SEDIMENT ROUTING IN STREAM CHANNELS: ITS IMPLICATIONS FOR WATERSHED REHABILITATION

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Abstract. In the Redwood Creek watershed in northern California, the combination of naturally unstable terrain and intensive land use has created a need for erosion control programs to rehabilitate heavily disturbed slopes. Major sediment sources generally occupy small, inaccessible portions of the basin that are in the stream channel or on footslopes adjacent to steep stream reaches. Large volumes of sediment are stored within the Redwood Creek channel itself and form a sediment source for downstream reaches. The best available erosion control measures, exemplified by those currently in use in Redwood National Park, are effective in dealing with erosion problems on heavily disturbed hillslopes. Early treatment of problems can prevent possible downslope cumulative impacts. However, because of the inaccessibility of some major sediment source areas, there is a limit to effectiveness of erosion control. Total drainage basin rehabilitation is not technically feasible, and basin-wide erosion control becomes, in part, a problem of managing land within recognized geologic constraints.

INTRODUCTION

In the northern California Coast Ranges, where erosion occurs at the highest rate in the conterminous United States, the combination of naturally unstable terrain and intensive land use has created the need for erosion control programs to rehabilitate heavily disturbed watersheds. Erosion control treatments used on roads and gullies have been successful. However, in large drainage basins, 500-1000 km^2 in size, major sediment sources generally occupy small, inaccessible portions of the basin that are in stream channels or on steep footslopes adjacent to streams and are difficult or impossible to treat. A basin-wide management plan for erosion control in such watershed must consider all sources of sediment and their relative contribution to streams, and the transfer of sediment throughout the watershed.

A description of sediment routing in a watershed quantifies the amount of sediment derived from different source areas, hillslope erosion rates, timing of transport, and locations and volumes of channel-stored sediment. In a watershed, sediment is transferred from hillslopes to channels through several processes. Any disturbance to a watershed will affect both the processes and the rates at which they occur, and the result is generally an increase in sediment yield. A disturbance may come in many forms: intense storms, fires,

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conversion of forests to agricultural land, introduction of grazing livestock, road construction and timber harvest.

Some disturbances may be treated to reduce the excess sediment load, whereas other source areas are so widespread or inaccessible that prevention of sediment delivery to streams is impossible. Before any watershed rehabilitation program directed at correcting disturbance-related problems is initiated, all compoments of the sediment routing regime should be evaluated. If we can quantify the routing of sediment through a basin, then we can better evaluate the effectiveness of erosion control at different locations in a basin.

DESCRIPTION OF AREA

Redwood Creek drains 720 km^2 in northwestern California (Fig. 1). It is underlain by the pervasively sheared and folded Franciscan rocks. The combination of highly erodible rocks, recent uplift and a high annual rainfall (1250 - 2500 mm) causes a naturally high sediment yield from this terrain. Recent land use changes in the basin have accelerated erosion even more, and presently the sediment yield of Redwood Creek is about 3,200 $t/km^2/yr$. (U.S.G.S. Water Resources Data for California, 1976-1979).

The Redwood Creek basin has been disturbed by timber harvest, road construction, and intense storms in recent years. Logging was initiated by the 1940's, but widespread logging of old growth trees did not occur until the 1950's and 1960's. By 1964, most of the land in the upper third of the basin was logged and by 1974, few areas of old growth redwood existed outside of park boundaries.

Widespread road construction accompanied timber harvest. For example, in the expanded park over 600 km of major haul roads exist, plus thousands of kilometers of skid trails. The road network disrupts the natural drainage patterns, road cuts intercept subsurface flow, unmaintained culverts plug and wash out road fills, and road fills are locally unstable. The problems that are caused by roads, and the approaches taken in correcting them, are discussed more fully in other papers in this volume.

In addition, since large-scale timber harvest began in the 1950's, five large floods occurred, in 1953, 1955, 1964, 1972 and 1975. These floods, especially that of 1964, severely affected the basin. The most dramatic effects of the 1964 flood were associated with those areas in the upper basin recently disturbed by logging and road construction. Many landslides and severe bank erosion occurred, and 3 m of channel aggradation was common in many reaches of Redwood Creek. Severe sedimentation problems threatened the alluvial groves of old growth redwoods in Redwood National Park, and a study was initiated to evaluate sedimentation and erosion in the Redwood Creek basin.

METHODS

Our approach in studying the Redwood Creek watershed has been to quantify sediment source areas in the entire watershed, to evaluate the storage capacity of tributary and mainstem channels, to monitor the timing and magnitude of transport events, and to compare annual sediment yields from several terrain types and time periods. Using this data base, we can then evaluate the significant source areas in terms of total sediment contribution, estimate residence times of sediment problems, and rank sediment problems according to severity.

Volumes of 634 streamside landslides were measured along 30 km of Redwood Creek upstream of Highway 299. Additionally, landslide volumes in 17 major tributaries were measured. Dates of landslides were obtained from aerial photograph interpretation and dendrochronological determinations. All stored sediment in Redwood Creek above the present thalweg was mapped, measured and classified for 96% of the total length of the creek. Sediment was classified according to its mode of storage (point bar, flood terrace, channel bed, etc.) and to its potential mobility (stable, vegetated and difficult to mobilize; or within active channel and easily mobilized.) The amount of aggradation in the channel was estimated from old bridge surveys, discussions with local residents, and biological evidence. Stored sediment measurements were also made in 24 of 74 second-order or higher tributaries. A detailed procedure of the above investigations and the preliminary results are both discussed in Redwood National Park Technical Report 3 (Kelsey et al, 1981).

We are in the process of evaluating sediment contribution from fluvial erosion on hillslopes to complete the sediment source study. Gullies are mapped on 10-20 ha plots, which represent a range of geologic and land use conditions. Ve measure the volume of material eroded from the gullies, hillslope gradient ind aspect. We also record the type of soil, bedrock geology, ground disturance, predominant vegetation, the cause of gullying (where possible), the ivailability of water on a site, and the location. Preliminary results ndicate that gullies developing on locally sensitive sites such as prairie ands contribute significant amounts of sediment to stream channels.

n order to assess sediment yield from the total basin, we have established everal gaging stations on the mainstem of Redwood Creek and on major tributaries. This cooperative program between the National Park Service and the .S. Geological Survey measures water and sediment discharge throughout the ear. Thus sediment yields past several stations within and outside the park an be compared.

CONTRIBUTION OF SEDIMENT SOURCE AREAS

n the Redwood Creek basin, the major sediment source areas are streamside andsliding, debris slides and avalanches, gullying, earthflows, and stream ank erosion. In addition, sediment stored in the main channel of Redwood reek was derived from other source areas, but now acts as a sediment source o downstream reaches. These sediment source areas make up only 17% of the otal basin area (Table 1).

andslides are most prevalent in the upper fourth of the basin. From the eadwaters to Highway 299 (see Fig. 1) about 1,920,000 t of sediment was elivered to the mainstem by landslides since 1947. About 50% of the slides ere associated with one or more roads. Most of the landsliding occurred ring the 1964 flood. These landslides are generally on steep (60%) slopes djacent to third-order or higher streams.

ediment from landslides in tributary basins reached the mainstem of Redwood eek relatively quickly. At present, tributaries store only a small percentage of the volume of sediment supplied to them by landslides (Pitlick, this volume). Major floods transport most of the tributary-stored sediment to the mainstem. The remaining sediment is usually trapped upstream of organic debris in channels. Thus, in the Redwood Creek basin, the relatively steep tributaries function more as sediment transporters rather than sites of long-term sediment storage.

TABLE 1

SEDIMENT SOURCE AREAS IN THE REDWOOD CREEK BASIN UPSTREAM OF PRAIRIE CREEK

Feature	Percent of Basin Area
Debris slides*	1
Debris avalanches*	0.2
Earthflows*	10
Very active earthflows*	2
Unstable streambanks*	3
Main channel stored sediment	0.5
TOTAL	16.7

* from Harden et al, 1978

Fluvial erosion on hillslopes is another major source of sediment. Gullying is common on logged areas where skid trails divert water and where road crossings on streams are abandoned. Gullies usually form within the first few years after a site is logged. Prairies are especially sensitive to water diversion by roads. Where logging occurred in the early 1970's, preliminary results indicate that the sediment yield from gullying ranges from 2500 t/km^2 on gentle, schist slopes with cohesive soil to 95,000 t/km^2 on steep sandstone slopes with noncohesive soils.

Rainsplash and sheetwash erosion occur on disturbed ground and compacted road surfaces, and they transport fine sediment to stream channels. Preliminary results suggest that in terms of total sediment input to Redwood Creek, sheetwash is not a major sediment contributor. Locally, however, the effects of rainsplash and sheetwash are severe and these processes are detrimental to restoring vegetation on disturbed sites.

Fill failures on roads and road washouts are also common on abandoned roads. Stream crossings vary greatly in size and distribution. Nevertheless, an average volume of road fill on a skid trail stream crossing is 60 - 70 m^3; of haul road crossings, 200 - 250 m^3. Road fills and crossings generally persist for several years, and it may take 10 - 50 years before a road crossing fails into a stream channel.

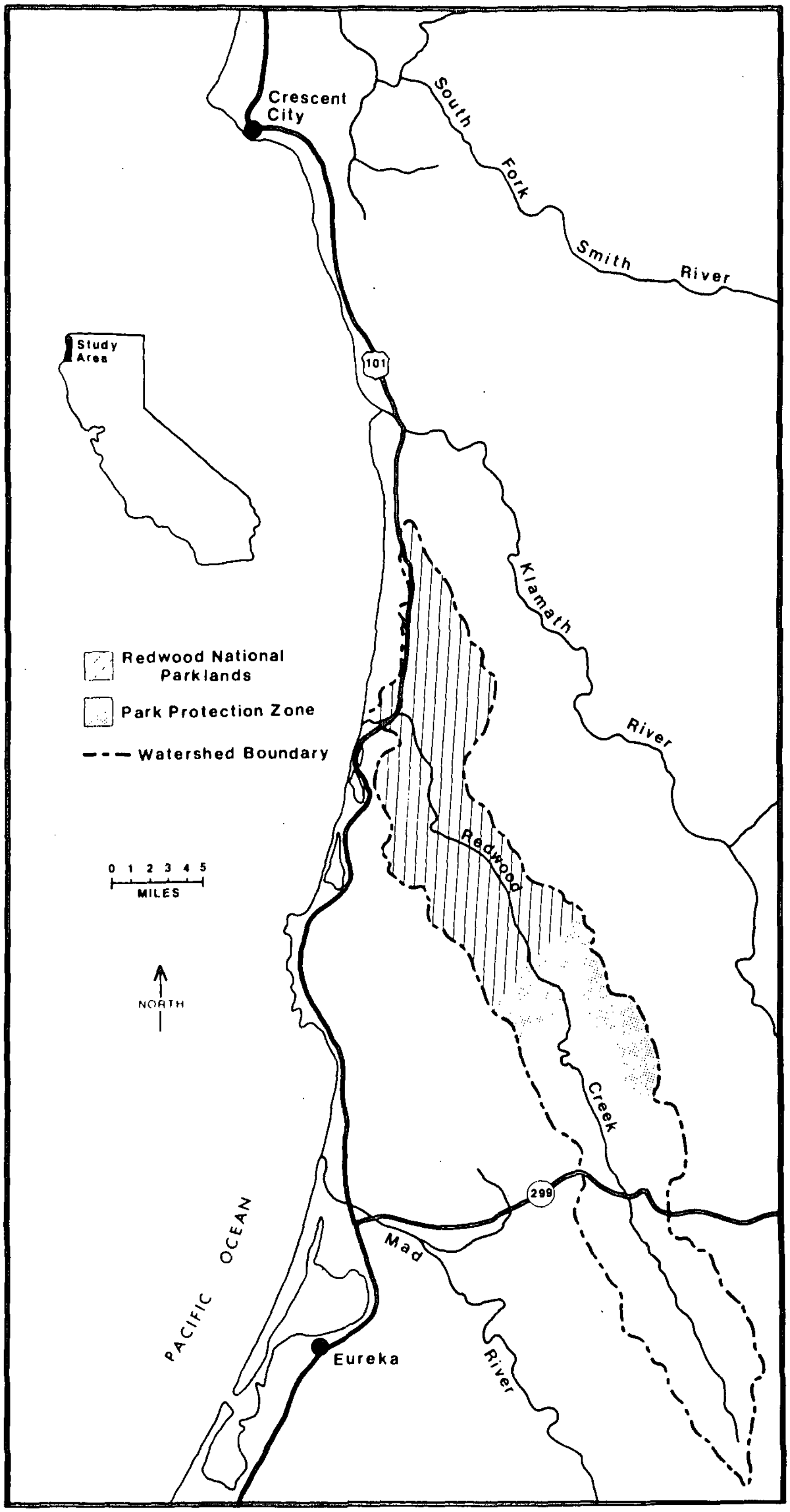

Figure 1: Location map for Redwood Creek watershed, northern California

Another major source of sediment to the reach of Redwood Creek in Redwood National Park is channel-stored sediment upstream of the park. This is well illustrated by evidence seen in the upper basin of Redwood Creek. The 1964 flood resulted in 1 to 3 m of channel aggradation in upstream reaches. From 1962 to 1966 the amount of sediment stored in the uppermost 21 km of Redwood Creek increased from about 40,000 t to over 2,000,000 t. Presently only 50% of that sediment remains in the channel, the other 1,000,000 t has been transported to reaches farther downstream.

Considering the entire length of Redwood Creek, we found that 17,000,000 t of sediment are stored in gravel bars and the channel bed of the mainstem. The annual bedload plus coarse suspended sediment is 150,000 - 450,000 tons/year (Knott, U.S.G.S., personnal communication). Thus the equivalent of 11 - 38 years of bedload and suspended sand discharge is stored in the mainstem of Redwood Creek. About 5,400,000 t of this sediment lies upstream of park boundaries, of which approximately 3,900,000 t is located within unvegetated reaches in the active channel and could be mobilized during high flows.

Spatial concentrations of stored sediment vary from 300 - 12,000 m^3 of sediment per 100 m of channel length. Thus, some reaches are obviously sediment storers whereas others are very efficient transporters. Identification of such reaches is essential in determining rates of sediment transfer in a watershed, and in recognizing reaches with potential sedimentation problems. Annual transport of bedload material out of the watershed is 150,000 - 450,000 t/yr. Because annual bedload transport out of the basin is only a fraction of the potential active channel sediment in the basin, transfer of material within the Redwood Creek basin itself is important in the definition of sediment routing for the watershed.

Land use disturbances initiated erosion from mass movement and fluvial processes in many localities. The resulting increase in sediment load in Redwood Creek caused several problems. Streambed elevation was raised as the channel bed aggraded. Channel aggradation was accompanied by channel widening and bank erosion. Bank erosion, in turn, undercut the toes of unstable hillslopes and in some cases caused the initiation of new landslides and the reactivation of old landslides. Streamside vegetation, such as old-growth redwood groves, were threatened by overbank flooding and an elevated water table. Pool/riffle sequences were disrupted, and streambed particle size decreased. Fish habitat and spawning grounds were disrupted. Aggradation in upstream portions of the stream became a source of sediment to downstream reaches. The transport of this channel-stored sediment can cause a similar sequence of problems in downstream reaches in future years.

TIMING OF SEDIMENT TRANSPORT

Timing of sediment transport is critical to aquatic life, especially to spawning anadromous fish because their eggs depend on streambed stability for survival. Sediment transport is a function of stream discharge, and thus rainfall. Most precipitation occurs predominately between October and April. The majority of sediment transport occurs during the two to six most intense storms of the winter. For example, about 85% of the total suspended sediment transported by Redwood Creek at Orick between 1971 and 1973 occurred in less than 5% of the time (Janda and others, 1975). On the average, more than 50% of annual sediment transport occurs only four days each year (Brown and Ritter, 1971; Kelsey, 1977). Infrequent, high-magnitude floods are major transporting events. For instance, in the 8,060 km^2 Eel River basin in northern California, 50% of the suspended sediment discharge for 1958 - 1967 occurred during the 30-day period December 23, 1964 to January 23, 1965 (Brown and Ritter, 1971). Because of these characteristics of sediment transport, erosion control and stream monitoring programs must be designed to work effectively during infrequent, high magnitude events.

IMPLICATIONS FOR WATERSHED REHABILITATION

A large watershed rehabilitation program is currently underway on logged lands recently added to Redwood National Park. These lands are in the lower third (240 km^2) of the Redwood Creek basin. The intent of the program, which was mandated by the U.S. Congress upon expansion of the Park (Public Law 95-250, March 27, 1978) is "to rehabilitate areas within and upstream of the park contributing significant sedimentation because of past logging disturbances and road conditions and to reduce the risk of damage to streamside areas of Redwood Creek" (U.S. House of Representatives, 1978). The current rehabilitation program in Redwood National Park deals with erosion problems that are accessible to equipment and work crews, and that are treatable with present technology. These constraints limit most rehabilitation work to recently logged hillslopes. The most significant rehabilitation treatments are the removal of road fill from stream crossings, the elimination of roads as barriers and diversions to runoff, the prevention of downcutting in gullies and newly excavated channels, and the revegetation of disturbed sites.

We feel the erosion control techniques used in Redwood National Park represent the current state-of-the-art in terms of types of problems that can be effectively treated (Kelsey et al, 1981). These techniques are used on recent (post-1970) tractor logged hillslopes and along the network of logging haul roads within the 20,000 ha park addition. Private lands within the basin upstream of Redwood National Park are presently not included in the program because untreated, logged areas still remain on park lands. Cooperative rehabilitation efforts with private landowners is a possibility at a future date.

The techniques used by Redwood National Park are most effective in controlling fluvial erosion from hillslopes, and they help ameliorate detrimental impacts on small tributary basins. Early treatment of problems may prevent downslope and downstream cumulative impacts. However, the effectiveness of current rehabilitation techniques is limited in terms of improving main channel conditions. Once sediment enters a channel it is difficult to prevent further sediment transport. Mass-wasting and channel-stored sediment are two major source areas that are not addressed to a great extent in the present program because they are technologically impractical to treat. Consequently, when considering the huge volumes of material involved in landslides and channel-stored sediment, total watershed rehabilitation is impractical. Erosion control techniques can ameliorate conditions in tributary basins, however, where less sediment is stored, and sediment flushing occurs more readily.

Some techniques that are based on a knowledge of stream processes may be useful on a small scale. Stored sediment in channels can be a sediment supplier to downstream reaches for years to come. Thus an extensive revegetation program directed at stabilizing eroding terraces and flood berms may be as or more effective in sediment control than the revegetation of slopes and may improve the aquatic habitat as well. Gravel excavation in critical areas may be necessary, although excavation is very expensive and may trigger troublesome side effects. In-channel devices may be installed to encourage pool formation in aggraded channels. Bank protection treatments may hinder bank erosion in critical reaches, where accelerated hillslope destabilization would cause further sediment problems.

CONCLUSION

Erosion control and rehabilitation measures can successfully treat problems on logged hillslopes. Early treatment of problems can prevent possible downslope and downstream cumulative impacts. An evaluation of sediment source areas shows, however, that major sediment source and storage areas are inaccessible and cannot be treated by present erosion control technology. Thus, the effectiveness of a total watershed rehabilitation program is limited by the physical processes which control erosion and sediment transport.

The above situation argues strongly for preventive erosion control through intelligent land management, minimal new road construction, and proper road maintenance. Preventive erosion control is feasible because erosionally sensitive areas can be identified, and many serious problems can be avoided with good land management practices. The challenge for watershed sediment control is in large part an economic, administrative, and political one of properly managing land within recognized physical constraints.

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FLOODS, SEDIMENTATION, AND ALLUVIAL SOIL FORMATION AS DYNAMIC PROCESSES MAINTAINING SUPERLATIVE REDWOOD GROVES

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There is an answer to the question as to why the redwood trees have shown such pertinacity of life in that particular environment, where their existence has been so successfully maintained, where other trees in other environments have shown no such life persistence. It is because that particular environment has proved to be peculiarly adapted to the well being of the sequoia, and conversely, the sequoia especially fits this particular environment. The reason for the great longevity of this forest species is that in that region there has been a perfect balance between the redwood tree and all or nearly all surrounding conditions. (Thomas Edison, 1926)

ABSTRACT

New sediment accretion to soil profiles was found to be related to tree ring growth acceleration in old redwood trees growing on alluvial soils subject to flooding. It is inferred that the vigor of growth of these trees is rejuvenated periodically by sedimentation of new soil material that is consistent in texture with past deposits. However, it was observed that drastic changes in quality of sediment, either due to change in texture, or in organic matter content, resulted in death to trees on these alluvial flats.

INTRODUCTION

The preservation of superlative redwood groves should be based upon an understanding of their relation to the dynamic processes of flooding and sediment deposition which has created and sustained them. Changes in these processes and the resulting change in conditions in these forests may be counter to preservation efforts.

The superlative groves of redwood (*Sequoia sempervirens* D. Don Endl.) on alluvial flats in north coastal California are both initiated and rejuvenated by relatively infrequent flood events. Management and preservation of these groves must involve a watershed management program that maintains a favorable magnitude and frequency of flooding and sediment transport. Long-term changes

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in the frequency of overbank flooding or in the quality of sediment may have unfavorable consequences for the vigor and longevity of the trees. This paper is concerned with the interrelationships between superlative redwood groves on alluvial soils and long-term watershed processes.

What are the conditions in which these tall trees have originated and survived? Can we use historical evidence as a basis for describing them, and what historical evidence is there? Have present conditions changed and in what manner? To what extent is restoration needed and feasible if deleterious change has occurred? How do we know what conditions at present may be deleterious, and how do we know if our actions are bringing them about? How do we achieve the proper balance between the requirements of these trees and environmental processes which affect the areas we presume to manage?

Finding answers to these questions requires a perspective in time that goes beyond the scope of daily decision-making based on economic and political criteria. It means assuming a perspective with a breadth in time comparable to the age of the trees. Frequently when we live and work in close association with the redwoods, it is difficult to maintain this perspective.

REVIEW OF PAST WORK

An awareness of the need for active management of the superlative groves is not new. In the early 1960's, Howard Libby of the Arcata Redwood Company established the "Tall Tree Committee" to advise the company on problems of sustaining the Libby Tree and the grove surrounding it (now known as the Tall Tree Grove of Redwood National Park). At that time, the top of the tree was dying back, and the bank of Redwood Creek was eroding. A series of steps was taken upon advice of the committee to solve the problems, including a revetment of a large redwood log against the bank, and moving the creek to the opposite side of the channel. This was done by excavating stream bed materials from one side of the channel and piling them alongside the eroding bank. During a period prior to this, Hammond Lumber Company had maintained the stream on the opposite side of the channel from the grove. This was done by the excavation of gravel and rock from the stream bed for surfacing roads. Since this operation stopped bed load had accumulated again and the stream shifted against the Tall Trees Grove bank. Thus the need for active management based on an understanding of natural processes continues.

The dynamic relationship between trees and soil of the superlative groves can be understood only in a whole watershed context. The soil of an alluvial flat was built up over centuries by flooding, which deposits the silt loam upon which the tall redwood trees grow. E. Fritz (1934) documented the history of deposition at Richardson Grove by examining the root system of a fallen redwood. He found that seven floods at varying intervals had deposited 11 feet of sediment. The root system of the tree responded to these continuous new layers of soil by developing successive layers of roots, each developing in what was the surface of the new sediment. Stone and Vasey (1968) found that redwood roots could rapidly grow upwards to occupy this new sediment. However, recreational use may impede this. Meinecke (1929) found that heavy foot or vehicle traffic results in soil compaction, which hinders the ability of roots to invade a new soil profile. Gravel introduced for road construction has the same effect.

The deleterious effect of flood-deposited gravels was verified later by Stone and Vasey in their studies. Helley and La Marche (1968) noted the relation between a change in sediment quality and the death of redwood trees along Blue Creek, a tributary of the Klamath River. In Rockefeller Grove at Bull Creek, the dynamic processes include not only flood, sedimentation, and bank cutting, but also fire (Zinke, 1977). These processes have led to the development of the largest biomass accumulation ever measured: 3461 metric tons per hectare, with a volume of 10,817 m^3 per hectare (Fujimori, 1977). In summary, there are dynamic events occurring in relation to redwood trees, some beneficial such as floods and related sediment, some detrimental such as floods with gravel and bedload deposition or excess compaction of soil.

I began soils studies relating to these problems shortly after the 1955 flood along the Eel River and its tributaties such as Bull Creek in order to understand some of these processes. This period of time has encompassed several flood depositions, as 1955, 1964, and 1974 in these groves, and has enabled the development of a chronology of the sedimentation for slightly more than a thousand years.

ALLUVIAL SOILS OF THE REDWOOD GROVES

The soil under a superlative redwood forest such as that at Bull Creek Flat is evidence of a dynamic process of periodic flooding and sediment deposition. The response of the trees varies. Sometimes growth accelerates and sometimes death occurs, either by felling the tree due to bank cutting, or swamping the base of the tree with sediment having undesirable characteristics.

The flood of 1955 cut a steep bank into the soils of Rockefeller Grove in lower Bull Creek Flat. I had a large pit excavated into this bank to expose the various sediment layers, as shown in Figures One and Two. A sketch of this pitface is shown in Figure Three. Soils were sampled at uniform intervals from this face. Samples were taken to allow measures of the soil bulk density (over dry weight per unit field volume), and various physical and chemical properties.

The most obvious feature of the soil was its layering in distinct beds of sediment deposition as seen in the figures. During excavation in the summer of 1958, the recent deposit of the flood of 1955 was apparent on top of the pit. This bed of recent flood sediment overlay at least fourteen other

Figure one: Upstream edge of Rockefeller grove on Bull creek showing cut bank from which soil samples were obtained.

Figure two: Detailed view of soil profile which supports the forest at Rockefeller grove showing successive layers of sediment with the deposit of the 1955 flood at the top, and the approximately 955 A.D. flood deposit in the hole at the base.

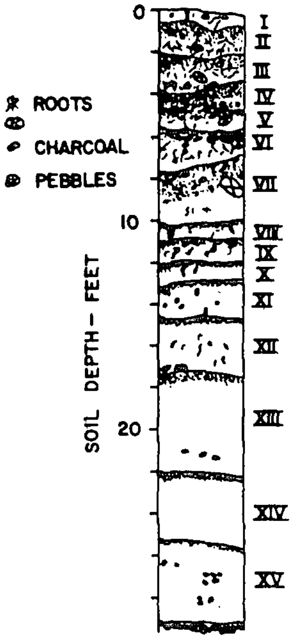

Figure 3: The deep alluvial soil with numerous flood deposit layers identified from youngest deposit as I, and oldest as XV.

identifiable sediment deposits. The soil was built of a column of sediment deposits 8.23 m deep, resting upon a stony layer that was obviously a stream deposit. The dynamic nature of the area was demonstrated by the flood of 1964 which tore another three meters out of this bank, felling a large tree. I subsequently measured this tree for foliage, bark, wood and root biomass and sampled it for chemical analyses (Zinke, Strangenberger, and Colwell, 1979). The flood of 1964 left a sediment deposit over the floor of the grove, and another flood and sediment deposit occurred in 1974. These have been monitored, and their properties determined. Thus, when one deals with an alluvial flat even with trees more than a thousand years old, the area is subject to continuous events of new flood and sediment accretion, bank cutting, and tree falling. Each site will have its own history, as well as extreme events shared in common with other sites, and this should be determined where such knowledge is critical to management perspective.

CHRONOLOGY OF SEDIMENT DEPOSITION

The chronology of the deposition layers is of immediate interest, since if this can be determined, it is possible to characterize the rate of the various dynamic processes occurring on the site, and the probability of occurrence of flood events that bring about sediment deposition.

Carbon 14 dating on deposited charcoal was carried out on the lowest of the sediment layers in order to obtain an age for the entire sediment profile (Dr. Hans Suess, School of Sciences and Engineering, U.C. San Diego, La Jolla). Charcoal samples from the bottom of the soil profile indicated an age of 1000 years ± 100 years.

Ages of nearby trees were of a similar order of magnitude; about one thousand years, with variation due to discontinuous rings, established by ring counts on a tree fallen in the 1955 flood. This indicated an age of 960 years at the cross section at 10 feet up the tree bole. The age of the lowest layer of this Bull Creek alluvium was judged to be 1000 years, substantiated by both the radio-carbon dating, and the tree ring analyses. The first soil layer was therefore initiated by a flood deposited sediment in 955 A.D.

I found that tree ring growth on the trees had a periodic variation in width that coincided with sediment deposition. An example is seen in Figure 4, showing periodic annual radial growth based upon tree ring width measurements. These data indicate a series of intermittent accelerations in growth rate. Known dated floods of 1934, 1916, and 1861 correlate with the three most recent growth accelerations as indicated by wider tree ring widths after these dates. Not all floods, however, result in sediment deposition, as some floods remove surface materials (Fritz 1956). Flood frequency may actually be higher than the frequency of growth accelerating sedimentation.

In order to determine the frequency of growth accelerating sediment deposition, I plotted the cumulative radial growth against time for two trees (Figure 5). One tree was located at 159 feet elevation above sea level in

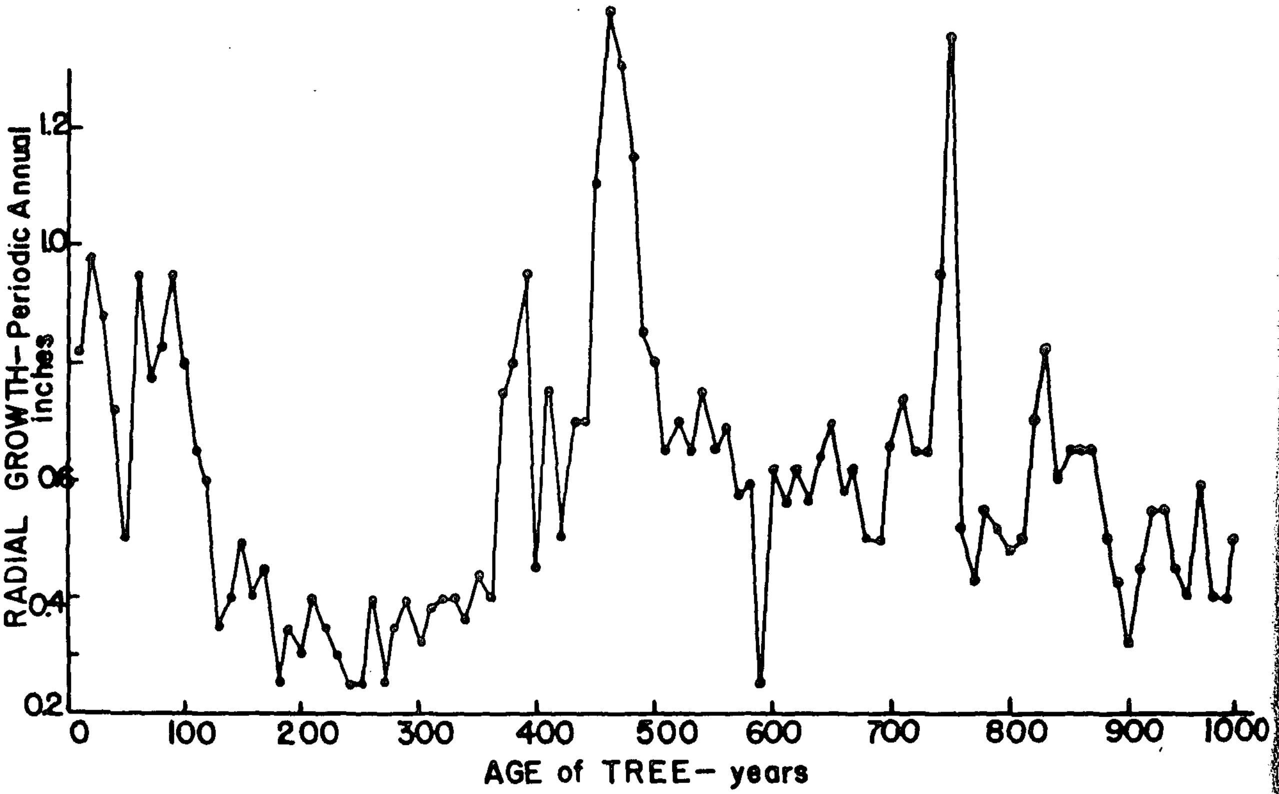

Figure 4: Radial width of tree rings measured on cross section of tree which fell near the deep soil excavation.

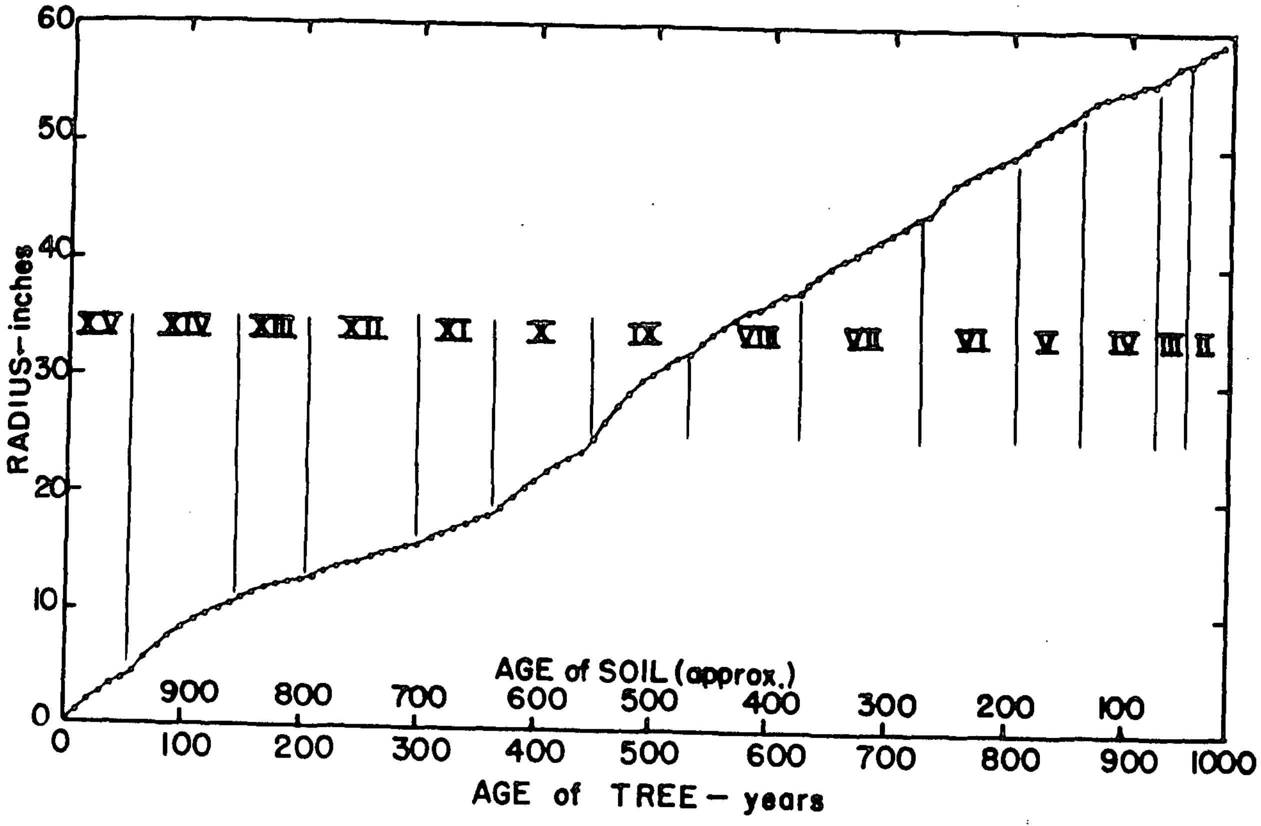

Figure 5: Cumulative radial growth and tree age from the tree which fell near the deep soil excavation in the flood of 1955.

the Rockefeller Forest at Bull Creek; the other was located at 170 feet elevation, but downstream in the Haas Grove on the main stem of the Eel River. Fourteen growth accelerations are shown, occurring at time intervals varying from 25 to 150 years. Table 1 shows the probability distributions for the intervals between periods of growth acceleration. As expected, the higher elevation tree at Haas Grove had a longer mean period between depositional events. Maximum stage of the 1955 flood was 178 feet above sea level at the confluence of the South Fork Eel and the Main Fork Eel; both sites are near the confluence and were inundated by that flood.

It is apparent that flooding and sediment deposition are periodic events, the only unique aspect being the length of the expected period between events on each alluvial flat. This will depend partly upon the natural regime of the particular watershed, and partly upon the elevation of the alluvial flat above the present streambed. In the case of the Rockefeller Grove flat on Bull Creek, the interval apparently did not change as the level of the flat rose through sedimentation because flooding heights are controlled by backwater due to the much larger flow of the main Eel level one mile downstream. This backwater type damming has been described on the Rio Grande by Kochel and Baker (1982). In the case of the Tall Tree flat on Redwood Creek, however, the main control is the elevation in the adjacent stream channel of Redwood Creek itself, as determined by bedload depositions in the creek.

There is a certain amount of error in the measurement of redwood tree age due to discontinuous rings (Fritz and Averell, 1924). This error may be 10% in a one thousand year old tree (E. Fritz, personal communication, 1961). This is about the magnitude of the error in radiocarbon dating for the same period. The error, although important in exact dating of a flood year, is not so critical in evaluating return intervals of events.

In addition to the frequency of occurrence of sedimentation events, it is important to evaluate the properties of the sediment, particularly with regard to the health of the trees. This vigor is already a problem with the Tall Tree as indicated by its top dieback.

PHYSICAL PROPERTIES OF SEDIMENTS AND DERIVED SOILS

I have measured various physical properties of the sediments and resulting soils in the alluvial groves along the Eel, and the Van Duzen Rivers. These properties were bulk density, or dry weight per unit field volume, the texture as percent sand, silt, clay, and the total depths of deposition. Sediment deposited in the 1974 flood along the Eel River was measured for volume weight and averaged 1.27 in Founder's Grove, and 1.21 in Rockefeller Grove. The sites were not significantly different, based upon 8 samples in each location. Apparently the value of 1.2-1.3 has been fairly consistent for the last thousand years as seems to be indicated for the bulk densities for the deep Bull Creek Flat profile plotted in Figure 6. For this profile, the bulk densities tend to be higher than for most forest soils, ranging

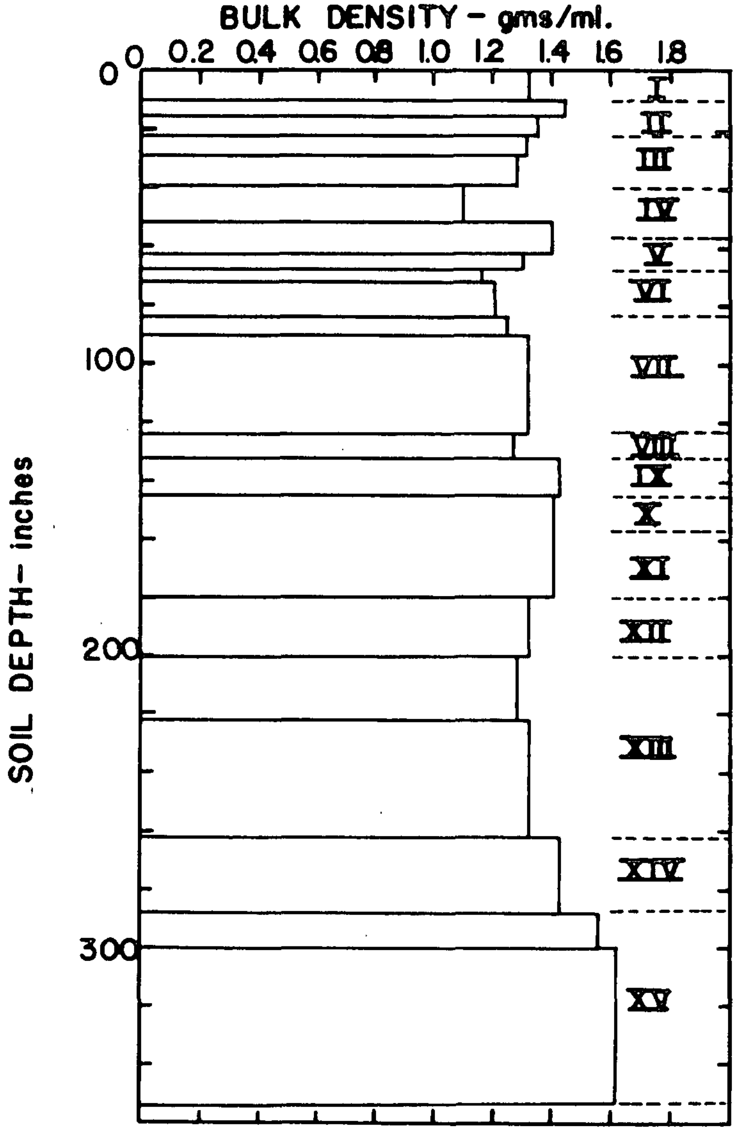

Figure 6: The bulk density (oven dry weight per unit volume) of the soil samples obtained from the deep soil excavation in Rockefeller grove. Original sediment initial density after first season settling ranged from 1.2-1.3.

Table 1: Cumulative probability of size of interval in years between tree ring growth accelerations assumed due to flood deposited sediment at two locations along the Eel River: Rockefeller Grove at 155' above sea level, and Haas Grove at 170' above sea level.[1/]

Cumulative Prob. % of Intervals	Rockefeller Grove years	Haas Grove years
≥10	27.3	48
20	31.3	57.3
30	36.5	66.4
40	43.3	76
50	51.9	86.4
60	63.4	98.2
70	79.3	112.5
80	103.3	131.2
90	148.0	160.8
n	14	27
mode	24.8	59.1
arith. mean	73.9	97.1

[1/] determined using Weibull function for cumulative probability. Using Chi-square, significance was .02 for Rockefeller Grove and .07 for Haas Grove.

from the 1.2 of the freshly deposited sediment to 1.6 in the lowest layers under compaction of the weight of the total sediment column. However, on surfaces which were exposed for longer periods, a surface soil below 1.2 in bulk density develops.

The coarse or gravel fractions were measured in all the samples, and for the sediment additions representing overbank flood stages and sedimentation there were few materials greater than 2 mm. in diameter. This was true for the entire depth of the sediment column.

A total of 1212 grams of sediment per square cm. of area was deposited during 1000 years on the Rockefeller Grove soil profile. Figure 7 shows the cumulative sediment amount during the centuries involved. Despite widely varying deposition intervals, the slope of this relation is fairly

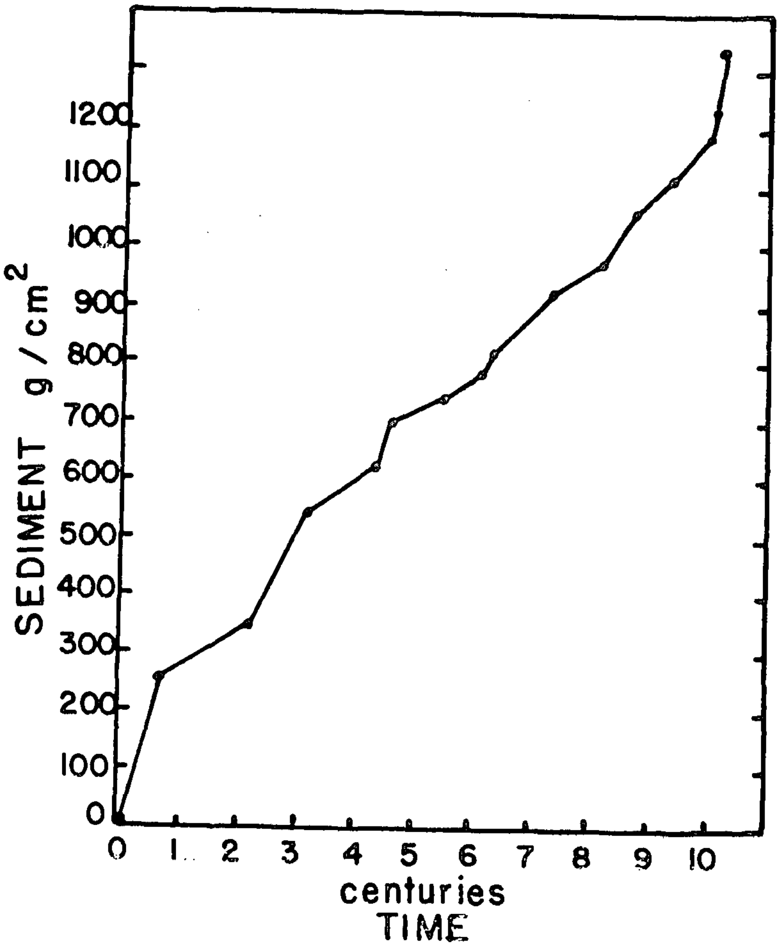

Figure 7: The cumulative sediment weight deposited during the past ten centuries at the Rockefeller Grove site. A value of 1212 grams per cm² measured up to 1955, with last plotted addition in 1964.

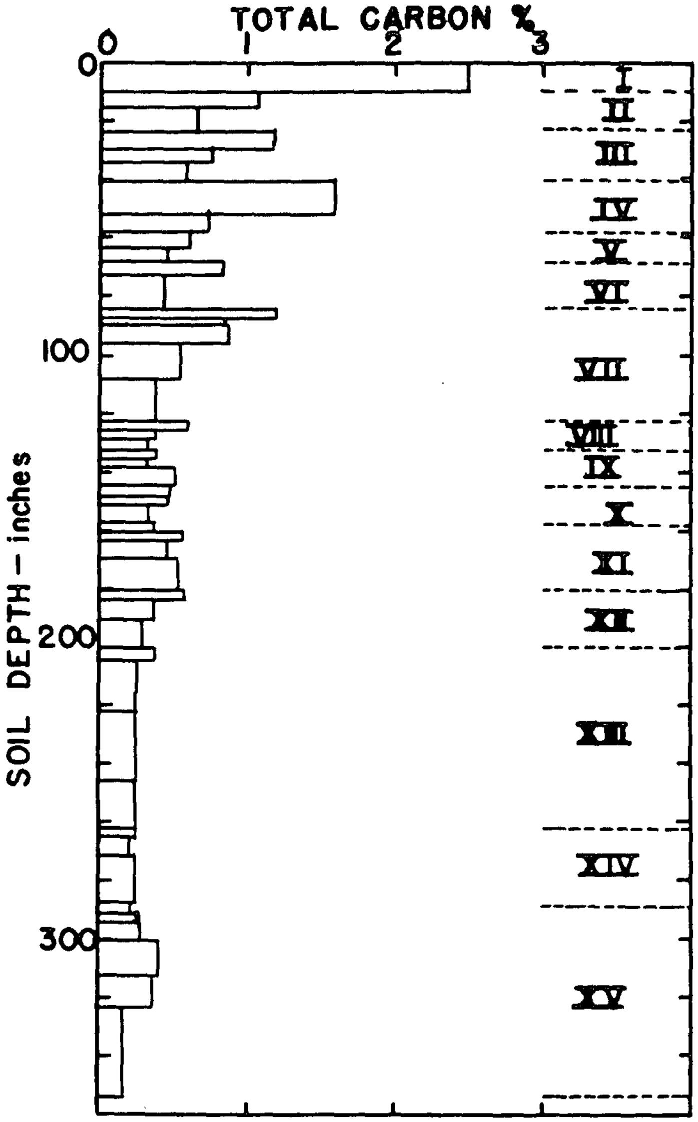

Figure 8: The carbon contents of the soil sample representing the various soil layers from the excavation in Rockefeller Grove (%C in the fine earth fraction less than 2mm on an oven dry basis.).

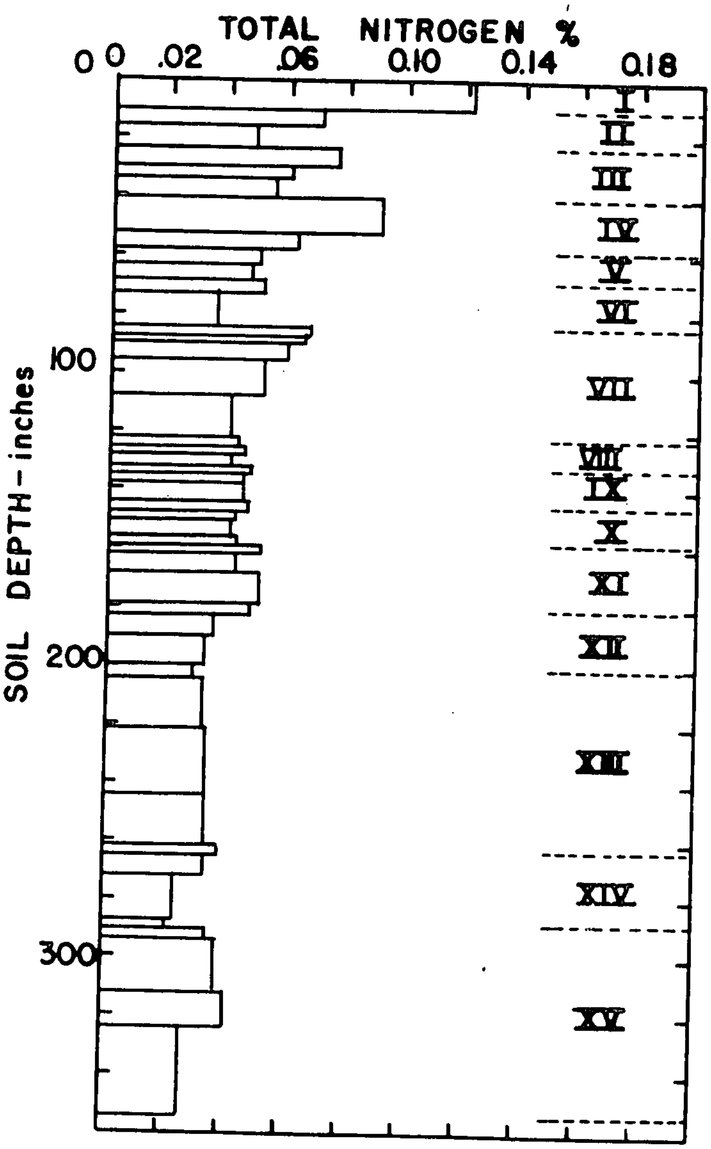

Figure 9: Total nitrogen contents of the soil samples representing the various soil layers from the excavation in Rockefeller Grove.

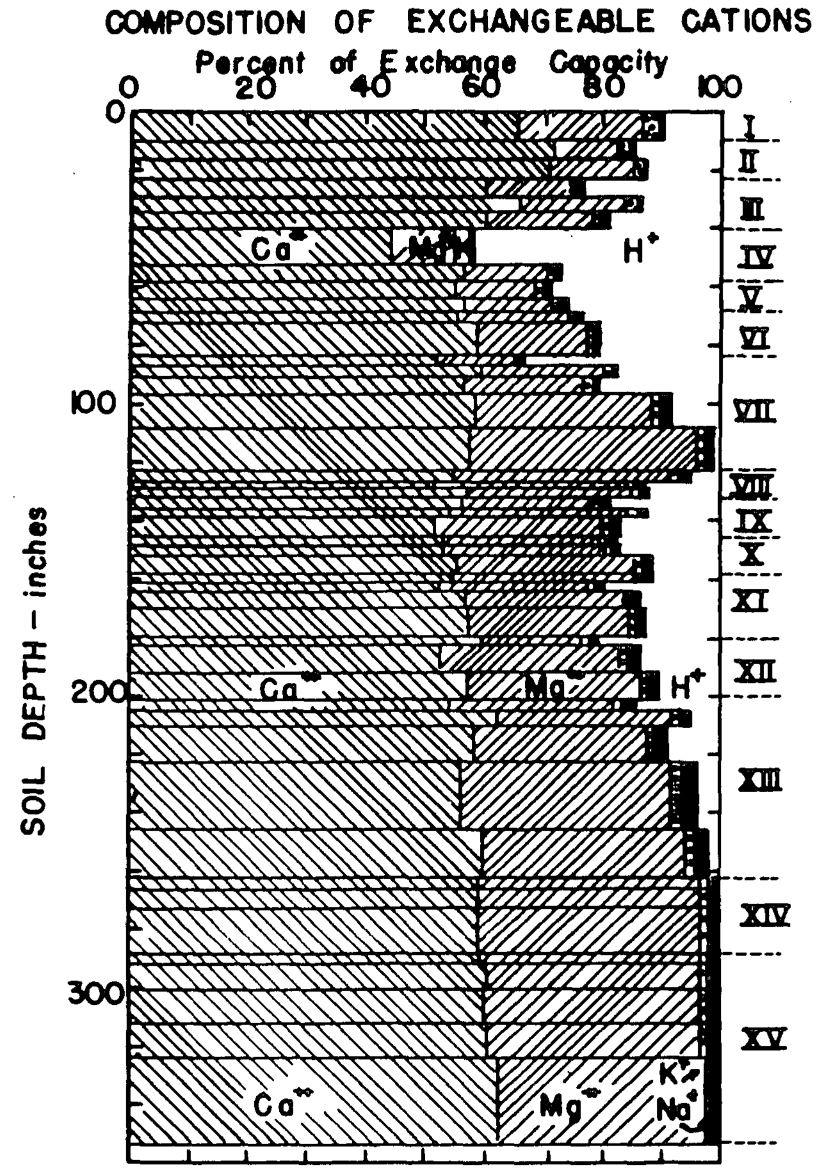

Figure 10: The exchangeable cation composition in the various soil layers in the Rockefeller Grove soil.

constant. Sixty percent of this deposition material was in the silt size fraction, or 728 grams. Fifteen percent of this material, 186 grams per cm^2 was clay less than 2 microns. The remaining 25 percent was sand (usually fine sand fractions). Sediment samples collected after the 1964 flood had slightly less clay content, averaging 13 percent for ten samples, and more silt with 71 percent, and less sand with 17 percent. However, there is a large variation within each deposition layer, with larger proportions of silt and clay in the topmost layers. This particle size distribution of the sediment resulted in no deleterious effects to the trees at the site, and was consistent for a long period of time. There is also textural variation across a redwood flat, with larger proportions of sand near the stream, and less inside the flat. Those concerned with preserving a grove for a long period of time on such a flat will need to anticipate a normal rate of sedimentation of a typical particle size distribution over the long period of time.

Each alluvial flat will have its own rate of accumulation based upon depth and duration of overflow flood waters. Of course, intervals between events will be variable. Certainly watershed disturbances such as fires, and natural landslides have occurred during the 1000 years of this record, and it is against this background that one needs to assess the possible effect of man-made disturbance of these hydrologic regimes. Figure 7 indicates that there may be periods of increased sedimentation, possibly due to local events augmenting sediment or to floods that are extreme in stage and duration. The trees are apparently unharmed as long as they are able to o-cupy the new sediment deposits with new roots, and are not physically felled by bank failure due to stream erosion, or sliding during the flood draw-down period.

CHEMICAL PROPERTIES OF SOILS DERIVED FROM SEDIMENT

Carbon, nitrogen, and various other chemical properties of the soil related to fertility were determined on the alluvial soils along the Eel River and Bull Creek. These elements generally show an increase in amount at the top of each new buried layer, decreasing to the top of the next layer. Successive surfaces of buried layers decrease in total content of these elements. This can be seen for carbon and nitrogen in Figures 8 and 9. It is apparent that both carbon and nitrogen are conserved in the buried layers, with an increase at each buried surface. These darker surfaces of the buried soils make it possible to identify the buried layers in the field excavation. Florence (1965) found that the new sediment, although low in fertility, had properties in terms of microbial processes that accelerated the availability of mineralized nitrogen and enhanced seedling survival. The various exchangeable cations follow a similar trend as seen in Figure 10, except that there is an obvious zone of depletion of these, and substitution by hydrogen in the most active current root zone above 2.54 meters depth. The consistent 60% calcium saturation below this depth is also of interest.

The return of redwood leaf litter to the soil surface with its content of the various elements most likely enriches the present sediment surface as long as it is exposed during the interflood interval. The extent to which this litter return enriches the particular soil depends upon the length of this interval, again a function of flooding probability, and height of the flat above the stream channel.

DEVELOPMENT OF THE FOREST ON SEDIMENT DEPOSITS

Redwood trees produce prodigious amounts of seed. During the redwood ecology studies in Humboldt Redwoods State Park, I collected seed along with leaf litter for several years. Seed counts were made of this material at locations along the South Fork of the Eel River, with seed amounts ranging from 2 to 27.9 million per acre per year. However, viability of the seed is less than 20%, and one rarely finds surviving seedlings from all this seed production each year in the groves. In contrast, following a flood year with sediment deposition, an invasion of young surviving seedlings, green as a lawn, develops on the new sediment deposit under the trees and as a margin to the grove. Figure 11 shows several age classes of such seedlings. In the foreground are the seedlings of the 1955 flood, in the middle the 1916 flood seedlings, and behind, the 1861 seedlings. Figure 12 is a photograph of Founders Grove. The seedling wave from the 1861 flood can be seen as a wall along the front of the grove itself composed of seedlings from floods of 100 years ago. Inside the grove are a few isolated giant trees, including the Giant Tree of Founders Grove, survivors of even earlier historic floods. Thus, the age class distribution within the superlative redwood grove gives us a clue to the periodicity of sediment-producing floods on that particular site, important information for the manager.

However, there may be detrimental effects of some flooding and deposition in redwood groves on alluvial flats. After the 1955 flood on upper Bull Creek Flat, we noticed that some of the large old trees of the grove had tops which were dying back. At the base of these trees we found deposits of sediment that were very coarse and gravelly, and choked with organic detritus. This material formed an abrupt interface with the previous silt loam deposits. Water perched at this interface during the wet season, and a blue anaerobic layer developed in the leaf litter which was buried there. The trees weakened by this abrupt change in quality of sediment were finally killed by redwood bark beetles (*Phleosinus sequoiae* Hopk.). Wherever the floods of 1955 and 1964 resulted in death to redwood trees along the Eel River, and Bull Creek, we found a deposit of coarse texture. E. Fritz (1956) reported that such a change in stream flow regime may be brought about by the sudden release of flood water and detritus due to the breaching of a log jam upstream.

A considerable loss of trees may also occur from actual failure of the stream banks where the stream cuts into such banks, and where quick drawdown following flooding causes saturated soil to slide along with trees into the stream. When these trees fall while the flow is still high, the tree bole is usually oriented downstream and parallel to the bank. Eventually such fallen trees protect the bank against further cutting by the stream. However, this natural tree groin formation formation is usually removed by the park manager, or if not, by poachers. This occurred at Cheatham grove on the Van Duzen River. This use of natural tree groins as a means of bank protection has been documented for large river systems by Framjl (1947).

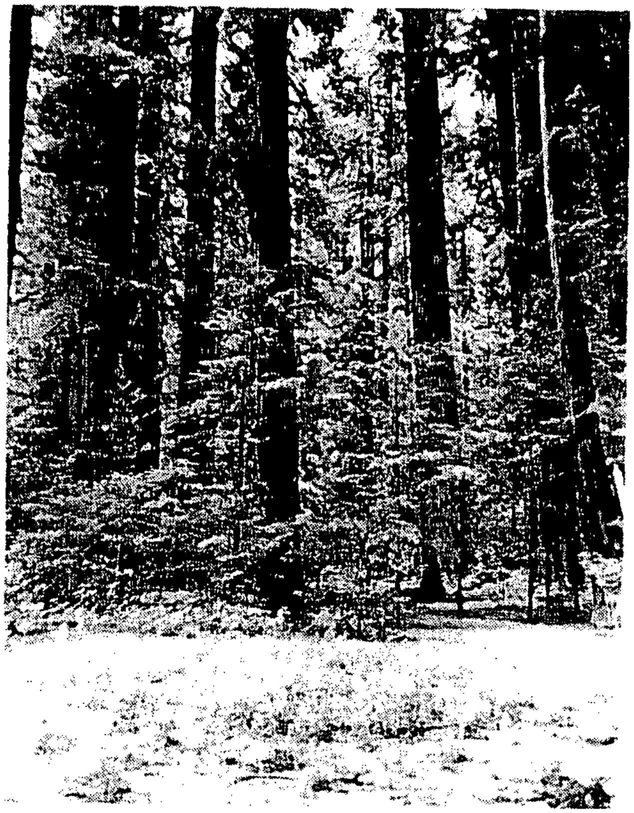

Figure 11:Seedlings of various age classes identifying sediment deposits in Stephens Grove. Foreground seedlings from 1955, intermediate height from 1916, and taller saplings from 1861.

Figure 12:Seedlings from the 1861 flood sediment now forming a wall on the outside of the Founders grove at the confluence of the main Eel and the south Fork.

RELATION BETWEEN WATERSHED CONDITIONS AND THE SUPERLATIVE REDWOOD GROVES

The close relation between the vigor of the trees, the dynamic processes of flooding and sedimentation, and a thousand-year consistent quality of sediment free from coarse fragments, or excessive bank cutting by the flooding stream, is apparent. In the case of Redwood Creek as well as in the case of the superlative groves on alluvial flats along rivers to the south, the maintenance of these groves involves avoiding undue changes in these processes. The flood events will certainly continue to occur. But the quality of the sediments reaching the alluvial flats may change. If coarse bedload material is deposited on such a flat, then the result may be a serious decline in tree vigor.

The watershed management objectives needed to maintain the balance in sediment quality favorable to the trees involve two major areas of concern: the first, the control of the channel immediately adjacent to the grove; and second, the goal of maintaining watershed conditions that minimize adverse changes in the flood and sediment regime of the stream.

The immediate goal of channel management needed to protect the Tall Trees Grove requires an assessment of the problem of potential bedload deposition in the grove related to local aggradation. Designing the means of protecting the grove against such an event can be formulated, possibly using groins, revetments, or guiding of the stream to the opposite side of the channel. A similar problem occurred at Cheatham Grove along the Van Duzen River, where excessive bank cutting was gradually destroying the grove. The problem was treated by a series of gravel fill groins extending into the channel, which diverted the river to the far shore. Sale of the fallen trees from this Nature Conservancy Reserve paid for the necessary work. Along Bull Creek, the State Park Department utilized channel clearing, and gabbions and rock revetments along the channel bank.

Upstream watershed management objectives will require an assessment of sediment and bedload sources, and the development of cooperative ways of dealing with a wide variety of owners and land use conditions. I made an initial determination of sediment sources on Redwood Creek for a study of buffer zones to the Park (Stone, Grah, and Zinke, 1969). The entire watershed was surveyed with regard to soil types and their slopes in the course of the California Cooperative Soil Vegetation Survey, making it possible to determine where critical areas of high erosion potential are located. The sediment entering the stream channel is largely a result of bank cutting and land slides. Sediment sources can be related to soil types as mapped along the banks of the creek and its tributaries. The length of stream bank occupied by each soil type was determined for forty-two and one-half-miles of banks of Redwood Creek above the Emerald Mile.

These data (shown in Table 2) indicate that twenty-eight and three-quarter-miles of bank will be actively feeding material into the channel from compound slides. These are areas of the blue-grey colored Atwell and Yorkville soil series. It is these materials which give the waters of Redwood Creek their characteristic grey color. These soil materials contribute not only

Table 2. Soil types along 42.5 miles of Redwood Creek from the Redwood National Park boundary to the Snow Camp area of the Six Rivers National Forest.

SOIL TYPE	EROSION SOURCE POTENTIAL	MILES* OF BANK	PERCENT OF DISTANCE
Atwell (823) or Atwell complex with Masterson or Hugo	Very high potential with numerous compound landslides	28.0	33.0
Yorkville (752)	Very high with compound landslides	0.75	0.9
High Terrace (400)	Moderate with debris slides and bank cutting	12.0	14.1
Masterson (821)	Moderate to low, block slides if dip of schist is downslope toward creek	43.75	39.7
Hugo (812)	Low-moderate. Debris sliding if steep slope or vegetation removed	8.5	10.0
Recent alluvial soil low terrace (200)	Low, unless bank cutting occurs	2.0	2.3

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*One mile of creek considered to have two miles of bank for this study.

to suspended sediment load but also to bedload, depending upon the proportion of coarse materials they contain. Stream cutting of the banks of the hgih terraces along the creek will be another source of bedload. These high terrace soils are historical beds of the creek and deltas of tributaries left stranded above the current grade of the creek as in Redwood Valley. There are 12 miles of such high terrace soils in the Redwood Valley area in the Beaver Creek and Minor Creek areas. Fifty-two and a quarter miles of moderately stable to stable banks occur along the areas where the Masterson and the Hugo soils line the creek. However, about half of these have slopes greater than 50% and thus are potential sources of increased sediment if surface erosion or mass movement is accelerated by land use activities. A minor distance of 2 miles of stream bank are occupied by recent alluvial deposits which have a low potential as sources of sediment and bedload. Given this array of sediment sources, the priorities of action needed to achieve stability of historic watershed processes can be attainted.

Most likely the Tall Trees Grove has a long history of flooding and sedimentation, as with other similar groves on alluvial flats, and it is necessary to see that this continues with minimum adverse change. This will be difficult, because the past half-century has been one of major changes on the watershed related to human use. As can be seen from the table, more than one third of the bank length is occupied by soils having a high erosion potential. These would be critical areas to monitor if it is thought that a problem requiring renovation exists. This evaluation does not involve tributary streams, for which a similar assessment should be made.

CONCLUSIONS

1. Each alluvial flat supporting superlative redwood groves is unique in its history of dynamic events of flooding, sedimentation, and response of the trees to these events.

2. The effects of sediment deposition may be detrimental or beneficial, depending upon the quality of the sediment deposited relative to the ability of the tree roots to invade this new material.

3. Fine sediment of a silt loam quality is generally beneficial, while coarse gravelly bedload deposits are detrimental.

4. Accelerated tree growth usually occurs following deposition of sizable amounts of beneficial sediment, and the increases in tree ring width can be used to date such flood-sediment deposition events.

5. An example of such a chronology is presented for Rockefeller Grove on Bull Creek Flat.

6. Redwood seedling survival is enhanced by new sediment deposition, resulting in age classes of trees in the groves dating such deposits.

7. The history of a particular grove such as the Tall Trees Grove can be interpreted by means of the sediment profile of the soil, by the tree ring history of periods of growth acceleration due to sediment, and by the age classes of trees present in the grove.

8. All of these indicate a history of dynamic flooding, sedimentation, and rejuvenation of tree growth on the alluvial soils of the superlative groves.

9. Management of these groves with the objective of their preservation must allow for such events and their maintenance.

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