I casually visited the drainage basin of Redwood Creek twice prior to initiation of my present intensive investigation of geomorphic problems in the basin. In the spring of 1965, I inspected the flood plain near State Highway 299 and Orick as part of a regional reconnaissance of stream sedimentation related to the destructive flood of December 1964. In the late spring of 1969 I walked the channel of Redwood Creek from the mouth of Prairie Creek to the mouth of Bond Creek in order to inspect parts of the newly established Redwood National Park.

During March 20-23, 1972, I served as part of a Department of the Interior-sponsored interdisciplinary professional team under the leadership of Dr. Richard C. Curry, investigating the actual and potential impact of timber harvest on Redwood National Park. The present level of involvement of the Geological Survey in Redwood Creek reflects that team's recognition that additional geomorphic data would assist the National Park Service to develop an effective means of dealing with those geomorphic processes that may threaten park resources. Between April 1972 and September 1973, I spent about 45 days within the Redwood Creek basin gaining background information needed to develop an effective study plan.

Subsequent to the start of the Geological Survey's intensive Redwood Creek studies in September 1973, I have spent more than 200 days within the basin in all types of weather. Professionals working under my supervision, and under that of Lee R. Peterson (Chief of the California District, WRD, U.S. Geological Survey), have prepared for public release 17 reports on subjects that are germane to presently pending legislation. In preparing these reports, my fellow authors and I drew heavily upon the professional experience of many of our Survey colleagues and also conferred for 30 or more days with professional foresters, hydrologists, engineering geologists, aquatic biologists, and plant ecologists from outside our agency.

This statement extracts from our previous reports key facts and ideas concerning recent modifications of park resources and the reasons for those modifications, as updated on the basis of more recent observations and analysis. A list of these reports is appended to this statement, as Appendix 1, and copies may be provided to the Subcommittee if it so desires.

THE PHYSICAL SETTING OF THE REDWOOD CREEK UNIT OF REDWOOD NATIONAL PARK.

The park-protection issues involved in Senate Bill 1976 focus primarily upon the Redwood Creek unit of Redwood National Park, which is located in the downstream end of the 278-square-mile drainage basin of Redwood Creek. During six years of available record, water years 1971 through 1976, Redwood Creek at Orick transported an average annual suspended-sediment load of 2,079,400 tons, or 7480 tons per square mile. During this period, Redwood Creek transported, on a per-square-mile basis, about 32 percent more suspended sediment than the nearby Eel River at Scotia, California which has previously been cited as the most rapidly eroding nonglaciated drainage basin of comparable size in North America (Brown and Ritter, 1969).

The physical setting and land-use patterns of the Redwood Creek basin have both contributed to its exceptionally high rate of erosion. The Redwood Creek basin annually receives about 80 inches of rainfall and it supports a dense vegetal cover. The rain comes mostly during prolonged, moderately intense winter storms. The basin consists mostly of intricately dissected, moderately steep to steep hillslopes carved from the closely fractured and pervasively sheared rocks of the Franciscan assemblage which, for the most part, has weathered to a mixture of noncohesive soils that are highly susceptible to erosion by running water and of clayey soils that are susceptible to mass failure when wet. Noncohesive soils in the steeper parts of the basin are also prone to mass failure, particularly following the loss of root strength and the increased soil moisture following timber harvest. Stable, deeply-weathered clayey soils are restricted for the most part to broad gently sloping ridgetops in the northern part of the basin.

This combination of physiography, surficial materials, and storm intensity makes the Redwood Creek basin highly susceptible to various forms of landsliding and erosion by running water once the vegetal cover is disrupted. Landsliding not only moves masses of soil and rock directly downslope and into stream channels, but it also locally disrupts the vegetal cover and leaves the underlying soil exposed to erosion by running water.

Road construction, grazing, fires, and timber harvest have increased the susceptibility of large parts of the Redwood Creek basin to erosion by causing vegetation and ground-surface disruption comparable to that caused by landsliding. The present vegetation distribution within the Redwood Creek basin provides visual documentation of the extent of man's activities in this area (Harden, 1977). About 15 percent of the drainage basin is covered with prairies and brush fields. These prairies have been grazed with varying intensity, and some have been plowed. The native bunch grass-herb flora has been largely replaced by introduced annual grasses and weeds that are more tolerant of heavy grazing. More than 60 percent of the basin consists of timberland harvested over the last 25 years. Logging during the 1950's and early 1960's was concentrated in Douglas-fir dominated forest in upstream parts of the basin, but more recent logging has been concentrated in redwood-dominated forest in downstream parts of the basin that are in close proximity to the park. About 12,000 acres of the recently harvested timberland (6.7 percent of the basin) bears residual stands of timber which will be relogged in the near future. Less than 44,000 acres (24.7 percent of the basin) bear intact old-growth or advanced second-growth forests. Additionally, more than 1100 miles of roads (exclusive of skid trails and temporary logging spurs) have been built in the basin; many of these roads were designed primarily to provide passage between commercial timberland and millsites. More than half of the remaining old-growth forest is commercial timberland that is either privately owned or publicly owned and administered or controlled by the U.S. Forest Service and Bureau of Land Management; the rest is preserved in Federal and State parks.

The Redwood Creek unit of Redwood National Park is at the lower end of this drainage basin (fig. 1). Prairie Creek is the only major tributary to enter Redwood Creek downstream from this unit. The Redwood Creek corridor, or "worm" as it is sometimes called, is an appendage to

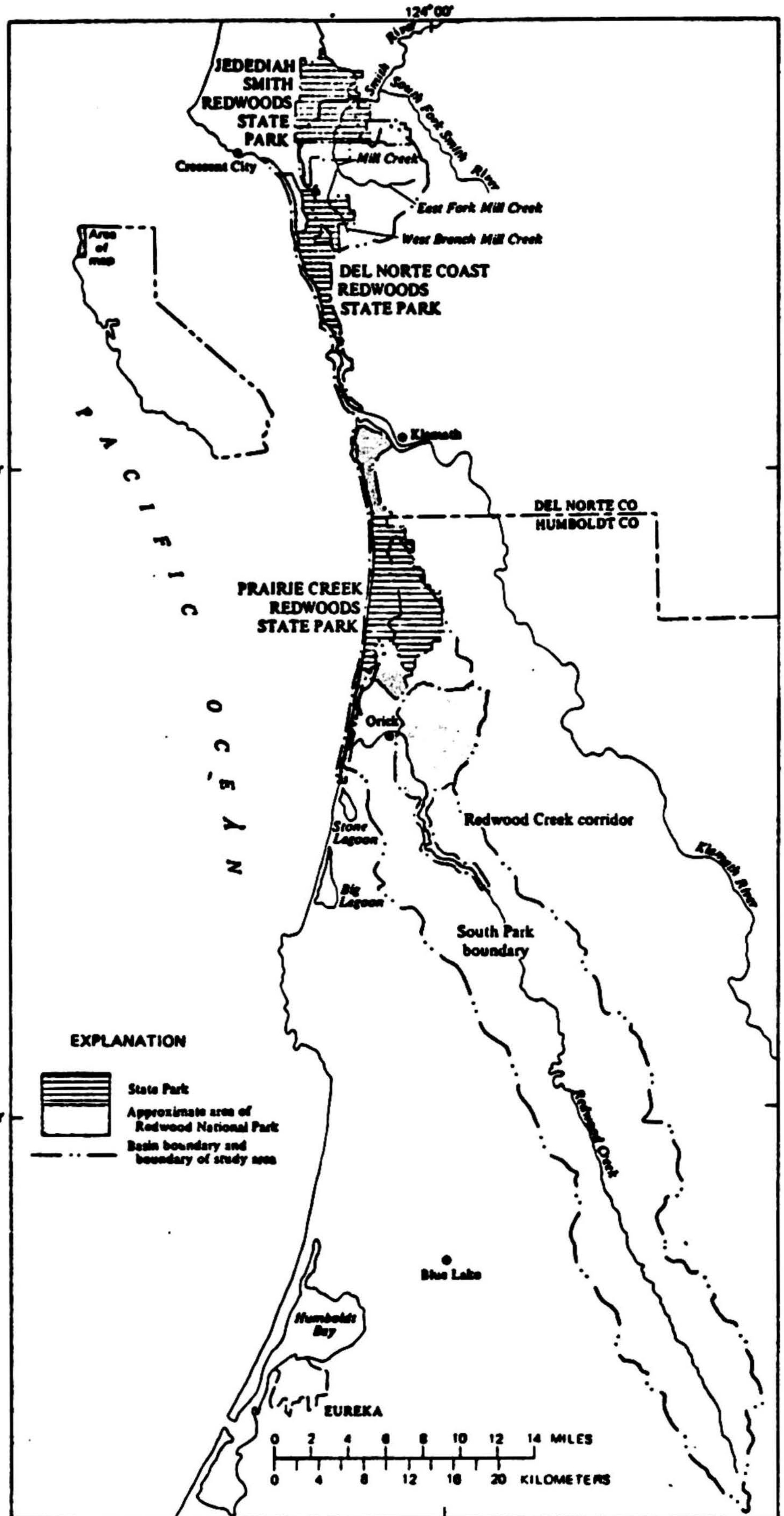


FIGURE 1. – Location map.

the main unit approximately 7 1/2 miles long; this appendage extends only about one-quarter of a mile upslope from each side of Redwood Creek. The Tall Trees Grove, a floodplain grove of coastal redwoods (Sequoia sempervirens) containing the first, third, and sixth tallest trees in the world, is located midway along the appendage. The second tallest tree is in another floodplain grove located about 1 mile downstream from the Tall Trees Grove.

THE GENERAL NATURE OF THE THREAT TO THE PARK RESOURCES.

Recent interactions among inherently unstable hillslopes, exceptionally severe storms, and major changes in land use have caused Redwood Creek and some of its principal tributaries currently to transport far more sediment than they have in the recent past. Dr. Henry Anderson (1976) has suggested that the present suspended-sediment discharge of Redwood Creek at Orick is about 7 1/2 times greater than its natural suspended-sediment discharge.[1/] The impact on individual tributaries has been highly variable.

1/ Dr. Anderson based his findings upon the relationship between average suspended-sediment discharges from 61 California streams and 10 physical attributes of drainage basins that control suspended-sediment discharge. His analytical technique was an analysis of principal components consisting of a factor analysis of the correlation matrix, Varimax rotation of the factors, and multiple regression.

The recently added stream-sediment load has caused readily apparent modifications of riparian and aquatic environments within the Redwood Creek corridor of Redwood National Park. The National Park Service and various environmentally concerned groups classify the recently modified aquatic and riparian environments as damaged park resources because these modifications reflect, in part, unnatural causes.

Much of the sediment which is either in transport or in temporary storage along Redwood Creek and its tributaries was undoubtedly initially set in motion by particularly severe storms in 1953, 1955, 1964, 1972, and 1975. These storms all appear to have produced closely comparable instantaneous peak discharges at Orick, but they were associated with significantly different areal distributions and quantities of rainfall and total flood runoff (figs. 2-7). Nonetheless, all six storms, even when viewed from a historical perspective going back to the late 19th century, appear to have been exceptionally intense.

The loci and types of erosional phenomena observed in the field and on time-sequential aerial photographs indicate that the amount of sediment put in motion as a result of these storms was substantially influenced by intensive timber harvest and other major changes in land use, as well as by the antecedent moisture conditions and the magnitude and duration of storms. For example, the streamside vegetation and channel configuration along downstream reaches of Harry Wier Creek, Miller Creek, Cloquet Creek, and Oscar Larson Creek (four adjoining parkland tributaries to Redwood Creek) were more drastically modified by storms that immediately followed intensive, tractor-yarded, clearcut

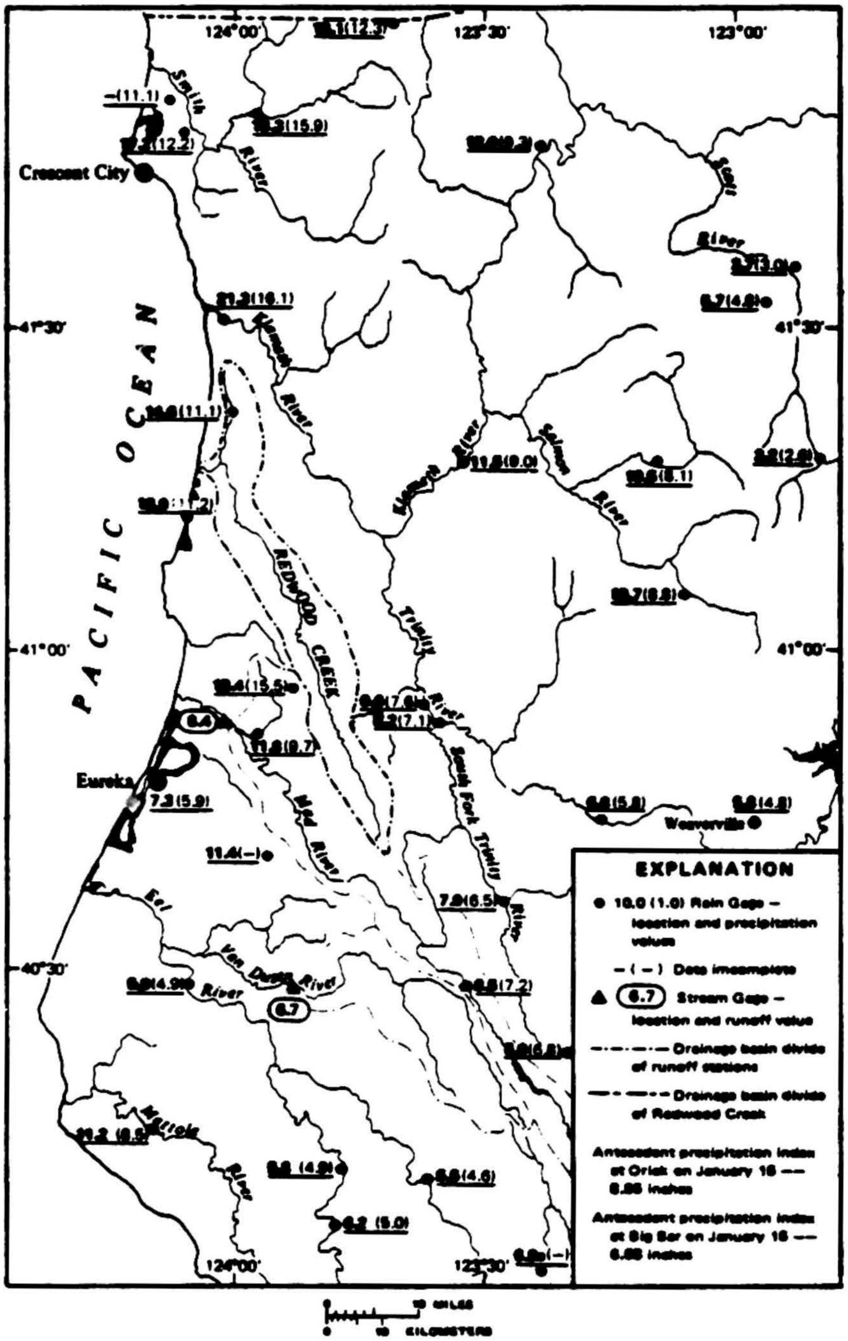


FIGURE 2. Precipitation and runoff, in inches, during the flood-producing storm of January 16-20, 1953 in northwestern California. Numbers outside of parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period, January 17-19, 1953.

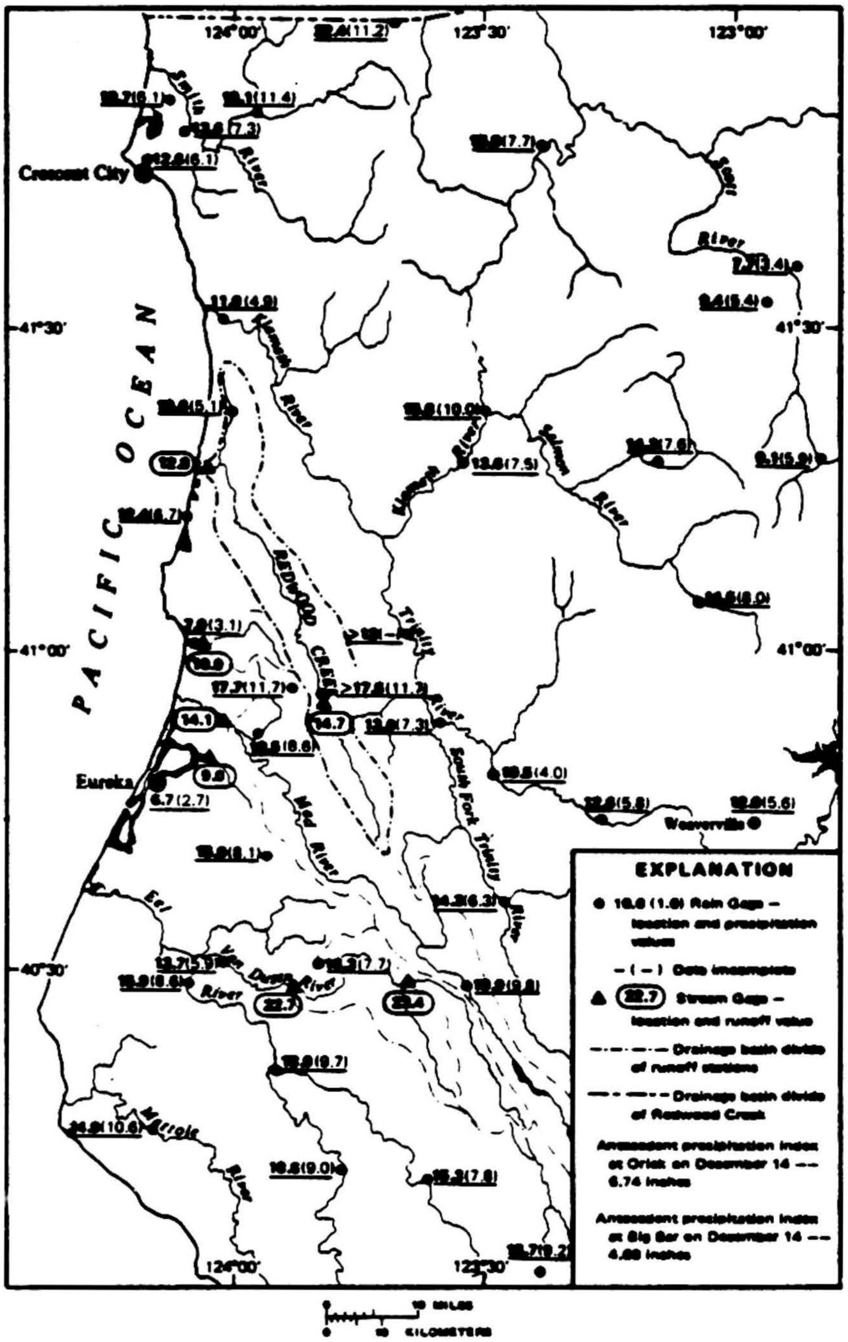


FIGURE 3. Precipitation and runoff, in inches, during the flood-producing storm of December 15-23, 1955 in northwestern California. Numbers outside of parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period, December 21-23, 1955.

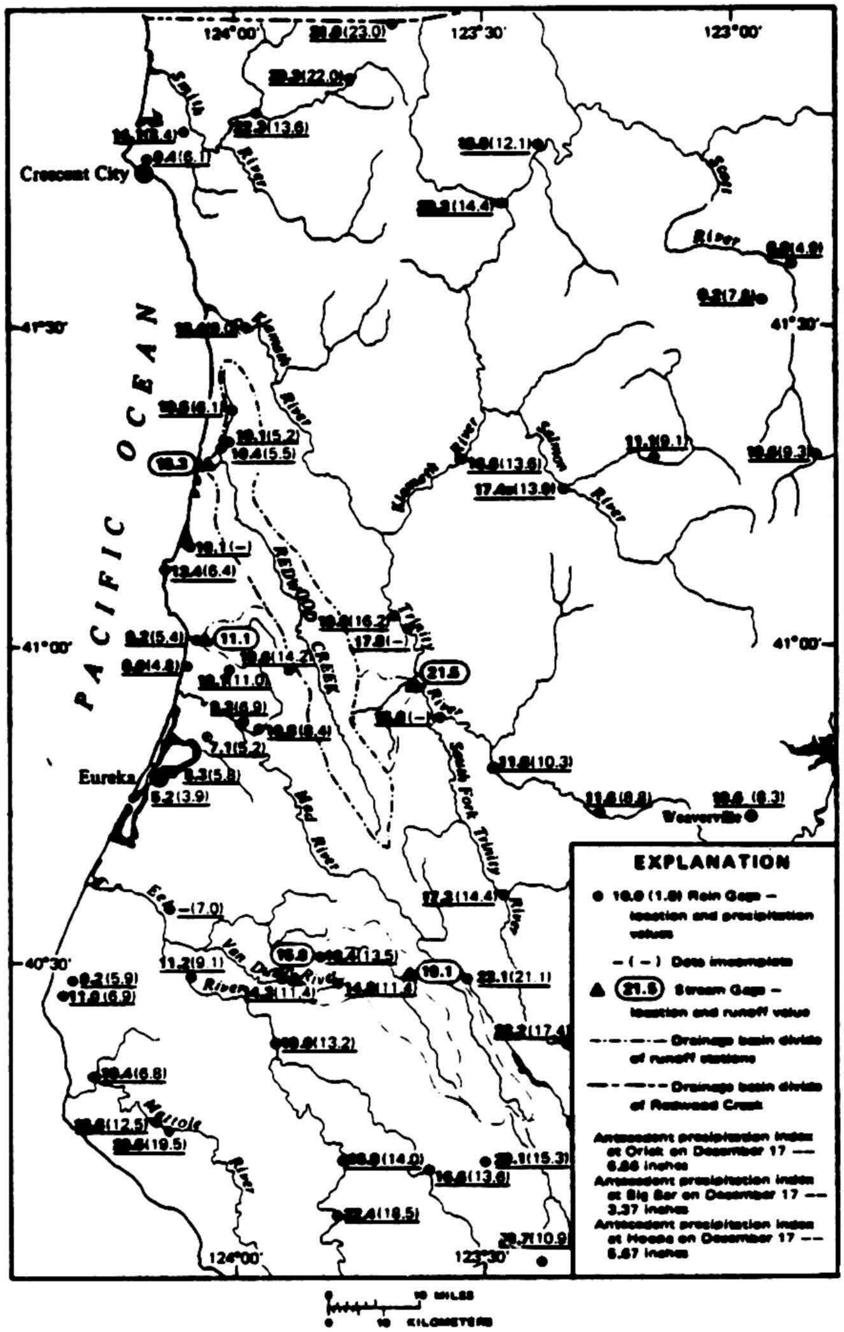


FIGURE 4. Precipitation and runoff, in inches, for the flood-producing storm of December 18-24, 1964 in north-western California. Numbers outside of parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period, December 21-23, 1964.

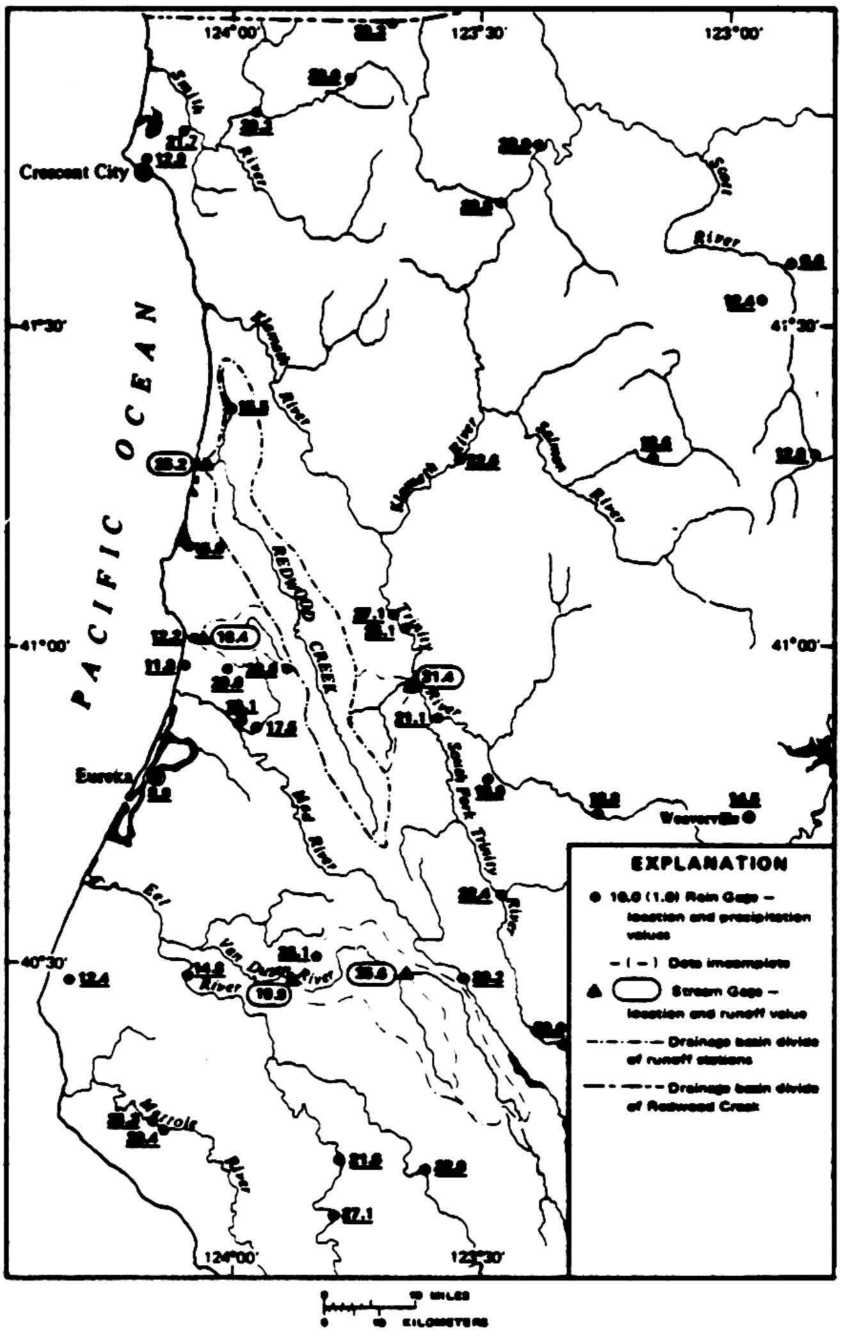


FIGURE 5. Precipitation and runoff, in inches, for the flood-producing storm period of December 18-31, 1964.

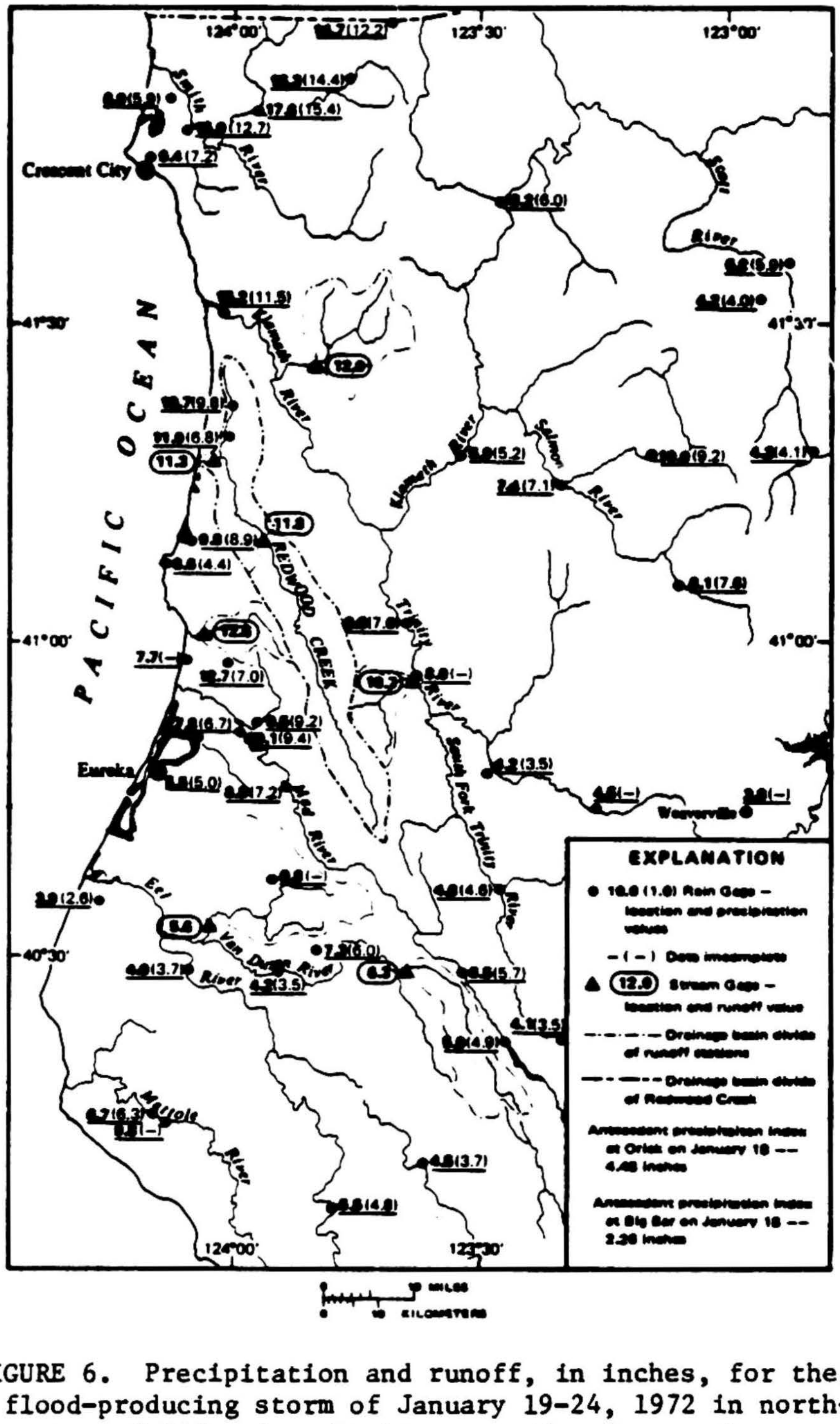


FIGURE 6. Precipitation and runoff, in inches, for the flood-producing storm of January 19-24, 1972 in north-western California. Numbers outside of parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period, January 21-23, 1972.

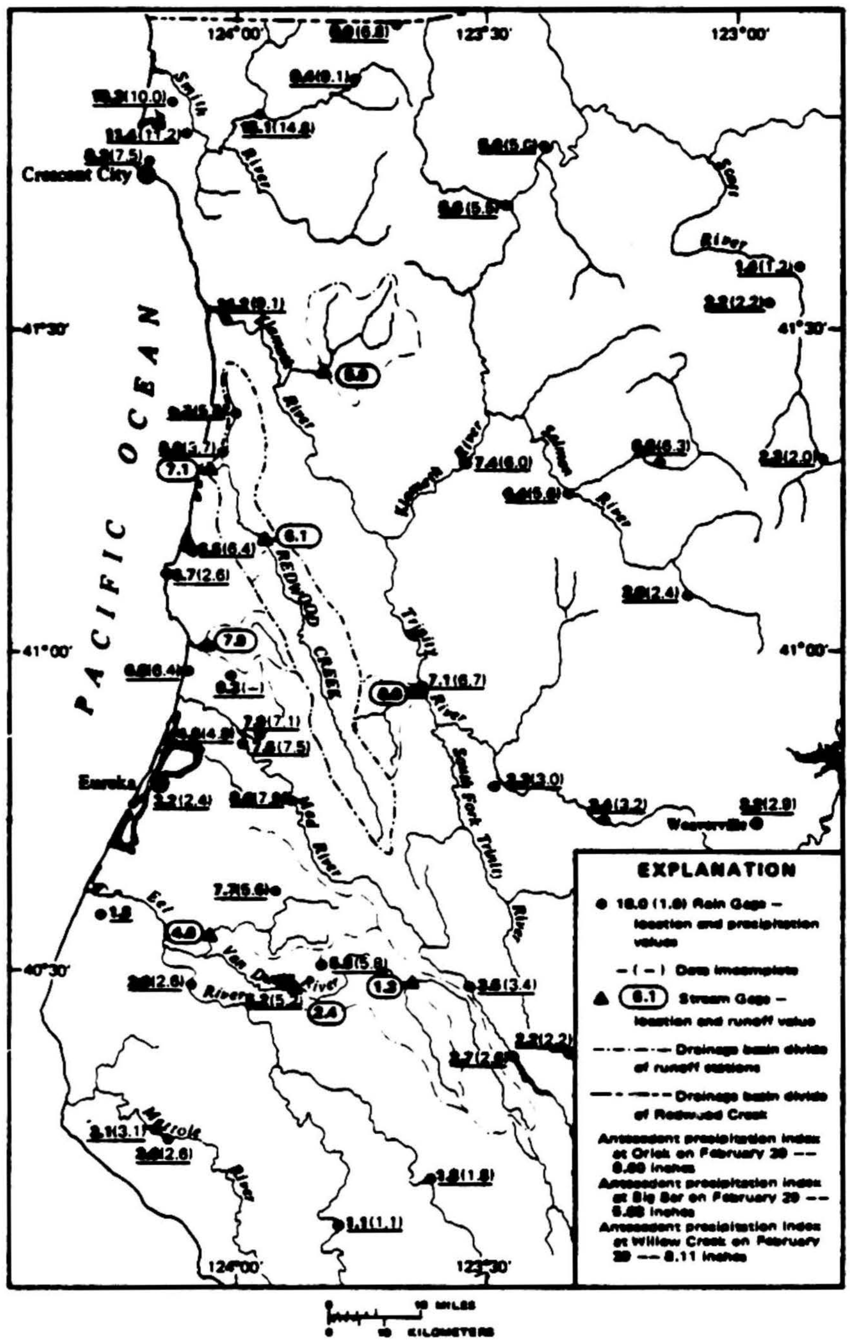


FIGURE 7. Precipitation and runoff, in inches, during the flood-producing storm of March 1-4, 1972 in northwestern California. Numbers outside of parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period, March 2-4, 1972.

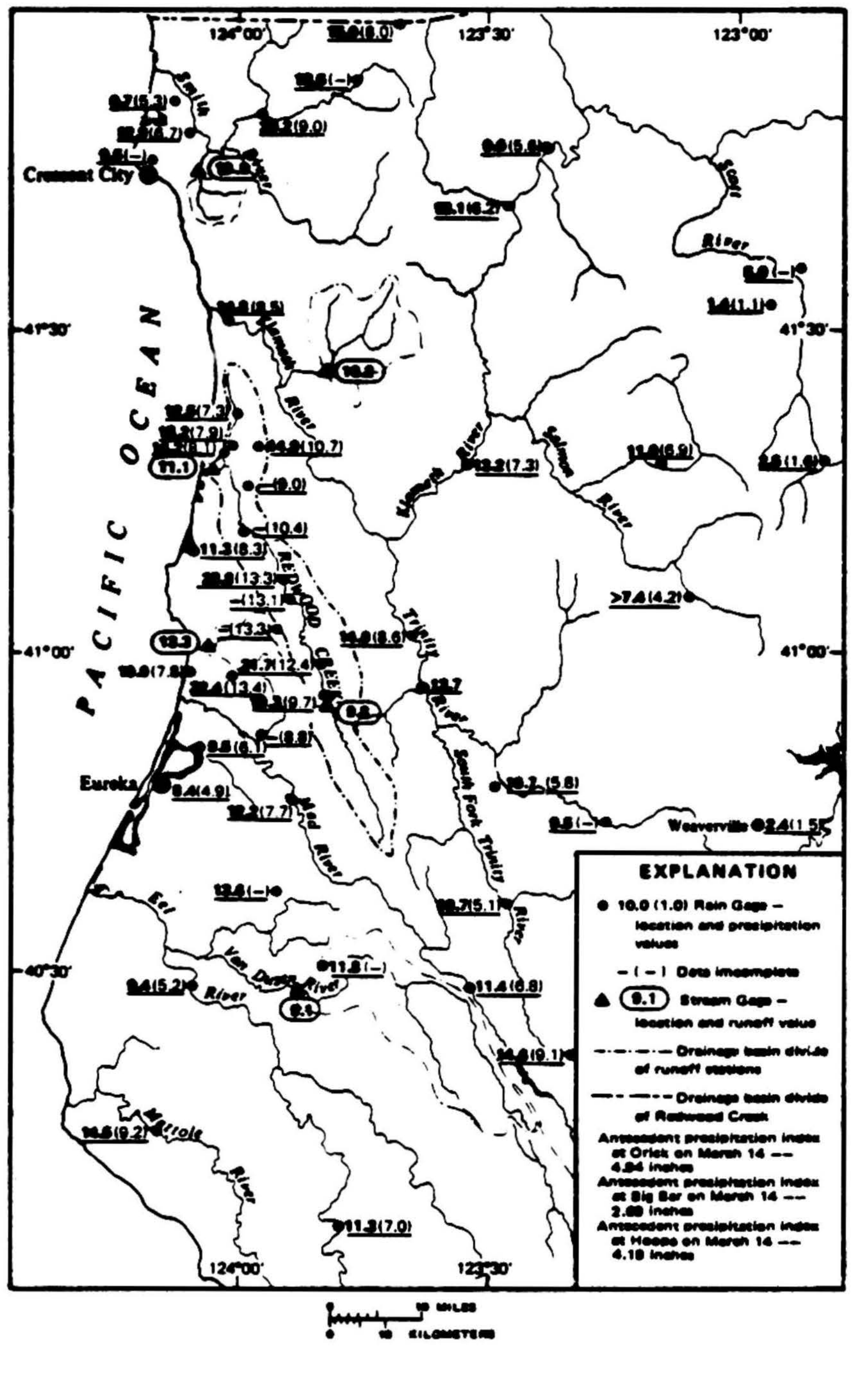


FIGURE 8. Precipitation and runoff, in inches, for the flood-producing storm of March 15-24, 1975 in northwestern California. Numbers outside of parentheses are rainfall totals for the storm, and numbers within parentheses are rainfall totals for the three-day period, March 17-19, 1975.

timber harvest in their headwaters than by comparable storms prior to harvest. The 1972 and 1975 storms were more damaging to the downstream reaches of Miller Creek than the 1964 storm; intensive timber harvest started in Miller Creek in 1969. Similarly, the 1975 storm was more damaging to Harry Wier Creek than either the 1964 or the 1972 storm; some timber harvest commenced in Harry Wier Creek in 1969, but the most intensive logging took place between 1972 and 1974. Downstream reaches of Cloquet Creek and Oscar Larson Creek, whose headwaters have been less severely disrupted by timber harvest than Harry Wier Creek and Miller Creek, sustained relatively little damage during the 1964, 1972, and 1975 storms. However, the upper and middle reaches of the south fork of Cloquet Creek, which were harvested in 1972 and 1973, were extensively modified by erosion and deposition caused by the 1975 storm.

The extent and intensity of ground disruption caused by timber harvest and road construction in this basin over the last 25 years have been extreme relative to those in most comparable basins in northwestern California. Not only has more than 60 percent of the drainage basin of Redwood Creek been harvested in about two and a half decades, but most of that harvest involved sequential logging of adjoining tractor-yarded clearcut units that were hundreds of acres in size. Field measurements recently supplied by C. J. Hauge of the California Department of Forestry to Dr. Clyde Wahrhaftig of the California Board of Forestry indicate that 30, 10-acre plots in tractor-yarded clearcut units in Del Norte and Humboldt Counties display an average of 4148 feet of skid trails with an average cut depth of 4 feet and an average fill depth of 3.9 feet. These same 30 units showed an average of 309 feet of haul roads with an average cut depth of 6.3 feet and an average fill depth of 6 feet.

Bulldozer-constructed layouts designed to minimize breakage during felling operations involve additional excavation and disruption of the land surface. Observations and aerial photographs suggest that in the immediate vicinity of the park, this mode of timber harvest disrupted significantly about 80 percent of the harvested surface area, and covered about 40 percent of that area with roads, skid trails, layouts, and landings (Janda and others, 1975A, p. 126).

Present and proposed future logging involves smaller, more dispersed harvest units and more sophisticated attempts at minimizing ground-surface disruption than were used in most of the logging that contributed to recent accelerated erosion. Recently strengthened regulations and review procedures result in proposed harvest plans being tailored to specific site conditions.

Much of the remaining commercial old-growth timber is on steeper, wetter hillslopes that are more susceptible to landsliding and in closer proximity to major stream channels than most of the previously harvested hillslopes in the lower Redwood Creek basin. Moreover, many of the natural debris barriers along streams flowing through the remaining old-growth forest have temporarily stored substantial quantities of sediment introduced into the streams as a result of the recent storms and upstream land-use changes. Removal of merchantable timber from these barriers may destroy their stability and cause the rapid release of stored sediment. The cumulative impact of recent land-use changes and storms on stream sedimentation would then be transmitted to downstream reaches in a brief period of time. This concentrated impact would probably be severely damaging to park resources. Additionally, the relative effectiveness of recently proposed timber-harvest techniques in mitigating past-harvest erosion in this type of terrain remains to be demonstrated. Thus, harvest of timber in these erosionally sensitive streamside zones will have to be thoroughly planned, skillfully implemented over an extended period of time, and carefully monitored in order to minimize the possibility of impacting further upon hillslope erosion and stream sedimentation. Monitoring is needed to check whether proposed mitigation measures provide the desired level of resource protection. An extended period of harvest helps to minimize the potential for cumulative impacts and allows monitoring results to be utilized in the planning effort.

The threat posed to park resources by harvest of some of the remaining old-growth forest is different from that associated with past harvest in that potential harvest-induced erosion problems appear to be fewer in number but potentially larger in size than most of those caused by past harvest. Substantial tracts of remaining old-growth forest are so inherently unstable that timber harvest, even if carried out with extraordinary care, will almost certainly result in massive landslides or gullies. Thus, if the potential for future damage to park resources resulting from timber harvest-induced erosion is to be minimized, future planning efforts may have to consider some deferral and abolition of harvest of selected sites. Massive erosion problems in some recently harvested areas suggest that they too may be so erosionally sensitive that, following rehabilitation and reforestation, they should not be reharvested. Thus, in order to maintain site productivity and to protect downstream park resources, it may be necessary to maintain some erosionally critical areas as perpetual timber reserves dedicated to watershed protection. Precise designation of the amount and location of the critical acreage could be made only after detailed, site-specific field investigations.

However, a working knowledge of this particular basin, and general principles of erosion, suggest that the critical old-growth acreage is scattered about and interspersed with cutover land and stable hillslopes. Moreover, that critical old-growth acreage is not all contiguous with the park or with blocks of privately owned intact old growth that are contiguous with the park. Thus, selective Federal acquisition of just the critical acreage would create a pattern of ownership that would make management of both the parklands and the commercial timberlands exceedingly difficult.

Given present drainage-basin conditions, even a relatively small addition of sediment has the potential for causing a disproportionately large impact upon park resources. If the potential for further adverse modification of aquatic and riparian environments within the Redwood Creek corridor is to be significantly diminished, the addition of sediment to streams within the Redwood Creek basin must be minimized until these streams re-establish channel configurations comparable to those that existed prior to recent widespread aggradation. Achieving this goal may require some deferral of future harvest in those tributary drainage basins that have been particularly severely impacted upon by prior timber harvest. This primary goal should, however, be tempered with the realization that, if all remaining commercial old-growth timber is ultimately to be harvested, continued deferral of timber harvest in especially unstable sites, until the end of old-growth harvest, may cause a concentrated harvest in these areas that could adversely impact upon stream sedimentation in and adjacent to the park.

THE EFFECT OF RECENT LAND-MANAGEMENT ACTIVITIES ON THE PARK RESOURCES.

The overall nature of recent modifications of park resources can best be understood by classifying the observed modifications into those along Redwood Creek, those along tributaries to Redwood Creek, and those on hillslopes, particularly hillslopes adjacent to the park boundary. Such a classification is desirable because different processes and events are responsible for environmental modifications observed in these different areas.

The aquatic and riparian resources of Redwood Creek are the resources that display the most conspicuous recent modifications. Unfortunately, these resources include those that are the most accessible and interesting to most park visitors. Lush riparian vegetation of Redwood Creek includes floodplain groves of redwood containing trees reported to be the first, second, third, and sixth tallest trees in the world. The creek itself provides park visitors with drinking water, gravel-bar campsites, and natural access to many of the park's most magnificent redwood groves. In addition, the creek provides habitat for the resident aquatic organisms and anadromous fish.

Recent aggradation along much of Redwood Creek can be qualitatively documented through inspection of repeated aerial and ground photographs going back to 1936, interviews with early visitors to the creek, and various types of botanical and stratigraphic evidence including buried old floodplain surfaces and logs. The most intense recent episode of aggradation throughout most of the basin appears to have been initiated by the December 1964 flood; major aggradation was also initiated by the floods of January and March 1972 and March 1975, particularly in the downstream third of the basin. Similar evidence indicates that aggradation has been associated with a shift to wider, shallower channel cross sections, lower stream-bank heights, and a more braided channel pattern.

Channel-geometry changes along the main channel of Redwood Creek since 1973 have been documented by periodically surveying and photographing about 50 monumented stream-channel cross sections (Nolan and others, 1976B). Figure 8 shows the results at two of these sections. Within the park, channel geometry changes along Redwood Creek have been most pronounced along a 9-mile-long reach extending upstream from Elam Creek to the mouth of the boulder-strewn, bedrock gorge near the southern boundary of the park. Figure 9 shows recent changes in channel geometry at the upstream side of the Tall Trees Grove; changes between 1972 and 1976 are based upon repeated level surveys, whereas the schematic reconstruction of the 1936 channel configuration is based upon aerial photographs as well as accounts and ground photographs of those who visited the Grove prior to initiation of the apparently continuing episode of pronounced aggradation and bank erosion. These channel changes have had an unmistakably adverse impact upon riparian vegetation and aquatic organisms along the park-owned reaches of Redwood Creek. Numerous streamside trees have been killed through direct toppling by bank erosion, burial by coarse-grained stream-bed material, and "drowning" by elevated water tables (fig. 10). Additionally, floating coarse woody debris has severely battered, abraded, and probably toppled some streamside trees.

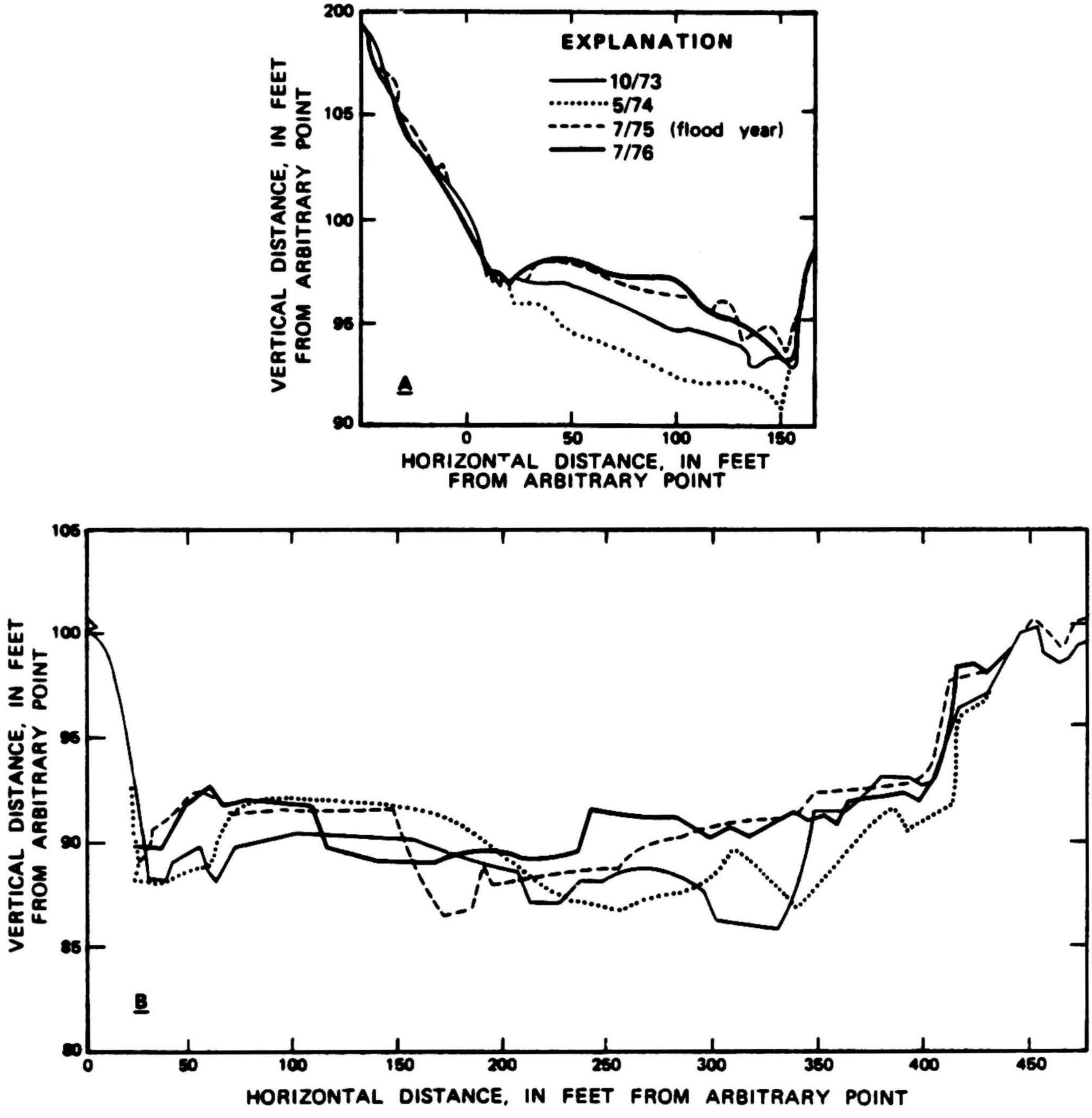


FIGURE 9. — Recent changes in stream-channel geometry along Redwood Creek. A. Mouth of gorge near southern boundary of park (1973 channel probably reflects aggradation during winter of 1971-1972); B. "Canoe Crossing Flat" downstream from mouth of Harry Wier Creek (Overbank deposition took place only in March 1975).

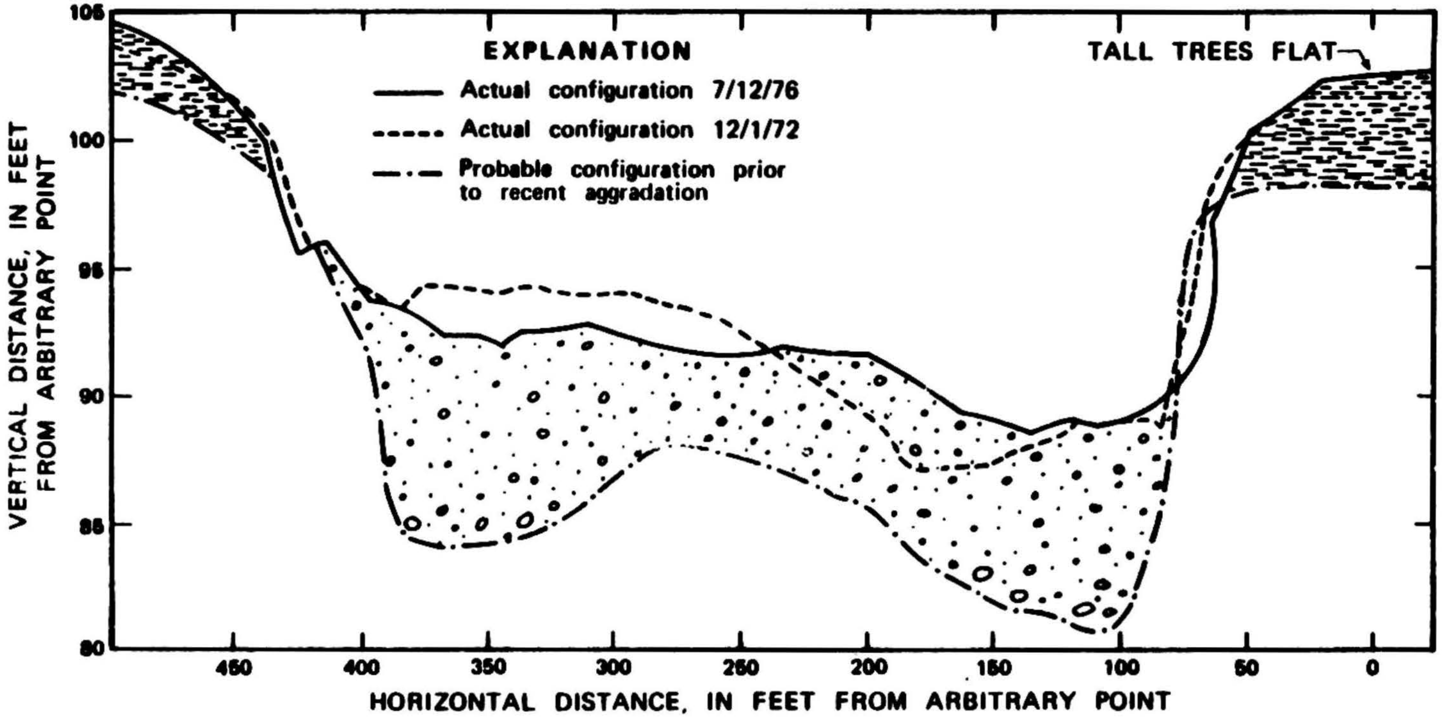
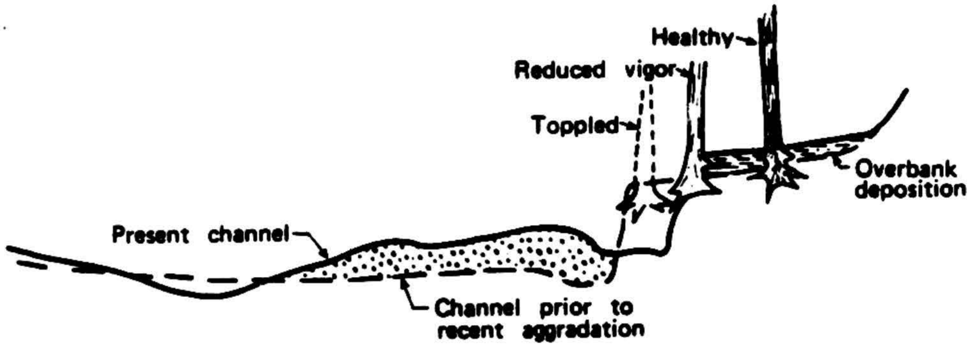
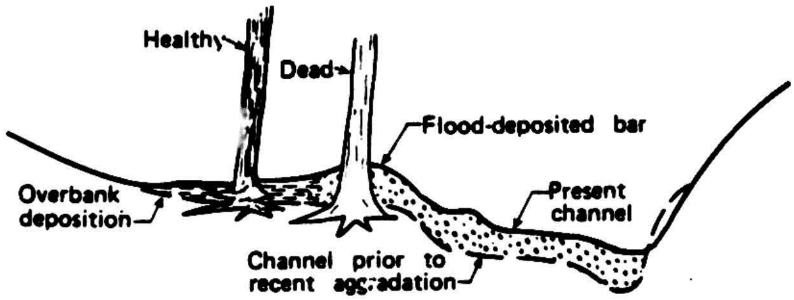


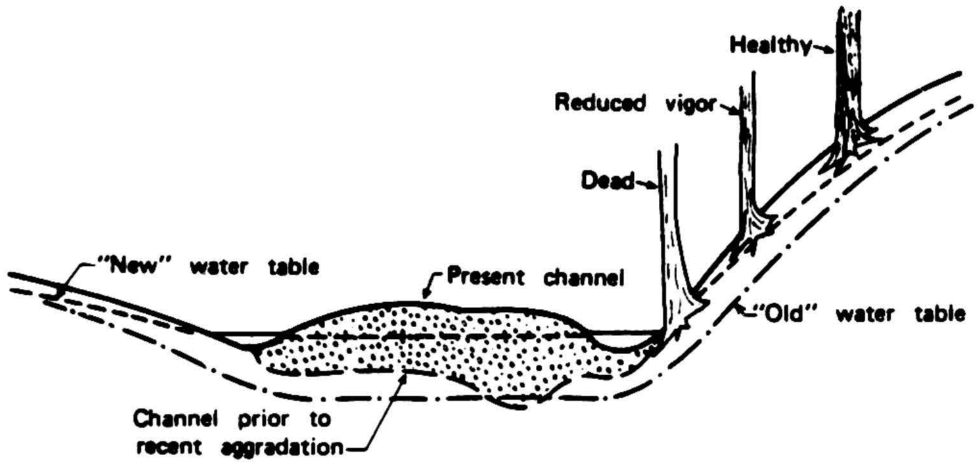
FIGURE 10.– Recent changes in stream-channel geometry at Tall Trees Flat near the mouth of Tom McDonald Creek.



A. Impact of streambank erosion



B. Impact of burial by coarse-grained (abrasive, "drought-fickle") sediment



C. Impact of higher streamside water table

FIGURE 11. — Schematic representation of some adverse impacts of recent channel geometry changes on streamside vegetation.

Large patches of bark and cambium have been stripped from some of the more exposed trees.

The frequency of floodflows capable of damaging streamside vegetation has increased in recent years because of a combination of (1) more frequent, prolonged, and severe storms, (2) man-induced increases in stream runoff (Lee and others, 1975), and (3) an apparent reduction in the channel's capacity to transmit floodwaters. Man's manipulation of Redwood Creek drainage basin has apparently increased runoff from storms associated with moderate antecedent moisture conditions more than runoff from storms with high antecedent moisture conditions (Lee and others, 1975); thus, man may have increased the frequency of stream discharges capable of interacting with streambank vegetation, but probably did not significantly increase the magnitude or frequency of major overbank flooding. Recent aggradation, despite a concomitant increase in channel width and a probable decrease in channel roughness, has probably reduced the capacity of some parkland reaches of Redwood Creek to retain flood discharges within the streambanks[2/].

2/ Along many northwestern California rivers recent pronounced aggradation typically has altered the hydraulic geometry at stream-gaging stations so that a given stream discharge is now associated with larger widths and higher velocities but shallower depths than previously (Knott, 1971, 1974; Janda and others, 1975A, p. 253). The increase in velocity appears to reflect burial of coarse channel-roughness elements rather than an increase in channel slope.

Two lines of indirect evidence suggest that man's activities may have increased Redwood Creek's load of coarse woody debris. Streambank exposures of prehistoric floodplain deposits rarely show concentrations of coarse woody debris. Moreover, a large proportion of the coarse woody debris that is either scattered about Redwood Creek's gravel plain or concentrated along its margins shows sawn ends and (or) logging cable scars.

The apparently unusually large and extensive damage associated with the recent floods is intriguing, because although closely comparable flood-producing storms are known to have occurred in the late nineteenth century, they apparently were not as damaging as the recent flood-producing storms. Measured amounts of storm precipitation, antecedent moisture conditions including snow accumulations at higher altitudes, and observed stages on nearby rivers indicate that under similar basin conditions the major storms of 1861 and 1890 probably would have produced flood peaks and volumes quite comparable to, or even larger than, those associated with the major floods that occurred since 1953 (Deborah R. Harden, written commun., 1977). Newspaper accounts and the distribution of even-aged stands of young trees on landslide scars and flood deposits (Helley and La Marche, 1973) indicate that the late nineteenth-century floods were locally quite damaging. However, comparisons of 1936 and 1947 aerial photographs with comparable photographs taken after the recent floods suggest that within the Redwood Creek basin the recent floods initiated or enlarged many more streamside landslides than the late nineteenth century floods (Nolan and others, 1976A). Additionally, massive aggradation following the 1964 flood along Redwood Creek upstream from highway 299 killed numerous streamside trees that were more than 250 years old. The death of these trees indicates that the erosion and sedimentation impacts of the 1964 flood far exceeded those of the late nineteenth-century floods. The capacity of the basin to resist flood-induced erosion may well have been reduced by recent changes in land use.

Along the parkland reaches of Redwood Creek, tanoak, hemlock, and Douglas-fir appear less tolerant of battering, burial, and elevated water tables than redwood. Some streamside redwoods, however, have been killed and others are in a state of declining vigor. Most of the killed trees are young trees growing at the outer edge of the flood-plain forest, but some are several centuries old.

The aquatic habitat now appears incapable of supporting as large or as diverse a population of organisms as it once did because recent aggradation and channel-geometry changes resulted in filling of summer rearing pools, burial of stable substrates such as bedrock blocks and large logs, and more frequent shifting of the gravel stream-bed materials. Additionally, bank erosion and timber harvest have removed shade-providing streamside vegetation. The intra-gravel habitat along lower Redwood Creek is also inferior because much silt and fine sand have been deposited in the matrix of the stream gravels. These fine sediments tend to impregnate the gravel and, thereby, to impede construction of redds by spawning fish, emergence of fry, and exchange of intragravel and surface waters. The degree to which these fine-sediment-impregnated gravels reflect recent changes in drainage basin conditions, however, is unknown.

Some park resources associated with tributaries to Redwood Creek appear also to have been modified by the recent combination of major storms and land-use changes. These tributary resources like those along Redwood Creek itself play important roles in the overall aquatic ecosystem. These tributaries all show steep irregular gradients with numerous barriers and cascades formed by wind-toppled trees and landslides. Floodplains are lacking along most of these tributaries; even along the downstream ends of the larger tributaries, floodplains are narrow and discontinuous. Large redwoods do occur locally in and adjacent to the streams. Some of the most photogenic scenes within the Redwood Creek unit are found along these tributaries. The roots and lower trunks of many streamside trees, as well as the trunks of many toppled trees have been polished and sculptured into bizarre shapes by long repeated contact with sediment-laden water. Other toppled trees have served as nurse logs for seedling trees. Much of the streamside landslide debris is covered with dense mats of ferns and moss. The overall visual effect obviously is pleasant to many people, probably because of the diverse combination of vegetation, light and shadow, water, soil, and rock.

Vegetation and woody debris in and adjacent to these tributaries exert major control on their character. Shade, organic detritus, and stable substrates are provided for aquatic organisms, sediment from upslope and upstream areas is trapped and stored, and stream velocity is moderated. Some trees and accumulations of coarse woody debris buttress stream banks and lessen erosion, whereas other similar accumulations deflect the stream current and cause streamside landsliies.

From the point of view of the overall aquatic ecosystem of Redwood Creek, the tributaries are an important source of food; they also provide cool water in summer, and shelter during freshets for fish that live primarily in the main channel. The natural barriers along all the parkland tributaries except Bridge Creek and Tom McDonald Creek prevent anadromous fish from using all but the most downstream parts of these streams. An interesting and diverse fauna of benthic invertebrates and amphibians, as well as a limited number of resident trout, however, live in these streams. Rooted plants are virtually absent, and periphytic algae are not abundant, except where natural breaks in the canopy or logging allow greater than normal light to reach stream surfaces. Therefore, most of the energy and food for the lower trophic levels of organisms that live in these streams come from fine-grained terrestrial organic detritus (for example, decomposing needles and leaves) rather than intra-aquatic sources.

All but the most obvious recent modifications of park resources are far more difficult to document along parkland reaches of tributaries than along Redwood Creek itself because large segments of most tributaries are and have been historically obscured on aerial photographs by the forest canopy. However, a combination of (1) aerial photograph interpretation, (2) repeated surveying, photographic, and visual observations over the last 8 years, and (3) comparisons between closely-spaced, geologically and physiographically similar drainage basins that are in different phases of the harvest-regeneration cycle suggest that although significant modifications have taken place, the modifications along the parkland reaches of tributaries are of more variable and generally lesser magnitude than along Redwood Creek. Apparently recent modifications observed along some tributaries include widespread streambank erosion, toppled streamside vegetation, increased numbers of small streamside landslides, filled pools, burial of coarse woody debris and vegetation by fine gravel, deposition of prominent layers of brownish silt and fine sand in unfilled pools, decreased availability of fine organic detritus, decreased stability of streambeds, and deposition of backwater berms and sidestream deltas at the tributaries mouths. These changes, in turn, have decreased the number and types of aquatic organisms that can inhabit these streams. Tributaries draining areas that have recently been heavily harvested display more prominent modifications than tributaries draining less intensively harvested areas.

The principal park resource on hillslopes well away from Redwood Creek and its major tributaries is the forest itself. Much of this forest is difficult for the average park visitor to traverse without trails but it provides valuable watershed protection, wildlife habitat, and pleasing vistas from high visitor-use areas. The principal causes of concern in these hillslope areas are the upslope enlargement of streamside landslides within the park, downslope propagation of landslides triggered beyond the park boundary, reactivation of old slides within the park by increased runoff from upslope cutover land, and certain "edge effects" at borders of recent timber-harvest units at the park boundary. These edge effects include fire, windfall, slope wash, debris flows, erosion and deposition associated with small ephemeral streams, and increased summer air temperatures and light intensities on the forest floor. To date, field observations indicate that only fire and accelerated erosion and deposition along some ephemeral draws have caused noteworthy modifications of park resources. In the autumn of 1974, a small fire that started during felling of timber near the park boundary spread a short distance into previously cutover land within the park.

The amount of erosion and deposition associated with ephemeral draws that flow from recent timber-harvest units into the park varies tremendously from draw to draw. Differences in the amount of erosion and deposition depend upon local differences in rock and soil type, depth of natural incision, the manner in which the draws interact with cableways, and bulldozer-constructed layouts and fire breaks, and upslope modifications of natural drainage patterns. Some of the ephemeral draws draining recent cable-yarded timber-harvest units at the park boundary appear unmodified, whereas others have deposited greater amounts of poorly sorted fine gravel and brownish mud within the park than have comparable streams draining uncut units along the boundary. Some accentuated channel erosion also appears to have taken place below some of the cable-yarded patch cuts on the park boundary. These changes in channel characteristics have modified the physical appearance of the forest floor and destroyed a few young trees and a small amount of groundcovering vegetation. However, transportation of unnatural mineral sediment and organic debris over the forest floor and along shallow draws into the park is generally restricted by low volumes and depths of storm runoff and the relatively rough and permeable forest floor. Similarly, incision is generally localized by abundant trees and coarse organic debris in and on the forest floor. Moreover, observations along the ephemeral channels in the southwestern part of the park during the winters 1974-75 and 1975-76 indicate that much of the sediment eroded from upslope tractor-yarded timber harvest units was at least temporarily stored among the slash within the cable-yarded units adjacent to the boundary. However, the future effectiveness of these cable-yarded units in buffering the park could be diminished if proposed upslope road construction and tractor-yarded timber harvest increase sediment yields to the extent that the storage capacity of these units is exceeded. Similarly, increased storm runoff could cause channel enlargement and decrease the stability of the slash debris dams.

THE REASONS FOR RECENT MODIFICATIONS OF PARK RESOURCES.

Most recent modifications of park resources are related to changes in stream channel and floodplain morphology and sediment type which in turn appear to have been caused by both short-lived episodes of storm-induced erosion and more persistent increases in storm runoff, suspended-sediment concentration, suspended-sediment discharge, and bedload discharge. The recent sequence of major storms would undoubtedly have caused some of the observed modifications of park resources even if no recent timber harvest had occurred within the basin. For example, conspicuous gravelly alluvial fans were deposited in 1972 and 1975 on the floodplain of Redwood Creek by Hayes Creek, a stream with a 0.58-square-mile drainage area mantled entirely by redwood-dominated old-growth forest except for 15 acres in its headwaters that were logged in 1962. Recent modifications are, nonetheless, larger and more prevalent along those tributaries and main channel reaches of Redwood Creek that have been subjected to recent large scale, tractor-yarded clearcut timber harvest. This mode of logging appears to have seriously altered both rainfall-runoff relations and stream-sediment regimes.

INCREASED STORM RUNOFF.

Three lines of evidence suggest that recent changes in land use within the Redwood Creek basin, particularly large-scale tractor-yarded clearcut timber harvest have significantly increased storm runoff volumes over those that would occur under pristine conditions--(1) a standard computer generated rainfall-runoff model, (2) synoptic measurements at seven tributary monitoring sites during nine storm periods, and (3) differences in water chemistry during runoff periods. These findings are compatible with hydrologic principles recently reinforced by results from paired watershed experiments in the Pacific Northwest (Harr, 1976).

A standard rainfall-runoff model applied to Redwood Creek runoff measured at Orick and rainfall measured at Prairie Creek State Park (Lee and others, 1975) suggests that a recent approximately 20-percent increase in average annual basin-wide runoff occurred at a time of particularly intensive timber harvest in the central and upper parts of

Redwood Creek basin. This model also suggests that runoff for individual storms associated with moderate antecedent moisture conditions was increased several times more than the total annual runoff, whereas runoff for storms associated with exceptionally low or high antecedent moisture was changed hardly at all. Thus, recent timber harvest may have increased the frequency with which Redwood Creek interacts with its banks, but probably did not change the frequency of overbank flooding for a fixed channel configuration.

Synoptic measurements at seven tributary monitoring sites during nine storms of low to moderate intensity (Table I) indicate that the recently harvested basins of Harry Wier Creek and Miller Creek typically produce several times more storm runoff, and show significantly higher runoff-precipitation ratios, than the geologically similar but relatively unharvested basin of Hayes Creek. Comparisons between storm runoff from the drainage basins of Lost Man Creek and Geneva Creek, which were harvested more than 10 years ago, with runoff from the geologically similar but relatively unharvested basin of Little Lost Man Creek, give similar results (Table I). Some apparent anomalies exist in these data; the most notable are exceptionally high runoff from Little Lost Man Creek during events I and IV and from Harry Wier Creek during event IV, and exceptionally low runoff from Miller Creek during event III. Nonetheless, the overall body of data is compatible with these observations. Some of the greater amounts of storm runoff from harvested basins can be accounted for by greater precipitation within those basins (Janda and others, 1975B), but the difference in

TABLE 1. *Water and suspended-sediment discharge for synoptically studied stream-monitoring sites during nine intensively sampled storm events*

[Numbers above the diagonal line are suspended-sediment discharges expressed in tons per square mile of drainage area. Numbers below the diagonal line are related to water discharge with the numbers outside of the parenthesis being the volume of storm runoff expressed in inches and the numbers within the parenthesis being the percentage of the storm precipitation that appeared as storm runoff. The synthesized record represents an estimate of the total suspended-sediment and water discharges for the 1975 and 1976 storm seasons computed from periodic mean daily values at the indicated stations and a continuous stream discharge record for Little Lost Man Creek. Rainfall values are expressed in inches]

Station name and No.	Synoptically sampled storm events									Synthesized record	Total rainfall 1975 and 1976 water years
	I	II	III	IV	V	VI	VII	VIII	IX		
Redwood Creek at South Park Boundary 11482200	210	12	51	163	-	0.6	120	239	11	- / -	-
Harry Wier Creek 11482225	130 / 1.1 (42)	5.8 / 0.3 (13)	2.4 / 0.1 (12)	7.2 / 1.0 (68)?	0.10 / .03 (2)	0.30 / .06 (5)	1.9 / 0.1 (10)	22 / 0.3 (18)	2.1 / .05 (6)	870 / 87	141
Miller Creek 11482250	86 / 1.2 (51)	4.6 / 0.3 (13)	3.0 / .01 (11)	4.1 / 0.3 (20)	0.14 / .05 (4)	2.0 / 0.1 (7)	2.6 / 0.1 (9)	14 / 0.4 (23)	2.6 / .05 (6)	670 / 99	140
Miller Creek at Mouth 11482260	170 / 0.9 (42)	3.7 / 0.2 (13)	4.6 / 0.2 (17)	8.9 / 0.3 (22)	0.13 / .05 (5)	2.0 / 0.1 (7)	5.8 / 0.1 (7)	70 / 0.4 (21)	1.5 / .05 (6)	1400 / 91	136
Hayes Creek 11482330	– / 0.5 (33)	0.2 / .03 (2)	0.6 / .01 (1)	1.3 / .05 (3)	0.00 / .01 (1)	0.00 / .03 (2)	0.1 / .02 (3)	1.0 / 0.1 (10)	0.39 / .04 (4)	80 / 50	132
Lost man Creek 11482450	33 / 1.1 (48)	– / – –	1.2 / 0.5 (5)	3.9 / 0.1 (9)	0.01 / 0.2 (2)	0.2 / 0.1 (7)	0.9 / 0.2 (17)	6.5 / 0.4 (31)	2.0 / 0.1 (11)	310 / 92	144
Little Lost Man Creek 11482468 & 11482470	19 / 1.8 (100)?	– / – –	0.6 / .01 (1)	1.2 / 0.2 (9)	0.00 / .02 (1)	0.1 / .04 (3)	0.3 / .07 (7)	2.5 / 0.2 (15)	0.40 / 0.1 (6)	150 / 83	135
Geneva Creek 11482475	4.8 / 1.1 (93)	– / – –	– / 0.3 (4)	1.8 / 0.4 (25)	– / – –	0.1 / 0.1 (9)	0.2 / 0.1 (15)	0.7 / 0.3 (28)	0.36 / 0.1 (13)	– / –	124

amounts of precipitation are much smaller than the differences in amount of runoff.

In keeping with the findings discussed in the two preceding paragraphs, comparisons of changes in the water chemistry of tributaries during synoptically sampled storm events (Iwatsubo and others, 1975 and 1977) suggest that recently clearcut tributary drainage basins produce more direct surface runoff and "quick return flow", and less subsurface flow than do unharvested basins (Dr. W. L. Bradford, written commun., 1977). Harvested basins typically show more pronounced dilution of dissolved constituents than unharvested basins during peak discharge.

Field observations during synoptically sampled storm events suggest that increased runoff from harvested basins reflects increases in the size of areas of surficial compaction and of seeps that substantially enlarge the partial drainage areas contributing to direct storm runoff.

INCREASED SUSPENDED-SEDIMENT DISCHARGE

In addition to Anderson's (1976) previously discussed statistical analysis of suspended sediment discharge records for Redwood Creek at Orick, at least three additional lines of evidence suggest that recent changes in land use, particularly large scale, tractor-yarded clearcut timber harvest, have increased the suspended-sediment discharges of Redwood Creek and its tributaries over what those discharges would have been under pristine conditions. The increases are substantial and persistent.

The additional lines of evidence are as follows:

1. Downstream changes in suspended-sediment discharge as observed at six stations along the main channel of Redwood Creek in relation to changes in potential natural and man-induced sediment sources.
2. Suspended-sediment discharge relations developed from periodic measurements at 26 sites along Redwood Creek tributaries displaying a wide variety of drainage basin characteristics.
3. Suspended-sediment discharge relations developed from periodic measurements and nine periods of intensive synoptic sampling at seven Redwood Creek tributary sites selected to hold drainage basin parameters other than extent and type of recent timber harvest relatively constant.

Main Channel Suspended-Sediment Discharge

Downstream changes in suspended-sediment discharge along Redwood Creek can be viewed from three different perspectives -- (1) comparisons between annual suspended-sediment discharges at two recording gaging stations near highway 299 (near Blue Lake) and at Orick, (2) comparisons between suspended-sediment discharge at six sites along Redwood Creek between highway 299 and Orick during the storm of February 25 through 27, 1976, and (3) comparisons between regression-adjusted mean suspended-sediment discharges at these same six sites. Comparisons between discharges at different sites appear more instructive if they are made on a per-unit-area basis rather than on an absolute basis. The locations and some significant drainage basin characteristics of all 6 sites are summarized in tables in Iwatsubo and others (1975, 1977). The geographic distribution and recent development of major erosional landforms in the Redwood Creek basin is portrayed by Nolan and others (1976A); selected aspects of recent timber harvest in the basin are shown by Harden (1977). These maps show that landsliding is particularly prevalent in the upstream parts of the basin, and that most recent intensive timber harvest is concentrated in the downstream parts of the basin.

Comparisons between annual suspended-sediment discharges[3/] at Redwood Creek near Blue Lake, the upstream-most station, and Redwood Creek at Orick, the downstream-most station, indicate that despite downstream decreases in prevalence of landslides as well as downstream reductions in average hillslope and channel gradients, suspended-sediment discharges on a per-unit-area basis remain high throughout the basin. A significant proportion of the recent suspended-sediment discharge, therefore, must be derived from sources other than presently active landslides. During the first 3 years of concurrent record (1973 through 1975) Redwood Creek near Blue Lake

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3/ Annual suspended-sediment discharges are computed from continuous records of stream discharge and suspended-sediment samples collected at least once a day, and more frequently during times of rapidly changing discharge.

consistently discharged on an annual per-unit-area basis slightly more suspended sediment than Redwood Creek at Orick, but the difference was significant only during the 1974 water year. Under the exceptionally dry conditions that prevailed during the 1976 water year, Redwood Creek at Orick transported only 36 percent of its 6-year average annual suspended-sediment discharge; however, on a per-unit-area basis, more than twice as much suspended sediment was transported past the station at Orick during the 1976 water year as past the station near Blue Lake.

In making similar comparisons of suspended-sediment discharges along Redwood Creek, timber company consultants (Winzler and Kelly, 1975; Ficklin and others, 1977; Wooldridge, 1977) have emphasized that suspended-sediment concentrations and discharges well upstream from most current timber harvest operations are equal to or perhaps even higher than suspended-sediment concentrations and discharges at Orick. Although this is true, the high suspended-sediment discharge from the headwaters of Redwood Creek is not derived primarily from natural sources. Quite to the contrary, aerial and ground observations indicate that resource-management actions in areas upstream from Redwood Creek near Blue Lake, including construction of Highway 299 and numerous timber and ranch access roads, timber harvesting during the 1950's and 1960's, and attempted conversion of forest to pasture, have initiated major and persistent erosion problems.

The two other perspectives for viewing downstream changes in suspended-sediment discharge, total suspended-sediment discharge for the period February 25 through 27, 1976[4/], and comparisons of regression-adjusted mean instantaneous suspended-sediment discharges for the period 1974 through 1976[5/], are applicable to six sites along the main channel of Redwood Creek, and therefore permit more precise recognition of potential sources of suspended-sediment discharge than comparisons of annual suspended-sediment discharges for stations near Blue Lake and at Orick.

4/ These values were obtained through synoptic measurements by six field crews stationed at three nonrecording stations at Redwood Valley Bridge, near Panther Creek, and above Harry Wier Creek, as well as at three continuously recording stations near Blue Lake, at the Southern Park Boundary, and at Orick.

5/ The regression-adjusted mean instantaneous suspended-sediment discharges were computed on a per-unit-area basis from an analysis of covariance for linear regressions developed from logarithmic transformation of instantaneous water and suspended-sediment discharges (K. M. Nolan, written commun., 1977).

Both sets of data suggest that the drainage area between the gaging station near Blue Lake and the Redwood Valley Bridge is not a major source of suspended-sediment discharge although that area has had an exceptionally active and complex recent history of landsliding (Nolan and others, 1976A). The central part of the Redwood Creek drainage basin between the Redwood Valley Bridge and the station upstream from the mouth of Harry Wier Creek appears to be the area that contributes on a per-unit-area basis the greatest amount of suspended sediment to Redwood Creek. This major source area has been subject to both widespread active landsliding (Nolan and others, 1976A) and extensive recent tractor-yarded timber harvest (Harden, 1977); timber harvest and road construction, particularly in streamside zones and in areas with a complex history of landsliding, have aggravated the naturally high erosion rate of this area. The part of the basin lying downstream from the station above Harry Wier Creek appears on the whole to produce, on a per-unit-area basis, exceptionally low suspended-sediment discharges. Extensive recent tractor-yarded timber harvest has occurred in this area, but the most erosionally-sensitive areas remain to be harvested. Additionally, the downstream part of the Redwood Creek basin, in comparison to upstream areas, has the largest proportion of intact old-growth and advanced second-growth forest (Iwatsubo and others, 1977) and the smallest extent of recently active landslides (Nolan and others, 1976A).

Tributary Suspended-Sediment Discharge

In order to sample a broad spectrum of different suspended-sediment discharge conditions in the vicinity of Redwood National Park, instantaneous suspended-sediment discharge measurements were obtained at 26 stations along tributaries to Redwood Creek under a wide range of hydrologic conditions, but with greatest emphasis placed on sampling during high runoff when most erosion occurs in this basin. The physical characteristics of all tributary drainage basins included in this aspect of our study are summarized in tables contained in Iwatsubo and others (1977). Seven drainage basins that have not been significantly impacted upon by recent timber harvest or road construction (High Slope Schist Creek, Gans South Creek, Gans West Creek, Low Slope Schist Creek, Hayes Creek, tributary to Lost Man Creek, and Little Lost Man Creek) were included in the sample in order to understand the natural variability in suspended-sediment discharge conditions. Additionally, seven drainage basins possessing generally similar physical characteristics but markedly different amounts of recent timber harvest were intensively and synoptically sampled throughout nine separate storm events in an attempt to isolate more precisely the potential impact of tractor-yarded timber harvest on suspended-sediment discharge.

Three lines of evidence developed from these data suggest that, although natural suspended-sediment discharges are exceedingly variable, suspended-sediment discharges from tributary drainage basins that have recently undergone extensive tractor-yarded clearcut timber harvest are many times greater than those from even unharvested tributary basins with particularly high natural suspended-sediment discharges. Again, the increases in suspended-sediment discharge after timber harvest are major and persistent. The three principal lines of evidence are the following:

1.) Comparisons of graphs of simultaneous determinations of instantaneous water and suspended-sediment discharge. In order to facilitate comparisons between drainage basins of diverse sizes, all of which experience at least a thousand-fold annual range in water discharge, logarithmic transformations of the data were plotted on a per-unit-area basis.

2.) Comparisons of regression-adjusted mean instantaneous suspended-sediment discharges for those streams where available data permit development of statistically significant linear regressions.

3.) Comparisons of suspended-sediment discharges for nine periods of synoptic sampling at seven tributary monitoring sites.

Graphs of logarithmic transformations of instantaneous water and suspended-sediment discharge of individual tributaries, when plotted on a per-unit-area basis, typically appear to consist of two linear segments with the high discharge segment being steeper and intersecting the lower discharge segment at a water discharge of about 12 cubic feet per second per square mile. Linear regressions were developed for the high steep limb of the relationships; this is the limb that describes conditions responsible for most of the total suspended-sediment transport from these basins. The regressions of only 15 tributaries, including three with relatively unharvested drainage basins, are significant at the 95 percent level. K. M. Nolan (written commun., 1977) has used an analysis of covariance to compute regression-adjusted mean suspended-sediment discharges for groups of statistically significant regressions. Regressions were grouped by holding a particular drainage-basin parameter, such as geologic setting or vegetal conditions, constant so that the possible role of other parameters in accounting for within-group differences in adjusted mean discharges could be investigated. Attempts to assign physical significance to comparisons between regression-adjusted mean suspended-sediment discharges should be tempered by the realization that this form of comparison purposely eliminates differences in mean suspended-sediment discharges that reflect solely differences in the observed ranges of water discharge. If differences in the observed ranges of water discharge reflect actual differences in drainage-basin parameters that control the magnitude of discharges of a constant frequency of occurrence rather than differences between discharges with different frequencies of occurrence, the observed differences in adjusted mean suspended-sediment discharges do not accurately reflect actual differences in suspended-sediment discharges.

One measure of the degree of natural variability in suspended-sediment discharge from streams draining the old-growth redwood-dominated forests of the lower Redwood Creek basin is provided by comparisons of regression-adjusted mean suspended-sediment discharges for the virtually unharvested basins of High Slope Schist Creek, Hayes Creek, and Little Lost Man Creek. The regression-adjusted mean for Hayes Creek is 1.8 times greater than the regression-adjusted mean of Little Lost Man Creek and 30.6 times greater than that of High Slope Schist Creek. These differences probably exaggerate the true differences in suspended-sediment discharge from these basins because High Slope Schist Creek and Little Lost Man Creek consistently yield, on a per-unit-area basis, greater water runoff than Hayes Creek.

Available data suggest that suspended-sediment discharges for Hayes Creek and Little Lost Man Creek are not anomalously low and that suspended-sediment discharges from these streams are actually somewhat higher than those from some other unharvested drainage basins in the lower Redwood Creek basin. Points representing simultaneous computations of instantaneous water and suspended-sediment discharge for Gans South Creek and Gans West Creek plot between the regression lines developed for High Slope Schist Creek and Hayes Creek. Low Slope Schist Creek and tributary to Lost Man Creek yield such exceptionally low amounts of water discharge that field crews have never measured discharges in excess of 12 cubic feet per second per square mile at these sites, even at times when adjacent streams have been yielding discharges considerably in excess of that amount.

Likewise, Miller Creek at its mouth appears not to yield anomalously high per-unit-area suspended-sediment discharges relative to other tributaries to Redwood Creek that have recently been intensively harvested. For example, data for Lacks Creek, Copper Creek, Bridge Creek, and Tom McDonald Creek generally cluster around or plot above the regression line computed from the Miller Creek data.

In any case, there is no reason to believe that contrasting the suspended-sediment discharges from Hayes Creek and Little Lost Man Creek with those from geologically similar, recently harvested basins of Harry Wier Creek and Miller Creek would tend to exaggerate the possible role of timber harvest in increasing erosion and suspended-sediment discharge.

Some contrasts between regression-adjusted mean suspended-sediment discharges for geologically similar drainage basins displaying contrasting amounts of recent timber harvest are quite striking and are statistically significant at the 95-percent level. Although considerable uncertainty may exist concerning the degree to which drainage-basin parameters other than the amount and type of recent timber harvest account for the observed differences in regression-adjusted mean suspended-sediment discharges, the striking fact is that the regression-adjusted means for recently harvested basins are consistently larger than those for unharvested basins. For example, in the case of streams draining the schist terrain on the western side of the lower Redwood Creek basin, the drainage basin of Tom McDonald Creek, which has had a long complex history of timber harvest, has a regression-adjusted mean suspended-sediment discharge that is 83 times larger than that of the unharvested basin of High Slope Schist Creek. The degree to which this difference reflects recent timber harvest is somewhat uncertain because Tom McDonald Creek is more deeply incised and displays more streamside landslides than High Slope Schist Creek. However, if the high suspended-sediment discharge is derived from steep, landslide-prone, but unharvested areas adjacent to Tom McDonald Creek, rather than from less steeply sloping but recently harvested land well away from the creek, that fact should be carefully weighed in planning any future harvest of the remaining old-growth in this basin in order to minimize the potential for harvest-accelerated erosion.

Similar contrasts can be made for streams draining the geologically complex terrain along the eastern border of the Redwood Creek unit of Redwood National Park. For example, the regression-adjusted means for the heavily-harvested drainage basins of Harry Wier Creek and Miller Creek near its mouth are respectively 1.9 and 3.5 times larger than that of the geologically similar but unharvested basin of Hayes Creek. Regression-adjusted means for Cloquet Creek and Oscar Larson Creek are associated with such large uncertainties that they are not statistically different from the adjusted means of any of the three previously-mentioned streams. Lost Man Creek, which was logged more than 10 years ago, has a regression-adjusted mean that is about 60 percent larger than that of the geologically similar but unharvested basin of Little Lost Man Creek; although this difference is small, it is statistically significant at the 95-percent level.

The contrasts between the regression-adjusted mean suspended-sediment discharges for Harry Wier Creek, Miller Creek at its mouth, and Hayes Creek greatly underestimate the actual differences in suspended-sediment discharge from these basins because Harry Wier Creek and Miller Creek consistently discharge, on a per-unit-area basis, more water than Hayes Creek (table 1). The differences in water discharge reflect differences in amounts of rainfall (table 1) and land use. A more realistic estimate of differences in suspended-sediment discharge is provided by the data collected during nine periods of intensive sampling at these sites. The most striking contrast is provided by the suspended-sediment discharges from the drainage basins of Miller Creek which was 77 percent harvested between 1969 and 1975, and Hayes Creek which is unharvested except for about 15 acres in its headwaters that were logged in 1962 During six intensively sampled storm periods Miller Creek transported from 3.9 to 70 times as much suspended sediment as Hayes

Creek on a unit-area basis; during two additional storm periods Miller Creek transported significant amounts of suspended sediment whereas Hayes Creek did not yield any detectable suspended sediment. A flow-duration analysis, based upon mean daily values of water discharge measured periodically at these sites and on the continuous record of water discharge at Little Lost Man Creek, suggests that during the 1975 and 1976 storm seasons Miller Creek transported about 17.5 times as much suspended sediment as Hayes Creek on a unit-area basis. The physiographic similarities between these two basins would not exist if the different rates of erosion implied by these different suspended-sediment discharges persisted long; recent timber harvest probably accounts for a substantial part of the observed difference.

Another instructive contrast is provided by suspended-sediment discharges from the geologically similar drainage basin of Lost Man Creek, 87 percent of which was harvested more than 10 years ago, and Little Lost Man Creek, of which only 6 percent has been harvested. Data in table 1 suggest that suspended-sediment discharges for Lost Man Creek are more than two times as large as those for Little Lost Man Creek. This contrast probably reflects in part the persistent erosional impact of timber harvest that took place prior to the establishment of the Park. The 0.08-square-mile drainage basin of Geneva Creek, which was also completely harvested more than 10 years ago, yields exceptionally low suspended-sediment discharges (table 1). However, this small basin, which displays little stream incision and an exceptionally dense stand of second-growth forest, is not as representative of typical regenerating tracts of second-growth forest as is the Lost Man Creek basin.

Indeed, the drainage basin of Berry Glen Creek, which entirely drains second-growth forest and which very nearly adjoins the Geneva Creek basin, has the highest computed regression-adjusted mean suspended-sediment discharge of any sampled tributary to Redwood Creek.

The Role of Tributaries in Supplying Suspended Sediment to Redwood Creek.

To assess the relative importance of tributaries in supplying suspended sediment to Redwood Creek, one must first appreciate some of the intricacies involved in routing sediment through a complex drainage basin, including the degree to which hillslope erosion, sediment transport, and stream channel geometry are influenced by extreme flood events. An assessment based merely upon data shown in table 1 and similar data presented by Winzler and Kelly (1975) and by Ficklin and others (1977) can be quite misleading.

Sequences of aerial photographs, stream gaging-station records, and observations of long-time residents of the area suggest that the relative importance of tributaries as direct sources of sediment for Redwood Creek is different during major floods than during discharges of lesser magnitude. During flows of low and moderate magnitude, a substantial amount of the sediment eroded from hillslopes and ephemeral channels is transported relatively short distances before it is deposited and temporarily stored behind small check dams comprised of natural woody debris and logging slash located lower on the hillslope or along small tributary channels; landslide barriers along some streams provide additional storage. Under these conditions, the larger tributaries and the main stream rework or even scour the alluvium previously deposited in and adjacent to their channels. In contrast, during extremely high flows much of the sediment previously deposited in temporary storage areas on hillslopes and in ephemeral channels and small tributaries is scoured out and delivered to the larger streams. Moreover, streamside landslides tend to be initiated in greater numbers during these events than under lower discharge conditions. Tributary scour and streamside sliding deliver more sediment to the larger channels than they can effectively transport. Thus, these major storms are typically times of channel aggradation along the larger streams (Hickey, 1968; Janda and others, 1975a; Kelsey, 1977). The important thing to note in this scheme of things is that during extreme floods much tributary-derived sediment is deposited along the larger channels, where it is a potential source of sediment in following years.

The impact of the major channel-modifying floods on suspended-sediment discharges is both immediate and of long duration. Particularly vivid examples/ are provided by the Eel River at Scotia and the Mad River at Arcata during the December 1964 flood. In 10 days of severe flooding between December 21 and 30, 1964, the Eel River transported about 145 million tons of suspended sediment past the town of Scotia--a load that is about 1.5 times the total suspended-sediment discharge of the Eel River over the entire preceding 7 years (Brown and Ritter, 1971). The suspended-sediment discharge for the Mad River at Arcata from December 18 through 31, 1964 was estimated to be about 10 million tons or approximately / seven times the average total annual suspended-sediment discharge for the 5-year period 1958 to 1962 (Rantz, 1965). The short-term record from Redwood Creek at Orick provides somewhat less dramatic examples; here, in just two days, March 18 and 19, 1975, Redwood Creek was observed to transport 1,324,000 tons of suspended sediment, which is equivalent to

64 percent of the 6-year average total annual suspended-sediment discharge at this site.

The long-term effects of the channel-modifying floods on suspended-sediment discharge are facilitated by increasing the amount of readily erodible sediment in and immediately adjacent to the stream channels. The significance of this effect is shown by the fact that, for a given stream discharge, suspended-sediment discharges immediately following the 1964 floods were two to five times greater than they were immediately prior to the floods. This impact persisted for several years. The effect has been observed in suspended-sediment discharge records collected throughout northwestern California (Anderson, 1970; Brown and Ritter, 1971; Knott, 1971, 1974; Brown, 1973, 1975).

Data in table 1 do not include an example of a major channel-modifying storm, it is, nonetheless, interesting to note that during nine intensively-sampled periods of low to moderate discharge the studied tributaries, even those draining heavily-harvested drainage basins, generally transported less suspended sediment, on a per-square-mile basis, than Redwood Creek at the Southern Park Boundary. Timber company consultants (Winzler and Kelly, 1975; Ficklin and others, 1977; Winzler, 1977; Wooldridge, 1977) have placed great emphasis on these findings, and particularly on the contrast in suspended-sediment discharge between

Miller Creek near its mouth and Redwood Creek at the Southern Park Boundary. In assessing the relative importance of tributary streams as sources of suspended sediment for Redwood Creek, this contrast in suspended-sediment discharge should be considered in conjunction with (1) the striking contrasts in water and suspended-sediment discharge between harvested and unharvested tributaries, as presented earlier in this Statement, and (2) the possibility that increased water and sediment runoff causes channel adjustments and erosion at sites well downstream from the initiating disturbance (Janda and others, 1975a, p. 256-257). Moreover, the ratio between the suspended-sediment discharge of individual tributaries and that of Redwood Creek varies considerably from storm to storm. Therefore, all available data should be considered in order to appreciate fully this variability and to estimate what conditions may prevail during major floods that are most likely to damage park resources.

The storm-to-storm variability in the importance of tributaries as suspended-sediment sources is well illustrated by the ratio between suspended-sediment discharge for Miller Creek near its mouth and that for Redwood Creek at the Southern Park Boundary during eight different storm periods (table 1). This ratio was as low as 0.05 during two storms (Storms IV and VII), but it was as high as 3.33 during one minor storm (Storm VI). During a more significant storm in November 1973 (Storm I), the ratio was 0.81. The November 1973 storm accounted for 64 percent of the total suspended sediment transported by Miller Creek during the eight periods of intensive sampling for which simultaneous data are available for both stations.

Attempts to place some limits on sedimentation conditions during infrequent, high-magnitude floods by extrapolating existing data to higher discharge conditions seems warranted because the extreme flood events have such a profound influence on stream-sediment regimes and channel configurations. Linear regressions describing relationships between suspended-sediment discharge and water discharge at 6 sites along Redwood Creek and 15 sites along tributaries, on a per-unit-area basis, suggest that the rate of increase in suspended-sediment discharge with increasing water discharge is consistently greater in the tributaries than along Redwood Creek itself. Therefore, at higher discharges the tributary and main channel relationships converge or even intersect (fig. 11). This form of extrapolation probably does not seriously misrepresent actual high discharge conditions because small streams for which high discharge data are available, such as Lost Man Creek, Little Lost Man Creek, and Mill Creek, do not show any tendency for the rate of increase in suspended-sediment discharge to decrease with increasing discharge, although such a tendency has been observed at some stations along Redwood Creek itself. The relationships for heavily-harvested tributaries tend to intersect the relationships for Redwood Creek at discharges that are likely to occur several times in any given decade. In contrast, the unharvested tributaries operate at such low levels that suspended-sediment transport relations tend to intersect those of Redwood Creek only at discharges that occur exceedingly rarely if at all. The existing data, therefore, can be used to infer that during major stream-sedimentation events the tributaries may indeed be major

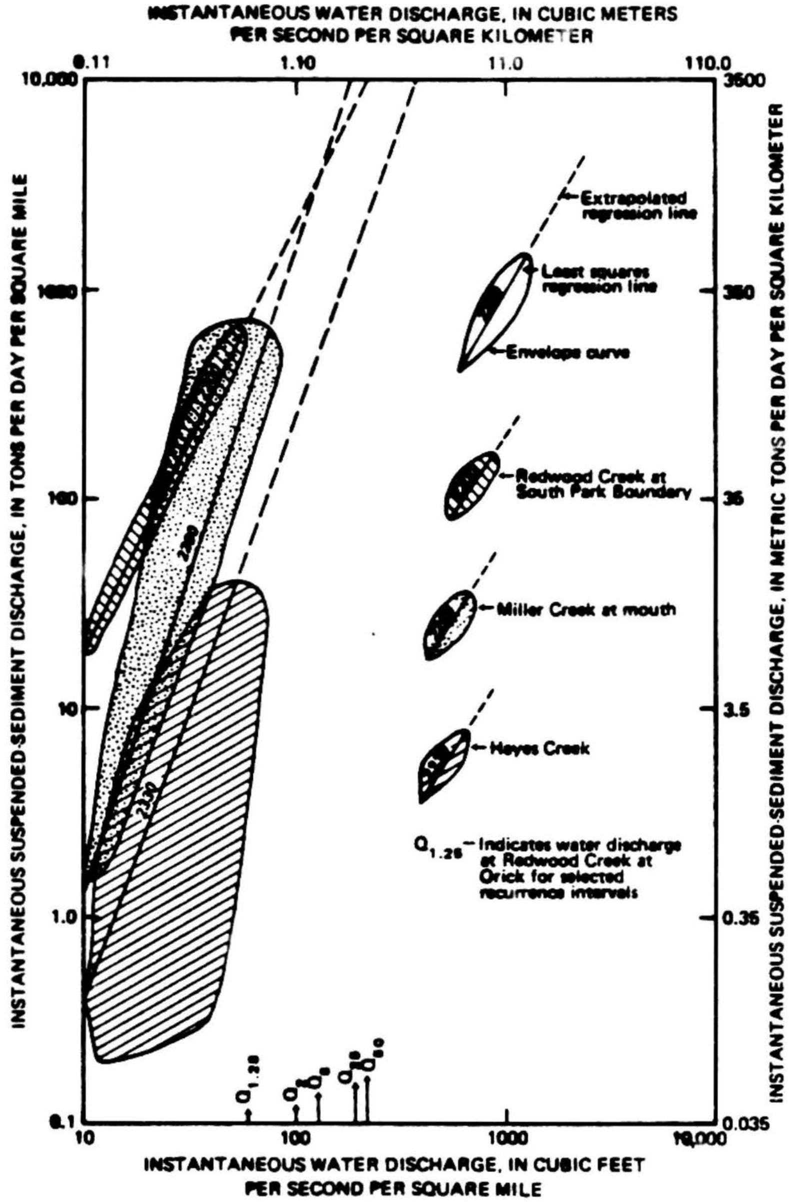

FIGURE 11. Sediment transport relationships Redwood Creek at South Park Boundary, Miller Creek at Mouth, and Hayes Creek showing envelope curves around actual data points and extrapolation of developed relations. The magnitude of floods of a given recurrence interval when expressed on a per unit area basis are commonly inversely related to drainage area. Therefore, the recurrence interval of a given per unit area discharge may be considerably less for small tributaries than for Redwood Creek at Orick and the sediment transport relationships may intersect more frequently than suggested by the recurrence intervals for just the larger streams.

contributors of suspended sediment to Redwood Creek, and that the heavily-harvested tributaries contribute many times more suspended sediment to Redwood Creek than the unharvested tributaries.

BEDLOAD DISCHARGE

The timing and amounts of recent changes in stream channel configurations discussed earlier in this testimony imply that the frequency and magnitude of bedload discharge have recently increased. Since 1973 these changes in streambed configuration have been documented through repeated surveys of monumented stream-channel cross sections at 50 sites along Redwood Creek and at 90 sites along tributaries. Earlier changes can be documented through comparisons of sequential aerial photographs, stream gaging-station records, and burial or excavation of definitive reference points such as bridges, prominent rock outcrops, and trees. Changes in streambed configuration appear to be more frequent and more conspicuous along recently-harvested tributaries than along unharvested tributaries.

Bedload discharge is more difficult to determine directly than suspended-sediment discharge because measurement procedures are tedious and time consuming, and because bedload movement is exceedingly erratic. Streambed materials commonly move in dunelike forms and, even when the streambed is reasonably planar, prominent surges in movement occur. Closely spaced samples often imply drastically different bedload transport rates. Relationships between instantaneous bedload discharge and instantaneous water discharge, on a per-unit-area basis, typically show a wide scatter. Linear regressions describing relations for six monitoring sites along Redwood Creek and five intensively studied tributary sites have low coefficients of determination and wide confidence limits; the regressions are, nonetheless, statistically significant at the 94-percent or higher levels. Data used to develop these relations are contained in either Iwatsubo and others (1975, 1977) or U.S. Geological Survey (1976, 1977). In spite of these difficulties, efforts to determine times and rates of bedload discharge are needed in order to increase our understanding of a phenomenon that accounts for a significant amount of the total sediment transport in the Redwood Creek basin and that has historically severely modified many park resources.

Absolute amounts of bedload transport and the ratio between bedload and total load differ significantly from time to time and place to place in the basin. Direct measurements at gaging stations near Blue Lake and at Orick indicate that during the 1974, 1975 and 1976 water years the total annual bedload discharge accounted for between 31 and 14.5 percent of the total load near Blue Lake and between 14 and 8 percent of the total load at Orick. J. M. Knott (written commun., 1975) has estimated, on the basis of sediment data collected during 1973 through 1975 and water flow duration data for 1954 through 1975, that long-term average bedload discharges for Redwood Creek at stations near Blue Lake, at South Park Boundary, and at Orick are 256,000, 421,000, and 182,000 tons per year, respectively. These bedload values account for 33, 28, and 10 percent of the estimated long-term average total sediment discharge near Blue Lake, at South Park Boundary, and at Orick, respectively. The concept that 57 percent less bedload moves past Orick than past the Southern Park Boundary is wholly compatible with the marked stream channel aggradation noted along the parkland reaches of Redwood Creek. Because about 6 million tons of streambed materials is now in storage along the main channel of Redwood Creek, over and above what was present in 1964, Knott's estimates also suggest that, even under ideal circumstances, Redwood Creek will probably not be able to return to its pre-1964 configuration for considerably more than 15 years.

Field observations indicate that bedload discharge occurs much more frequently and persistently along Redwood Creek than along its tributaries, and that bedload discharge is more frequent and voluminous along those tributaries with heavily harvested drainage basins than along those draining intact old-growth forest. Stream-discharge thresholds for initiation of bedload movement appear to fall between 9 and 13 cubic feet per second per square mile for recently harvested basins and between 22 and 31 cubic feet per second per square mile for unharvested basins. Although bedload transport was frequently observed along streams with recently harvested drainage basins, measured bedload discharges are sufficient to allow comparisons between transported bedload volumes for different streams to be made for only two storm periods (table 2). No bedload movement occurred in the unharvested basins during these storms, whereas in the harvested basins bedload accounted for between 5 and 50 percent of the total sediment load. Statistically significant linear regressions could be fitted to the bedload discharge versus water discharge relationships at six sites along Redwood Creek and at five tributary monitoring sites. As in the case of suspended-sediment discharge, comparisons of these bedload relationships, when made on a per-unit-area basis, suggest that the rate of increase in bedload discharge with increasing water discharge is

TABLE 2. *Bedload discharges and total sediment discharges for six synoptically studied stream monitoring sites for two intensively sampled storm periods*

[Numbers above the diagonal line are bedload discharges; numbers after the diagonal line are total sediment discharges (that is, bedload plus suspended load). All data are presented as tons per square mile of drainage area]

Station name and number	Synoptic III	Synoptic VIII
Harry Wier Creek 11482225	0.4/2.8	4.21/26.2
Miller Creek 11482250	0.15/3.15	4.10/18.1
Miller Creek at Mouth 11482260	1.5/6.1	13.17/83.2
Hayes Creek 11482330	0/0.6	0/1.0
Lost Man Creek 11482450	-	6.39/12.9
Little Lost Man Creek 11482468 and 11482470	0/0.6	0/2.5

consistently greater along the tributaries than along Redwood Creek. Thus, even though Redwood Creek at low discharges transports more bedload than the studied tributaries, on a per-unit-of-drainage-area basis, at higher discharges the relationships are reversed. This reversal appears to occur at discharges that are low enough that they can be expected to occur at least once in any given year. Therefore, tributary streams may be major contributors to the bedload of Redwood Creek, even though they do not transport streambed materials as persistently as the main channel.

THE WAYS IN WHICH LAND-USE CHANGES HAVE AGGRAVATED THE PROCESSES THAT ACCOUNT FOR RECENT MODIFICATIONS OF PARK RESOURCES

The reasons why recently increased runoff and erosion in large part reflect land use can most graphically be observed through aerial and ground observations of the type and intensity of erosion in the affected areas. While these types of observations may not readily lend themselves to quantifying land-use impacts upon erosion, they are, nonetheless, essential in designing prescriptions to mitigate the problem. The accelerated erosion induced by past land-use practices, particularly road construction and tractor-yarded clear-cut timber harvest in the Redwood Creek basin,appears to reflect mostly the cumulative impact of a great many relatively small problems. The erosion problems mostly involve fluvial and fluvial-induced mass-movement processes operating along pre-existing stream channels, as well as along skid trails, at landings, along roadside ditches, and at fill-and-culvert stream crossings. These processes are initiated primarily because road construction and yarding operations commonly have exposed large areas of bare mineral soil, obliterated the finer details of the natural drainage pattern, and concentrated runoff at a limited number of pre-existing channels. These erosion processes are further aggravated by increased runoff, which in turn reflects increased surface compaction and seepage along roads and skid trails. Additionally, past timber harvest and road construction in steep streamside environments and in areas that have histories of complex mass movement have particularly accelerated landslide erosion. Many of the large streamside debris slides along Redwood Creek upstream from State Highway 299, moreover, are intimately associated with and appear to have been caused by roads, skid trails, and landings. However, large landslides directly attributable to recent road construction and timber harvest are not abundant in the lower Redwood Creek basin. This circumstance could change drastically if harvest of the remaining old growth timber in steep unstable streamside environments of the lower Redwood Creek basin is not planned and implemented with extreme care.

Recent increases in storm runoff and bedload sediment discharge appear capable of initiating erosion processes with built-in, self-reinforcing feedback loops by causing streambed aggradation, more frequent lateral shifting of anabranchs, and more frequent occurrence of bank-to-bank discharge. These alterations of stream runoff and sedimentation processes result in accentuated streambank erosion which commonly topples riparian vegetation and initiates streamside landslides. The toppled riparian vegetation and slide debris, in turn, may cause local channel aggradation and deflection that allow the whole process to feed on itself. Thus, the erosional impact of particular landslides, roads, and timber harvest units may extend well beyond the boundaries of the initiating disturbance.

The persistence of the erosional impact of recent large-scale, tractor-yarded clearcutting appears to be quite variable, depending upon details in site conditions, original logging and reforestation procedures, and the sequence of climatic events following logging.

In this regard, it is extremely important to realize that the silvicultural term "restocked" is not synonymous with "erosionally stabilized". An area fully restocked with seedlings that are 8 to 12 inches tall can still be the site of harvest-accelerated erosion. Even young second-growth forests with closed canopies often still have considerable amounts of bare mineral soil exposed on the forest floor. Nonetheless, aerial photographs and ground observations within the Redwood Creek basin suggest that hillslopes, except those cut by deep gullies or persistent shallow debris slides, have generally become stabilized and re-vegetated 6 to 10 years after yarding. Synoptic storm measurements and field observations suggest that stream-sediment loads may remain high relative to those in uncut basins for a longer period of time than that required for hillslope stabilization because of large quantities of sediment placed in temporary storage behind coarse woody debris in and adjacent to the channels. This persistent impact allows the impact of separate timber-harvest units on stream channels to become cumulative and perhaps to initiate feedback mechanisms.

Although much tractor-yarded clearcut timber harvest is still being carried out throughout much of the Redwood Creek basin, major improvements in forest practices over the last 3 years have sharply limited the amount of new ground surface disruption caused by on-going timber harvest. These changed practices reflect (1) recent application of advanced forest technology, (2) increased regulatory authority offered by the new California Forest Practices Act, Coast Forest District Rules (September 1975), (3) rigorous enforcement of those rules as well as other California statutes concerning fish and game and water quality, and (4) increased cooperation and communication between the National Park Service and neighboring timber companies as evidenced by the companies Special Restrictive Operating Practices and the U.S. Justice Department's Redwoods Agreements. Improved road construction and maintenance schedules, particularly with regard to fill-and-culvert stream crossings, have lessened the impact of roads on stream sedimentation. The overall timber harvest rate is slower, the individual timber harvest units are much smaller, and the distribution of harvest units is more dispersed than formerly. Moreover, most timber harvest in erosionally sensitive areas and areas in close proximity to the park boundary now involves yarding by various cable systems. On hillslopes steeper than about 35 percent, cable-yarding generally results in substantially less ground surface disruption than would tractor-yarding of the same site. However, considerable disruption within some cable-yarded units is still caused by bulldozer-constructed layouts, fire breaks, and interactions between cableways, incised draws, and sharp hillslope deflections. Furthermore, cable-yarding equipment requires construction of wide roads and large landings. Sufficient data to isolate the impact of recently modified practices on stream sediment loads in any sort of quantitative manner simply do not exist. However, observations of erosion and deposition within and immediately downslope from recently harvested units suggest that the modified practices have substantially mitigated the impact of timber harvest on stream sedimentation but that they have not entirely stopped that impact. A substantial part of that mitigation reflects the fact that the neighboring timber companies have temporarily delayed harvest of their most erosionally sensitive old-growth acreage. Timber harvest still appears to be directly responsible for the addition of a significant increment of sediment to the already over-loaded channels of Redwood Creek and its major tributaries. Future harvest of erosionally sensitive acreag could add another major increment of sediment to this system.

LANDSLIDES AS SEDIMENT SOURCES

Landslides and other forms of mass movement have clearly played a prominent role in sculpturing the Redwood Creek basin. More than 30 percent of the basin is underlain by distinct landforms that can be identified on aerial photographs as having been formed by past or present mass movement (Nolan and others, 1976A). Moreover, field inspection of additional large forested tracts reveals distinctive micro-topography, colluvium, and vegetation patterns suggestive of episodic debris slides or persistent soil creep and slow sliding. Mass movement can contribute sediment to Redwood Creek and its tributaries in three general ways. First, material can fall, slide, or flow directly into stream channels. Secondly, mass movement disrupts vegetation and ground surfaces, thereby exposing bare mineral soil and making it more susceptible to fluvial erosion. Thirdly, sediment deposited in valley bottoms during past episodes of widespread mass movement may be eroded as a result of recent increases in runoff and stream channel widths.

In response to the recent major storms and land-use changes discussed earlier in this Statement, mass movement has become far more active than in the recent past (Nolan and others, 1976A). For example, in 1947 about

30 debris slides were discernible adjacent to the main channel of Redwood Creek; in 1973, 341 such slides were present (Janda and others, 1975A). Similarly, in 1947, about 9 major debris avalanche scars were present in the Redwood Creek basin, whereas in 1973, 91 such scars were present (Janda and others, 1975A).

Thus, considerable evidence exists to indicate that mass movement is a major potential sediment source for Redwood Creek; however, considerable professional disagreement exists with regard to the relative importance of other major potential sediment sources, including recent timber harvest and road construction.

Assessing the relative importance of landsliding and recent timber harvest as potential sources for the presently high stream-sediment loads in the Redwood Creek basin is difficult in part because those categories are not mutually exclusive. Some landsliding has been directly and indirectly initiated or accelerated by recent timber harvest and associated road construction. Direct causes include changes in hillslope stress distribution by roadcuts and fills and reduction of that part of the effective soil shear strength associated with tree roots. Indirect causes include increased or concentrated storm runoff, increased persistence of seasonally high soil-moisture levels, and loss of lateral toe support by bank erosion related to harvest-induced channel aggradation or deflection. Individual major sediment contributions from landslide areas in Redwood Creek basin appear to be more episodic, localized, and massive than those from most recently harvested lands not directly associated with landslides.

Despite the prominent differences in the style of erosion shown by most landslides and most recently harvested lands, it is nonetheless instructive to compare the relative amount of area included within these two potential sediment source areas. A large proportion of the landslide-carved topography in the Redwood Creek basin is not currently active. Much of the old stable landslide topography bears well-developed soil profiles and mature old-growth forest, and therefore probably has not been active for several thousand years. About 6 percent of the Redwood Creek basin experienced debris slides, debris avalanches, vigorous earthflow, or repeated small scale sloughing and sliding along stream channels, and an additional 10 percent of the area experienced slow, less disruptive earthflow between 1947 and 1974 (Nolan and others, 1976). During this same period more than 60 percent of the Redwood Creek drainage basin experienced some timber harvest, mostly involving tractor-yarding and either the clearcut or the seed-tree-leave silvicultural systems (Janda and others, 1975A). However, not all the recently harvested lands have become major sediment sources; differing site conditions and harvesting techniques resulted in drastically different erosional impacts in different areas. Precise delimitation of harvested areas that have been heavily impacted has not been attempted because the relatively small-scale processes that account for much erosion in these areas, such as sloughing of roadside ditches and rilling of skid trails, are difficult to recognize and to map from aerial photographs. A combination of air-photo interpretation and field examination suggests that the severely eroded recently harvested land is considerably more extensive than the recently active landslides.

Attempts to define precisely the relative importance of landsliding as a sediment source give widely disparate results (U.S. Dept. of Agriculture, River Basin Planning Staff, 1970; Colman, 1973; Janda and others, 1975A, p. 232; Ficklin and others, 1977, p. 33), in part because some investigators group streambank erosion and landsliding into a single category. For example, Ficklin and others (1977) attribute as much as 75 percent of the sediment transported by Redwood Creek to mass-wasting processes that feed sediment directly to Redwood Creek; these authors include sliding, slumping, creeping, and bankcutting in their working definition of mass wasting. In contrast, the U.S. Department of Agriculture's River Basin Planning Staff (1970, p. 70) attributed only 29 percent of their estimated total sediment yield from the Redwood Creek basin to landsliding. The River Basin Planning Staff (1970, p. 59 and 70) also estimates that the combined contribution of landsliding and streambank erosion may account for 94 percent of the total sediment yield from the Redwood Creek basin. However, they, unlike Ficklin and others (1977), place emphasis on the small tributaries rather than the main channel; they suggest that 58 percent of the streambank erosion occurs along small second-order streams and that only 10 percent of the streambank erosion occurs along the large fifth- and sixth-order streams. The River Basin Planning Staff (p. 57) also suggest that the prevalence of streambank erosion may in part reflect increases in runoff brought about by poor land-management practices.

In his September testimony before the Senate, John Winzler (p. 5) directly quotes a 1972 report by the U.S. Department of Agriculture Field Advisory Committee-Interagency Study Team, as follows, "90 percent of the sediment in Redwood Creek comes from streamside slides and mass movement." Apparently no such report exists; perhaps Winzler intended citation of the River Basin Planning Staff Report of 1970. However, if that is the case, the direct quote in Winzler's testimony was not extracted verbatim from the 1970 report; it appears to be his interpretation of data presented in tabular form in that report, and discussed in the preceding paragraphs of this testimony.

Based upon close similarities displayed by the clay mineralogy of modern suspended sediment, surficial and subsurface flood-plain deposits, and subsurface horizons of the Masterson soil series, timber company consultants (Winzler and Kelly, 1975; Ficklin and others, 1977) have stated that the sediment transported by Redwood Creek is presently and has been for the last 3,000 years derived predominantly from deep-seated mass movement phenomena over which the activities of man exert little influence. Although their conclusion is compatible with their data, it is not proven. I believe that the clay-mineral data merely indicate that some sources of suspended sediment have been the same for some time; those data cannot be used to infer anything with regard to sources of bedload. Moreover, it is exceedingly difficult to base statements concerning erosion processes and rates solely upon clay mineral data. Erosion and sediment-transport processes can be inferred from clay-mineral data only if the sediment source and the process are uniquely linked; such is not the case in Redwood Creek. The soil horizons which Winzler and Kelly (1975) believe to have been eroded only by deep-seated processes are the B22 and the B3 horizons of the Masterson soil series. At many places these horizons occur within 2-1/2 feet of the land surface; material removed from them can, therefore, be delivered to streams by gullying of skid trails and by direct sidecasting of road spoil, as well as by natural and man-induced landsliding. As noted earlier, Carl Hauge of the California Division of Forestry has found that 35 recently tractor-yarded 10-acre study plots in Humboldt and Del Norte Counties show on the average 4,148 feet of skid trails and that the average depth of cut and fill along those skid trails is about 4 feet.

Even when a unique process-source relationship exists, clay mineralogy data cannot be used to infer anything with regard to rates of erosion. For example, if natural slides were the primary natural sources of suspended sediment, and if the activities of man accelerated natural slides and initiated new slides, the clay mineralogy of the suspended-sediment load would remain constant.

I believe that measured sediment loads, the spatial distribution of major erosional landforms, and the lithologic heterogeneity of the bed material of Redwood Creek indicate that the sediment load is not derived predominantly from any one source or process; rather the presently high sediment loads of Redwood Creek and its tributaries reflect a complex suite of both mass-movement and fluvial-erosion processes operating on a geologically heterogeneous and naturally unstable terrain. Recent timber harvest and associated road construction have had, and are continuing to have, an adverse impact upon the natural erosional instability of this basin. Recent damage to park resources, in part, reflects that impact.

SUMMARY

The Redwood Creek unit of Redwood National Park is located in the downstream end of a drainage basin that is eroding exceptionally rapidly. Redwood Creek during the 6 year period of available record (1971-1976) transported on a per square mile basis about 32 percent more suspended sediment than the nearby Eel River at Scotia, California which has previously been cited as the most rapidly eroding nonglaciated basin of comparable size in North America. The exceptionally rapid rate of erosion implied by the suspended-sediment discharge reflects a combination of (1) intricately dissected, moderately steep to steep terrain, (2) readily erodible rocks and soils, (3) frequent prolonged, moderately intense winter storms, and (4) recent major changes in land use, particularly timber harvest and road construction. Major erosion-causing storms in 1953, 1955, 1964, 1972, and 1975, even when viewed from a historical perspective going back to the late 19th century, appear to have been exceptionally intense. More than 60 percent of the basin consists of timberland harvested over the last 25 years; most of that harvest involved sequential logging of adjoining tractor-yarded clearcut units that were hundreds of acres in size. Tractor-yarded clearcut timber harvest in the immediate vicinity of Redwood National Park has disrupted significantly about 80 percent of the harvested surface area, and covered about 40 percent of that area with roads, skid trails, layouts, and landings. The average depth of cut and fill along the skid trails is about 4 feet.

The spatial distribution of major erosional landforms, measured sediment loads, and the lithologic heterogeneity of the bed material of Redwood Creek indicate that the sediment load is not derived predominantly from any one source or process; rather the presently high sediment loads of Redwood Creek and its tributaries reflect a complex suite of natural and man-induced mass movement and fluvial erosion processes operating on a geologically heterogeneous and naturally unstable terrain.

Several independent lines of evidence suggest that the recent major land-use changes have adversely impacted upon the natural erosional instability of this basin, and significantly increased water and sediment runoff during storm periods. Inspection of time sequential aerial photographs in conjunction with field observations indicates that although infrequent exceptionally intense storms control the timing and general magnitude of major erosion events, the loci, types, and amounts of erosion that occur during those events are substantially influenced by land use.

Measured sediment discharges lead to similar conclusions. For example, statistical analysis of suspended-sediment discharges and 10 physical variables that control erosion for 61 California streams by Dr. H. W. Anderson (formerly with U.S. Forest Service, Pacific Southwest Forest and Range Experiment Station) suggests that the present suspended-sediment discharge of Redwood Creek at Orick is about 7-1/2 times greater than its natural suspended-sediment discharge. The impact of changed land use on individual tributaries has been highly variable. Some tributary basins that have been particularly severely disrupted by recent timber harvest yielded more than 17 times as much suspended sediment during the 1975 and 1976 storm seasons as comparable nearby unharvested basins. During that same period, some tributary basins harvested more than 10 years ago yielded more than two times as much suspended sediment as comparable unharvested basins. Although difficult to determine precisely, bedload discharges appear to have been impacted upon at least as severely as suspended-sediment discharges by recent timber harvest and road construction. The importance of the tributaries, particularly those with recently harvested drainage basins, as contributors of sediment to Redwood Creek is most pronounced during major channel-modifying floods that have an immediate and persistent impact upon stream sediment regimes.

The erosional impact of past timber harvest in the Redwood Creek basin represents primarily the cumulative impact of a great many small erosion problems caused not so much by the removal of the standing timber as by the intensity and pattern of ground-surface disruption that accompanied the removal. Increased sediment discharges seem to reflect increases in water runoff, as well as greater exposure of bare mineral soil along roads and within timber harvest units. Intensified water and sediment runoff appear to have caused channel adjustments and erosion at sites well downstream from the initiating disturbance.

Readily apparent modifications of riparian and aquatic environments occurred during recent major storms throughout the Redwood Creek basin. Recent modifications of parkland reaches of Redwood Creek and its tributaries, although less conspicuous than modifications in areas upstream from the park, are substantial and continuing. The recently modified parkland environments appear to reflect stream channel adjustments to recently increased water and sediment discharges, and are considered by the National Park Service and various environmentally concerned groups as damaged park resources because the modifications reflect, in part, unnatural causes. Numberous streamside trees have been killed or placed in a state of declining vigor by bank erosion, burial by coarse-grained streambed material, and "drowning" by locally elevated water tables. Additionally, floating coarse woody debris has severely battered, abraded, and probably toppled some streamside trees. The aquatic habitat now appears incapable of supporting as large or as diverse a population as it once did because recent aggradation and channel-geometry changes resulted in toppling of shade-providing streamside vegetation, filling of summer rearing pools, burial of stable substrates such as bedrock blocks and large logs, and more frequent shifting of streambed materials. The intra-gravel habitat along Redwood Creek and many of its tributaries is also inferior because much silt and fine sand have been deposited in the matrix of the stream gravels. The type and extent of recent channel modifications indicate that these streams are clearly overloaded with sediment in temporary storage and that the introduction of even a relatively small addition of sediment has the potential for causing a disproportionately large impact upon park resources.

Present and proposed future timber harvest involves smaller, more dispersed harvest units, and more sophisticated attempts at minimizing ground-surface disruption than were used in most of the harvest that contributed to recently accelerated erosion. Moreover, recently strengthened regulations and review procedures result in proposed harvest plans being tailored to specific site conditions.

However, application of improved timber harvest technology alone will not assure protection of park resources. Much of the remaining commerical old-growth timber is on steeper, wetter hillslopes that are more susceptible to landsliding and in closer proximity to major stream channels than most of the previously harvested hillslopes in the lower Redwood Creek basin. Moreover, many of the natural debris barriers along streams flowing through the remaining old-growth forest have temporarily stored substantial quantities of sediment introduced into the streams by the recent storms and upstream land-use changes. Removal of merchantable timber from these barriers may destroy their stability and cause the rapid release of stored sediment. The cumulative impact of recent land-use changes and storms on stream sedimentation would then be transmitted to downstream reaches in a brief period of time. This concentrated impact would probably be severely damaging to park resources. Additionally, the relative effectiveness of recently proposed timber harvest techniques in mitigating post-harvest erosion in this type of terrain remains to be demonstrated. Thus, harvest of timber in the erosionally sensitive streamside zones will have to be thoroughly planned, skillfully implemented over an extended period of time, and carefully monitored in order to minimize the possibility of impacting further upon hillslope erosion and stream sedimentation. Monitoring is needed to check if proposed mitigation measures provide the desired level of resource protection. An extended period of harvest helps to minimize the potential for cumulative impacts and allows monitoring results to be utilized in the planning effort.

The threat posed to park resources by harvest of much of the remaining old-growth forest is different from that associated with past harvest in that potential harvest-induced erosion problems appear to be fewer in number but potentially larger in size than most of those associated with past harvest. Substantial tracts of remaining old-growth forest are so inherently unstable that timber harvest, even if carried out with extraordinary care, will almost certainly result in massive landslides or gullies. Thus, if the potential for future damage to park resources resulting from timber harvest-induced erosion is to be minimized, future planning efforts may have to consider some deferral and abolition of harvest of selected sites. Massive erosion problems in some recently harvested areas suggest that they too may be so erosionally sensitive that following rehabilitation and reforestation, they should not be reharvested. Thus, in order to maintain site productivity and to protect downstream park resources, it may be necessary to maintain some erosionally critical areas as perpetual timber reserves dedicated to watershed protection. Precise designation of the amount and location of the critical acreage could be made only after detailed, site specific field investigations. However, a working knowledge of this particular basin and general principles of erosion suggest that the critical old-growth acreage is scattered about and interspersed with cutover land and stable hillslopes. Moreover, that critical old-growth acreage is not all contiguous with the park or with blocks of privately-owned intact old growth that are contiguous with the park. Thus, selective Federal acquisition of just the critical acreage would create a pattern of ownerships that would make management of both the parklands and the commercial timber lands exceedingly difficult.

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