RECENT CHANGES IN CHANNEL-STORED SEDIMENT
REDWOOD CREEK, CALIFORNIA

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ABSTRACT

Stream channels form a link between hillslope erosion processes and sediment transport processes in that they temporarily store sediment before transporting it out of the system. Storage of alluvium in the mainstem of Redwood Creek was quantified for three time periods spanning 35 years (1955-1980). An unusual amount of aggradation occurred during the December 1964 flood (a 50-year flood), and increased the total volume of sediment stored on the valley floor by almost 1.5 times to 16 x 10^6 m^3. High landslide activity of the 1964 flood contributed to 5.25 x 10^6 m^3 of sediment to the mainstream of Redwood Creek, and channel storage increased by 4.74 x 10^6 m^3. Moderate to high flood flows (2-20 year recurrence intervals) following 1964 eroded sediment in the upper basin and redeposited it in downstream reaches, causing little change in the total sediment on the valley floor.

Presently, sediment is stored in several geomorphic compartments, and some compartments (such as recent gravel flood terraces, debris jams, stable alluvial terraces and strath terraces) are only found in particular reaches of Redwood Creek. Potential mobility of sediment stored in Redwood Creek was characterized as active, semi-active, inactive and stable, depending on its distance from and height above the thalweg, and the age and type of vegetation on the deposit.

To identify active sediment in the channel bed, the amount of scour and fill occurring during various flows was determined through scour chains and discharge measurement notes. In this gravel-bedded stream, depth of scour increases downstream for equivalent discharges and depth of scour increases with increasing discharge at a given station.

Sediment was not distributed uniformly downstream and maximum deposition occurred in areas of ancient deposition. Valley width is a more important control on sediment distribution than channel gradient, sites of sediment input, or drainage area.

Attrition of Redwood Creek bed material during transport is high. A tumbling experiment indicated that schist bed material breaks down more quickly than sandstone pebbles. Erosion of bed sediment that had been deposited in the 1964 flood contributed greatly to annual bedload transport in the upper reaches of Redwood Creek for several years after the 1964 flood. Current sediment yields for Redwood Creek are 2,700 metric tons per square kilometer per year ($t/km^2/yr$) in the upper basin and 2,200 $t/km^2/yr$ at the mouth, and bedload constitutes 20% and 11% of the total load at these stations, respectively.

Residence times of active and semi-active sediment generally decrease downstream, but increase for stable sediment. Residence times range from decades for sediment in the active channel bed to thousands of years for sediment in stable floodplain deposits. Average velocities of stored sediment are highest for active sediment, and decrease with decreasing activity levels. Recovery time for the channel in response to the 1964 flood has been slow, and total recovery will take more than a century.

I. INTRODUCTION

Historically, geomorphologists have studied both hillslope erosion processes and sediment transport in rivers, but few studies have quantified a link between these two areas - the storage component of channels. Channels may temporarily store sediment derived from hillslope erosion before transporting it out of the system. The quantity of sediment and its residence time varies with the type of system. Streams in steep mountainous terrain store little sediment for relatively brief periods of time, whereas rivers in broad alluvial valleys store vast quantities of sediment in their floodplains for thousands of years.

As a result, channel storage may modify the effects of hillslope erosion on sediment yield measurements made at a point downstream. Thus sediment yield measurements may not truly reflect current rates of hillslope erosion in a watershed. Nevertheless, changes in sediment yield are often used to detect changes in rates of hillslope erosion due to land use modifications. In basins where channels store a significant portion of sediment in transport, it is not valid to assume a constant relation between hillslope erosion and sediment yield because the amount of alluvial storage can change in response to modifications in a watershed.

An example of recent changes in alluvial storage is found in Redwood Creek in Northern California. Extensive land use changes in recent years combined with several large storms caused widespread erosion and channel changes in Redwood Creek (Janda et al., 1975). Massive amounts of landsliding, gullying and bank erosion occurred, resulting in widespread channel aggradation. Aquatic and riparian resources, including some of the magnificent redwood forests of Redwood National Park, were threatened by bank erosion and deposition of coarse alluvial sediment in low-lying areas (Janda et al., 1975).

In order to help understand these problems, a sediment budget study was initiated in 1978 to document sediment sources, storage and transport in the watershed. This paper addresses one component of the study, alluvial storage of sediment in Redwood Creek. My approach was to quantify the volume of sediment stored on the valley floor under pre-1947 conditions, the increase due to the 1964 flood, and the amount present in 1980. The purpose of the study is to describe the factors controlling deposition and subsequent erosion of flood deposits. I tried to follow the transfer of those flood deposits downstream, to estimate particle velocity and to estimate the residence times of sediment at different locations on the valley floor.

To accomplish this, I considered the mainstem of Redwood Creek to be a continuous conduit of sediment composed of several storage compartments, including debris jams and fans, mid-channel bars, point bars, the channel bed and floodplain deposits. Sediment in these storage compartments was divided into four classes (active, semi-active, inactive and stable) according to its potential mobility. All stored sediment is in transit downstream, but the rate at which it moves varies with its size and location on the valley floor. I applied the continuity equation to several reaches of the stream to document sediment input (I), the change in storage (ΔV_s), and output (O) from each reach. These factors must balance, as shown in the continuity equation:

$$I + \Delta V_s = 0 \quad (1)$$

I then used these data to compute residence times and average particle velocities for sediment in various stability classes and locations on the valley floor, according to the method laid out by Dietrich and Dunne (1978). This study addresses only storage in the mainstem; channel storage in tributaries is discussed by Pitlick (1982).

II. PREVIOUS STUDIES

The sediment budget concept as applied to forested drainage basins is relatively new, and only recently have studies from a wide variety of field areas been published. The use of sediment budgets has been explored by several investigators (Swanson et al., 1982). Dietrich and Dunne (1978) discussed the construction of sediment budgets with an example from a small undisturbed basin in western Oregon. Lehre (1981) described sediment sources and sediment yield in the Coastal Ranges of California, and Kelsey (1977) formulated a sediment budget for the Van Duzen River in northern California. Reid (1981) and Madej (1982) extended sediment budget calculations to basins disturbed by recent logging and road construction. Swanson and Lienkaemper (1982) used a sediment budget to analyze the transport of inorganic and organic material in both old growth and logged watersheds.

Most sediment budget studies to date have focused on small watersheds (less than 25 km^2) in steep forested areas where little sediment is stored in channels or the floodplains. Few studies have quantified in detail the role of alluvial storage in sediment budgets. Dietrich et al. (1982) described an approach for such quantification, using the age distribution of alluvial deposits to calculate residence times for sediment. Trimble (1981) addressed the question of sediment storage in a disturbed basin in Wisconsin where floodplain storage is significant.

Several investigators have addressed changes in channel storage through studies of changes in channel cross-sections (Ritter, 1968; Hickey, 1969; Nolan and Marron, in press). Stewart and La Marche (1967) calculated net scour and fill for several reaches that were modified by a large flood. Through a study of cross-sectional changes in northern California streams, Lisle (1982) described the effects of changes in stored sediment (from aggradation and degradation) on riffle/pool morphology with implications for bedload transport rates.

III. STUDY AREA

Redwood Creek drains a 720 km^2 basin in northern California (fig. 1). For much of its 108 km length it flows along the trace of the Grogan Fault, which juxtaposes two distinct bedrock types. The east side of the basin is generally underlain by unmetamorphosed sandstones and siltstones of the Mezozoic Franciscan Assemblage, whereas the western side is predominantly underlain by a quartz/mica schist. The basin receives an average of 2000 mm of precipitation annually, most of which falls between October and March. Total basin relief is 1615 m; average hillslope gradient is 26%.

Early aerial photographs taken in 1936 and 1947 show a basin that was covered with old-growth redwood and Douglas fir forests and a few areas of prairie. Redwood Creek was narrow and sinuous in most reaches, with a thick canopy of trees over much of its length. Wide alluviated reaches were apparent in Redwood Valley and near the mouth of Redwood Creek. Many of the alluvial deposits were vegetated with conifers and hardwoods. Very little logging or road construction had occurred by 1947. Timber harvest began in earnest in the mid-1950's, and by 1962 45% of the old-growth coniferous forest had been logged. By 1978 this figure rose to 81% (Best, in press). Thousands of kilometers of logging roads were built. Recent erosion rates measured by Janda (1978) are probably 7½ times greater than the natural rate estimated by Anderson (1976).

Large floods occurred in 1861, 1890, 1953, 1955, 1964, 1972 and 1975 (Harden *et al.*, 1978). The flood of 1964 was especially damaging and caused dramatic changes in Redwood Creek, even though the peak flow of the 1964 flood was not unusually high (recurrence interval of 45-50 years)(Coghlan, 1984). Harden *et al.* (1978) partially attributed the disparity between flood size and magnitude of hillslope erosion, to the change in land use.

The 1964 flood caused widespread aggradation in Redwood Creek and other nearby rivers. Channel changes were most severe in the upper basin, where both the storm and previous logging activity had been most intense. The most prevalent deposit in upper reaches are gravel berms up to 9 m high consisting of coarse gravel and located against valley walls (fig. 2). Previous studies of the effects of the 1964 flood on nearby rivers (Helley and LaMarche, 1973) mention similar depositional forms. The berms were deposited almost continuously on both sides of the river in upstream areas, and in many areas they buried pre-existing vegetated bars. Janda *et al.*(1975) dated some conifers killed by the burial as over 200 years old. Also, in lower reaches sandy deposits from the 1964 flood overlie floodplain soils which formerly received only fine-grained overbank deposits. This suggests that the 1964 aggradational event has been unmatched in historic time. Nevertheless, major channel aggradation may have occurred in the past. Helley and LaMarche (1973) and Kelsey (1977) suggested other possible periods of aggradation in 1590, 1735 and 1861 in nearby watersheds, based on preserved alluvial terraces. Evidence for these events in Redwood Creek, however, is poorly documented.

Redwood Creek changes dramatically in character from steep, narrow headwater reaches to wide, gentle downstream areas. Forest type, bedrock geology, dominant erosion processes and land use practices also vary downstream. In

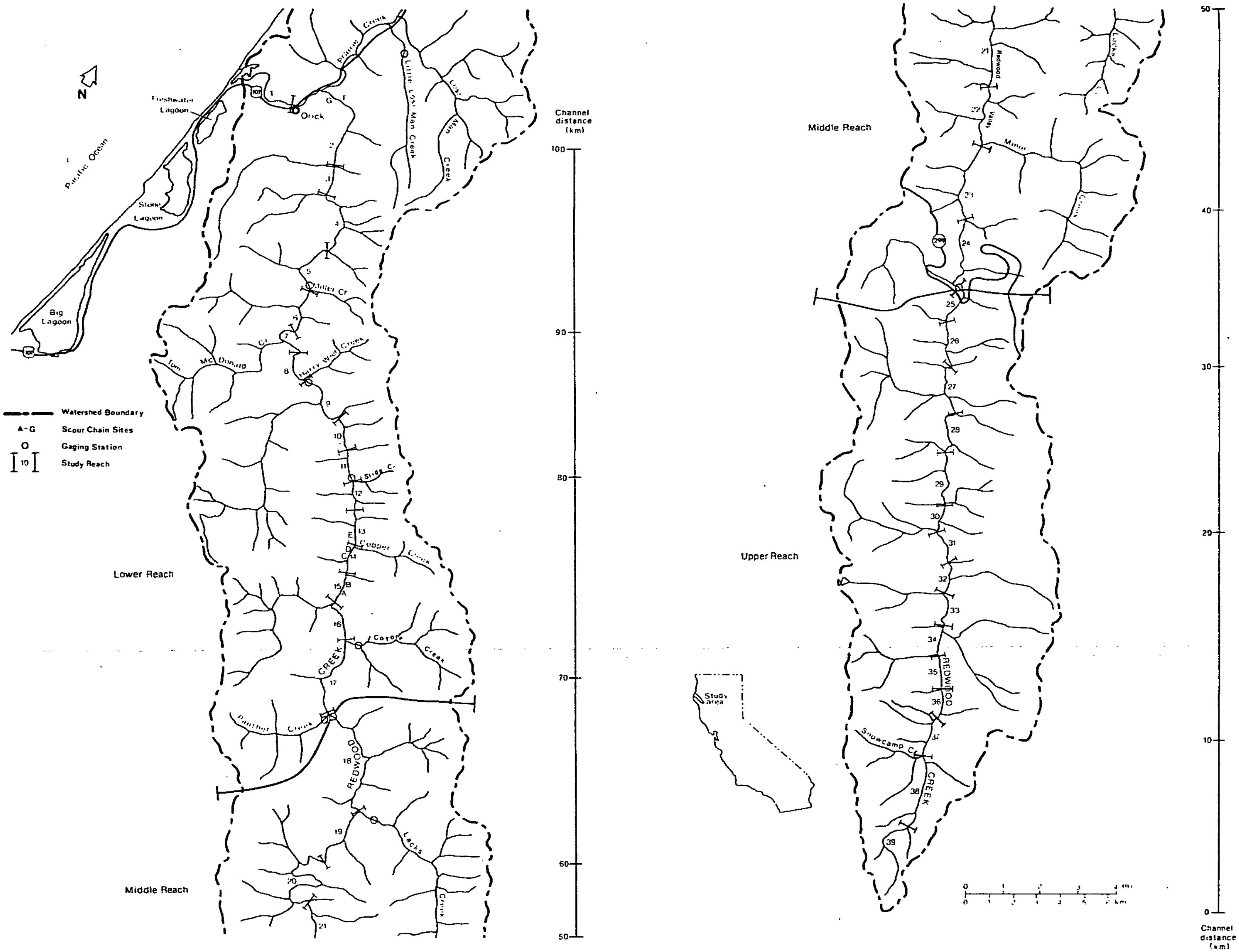


Figure 1. Map of Redwood Creek showing locations of study reaches, gaging stations and scour chain sites.

this study, I divided Redwood Creek into 39 study reaches for detailed mapping (fig. 1). Reaches were distinguished on the basis of field and aerial photography observations of channel and valley width, bed material and bedforms, channel gradient and streambank stability. Reaches vary from 1 to 7 km in length. Kelsey et al. (1981) described details of most study reaches.

In addition, three general reaches (upper, middle and lower) were defined by the location of USGS stream gaging stations (fig. 1). The upper reach is relatively steep (average channel gradient = 1.2%) and bouldery. The valley is narrow and shows evidence of many streamside landslides occurring in the past. Extensive gravel berms were deposited in this area during the 1964 flood and many debris jams block the channel. The forest on the surrounding slopes is predominantly Douglas fir, of which 80% has been tractor logged since 1948. A U.S. Geological Survey gaging station is located at the downstream end (drainage area (A) = 175 km^2).

In the middle reach, the valley becomes abruptly wider in the area called Redwood Valley. Earthflows are a dominant erosional process on hillslopes and low (5 m high) alluvial terraces are prominent. The channel is wide and braided, and average channel gradient is 0.45%. One exception is Study Reach 20 which has a narrow meandering channel incised deeply into Pleistocene terraces. Logging impacts have not been as severe here, but grazing, residential development, and road construction have affected this part of the basin. Downstream of Redwood Valley the valley narrows again; here the channel is rocky with a moderate gradient of 0.35% and few terraces. Ninety percent of the forest in this area was tractor and cable logged between 1948 and 1978 (Best, in press). A gaging station is located above Panther Creek (A = 424 km^2) (fig. 1).

The lower reach flows mostly through National Park lands. The upstream portion has a steep section called the gorge (1.4% gradient) where Redwood Creek flows among large boulders at the base of a prominent earthflow. Downstream of the gorge the valley becomes very wide and channel gradient is gentle (0.1 - 0.2%) Little evidence of streamside landsliding is present. The forest is predominantly redwood, of which 70% was logged by 1978. A gaging station is located at the U.S. Highway 101 bridge in Orick. The channel in the remaining four km downstream of the Orick gaging station is confined by flood protection levees built in 1968, influenced by tidal fluctuations, and empties into the Redwood Creek estuary.

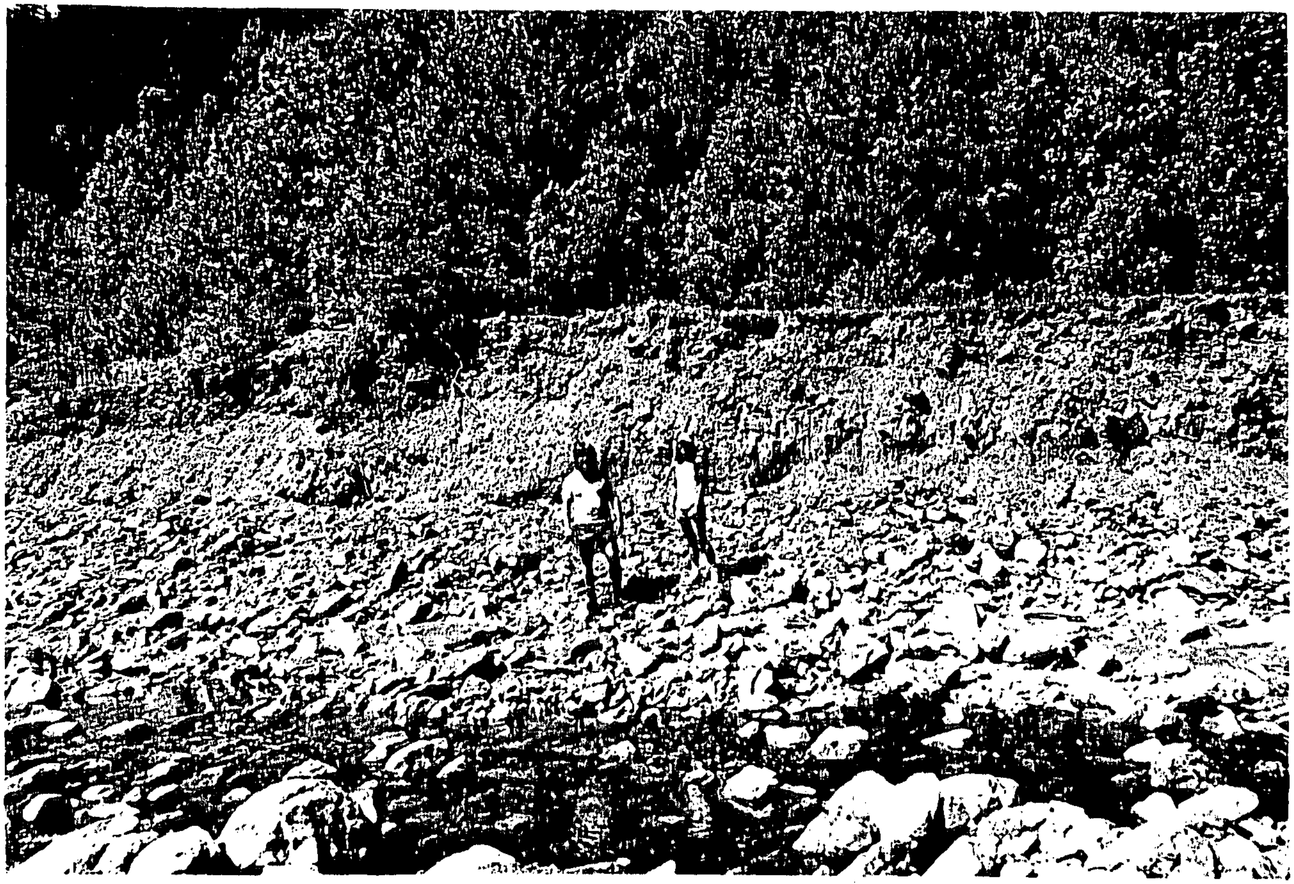


Figure 2. August 1983 photograph showing flat-topped gravel flood berm deposited in upper reach of Redwood Creek during December 1964 flood. Note coarse, unsorted nature of material, young trees growing on the surface, and its location against valley wall, away from active channel. Deposit was more extensive in 1964.

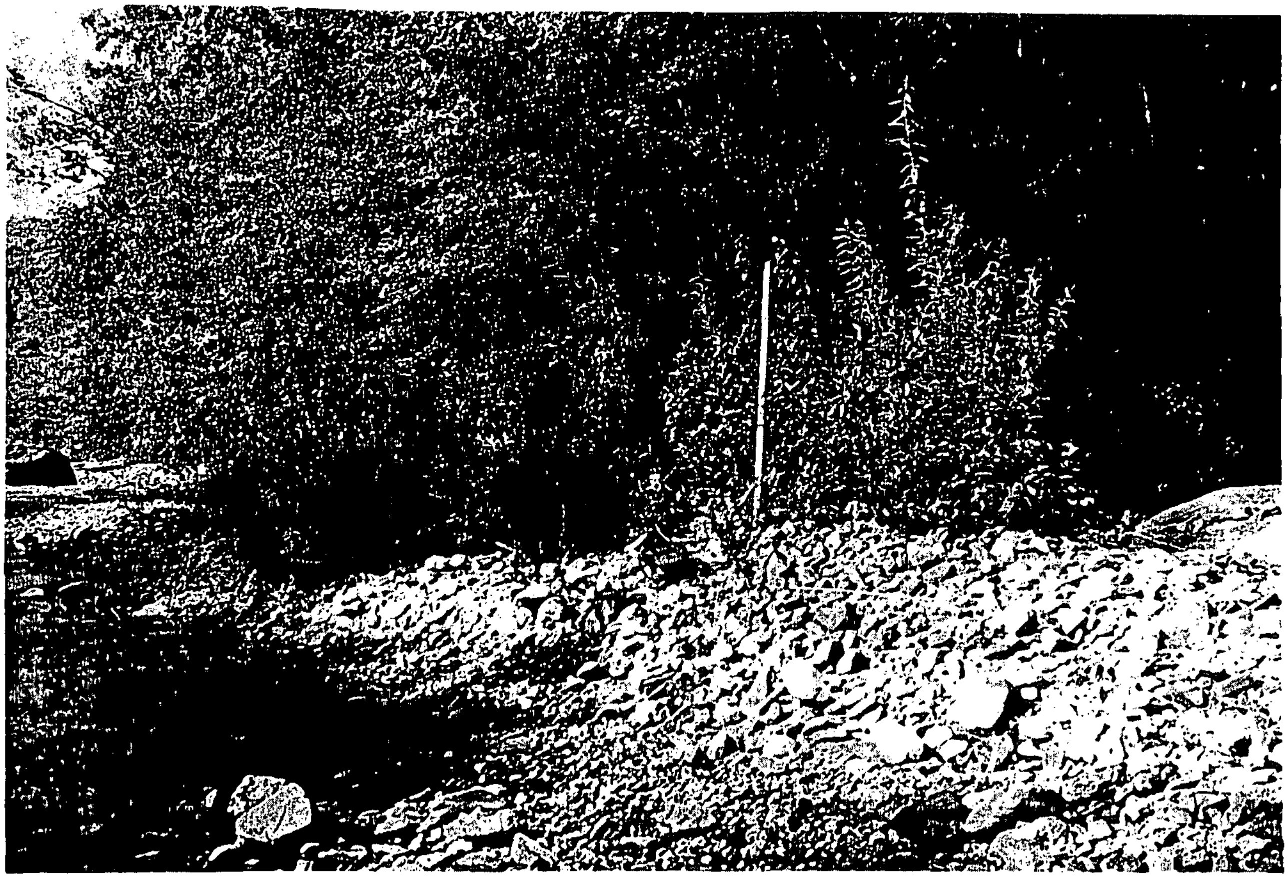


Figure 3. August 1983 photograph showing coarse lobate bar located at Km 30 in Redwood Creek. Note thick alder growth on bar surface which dates from 1972. There is no evidence of recent movement of bar surface.

IV. METHODOLOGY

A. Aerial Photograph and Field Measurements

The first step in this study was to quantify the amount of alluvium stored in the Redwood Creek channel under pre-1947, undisturbed conditions. Under these conditions, Redwood Creek stored sediment as gravel bars, floodplain deposits, and channel sediment below the thalweg. To estimate the volume of this alluvium, I relied on aerial photograph sets taken in 1936, 1947, and 1954. The resolution and scale varied from set to set. I measured the area of the deposits with a planimeter and estimated heights of bars based on surrounding trees, boulders, bridges, etc. Volume of sediment was calculated as (area of deposit x height above thalweg). Historical photographs and records were used to verify estimates made from photographs. The tree canopy obscured the channel in some reaches, but in general major features were visible. Because all measurements of bar heights were based on thalweg elevation, for this study I assumed the thalweg in 1947 was stable, neither aggrading nor degrading. This seemed reasonable because no significant aggradation had occurred in nearby basins since 1861 (Helley and LaMarche, 1973).

I made no attempt to estimate the amount of sediment below the 1947 thalweg above a bedrock base, although this storage compartment may be significant in a geologic time frame. The few drill logs (California Department of Transportation, unpublished data) show alluvium in Redwood Creek to be less than 1.5 m thick at the State Highway 299 bridge and greater than 23 m thick near the mouth at the Orick U.S. Highway 101 bridge (fig. 1).

The December, 1964 flood caused widespread landsliding, bank erosion, channel widening and aggradation. Evidence for the aggradation is best seen in the upper reach (fig. 1) where flat-topped gravel berms were deposited and preserved during subsequent channel downcutting (described earlier, fig. 2). The top of the berms probably represents the approximate level of the channel bed during the flood. High water marks (silt lines and abrasion marks on tree trunks) found several meters above the tops of the berms provide evidence that the berm surfaces were actually the channel bed at flood stage. Also, aerial photographs taken in 1965 and 1966 show some areas where the berm surfaces were not yet incised at that time.

Downstream of the berm deposition areas, aggradation was widespread but not as deep. Large lobate bars, composed of coarse cobbles and boulders, were deposited. By 1980 they bore a thick growth of alder dating from 1964-1970 (fig. 3). Other field indications of channel aggradation are trees buried by gravel in 1964 and buried boulders (fig. 4).

To measure the volume of sediment from the 1964 flood, I used field evidence, aerial photographs taken in 1962, 1965 and 1966, bridge surveys and discussions with local residents. During the 1980 field season, field evidence of 1964 flood deposition was best preserved in the uppermost third of the watershed. Farther downstream channel changes were not as severe, deposits were not as extensive and later floods reworked the 1964 deposits. Thus, the reliability of the 1964 estimates decreases downstream, and accuracy probably ranges from ± 15% in the upper basin to ± 40% downstream.

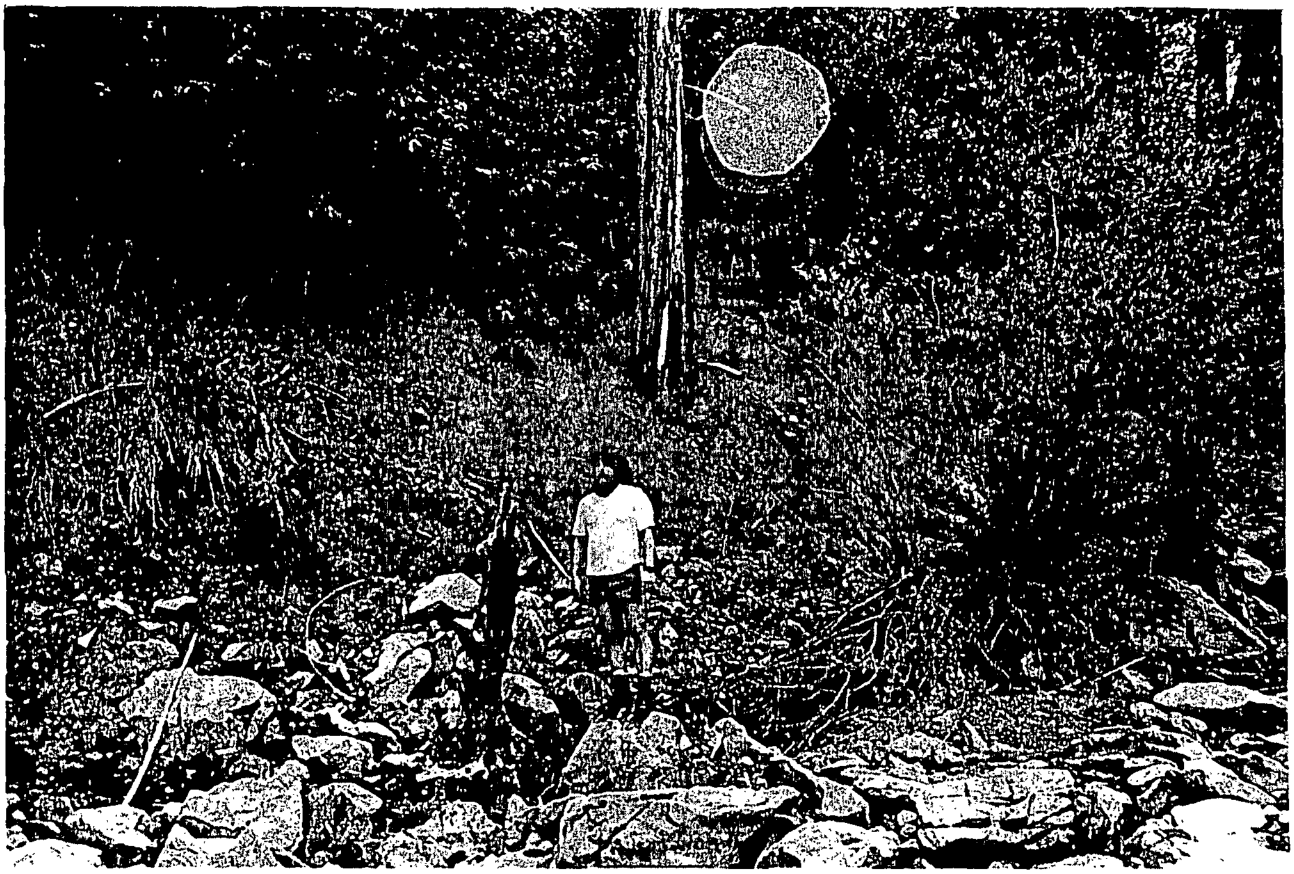


Figure 4. August 1983 photograph showing an example of aggradation from 1964 flood which buried and killed trees on former streambank.

Volumes of sediment present in the 1980 channel of Redwood Creek were measured in the field and with aerial photographs. Where storage features were small, the dimensions were measured by tape or rangefinder in the field. For larger bars and terraces an accurate ground scale from 1978 aerial photographs (enlarged to 1:2000) was measured, and the area of the feature was planimetered from the photos. Heights of gravel bars and terraces above the 1980 thalweg were surveyed with a hand level and stadia rod for both small and large features. In addition, I described all bars in terms of the age and type of vegetation growing on them, the size characteristics of the material (boulder, cobble, pebble or sand) and the presence of partially buried trees or artifacts. The accuracy of the 1980 measurements above the thalweg is excellent (probably ± 10%).

To estimate the volume of sediment due to channel bed aggradation (that is, stored below the 1980 thalweg but above the 1947 level), I used several approaches. Local landowners described channel changes. Buried tree stumps, boulders, car bodies and other objects which were slightly exhumed gave an indication of recent amounts of aggradation. At a few sites, records from bridges showed a history of aggradation and subsequent downcutting. Use of sequential air photos also helped determine channel changes through time. In several instances I saw boulders in the channel which were present in the 1962 air photos, totally buried in 1966, and partly exposed in 1980. Locally, bedrock outcrops are now exposed in the channel bed, indicating no aggradation at those points. Finally, annual surveys of channel cross-sections document changes in bed elevation in Redwood Creek since 1973. Nolan and Marron (in press) discuss details of the cross-section surveying and its results. Estimates of volumes of channel bed sediment were subject to considerable error, probably up to 50% of the true value.

The thickness of recent overbank deposits was estimated by digging shallow trenches or taking soil auger samples on floodplain deposits. I distinguished fresh deposits by the lack of weathering or organic accumulation in the sands and silts lying above an older humic horizon. Recent layers ranged from 0.1 - 1.0 m thick.

B. <u>Scour and Fill Measurements</u>

To calculate residence times of stored sediment, the quantity of sediment in the channel bed that is mobilized during high flows must be known. Two approaches were used to estimate scour and fill depths both in the thalweg and on bars during winter flows. First, in 1981 scour chains were installed at seven cross-sections in Redwood Creek (fig. 1), with three to five chains at each cross-section. A backhoe dug pits as deeply as possible (1.2 - 2 m) in the channel bed. Lengths of steel chain 0.6 cm thick were anchored with 0.6 cm rebar at the base of each pit, and pits were backfilled while the chain was held vertically. Excavated areas were compacted and smoothed over to reestablish original bed elevation and shape. Cross-sections and chain locations were surveyed and photographed.

Backfilling a pit does not reconstitute the exact fabric and stratigraphy of the original bed material, so conceivably scour chain areas might behave differently than the rest of the channel bed at high flows. However, post-winter surveys showed no differential scour or fill at scour chain locations compared with adjacent unexcavated portions of the channel bed. During the winter of 1981-1982, the peak flow had a recurrence interval of two years. After winter flows receded, the chains were excavated with a backhoe, the depth of burial was measured, and the entire cross-section was resurveyed to determine the amount of scour and subsequent fill at chain locations.

The second method of determining depth of scour was the use of U. S. Geological Survey Discharge Measurement Notes (USGS Forms 9-275-F). These measurements are available for seven stations on Redwood Creek for a range of discharges. They indicate the magnitude of scour and fill during successive measurements at a cross-section during periods of high discharge since 1975.

C. Relative Age Estimates of Sediment

In order to evaluate the length of time sediment will remain on the valley floor, it is necessary to know the age of a deposit; that is, the time since the sediment entered the deposit (Dietrich *et al.*, 1982). Because the absolute age of many deposits in Redwood Creek was unknown, I used a relative age scale to categorize deposits. My estimate of relative age is based on the "activity level" of a deposit, ranging from easily mobilized to stable.

Several lines of evidence were used to estimate the relative ages of sediment. I dated trees growing on deposits wherever possible to obtain a minimum age for the sediment. The presence of annuals, shrubs, and other perennials indicated whether or not sediment had moved recently. Sequential aerial photographs were used to identify the time period in which a new feature was deposited, or when an old feature was eroded. Scour chains and successive discharge measurements from cableways indicated the depth of channel bed activity during flood flows.

Using these indicators, I developed a rating scheme to classify which storage elements were "young" or active, that is, in which new fluxes of sediment occur frequently, and those that were "old" or stable, which show little exchange between sediment in the deposit and sediment in transport. The four categories I used are active (Ac), semi-active (Sa), inactive (Ia) and stable (St) (fig. 5 a and b).

Active sediment is transported during moderate flood flows with a recurrence interval of one to five years. Vegetation on active sediment is absent or sparse. Cross-section survey data and scour-chain data show channel shifting and scour and fill in active sediment during moderate flows. Bed sediment to the depth of scour (estimated from chains and cross-sectional surveys) is categorized as active. In upstream areas, active sediment may be trapped by weak or unstable debris jams which are subject to collapse under moderate flood flows. Active sediment may also be found in bars less than one meter high, composed of pebbles, sand and some cobbles.

Semi-active sediment is mobilized during higher flows, such as a 5-20 year flood. At such flows, sediment covered with shrubs and young trees as well as some cobble and boulder deposits are mobilized. Parts of flood berms and terraces may be transported due to lateral erosion.

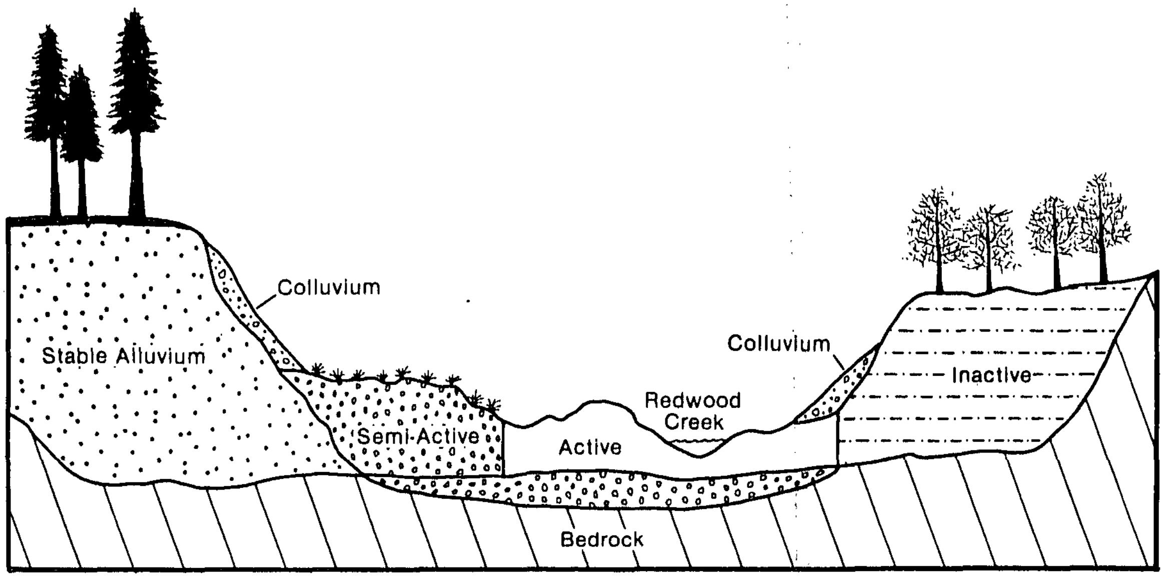


Figure 5.a. Schematic cross section of four sediment reservoirs in Redwood Creek: active (Ac), semi-active (Sa), inactive (Ia) and stable (St) sediment.

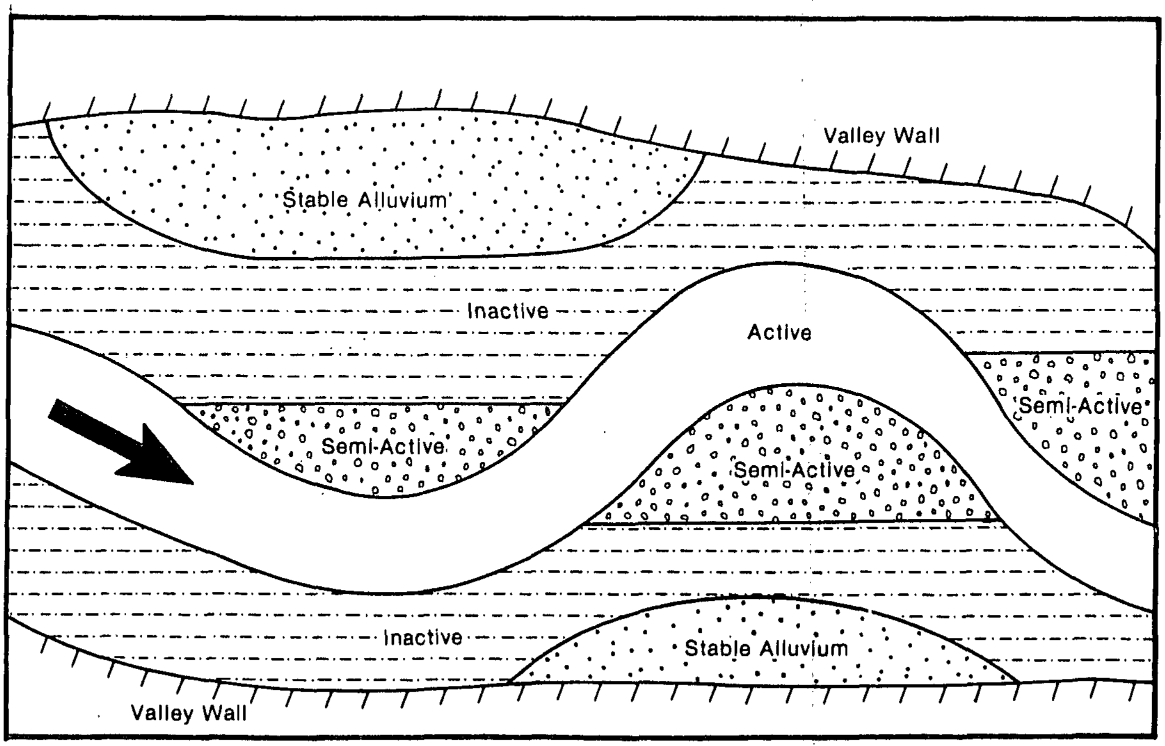


Figure 5.b. Schematic plan view of four sediment reservoirs in Redwood Creek.

Figure 6. 1978 vertical aerial photograph (scale 1:6000) showing classification of sediment reservoirs in Redwood Creek at Km 100 near Orick. Flow is from left to right. Ac=active, Sa=semi-active, Ia=inactive, and St=stable sediment.

Inactive sediment is stationary until 20 to 100 year floods occur. In addition to mobilizing more active sediment, such flows may mobilize inactive sediment found in coarse lag deposits, three to five m high gravel berms, strong, coherent log jams, and floodplain deposits.

Stable sediment has not been mobilized historically and comprises some floodplain and terrace deposits (fig. 6). The majority of sediment stored in alluvial terraces covered with old growth forests is not in transport in the short term, although a fresh veneer of silt and fine sand may be deposited on them at very high flows. In this respect, these are not terraces as defined by Leopold et al. (1964) as abandoned floodplains, because fine-grained deposition still occurs on them during large floods. Some bank erosion of stable terraces occurs and mass movement occasionally reactivates sediment stored on terraces well above the present channel. For this study, only stable terraces adjacent to the channel are included; sediment on terraces more than 10 m above the channel was not measured because such sediment is not currently affected by Redwood Creek.

The floodplain near the mouth of Redwood Creek stores tremendous quantities of stable alluvium, down to an unknown depth (>23m). However, flood levees built in 1968 isolated the floodplain from the river and no erosion or deposition on the floodplain has occurred since then. Because the floodplain was artificially stabilized it is not included in the analysis of the present distribution of stored sediment. Nevertheless, it is estimated to store 23.4 X 10^6 m^3 of fine-grained alluvium above the present thalweg of the river.

D. Sediment Characteristics

Physical characteristics of sediment in storage determine whether it will be transported as bedload or suspended load. The character of channel material reflects properties of the soil mantle, underlying geology, dominant hillslope erosion processes and fluvial sediment transport processes. Size distribution analyses of sediment discharge samples from Redwood Creek (Iwatsubo et al., 1975) indicate that 2 mm is the particle size division between bedload and suspended load. Size distribution and lithologic analyses of bed material are presented by Nolan and Marron (in press). Bulk densities of stored sediment were measured with a Soil Test Volume Measurer at several sites in the watershed. Last, relative resistance of bed material to breakdown during transport was determined through an attrition experiment (described below).

V. RESULTS AND DISCUSSION

A. Temporal Changes in Sediment Storage

The quantity of sediment stored in Redwood Creek has increased dramatically in recent years. Under undisturbed conditions before 1947, the Redwood Creek channel was narrow and sinuous, with a thick canopy of trees and few landslides. Nolan and Marron (in press), Janda et al. (1975), and Best (in press) describe undisturbed basin conditions in more detail. Measurements from aerial photographs indicate that under pristine conditions, Redwood Creek stored 11 X 10^6 m^3 of sediment, of which 50% was in stable terraces. Differentiation of active, semi-active and inactive sediment from early photographs was not feasible.

As a result of the 1964 flood, the total volume of stored sediment in Redwood Creek increased to 16 X 10^6 m^3, 1.5 times greater than 1947. After the 1964 flood and its associated aggradation, several years of moderate flows eroded roughly half of the sediment from aggraded upstream reaches. Some of this eroded material was deposited in downstream reaches, where cross-section surveys show recent aggradation.

Large floods in 1972 and 1975 did not cause major deposition in the upper reach, but did leave flood deposits downstream. For example, flat-topped gravel berms were deposited in Redwood Valley, and alluvial terraces in the park received fresh layers of silt. Deposition resulting from the 1972 and 1975 floods was not quantified separately in this study. Because of the redistribution of 1964 flood deposits downstream, and the addition of sediment from the 1972 and 1975 floods, the total volume of sediment measured in Redwood Creek in 1980 was slightly greater than the 1964 total. Also, the total volume of sediment in 1980 would have been even greater but for gravel excavation in Redwood Creek. Approximately 1.15 X 10^6 m^3 (2.2 X 10^6 metric tons (t)) of gravel was removed from the bed of lower Redwood Creek for road construction during the past 25 years (Milestone, 1978). This amount represents 23% of the increase of sediment storage over 1947 levels.

The spatial distribution and cumulative volumes of total stored sediment for the three time periods (1947, 1964 and 1980) are displayed in fig. 7. In 1947, the center of mass of total stored sediment in Redwood Creek was at Km 64 (near Lacks Creek). In 1964 it shifted slightly upstream to Km 61, and by 1980 it had shifted downstream to Km 78. Based on cross-sectional data, Nolan and Marron (in press) describe how the locus of maximum aggradation has moved downstream in recent years.

A comparison of the three lines in fig. 7 shows some other differences between the three time periods. The slopes of the three lines are relatively gentle until Km 42 where they increase sharply near Redwood Valley. This indicates that Redwood Valley was a high storage area in 1947 and has remained so. The reach between Lacks and Slide Creeks (Km 63 to Km 80) is narrow and stores relatively little sediment, resulting in gentle slopes for the three lines in fig. 7. High storage areas downstream of the gorge (Km 80) show a rapid increase in storage volume (steeper lines). The rate of increase of storage volume under pre-1947 conditions downstream of the gorge was less than in 1964 or 1980.

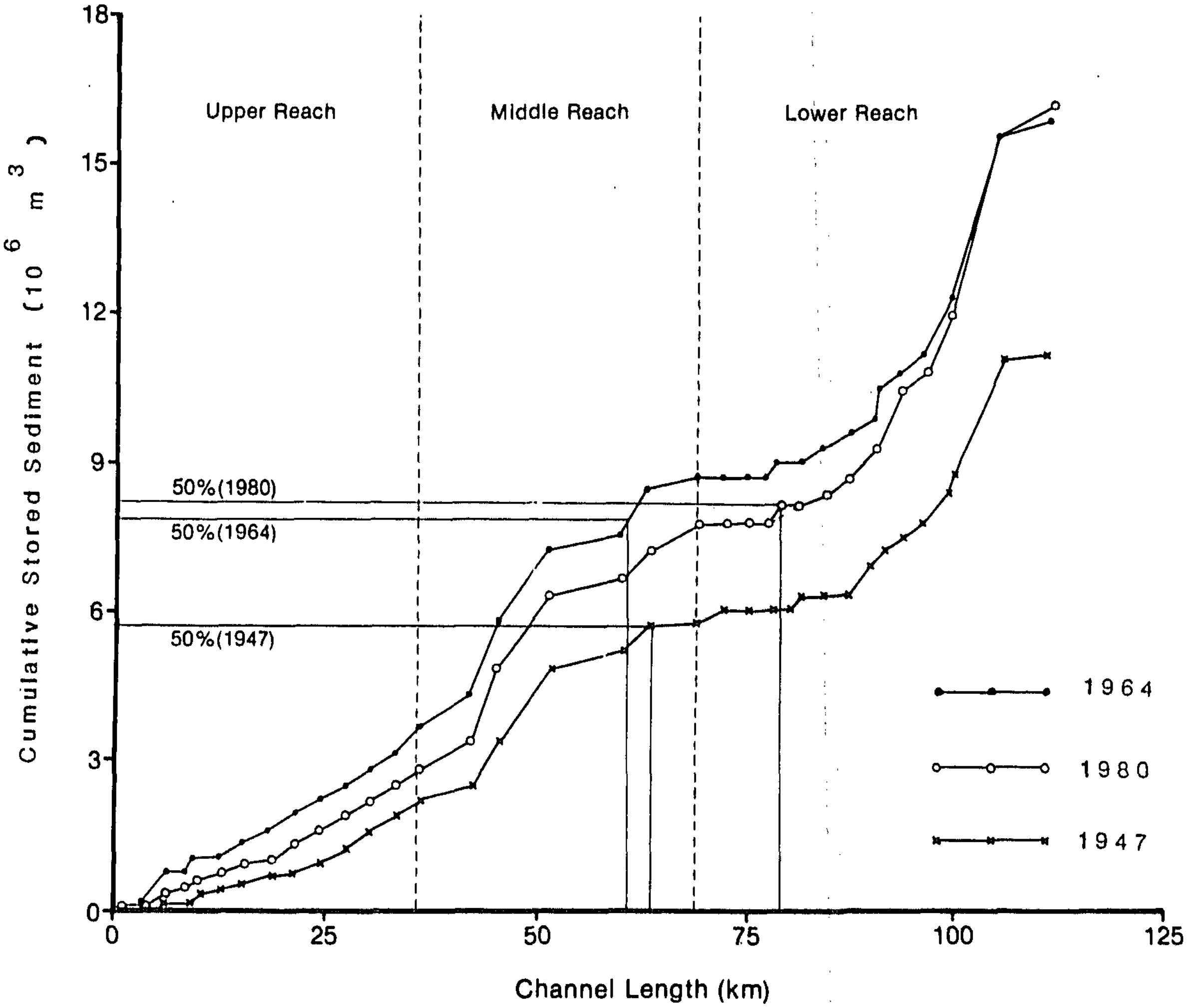


Figure 7. Cumulative volumes and spatial distribution of stored sediment in Redwood Creek as of 1947, 1964 and 1980. Center of mass for each time period indicated by the '50%' line.

Fig. 8 shows that all individual study reaches stored more sediment in 1980 than in 1947 although some areas are not much higher than the 1947 level. All reaches upstream of Study Reach 14 stored more in 1964 than at present, and downstream reaches stored more in 1980. This is due to the downstream transport and redeposition of sediment originally deposited in upstream areas in 1964, deposition from the 1972 and 1975 floods in lower reaches, and an increase in lower basin landslides between 1966 - 1980 (Kelsey _et al._, in press).

Table 1 summarizes changes in metric tons (t) of stored sediment ($\Delta V'_s$) in three sections of the creek in 1947, 1964 and 1980. Excess sediment is defined as the increase of sediment over 1947 levels. As of 1964, a total of 4.7 X 10^6 m³ (9.1 X 10^6 t) of 'excess' sediment was deposited above the pre-1964 background of sediment in Redwood Creek.

An excess of sediment over 1947 levels still exists in all study reaches of Redwood Creek (table 1). Presently, 1.3 X 10^6 t are still left in the upper basin, which represents 46% of the 1947 to 1964 sediment increase. However, the total volume of excess sediment is not a direct indication of future sediment movement. Instead, the type of storage reservoir will determine the potential for future erosion and transport of excess sediment. For example, in the upper reach 850,000 t (or 65%) of the present excess sediment is stored in inactive gravel berms. The channel bed itself has degraded very slowly in recent years (Nolan and Marron, in press). Much of the excess sediment here will probably persist for decades, as discussed below.

In contrast the lower reach stores the greatest volume of sediment (5.9 X 10^6 t) in excess of 1947 levels, and 70% of that amount is in the aggraded active channel bed. Here it is likely that the channel will continue shifting and braiding for many years. Several years of moderate flows will begin to flush excess sediment downstream and out of the system. Cross-sections in this reach show the greatest magnitude of recent change (Nolan and Marron, in press). Total stored sediment above the 1947 datum in Redwood Creek is equivalent to 13,000 t/km². This represents a large in-channel sediment supply, and consequently a strong potential for high bedload transport rates in the future.

Erosion of the 1964 flood deposits influenced bedload sediment yield for many years. For example, between 1965 and 1980 1.5 x 10^6 t of sediment (or 8600 t/km²) were eroded from the upper reach (table 1). However, 1972 aerial photographs and field evidence suggest that most of this sediment was eroded within eight years of its initial deposition in 1964. Consequently, the bedload sediment yield due to erosion of flood deposits at the Blue Lake gaging station was probably 8600 t/km²/8 years or 1075 t/km²/yr. Currently the bedload transport rate measured at this station is only 530 t/km²/yr (Crippen, written communication, 1981). Unfortunately no sediment discharge measurements are available before 1973 for this station. However, stations on nearby rivers also showed high increases in sediment yield for several years after 1964 (Knott, 1974). For example, on the Trinity River at Hoopa, the long-term bedload transport rate is 100 t/km²/yr. In water year 1965 (which includes the December 1964 flood), bedload transport was about 1300 t/km²/yr, and in the following five years bedload transport rates remained elevated at

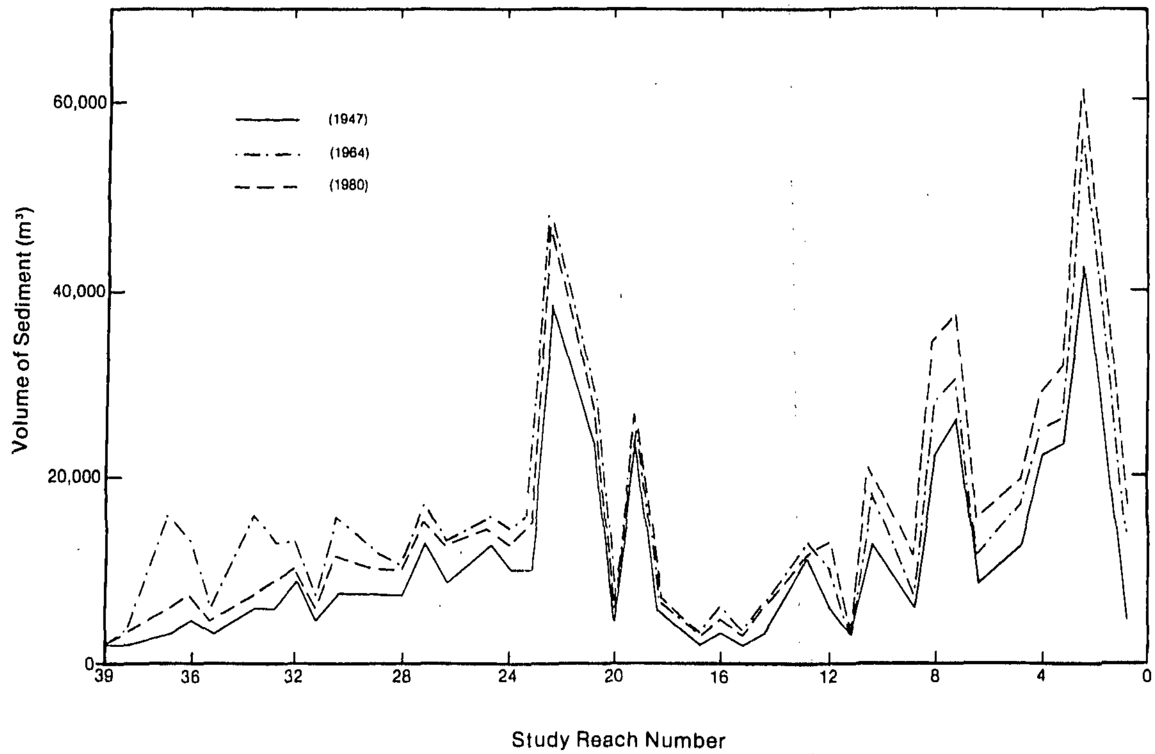


Figure 8. Volumes of stored sediment in individual study reaches as of 1947, 1964 and 1980. Locations of study reaches shown on Figure 1.

Table 1

Net changes (in metric tons*) in stored sediment, $\Delta V'_s$, 1947, 1964, 1980.

Reach	$\Delta V'_s$ (t) 1947 to 1964	t/km^2	$\Delta V'_s$ (t) 1964 to 1980	t/km^2	'Excess' V'_s 1980 - 1947	t/km^2	Current bedload transport rates** (t/km²/yr)
Upper	$+2.8 \times 10^6$	16,000	-1.5×10^6	-8,600	$+1.3 \times 10^6$	7,400	530
Middle	$+2.5 \times 10^6$	11,700	-0.3×10^6	-1,400	$+2.2 \times 10^6$	10,300	400
Lower	$+3.8 \times 10^6$	11,500	$+2.1 \times 10^6$	+6,300	$+5.9 \times 10^6$	17,800	240
Total Channel	$+9.1 \times 10^6$	12,600	$+0.3 \times 10^6$	+ 400	$+9.4 \times 10^6$	13,000	

* - Assumes a bulk density of 1.92 g/cm³.

** - Based on sediment discharge measurements from 1971 to 1980.

about 300 t/km²/yr (Knott, 1974). These measurements reflect not only bedload from the erosion of flood deposits, but also bedload derived from several sediment sources active in the basin (tributary input, landslides, gullies, bank erosion) as well as channel scour.

A similar comparison at the old South Park Boundary gaging station (Km 80) shows an estimated 1965-1972 bedload sediment yield of 475 t/km²/yr due to erosion of flood deposits as opposed to the measured 400 t/km²/yr from all sources at present. These data suggest that erosion of the 1964 flood deposits in the period 1965-1972 resulted in bedload transport rates as high as the total bedload sediment yield currently measured in Redwood Creek due to all sediment sources. Because other sediment sources were also active from 1965-1972, total bedload sediment yield for that period was probably much higher than at present.

Several other studies support this suggestion. Nearby rivers responded to an increase in sediment load from the 1964 flood with changes in channel geometry resulting in high bedload transport rates (Lisle, 1982). Madej (1982) found that a western Washington stream became wider and shallower and bed shear stress changed in order to transport an increased sediment load. Redwood Creek responded similarly in that width increased, depth decreased and the resulting distribution of bed shear stress permitted higher bedload transport rates after the 1964 flood. Thus, the recent increase in stored sediment has affected bedload transport rates and channel geometry throughout the length of Redwood Creek.

B. Depths of Scour and Fill

Potential mobility of sediment presently in Redwood Creek can be characterized as active, semi-active, inactive and stable. To identify active sediment in the channel bed, the amount of scour and fill occurring during moderate flows must be known. For this purpose, scour chains and discharge measurement notes were used.

Scour chain data indicate the depth of channel bed mobilization during moderate flood flows and the degree to which features were active. The data show that the magnitude of scour and fill in Redwood Creek is quite large, even at moderate flows. Scour and subsequent fill did not modify the shape of gravel bars in many cases. According to Leopold et al., (1964), a gravel bar retains the same form from year to year even though a considerable amount of material may be transported through it.

Fig. 9 shows examples from three of the seven scour chain sites. The depth at which chains were found indicate the depth of scour and subsequent fill during winter flows of 1981 - 1982. Appendix A lists the actual amount of scour and fill at each chain location. At Sites D and E, general cross-sectional form did not change after episodes of scour and fill. It was not possible to install chains directly in the thalweg; however, scour in the bed adjacent to the thalweg and on low bars was 0.7 - 1.2 m deep. The channel bed was mostly cobbles (D_{50} = 32 mm), but boulders 25 cm to 55 cm in diameter were deposited on top of the chains during the fill episode. Below a coarse armor layer at the bar surface, bed material generally consisted of coarse sands and pebbles.

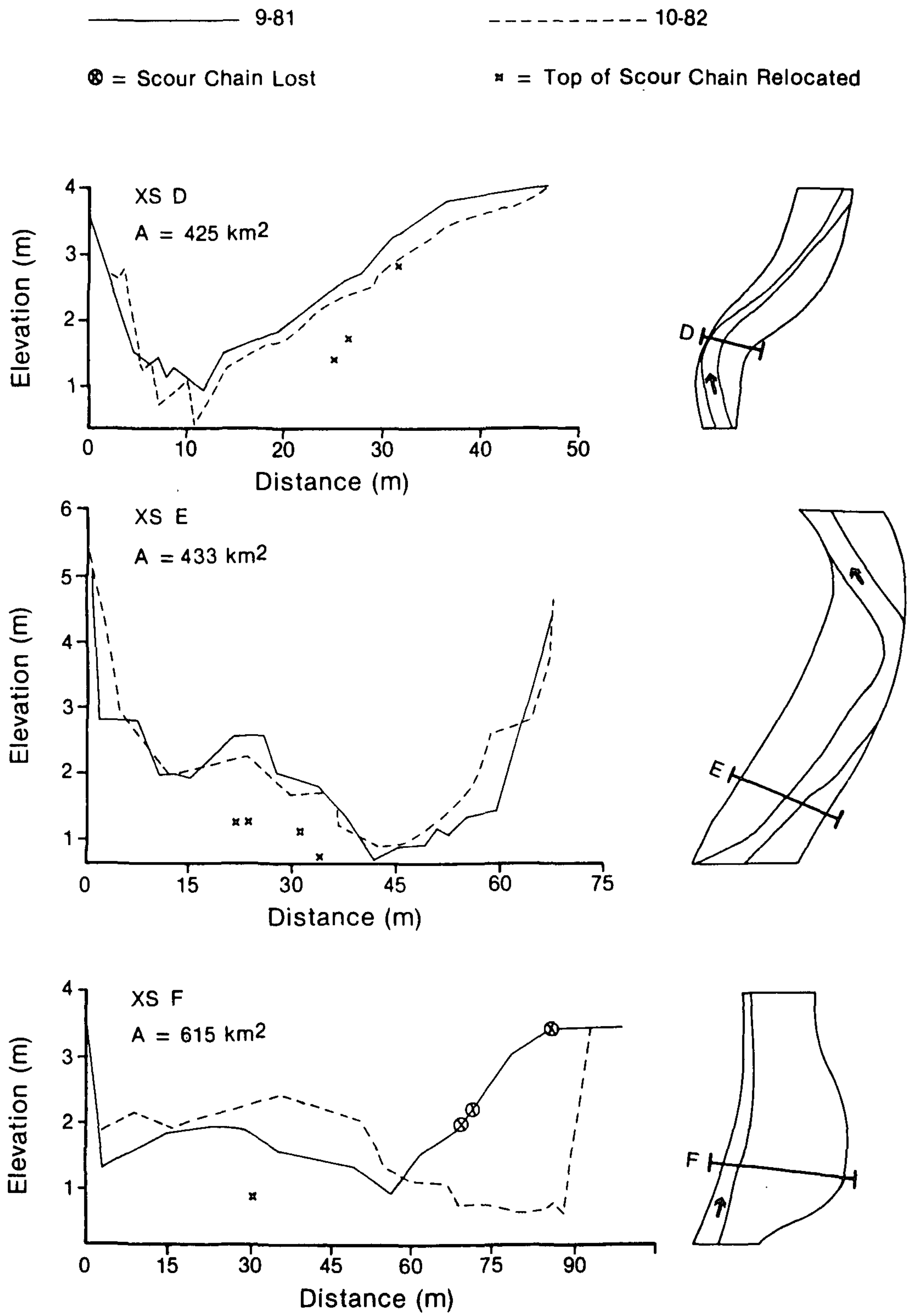


Figure 9. Cross-sectional profiles of Redwood Creek in 1981 and 1982. An 'x' indicates locations of top of scour chains after winter, 1981-1982. Plan maps show relation of cross-section to channel form.

At a depth of 1-2 m however, was a layer of large boulders (1-1.2 m in diameter). Scour did not proceed below this layer of large boulders, and it is unlikely that this layer would be mobilized even at higher flows. The high bar at the right bank of Site D was classified as semi-active because little modification occurred. Otherwise sediment in Sites D and E was classified as active.

Site F showed major changes after winter flows. The thalweg shifted towards the right bank. A scour chain near the left bank indicated 1.0 m of scour with 1.3 m of fill. Several other 2 m long chains were lost due to 25 m of erosion along the right bank. Bank erosion was widespread in this area and was not localized at chain locations. The gravel deposit at the right bank had previously been classified as semi-active because of its vegetative cover of grasses and shrubs. Excavation of gravel from the bed downstream of Site F during the fall of 1981 may have caused the thalweg to shift in this direction and erode the bar. The remainder of the sediment in this cross-section was classified as active, and consisted mostly of sand and pebbles.

Discharge measurement notes indicate which areas of the channel bed scoured and filled during moderate to high flood flows (flows with recurrence intervals of one to ten years). Discharge measurement notes were available for seven stations on Redwood Creek for various storms. Fig. 10 shows examples of scour and fill at three stations during the flood of January 13-14, 1980 at close to bankfull discharges. Station "A" is located in the upper basin, and the channel bed consists of cobbles and some boulders (D_{50} = 45 mm). During this flood the channel bed was mobilized to a depth of 0.1 - 0.2 m with some fill at the right bank. Downstream at "B" the bed consists of sand and pebbles with a few cobbles (D_{50} = 22mm), and is mobilized to a depth of 0.6 m. At Station "C" the bed is also pebbly (D_{50} = 22 mm). The channel bed scoured 0.6 - 1.3 m deep at the peak of the flood and filled during receding flows. The post-flood cross-section is similar to the pre-flood configuration. Thus successive cross-section surveying done only at low flows does not necessarily indicate the depth of sediment movement at a cross-section.

Sediment in the gravel bars in fig. 10 was classified as "active" according to the rating scheme described above because it was mobilized at moderately low flows. Because gaging stations are usually located in straight narrow reaches without extensive gravel berms or low terraces, or on bridges where the channel is confined, semi-active and inactive sediment storage sites are not represented at gaging station sites.

To generalize the extent of scour at different flows at various stations, I used U.S.G.S. current meter discharge measurement notes from 1972 to 1983 (Appendix B). To compare equivalent discharges for different stations, I transformed discharge data into a dimensionless index, $Q/Q_{1.2}$, where $Q_{1.2}$ is the discharge with a 1.2 year recurrence interval for that station. Estimates of $Q_{1.2}$ were based on equations given in "Magnitude and Frequency of Floods in the United States" (Young and Cruff, 1967). The maximum depths of scour for several discharges were plotted for three stations (fig. 11). Best fit regression lines were computed for each station. The data are scattered, but the correlations are significant at the 95% level. In general depth of scour increases downstream for equivalent discharges, and depth of scour increases with increasing discharge at a given station.

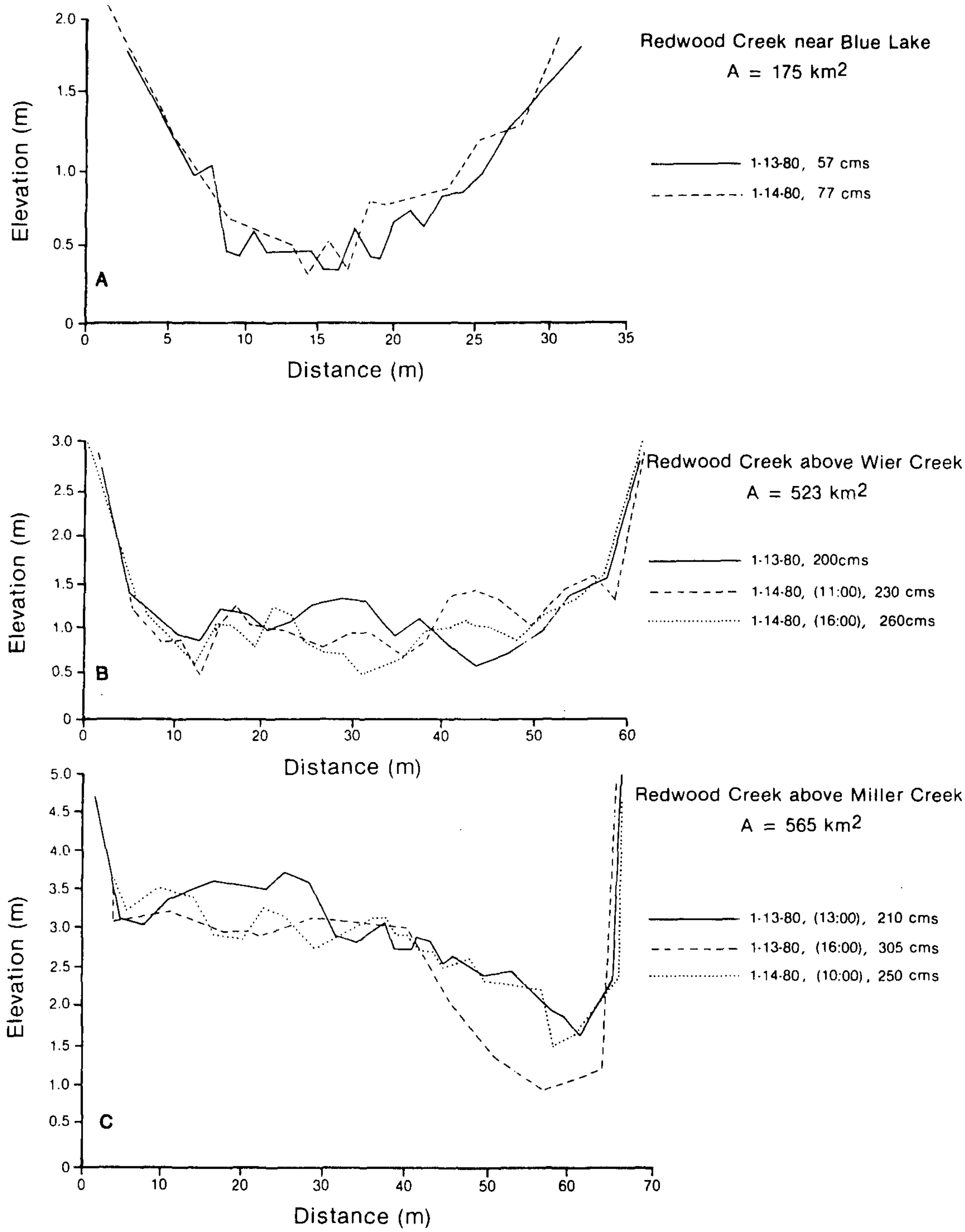


Figure 10. Cross-sectional profiles of Redwood Creek at stream gaging stations showing changes in bed elevation during flood of January 13-14, 1980.

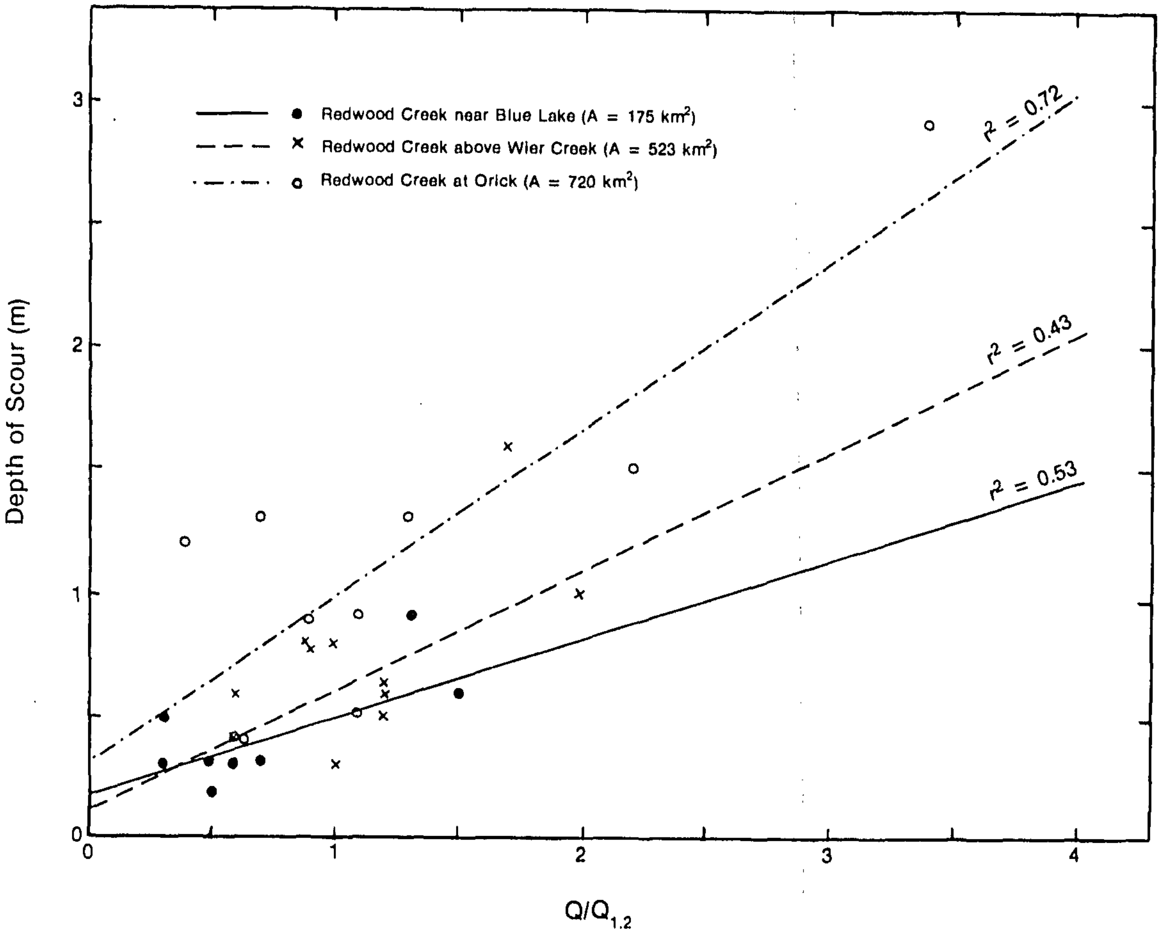


Figure 11. Plot of maximum depths of scour against dimensionless discharge index, $Q/Q_{1.2}$ for three gaging stations in Redwood Creek. Data include measurements from 1972 to 1983. Best fit regression lines (α =0.05) shown for the three stations.

C. Bed Material Attrition

Some of the sediment presently stored in the Redwood Creek channel bed will not be transported as bedload, but instead will break down during transport and will be carried as suspended load. Several lines of evidence point to a high rate of breakdown, or attrition, of bed material in Redwood Creek. First, bedrock in the basin is highly sheared and fractured, and in general is very friable. Preliminary data suggest that bed material roundness generally increases downstream. In the upper basin bedload makes up 20% of the total load, but at the mouth the percentage drops to 11% (Crippen, 1981, written communication). Suspended sediment discharge seems to increase slightly downstream, from 2100 $t/km^2/yr$ in the upper basin to 2200 $t/km^2/yr$ at the mouth. The incidence of cracked cobbles exposed on gravel bar surfaces at low flow is high throughout the basin. Lastly, an attrition experiment (described below) showed a high rate of reduction in weight in particle size classes from 2 to 90 mm in diameter.

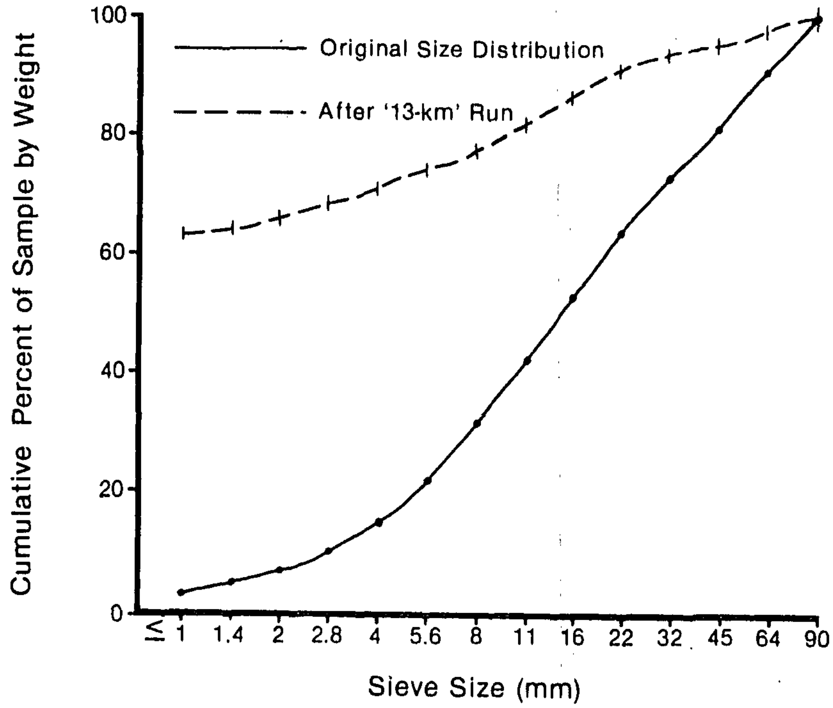
The attrition experiment used a Los Angeles Rattler Machine with a 0.7 m diameter revolving steel barrel. Mounted on the interior wall of the barrel was a 9 cm steel shelf which caused material to freefall in the cylinder during part of each revolution. Water could not be used in the machine, so the sediment was tested dry. These two factors created an environment different from a natural stream channel. Attrition rates calculated from these "tumble kilometers" cannot be directly converted to actual stream transport distances, but relative changes in weights of size classes should represent relative attrition rates in the true stream channel.

For the experiment, two 12-kg core samples of bed material were collected upstream of Copper Creek at Km 77 (Sample 1) and at Km 89 upstream of Tom McDonald Creek (Sample 2) in Redwood Creek and analyzed for size distribution and lithology. Composition of the samples showed 5% (Sample 1) and 15% (Sample 2) of the sediment by weight was less than 2 mm in diameter. The samples were run for a total of 13 'tumble kilometers,' at which point two-thirds of the material (64% - Sample 1, 69% - Sample 2) had broken down into the <2mm size fraction (fig. 12).

Bed material ≥8 mm in diameter was classified as sandstone, schist, or other (chert, conglomerate or metavolcanic). The size fraction ≥8mm composed over two-thirds (66 and 78%) of the original bed material. Schist originally made up 20 and 27% of the bed material by weight, and sandstone made up 63 and 67%, respectively. The fact that more sandstone by weight exists in the channel bed, even though the portions of the basin underlain by schist and sandstone are approximately equal, suggests that attrition of schist particles is more rapid or that sandstone terrain contributes more coarse sediment.

The percentage of weight loss in size classes varies with lithology. At the end of the run, the percentage of schist material equal to or greater than 8 mm was reduced 83 - 85%, whereas the sandstone percentage was only reduced 46 - 52%. These specific attrition rates are not directly equivalent to those occurring in Redwood Creek; however, they do indicate that attrition is an important fluvial process in this basin, and that schist breaks down more readily than sandstone. Cameron and Blatt (1971) showed that sand-sized

Sample 1



Sample 2

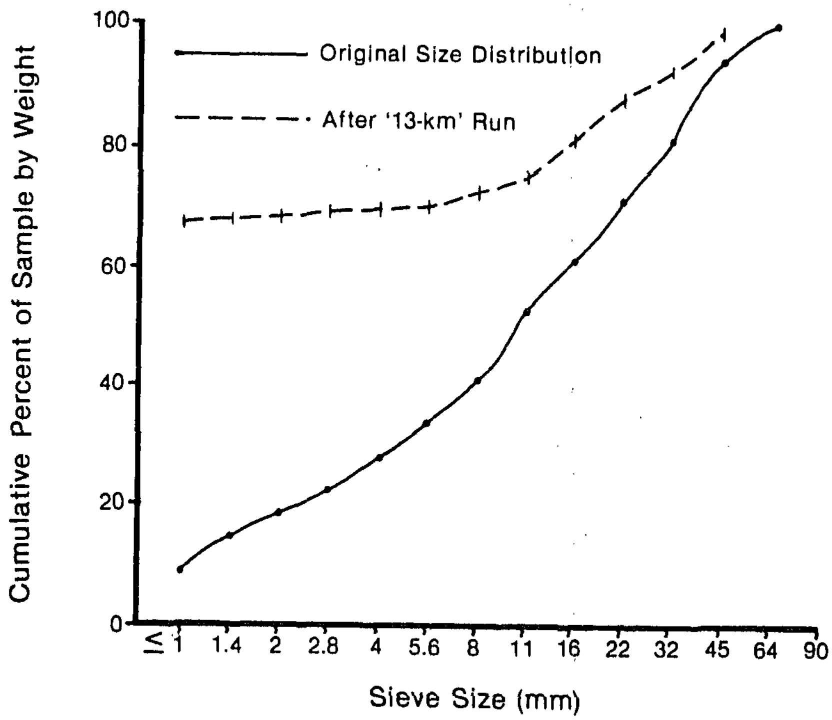


Figure 12. Cumulative curves of particle size distribution data for samples used in attrition experiment. Note that in both cases nearly two thirds of the material broke down to the 2mm fraction after 13 'tumble kilometers.'

fragments of schist were mechanically destroyed by less than 25 km of transport in a Black Hills, South Dakota stream. Using New Zealand rocks in a tumbler experiment, Adams (1978) also found that schist pebbles broke down much more readily than sandstone ones.

Schist is a fairly common bed material in the lower 20 km of Redwood Creek (Nolan and Marron, in press), but because of its highly foliated nature it breaks down quickly. Thus, there must be a high replacement of schist particles from tributaries in this lower reach. Because schist breaks down easily, it probably constitutes a large fraction of the particles less than 8 mm in diameter and contributes greatly to the suspended load.

A high attrition rate in Redwood Creek bed material implies that much of the sediment presently in channel storage will be broken down to suspended sediment size during future transport. In addition, as Dietrich and Dunne (1978) have argued, the long residence times of inactive and stable sediment allow the weathering and breakdown of stored sediment in place. Thus, estimates of residence times of deposits based on bedload transport rates alone will overestimate the persistence of those storage compartments. Some sediment stored in the Redwood Creek bed in the upper basin, especially schist particles, will be transported as suspended sediment by the time it reaches the mouth of Redwood Creek.

D. Distribution and Quantity of Channel-Stored Sediment

Sediment is stored in the Redwood Creek channel in several types of storage compartments such as point bars, mid-channel bars, debris jams and alluvial terraces. Stability and persistence of storage compartments also vary, according to their size and location in the channel. However, sediment compartments are not directly related to the stability ratings described above. For example, a point bar may have active, semi-active and inactive sediment stored within it (fig. 5b). Fig. 13 shows the relative amount of sediment in each storage compartment. It is interesting to note that 23% of the total sediment is stored in compartments that were not present in Redwood Creek before 1947 (flood-deposited gravel berms and aggraded channel bed).

Some storage compartments and depositional forms are found only in particular reaches of Redwood Creek (fig. 14). Terrace-like gravel berms in the upper basin date from the large floods of 1964 and 1972, and are similar to those described by Scott and Gravlee (1968) in the Rubicon River. The berms are poorly sorted, ranging from sand-sized particles to boulders 0.3 m in diameter (fig. 2).

In some berms the gravel is very angular, indicating little fluvial transport before deposition. Also some landslides which occurred during the 1964 flood (as documented by aerial photography) have unmodified berm deposits at their toes. This indicates that, at least locally, major landslides occurred prior to the deposition of the berms, and no slide activity has occurred since.

Strath terraces up to 60 m high are common between Km 12 and Km 50 (fig. 14). Sand and gravel from recent flood events were freshly deposited on top of older soil found on lower terraces in this area. Extensive alluvial terraces are located in the downstream third of the channel, and are important in supporting stands of old-growth redwoods.

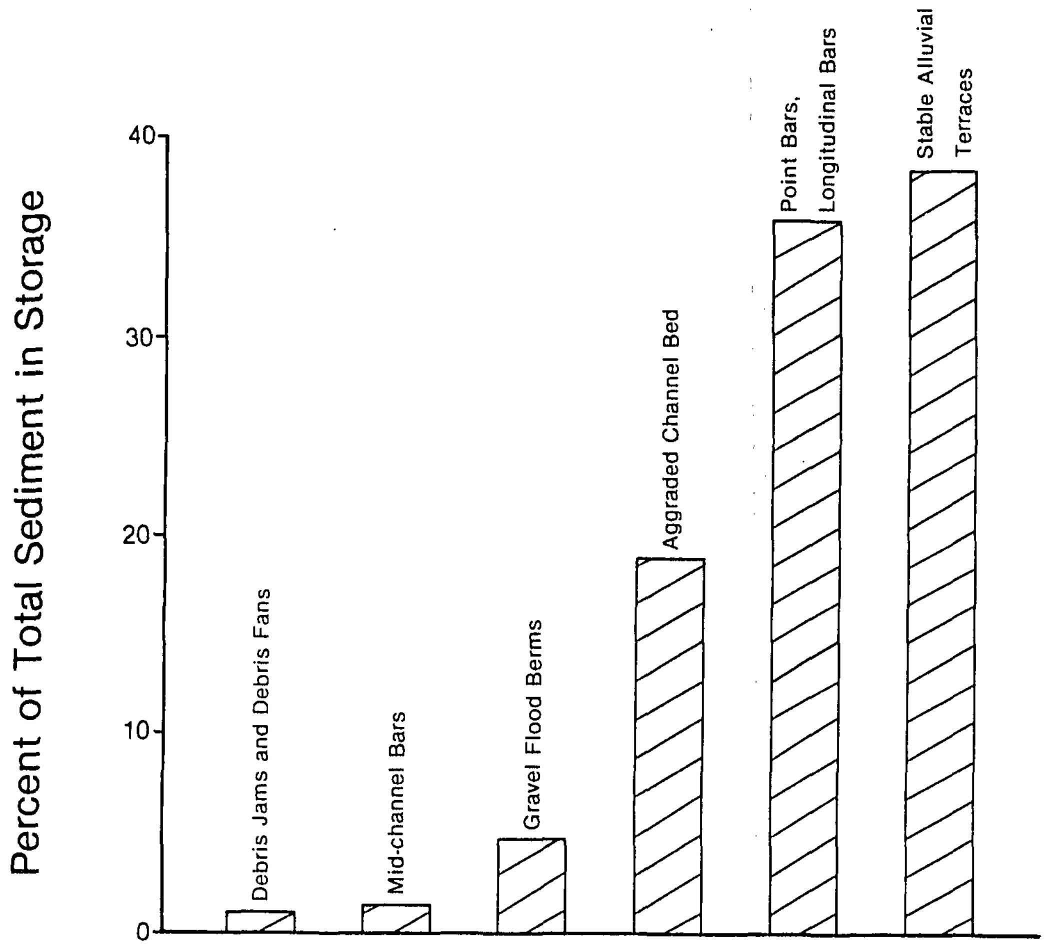


Figure 13. Histogram showing distribution of stored sediment in various compartments in Redwood Creek as of 1980.

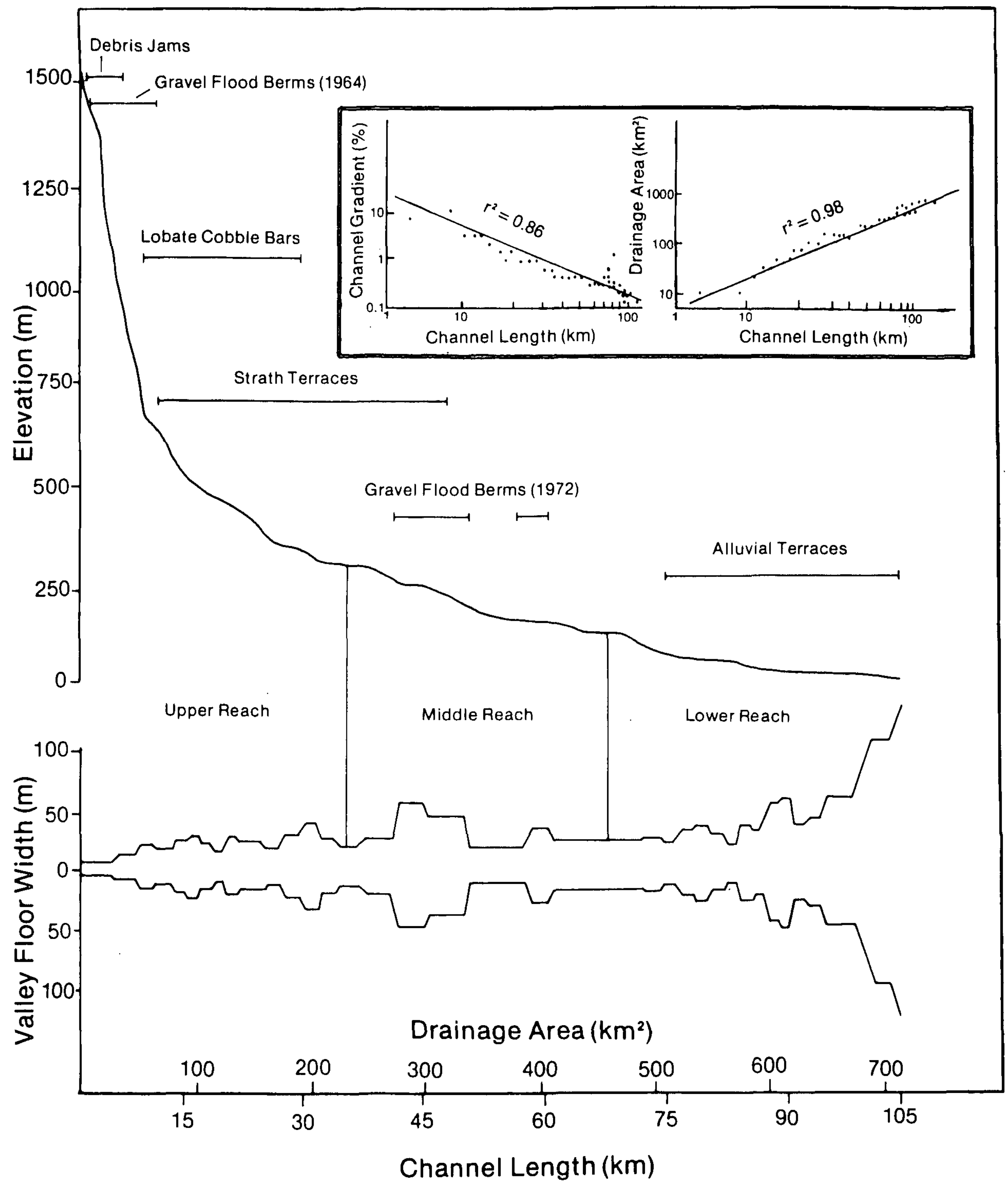


Figure 14. Longitudinal profile of Redwood Creek showing distribution of localized sediment compartments along certain reaches of the creek. Valley widths for Redwood Creek are drawn on the same horizontal scale as the profile. Good relationships exist between channel length and channel gradient and between drainage area and channel length.

Although organic debris is important in storing channel sediment in Redwood Creek tributaries (Pitlick, 1982), debris jams store less than 1% of the total stored sediment in the mainstem of Redwood Creek. Jams that span the channel width, and thus form effective sediment traps, only occur where the drainage area is less than 65 km² (upstream of Lake Prairie Creek). Keller and Swanson (1979) also found that debris concentrations generally decrease downstream. Cut logs are a major component of debris jams, so jams may have been even less numerous under natural conditions.

Even though organic debris does not directly trap much sediment in Redwood Creek, it does influence channel and floodplain deposits. Large logs which lie parallel to the stream banks often act as bank protection and hinder bank erosion. Small log jams on bars form an environment locally protected from high flows, and vegetation often establishes around these jams before other spots on the bars. Jams thus give some stability to bars through the establishment of vegetation. Swanson and Lienkaemper (1982) found this to be true on the Hoh River in Washington as well. Alternately, jams can divert or deflect flow, which promotes local bank instability and scour of bed material.

In addition, the distribution of sediment of different relative activities (sediment reservoirs) varies systematically downstream (fig. 15). Active bed sediment (Line Ac) makes up more of the stored sediment in upper study reaches than other classes. It decreases in relative importance in the mid-basin. Downstream of the gorge (Km 80) relatively more sediment is active, despite the presence of large alluvial terraces. The increase in mobile sediment here does not necessarily indicate higher transport rates or a lower threshhold of movement initiation than in upstream reaches, only that a higher percentage of sediment within the sample reach is frequently transported. Frequent channel shifting, a braided channel pattern, and large expanses of unvegetated bars attest to the importance of active sediment in these lower study reaches.

The percentage of semi-active sediment (Line Sa) generally decreases downstream, as does the percentage of inactive sediment. Inactive sediment (Line Ia) increases in relative importance near the mouth of Redwood Creek where large areas of alluvial deposits occur.

Stable alluvial sediment (Line St) is rare in steep, headwater channels, and becomes most important near Km 40 (Redwood Valley area). From this point downstream the percentage of stable sediment in the basin decreases slightly, even though stable sediment remains volumetrically the largest storage compartment from Km 40 to the mouth. More than a third of all sediment in Redwood Creek is stable, and it is a major component of alluvial storage for most of the drainage length.

A total of 16 x 10^6 m^3 of sediment is stored on the Redwood Creek valley floor, plus the additional 23 x 10^6 m^3 stored in the floodplain at Orick, mentioned earlier. Unlike tributaries, however, which store 95% of the sediment in 50% of their drainage lengths (Pitlick, 1982), alluvial storage in the main channel of Redwood Creek is not quite as concentrated. Ninety-five percent of the total stored sediment in Redwood Creek is located in 65% of its drainage length.

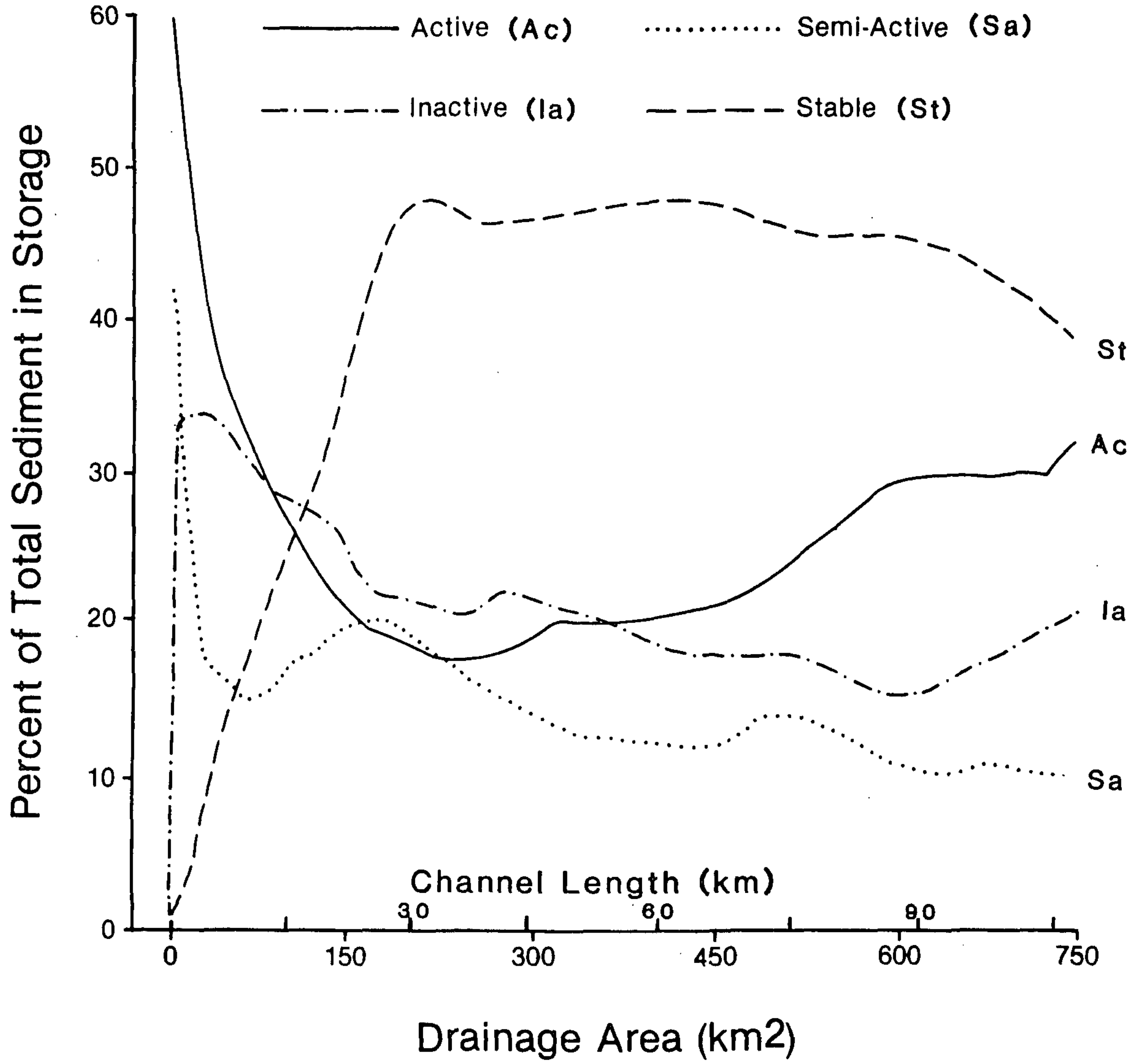


Figure 15. Distribution plot of sediment of different relative activities (sediment reservoirs) against drainage area.

E. Controls on Sediment Distribution

Sediment is not distributed uniformly in a channel; some reaches store more than others. In this study I attempted to identify the factors controlling sediment distribution in stream reaches with varying physical characteristics. The factors used for comparing volumes of stored sediment per reach were drainage area, sediment input to that reach, channel gradient, boundary shear stress and valley width (Appendix C). Because study reaches are not of equal length, I compared the sediment storage in different reaches based on the index "m^3 of sediment/m of channel" (V_s). All correlations used in the following analysis are significant at the 95% confidence level, unless stated otherwise. V_s in the basin ranges from 5 m^3/m in the headwaters to 600 m^3/m near the mouth. Lower Redwood Creek and Redwood Valley are the highest storage areas in the basin. Storage volume per unit distance generally increases with drainage area (A), but there is much variation (fig. 16). In this case, the data do not fit a simple power function well ($r^2 = 0.28$), especially near Km 80, the gorge (A = 475 km^2). The third degree polynomial $V_s = -3992 + 227\,A - .084A^2 + .0009\,A^3$ ($r^2 = 0.58$) describes the data better than a simple power function, but 42% of the variation in stored sediment is still left "unexplained" by that approach. Storage volume must be controlled by factors other than drainage area in much of Redwood Creek.

Volume of sediment input to a channel will influence the magnitude of sediment transport and sediment deposition in the channel. Landslides, for example, have contributed a large amount of sediment to Redwood Creek, both locally and in total. The 1964 flood triggered a large amount of landsliding along Redwood Creek and its tributaries, and caused major deposition in Redwood Creek. Kelsey (in press) describes sediment discharge by landslides into the mainstem of Redwood Creek in the periods 1954-1966 and 1966-1980. In general, most pre-1966 landslides occurred during the 1964 storm. Total landslide input to the mainstem of Redwood Creek is the sum of mainstem landslides and the estimated input from tributary landslides that reached the mainstem. Fig. 17 shows the cumulative volumes of total landslide input to the mainstem (5.25×10^6 m^3)(from Kelsey, in press) and the deposition in Redwood Creek (4.74×10^6 m^3) resulting from the 1964 flood; that is, the sediment that remained in the valley was 90% of the volume of sediment influx from landslides to the mainstem. Kelsey (1977) showed that in the nearby Van Duzen River (A = 1115 km^2) for the same time period, landslide input was 8.54×10^6 m^3 and the increase in valley storage was 64% of this volume (5.5×10^6 m^3). In addition to landslide input, however, fluvial erosion due to hillslope gullying and bank erosion during the 1964 flood was also a major sediment contributor, but it has not yet been quantified in Redwood Creek.

The slopes of the lines in fig. 17 indicate that landslide input and sediment deposition in the upper 15 km increased at about the same rate. Between Km 15 and Km 80 landslide input generally continued to increase sharply, whereas deposition did not, except in Redwood Valley (Km 35-65) where much sediment was deposited. From Km 80 to the mouth (downstream of the gorge) this trend reversed and deposition increased sharply while landslide input leveled off.

If the three general reaches of Redwood Creek (upper, middle and lower) are considered, a pattern of sediment input from landslides and deposition emerges (table 2). The areas with the highest landslide input showed the highest

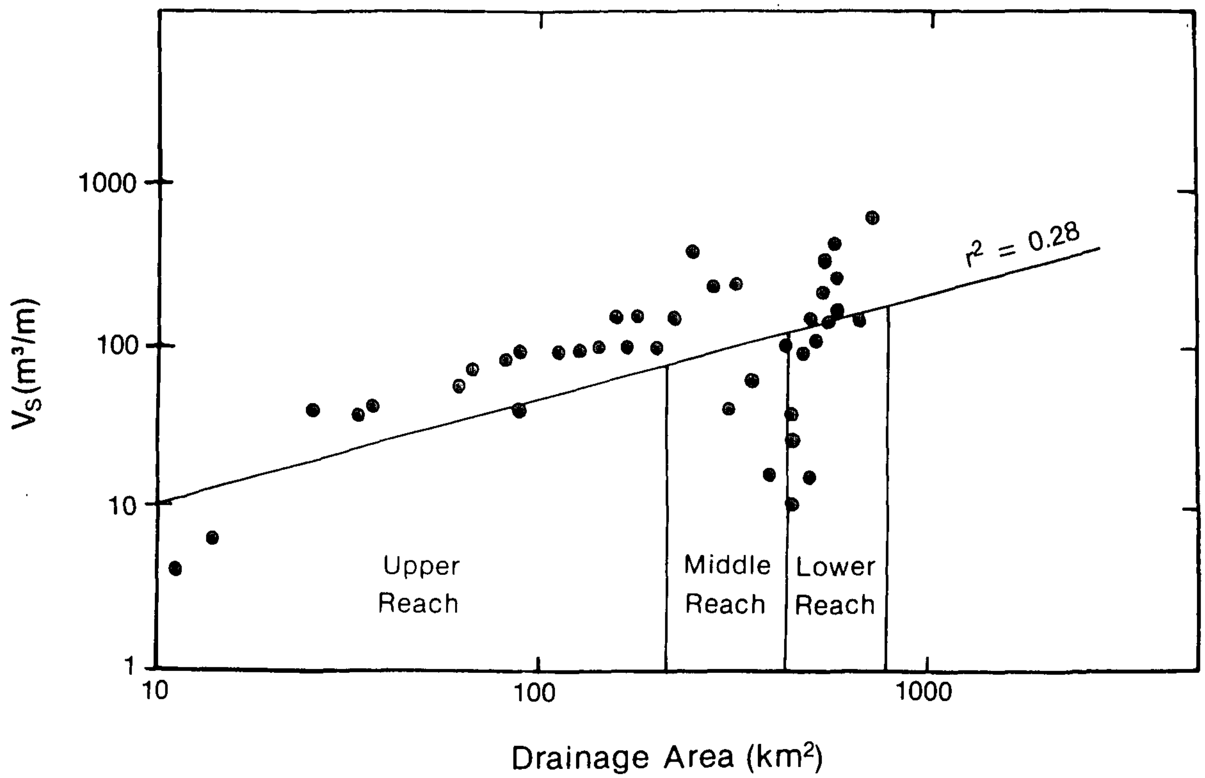


Figure 16. Logarithmic plot of volume of stored sediment per unit distance (V_s) against drainage area.

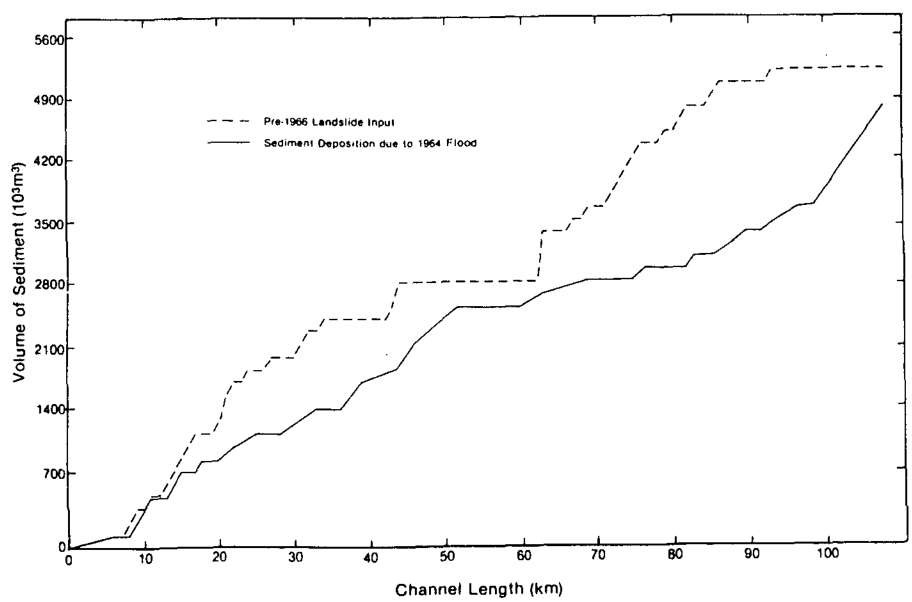


Figure 17. Cumulative volumes of total landslide input to the mainstem of Redwood Creek and the deposition in Redwood Creek resulting from the December 1964 flood. Landslide data are from Kelsey et al. (in press).

Table 2

Comparison of landslide input and changes in channel stored sediment due to the 1964 flood.

REACH	REACH LENGTH (km)	LANDSLIDE INPUT* 1954 - 1966 (m^3/km of channel)	INCREASE IN STORED SEDIMENT IN 1964 (m^3/km of channel)	INCREASE OF STORED SEDIMENT 1947 - 1964 (PERCENT)
Upper	35.5	66,000	41,000	190
Middle	33.3	37,000	39,000	120
Lower	35.6	47,000	56,000	130

* - From Kelsey, et al. (in press).

percent increase in storage over previous levels. However, if the actual amount of deposition in individual study reaches is compared with landslide input to that reach (fig. 18), there is no discernible relationship. This suggests that channel and valley characteristics in a study reach, rather than sediment input at a point, control where deposition occurs.

An important study reach characteristic is channel gradient. Other studies (Pitlick, in press) have shown that deposition is generally confined to low gradient reaches. In Redwood Creek, the amount of channel-stored sediment per unit channel length in 1980 increased with decreasing channel gradient, S (fig. 19). Channel gradient decreases with increased drainage area ($S = 87A^{-0.9}$)($r^2 = 0.89$). Nevertheless, a comparison of fig. 16 to fig. 19 shows that in Redwood Creek, V_s correlates better with channel gradient than with drainage area ($r^2 = 0.43$ and 0.28, respectively). Channel gradient, in turn, is controlled to a certain extent by bedrock geology and sediment input.

For example, where earthflows have delivered huge boulders to Redwood Creek that cannot be transported by present flows, the channel gradient is steeper than in adjacent study reaches (Reaches 11 and 38).

Deposition may also be related to the amount of force available to move sediment on the streambed. In river channels, the average total force per unit area on the stream boundary (τ_b) is approximately equal to the downslope component of the weight of water, or γds, where 'γ' is the specific weight of water, 'd' is depth of flow and 's' is water surface slope. Water surface slope 's' must be close to bed slope 'S' on an average over long reaches. Resistance to flow is generated by bank curvature and irregularities, bed topographic features such as bars, and by stationary and moving sediment. If it is assumed that stationary roughness or resistance features of the channel change little over Redwood Creek, then as τ_b decreases, less force is available to move sediment, and deposition would tend to occur.

'τ_b' for reaches in Redwood Creek was defined for bankfull discharge. The relationship of V_s to τ_b is described by $V_s = 4.5 \times 10^6 \tau_b^{-0.94}$, $r^2 = 0.44$ (fig. 20). That the relation is not stronger may be because much of the deposition of V_s occurred during different hydraulic geometry and flow conditions (and thus different τ_b conditions) than at present. Few data are available for determining accurate values of τ_b during the 1964 flood. Also, the assumption that resistance features change little in Redwood Creek may not be valid.

The distribution of V_s correlates best with valley width (fig. 21) ($r^2 = 0.77$). Valley width was defined as the average width in a study reach that was inundated by the 1964 flood. Valley widths are shown schematically in fig. 14. V_s is highest in areas of large valley widths. In the Redwood Creek basin, structural and bedrock controls influence valley width. In geologic time, climate, tectonics, and general landscape evolution may affect valley width, but in terms of recent changes in Redwood Creek, valley width can be assumed constant through time.

If V_s is related to valley width, then it follows that relatively recent deposits (active, semi-active and inactive sediment) should occur in the same reaches that ancient deposition (stable sediment) occurred. This is indeed the case, as shown in fig. 22.

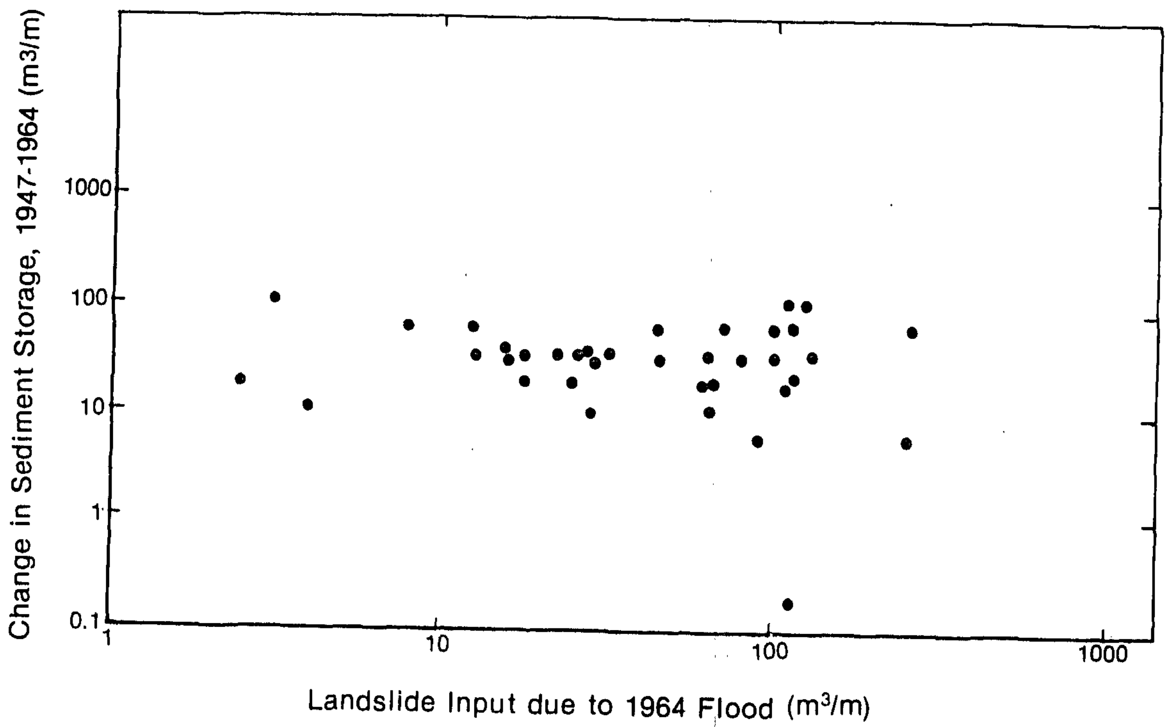


Figure 18. Logarithmic plot of changes in stored sediment in Redwood Creek due to the 1964 flood against landslide input due to the same flood. No line was drawn because the regression analysis showed no relationship (r^2=0.02)

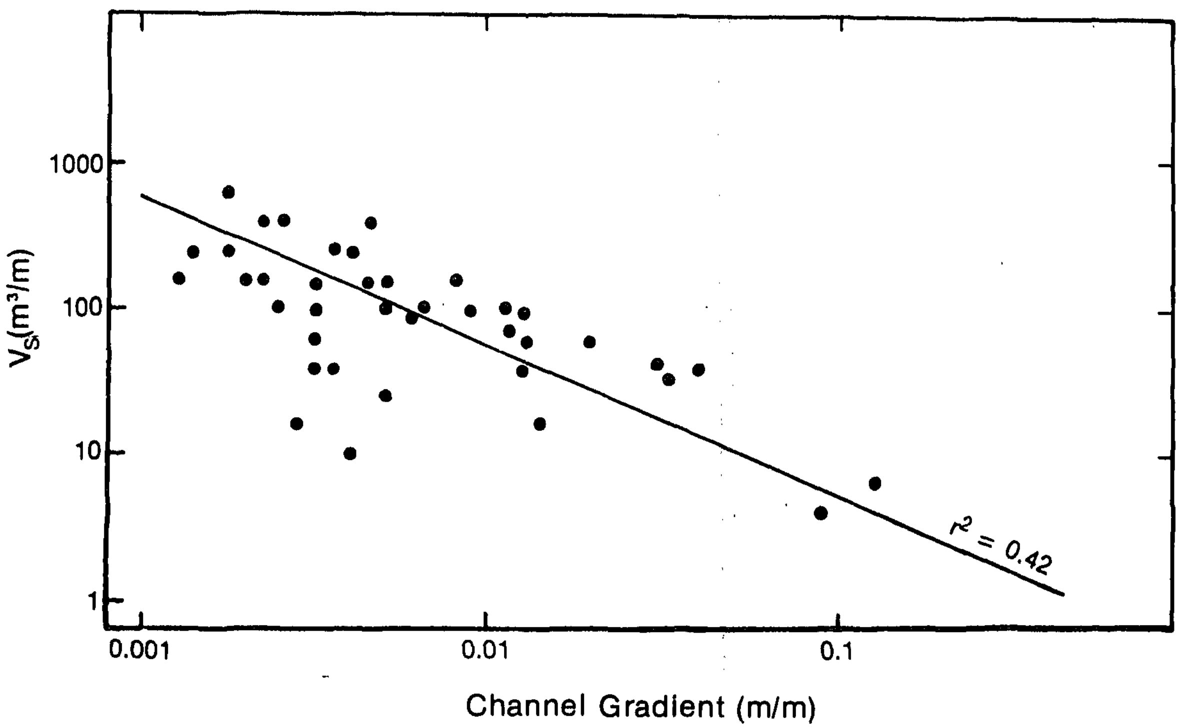


Figure 19. Logarithmic plot of volume of stored sediment per unit distance (V_s) against channel gradient.

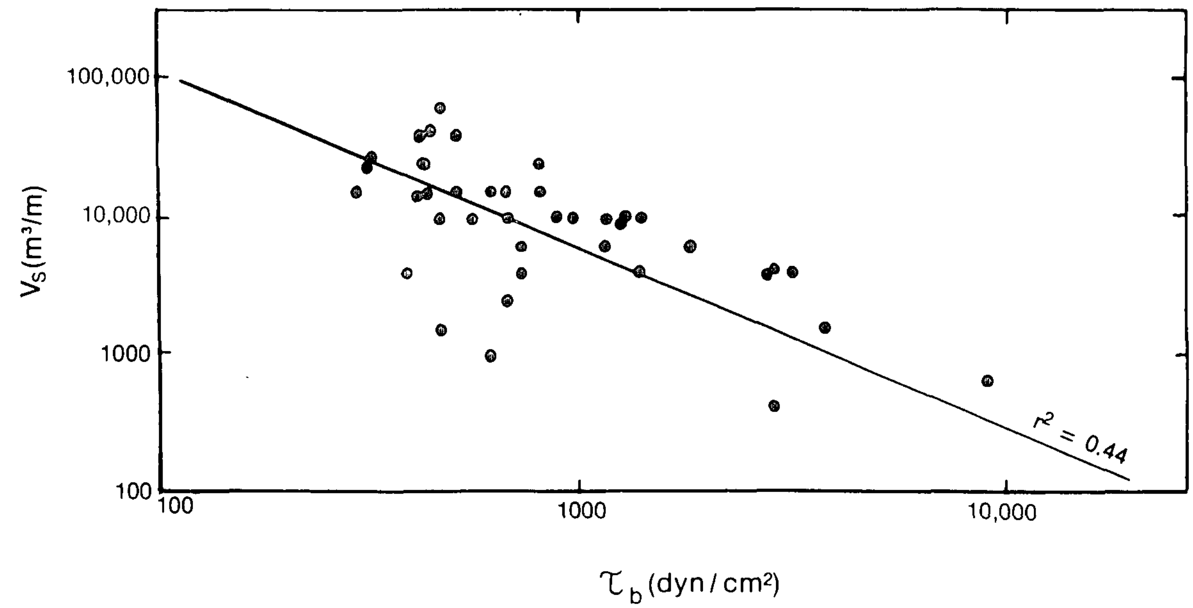


Figure 20. Logarithmic plot of volume stored sediment per unit distance (V_s) against the boundary shear stress (τ_b) calculated for Redwood Creek at bankfull discharge.

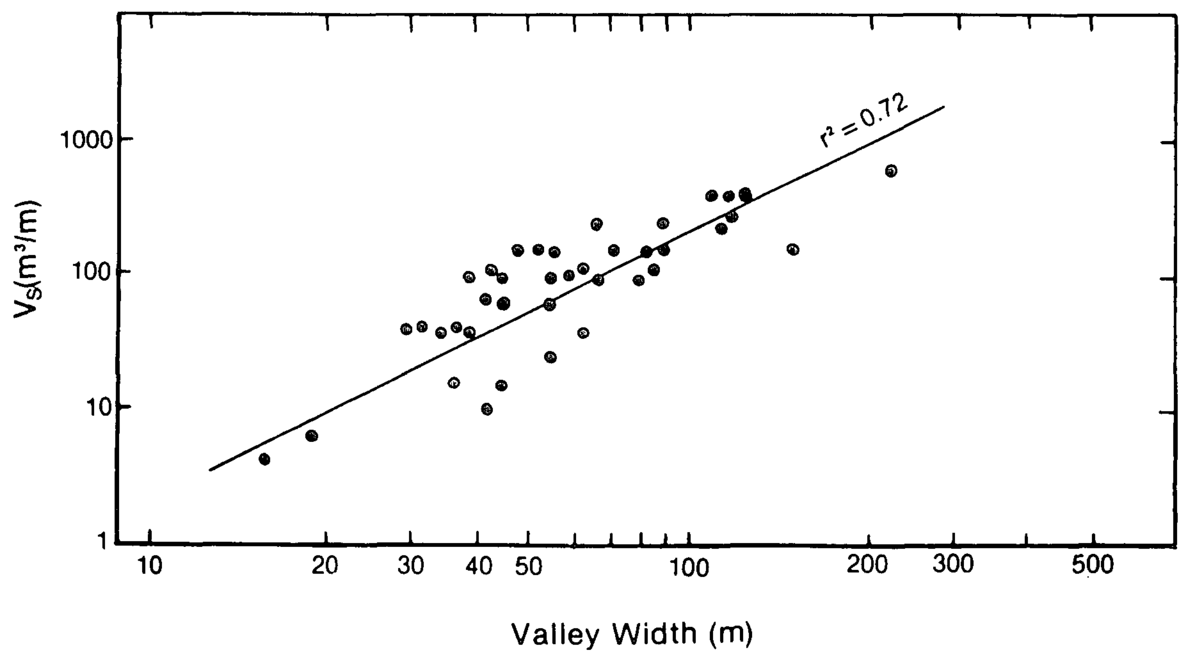


Figure 21. Logarithmic plot of volume of stored sediment per unit distance (V_s) against valley width in a study reach.

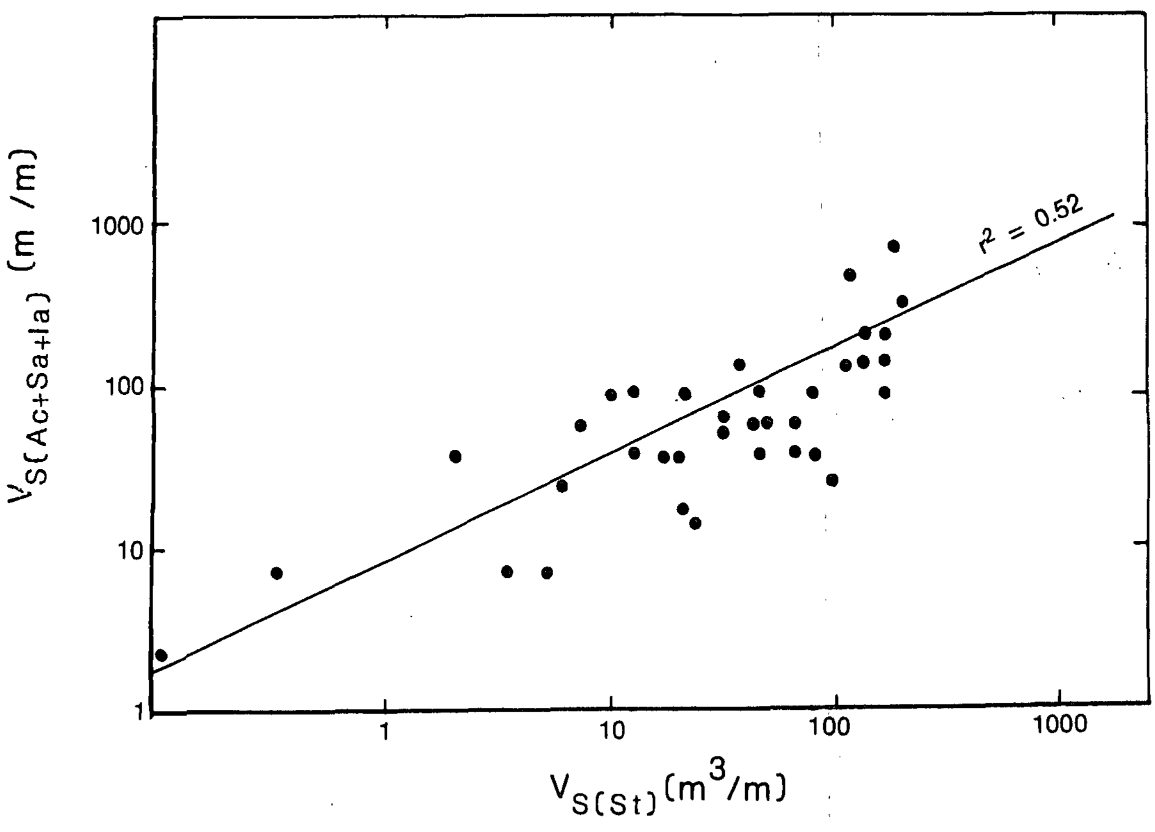


Figure 22. Logarithmic plot of volume of active, semi-active and inactive sediment per unit distance against volume of stable stored sediment per unit distance for study reaches in Redwood Creek.

Thus sediment deposition in a reach is most strongly controlled by valley width in that reach. Generally deposition in Redwood Creek due to the 1964 flood occurred downstream from areas of high sediment input, and specifically deposition occurred in areas of large valley width and gentle stream gradient. If a large influx of sediment occurs in the future, sites of deposition could probably be predicted by considering sites of past deposition; that is, reaches with large valley widths and gentle stream gradients.

F. Residence Times of Stored Sediment

A critical part of describing sediment storage in channels is defining the residence time, or persistence, of the stored sediment. In order to do this, the volume of sediment in various reservoirs must be known as well as the rate of sediment transport through the system. Residence times for sediment in Redwood Creek were estimated for the four types of sediment reservoirs (active, semi-active, inactive and stable) by dividing the volume of sediment per meter of reservoir (V_s) by the bedload discharge rate (Q_B). Following the approach of Dietrich and Dunne (1978), I defined volume of sediment and bedload discharge as power functions of drainage area (A), $V_s = aA^m$ and $Q_B = bA^n$, and drainage area as a function of reservoir length (X), $A = cX^p$. Then the residence time per meter of reservoir length is:

$$\frac{dt}{dX} = \frac{aA^m}{bA^n} = \frac{a(cX^p)^m}{b(cX^p)^n} = \frac{a}{b} c^{(m-n)} X^{(m-n)p} \qquad (2)$$

[see Dietrich and Dunne (1978) for a more complete discussion]. Dietrich et al. (1982) have subsequently shown that this estimation of residence time is not dependent on the actual process of sediment transport through a given reservoir.

The relationships among drainage area, reservoir length and volume of sediment (table 3) were defined on the basis of values measured in the field (described in previous sections) and from topographic maps. The power function for channel length and drainage area has an excellent fit ($r^2 = 0.98$) (fig.14). The relationship for bedload discharge (fig. 23) is based on bedload measurements made for eight to ten years at three gaging stations on Redwood Creek where A = 175, 474 and 720 km². At those locations bedload constitutes 20, 16 and 11% of the total load (93,500; 193,000 and 173,000 t/yr) respectively (Crippen, 1981 unpublished data). Total load measurements are also available for three tributaries draining three types of terrain typical of the Redwood Creek basin. Lacks, Coyote and Panther Creeks (A = 44, 20, and 16 km² respectively) transport about 35, 23 and 19% of the total load as bedload, or 11,000; 15,000; and 2,100 t/yr (fig. 23) based on three years of record (K. Lee, written communication, 1983). The relationship defined by fig. 23 is good ($r^2 = 0.88$) and is used in table 3; however, because the bedload data are based on different lengths of record, the relationship may be modified slightly as more hydrologic data become available.

Four separate power functions were computed to define the relationships of the four types of sediment reservoirs to drainage area. As discussed previously, several factors influence the downstream increase of stored sediment. In

Table 3

Definition of power functions.

Reservoir	Relation	a	b	c	m	n	p	r^2
Entire channel	$Q_B = bA^n$		272			1.04		0.88
	$A = cX^p$			1.28×10^{-4}			1.34	0.98
Active* (Ac) sediment	$V = aA^m$	0.64			0.70			0.49
Ac + Sa sediment	$V = aA^m$	1.29			0.65			0.47
Ac + Sa + Ia sediment	$V = aA^m$	0.79			1.05			0.45
Ac + Sa + Ia + St sediment	$V = aA^m$	0.04			2.20			0.45

* - Ac = Active; Sa = Semi-Active; Ia = Inactive; St = Stable sediment reservoirs.

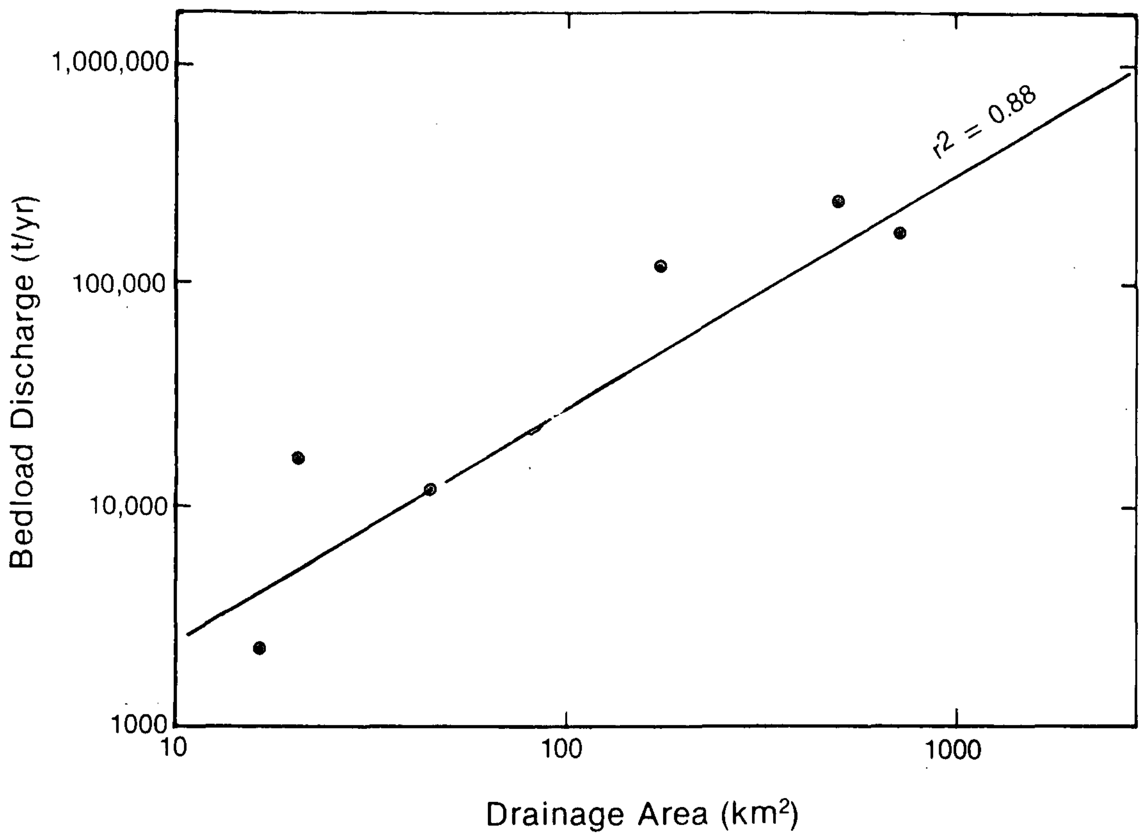


Figure 23. Logarithmic plot of annual bedload discharge computed for six gaging stations in Redwood Creek against drainage area.

order to use a simple power function relationship between sediment in storage and channel length, I omitted anomalously low values for reaches near Km 80 (the gorge) and computed a least-squares regression through the remaining data. The four power functions used for the four sediment reservoirs are listed in table 3. For active sediment, this relationship is $V_s = 0.64 A^{0.70}$, $r^2 = 0.49$. When active sediment is mobilized, it moves down the channel through the active reservoir, and residence time is V_s/Q_B, as stated earlier. However, when semi-active sediment is mobilized, bedload exchanges with semi-active bars and semi-active sediment moves into the active reservoir. Because semi-active sediment moves down the channel through both semi-active and active reservoirs, the residence time is $[V_s \text{ (active)} + V_s \text{ (semi-active)}]/Q_B$. Likewise, inactive sediment, once mobilized, moves through the inactive reservoir and exchanges with semi-active and active reservoirs, and its residence time is $[V_s \text{ (active)} + V_s \text{ (semi-active)} + V_s \text{ (inactive)}]/Q_B$. Stable sediment moves through all four reservoirs. In defining the 'stable' power function, I included the stable sediment near the mouth that is now protected by flood levees because this sediment is 79% of the total amount of stable sediment in the basin.

Integrating Eqn. 2 between two points in a reservoir gives the residence time through that section of the reservoir (Dietrich and Dunne, 1978):

$$\int_{t_1}^{t_2} dt = \int_{X_1}^{X_2} \frac{a}{b} c^{(m-n)} X^{(m-n)p} \, dX$$

$$t_2 - t_1 = \frac{\frac{a}{b} c^{(m-n)}}{1 + (m-n)p} X^{(1 + (m-n)p)} \Bigg|_{X_1}^{X_2} \qquad (3)$$

Using this approach, I computed residence times for active, semi-active, inactive and stable sediment in the upper, middle and lower reaches of Redwood Creek (table 4). The three reaches are approximately equal in length (35.5, 33.3, and 35.6 km, respectively). Velocity of sediment is simply defined as the length of the reservoir divided by the residence time of sediment in that reservoir (table 4). As expected, active sediment is the reservoir with the shortest residence time. For example, a particle entering the active channel bed at Km 35.5 (the upstream end of the middle reach) would take 11 years under average transport conditions to travel out of the middle reach. This is the same order of magnitude for residence time as the one for gravel bars estimated by Dietrich and Dunne (1978) for Rock Creek. Residence time for active sediment decreases downstream, and particle velocity increases. This seems reasonable because widespread channel aggradation in the lower reach has caused channel adaptations (channel widening, decrease of depth) (Nolan and Marron, in press) that would tend to increase sediment transport there. A velocity of 3000-4000 m/yr is much higher than the 234 m/yr reported by Milhous (1973) for Oak Creek, or the estimated velocities in Rock Creek (Dietrich and Dunne, 1978), both of which are small streams transporting considerably less bedload than Redwood Creek.

Table 4

Residence times of sediment in storage reservoirs.

Sediment Reservoirs	Residence Time Functions	Years	Velocity, V m/yr
Active	$0.09\ [X_2^{0.54} - X_1^{0.54}]$		
-upper reach (35.5 km)		26	1365
-middle reach (33.3 km)		11	3030
-lower reach (35.6 km)		9	3950
Semi-active	$0.33\ [X_2^{0.48} - X_1^{0.48}]$		
-upper reach		50	710
-middle reach		19	1750
-lower reach		15	2370
Inactive	$2.63 \times 10^{-3}\ [X_2^{1.01} - X_1^{1.01}]$		
-upper reach		104	340
-middle reach		99	335
-lower reach		106	335
Stable	$1.76 \times 10^{-9}\ [X_2^{2.55} - X_1^{2.55}]$		
-upper reach		700	50
-middle reach		3100	10
-lower reach		7200	5

Residence times for semi-active sediment also decrease downstream. Semi-active sediment moves slower than active sediment in the upper basin, but the difference is negligible in the downstream reach. Both active and semi-active sediment move on the same order of magnitude. Scour and fill data indicate frequent erosion of semi-active sediment in the downstream reach. Because most sediment transport in North Coast streams occurs at relatively high discharges (Ritter, 1968) when both active and semi-active sediment are mobilized, their similar residence times should not be unexpected.

Inactive sediment persists for an order of magnitude longer than active or semi-active sediment and residence times are approximately constant downstream. In the upper reach inactive sediment consists of high, flood-deposited gravel berms in a narrow valley. Downstream, inactive sediment consists of flood deposits on a wider floodplain. This indicates that some effects of a large depositional event such as the 1964 flood will persist on the order of a century.

Stable sediment, of course, has the longest residence time - an order of magnitude greater than inactive sediment. Residence times increase downstream, where a wide valley permits the formation and preservation of broad alluvial terraces. Old-growth redwood trees on these terraces are 400 to 600 years old, and some of them may have sprouted from even older trees. The long residence times of inactive and stable sediment allows the weathering and breakdown of coarse stored sediment to suspended load size as Dietrich and Dunne (1978) have argued.

The bedload discharge function is based on total load measurements made during the last 10 years. This period includes the flood of 1975, which had a recurrence interval of approximately 10 - 20 years. The transport relationship defined in table 3 is probably accurate for discharges up to the 20-year peak flow. However, the above discussion of residence times assumes the volume of sediment in each reservoir and the bedload transport rates remain constant through time. Because Redwood Creek is still adjusting with in-channel and hillslope changes, the bedload transport function may shift in the future. If a flood of an extreme magnitude occurs, the bedload function and residence times may need to be recalculated.

The effectiveness of an event is measured not only in terms of sediment transport, but also by net erosion and changes in channel form (Wolman and Gerson, 1978). If the recovery time of a system is greater than the recurrence interval of the event, the channel will not be in equilibrium with the current channel-forming discharge. Wolman and Gerson cited examples of rivers in temperate regions which regained their original width in a matter of months or years after the occurrence of channel-widening floods with a recurrence interval of 50 to 200 years. In Redwood Creek, however, it appears that changes in sediment storage (and related changes in channel geometry) due to a flood with a recurrence interval of 50 years will persist for a century or more. In this case recovery time is longer than the recurrence interval of the 1964 flood. The recurrence interval of the 1964 episode of hillslope erosion is unknown; nevertheless, it is greater than that of the 1964 peak flow discharge. Beven (1981) discussed the effects of sequencing on effectiveness of events, which may indeed be important in Redwood Creek.

In some basins, lack of recovery is due to the fact that thresholds of competence to transport large sediment particles are not exceeded (Wolman and Gerson, 1978). In Redwood Creek, this is not the case because particle sizes of stored sediment can be transported at 5 - 20 year peak discharges if they are located near the thalweg. Non-recovery in Redwood Creek results from the inability of moderate flows to erode the vast amounts of 'excess' sediment deposited throughout the valley width.

VI. CONCLUSION

As a result of the December 1964 flood in Redwood Creek, the distribution and quantity of sediment stored in the main channel changed drastically. New storage compartments (flat-topped gravel berms and an aggraded channel bed) were created. Sediment input to a reach is related to a general increase in stored sediment, but the channel and valley characteristics of a specific reach controls the local distribution of stored sediment. Volume of stored sediment is greatest in areas of large valley widths and gentle channel gradients. The net amount of sediment stored in Redwood Creek in 1964 did not decrease by 1980. Instead, erosion in the upper basin and additional deposition in the lower basin redistributed much of the active sediment. Unless sediment input to Redwood Creek from hillslope processes increases in the future, the volume of stored sediment will slowly decrease through time. The persistence of deposits varies according to storage reservoirs. Residence times of active and semi-active sediment are on the order of a few decades, whereas inactive sediment will persist for on the order of a hundred years. Residence time for sediment in stable terraces is in the thousands of years. Recovery of the entire system to a major aggradational event is slow.

Channel stored sediment is an important part of the sediment transport regime. Erosion of 'excess' bed material that was previously deposited in the channel contributed greatly to bedload transport rates after the 1964 flood. In-channel storage provides a ready supply of bedload-sized material for future transport at high flows. High bedload transport rates will probably continue for several decades due to the persistence of sediment deposits.

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APPENDIX A

Depths of scour and fill in channel bed at scour chain sites.

Scour Chains

Site	Chain Number	Scour (m)	Fill (m)
A	1*	>0.2	-
	2*	>0.6	-
B	1*	>0.6	-
	2*	>0.6	-
	3*	>0.6	-
C	1*	>1.2	-
	2*	>1.2	-
	3*	>1.2	-
D	1	0.9	0.7
	2	0.8	0.4
	3	0.3	0.1
E	1	1.2	0.8
	2	1.2	0.7
	3	0.7	0.6
	4	0.9	0.8
F	1	1.0	1.3
	2	1.0	1.3
	3*	>1.8	-
	4*	>1.8	-
	5*	>1.8	-
G	1*	>1.2	-
	2*	>1.2	-
	3*	>1.2	-

* = Chains not recovered, scour depth listed is depth of hole dug at scour chain sites without hitting chain.

APPENDIX B

Scour/Depths Estimated from

USGS Current Meter Discharge Measurements

Station	Date	Maximum Depth of Scour (m)	Discharge (cms)	$Q/Q_{1.2}$
Redwood Creek at Blue Lake, Km 35.5 ($Q_{1.2}$≈120cms)				
	2/19/75	0.6	180	1.5
	2/26/76	0.3	78	0.7
	2/26/76	0.3	65	0.5
	2/28/79	0.3	40	0.3
	1/13/80	0.2	59	0.5
	1/14/80	0.3	77	0.6
	12/22/81	0.5	32	0.3
	1/26/83	0.9	158	1.3
Redwood Creek above Harry Weir Creek, Km 85.8 ($Q_{1.2}$≈224cms)				
	4/01/74	1.6	379	1.7
	2/26/76	0.8	207	0.9
	2/26/76	0.8	200	0.9
	12/14/77	1.0	456	2.0
	12/15/77	0.6	259	1.2
	1/19/78	0.6	136	0.6
	2/28/79	0.4	140	0.6
	1/14/80	0.8	231	1.0
	1/14/80	0.5	259	1.2
	2/10/82	0.6	270	1.2
	2/16/82	0.3	213	1.0
Redwood Creek at Orick, Km 104.4 ($Q_{1.2}$=289cms)				
	1/22/72	2.9	974	3.4
	3/03/72	1.5	631	2.2
	3/19/75	1.3	416	1.4
	2/26/76	0.9	252	0.9
	12/15/77	0.9	311	1.1
	1/19/78	0.4	171	0.6
	1/14/80	0.5	328	1.1
	12/14/81	0.4	163	0.6
	12/22/82	1.3	195	0.7
	1/24/83	1.2	121	0.4

APPENDIX C

DATA FOR STUDY REACHES

Study Reach Number	Drainage Area (km^2)	Channel Length (km)	V_s(1947) (m^3)	V_s(1964) (m^3)	V_s(1980) (m^3)
39	11	4.90	2,400	23,500	23,500
38	14	3.45	6,500	45,300	25,500
37	25	2.20	29,200	319,300	96,000
36	35	1.10	35,200	124,500	54,600
35	37	1.60	24,600	74,300	54,000
34	63	1.40	54,900	205,000	84,300
33	66	2.05	89,500	218,800	157,000
32	86	1.65	110,200	179,000	148,500
31	89	1.80	59,400	98,800	81,200
30	109	1.50	87,100	212,300	148,200
29	122	3.60	220,100	332,100	300,000
28	145	2.35	139,300	211,100	203,300
27	159	3.00	355,100	457,000	407,900
26	169	2.80	212,700	320,500	295,400
25	176	2.35	268,500	325,800	302,300
24	200	3.40	275,400	440,700	381,900
23	216	4.45	398,500	626,300	604,500
22	261	2.85	1,075,300	1,352,700	1,327,900
21	292	5.95	1,303,700	1,670,000	1,577,300
20	314	7.50	253,500	347,445	327,700
19	319	2.80	614,700	682,000	724,600
18	372	6.15	222,700	330,700	326,000
17	410	3.65	22,100	69,400	65,100
16	433	1.80	19,600	70,600	51,200
15	454	1.10	7,000	16,000	10,700
14	458	1.60	27,500	67,200	67,200
13	468	1.75	170,000	185,500	178,600
12	475	1.30	63,500	117,600	137,800
11	479	1.65	20,000	20,300	21,000
10	485	1.50	166,500	255,500	286,400
9	520	2.65	100,500	164,600	267,000
8	531	1.80	376,800	475,800	605,000
7	551	2.05	517,800	606,500	739,200
6	562	2.10	142,200	211,700	280,000
5	573	2.55	300,400	389,600	473,100
4	584	2.95	610,000	713,200	829,800
3	593	1.40	308,300	362,400	427,700
2	719	5.70	2,426,900	3,198,700	3,483,200
1	729	3.60	125,200	448,600	551,300

APPENDIX C

DATA FOR STUDY REACHES

Study Reach Number	Valley Width (m)	Channel Gradient (Percent)	Boundary Shear Stress (dyn/cm²)	Pre-1966 Landslide Volumes (m³)
39	15.2	9.10	2,730	0
38	17.7	12.20	9,100	93,700
37	36.6	4.00	2,635	254,200
36	31.4	3.30	2,970	76,300
35	30.5	3.00	2,682	198,700
34	42.7	1.90	1,724	184,200
33	51.2	1.25	1,054	205,300
32	39.3	1.20	1,245	136,900
31	27.7	1.24	1,341	113,300
30	57.0	1.20	910	385,100
29	51.2	1.20	1,054	223,100
28	36.3	0.90	1,293	70,100
27	51.2	0.80	766	85,300
26	76.8	0.60	527	277,100
25	45.7	0.50	575	43,700
24	40.5	0.50	445	41,800
23	48.8	0.45	484	72,000
22	104.9	0.44	460	325,100
21	85.3	0.38	398	48,300
20	33.2	0.35	364	31,200
19	61.0	0.35	733	6,900
18	39.6	0.30	718	696,000
17	42.7	0.27	445	235,600
16	52.7	0.48	656	213,000
15	39.6	0.40	599	271,000
14	57.9	0.32	671	42,400
13	76.2	0.66	1,183	157,100
12	54.9	0.31	833	56,600
11	33.5	1.40	3,760	181,300
10	76.2	0.30	625	68,400
9	62.5	0.26	625	162,300
8	106.7	0.26	390	22,800
7	115.8	0.23	412	61,700
6	65.5	0.23	412	52,900
5	82.3	0.20	390	58,500
4	111.3	0.17	305	49,300
3	111.3	0.14	290	25,200
2	213.4	0.18	430	18,600
1	140.2	0.12	290	0