ANALYSES OF HYDROLOGIC AND EROSIONAL IMPACTS OF FOREST HARVEST PRACTICES ON REDWOOD CREEK, HUMBOLDT COUNTY, CALIFORNIA

by

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ABSTRACT

Redwood Creek is hydrologically a very dynamic basin ranging in discharge from about 10 to over 50,000 cfs. Wash load concentrations range up to 8,200 mg/l with an estimated 780,000 tons per day of peak flood discharge. Bed load can contribute up to 40% of the total sediment discharge of Redwood Creek.

Peak flood flows buffer at 50,000 cfs with five floods of this magnitude in the last 22 years. The buffering action may be tidal effects, instabilities in the cross-section or changes in approach velocity or combinations of each. In any event, little can be concluded on the recurrence frequency of maximum flood flows based on current flood records.

Cutting of the forests started with early settling, clearing for ranches, field crops, etc. Commercial forest harvest started in the 1940's and is continuing. Relationships of forest harvest to floods, soil erosion and bed load movement are analyzed in this report.

To date there is no evidence that forest harvest in Redwood Creek has altered rainfall-runoff relationships or contributed to significant increases in discharge (including flood flow), wash or bed load movement.

All data analyzed for contribution of tributaries of Redwood Creek either as discharge, wash load or bed load indicate their contribution is an insignificant fraction and always less than the error of measurement for the equivalent value in Redwood Creek (Table 4).

No data reported indicate any tributary as a source of increased flow or sediment. Sediment and discharge appear to be uniformly contributed in the upper 25% of the Redwood Creek watershed. In the lower 40 miles of the channel, there is an increasing sediment concentration progressively downstream, indicating the main channel is the source of sediment. In eight synoptic events studied between November 1973 and February 1975, only once (a low flow storm, 1 cfsm in Redwood Creek) did a tributary have either a wash load concentration of unit area contribution equal to or greater than the main channel. Even for this unique storm, the contribution of sediment of Miller Creek (2.7 tons) is within the error of measurement of Redwood Creek--110± 30 tons. Predicted average daily suspended sediment for November in Redwood Creek is 962 tons, based on a mean daily flow of 1,180 cfs. The unique storm increased flow of downstream tributaries but did not impact the main stem of Redwood Creek.

The average ratio of Redwood Creek to Miller Creek is 20.1:1 for unit area contribution of total suspended sediment and 9.1:1 for average suspended sediment concentration for February 1975. Miller Creek contributed 7.9 tons of sediment in a February storm, while Redwood Creek produced 21,960 tons--again a tributary contribution which is not within 0.1% of the error of measurement for Redwood Creek.

The examples provide a relative base for evaluating impacts of logging as the upper 430 ac. of Miller Creek were 90% recently logged, and the total (870 ac.) basin was 77% recently logged.

The overwhelming evidence of forest hydrology research points to slight increases in water yield when forests are clearcut. The water yield increase is a direct proportion of the area of the basin cut and the magnitude of potential increase. The current rate of conversion of the old growth Redwood forest is 2.4% per year of the area of Redwood Creek above Prairie Creek. Hydrologic impacts might increase annual water yield 1.98% above Prairie Creek and 1.77% at Orick, a calculated increase of 14,250 ac.-ft. of runoff. Impacts of forest harvest on flood flows of Redwood Creek are insignificant--much below the detection limits of USGS gauging.

Rainfall-runoff and soil erosion relationships are dominated by climate-soil-geology interactions in Redwood Creek. Examples of the dynamics of climatic change are attested to by the 230% increase in annual runoff from increased rainfall in consecutive years (an increase of 46.5 in.). This is a 3-fold greater impact than forest harvest occurring on 100% of the basin, not just 2.4%.

The highly variable and intense amounts of rainfall (both short term and annually) received by Redwood Creek, combined with inherently unstable geologic formations and soil types, dominates the hydrologic and erosional regimes. Channel characteristics and movement of suspended and bed materials are a function of these natural factors.

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INTRODUCTION

The following report analyzes the relationship of forest harvest to hydrology and peak flood discharges in Redwood Creek, Humboldt County, California. It also considers the relationship of peak flood discharge to suspended sediment and bed load movement. Redwood Creek has a total horizontal projection area of 278 square miles (sq. mi.). Prairie Creek, the major downstream tributary, has an area of about 30 sq. mi. and flows into Redwood Creek from the north. Cursory field reconnaissance was made by the author of portions of Redwood Creek in June 1977, including much of the lower channel as well as general watershed conditions. The following report considers hydrologic, channel and watershed conditions of Redwood Creek in the 248 sq. mi. area upstream from Prairie Creek.

The controversy on impacts of forest harvest practices on hydrology and erosional processes in Redwood Creek has resulted in substantial literature, some of which is not technically enlightening or relative to the problem (Earth Satellite Corp., 1972). Published and Open File U. S. Geological Survey (USGS) reports provide a good source of data and have been analyzed and portions incorporated in the following report. Janda, et al. (1975) provide the most complete data base and descriptions of the Redwood Creek watershed. Sediment and bed load data from Iwatsubo, et al. (1975, 1976) and Winzler and Kelly (1975, 1977) provide a basis for understanding rainfall-runoff-sediment relations.

The Redwood Creek Basin

The climate of the basin is well described in a general fashion (Janda, et al. 1975), but records are essentially devoid of adequate documentation of distribution of precipitation by storms, seasonally or annually over the basin. Other types of climatic data such as evaporation, solar radiation and wind speed are nonexistent.

It is generally assumed that average annual precipitation is about 80 area inches (in.) over the basin. Helley and LaMarche (1973) modified Rantz's (1968) analysis of average annual precipitation to show an average of 70+ in. of precipitation over most of the basin, with an area on the east side of the basin between Miner Creek and approximately Copper Creek receiving 90 in. As the area of 90 in. is substantially smaller than that of 70 in., and a significant rain shadow should exist in the elongated Redwood Creek valley, an average value for the basin probably is much closer to 70 in. than 80. These analyses ignore known orographic influences on rainfall distribution (see below), so must be considered as gross approximations.

Mean annual precipitation at Prairie Creek State Park (near Orick) is 69.41 in. with a standard deviation of 10.8 in. or 16%. Yearly values range from 53.88 to 89.96 in. (Janda, et al. 1975). Other precipitation data are sparse over the basin, but the few records available indicate highly variable time and spatial distributions. Prevailing southwesterly wind suggests tributaries draining the east side of Redwood Creek should receive increased amounts of rainfall, particularly during vigorous wind-driven winter rain storms.

Usual orographic processes should prevail in Redwood Creek as an increase in precipitation with increasing altitude, usually about 10 in. per 1000 ft. of increased altitude. The brief record (1964 through 1972), maintained by the California Department of Water Resources near Board Camp Mountain on the south boundary of the watershed, gave a 9-yr. average of 103.37 in. with a standard deviation of 24 in. or 23%. Runoff of Redwood Creek was very close to its long term average (1964 through 1972) indicating that southern headwaters of Redwood Creek receive about 1.5 times as much precipitation as the Prairie Creek-Orick area. A similar rainfall pattern for a single storm (Feb. 5-7, 1975) was reported (Winzler & Kelly, 1977) where Prairie Creek and other lower stations had 0.06 to .4 in. of rain, while the east divide between Redwood and Little Creeks received 1.42 in. Similar spatial and timing of rainfall synoptic events are reported by Winzler and Kelly (1975), Janda, et al. (1975a), and Iwatsubo, et al. (1975).

Low to moderate intensity storms usually obey orographic processes to a much better degree than vigorous, long recurrence interval rain storms. Major rain storms with recurrence frequencies of 2 to 5 years are usually produced by very vigorous frontal systems which have very little temperature stratification close to the earth's surface. They are usually very turbulent accompanied by strong winds and do not show an orographic distribution of precipitation over small basins, such as Redwood Creek.

Typical coastal maritime climates and orographic rainfall intensities are usually low (0.2 to .3 in. per hour) but durations are frequently long. Storm durations of 6 hours can produce 2 to 2.6 in. of rain once every 2 years with 4.5 to 6 in. in a 24-hour period. Ten-year recurrence frequency rainfalls will produce 2.8 to 3.4 in. in 6 hours and 7 to 8 in. in 24 hours.

The seasonal distribution of precipitation is maritime with about 80% falling between November and March. Summers are usually dry. In summer, northern portions of the watershed are strongly influenced by coastal fog, while southern portions are much warmer and receive considerably more sunshine. In winter, the southern basin is colder receiving some snow which, on the average, persists for only a few days.

As the upper basin (southern portion) of Redwood Creek has a substantially higher average altitude, it also has a greater density of streams than northern portions of the watershed. The basin above the Redwood Valley bridge and Lacks Creek, a major tributary, have a range in stream density from 8.6 to 9.1 miles of stream per square mile (mi/sq.mi.) of watershed area. Downstream tributaries usually range from less than 4 to 8 mi/sq.mi. (Iwatsubo, et al. 1976). These data verify the occurrence of usual orographic influences as increasing precipitation in southern portions would develop an increased stream density, as opposed to lower elevations and lower precipitation in northern tributaries with decreased stream density.

Hillslope gradients tend to be more gentle in upper altitudes of the watershed than adjacent to Redwood Creek. Average hillslope gradient for the basin is 34% (18.8^{0}) with a standard deviation of 32% (Janda, et al. 1975). Hillslopes steeper than 40% (21.8^{0}) occur on 25% of the area and steeper than 50% (26.6^{0}) on 12% of the area. Average hillslope length is 1600 ft. with a standard deviation of 63% (1008 ft.). Slopes longer than 2000 ft. occur on 36% of those measured (Janda, et al. 1975). Hillslopes immediately adjacent to Redwood Creek are nearly twice as steep as the average for the entire basin. Measurements by Abney taken between Snowcamp Creek and Hayes Creek have an average of 60% slope or 36^{0} with a standard deviation of 13% (Janda, et al. 1975; cited Colman, 1973).

Two dominant forms of vegetation occur over the basin--natural coniferous forests and natural prairies. Prairies are currently utilized for ranching, grazing, etc., while the coniferous forest is utilized for wood and fibre. Most prairies occur on inherently unstable geologic materials. Geologic materials occupied by coniferous forests range from stable to as unstable as the prairie. Land forms upstream from the mouth of Prairie Creek show 36.4% have had former mass failures. Creep, slumping and flow movements classified in general as earth flows are the most visually obvious form of mass movement in Redwood Creek. Many of these earth flows, which extend from the ridgetop to the valley bottom, become increasingly active on the steeper slopes in close proximity to Redwood Creek. Surface movement of most flows seems to be only a few feet per year. However, several very active flows may move over 10 ft. per year (Janda, et al. 1975). Sediment and bed material delivered to Redwood Creek occurs not only directly from movement of the flow but also from erosion and gulleying over the unstable surface of the earth flows. Janda, et al. (1975) states, "Most of the material delivered to the stream is sand size or finer and capable of being transported in suspension. Probably less than 30% of the earth flow delivered sediment is transported as bed load."

The channel of Redwood Creek has been segregated into reaches that have in common many channel characteristics. Janda, et al. (1975) utilized Colman's 1973 work, modifying and elaborating on the exact nature of the channel. Even portions of the 7 reaches, as outlined by Janda, et al., could be further subdivided as they include nontypical sections. The following description of reaches is taken from Janda, et al. (1975).

Reach 1. Lower Redwood Creek is characterized by a braided channel set in the relatively broad valley with a moderately active flood plain. Channel gradients range from 8 to 40 ft. per mile, averaging about 11 ft. per mile. The lower 4 miles of the channel have been riprapped to protect Orick on the flood plain. About 41% of the unlined channel along reach 1 is actively eroding. This reach is approximately 16 miles long, extending from the mouth to the lower end of the narrow rocky gorge.

Reach 2 extends about a mile upstream to the southern boundary of Redwood Creek National Park (miles 16 to 17). It is a steep, narrow rocky gorge with many large blocks of bedrock in the channel and on the banks. The gradient is highly irregular but averages about 47 ft. per mile. Over 50% of the stream banks in this reach is actively eroding. Non-eroding banks are often protected by large bedrock blocks. East sides of the channel bank are underlain by siltstone and sandstone formations which are actively eroding as large slides and earth flows. This past and continuing vigorous mass movement accounts for the large angular blocks in the channel. The narrow channel and large blocks of rock impede flood flow increasing the height of a flood stage in reach 3.

Reach 3. Between Copper Creek and the southern park boundary, the channel becomes noticeably wider with an average gradient of 35 ft. per mile, ranging from 31 to 38. Sixty-eight percent (68%) of the stream banks are actively eroding. Hillslopes above and adjacent to the stream show considerable natural instability. About a half mile downstream from Copper Creek, a massive old slide causes over a 90^{0} change in the direction of low to moderate flows. This abrupt change in flow direction impedes flood flow causing an increased upstream stage and reduced velocity. A large bed load deposit remains from the 1975 flood on the west. The east bank for about 300 yds. is very unstable. This reach extends to mile 19.

Reach 4. The channel between Lacks and Copper Creeks (8.8 mi., river mi. 19 to 28) is characterized as narrow, lacking a flood plain or recent alluvial terraces with a gradient from 19 to 30 ft. per mile, averaging 22 ft. per mile. Active soil erosion occurs on 52% of the stream bank. Hillslopes adjacent to the channel have abundant mass movement. Old terraces occur just downstream from Lacks Creek.

Reach 5. The channel upstream from the mouth of Lacks Creek to Highway 299 bridge (16 mi.) is quite variable in character (river mi. 28 to 44). The average gradient for the entire reach is 24 ft. per mile with the upper third being 32, and lower two-thirds 21 ft. per mile. Increased channel width occurs in the upper 13 miles. There are several broad, old alluvial terraces with active lower flood plains. Stream banks are actively eroding in over 56% of the channel.

Redwood Creek must have been dammed to over 100 ft. by a massive past earth flow near Garett Creek. Remnants of old terraces occur in reach 4. Terraces also occur at several elevations above the current water level. Redwood Creek meanders through resistant geologic formations and old terraces in river miles 29 to 31.

Reach 6. Upstream from Highway 299 bridge for 14.5 mi. to Snow Camp Creek, Redwood Creek has a channel gradient ranging from 34 to 500 ft. per mile, averaging 83 ft. per mile. Active stream bank erosion occurs on 62% of the stream banks. Slides occur on nearly every bend of the channel. (The channel in reaches 6 and 7 was not inspected on the ground by the author.)

Channel 7. The upper 4.5 miles of Redwood Creek above Snow Camp Creek is characterized by steep gradients, alluvial deposits of large size materials and a channel gradient that ranges from 125 to 1,000 ft.

per mile, averaging 550 ft. per mile. Flow is intermittent in portions of this reach on dry years. Active erosion occurs on 64% of the stream banks.

Hydrometeorological Numbers and Their Meaning

Though often not mentioned, it should be understood that any measurement (discharge, suspended sediment, rainfall, etc.) has associated with it unavoidable errors. This is particularly true in the development of hydrometeorological data. Discharge records from recording gauging stations are dependent on a stable and accurate relationship between measured stage and predicted discharge. Many factors can greatly affect the accuracy of any predicted discharge measurement, starting with the quality of the stage-discharge equation. As discharge is estimated by the average velocity of flow through a given cross-sectional area, any errors or changes in the stream cross-section will automatically induce errors in estimated flow. The fact that stage can be measured with considerable accuracy does not mean that this accuracy follows through in the estimation of discharge.

The magnitude of error in a typical set of discharge data which correspond to the USGS designation of 'good,' might have a 95% confidence interval for a 10% accuracy. This means that we are 95% sure (1 chance in 20 of being wrong) that the true value of discharge is within ± 10% of the measured (or reported) value. This relationship applies within the range of recorded stages and actually measured discharges. When extrapolation of the stage-discharge equation to flood peaks is considerably greater than any actual discharge measurement, errors of estimation of discharge can greatly increase. Increased errors can be related not only to just the pure error in extrapolating the velocity of flow through the cross-section, but also to the fact that physically the cross-section itself becomes very unstable during flood flow and may have significantly greater area due to movement of bed material or changes in approach velocity.

Early published Water Supply records indicate with an asterisk the date on which a discharge measurement was taken. For instance, the December 22, 1955 flood was estimated from discharge measurements that ranged up to about 50% of the peak discharge (a 25,000+ cubic feet per second, cfs, measurement taken November 24, 1953). As the practice of indicating the day of discharge measurements was terminated with water year September 1960, the information is not readily available on the range of actual discharge measurements in relation to measured stage for later floods.

Calculation of quantities of sediment yield in tons per day requires both determination of discharge and concentration of suspended sediment, neither of which can be done with great accuracy. For example, discharge is estimated at 200 cfs ± 10%. Suspended sediment is estimated at 1000 mg/l ± 20%. True discharge should be between 180 and 220 cfs and sediment between 800 and 1200 mg/l. Thus, the quantity of suspended sediment can only be calculated within ± 30%, or a range of 60%.

Hydrology of Redwood Creek

Redwood Creek varies in flow from about 10 cfs (gauge height 5+ ft.) to over 50,000 cfs (gauge height 24 ft.). Table 1 (modified from Janda, et al. 1975) shows the instantaneous peak discharges and the average daily flood flow in cfs for varying recurrence intervals.

The average runoff by water years since 1953 is 54.8 area in. (Table 2) with a standard deviation of 25% (13.8 in.). The magnitude of year to year variation is attested by the lowest runoff of record (1967-68) of 32.5 in. and the largest runoff in 1973-74 of 84.2 in., a departure of minus 22.3 and plus 29.8 in. Table 2 also summarizes annual peak and low flows by water years, indicating the number of days each year that peak flows exceeded the mean annual flood or the expected one-year daily mean average flood flow. Estimated instantaneous peak discharge of the mean annual flood is 28,830 cfs with an average daily discharge of 18,500 cfs. On the average, this flow will be equalled or exceeded once every 2.3 years. In general, the major floods have occurred during water years that had higher than average runoff. Trends in unusually wet or dry periods are not apparent

Table 1. The Instantaneous Peak Discharge and Average Daily Flow for Flood Events of Varying Recurrence Intervals

Recurrence Interval (Yrs.)	Instantaneous Peak Discharge (cfs)	Average Daily Discharge (cfs)
1	8,500	6,900
2	25,400	17,300
2.3	28,830	18,500
5	37,200	26,500
10	45,300	33,900
25	55,700	44,600
50	63,600	53,800
100	71,500	64,100

Table 2. Annual Runoff and Peak Flood Flows by Water Years

Water Year	Runoff (inches)	Instantaneous Flows Peak (cfs)	Instantaneous Flows Minimum (cfs)	Number of Days Flow Exceeded Mean Annual Flood	Number of Days Flow Exceeded Expected Yearly Flood
'53-54	60.8	27,200	18	1	10
54-55	37.3	28,100	17	1	2
55-56	79.2	50,000	20	2	18
56-57	51.7	24,100	18	0	8
57-58	66.2	22,200	17	0	16
58-59	36.0	17,500	13	0	5
59-60	40.9	24,900	18	0	5
60-61	52.9	14,700	18	0	6
61-62	37.8	21,800	22	0	2
62-63	59.7	26,100	24	0	2
63-64	51.3	37,700	20	1	6
64-65	71.6	50,500	13	4	15
65-66	42.8	39,600	13	1	6
66-67	51.1	24,500	19	0	5
67-68	32.5	14,900	19	0	1
68-69	58.1	17,200	21	0	6
69-70	50.0	28,000	13	0	11
70-71	68.9	30,500	11	0	10
71-72	71.8	49,700	16	4	12
72-73	37.7	10,000	12	0	0
73-74	84.2	24,800	12	0	16
74-75	63.7	50,200	9	1	11
Average	54.8	28,830	16	.7	7.9

in this brief runoff record. Short term annual averages would show periods of below average annual runoff, such as 1958 through 1962 (average 41.9 in.) and above average runoff such as 1970 through 1975 (average 65.3 in.). Unusually high and low years appear to occur randomly. During the lowest water yield year of record (1967-68, 32.5 in.), there was only one day with a mean daily flow greater than the expected yearly flow, and the peak flood was only 14,900 cfs. Water year 1972-73 had slightly greater runoff (37.7 in.) but a lower peak discharge (10,000 cfs) and no days of mean flow which exceeded the expected yearly flow.

Flooding of Redwood Creek

Historic floods (Helley and LaMarch, 1973) of a magnitude similar to the December 1964 occurred around 1600 and 1750. Other evidence indicates major flooding in the winter of 1861-62.

The first well-documented recent flood was that of January 1953 (Rantz, 1959). The rain creating this flood was a very intense regional storm extending from northern California through western Oregon. The greatest storm rainfall recorded by the Weather Bureau was 21.21 in. at Klamath, California. Privately owned precipitation gauges registered 23.02 in. at Crescent City. The greatest 24-hr. precipitation recorded was 9.6 in. at Klamath. Antecedent rain-soil moisture conditions were favorable for a wet mantle flood, as 6 moderate to intense storms preceded the January storm in December 1952.

No gauging station was operating on Redwood Creek in January 1953. Slope area discharge measurements were taken, and based on the stage-discharge relationship established after installing a gauging station in September 1953, an estimate was made of peak discharge of 50,000 cfs (stage 23.95 ft.). A regional flood frequency analysis indicated a recurrence interval of 50 yrs. for this flood.

The next major flood (Hofmann and Rantz, 1963) occurred December 15-20. This rain storm accompanied by high winds and moderate to intense rain centered over an area between the Eel and Russian Rivers. The December 15-20 storm was followed closely by a much more intense storm, December 21-24. Practically all of the rain fell in 72 hrs. causing widespread major flooding. Reported amounts varied from 7.5 in. in 24 hrs. near San Francisco Bay to 10.75 in. in the Russian River basin.

All of the damage from the flood of December 21 and 22 in Redwood Creek occurred in the town of Orick (Hofmann and Rantz, 1963). The maximum stage and discharge of Redwood Creek were identical to those of the January 1953 flood. Hofmann and Rantz suggest several other floods of this magnitude have probably occurred since the great floods of the winter of 1961-62. Redwood Creek rose rapidly covering most of the area of Orick to a depth of about 4 ft. Nine hundred and ten (910) acres of agricultural land were inundated with damage to roads, bridges, etc. Subsequent flooding occurred in late December and January (22,200 cfs, 20.0 ft. stage), inundating some of the same areas but causing little additional damage.

The December 1964 flood was more or less a replay of the December 22, 1955 floods. A series of moderate to intense rain storms preceded the flooding in late November and early December. Rainfall rates in excess of 8 in. in 24 hrs. were common throughout the north coast region. Five-day rainfall rates between December 19 and 24 exceeded 20 in. in many places, and freezing levels went to 10,000 ft. melting snow left by an unusually cold storm early in December. Redwood Creek rose to a stage of 24.0 ft. with an estimated discharge of 50,500 cfs. Orick was again flooded with damage much the same as 1953 and 1955.

While differences in flood flow per unit basin area occur between major drainages, and within tributaries of a given drainage, it is quite possible that substantially more watershed area of Redwood Creek produced a peak discharge of 243 cfsm (peak at Blue Lake station) in the 1964 flood. A flood flow of 67,500 cfs would have occurred at Orick had the total watershed produced at this rate. If only that portion of the watershed upstream from Prairie Creek had this contribution, then flow would have still exceeded 60,000 cfs.

The fact that the Orick gauging station seems to buffer flood flows at about 50,000 cfs suggests some possible problems with establishing magnitudes of the peak flood flows on Redwood Creek. This might be particularly true with the December 1964 flood in view of the intensity of the rain storm and magnitude of regional flooding. Discharge records are not available for the Mad River; however, portions of the Eel River to the southwest produced record flood yields of over 580 cfsm. Discharge of the Eel River went from 4,600 cfs to 752,000 cfs in 5 days. In places, it rose 90 ft. above its normal low water level.

Flooding of this nature on major drainages usually results from widespread, very intense rainfall with synchronization of peak flows from tributaries. Very frequently, the unit area contribution to peak flood flows is nearly equal from all tributaries, all aspects and different average basin altitudes. Considering the massive and widespread nature of the 1964 rain storm (record floods on the Klamath, Trinity Smith and Eel Rivers), it is very unlikely that the 210-sq. mi. downstream area from the Blue Lake gauging site on Redwood Creek would have produced significantly less runoff (about 160 cfsm) as compared with the upstream area which produced 243 cfsm. This analysis leads to the conclusion that the Orick gauging station may very significantly underestimate major flood discharges.

The occurrence of floods which have exceeded the expected 5-yr. recurrence frequency is shown in Table 3. The January 18, 1953 storm is reported by Rantz (1959) as a 50-yr. event. Table 3 shows that there have been 6 storms in excess of the instantaneous peak of a 10-yr. storm (45,300 cfs) in the 22 yrs. of record. If a 10% accuracy limit is accepted, then all but two floods (January 1964 and 1966) are equal. A 20% accuracy limit suggests there are no significant differences between any floods in

Table 3. Occurrence of Floods Which Exceeded the Expected 5-Yr. Recurrence Frequency (37,200 ± 3,700; range 33,500-40,900)

Date	Peak Flow	cfsm	Inches Annual Rainfall
Jan. 18, 1953	50,000	180	?
Dec. 22, 1955	50,000	180	79.2
Jan. 20, 1964	37,700	136	51.3
Dec. 22, 1964	50,500	182	71.6
Jan. 4, 1966	39,600	142	42.8
Jan. 22, 1972	45,300	163	71.8
Mar. 3, 1972	49,700	179	71.8
Mar. 18, 1975	50,200	181	63.7

Table 3. A gauge height in ft. of 23.95, 23.95, 24.0, 23.67 and 23.82 is reported for the 1953, 1955, 1964, 1972 and 1975 floods, respectively. The diking system installed by the Corps of Engineers in 1968 now confines flow of Redwood Creek to a riprapped channel. Thus, the measurement of nearly equal gauge height for these floods of near equal discharge, before and after riprapping the channel, might be suspect in view of the magnitude of regional flooding. Winzler and Kelly (1977) reported measured flow of 50,600 cfs of discharge at the Orick station 2 hrs. after the USGS flood peak of 50,200 cfs had passed on March 18, 1975.

Nearly equal stages before and after riprapping, pre-1964 and post-1968, suggest greater discharges must have occurred in earlier floods as about 36,000 ac-ft were stored in the greater Orick area. Combining the accuracy of estimation of discharge ± 10% with impacts of the altered channel leads to the conclusion that the magnitude and recurrence interval of major floods on Redwood Creek are poorly understood. It seems very likely that the 1964 flood had discharge in excess of 65,000 cfs (based on 243 cfsm at Blue Lake station and regional flooding) and 50,000± cfs floods can be expected about every 5 years.

A possible cause of errors in estimation of peak flood discharge is instability of the cross-sections. Calculations of the velocities of flow at which bed of Redwood Creek becomes unstable indicates (discussed in detail in later sections) a layer 3-6 ft. deep could be moving at 3-6 ft/s, an error in flows of from 2,200 to 9,000 cfs.

A gauging station 10 ft. in elevation and 2 1/2 mi. from the Pacific Ocean may also be influenced by tidal action. Extremely high tides correlate with strong winds, intense low pressure and very heavy rainfall--all factors which also correlate well with floods. Backwater influences could easily influence maximum stages on Redwood Creek.

SEDIMENT TRANSPORT

Einstein (1964) states, "Every sediment particle which passes a particular cross-section of the stream must satisfy two conditions: 1, it must have been eroded somewhere in the watershed above the cross-section; 2, it must be transported by the flow from the place of erosion to the cross-section." Sediment loading factors are thus the availability of erodible material and the stream transporting ability. In most streams, fine particles of a size which can be easily carried by the stream are limited in availability. This fine particle load is designated as 'wash' load. The coarser part of the total sediment load, that part which is difficult to move by flowing water, is limited in rate by the transporting ability of the flow. This load is designated as 'bed' load. A particle of given size might be bed load at one rate of discharge but becomes suspended with increased flow velocity from an increased discharge rate. The bed of a channel affords a continuously and fully available source of particles for bed load transportation. Thus, any channel has a capacity load which depends on flow rate, the nature of the channel and the size and range of bed sediments.

The capacity load of a channel is highly variable in both space and time, fluctuating with velocity and turbulence of fluid flow and quantities of entrained material. Residual impacts of the character of bed load source and deposition may be observed in the channel. Bed load functions are difficult to measure and may either be random or predictable, depending on stream flow and channel conditions.

Wash load in contrast to bed load is not represented by a residual effect in the channel, and thus, the channel is unaffected by the transport capacity, as neither scour nor deposition from wash load occurs.

There is, however, an interaction between the quantity of wash load and the movement of bed load. Vanoni (1941) has shown that additions of suspended sediment up to 0.6% by weight (6,000 mg/l) increases the velocity of streamflow. Friction forces from the bed and banks and dampening effects of turbulence and eddies are reduced, thus resulting in increased velocity. It has also been shown that the more dense fluid has an increased buoyancy, thus is able to move or suspend larger particles. Moving water obeys the formula for kinetic energy where $K = 1/2mv^2$. Increasing the wash load increases the mass and the velocity in the manner that doubling the velocity of flow results in a 32-fold increase in the quantity of suspended material that can be carried, and a 64-fold increase in the size of particle that can be carried. The mean velocity of flow can be calculated from the Manning equation where:

$$V = \frac{1.49}{n} \times R^{2/3} S^{1/2} \qquad \text{(equation 1)}$$

where

V = mean velocity in feet per second

n = the Manning coefficient for channel roughness ranging from 0.04 to 0.07 for natural stream channels

R = the hydraulic radius in feet, and

S = the slope in feet per foot.

The hydraulic radius is a channel shape factor which relates the cross-sectional area through which water is flowing to the wetted perimeter measured at the right angle to the direction of the flow. Several empirical relationships have been reported (Shulits and Corfitzen, 1937) which predict the diameter of bed load material that might be moved based on hydraulic characteristics of the channel. Three of these equations are:

$$D = 3{,}080\ (rs) \qquad \text{(equation 2)}$$

$$D = 4{,}770\ (Qs^{1/3}/w) \qquad \text{(equation 3)}$$

$$D = 12{,}000\ (Q^{2/3}s/w^{2/3}) \qquad \text{(equation 4)}$$

where

D is the diameter in millimeters

Q is discharge in cubic feet per second

s is slope in feet per foot

w is width in feet, and

r is hydraulic radius.

Channel geometry and related hydraulic characteristics are physical functions of certain parameters of the stream. Birot (1960) suggests that such formulas utilizing slope and hydraulic radius "are a limited value for most rivers are very far from saturation with suspended material." He goes on to point out that the exceptions are those rivers which have an unlimited supply of fine material such as certain in northern China.

Deposition of suspended material will be a function of settling velocity for turbulent flow. This equation is:

$$V_s = \sqrt{(s - 1) \frac{4 g D}{3 C_r}} \qquad \text{(equation 5)}$$

where

V_s is settling velocity in centimeters per second

s is specific gravity of suspended material

D is grain diameter

g is the accelration of gravity (980 centimeters per second^2)

C_r is the coefficient of resistance (a function of the Reynolds number about .5 for a large range of Reynolds numbers above critical velocity).

Rubey (1933) utilized certain constants to solve the above equation for a size range of natural sediment grains. He assumed a particle specific gravity of 2.65 at a temperature of 16^o C. This predicts that a 10 mm diameter particle (.4 in.) has a settling velocity of 1 ft. per sec. (ft/s). A 100 mm (3.9 in.) is 3.5 ft/s; 200 mm (7.8 in.) is 5 ft/s;and 1,000 mm (39 in.) is 10 ft/s. When the energy imparted by the hydraulic lift of the velocity of flow exceeds a certain value, particles are detached from the bed and follow a trajectory through water. The distance carried will be a function of water turbulence, velocity of flow, and settling velocity of the particle. The velocity of flow at the base of the bed depends on the hydraulic radius in a rather complex way. The hydraulic radius is proportional to the average velocity which varies as $r^{2/3}$. The average velocity of the stream and the velocity at the bed is inversely proportional to the logarithm of the hydraulic radius (r). r becomes greater for a given discharge as the depth increases with a nearly fixed width. These relationships provide a basis for an optimum r, giving the greatest possible capacity to transport sediment and bed as a relationship between the width and increased velocity at the bed.

While many of these studies provide reasonably accurate estimations of sizes and the velocity of transported particles, they do not provide a base for predicting the overall quantity of sediment and bed load transported. The term 'sediment rating curve' is usually applied to a relationship that attempts to predict suspended sediment discharge from streamflow. These relationships often predict instantaneous suspended sediment concentrations in relation to instantaneous flow, or may predict suspended sediment discharge per day in relation to mean daily flow. Linsley, et al. (1975) points out that these relationships are only approximate. Given discharge may have a suspended sediment load varying from 20 tons to over 12,000 tons per day. This variation occurs randomly depending on the distribution of rainfall, several other runoff factors, and heterogeneous characteristics of usual basins.

Nelson (1971) related instantaneous suspended sediment concentration (mg/l) to discharge (cfs) in the Snohomish River basin in western Washington. For equal average winter flood flow on the Middle Fork of the Snoqualmie River, suspended sediment might vary from 80 to 600 mg/l (standard errors = 0.39 log units). The South Fork of the Snoqualmie River, which is substantially smaller, has a range of 30 to 300 mg/l for equal mean annual flood flows (standard error = 0.403 log units). Neither correlation coefficients nor coefficients of determination were reported for these graphic relationships. The maximum suspended sediment concentrations measured was 2,410 mg/l for the Tolt River, with a discharge of 660 cfsm when the sediment measurement was obtained. Maximum value for the Skykomish watershed (834 sq. mi.) was 784 mg/l with a discharge of 531 cfsm. Nelson concluded, "Only slight changes in sediment-transport pattern probably occur as a result of human activity."

The relationship between suspended sediment and discharge in other northwest streams is also poorly correlated for the total range of sediment and discharge measurements. Frequently, correlations are obtained for minimal levels of suspended sediment at moderate winter flows (100 cfsm and sediment 20-30 mg/l). In this range of discharge, usual erosional processes are taking place such as re-entrainment of fine bed materials, wash of dry ravel, abrasion of pebbles, rocks, etc. Once discharge exceeds a finite limit, random processes are initiated giving unpredictable relationships between increasing discharge and rapidly varying suspended sediment concentrations (Brown, 1972; Wooldridge, unpublished research, Clearwater River Basin, Washington). The flood flow dynamics of northwest rivers, as measured by unit land area, produce flood flows ranging up to 930 cfsm with many 50 to 250 sq. mi. river basins in the 200-500 cfsm range.

Summary of the discussion presented in this section reveals that the hydraulic radius, a combination of wetted perimeter and cross-sectional area in combination with slope of the free water surface, allows prediction of the size of bed load material that will be moved. This, in combination with flow velocity and predicted settling velocity, allows an analysis as to whether transportation of a particular piece of bed material will continue or deposit as bed load. A linear flow velocity of 5 ft/s is adequate to continue the transport of rocks up to an average diameter of

7.8 in. An average flow velocity of 10 ft/s is sufficient to transport bed of 39 in. in approximate diameter. Flood flow conditions on Redwood Creek which produce these lineal flow velocities make quantitative determination of discharge, suspended sediment and bed load transport physically impossible. It can only be assumed that the physical processes governing this transport are accurate, and when these flow velocities take place, the continuous supply of bed material in Redwood Creek will be transported.

HYDROLOGIC PROCESSES IN REDWOOD CREEK

Voluminous recent literature reviews on relationships of water quality and yield to forest harvest, slash burning, forest road construction, etc. are available (EPA 1975, 1976; USDA F.S. 1974). The degree to which any published research applies to Redwood Creek is unknown. Studies currently underway in Redwood Creek probably give the best overall indications of how hydrologic processes within the Redwood Creek watershed can be related to the state of our technical knowledge.

Transport of Suspended Sediment in Redwood Creek

Contrary to many watershed studies (Nelson, 1971; Brown, 1972), the suspended sediment load in Redwood Creek is very well correlated with streamflow. Seven storms (Janda, et al. 1975a) and three measurements (Winzler and Kelly, 1977) are plotted in Figure 1. These values give a range of suspended sediment from 123 to 8,200 mg/l with a discharge range from 180 to 50,600 cfs. The regression equation for this relationship is:

$$Qs = 4.615 \ Qw^{0.694} \qquad \text{(equation 6)}$$

where

Qs is instantaneous suspended sediment (mg/l)

Qw is instantaneous discharge (cfs)

The coefficient of determination is 0.92. Another equation relates daily sediment (tons/day) production to discharge (Janda, et al. 1975):

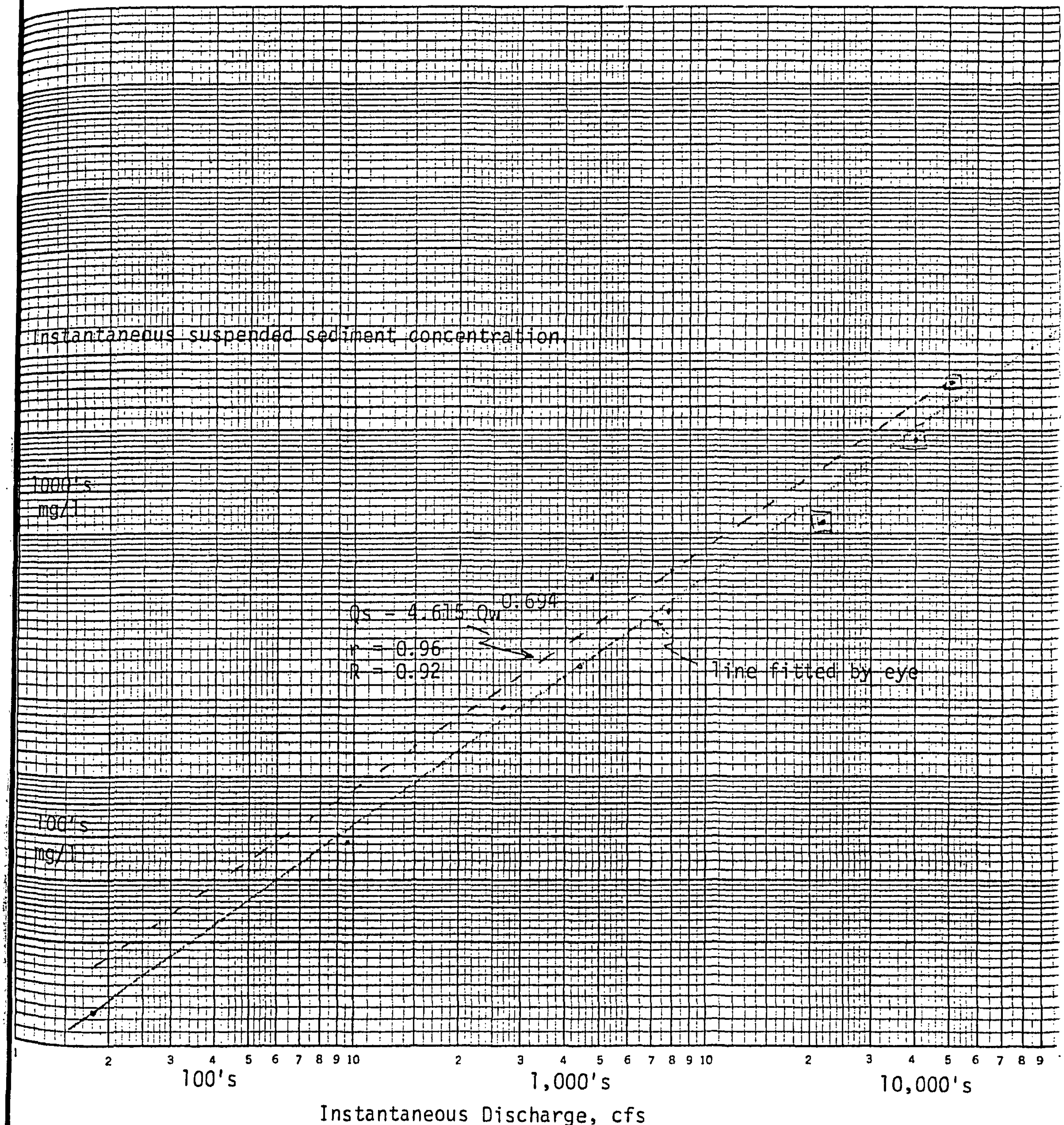
$$Qs = 0.0001 \ Qw^{2.2984} \qquad \text{(equation 7)}$$

where

Qs is instantaneous sediment discharge (tons per day)

Qw is instantaneous stream discharge (cfs).

Figure 1. The relationship between instantaneous suspended sediment concentration and instantaneous discharge (analysis by Wooldridge from data of Janda, et al. 1975a and Winzler & Kelly, 1977).



No coefficient of determination was given, but the graphic relationship is good. Daily suspended sediment discharge was related to mean daily stream discharge at Orick by the equation:

$$Qs = 0.0004\ Qw^{2.0772} \quad \text{(Janda, et al. 1975) (equation 8)}$$

This equation has a coefficient determination of 0.9958. A coefficient of determination of this magnitude gives a correlation coefficient of .998, a nearly perfect relationship. This means that wash load in tons/day of suspended sediment may be very accurately predicted by daily discharge.

Winzler and Kelly (1975) analyzed 423 suspended sediment measurements over the lower 37 miles of Redwood Creek. A regression equation was developed which shows suspended sediment concentration is:

$$SS = 2.01X + 337.2 \qquad \text{(equation 9)}$$

where

SS is suspended sediment in mg/l, and
X is distance in miles from the source.

This equation predicts an average suspended sediment concentration of 377 mg/l as a unit of water flows past the US 299 bridge. On arrival at MacArthur Creek near Orick, this same unit of water would have an increase of 3.3-fold in volume and a suspended sediment concentration of 455 mg/l. For example an acre-foot (ac-ft) of streamflow would transport an average of 1,026 pounds (pd) of sediment past US 299 bridge. Streamflow from the tributaries would increase the water volume to 3.3 ac-ft and a total sediment of 1,238 pd/ac-ft. Redwood Creek must entrain 700 pd (0.35 ton) of sediment per ac-ft of streamflow between these two points (in 37 mi.). An average discharge of 1,000 cfs at US 299 would carry 693 tons per day under the bridge. Flow of Redwood Creek at the mouth of MacArthur Creek would average 3,300 cfs and carry 4050 tons of sediment per day, an increase of 3,357 tons.

The same calculation for the mean annual flood which would have a flow of 5,100 cfs at US 299 bridge and 17,000 cfs at MacArthur Creek would carry 5,180 tons and 20,835 tons, respectively. This is an increase of 15,655 tons in 37 mi. of channel (423 tons per mi.). If the channel produced this suspended load uniformly, it would be a quarter of a ton per yard of channel length.

Equation 8 predicts a suspended sediment load of 171,480 tons per day at Orick for the same annual flood. If this sediment load is distributed as per the previous calculation, 42,630 tons would come from the upstream area and 128,850 from below Highway 299 bridge. If contributed uniformly over the lower 40 miles of river channel, this would be 1.83 tons per lineal yard of channel. Again, if the wetted perimeter of the channel produced this load, it would require about one inch in depth of material per square yard. On the average, the lower channel is in excess of 50% eroding banks with a substantial quantity of eroding material supplied from banks outside of the wetted perimeter. Many of the active earth flows must contribute several inches and possibly even several feet of eroding sediment and bed material during flood discharge. These calculations verify the fact that the channel of Redwood Creek is totally capable of producing the sediment load carried.

This thesis is supported by the recorded suspended sediment concentrations of Redwood Creek and tributary streams at comparable times. Almost without exception, Redwood Creek has several-fold greater suspended sediment concentrations than any tributaries (Winzler and Kelly, 1975, 1977; Janda, et al. 1975a). For example, storms between November 1973 and February 1975 had a range of sediment concentration in Redwood Creek from 123 to 2,340 mg/l. (Portions of these data are summarized in Table 4.) The only time a tributary had a greater sediment concentration was a flow of 1 cfsm in Redwood Creek (123 mg/l). Upper Miller Creek had a flow of 9 cfsm (200 mg/l). At the mouth, flow was 4.6 cfsm with 189 mg/l. In a

Table 4. Total Suspended Sediment, Average Suspended Sediment Concentrations, and Associated Rain for Redwood Creek and Certain Tributaries by Synoptic Events (adapted from Janda, et al. 1975a)

Stream	Area (Sq.Mi.)	Nov. 7 to 9, 1973 Rain (in.)	Nov. 7 to 9, 1973 Total Sediment (tons)	Nov. 7 to 9, 1973 Average Sus. Sed. Conc. (mg/l)	Feb. 28 to Mar. 3, 1974 Rain (in.)	Feb. 28 to Mar. 3, 1974 Total Sediment (tons)	Feb. 28 to Mar. 3, 1974 Average Sus. Sed. Conc. (mg/l)	Feb. 8 to Feb. 9, 1975 Rain (in.)	Feb. 8 to Feb. 9, 1975 Total Sediment (tons)	Feb. 8 to Feb. 9, 1975 Average Sus. Sed. Conc. (mg/l)	Feb. 12 to 14, 1975 Rain (in.)	Feb. 12 to 14, 1975 Total Sediment (tons)	Feb. 12 to 14, 1975 Average Sus. Sed. Conc. (mg/l)
Redwood Cr. @ So. Park Bound.	183.00	N. D.	38,430	1,800	N. D.	29,829	1,226	N. D.	21,960	2,260	N. D.	43,737	2,340
H. Weir Cr. 50% cut	2.96	2.6	385	724	1.4	21	71	1.0	6	94	1.7	65	82
Miller Cr. 95% cut	0.67	2.4	58	465	1.4	3	38	1.0	2	101	1.8	9	129
Miller Cr. @ Mouth 75% cut	1.36	2.2	231	635	1.4	12	87	1.0	8	249	1.7	95	603
Hayes Cr. 2% cut	0.58	1.6	N. D.	-	1.6	1	17	0.8	T*	5	1.4	1	18
Lost Man. Cr. 85% old cut	3.97	2.3	131	207	1.4	15	30	1.0	4	33	1.2	26	58
Little Lost Man. Cr. 5% cut	3.64	1.6	69	97	1.6	4	12	1.0	1	14	1.5	9	30
Geneva Cr. 100% cut	0.08	1.2	3	32	1.6	T*	15	0.8	T*	7	1.2	T*	9

*T = less than 0.5 ton

Peak Discharge per Square Mile	Nov. 7 to 9, 1973	Feb. 28 to Mar. 3, 1974	Feb. 8 to Feb. 9, 1975	Feb. 12 to 14, 1975
Redwood Cr.	43 cfsm	24 cfsm	26 cfsm	44 cfsm
Tributaries	60 to 90 cfsm	12 to 25 cfsm	7 to 15 cfsm	12 to 40 cfsm
Antecedent Prec., Prairie Cr.	9.62 in.	6.78 in.	6.03 in.	7.98 in.

range of flows from 978 to 8,000 cfs, average sediment concentrations in tributaries ranged from 3.2 to 20% of that in the main stem. These tributaries contain 5.1% of the watershed area upstream from Prairie Creek and contribute 0.1 to 2.3% (varying with storms) of the sediment carried by the main stem.

Tributaries reported with data summarized in Table 4 represent a variety of forest conditions ranging from about 5% cut to 100% clear-cut. The combined area of the tributaries (12.59 sq. mi.) is 6.9% of the watershed upstream from the south Park boundary. The average contribution of these watersheds to the suspended sediment load of Redwood Creek ranges from 0.9% to 2.1% averaging 0.7%. The fact that variation between storms does occur is indicated by the range in sediment production. Two storms of approximately equal hydrologic response (November 1973, February 12-14, 1975) had almost equal unit area contributions of runoff in Redwood Creek (43-44 cfsm). In the first storm, the combined production of the 6 tributaries was 2.1% of the total load carried by Redwood Creek. In the February 12-14, 1975 storm, with near equal discharge and total sediment load, the 6 tributaries only produced 0.4% of the total load of Redwood Creek (Table 5).

Reduction in sediment production may be attributed to the very rapid regrowth of vegetation of those watersheds which had sustained some degree of recent forest harvest. It must be emphasized, however, with all of these data that the determination of sediment contribution from tributary watersheds is a fraction of the error of determining the total suspended sediment load of Redwood Creek. These floods also have only one-sixth of the potential magnitude of transporting power of major winter floods such as 1964, 1972 or 1975. During major floods, the contribution of tributaries is even less significant than for the storm and flow data reported by Janda, et al. 1975a (Table 4).

Similar comparisons are made in Table 5 where the total suspended sediment in tons transported by Redwood Creek is compared to the total sediment production of the 6 tributaries for four storms.

The simple facts that suspended sediment concentration increases with progression downstream in Redwood Creek, and that suspended sediment concentrations during major storm flows are always many-fold greater in Redwood Creek than contributing tributaries, clearly identify the main channel of Redwood Creek as the source of suspended materials. Often, both the discharge and suspended sediment load of tributaries to Redwood Creek are within the 10% error of determination of these values for Redwood Creek. For example, if a 10% accurate estimate of discharge is assumed and a 30% accurate estimate of total suspended sediment load, then predicted discharge February 12-14, 1975 (Table 4) of Redwood Creek would range ± 805 cfs from the estimated 8,052 cfs (7,147 to 8,857 cfs). Total suspended sediment would range ± 690 mg/l from the estimated 2,340 mg/l (1,650 to 3,030 mg/l). The range in estimate of total suspended sediment in Redwood Creek would be 30,615 to 56,858 tons. The total contribution of suspended sediment of the 6 tributaries is 0.7% of the error of estimate and 0.4% of the estimated value for the February 12-14, 1975 storm.

The excellent relationship between suspended sediment concentrations and discharge of Redwood Creek suggests that physical processes eroding banks and re-entraining suspended and bed load are very uniform and predictable. The numerous massive earth flows provide an unlimited supply of fine material, leading to a capacity load for each stage of discharge with little difference in sediment concentration between rising and falling stages.

These relationships clearly identify the main channel of Redwood Creek as the most significant source of suspended and bed loads. This conclusion supports the conclusions of Harward and Youngberg (1977) and their identification of clay mineralogy in alluvial soils as identical with clay mineralogy of present day suspended loads in Redwood Creek. The suspended load has its origin either as material entrained in/or adjacent to the main channel or from abraision of bed load in the main channel.

The fact that alluvial deposits 3- and 4000 yrs. old have the same clay mineralogy as currently deposited alluvial and suspended materials transported in Redwood Creek indicates that ongoing processes are not new.

These data, coupled with the fact that no tributaries to Redwood Creek even approach the suspended sediment concentration or total sediment load, clearly identify the main channel as the source of sediment. If erosion, either surface or channel, were taking place in significant quantities from any tributaries (clearcut or not), these tributaries should produce sediment concentrations significantly in excess of those found in the main channel.

Others identifying increased sediment loads, as a result of forest road construction and forest harvest, report sediment concentrations in treated small tributaries in excess of the sediment concentration in the larger receiving tributary. The fact that this does not occur in Redwood Creek, and that the contribution of sediment from any particular tributary is within the error of estimation of the quantity in Redwood Creek, indicates that forest practices have an insignificant impact on Redwood Creek.

Table 5. Source of suspended sediment in the main channel of Redwood Creek and percent contribution of six tributaries with 6.9 percent of the watershed area (adapted from Janda, et al. 1975a).

Date	Redwood Creek So. Park Boundary	Total Sediment for Tributaries	
	Sediment (Tons)	(Tons)	% of Total
Nov. 7-9, 1973	38,430	819	2.1
Feb. 28-Mar. 3, 1974	29,829	53	0.2
Feb. 8-9, 1975	21,960	19	0.1
Feb. 12-14, 1975	43,737	196	0.4

Bed Load Movement in Redwood Creek

The bed load function of a given channel is the rate at which various discharges will transport different grain sizes of bed material. Bed material is defined as that part of the sediment load of the stream which is composed of particle sizes found in appreciable quantities in the shifting portions of the stream bed. Linsley (1975) states, "Accuracy of instruments for bed load measurement is so uncertain that field comparisons of the bed load formulas is very difficult. The validity of bed load formulas is, therefore, quite indefinite." Einstein (in Chow: Applied Hydrology, 1964) reviews numerous equations and procedures for estimation of bed load function and transport of bed load material. Few of these theoretical or empirical relationships would apply with any accuracy to Redwood Creek. It is possible, however, to use certain equations to predict the sizes of material which might be moved during certain flows in Redwood Creek and to apply these data to various reaches of Redwood Creek.

Three equations were tested for two discharge rates on USGS cross-sections 17 and 32 (17 at mile 12.5 near the Tall Tree Grove; 32 at mile 24.5 near the mouth of Panther Creek). These equations are (Shulits and Corfitzen, 1937):

$$D = 3{,}080\ (rs) \qquad \text{(equation 2)}$$

$$D = 4{,}770\ (Qs^{1/3}/w) \qquad \text{(" 3)}$$

$$D = 1{,}200\ (Q^{2/3}s/w^{2/3} \qquad \text{(" 4)}$$

where

D is the diameter in millimeters that can be moved

Q is discharge in cubic feet per second

s is slope in feet per feet

w is width in feet, and

r is the hydraulic radius, (a ratio of the cross-section area of the section to the wetted perimeter in feet.)

For particle size movement at the cross-sections and for flood flow of 50,000 cfs, and the mean annual flood at Orick, calculations are as follows:

	Cross-section 17		Cross-section 32	
Q(cfs)	35,640	25,400	26,800	15,280
S(ft/ft)	0.00171	0.00171	0.004509	0.004509
w(ft)	275	275	164	164
r(ft)	13.5	7.1	20.1	10.8

Predicted particle size for the 3 equations are:

	Tall Tree Area (17)				Panther Creek (32)			
	50,000 cfs		Mean Flood		50,000 cfs		Mean Flood	
	(mm)	(in)	(mm)	(in)	(mm)	(in)	mm)	(in)
Equation 2	71	2.8	37	1.3	279	11.0	150	5.9
3	68	2.7	61	2.4	144	5.7	119	4.7
4	53	2.1	42	1.7	169	6.7	111	4.3

The above calculations utilizing the three equations obviously do not give precise answers, but do indicate--based on discharge hydraulic radius and slope--there is a substantial difference in the two cross-sections for transport bed material. Flow energy in the vicinity of Panther Creek will transport rocks from 5 to 7 or 8 in. in diameter during a 50,000 cfs flood at Orick. The Tall Tree area, however, will only transport rocks with diameters in the range of 2 to 3 in. The mean annual flood will transport rocks from 4 to 6 in. through the Panther Creek cross-section, while the Tall Tree area will transport rocks from 1½ to 2 in. in diameter.

The difficulty with these types of calculations is the assumption that slope of the free water surface stays the same for the various discharges. The free water surface of Redwood Creek has varying slopes with varying discharge rates. The high water level of the long return interval flood may be controlled by factors which are not operable during lower flow periods. It is assumed that the level of the free water surface changes about 12 ft. at the Tall Tree Grove with a flow of 50,000 cfs at Orick. If there is a downstream constriction in the channel, which causes a greater than 12 ft. rise in stage, then the hydraulic radius would be reduced causing finer bed materials to be deposited.

Changes in slope of the free water surface in a stream, such as Redwood Creek, can be caused by several types of energy dissipation. Leopold (1964) defines three appropriate types. One, "skin resistance" depends on the given shape and size of the cross-section and the roughness of the boundary surface. In a stream such as Redwood Creek, which has very substantial changes in stage during flood flow, skin resistance as a boundary effect can be greatly increased by vegetative growth or decreased by earth flows, as Redwood Creek leaves its normal channel with increasing stage. A second type is "internal distortion resistance." This may be caused by bars, bends, boulders undulating in the bed or protuberances from the bank which increase turbulence and eddies. In open channels, the internal distortion resistance may be much greater than skin resistance. Excellent examples of this type of resistance are found in the area termed "the gorge" just downstream from the south boundary of Redwood National Park. The third type is termed "spill resistance." Energy is dissipated by a sudden reduction in velocity caused by very tight curvature of the channel or other types of obstructions. Excellent examples of spill resistance occur about a half mile downstream from Copper Creek and in reach 5 above Lacks Creek. Old massive earth flows have obstructed the flow of Redwood Creek causing very abrupt turns in the channel. During flood flow, these obstructions cause a substantial increase in the free water surface reducing slope and reducing the hydraulic radius.

The previous analysis of factors influencing the size of bed load movement indicates when all else is held constant, the hydraulic radius is the determining factor. Calculations of the change in hydraulic radius with increasing stage were made for 3 of the USGS cross-sections. Cross-section 3 is near mile 5 from the mouth of Redwood Creek. It has a stream width of about 350 ft. and an expected change in stage (for 50,000 cfs) of about 20 ft. This would give an average flow velocity of slightly more than 7 ft. per second during peak flows. In this section, the hydraulic radius approximately equals the depth of flow. With an increase in stage to 10 ft. a hydraulic radius would be 9.4. An increase in stage to 20 ft. would give a hydraulic radius of 17.9.

Cross-section 32 occurs near the mouth of Panther Creek at mile 24.5. Here an increase in stage of 10 ft. would give a hydraulic radius of 8.9. An increase in stage of 20 ft. would give the hydraulic radius of 16.0.

A confined area of channel with a gravel bed width of 60 ft. upstream from Copper Creek gave a hydraulic radius of 8.3 with a 10 ft. increase in stage and 13.8 with a 20 ft. increase in stage. Equations for prediction of the size of bed material which might be moved by varying sets of stream conditions must also interact slope. Upstream cross-sections were over twice as steep, 0.005 ft/ft compared to 0.002 ft/ft.

Calculations on bed movement by Leopold, et al.(1966) show larger flow is required to move particles of a given average size which are closer to one another than if they are spaced far apart. The influence of spacing decreases with increasing size becoming negligible for spacings greater than about 8 diameters. For example, a discharge of 11 cfs per foot of channel width would not move a 500-gram particle if spaced at 1 diameter, but the same discharge would move 5,000-gram particles if spaced more than 5 diameters apart.

Extrapolation of these data to Redwood Creek shows that the average velocities in cubic feet per second per foot per channel range from 59 to 160 cfs per foot for the mean annual flood of 28,500 cfs. For peak discharges of 50,000 cfs, these same values range from 74 to 247 cfs per foot of channel, based on cross-sections of the Redwood Creek channel (Janda, et al. 1975). These data also suggest that Redwood Creek has adequate flow energy to move substantial amounts of bed load.

Verification of these calculations are confirmed by Data Release No. 1 (Iwatsubo, et al. 1975). On January 17, 1974, a discharge of 1,549 cfs in Redwood Creek near Blue Lake had only 40% of the total sediment load smaller than 2 mm with the balance (60%) up to 2.5 in. (64 mm) in size. On April 3, a lesser discharge of 1,120 cfs had bed load particles up to 3 in. (76 mm) in size with 10% of the total bed load between 1.3 and 3 in. (32 and 76 mm). Redwood Creek at Orick with discharges ranging only up to 4,670 cfs frequently had sediment load with sizes up to 1.3 in. (32 mm) in diameter. Similar data (Iwatsubo, 1976) show Redwood Creek at Redwood Valley bridge near Blue Lake having material up to 3 in. (76 mm) in diameter on two occasions in February and up to 2.5 in. (64 mm) in diameter on March 22, 1975. This particular storm had instantaneous discharge of 2,350 and moved a total bed load of 14,700 tons per day. The mid-February storm had 1,850 cfs near Blue Lake with 6,430 tons per day of bed load. Downstream at Redwood Creek, at the south boundary of the Park near Orick, discharge was 7,180 cfs with 3,430 tons per day. A little farther downstream, on a declining stage, Redwood Creek above Harry Weir Creek had a discharge of 6,030 cfs with 18,200 tons of bed load per day. This material ranged in size to 3 in. (76 mm).

The late March 1974 storms (Winzler and Kelly, 1975) show close correlation between increases in suspended and bed load transport with bed load averaging up to about 40% of the total load. Accurate bed load data are extremely difficult to obtain, particularly for peak storm discharge.

For the flood discharges used in the previous calculations of diameters of bed load, mean flow velocity through cross-sections ranges from 5 to 12 ft. per sec. (3 to 8 mi. per hr.). Average flow velocities of this magnitude sustained for the duration of a flood flow equivalent to the mean annual flood in December 1955 would provide sufficient time for suspended material to travel from 128 to 250 miles. Even bed material moving at one-quarter the rate of suspended material could travel 30 to 60 miles down the stream channel. Verification of these calculations are supported by published data from both Redwood Creek (Iwatsubo, et al. 1975-1976) and the 1964 flood on the Eel. The increase in discharge of the Eel River from less than 5,000 to over 750,000 cfs with a 90-ft. rise in stage transported a tremendous sediment load. Fifty-five percent (55%) of the total suspended sediment discharge of the Eel for over 8 years took place in 3 days, estimated a 116 million-ton deposition during the flood with only 94 million in the previous 8 years. The bed load component varied between 10 and 40% of the total transported material (Helley and LaMarche, 1973).

Typical of the very dynamic forested watersheds in steep mountainous terrain, massive amounts of sediment discharge can occur in a very brief time. The potential energy of a particular watershed may be estimated by the unit area flood discharge. Redwood Creek has maximum unit area discharges of 240 cfsm. Streams in the Pacific Northwest, particularly on the west coasts of Oregon and Washington, range to 300 and 400 cfsm in estimated 25- to 50-yr. recurrence interval flood flows. During such storms, thousands of yards of channel can be eroded. In some cases (the Hoh River), the channel might move three-quarters of a mile to a new location across the flood plain, leaving the previous channel dry. Downstream channel reaches will pass millions of yards of sediment without a significant change in appearance. The dynamics of these massive transports of sediment are purely a function of the streamflow energy resulting from a large free water input into the basin as rainfall or combinations of rain on snow.

The close correlations between discharge of Redwood Creek and suspended sediment yield suggest equally good relationships should exist for suspended sediment and bed load transport, even though to date these relationships are poorly documented. For a flood flow, such as the 1964 flood, about one million tons of suspended material should have been transported past Orick, with a mean daily flow of 43,200 cfs (Janda, et al. 1975, equation 8 of this report). If approximately 40% of the total load is bed load, then bed load yield should have been 665,000 tons with a total sediment load of 1,660,000 tons. Undoubtedly, most of these calculations are conservative, as it may be anticipated that extended periods of wet weather result in more active movement of earth flows, thus departing from the average conditions which can only be measured during less intensive rain storms and lesser stream flow.

Again, using equation 8 (Janda et al. 1975), the mean daily discharges of Redwood Creek at Orick for the December 21 to 24, 1964 flows were used to calculate a total suspended load of 2,230,000 tons. If the usual relationship between suspended and bed load exists, then the total sediment yield would have been 3,720,000 tons with 1,490,000 tons of bed transported. Adequate data on sequential sampling are not available from the recent Data Releases (Iwatsubo, et al. 1975, 1976) to verify these relationships for more recent storms. The mean daily flow of 38,500 cfs on March 22, 1975 should have had a predicted yield of 664,000 tons of suspended sediment. No estimate of bed load movement is given for that date.

A storm on February 9, 1975 produced 6,900 tons of bed load with an average discharge of 4,770 cfs (sediment at the south Park boundary discharge at Orick). This discharge would have a predicted (equation 8) suspended sediment load of 10,268 tons per day. If the bed load discharge was equal at Orick, the total load would have been 17,170 tons of which the 6,900 tons of bed load are equivalent to 40%.

These data lead to the conclusion that Redwood Creek is probably near capacity for suspended or wash load during any period of storm runoff. The little data available would indicate that this wash load will entrain approximately a 40% bed load.

The conclusion formed from these analyses is that Redwood Creek is unique in that it has available a near saturation capacity of fine material from exposed earth flow adjacent to the channel. It also has continuously available bed load from the channel for a capacity load in equilibrium with the energy provided by a discharge rate.

Equations 6, 7 and 8 establish very predictable relationships between instantaneous suspended sediment concentration and instantaneous discharge (equation 6); instantaneous sediment discharge in tons per day and instantaneous stream discharge (equation 7); and production of sediment on a daily basis (equation 8). The nearly perfect correlation exhibited by equation 8 identifies that very predictable physical processes, associating suspended sediment and discharge, are taking place in Redwood Creek. Only 0.004% of the variation in daily sediment production is not accounted for as stream discharge increases and decreases. Equation 9 identifies the main channel of Redwood Creek as a prime source of suspended sediment.

The identification of soil mineralogy (Harward and Youngberg, in Winzler and Kelly, 1977) over the past 4 or more thousand years offers conclusive evidence that current physical processes in Redwood Creek are those that have endured for several thousand years. Suspended sediments occurring as wash load in Redwood Creek have their origin in materials adjacent to or in the channel, and these minerals are identical to minerals occurring in successive depositions in 4000-yr. old alluvial soils--indicating no recent change in sedimentation-erosion relationships of Redwood Creek.

These data are also confirmed by the fact that peak flow data of Redwood Creek always have higher suspended sediment concentrations than samples taken simultaneously from tributaries. A high percentage of the Redwood Creek watershed discharges directly into Redwood Creek, rather than through a tributary system, providing both the source for increased stage and sediment.

As Redwood Creek has a saturation capacity of both fine and bed material in and adjacent to the channel, transportation of this material will be a pure function of flow velocity and discharge rate. Travel velocity for sediment moving in Redwood Creek will accelerate on rising stage to a maximum velocity at peak flow and decelerate and deposit on falling stage. The wash load will flush the watershed during the mean annual flood. Floods of the magnitude of the 1964 flood provide sufficient energy to transport bed load rocks 2 to 3 in. in diameter 30 to 60 mi. The configurations of bars and bed of the channel of Redwood Creek following major floods are purely factors of the streamflow dynamics, caused in combination by geologic and climatic factors and independent of Man-caused effects.

Entrainment of sediment and deposition of this load is a function of energy acretions from slope or channel roughness and dissipation in relationships to the slope of the free water surfaces, caused by resistance of skin (vegetation or boundary effects on the wetted perimeter); internal distortion (bars, bends, boulders, etc.); and spill (factors of the channel which would cause a hydraulic jump and reduction in velocity).

The above resistances are not constant but vary with varying stages of discharge. Thus, a spill resistance might be effective in a particular reach of channel at a flow of 50,000 cfs, resulting in substantial deposition of bed load, where it is not equally effective at a flow of 20,000 cfs allowing continuous transport of bed load or possibly even substantial scour.

FOREST PRACTICES AND HYDROLOGY OF REDWOOD CREEK

Redwood Creek will obey physical and theoretical laws which govern relationships between forest harvest, stream flow and water yield. In combination, hydrologic factors and processes affected demonstrate increased water yield, as stored soil moisture usually lost from the watershed by evapotranspiration is conserved for release as stream flow during summer dry periods and initial recharge of the soil profile in the fall. Forest Service research on Casper Creek near Ft. Bragg (Rice, personal communication) verifies that increased peak flows from early fall rains occur during the soil recharge period, but peak flood flows from major winter storms are not affected by forest harvest. These results have been obtained on experimental watersheds in humid, temperate coniferous and hardwood forests across the Nation (Hibbert, 1967; Hewlett and Helvey, 1970; Rothacher, 1973: Gilleran, 1968; Harper, 1969; Harr, et al. 1975; Harris, 1973).

Forest hydrology research on experimental watersheds measures stream discharge through flumes or weirs with a 98- to 99% accurate estimate. Even on research watersheds, usually 30% of the basin area has to be treated (clearcut) in one year before statistically significant increases in water yield can be measured. Most research data on hydrologic impacts of forest harvest are from small experimental watersheds (0.3 to 2 sq. mi.), where a single 100% area treatment impacts the total watershed.

The few studies that have utilized published surface water records (USGS) in analysis of impacts of forest harvest of water yield have been inconclusive. Even urbanization studies utilizing surface water records have difficulty in establishing either increases in instantaneous peak flows or yield (Wooldridge, et al. 1975). Maytin and Tinney (1962) concluded that logging 64% of the Naselle watershed over 27+ years had negligible influence on water yield or base flow. Wooldridge (unpublished research) found similar results for the Wynoochee after 60% logging and repeated wild fires through the late 1930's.

Two factors contribute to these negative results: one, all of the above studied progressions over many years so that percentage of the watershed impacted was not sufficiently large to cause a significant hydrologic change, and two, stream gauging to a 90% accuracy is not sufficient to detect a change in hydrologic regime.

Consideration of gross hydrologic impacts of forest harvest can be analyzed in terms of the individual hydrologic processes which might be affected--interception, transpiration and infiltration. The initial hydrologic impact of felling a timber stand and yarding of logs is reduction of interception and elimination of transpiration losses. Forest interception studies have been reviewed by Zinke (1967) with the conclusion that interception represents a loss of precipitation which would otherwise reach the forest soil. This loss can be subdivided into interception storage and evaporation during the storm. Interception storage varies from 0.02 to .36 in. depending on species, stocking and age of the forest stand. Interception losses may be large in regions of frequent light rain and/or high evaporation. Interception losses are usually low in regions of low evaporation or where they are compensated by fog or cloud drip. He concludes, "It is questionable whether the interception of precipitation always presents a loss to the yield of water from an area." From a pure energy balance point of view, moisture intercepted in the canopy of a tree from rainfall may reduce a subsequent demand for stored soil water which would pass through the tree as a transpiration loss. In any event, the total magnitude of interception (.2 to .4 in. in storms of 5-10 in.) of a mature Redwood forest is insignificant in a long duration, intense winter storm.

The most significant influence of removal of the forest canopy is reduction in transpiration losses during summer dry periods. In order for this hydrologic mechanism to be operative, the soil must be deep enough and have an adequate moisture storage capacity so that evaporation losses from the soil will not be equivalent to the conservation of transpiration losses. Shallow soils (less than 30 in.) in the environment of Redwood Creek would not produce increased water yields, as evaporation from the soil would equal or exceed the conserved transpiration losses. The duration and magnitude of conservation of transpiration losses is dependent on the rapidity of re-establishment of vegetation and potential evaporation. Rapidly sprouting species, such as Redwood, ceanothus, willows, tan oak, vine maple, etc. or rapid establishment of primary invaders (red alder) greatly reduce and shorten the duration of anticipated increases in water yield resulting from harvest of forest stands.

Theoretically, the water yield increase following harvest of a forest stand should be a direct proportion of the potential increase attainable and the percentage of the area treated. Forest hydrology research usually treats 100% of small watersheds to identify the maximum potential impact on water yield increase or water quality. These water yield increases range from a fraction of an area inch in arid areas of Arizona to 18 to 22 area inches on the H. J. Andrews (Rothacher, 1970a). The occurrence of average or smaller than average rain storms and combined impacts of reduced interception and reduced transpiration produces significant water yield increases during small storms--a type of impact consistently identified in forest hydrology research (Harr, 1976; Harr, et al. 1977; Rothacher, 1970a,1973).

The basis for understanding that annual runoff in area-in. of a forest basin may be increased by forest harvest without impacting peak winter flood flow depends on an understanding of pathways of water movement in a basin and sources of water to streams. The hydrology of forested watersheds is best described by Hewlett and Troendle (1975) where careful discussion is given to the concept of a "variable source area" of stream flow as opposed to the Hortonian concept (1945) that overland flow or surface runoff dominated the rainfall-runoff process.

Foresters have long noted that surface runoff or overland flow does not occur in forests, even in very humid areas such as the western Olympics following extended periods of intense rainfall (0.4 to 0.6 in. per hr. for 24 hrs.). Storm runoff occurs in part from a small percentage (3%) of channel interception of rain but continues to increase because of subsurface flow to the stream. A very dynamic moisture storage zone expands due to downslope movement of soil water, increasing free water in seeps, draws and a shallow zone adjacent to the stream. Downslope movement of soil moisture is due to the cohesion between water molecules, so that movement of soil water is under slight tension. This slight tension draws water downslope in response to hydraulic gradients, more or less parallel to the slope surface of the soil.

LaRock (1967) has shown that forest soils can infiltrate and transmit water at a rate equal to the rainfall rate. A 1.1 in. rain storm had peak intensities of 0.2 in. per hour. The peak flow rate 16 in. deep in the soil was 0.18 in. per hour, declining to 0.02 in. per hour 48 hours later. Moisture content changed from 19.5% to 17%.

The soil matrix may be viewed as a continuum of random sized pores in which soil water flows as a film in close contact with the surface of soil particles. A free water input on the soil surface from rainfall or snowmelt releases downslope moisture for flow through the soil profile to the stream. The soil water system is very dynamic and responsive as indicated by an increase in soil moisture flow 16 in. deep in the soil, resulting from less than 0.05 in. of rain on the forest canopy. Wetting the forest canopy reversed the tension gradients, allowing increased moisture to flow through the soil profile when transpiration demand was eliminated.

Climatic and soil conditions comparable to Redwood Creek occur in the coastal areas in Washington and Oregon. The H. J. Andrews, Alsea basin, Naselle River and Clearwater River of the Olympics offer comparable rainfall and humid forest conditions. Forest soils in this humid zone have infiltration and percolation rates which range from a few tenths of an inch per hour to hundreds of inches per hour (Brown, 1972).

Harr and Yee (1975) in central coastal Oregon studied two soils series formed from the Tyee sandstones. Movement of water was predominantly subsurface as unsaturated flow, even in 1973-74--one of the wettest years on record for the area. In a later report, Harr (1977) studied a forested slope in western Oregon which averaged 75% (36.9^{o}) ranging from 50% near the ridge to 110% adjacent to the stream. Saturated hydraulic conductivities ranged from 13 to 16 in./hr. in surface soils to 0.06 in. per hr. in the subsoil (40-60 in.). Ninety-seven percent (97%) of the storm runoff reaching the stream channel occurred as subsurface flow with only 3% as channel interception.

Detailed inspection of several recent clearcuts (Figure 2) revealed no indications of surface runoff, overland flow or soil erosion, even on severely disturbed fire lines cut by tractors. Examination of older tractor logged areas (Figure 3) in the upper drainage of Redwood Creek also indicated a general absence of overland flow and surface soil erosion on a very high percentage of the tractor disturbed areas. Figures 2 and 3 both indicate rapid resprouting of native plants; similar new growth also establishes rapidly on old logging roads (Figure 4).

A general lack of surface runoff is also supported by evidence in the Earth Satellite Corporation (1972) photo review of conditions in Redwood Creek. Figures 8 through 21 show various views of a tractor logged, 320-acre clearcut on Bridge Creek. The area was logged in 1970-71 and broadcast burned in October 1971. Authors of the report did not identify any areas of surface soil erosion in spite of the fact that the 3 months prior to the date the photos were taken (January, February and March) were the third wettest 3 months on record for Redwood Creek. A flood with an estimated 10-yr. recurrence interval occurred on January 22 (45,350 cfs) only to be followed by a flood with an estimated 20-yr. recurrence interval (49,700 cfs) on March 3, 1972. Figure 10, in this series, demonstrates that erosion with an unknown exact source in the forest is definitely different from erosion from the channel or bed of Bridge Creek.

When rainfall rates exceed the infiltration capacity of the soil, dramatic surface runoff and surface soil erosion occur.[1/] An example of this is shown in Figure 5 where a high intensity rain produced surface runoff on an area of recent wild fire in eastern Washington. Rilling with massive amounts of soil erosion occurs throughout small basins, concentrating flow in draws, causing mud flows and flooding in larger tributaries. An estimated 103 tons of soil per acre were eroded from this hillside in Figure 5.

If surface runoff or overland flow were occurring in Redwood Creek, the evidence would be equally obvious. In the Earth Satellite Corporation report, particularly Figures 8, 9, 10, 12, 13, 14 and 15 show some erosion from concentrated flow on a tractor road which washed to water bars. The soil infiltration capacity of even disturbed, tractor logged clearcuts, as shown in these and other figures, is attested to by the lack of evidence of surface runoff and surface soil erosion--even though the three previous months had the third greatest stream runoff on record (45 in. of runoff in January, February and March with 14 in. in the previous December) and two long return interval floods in a 6-wk. period. These same observations and comments are appropriate for other photographs in the Earth Satellite Corporation report. Figures 44 and 44a show an area which has been cleared

[1/]The author has been studying these phenomena for over 20 years.

for a log deck. There are no indications of surface runoff or surface soil erosion from this area. Figures 72, 73 and 76 also indicate good infiltration and a lack of surface runoff. Other figures shown in the report indicate that large amounts of runoff came from undisturbed areas (Figure 41), so it should not be surprising that large amounts of runoff also would come from other disturbed areas, as the March 3, 1972 flood was the largest flow since the December 22, 1964 flood.

Obviously, large amounts of surface runoff occurred from some of the prairie soils, and mass failures did occur due to plugging of culverts on both forest and public roads.

Although there is voluminous literature relating forest roads and water quality (EPA, 1975, 1976), few site specific conclusions can be gleened as to the potential impact of forest harvest roads outside of the area on which the research was accomplished. In most research reported, results have been confounded by long return interval rain storms, where very significant impacts of roads on erosion occur (Dyrness, 1967) or the lack of intensive rain storms, where negative or inconclusive results are reported (Wooldridge, ongoing studies). Those categories of results in between indicate a rapid hydrologic return to pretreatment conditions (Harris, 1973).

Data available indicate that forest roads are usually the prime source of increased suspended sediment, their impact lasting for a few years in humid forest conditions. Much of the literature concerning impact of forest roads has resulted from analyses following long return interval rain storms. Rothacher and Glazebrook (1968) found that most culverts were hydraulically adequate for the 50-100-yr. rain storm. The major problem during record breaking storms (such as 1964-65) was culverts failing because of impairment of flow plugged by debris.

Reported impacts of forest harvest roads on water yield or timing of flow are conflicting and unresolved. There is general agreement that the forest harvest road system far overshadows logging, fire or related activities as a cause of accelerated erosion. Roads frequently trigger mass failures (Dyrness, 1967); however, as previously stated, many of the studies of road failure have followed long return interval rain storms. Rice et al. (1972) states, "Because of the diversity of species within a natural forest ecosystem, bare areas are quickly invaded by pioneer species and initially high rates of sediment production decline rapidly." Erosional recovery does not require the return to pre-disturbance conditions, but rather to the cessation of accelerated erosion which occurs much sooner.

Forest Harvest and Water Yield in Redwood Creek

The hydrologic regime of Redwood Creek suggests that usual rainfalls are infiltrated with a subsurface flow of soil water to free water surfaces in or adjacent to streams. Moisture flows through the subsoil predominantly in an unsaturated state under a slight tension. Saturated flows may occur in very limited areas at the bottom of slopes in close proximity to the stream. Numerous mathematical models (Fox, 1976; Freeze 1972a, 1972b; Stephenson and Freeze, 1974), field studies (Weyman, 1970, 1973) and observations (Whipkey, 1965, 1969) support this conclusion. Redwood Creek will behave similar to the Alsea basin, H. J. Andrews and the Clearwater River, and these results can also be extended to humid coniferous forests in other areas.

The progression of logging in Redwood Creek as reported by Miles (1975) is:

Pre- to 1955	22%	35,100 acres
1956 to 1965	29%	46,800 acres
1966 to 1975	22%	35,100 acres

Thus, of the 248-sq. mi. of Redwood Creek upstream from Prairie Creek, 73% has been logged, either clearcut or selection. It is suggested (Miles, 1975) that the conversion of old growth Redwood stands will continue at approximately this rate, 2.4% or 3,800 acres per year. Hydrologic recovery takes place rapidly in Redwood Creek through sprouting of numerous species, replanting schedules currently used, and invasion of disturbed areas of the forest stand by other plants. If the re-establishment and hydrologic recovery is linear for 5 yrs., then a 20% recovery will be anticipated each year following timber harvest. Thus, if the current acreage is clearcut, 3,800 ac., then the previous year would have recovered 20%; 2 years prior, 40%; and 3 years prior, 60%, etc. giving a total impacted acreage for any given year of 11,400 acres.

Areas of clearcut can anticipate a water yield increase equivalent to 1% per percentage of watershed clearcut of the potential total water yield increase. Water yield increases in similar coastal climates vary from 14 to 16 in. on the Alsea studies to 18 to 22 in. on the Andrews, larger yields occurring during wetter years. It is assumed that total potential average water yield increase in Redwood Creek is 1.25 ac. ft. per acre of clearcut (15 area-in.). Then, 14,250 ac.-ft. (11.400 ac. x 1.25 ac-ft/ac) of increased water yield can be anticipated for the average year. Redwood Creek upstream from Prairie Creek produces an average of 718,665 ac.-ft. of runoff. The potential water yield increase from forest harvest is 1.98% of the total runoff above Prairie Creek, or 1.77% of the long time average runoff of Redwood Creek at Orick.

If this runoff were to occur as sustained even flow, it would have an average increase for the year of 19.7 cfs/day. Forest hydrology research indicates that low flows can be substantially increased on a percentage basis. Thus, late summer and early fall flows are augmented.

Mean daily streamflow declines through April, May, June and July to the lowest two months--August and September--which average about 40 cfs daily flow. These two months would have the highest percentage response if the anticipated 19.7 cfs resulting from forest harvest were to occur. October averages 204 cfs mean daily flow with a range from 24 cfs (1964-65) to 1,559 (1962-63). On dry years such as the fall of 1964, the augmentation of streamflow would be very beneficial. On wet years, such as the fall of 1962, addition of 19.7 cfs to a mean daily flow of 1,559 is insignificant. With progression in the water year, mean daily flows for November and December are 1,186 and 2,470 cfs, respectively. Obviously, the augmentation of flow which might occur due to forest harvest is outside the accuracy of determination of mean daily flow during late fall and early winter.

The conclusion that forest harvest has had an insignificant impact on the water yield of Redwood Creek, based on the foregoing analysis, seems to question reported rainfall-runoff results by Lee, et al. (1975). A brief analysis of the study by Lee, et al. might be worthwhile. Their abstract states, "These comparisons indicate the runoff increased about 20% as a result of change in hydrology and not as a result of climatic change." These predicted results were for 1968, -70 and -72. If these predicted results are accurate, then they should be valid for the 1970 through 1975 period also. A 20% change in the hydrology of Redwood Creek should apply to the total basin for all of the years, not just for the selected data used in their study.

A 20% increase averaged for water times and years 1970 through 1975 predicts 193,490 ac/ft increased yield. This is equivalent to 13.1 area in. for the entire Redwood Creek watershed or equivalent to 19+ in. of additional runoff from all of those acres which have ever sustained a forest harvest operation--1940's to 1975. Obviously, an increase in flow of this magnitude is physically impossible, as runoff would frequently exceed rainfall.

Evaluation of the methods used by Lee, et al. suggests that there are several inappropriate uses. First, the basic method (Kohler and Linsley, 1951) was developed to accommodate "special problems encountered in flood forecasting." Kohler and Linsley emphasize that the technique used is one of estimation of a volume of runoff to be expected from a given volume of rainfall in the fundamental problem of flood forecasting. Methods used by Lee, et al, which selected storms only during the storm season, eliminates most of the potentially significant impacts of forest canopy removal, i.e., conservation of transpiration losses. The assumption that the initial magnitude of base flow was equal to runoff on the day before the storm (equivalent to 0.98 recession coefficient) is obviously greatly in error for a dynamic watershed such as Redwood Creek during the storm flow season. Use of a surface runoff coefficient in a forested watershed is totally erroneous. The assumption that the calibration periods (1954, -56 and -58) preceded intensive logging is in error based on Miles' (1975) report. It would seem that by 1958, 54,120 acres of the upper watershed had sustained forest harvest. Also, this is the portion of the watershed upstream from Prairie Creek, and as previously indicated, these headwaters receive 1.5 times as much annual precipitation as downstream areas in the watershed. This is probably one of the most serious problems with the method used, as spatial distribution of rainfall over the watershed varies within and between years. For the years used for calibration, rainfall was relatively uniform ranging from 80 to 90 in./yr. It might be anticipated that distribution of rainfall when uniform is random for those years. The years used for testing of treatment effect had a range in rainfall from 54 to 72 in. including one of the lowest runoff years of record. Certainly, rainfall patterns were not consistent with those of calibration years--a fact that could very easily throw systematic error into a runoff model, particularly a model which was not designed for repeated use and accumulating runoff sums. Errors in predicting rainfall-runoff relations for short term discrete storm runoff events may be acceptable. However, these errors are obviously systematic when used for consecutive storm periods.

In summary, the value of rainfall-runoff relations as described by Lee, et al. is unknown. Prediction of a 20% increase in runoff from streamflow data that have a potential 10% error leads to a number of uncertainties. The fact that the Redwood Creek watershed has strong orographic influences, which coincided with early areas of logging, suggests that upstream areas inherently have higher water yields than downstream areas, and any increases in yield from forest harvest were incorporated as calibration. The calibration for pretreatment years, as assumed by Lee, et al., is grossly in error as progression of forest harvest has, on the average, removed 2.4% of the forest canopy per year since the mid-'40s. The hydrologic condition of the Redwood Creek watershed, at least as far as progression in acreage of forest harvest, is equal for both the calibration and treatment period--only later cutting is mainly in northern portions of the basin.

It must be concluded, until proven otherwise, that Redwood Creek essentially responds in a pattern very similar to experimental watersheds studied in the humid, temperate, coastal forest regions in Oregon and Washington. The hydrologic impacts of forest harvest reduce interception loss, making insignificant amounts of precipitation available for storage in the soil. More importantly, forest canopy removal eliminates transpiration loss which increases the amount of stored soil water available for streamflow during summer, early fall and winter recharge periods.

Detailed analyses of non-saturated flow research in forest soils indicate a potential for transmission of rain as flow through the soil at a rate which will satisfy storm runoff. Detailed study of these processes has been accomplished on plots and reported. These plot data are now being extended to experimental watershed data (Wooldridge, et al., benchmark studies, western Olympics), which to date verify the concept of contribution of subsurface flow to streamflow at rates which satisfy both minimum and maximum streamflow rates (up to 300 cfsm).

Experimental watershed studies using control discharge sections (flumes and weirs) with a 98- to 99% accurate estimate of discharge have identified increased water yields, but failed to document impacts on peak flood flows.

Until additional technical hydrologic data are available, which contradicts these published research findings, it must be assumed that Redwood Creek is part of the normal population of humid forested watersheds and will respond hydrologically in usual flow patterns. Research in the Redwood forest type at Casper Creek confirms this conclusion.

Forest Harvest and Flood Flows of Redwood Creek

Errors inherent in gauging station operation and estimation of discharge indicate that for much of the year, the magnitude of potential water yield increase due to forest harvest is much less than the precision of streamflow measurement. A magnitude of error expressed as a confidence interval for a set of data might have an accuracy of ± 10%, 95% of the time, corresponding to data termed 'good' by the USGS. A single storm that occurred between March 17 and 20, 1975 could have an error of estimation of runoff of 13,900 ac.-ft.

This storm had a calculated water yield of 138,920 ac.-ft. An accuracy of ± 10% would suggest that the true runoff ranged from 125,000 to 152,800 ac.-ft. The potential water yield increase of 14,250 ac.-ft. can certainly be absorbed in the uncertainty of the true runoff for these four days of flow of Redwood Creek.

The magnitude of impacts of forest harvest on flow of Redwood Creek can be related to changes in stage and changes in flow rate. The rating curve for Redwood Creek for water year October 1974 to September 1975 gives the following approximate relationships of change in stage to change in discharge:

Stage (ft.)	Discharge (cfs)	Average Change in Flow Per 0.01 ft.	Stage (ft.)	Discharge (cfs)	Average Change in Flow Per 0.01 ft.
10	5,600	13	17	23,000	30
11	6,900	17	18	26,000	30
12	8,600	21	19	29,000	30
13	10,700	23	20	33,000	40
14	13,000	31	21	38,000	50
15	16,100	39	22	43,000	40
16	20,000	30	23	47,000	50

Through the range of these discharges for Redwood Creek at Orick, it is apparent that a change in stage of .01 ft. will induce a variation in estimated discharge ranging from 13 cfs at a 10-ft. stage to 50 cfs at a 23-ft. stage. Again, a ± 10% error in estimation of true discharge would give the 10-ft. stage a range of 5,040 to 6,160 cfs (a range of 1,120 cfs). During high flows (stage 23 ft.), this range of estimation is from 42,300 to 51,700 cfs. Again, any potential impact of forest harvest in Redwood Creek is well within the magnitude of the error of the estimation of discharge.

Even if all of the expected increase in flow was to occur in the four recharge months--September, October, November and December--then mean daily flow would be increased an average of 60 cfs, a magnitude of flow which is still only 10% of the expected error in determination of true discharge at a stage of about 10 ft. At flood flows (stage 23 ft.), the potential impact of clearcut forest harvest is less than 1% of the error in estimating true discharge; ± 4,700 cfs gives a spread for true discharge of 9,400 cfs.

Estimation of the peak unit area discharge for Redwood Creek for a 10-yr. return interval rain storm also indicates that presence or absence of a forest canopy has an insignificant effect on peak flow. Assume a rainfall rate equivalent to a 10-yr. return interval storm for 6 hours of .6 in. per hour, which was preceded by 18 hours of rainfall with a total of about 4 in. It is quite possible that the day prior to this storm could have also rained a couple of inches. The 24-hr. rainfall would be equivalent to a 10-yr. return frequency storm (7.6 in.). As the final high intensity of the storm has followed a series of lesser storms, it may be assumed that the storage capacities for interception in both the canopy and forest litter and moisture storage capacity in the forest soil are satisfied. The "wet mantle condition" produces major winter floods (Rothacher, 1973). In aggregate, the interception storage capacities are less than .3 in. of rain and would have been satisfied during early portions of the storm. Kittredge (1948) reports on a modified rational equation which incorporates a slope area factor (Burkli-Ziegler formula). The equation is:

$$Q = CiA \left(\frac{s}{A}\right)^{0.25} \quad \text{(equation 10)}$$

where

Q is maximum discharge rate in cfs

C is a retention coefficient varying from .2 to .75

i is average precipitation in inches per hour during th concentration time

A is area in acres

s is average slope in feet per thousand feet.

Harr found the coefficient C ranged from 23- to 51% for a small basin in Oregon. Larger numbers associated with increased rainfall. If the equation is solved for a square mile flood flow of average slope--34%--(Janda, et al. 1975) numerical solution is as follows:

$$Q = 0.5\ (0.6)\ 640 \left(\frac{340}{640}\right)^{0.25} = 164 \text{ cfsm}$$

If the Redwood Creek watershed were to produce this flow synchronously, flow at Orick would be 45,570 cfs. This calculated flow is in good agreement with the anticipated instantaneous discharge from a 10-yr. flood of 45,300 cfs (Janda, et al. 1975), supporting Rothacher (1973), "Present indications point to the overriding influence of climatic pattern in determining major peak streamflow."

Even the bare forest soil areas, such as the Bridge Creek clear-cut, have infiltration capacities in excess of .6 in. per hour. Percolation and lateral transfer to the stream system is also in excess of .6 in. Recorded instantaneous peak flood yields for Redwood Creek range up to 243 cfsm for the 1964 flood upstream in Redwood Creek. The entire watershed averaged 182 cfsm peak discharge rate. The presence or absence of forest cover is inconsequential with the rainfall intensities and durations that occur during wet mantle storms. This hypothetical analysis is substantiated by research on subsurface movement of soil water on steep forested slopes (LaRock, 1967; Harr, 1977; Hewlett, Troendle, 1975).

Rothacher (1973) concluded logging in the Douglas-fir forest has only minor effect on major peak streamflows which occur when soils are thoroughly wet. Hewlett and Helvey (1970) were unable to demonstrate clearcutting had any impact on increased peak flows of major storms. Similar results have been reported by Gilleran (1968), Harr (1977) and Harris (1973). The overwhelming evidence in Redwood Creek supports subsurface movement of storm flow to the stream channel, as described in the studies cited.

The mechanisms for transporting subsurface storm flow are apparently not impacted by clearcut forest harvest. If a very high percentage of the area is impacted and impervious, as the result of compaction by forest roads, accelerated runoff may occur changing the storm hydrograph. There is no evidence that this condition exists in Redwood Creek. The conclusion, therefore is that clearcut forest harvest with or without slash burning will increase forest water yield. For the unit area of land treated, an expected increase in Redwood Creek would be 15 area in. or 1.25 ac/ft/ac clearcut. Hydrologic recovery is rapid through sprouting and re-establishment by invading plants. The water yield increase would decline proportionately for each of the following 5 consecutive years, until yields would be equivalent to the pretreatment time (Swank and Helvey, 1970).

The progression of cutting in Redwood Creek (2.4% per yr.) has been maintained at a level below the detection limits of the stream gauging station at Orick. Experimental watershed research requires very accurate measurement of discharge to establish impacts of forest canopy removal on water yield. To date, research results establishing impacts on flooding and peak runoff have been negative.

EARTH FLOWS AND THE REDWOOD CREEK CHANNEL

Massive earth flows into Redwood Creek have obviously, in the past, blocked the main channel on many occasions and at many locations. Alluvial soils of the Tall Tree Grove were undoubtedly formed in part following complete or partial blockage of the channel downstream. Figure 6 demonstrates the process showing a small slide partially blocking the channel during low flow.

Large earth flows and slides over several thousand years have occurred on numerous reaches of Redwood Creek. Evidence of more recent of these massive earth flows remain as blocks and rock debris in portions of the main channel (reach 2). Usually, reaches with block and rock debris will be much steeper (0.00890 ft/ft) than average (reach 1, 0.00208 ft/ft; reach 3, 0.00663 ft/ft) and have very few pool-riffles formed. The channel immediately upstream will have extensive deposits of bed load and a much wider abraided channel.

These channel features are very similar to many glaciated rivers in the Pacific Northwest. Glaciated valley river channels show a series of breaks in slope associated with large block debris deposited by the temporary terminus of the glacier. A mile or so of stream channel will be quite steep and turbulent through large block boulders leading into level meandering reaches of the channel.

A large slide probably occurred about a thousand years ago downstream from the mouth of Copper Creek. This slide created a lake about 40 ft. deep as evidenced by the delta of Copper Creek and depositions of outwash material. Figure 7 shows the stump of a large Redwood which has endured a flood history similar to the Tall Tree Grove. This Redwood initially established on a gravel bar at a height equivalent to about the middle of the photograph. Subsequently, depositions of silt occurred in many layers to a depth of about 10 ft. A large adventitious root grew on the left near the top of the shovel handle. Figure 8 was taken to the left side of the stump where the depositions of silt remain as major deposits. The upper deposit is indicated by a shovel and 6 ft. of tape measure. The lower layer covers rock and gravel level with the base of the large rock. There were at least 9 sublayers of depositions of sand and silt in the 10-ft. depth of deposited silt.

The first layer deposited (lower layer) existed as a stable soil surface for some number of years, based on the extensive surface root development--a characteristic of Redwood rooting. Probably, about three hundred years ago, another slide occurred impounding a lake again and contributing the additional silt for the upper layer. The sequence of events leading to such deposition requires first, the formation of a very quiet water body 40 ft. deep to provide deposition for a delta of Copper Creek, and layers of fine silt and sand size particles. These particle sizes are normally carried in the wash load of Redwood Creek and would not be deposited in normal flood flow. Also the occurrence of a delta of coarse gravel and cobbles 30 to 40 ft. above the current river bed requires deposition in an impoundment.

With time, Redwood Creek eroded a channel through the impounding slide to near its current elevation. The lower layer of deposited silt then formed a soil profile, probably above the flood plain as the extensive root development occurred only at one depth. About three hundred years ago, another massive slide occurred again impounding Redwood Creek. Depositional processes were again initiated with successive layers of silt deposited, forming the upper major layer and current soil surface. Again, erosional processes continued and Redwood Creek cut a channel to its previous (and current) level. In recutting the channel, however, Redwood Creek meandered back and forth eroding substantial amounts of the previously deposited silt.

In this process of erosion, depositions of alluvial silt around the large old Redwood were removed, exposing the lower trunk and adventitious roots. Currently, the river during flood stage is undercutting the stump and continuing to erode the deposited silt. Figures 9, 10 and 11 are a sequence progressing from downstream toward Copper Creek through a current slide area. Flood flows in this reach of the channel are very significantly impacted by spill resistance caused by a very abrupt change in channel curvature at the lefthand side of Figure 9. Flow energy is dissipated in this very tight channel turn causing a significant increase in stage, as a hydraulic jump with a reduction in flow velocity and hydraulic radius. These factors contributed to depositions of considerable bed load as shown in Figure 11. Several large bedrock blocks from the old slide also are creating internal resistance to flow and are rapidly eroding (left side of Figures 9 and 12). Erosion of these blocks and the tight channel curve will allow increased flow velocity to further scour of the upstream channel.

Massive slides such as the one pictured in Figures 9, 10 and 11 frequently leave large amounts of residual rock blocks in the channel (Figure 13). During peak flood flows, rocks of this size (Figure 12) dissipate flood flow energy by internal distortion, causing scouring of bed in front and to the sides of each rock. Larger material in the background was deposited as bed at a substantially greater flood flow (March 1975). Fine material in the foreground has been deposited as bed in subsequent, lesser flood flows.

When a section of the channel has a substantial spill resistance, inducing a large hydraulic jump as depicted in Figures 9 through 13, it is usually accompanied by accelerated velocities in portions of the channel immediately downstream from the source of spill resistance. Figure 12 is an upstream view below the sharp channel turn of Figure 9. The large rock blocks are probably remnants of a portion of the massive slide causing the impoundment near Copper Creek. The increased velocity induced by hydraulic jump is adequate to continuously remove large amounts of earth flow material from the right bank. Earth flows from either bank or their erosion in this section of river would alter both upstream and downstream deposition and scour patterns. Erosion of earth flow materials or altering the large blocks, causing internal distortion resistance, also will increase flow velocities allowing scour upstream with deposition at some downstream reach.

There is every indication that these processes have been very active in the past in several other reaches of Redwood Creek and are currently active, though possibly not to the degree that they were in the past. The remnants of alluvial terraces above Garett Creek and the extensive alluvial terraces above Lacks Creek indicate impoundments or changes in channel elevation of over 100 ft. More study would be necessary to determine whether a single impoundment near Garett Creek created all upstream alluvial terraces or whether there were separate impoundments. The geologically resistant formations and old terraces between river miles 29 and 31 have also contributed to formation of upstream terraces and flood plains. Redwood Creek has since cut down through these alluvial terraces, leaving them well formed above Lacks Creek but only as remnants between Lacks and Garett Creeks.

Reach 2, the first mile inside the south boundary of Redwood National Park, shows extensive and massive old sliding with large residual bedrock blocks now obstructing the channel (Figure 14). This mile is very steep (47 ft./mi.) in comparison to upstream and downstream reaches. In a manner very similar to impoundment by earth flow, these large blocks impede peak flood discharge reducing flow velocities (internal distortion resistance), causing a hydraulic jump and extensive deposition of bed load in upstream sections, as shown in Figure 15. Sections such as reach 2 are channel control sections during major floods. Any changes in the configuration of these control sections will in turn either accelerate bed movement through the section or impound bed above the section. Currently, these large blocks impede peak flood discharge causing extensive deposition of bed load as shown upstream (Figure 15).

Similar to the reaction of spill resistance, the internal distortion resistance caused by the large blocks allows the acceleration of flow immediately downstream. Bed material in this reach of the channel is substantially larger and channel erosion very vigorous. The combined impacts of these above processes cause a hydraulic jump with dissipation of flow energy. Figure 15 shows extensive deposits of large bed material on the left side of the channel. On the right side, there is a large bedrock block which has a substantial amount of woody debris piled against it. The deposition of both bed and formation of the log jam is caused by the downstream hydraulic jump and reduction of flow velocity through this reach of stream. During flood stage, when the bed material on the left was deposited, there was probably a substantial mount of bed also deposited through the water on the right. This bed was eroded on declining stage and deposited downstream.

The quantity and size of rock material contained in earth flows varies considerably. Figures 17 and 18 show earth flows of predominantly fine textured and small rock material. These flows agree with Janda's statement that a very high percentage of the material will be washed as suspended sediment. Figures 19 and 20 show two slides with a high percentage of coarse rock material. These rocks leave a residual impact deforming the channel, as the large rocks are transported only as bed during major flood flows. Figures 20, 21 and 22 show a downstream progression from an active slide which contains a substantial amount of large rock material. Large angular boulders are in the channel at the base of the slide (Figure 20). Some of these large rocks have been transported a short distance downstream (Figure 21). A large bed of subangular rocks varying from 2 to 6 in. in size occur several hundred feet downstream from the slide. The sequence of erosion and deposition shown in these figures is unknown, so the age of the bed material in Figure 22 is also unknown. From the amount of vegetation established on it, it would appear to be very recent (since the March 1975 flood).

The channel below the Tall Tree Grove, as inspected by reconnaissance of aerial photographs, indicated several potential areas of constriction. These could either be a constriction due to skin resistance (heavy growth of vegetation on both sides of the channel) or actual constriction by spill resistance due to stable rock or channel banks. As sections of reach 1 are relatively flat (8 ft. of slope/mi.), increases in stage of 20 ft. have a potential impact for over 2 1/2 mi. of channel.

The very tight curvature turn at the upstream reach above the Tall Tree Grove has led to a substantial deposit of bed material on the inside of the turn (Figure 23). In keeping with usual processes, as flow of the river is forced into a very tight turn, spill resistance results in a hydraulic jump with increased free water surface upstream and decreased velocity. When impeded flow makes the turn for the long straight reach past the Tall Tree Grove, it accelerates transporting bed material past the Tall Tree Grove to the next channel control section, where energy again dissipates and flow velocity is reduced. Inspection of aerial photography suggests that this control reach of channel is just downstream from the very abrupt channel turn directly through the Tall Tree Grove.

The current configuration of the flow pattern and deposition of bed does not indicate danger to the Tall Trees. The channel is straight through this reach; erosion should occur on the outside of the meanders away from the Tall Tree Grove. Deposits for Tom McDonald Creek are insignificant during flood flow. The minor obstructions mentioned in the Winzler and Kelly report of October 8, 1975 are not significantly impacting flow or deposition processes in the main channel. Control of the Tall Tree reach is some place below the very tight radius curve downstream from the Tall Tree Grove. This control section will regulate deposition and scour through the reach of channel surrounding the Tall Tree Grove.

The dynamics of streamflow in Redwood Creek are attested to in many reaches of the channel by the very dramatic changes in stage that take place during flood flows. Figure 24 shows the bridge near the mouth of Panther Creek. In 1964 the bridge was 10 ft. lower than it is currently and was washed out by the December flood. Changes in stage at this location (Figure 24) are in excess of 25 ft. A cross-sectional area of 2,500 sq. ft. was estimated with a flow of 26,800 cfs at this location when Orick records 50,000 cfs. This would give an average flow velocity of 10.7 ft/s through the cross-section. Bed material of the channel will become very unstable at this flow velocity. Skin resistance from well vegetated channel banks would require greater velocities in the center of the channel. Small rocks of the bed would cause a very narrow turbulent boundary layer contributing significantly to instability and flow of the bed.

The stability of massive earth flows adjacent to the channel must correlate with cyclic wet and dry periods which may extend over many years. For example, a decade of much greater than average annual precipitation would accelerate the movement of earth flows. Correlated with this higher than average precipitation would be higher than average streamflow, erosion rates and energy to transport suspended and bed material. Increased stage associated with greater discharge would add to the zone of saturated earth flow adjacent to the channel, adding to the rate of wasting. Even with the expected correlation of higher than average streamflow with higher than average mass wasting, there are still those random storm events and very dry years which occur independently of the cycle. Thus, if a long return interval winter storm were to occur during a period of wetter than average condition, the hydrologic impacts and instabilities initiated would have a long term residual effect.

It must be speculated that these climatic conditions have occurred over the past few thousand years, causing massive earth flows and impoundments of Redwood Creek. If these factors have operated in the past to a greater degree, they are without a doubt operative now to a lesser degree.

The brief record of both rainfall and runoff for the greater Redwood Creek area does not allow assessment of whether current climatic conditions are wetter or drier than the long time average. The suggestion that the 1964 flood was at least on a regional basis approximately a 100-yr. recurrence interval flood suggests that it should have very significant residual effects on the channel. With improved records for both rainfall and runoff, interpretation of predictable relationships on Redwood Creek might identify simultaneous dates of past flooding, as already identified by Harward and Youngberg. The very cursory study of the alluvial deposits at Copper Creek would indicate that a massive slide may have occurred about a thousand years ago with subsequent sliding around 1600 or even 1750--dates already identified as approximate times of historic flooding. If historic floods leave such a distinctive mark on the channel, it is not surprising that a flood of the 1964 magnitude might also leave a mark on the channel.

CONCLUSIONS

Analyses of hydrometeorological data available for interpreting the relationships of discharge of Redwood Creek to entrainment of suspended and bed sediments and deposition of these with their potential impact on Redwood National Park have led to several conclusions.

1. It is recognized by hydrologists working with sediment, bed load and discharge measurements in river systems similar to Redwood Creek that obtaining accurate data, particularly during peak flood runoff, ranges from very difficult to impossible. Ample measurements for low to moderate stage-discharge relationships have been taken for Redwood Creek, but the stage-discharge equation has questionable accuracy at higher flows (40,000+ cfs). Plotting the stage-discharge relationship for water year 1974-75 data shows a very abrupt break in slope between stage 17 and 24 ft. Flood flows for the period of record (22 yrs.) buffer at 50,000 cfs, even though the 1964 flood should have had substantially greater discharge.

None of the data or reviewed makes any reference to the potential relationship between extreme high tide and maximum stage on Redwood Creek. A gauging station within 2 1/2 mi. of the ocean at an estimated elevation of 10 ft. certainly has the potential for tidal influence. Data available indicate that correlated climatic factors of strong winds, unusually low atmospheric pressure and very heavy rainfall coincide with peak flood discharge and maximum high tides. It is possible that backwater effects from high tides are buffering the flood flows of Redwood Creek at about 24 ft. of stage.

If tidal effects on stage recording can be ruled out, then the stability of the cross-section and changes in approach velocity must be investigated.

2. Redwood Creek is a very unique, humid forest watershed as it has available a saturation capacity of fine material for a wash load in/and adjacent to the main channel for all increasing average winter flows. The saturation capacity of wash load will contribute to increased stream velocity and increased capability of transporting a capacity load of bed material. The capacity to transport bed load increases through increased buoyancy of a denser transporting fluid and increased velocity and discharge of Redwood Creek. Studies to date in Redwood Creek of discharge and suspended sediment give very predictable relationships. Thus, increasing stream energy associated with higher stage and increasing discharge allow a maximum entrainment of wash load. Concurrent studies of a relationship of wash or suspended load to bed load are not as well documented. However, poor documentation is probably an artifact of the difficulty of obtaining accurate bed load measurements during high energy flood flows, rather than the fact that a wash load-bed load relationship does not exist. Analyses of available data with simultaneous measurements of suspended and bed load indicated 60% suspended or wash load and 40% bed load for a number of stages in Redwood Creek.

3. The very predictable relationships, discharge and suspended load, and the significant increases in suspended sediment concentrations progressively downstream in Redwood Creek clearly identifies the main channel or adjacent banks as the source of suspended sediment. This conclusion is substantiated by the fact that suspended sediment concentrations in tributary watersheds never exceed or even approach the concentration in Redwood Creek during flood flows (Redwood Creek 5- to 30-fold greater). Conclusive support also is offered by the identical mineralogy of soil colloids currently in suspended sediment loads and previously deposited alluvial soils 3- to 4000 yrs. old. Current runoff-erosion processes operative in Redwood Creek predate forest harvest activity by several thousand years. These processes will undoubtedly continue ad infinitum.

4. A correlary to conclusion 3 may be made. As the main channel of Redwood Creek is the source of wash and bed load, then forest harvest has not significantly impacted suspended sediment or bed load relationships in Redwood Creek. This, again, is substantiated by the fact that concentrations of suspended load and the total quantity of sediment transported by tributaries are an insignificant fraction of the movement in Redwood Creek. The aggregate contribution of many tributaries (independent of forest harvest) is within the error of determining the actual concentration or quantity in transport in Redwood Creek. It must be concluded, as with numerous similar forest hydrology studies, that the dynamics of climate interacting with soil and geologic formations in Redwood Creek completely dominate the rainfall-runoff relationships and erosional potentials.

5. Impacts of the current rate of conversion of old growth Redwood forests have an insignificant impact on potential increases in water yield (total annual runoff). Assuming 2.4% of the area upstream from Prairie Creek is clearcut annually, and hydrologic recovery is achieved in 5 yrs., a total of 11,400 ac. may sustain increased water yield. Based on average annual precipitation and usual impacts of forest harvest, a potential increase of 1.98% in annual runoff of Redwood Creek above Prairie Creek is predicted (1.77% below Prairie Creek at Orick). The predicted increase in water yield is 14,250 ac-ft annually (1.25 ac-ft/ac of clearcut). This increase sustained as even flow averages 19.7 cfs per day. Currently, there is no valid means for allocating the increase, other than assuming a maximum percentage response occurs during the driest season and a maximum quantitative response in early recharge of the soil mantle. Maximum potential increases, no matter how they are calculated--stage or discharge or when they occur--are always within the error of estimating stage or discharge for Redwood Creek.

6. The year to year variation in water yield of Redwood Creek exceeds by 3-fold any potential impact that forest harvest could have. Annual runoff has increased as much as 230% (46.5 area in.) between

consecutive years. This increase is 3-fold greater than the maximums predicted for forest harvest and it occurs on 100% of the Redwood Creek basin area. The hydrologic dynamics induced by this magnitude of natural change exceed by many fold any potential impacts of forest harvest on runoff or erosional processes.

In a like manner, year to year variation in instantaneous peak flows vary 3- to 5-fold between years (range 10,000 to 50,500 cfs). The potential impact that forest harvest could have on instantaneous peak flow is less than a fraction of 1% of the error in determining peak flow on Redwood Creek.

7. The velocity of travel of wash and bed load is very dynamic during major winter floods. Upstream reaches of Redwood Creek will move particles 6 to 8 in. in diameter and larger at 25% the rate of wash load travel. The average travel rate of wash load is sufficient to move 250 mi. during peak flood runoff. Bed load travelling at 25% of the wash load speed would travel 30 to 60 mi. Travel for floods equal to the December 1964 flood could be 2-3 fold greater. Thus, bed load particles 2-4 in. in diameter in the approximate vicinity of Lacks Creek could easily travel to the ocean during a single short flood peak. Deposition and re-entrainment of bed load can only be assessed based on dispostion of energy required for movement. Many reaches of Redwood Creek have internal distortion, spill and skin resistances sufficient to allow deposition of substantial amounts of bed load. The dynamics of energy dissipation are not constant but vary with varying stage and discharge. Thus, a reach of channel which would deposit bed at a low stage would also re-entrain and transport even larger bed at a greater stage. In a like manner, a channel reach will act as a control for bed load transport during a 50,000 cfs flood at Orick and be insignificant during a 20,000 cfs flood.

8. The brief period of record of hydrometeorological data does not allow assessment of trends in climatic cycle. Rainfall-runoff relations are only poorly documented since 1953 and even now are not receiving sufficiently accurate documentation to interpret the dynamics of the Redwood Creek basin. Relationships of past floods to the current status of the Redwood Creek channel can only be speculated. Assertions that forest harvest has aggravated soil erosion and/or bed load movement are not documented. Currently, there are no available technical hydrologic methods which can improve the predictive ability for runoff-erosion processes operative in Redwood Creek. Adequate data for good simulation (computer modeling) do not exist.

An improved understanding of bed load transport processes, past and future, could be achieved by detailed study of the slope of the free water surface of the channel in relation to control sections. Such a study would include age and position of past alluvial deposits and analyses of channel energy disposition. Results of a channel study would provide an improved understanding of processes of scour and deposition and sources of wash and bed loads. These data also would improve the understanding of hazard to the Tall Tree Grove.

Analyses of data available lead to the conclusion that Redwood Creek is dominated by climatic-soil and geologic factors over which Man has no influence. With this conclusion, it then follows that sediment movement into and through Redwood National Park is also dominated by the same relationships. Forest harvest in Redwood Creek has not significantly influenced these relationships.

Figure 2. Detailed inspection of a recent clearcut which had slash burning in the fall of 1976 revealed no surface runoff, overland flow or soil erosion, even on portions of the fire line road made by tractor which were severely distrubed. By June of 1977, many of the native species have either sprouted or reinvaded the burned area.

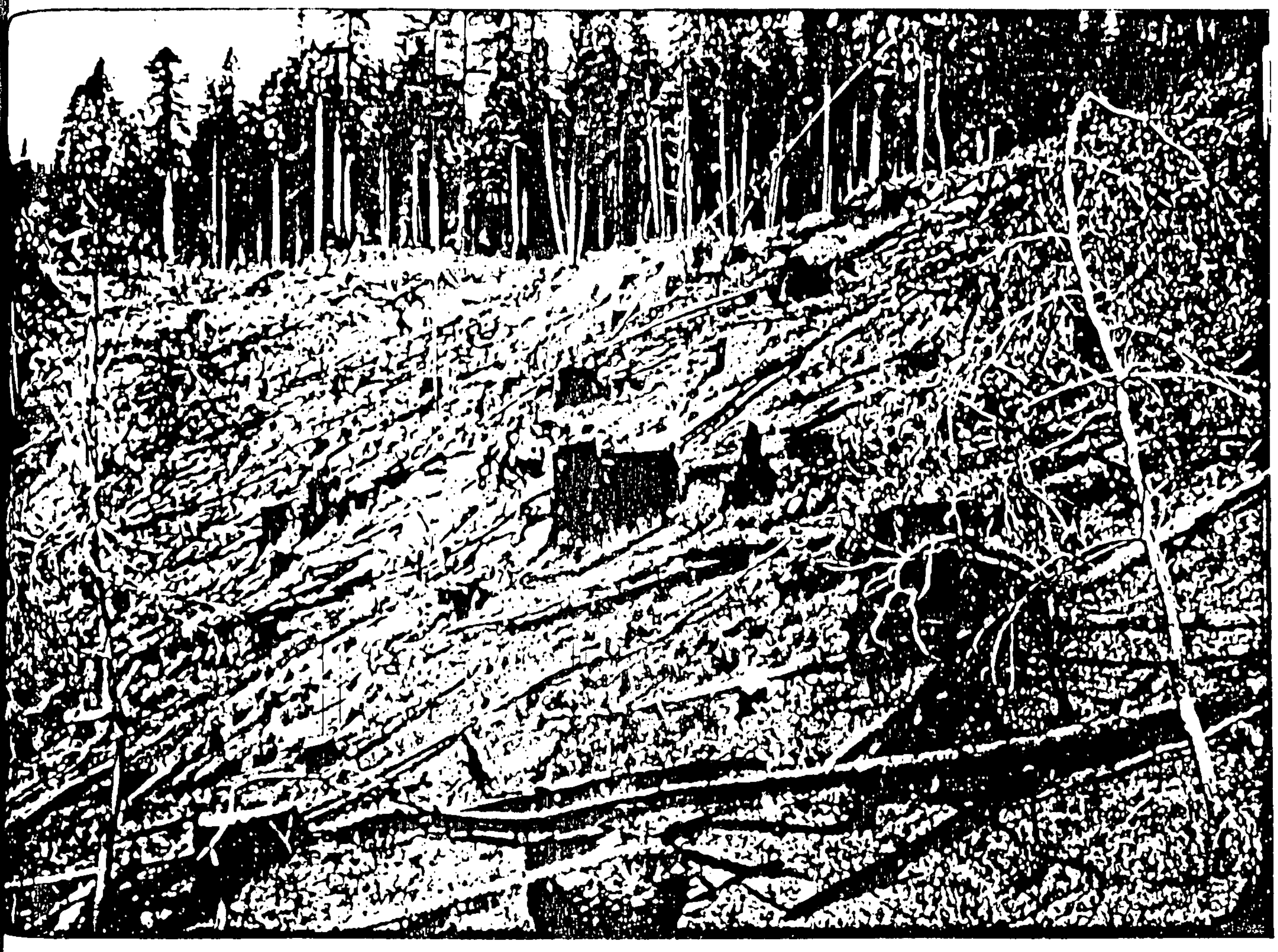


Figure 3. A 2 or 3-yr. old clearcut also shows no indications of surface runoff or soil erosion, even where tractor trails come directly down the hill.

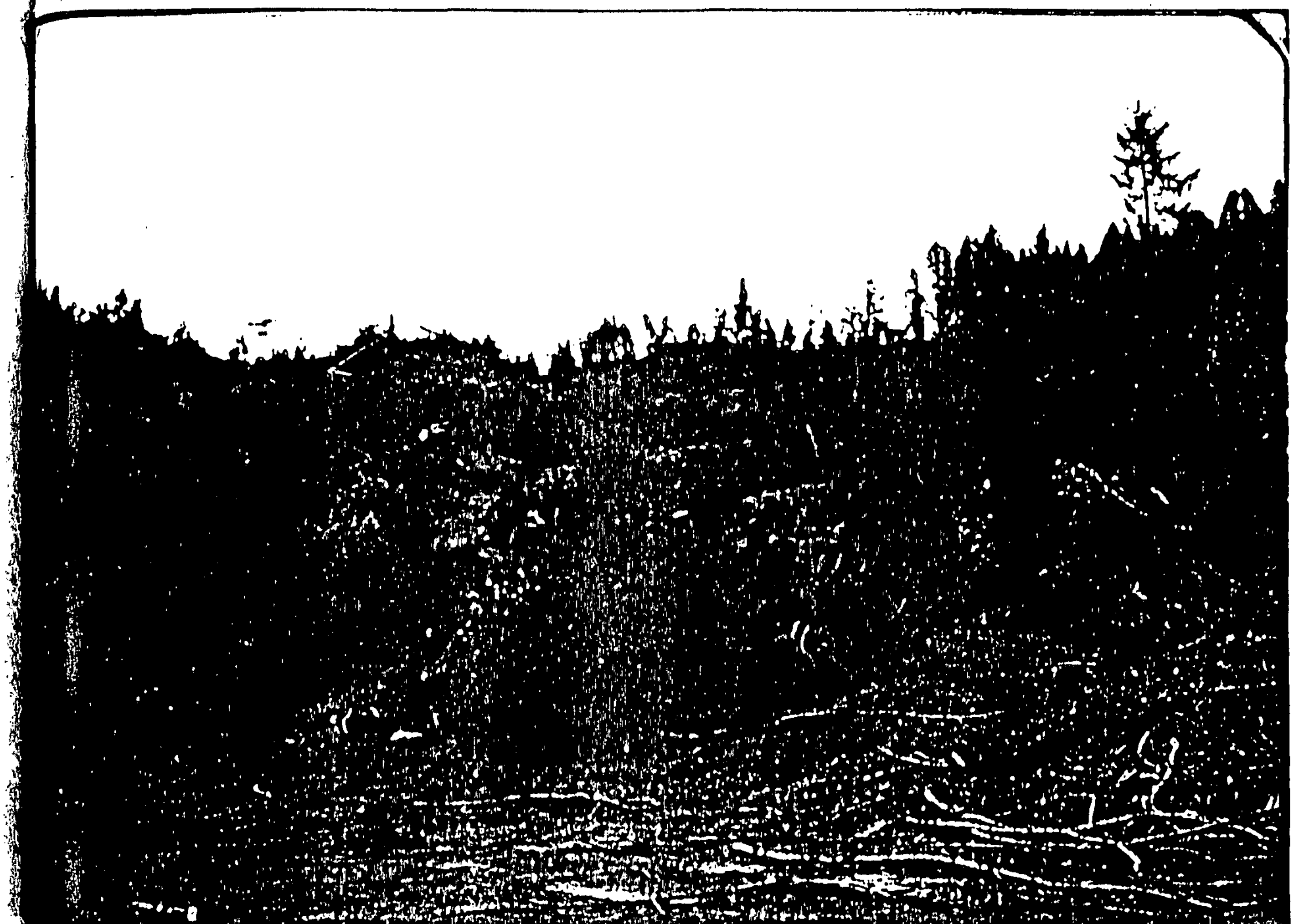


Figure 4. A very slight indication of surface runoff runs diagonally to the lower right corner of the photo. Establishment and growth of plants are the same age as date of abandonment. Vegetation adjacent to the road also offers significant protection.

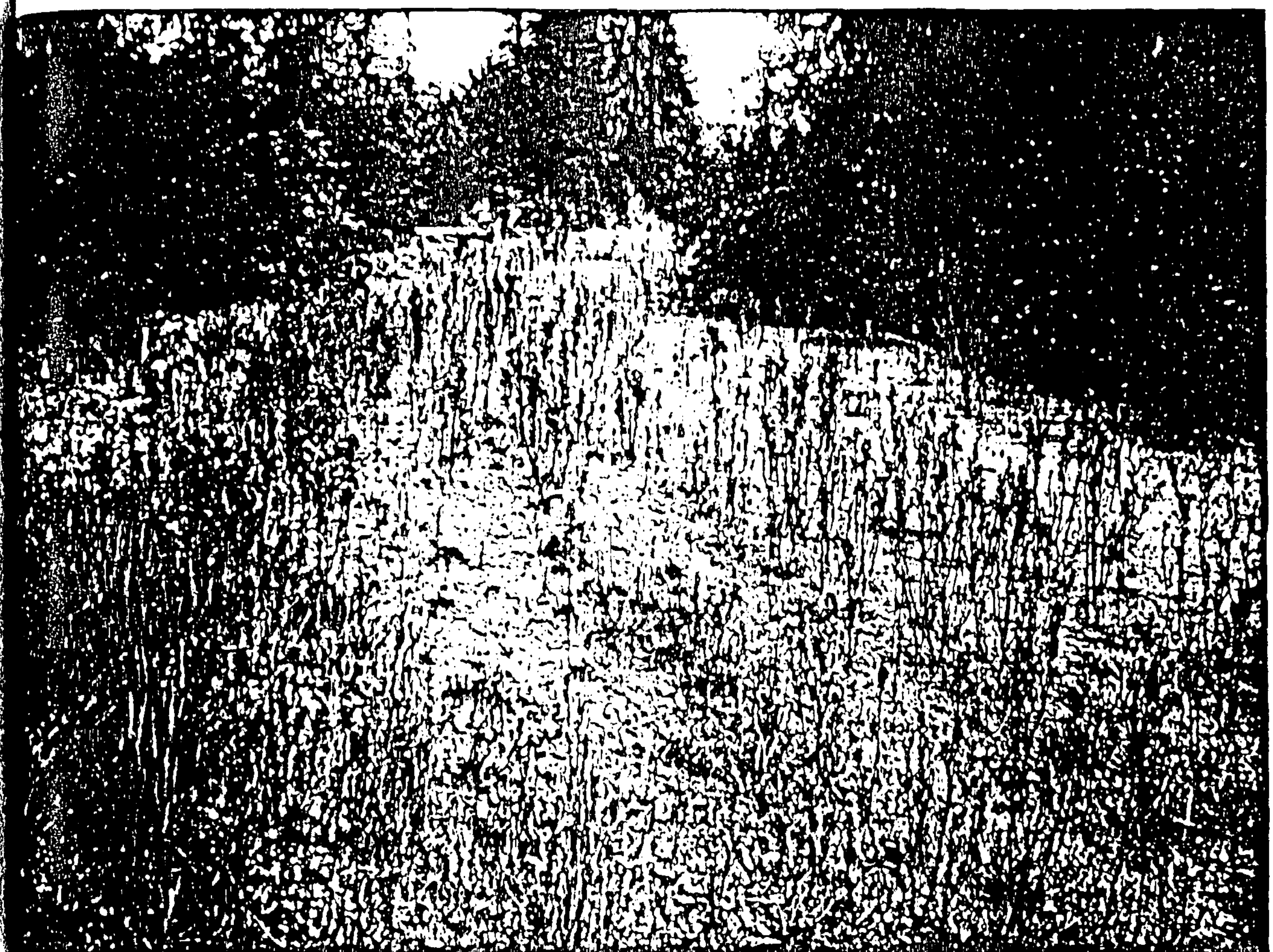


Figure 5. An example of massive soil erosion is included so that the visually obvious features of erosion may be noted. The rainfall rate exceeded the infiltration capacity of the soil; thus, surface runoff occurred carrying an estimated 103 tons of erosion per acre. This photo was taken in the Ponderosa pine zone of eastern Washington.

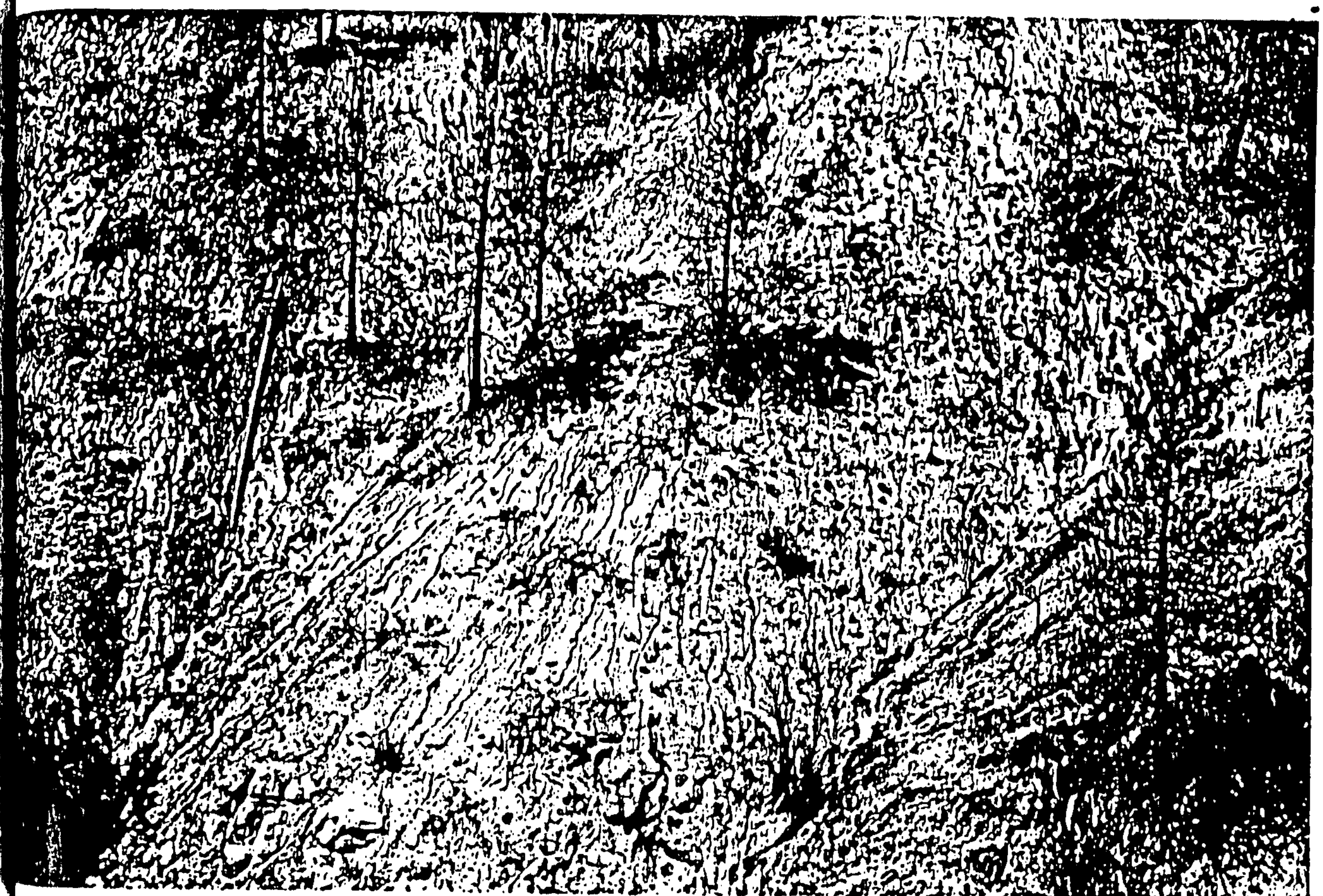


Figure 6. This large, natural earth flow has also been photographed in Figure 62 (Earth Satellite Corporation, 1972). The 1972 view shows no high water mark from the early March flood, indicating that the earth flow occurred following the flood. This process is totally natural as flood flows of Redwood Creek remove the earth flow which has encroached on the channel, only to be followed by subsequent movement of the earth flow replacing the material. As no high water mark shows in Figure 6 from the March 1975 flood, it must be assumed that the earth flow again replaced the material washed away by that flood.

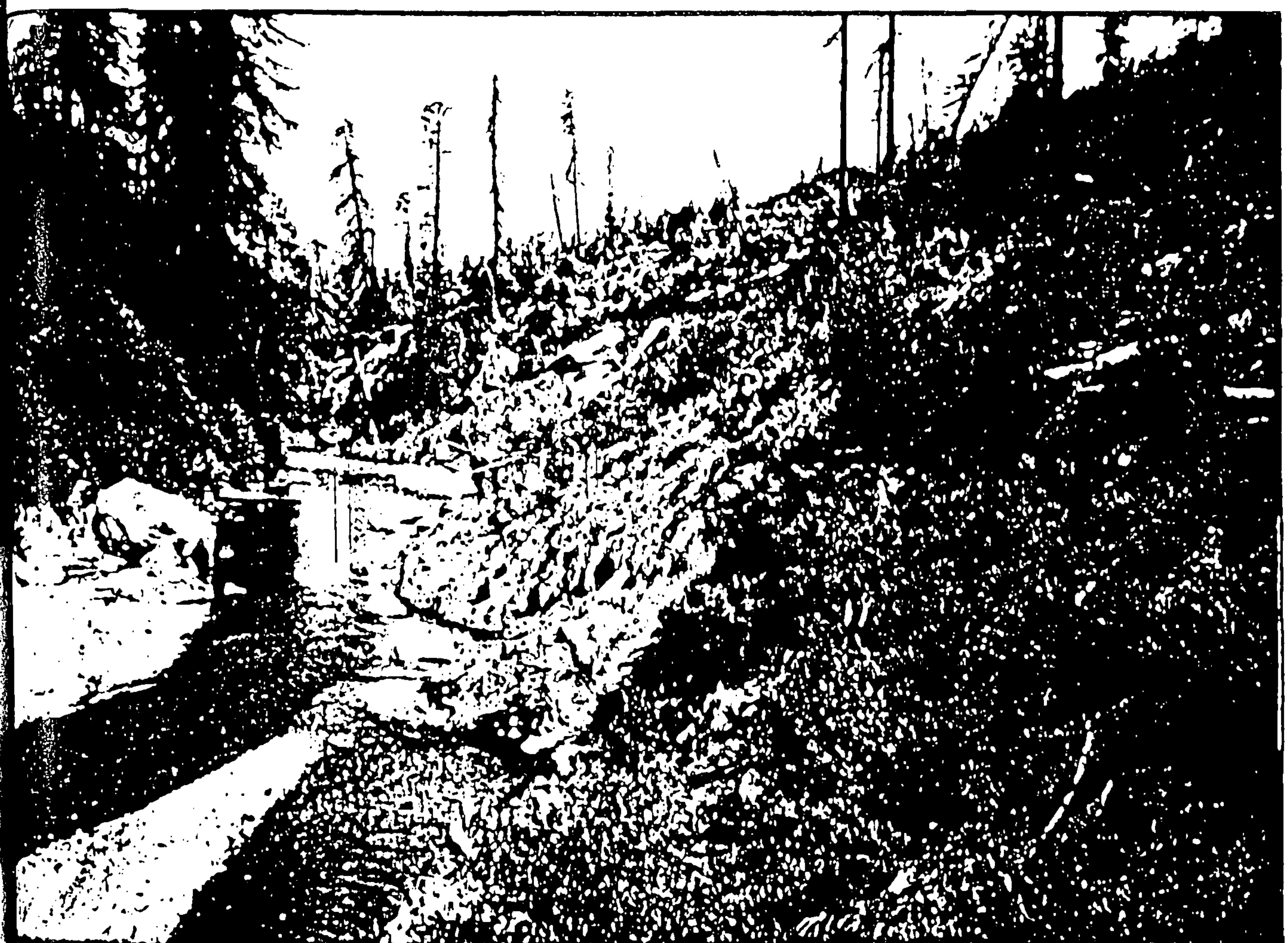


Figure 7. This Redwood established as a seedling at an elevation equivalent to about the middle of the picture. A downstream impoundment and successive depositions of silt allowed development of large adventitious roots near the top of the shovel handle with indications that silting occurred 4 ft. higher (near the springboard notch).

Figure 8. Two major depositions of silt have occurred just to the left of the large Redwood stump. The first layer formed a soil surface for many years, as indicated by the extensive rooting. The second layer approximately 6 ft. deep formed about 300 yrs. later, providing a new surface for soil profile development (top of the tape).

Figure 9. The sequence of Figures 9, 10, 11 and 12 show about 400 yds. of a naturally extremely unstable slide area adjacent to the channel of Redwood Creek. This is either part of or the upper boundary of the massive natural slide which impounded Redwood Creek to provide for the silt soils formed as shown in Figure 8. The left side of Figure 9 shows a very abrupt curve in the channel of Redwood Creek. During flood flow, this curve requires almost a 90^{o} change in flow direction. Spill resistance causes a hydraulic jump increasing the free water surface which allows for the deposition of bed load, as shown in Figures 10 and 11.

Figure 10. Flood flows deposit a substantially greater amount of bed between the photo point and the far bank. Declining stage accelerates flow through the far section, removing deposited material. This same phenomena also occurs on the left side of Figure 9. The stump floated in during a much lower flow.

Figure 11. Under moderate streamflow, maximum velocities occur against the far bank. Minimum velocities, due to hydraulic jump, occur near the photo station. During flood flow, substantial amounts of bed would be deposited near the far bank. As in Figure 10, this material would be subsequently eroded by declining stage or later lesser flows.

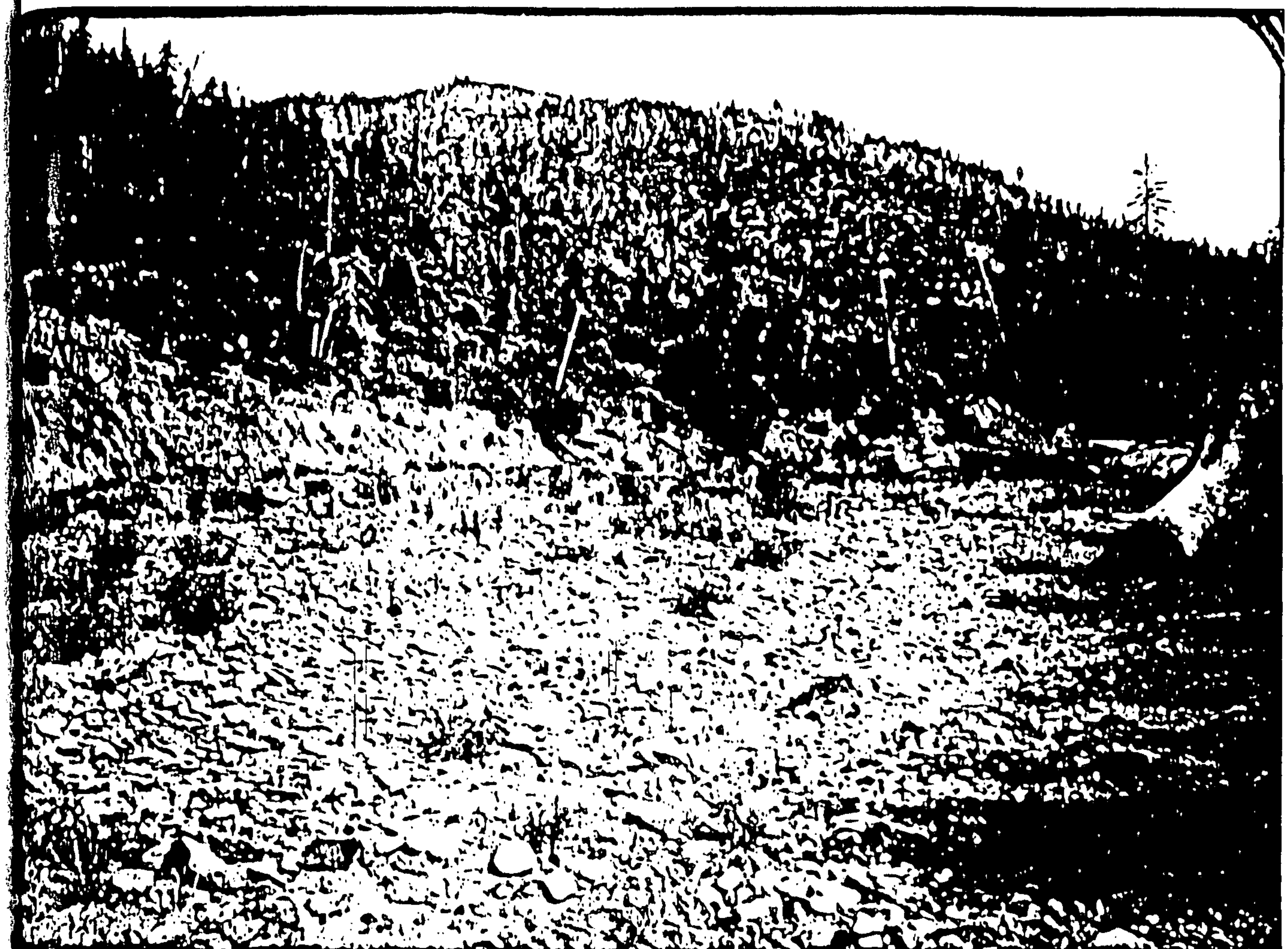
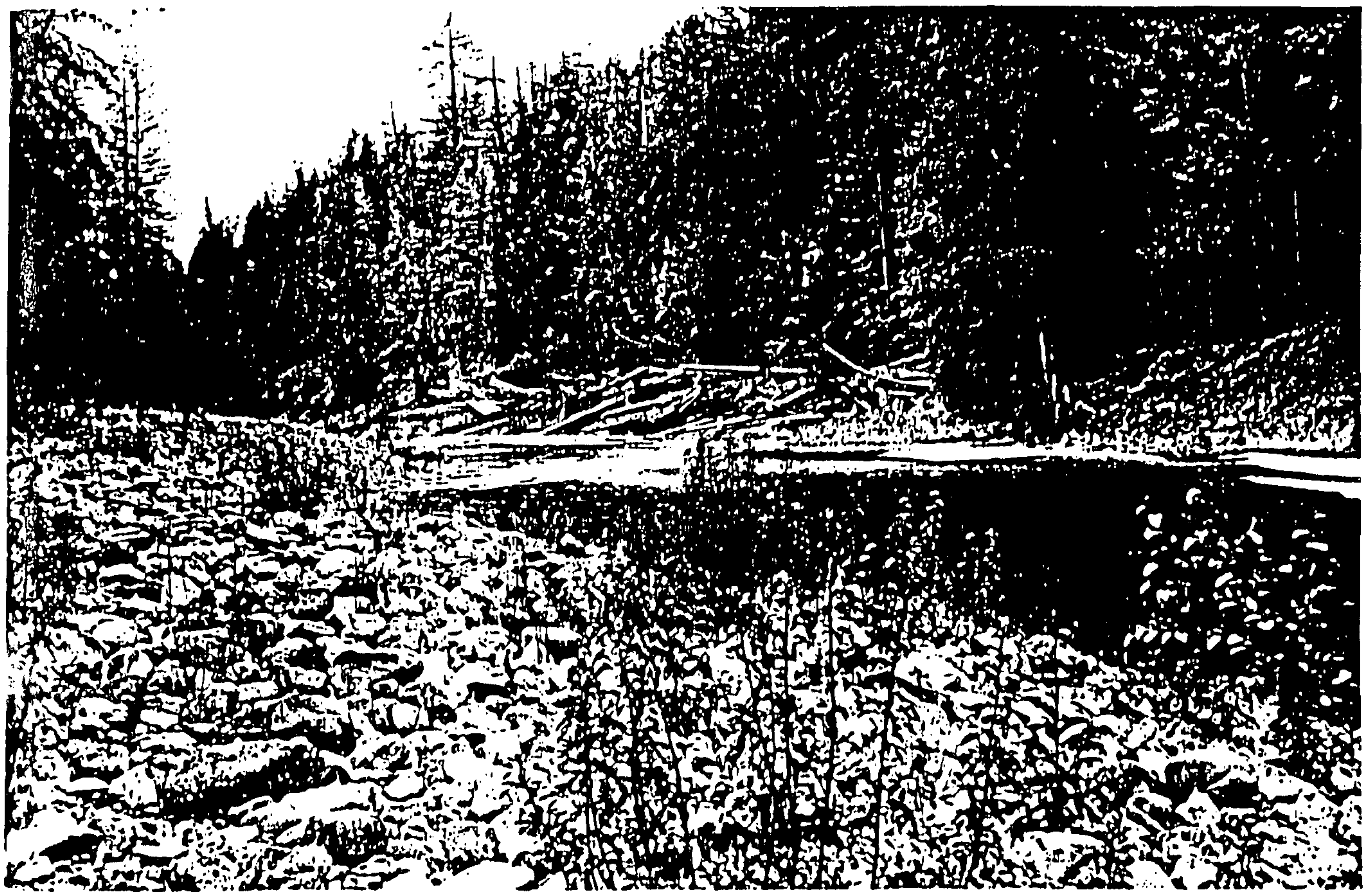


Figure 12. Downstream from the 90^0 channel turn, flow velocities increase as a result of increased slope due to the hydraulic jump. Moderate to large size rocks occur in the channel as remnants of the earlier massive slide which impounded upstream reaches of Redwood Creek. This slide probably caused the impoundment which allowed establishment of the Redwood shown in Figure 7 and deposition of the soils shown in Figure 8, estimated to be 2- to 3000 yrs. ago.

Figure 13. Upstream bed material at the head of the long slide (Figures 9, 10 and 11) is relatively coarse, probably deposited by the last major flood in March 1975. The many large rocks are remnants of earlier slides as surrounding finer material has been washed away. This view looks straight into the 90° channel turn (to the right of the large rock on the left of the photo).

igure 14. The reach of the channel termed "the gorge" just north of Redwood Park boundary has several immense bedrock blocks imbedded in the channel bank as well as in the channel. Blocks of this size provide excellent flow energy dissipators, internal distortion resistance causing upstream increases in free water surface with reduced flow velocity.

Figure 15. The log jam at the south Park boundary has been formed by reduction in flow velocity due to spill and internal distortion resistance in the downstream (Figure 14) area termed "the gorge." Were it not for these resistances to flow, increasing the level of the free water surface and decreasing the velocity of flow, the bed load on the left and the log jam would not form.



ure 16. Energy of flow velocity is also dissipated by skin resistance of well-vegetated channel banks. Reduced flow velocity at boundaries of the wetted perimeter against the banks causes increased velocity in the main bed of the channel, resulting in less deposition with increased ability to transport bed load.

Figure 17. Numerous fine textured, natural earth flows occur along the main channel of Redwood Creek. Some of these flows are below forested areas, while others (Figure 18) are below prairies. These flows can be characterized by the percentages of fine textured material. This figure shows a predominantly fine textured earth flow. The relative rates of movement of this earth flow are not influenced by presence or absence of forest cover, but rather the dynamics of the channel of Redwood Creek as the earth flow will replace material at a rate equal to its removal by flood flows of Redwood Creek.

Figure 18. Prairies form on soils of predominantly fine textured materials. Again, natural earth flows with their origin in or close to prairies supply a saturation load of wash material, which is removed by prolonged high stage. The flows are sufficiently active to replace the wash material following decline of the flood.

Figure 19. The area upslope from this natural earth flow has a long history of instability as indicated by the numerous leaning trees. This earth flow carries a larger component of medium size rocks, which are residual in the channel following high flow and removal of bed and wash load.

Figure 20. Moderate to large size rocks are also residual in the channel at the base of this natural earth flow. Flood flows equivalent to the March 1975 flood would transport rocks of this size.

Figure 21. A few larger rocks have washed downstream from Figure 20. The 1976-77 winter did not have flood flows sufficient to transport these rocks.

Figure 22. Several hundred feet downstream, a bar of subangular rocks 2 to 6 in. in size has had its source in the upstream earth flow. A major flood will transport a very high percentage of these rocks.

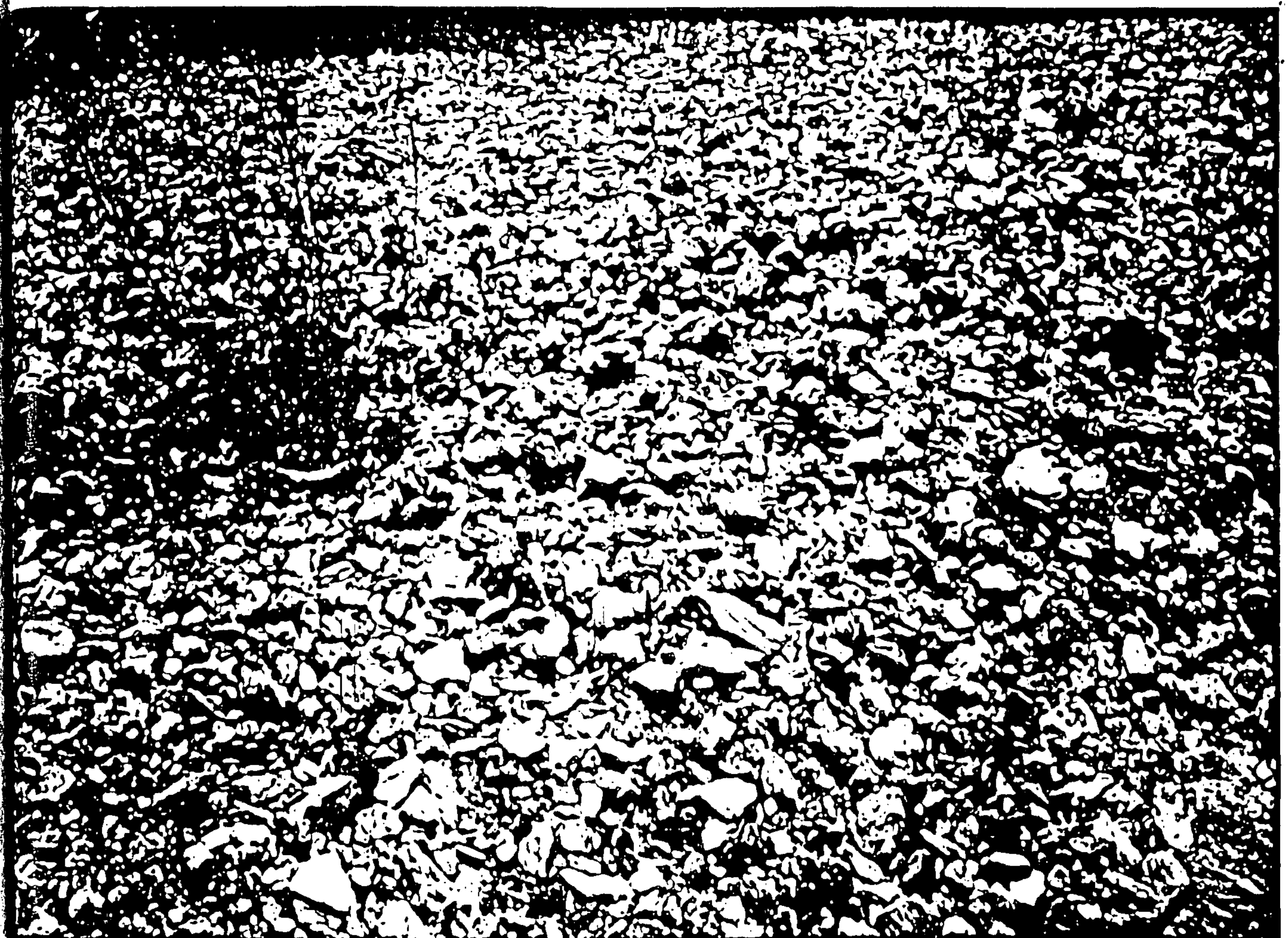
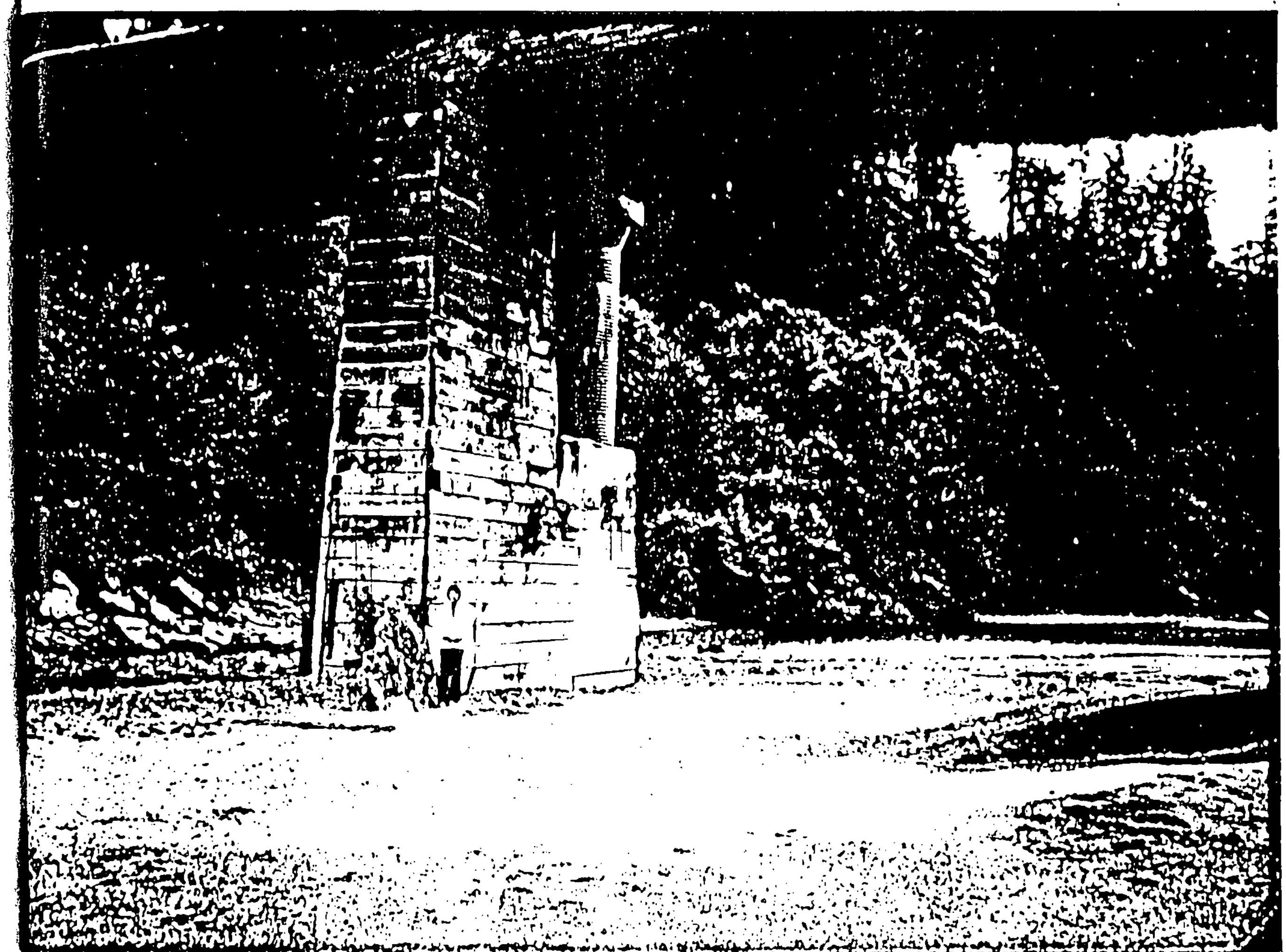


Figure 23. The curvature of the channel upstream from the Tall Tree Grove exceeds 90°. The spill resistance caused by this extremely tight channel curve induces spill resistance allowing deposition of bed on the inside of the turn. Flow accelerates immediately downstream from the hydraulic jump, transporting bed through the straight reach along the Tall Tree Grove.

Figure 24. This bridge was 10 ft. lower in 1964 and removed by the flood. Change in stage exceeds 25 ft. in this cross-section just above the mouth of Panther Creek. Average flow velocities through this section are 10.7 ft/s. The bed of the channel is very unstable at these flow velocities.



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