Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

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U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, ***Secretary***

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, ***Director***

Library of Congress Cataloging in Publication Data

Geomorphic processes and aquatic habitat in the Redwood Creek Basin, northwestern California.
(U.S. Geological Survey professional paper ; 1454)
Bibliography: p.
Supt. of Docs. no.: I 19.16:1454
1. Geomorphology—California—Redwood Creek Watershed. 2. Slopes (Physical geography)—California—Redwood Creek Watershed. 3. Redwood Creek (Calif.)—Channel. 4. Stream ecology—California—Redwood Creek Watershed. I. Nolan, K.M. (Kenneth Michael), 1949- . II. Kelsey, H.M. III. Marron, D.C. IV. Series: Geological Survey professional paper ; 1454.
GB565.C2G46 1990 551.4'09794 86-600236

For sale by U.S. Geological Survey, Information Services
Box 25286, Federal Center, Denver, CO 80225

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By Mary Ann Madej[1]

ABSTRACT

Stream channels form a link between hillslope erosion and sediment transport processes because they temporarily store sediment before it is transported out of the system. Storage of alluvium in the main stem of Redwood Creek was quantified for three time periods totaling 35 years. An unusual amount of aggradation during the December 1964 flood (a 50-year flood) increased the total volume of sediment stored on the valley floor by almost 1.5 times to 16×10^6 m^3. Although moderate to high floodflows (2–20 year recurrence intervals) in subsequent years eroded sediment in the upper basin and redeposited it in downstream reaches, little change in the total amount of sediment stored on the valley floor occurred. The potential of stored sediment for transport was characterized as active, semiactive, inactive, or stable. Depths of scour in the gravel bed were computed from scour-chain data and from successive discharge measurements made from selected cableways. In this gravel-bed stream, depth of scour increases downstream for equivalent discharges and also increases with increasing discharge at a given station.

Sediment is stored in several types of geomorphic features. Some of these features (such as recent flood-deposited gravel terraces, debris jams, stable alluvial terraces, and strath terraces) are found only locally along Redwood Creek. Landslide activity exacerbated by the 1964 flood contributed 5.25×10^6 m^3 of sediment to the main stem of Redwood Creek, and channel storage increased by 4.74×10^6 m^3. Maximum sediment deposition did not, however, occur at sites of the most intense landslide activity but rather occurred in areas of prior deposition. Valley width is the most important control on sediment distribution.

Erosion of bed sediment deposited by 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 (Mg/km^2)/yr in the upper basin, where bedload is 20 percent of total load, and 2,200 (Mg/km^2)/yr at the mouth, where bedload is 11 percent of total load. The particle sizes of Redwood Creek bed materials decrease rapidly during transport. A tumbling experiment indicated that schist clasts break down more quickly than sandstone clasts.

Residence times of active and semiactive sediment generally decrease downstream, but residence times increase in a downstream direction for stable sediment. Residence times range from decades for sediment in the active channel bed to thousands of years for sediment in stable flood-plain deposits. When stored sediment is mobilized, average velocities are highest for active sediment. The channel has recovered slowly from effects of the 1964 flood. Total channel recovery will take more than a century.

INTRODUCTION

Historically, geomorphologists have studied both hillslope erosion processes and sediment transport in rivers, but few studies have quantified a linkage between these two processes—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 stored and its residence time vary with the type of fluvial system. Streams in steep mountainous terrain store little sediment for relatively short periods of time, whereas rivers in broad alluvial valleys store large quantities of sediment in their flood plains for thousands of years.

In the latter case, channel storage of alluvium can buffer the release of sediment from a drainage basin. Sediment eroded from hillslopes can reside in stream channels for long periods before eventually being transported out of the basin. In such situations, downstream sediment yields will not completely document upstream erosion rates. Some estimates of the volume of sediment stored in channels, knowledge of when that sediment was put into storage, and the rate at which sediment moves through the basin must be known.

Recent changes in the storage of alluvium along the channel of Redwood Creek in northern California present a dramatic example of the capacity of a channel to buffer the release of sediment. Extensive land use changes in recent years, combined with several large storms, caused widespread erosion in Redwood Creek (Janda and others, 1975). Massive amounts of landslid-

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ing, gullying, and bank erosion occurred, causing widespread channel aggradation and dramatic increases in the volume of sediment stored along the channel of Redwood Creek. Deposition of coarse alluvial sediment in low-lying areas was sufficient to threaten aquatic and riparian resources of Redwood National Park.

This paper discusses recent changes in the storage of sediment in Redwood Creek. The volume of sediment stored on the valley floor under pre-1947 conditions, increases in volume of stored sediment due to a major flood in 1964, and the volume of sediment present in 1980 are quantified. In addition, factors that controlled deposition and factors responsible for transfer of those flood deposits downstream are described.

To accomplish the objectives listed above, the main stem of Redwood Creek has been treated as a continuous conduit of sediment composed of several storage features: debris jams and fans, midchannel bars, point bars, the channel bed, and flood-plain deposits. Sediment in these storage features was divided into four classes or sediment reservoirs—active, semiactive, inactive, and stable—according to its potential mobility. All stored sediment has been considered to be in transit downstream, but the rate at which it moves varies with its size and location on the valley floor. A continuity equation was applied to several reaches of the stream to document sediment input (I), the change in storage (ΔV_s), and the output (O) from each reach. These factors must balance, as shown in the continuity equation:

$$I+\Delta V_s=O \tag{1}$$

These data were then used to compute residence times and average particle velocities for the four sediment reservoirs and for different locations on the valley floor, according to the method laid out by Dietrich and Dunne (1978). This study addresses only storage in the main stem; channel storage in tributaries is discussed by Pitlick (chap. K, this volume).

ACKNOWLEDGMENTS

Many of the data in this study were collected with the able field assistance of P. Routon, R. Belding, N. Varnum, V. Ozaki, J. Florsheim, T. Walter, T. Marquette, and B. Brower. Access to Redwood Creek on private land and historical information on Redwood Creek were kindly given by J. Massei, B. Frankie, T. Russ, T. Stover, K. Bareilles, Kerr Land and Timber Company, and Simpson Timber Company. The paper benefited greatly by reviews and comments of William Dietrich, Thomas Dunne, Fred Swanson, and Harvey Kelsey. Additional comments by Gordon Grant are appreciated. I thank the clerical staff of the Arcata Office of Redwood National Park for their patience and assistance.

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, Janda, and others, 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 Coast 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, Fredrickson, and McCorison (1982) used a sediment budget to analyze the transport of inorganic and organic material in both old-growth and logged drainage basins.

Most sediment budget studies to date have been on small drainage basins (area less than 25 km^2) in steep forested areas where little sediment is stored in channels or flood plains. Few studies have quantified the role of alluvial storage in sediment budgets. Dietrich and others (1982) described an approach for such quantification, which uses 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 flood-plain storage is significant.

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

STUDY AREA

Redwood Creek drains a 725-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 Mesozoic Franciscan assemblage, whereas the western side is predominantly underlain by

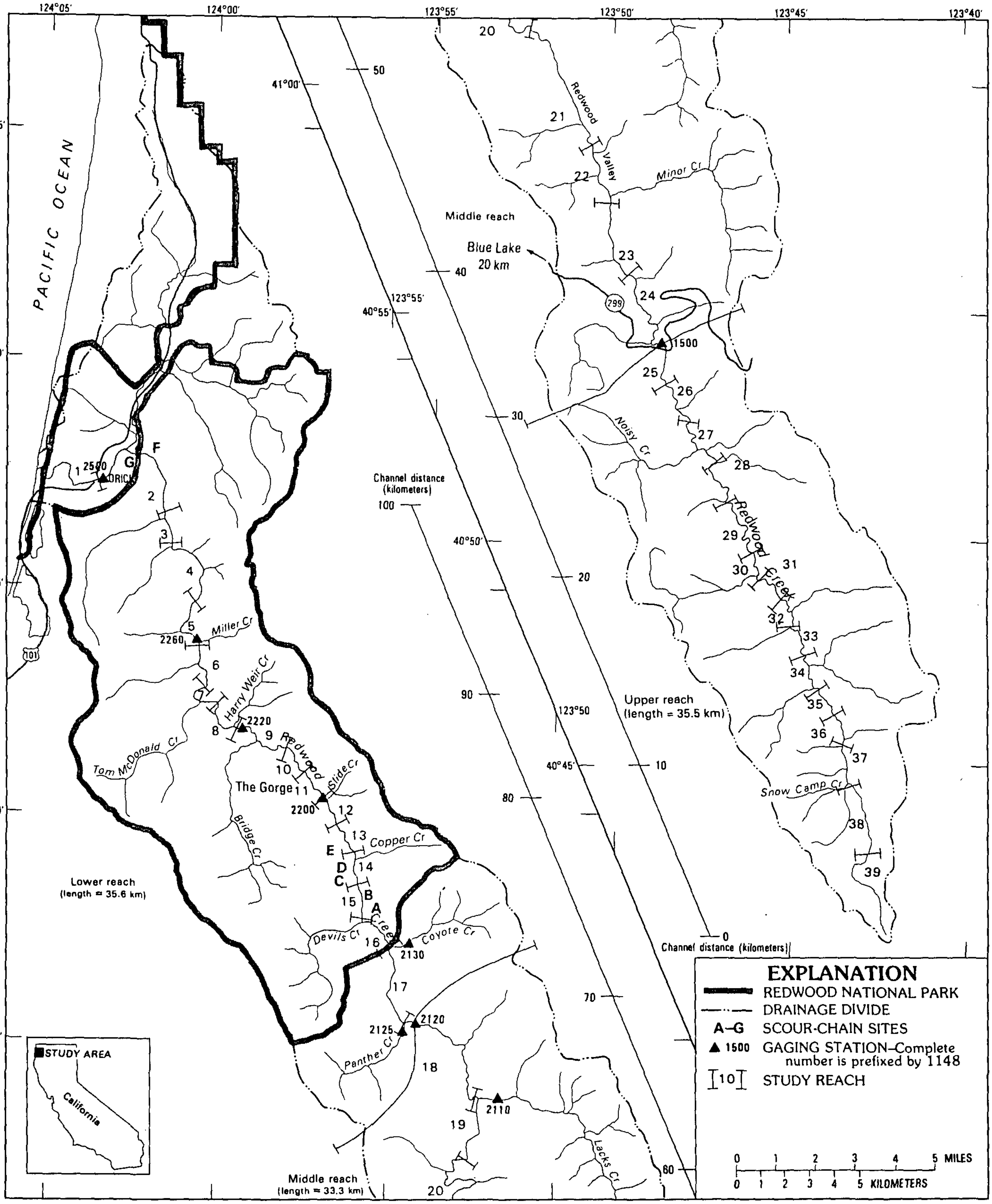

FIGURE 1.—Locations of study reaches, gaging stations, and scour-chain sites, Redwood Creek.

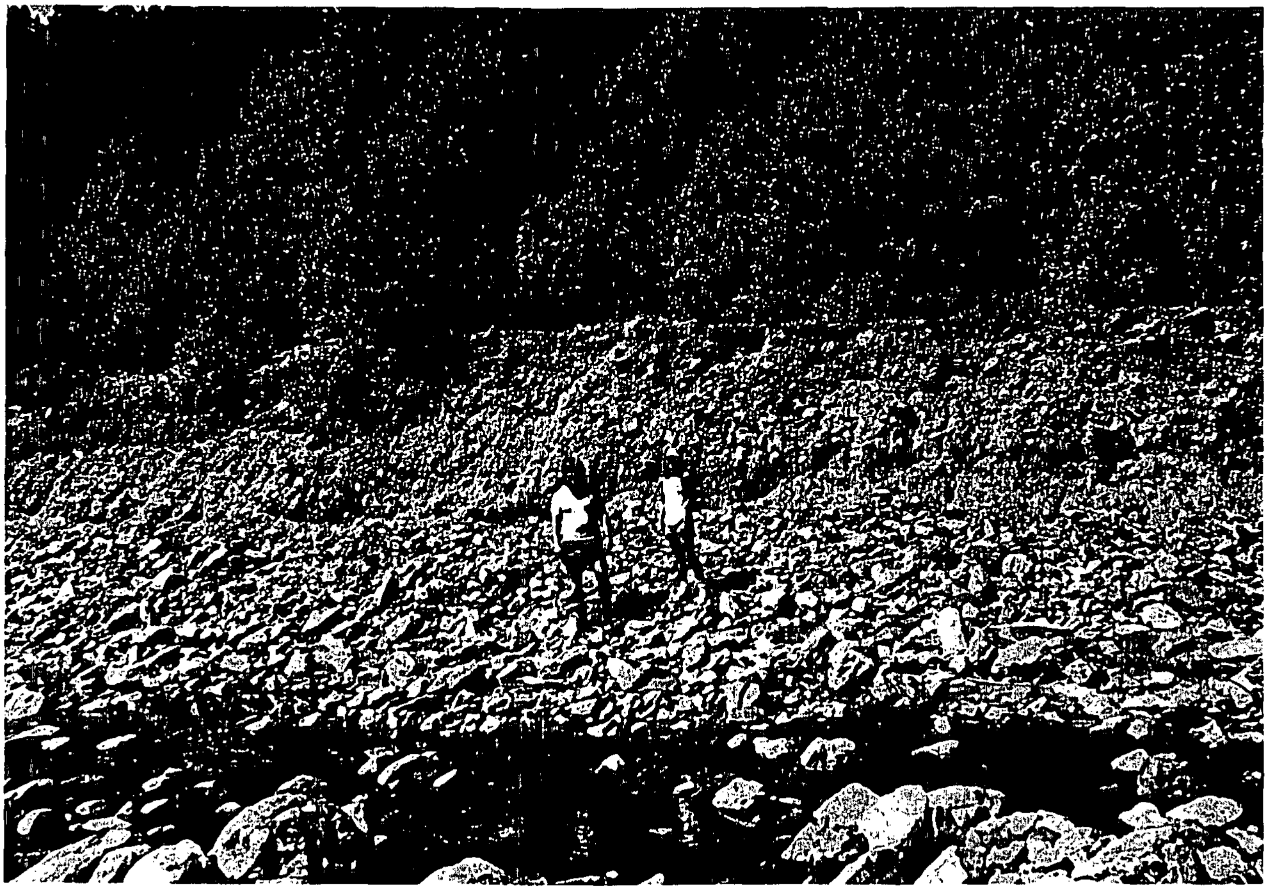

FIGURE 2.—Flat-topped gravel berm deposited in upper reach of Redwood Creek during December 1964 flood (photographed August 1983). Note coarse, unsorted nature of material, young trees growing on the surface, and location against valley wall away from active channel. Deposit was more extensive in 1964.

a quartz-mica schist. The basin receives an average of 2,000 mm of precipitation annually, most of which falls between October and March. Total basin relief is 1,615 m; average hillslope gradient is 26 percent.

Early aerial photographs taken in 1936 and 1947 show that the basin 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 Redwood Creek basin in the early-1950's, and by 1966, 55 percent of the old-growth coniferous forest had been logged. By 1978 this figure rose to 81 percent (chap. C, this volume). Thousands of kilometers of logging roads were built during this time. Recent erosion rates measured by Janda (1978) are about 7.5 times greater than the natural rate estimated by Anderson (1976).

Large floods occurred in the Redwood Creek basin in 1861, 1890, 1953, 1955, 1964, 1972, and 1975. The flood of 1964 was especially damaging and caused drastic 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 and others (1978) discussed the disparity between flood size and magnitude of hillslope erosion and attributed it in part to the change in timber harvest activities.

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 deposits in the upper reaches of Redwood Creek are gravel berms that are as much as 9 m high and consist of coarse gravel (fig. 2). Previous studies of the effects of the 1964 flood on nearby rivers (Helley and LaMarche, 1973) mention similar deposits. The berms were deposited almost continuously on both sides of the river in upstream areas, and in many areas they buried preexisting vegetated bars. Janda and others (1975) dated some conifers killed by the burial as over 200 years old. Also, in lower reaches sandy deposits from the 1964 flood overlie soils on flood-plain deposits that formerly received only fine-grained overbank deposits. This arrangement suggests that the 1964 aggradational event has been unmatched in historic time. Although Helley and LaMarche (1973) and Kelsey (1977) presented evidence of other periods of aggradation (in 1590, 1735, and 1861) in nearby drainage basins, evidence for such events in Redwood Creek is poorly documented.

Redwood Creek changes drastically in character from steep and narrow in headwater reaches, to wide and gently sloping in downstream reaches. In this study, Redwood Creek was divided into 39 reaches for detailed mapping (fig. 1). Reaches were distinguished on the basis of field observation and interpretation of aerial photographs regarding channel and valley width, bed material and bedforms, channel gradient, and streambank stability. Reaches range from 1 to 7 km in length. Kelsey and others (1981) described details of most study reaches.

In addition to the 39 reaches mentioned above, three general reaches (upper, middle, and lower) were defined (fig. 1). The upper reach is relatively steep (average channel gradient=1.2 percent) and bouldery. The valley is narrow and shows evidence of many past streamside landslides. 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 percent has been tractor logged since 1948. At the downstream end of the upper reach is a U.S. Geological Survey (USGS) gaging station, above which the drainage area is 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. With the exception of reach 20, which has a narrow meandering channel incised deeply into Pleistocene terraces, the channel in the middle reach is wide and has an average channel gradient of 0.45 percent. Logging impacts have not been as severe here as in the upper reach, but grazing, residential development, and road construction have affected this part of the basin. Downstream from Redwood Valley the valley narrows again, and here the channel is rocky with a moderate gradient of 0.35 percent and few terraces. Ninety-two percent of the forest in this middle reach was tractor and cable logged between 1948 and 1978 (chap. C, this volume). A gaging station upstream from Panther Creek measures flow from a drainage area of 424 km^2.

The lower reach flows mostly through national park lands. The upstream portion has a steep section called the gorge (1.4 percent 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 the channel gradient is gentle (0.1–0.2 percent). Little evidence of streamside landslides is present in this reach. The forest is predominantly redwood, of which 70 percent was logged by 1978. A gaging station is located at the U.S. Highway 101 bridge in Orick. The channel in the remaining 4 km downstream from the Orick gaging station is confined by flood protection levees built in 1968 and is influenced by tidal fluctuations.

METHODOLOGY

AERIAL PHOTOGRAPHIC 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, sediment was stored in Redwood Creek as gravel bars, flood-plain deposits, and channel sediment below the thalweg. An estimate of the volume of this sediment was determined by using aerial photographs taken in 1936, 1947, and 1954. The resolution and scale varied among three sets of photographs. The areas of the deposits were measured from the photographs with a planimeter, and heights of bars were estimated by comparison with surrounding trees, boulders, bridges, and other objects of known dimensions. The volume of sediment was calculated from the product of area of deposit and height above thalweg. Historical photographs and records were used to verify dimensions estimated from photographs. The tree canopy obscured the channel in some reaches, but, in general, major features were visible. All measurements of bar heights were based on the elevation of the 1947 thalweg because it was assumed to be stable, neither aggrading or degrading. This assumption seemed reasonable because no significant aggradation had occurred in nearby basins since 1861 (Helley and LaMarche, 1973).

No attempt was made to estimate the amount of sediment below the 1947 thalweg, although this storage compartment may be significant in geologic time. Only a few drill logs are available (California Department of Transportation, unpub. data, 1927, 1963, 1987), which show alluvium in Redwood Creek to be less than 1.5 m thick at the State Highway 299 bridge and greater than 25 m thick near the mouth at the Orick U.S. Highway 101 bridge (fig. 1).

The type of field evidence used to distinguish the deposits that resulted from the 1964 flood are discussed

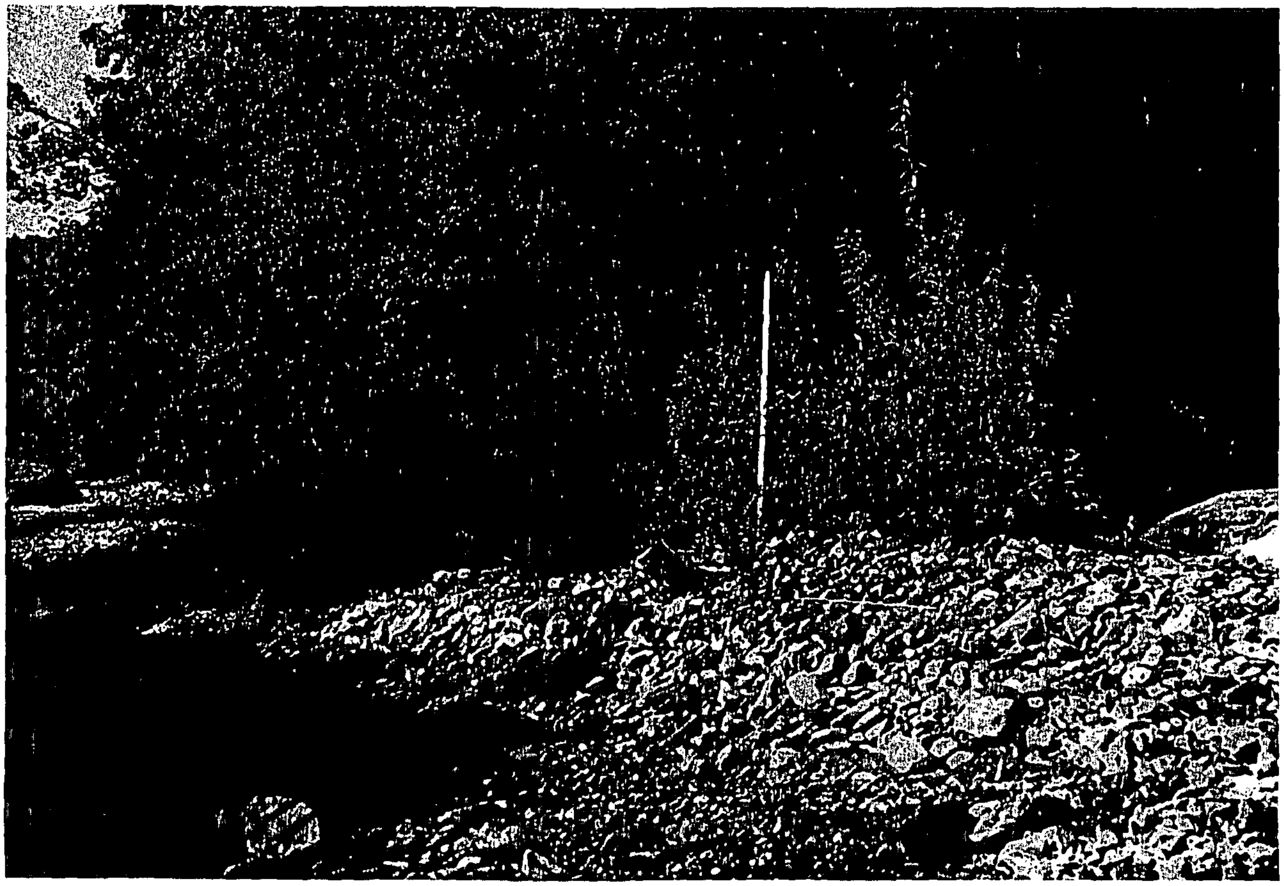

FIGURE 3.—Coarse lobate bar located at kilometer 30 in Redwood Creek (photographed in August 1983). Note thick growth of alder on bar surface, which dates from 1972. There is no evidence of recent movement of bar surface. Height of rod is 2 m.

in the following two paragraphs. Evidence for aggradation resulting from the 1964 flood is best preserved in the upper reach (fig. 1) where flat-topped gravel berms (fig. 2) were deposited. The top of the flood berms were assumed to represent the height to which sediment filled the channel 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 area where the massive, flat-topped berms were deposited, aggradation during the 1964 flood did not occur to as great of depths as above but was still widespread. In the downstream areas, large lobate bars composed of coarse cobbles and boulders were deposited. In 1980 these bars bore a thick growth of alder dating from 1964 to 1972 (fig. 3). In these downstream reaches, channel aggradation was still sufficient to bury trees and large boulders (fig. 4). The volume of sediment deposited in this area as a result of the 1964 flood was estimated by using the field evidence discussed above; 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, where channel changes were not as severe, later floods had reworked the 1964 deposits. Thus, the reliability of the volume estimates of sediment related to the 1964 flood decreases downstream. Accuracy of volume estimates probably ranges from ±15 percent in the upper basin to ±40 percent downstream.

Volumes of sediment stored in the 1980 channel of Redwood Creek were measured in the field. 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 was measured in the field and transferred to 1978 aerial photographs (enlarged to 1:2,000 scale), and the area of the feature was planimetered from the photographs. Heights of gravel bars and terraces above the 1980 thalweg were surveyed with a hand level and stadia rod for both small

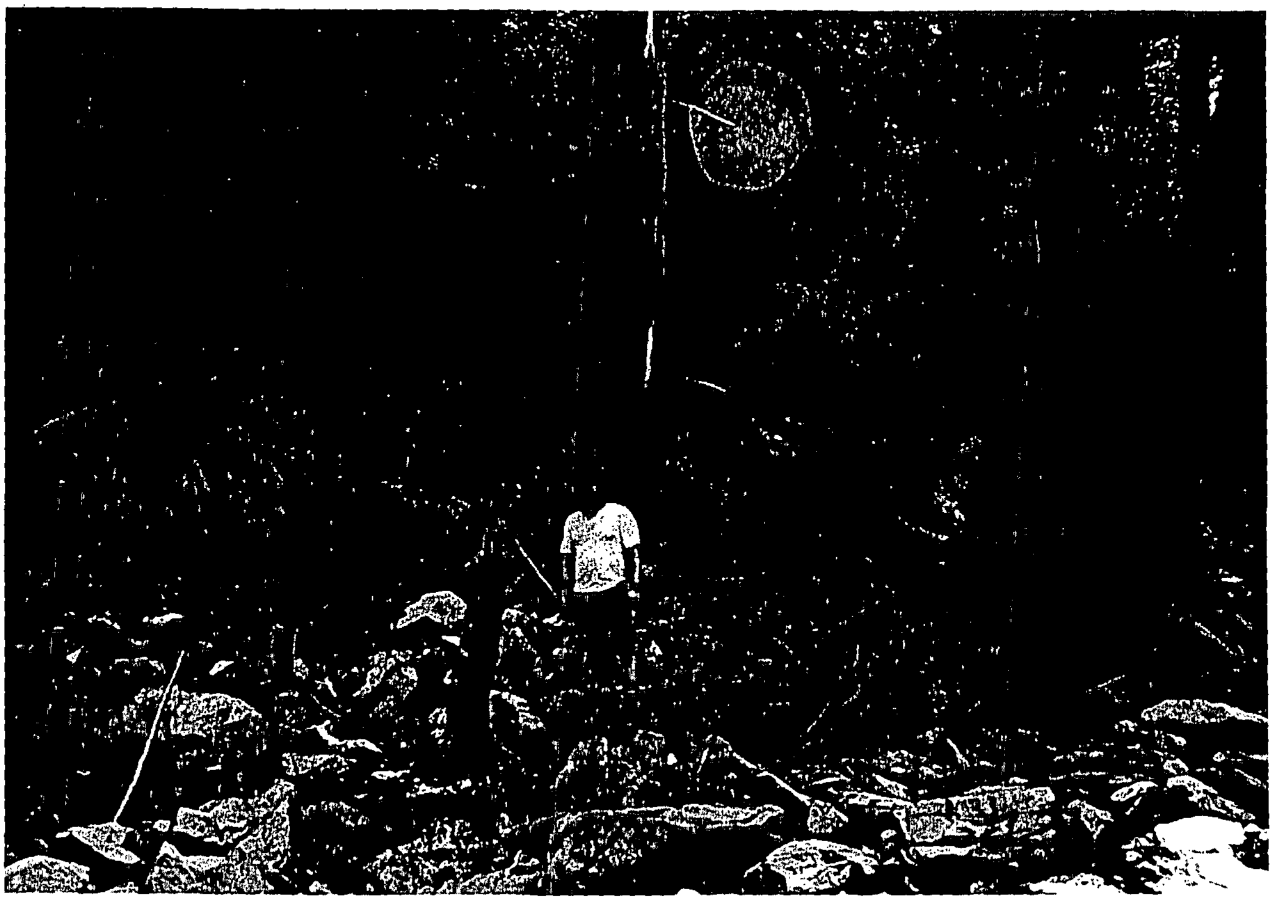

FIGURE 4.—Trees buried and killed by aggradation attributed to flood of 1964. Photographs taken August 1983 near kilometer 9.

and large features. In addition, all bars were described in terms of the age and type of vegetation growing on them, the size of material (boulder, cobble, pebble, or sand), and the presence of buried trees or artifacts. The accuracy of the 1980 measurements of volume of sediment stored above the thalweg is considered excellent (probably within ±10 percent of the actual value).

Several approaches were used to estimate the volume of sediment stored due to channel bed aggradation (that is, stored below the 1980 thalweg but above the 1947 level). Descriptions of channel changes by local landowners provided some information. Buried tree stumps, boulders, car bodies, and other objects that were partly exhumed gave an indication of recent amounts of aggradation at many locations. At a few sites, records from bridge surveys showed a history of aggradation and subsequent downcutting.

Use of time-sequential aerial photographs also helped determine changes in the amount of sediment stored on the channel bed. At several localities, boulders in the channel, which were visible on the 1962 aerial photograph but totally buried on the 1966 photographs, were partly exposed in 1980. Locally, bedrock outcrops were exposed in the channel bed, indicating no aggradation in 1980 at those points. Finally, annual surveys of channel cross profiles document changes in bed elevation in Redwood Creek for the last 9 years. Nolan and Marron (chap. N, this volume) discuss details of the cross-profile surveying and its results. Estimates of volumes of channel bed sediment were subject to substantial error, probably up to 50 percent of the true value.

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

SCOUR AND FILL MEASUREMENTS

To calculate residence times of stored sediment, the quantity of sediment mobilized in the channel bed during high flows must be known. Two approaches were used to estimate the depth of scour and fill in the thalweg and on bars during winter flows. First, scour chains were installed in 1981 at seven cross sections in Redwood Creek (fig. 1). Three to five chains were installed at each section. Pits were dug with a backhoe as deeply as possible (1.2–2 m) into the channel bed. Lengths of steel chain 0.6 cm thick were anchored with steel rods 0.6 cm in diameter at the base of each pit, and pits were backfilled while the chain was held vertically. Excavated areas were compacted and smoothed to reestablish original bed elevation and shape. Cross sections and chain locations were surveyed and photographed. Because backfilling a pit does not restore the fabric and stratigraphy of the original bed material, scour chain areas might behave differently than the rest of the channel bed at high flows. Nevertheless, postwinter surveys showed no differential scour or fill at scour-chain locations compared with adjacent unexcavated portions of the channel bed. After winter flows receded, 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 USGS discharge measurement notes. 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 from 1975 to 1981.

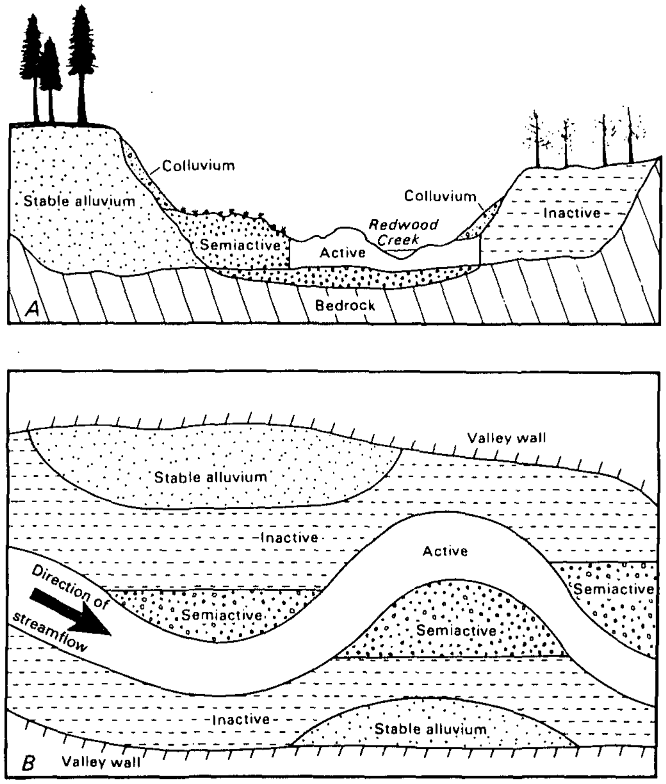

FIGURE 5.—*A*, Schematic cross section of four sediment reservoirs in Redwood Creek: active, semiactive, inactive, and stable. *B*, Schematic plan view of four sediment reservoirs in Redwood Creek.

RELATIVE AGE ESTIMATES FOR SEDIMENT

To estimate 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 was deposited (Dietrich and others, 1982). Because the absolute age of many deposits in Redwood Creek was not known, a relative age scale was used to categorize deposits. Estimates of relative age were based on the "activity level" of a deposit, ranging from easily mobilized to stable.

Several lines of evidence were used to support the relative age estimates. Trees growing on deposits were dated 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. Time-sequential aerial photographs showed 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 to what depth the channel bed was active during floodflows.

By using the indicators mentioned above, a rating scheme was developed to classify sediment deposits ranging from "young" or active to "old" or stable. The four categories, or sediment reservoirs, defined within this range are active, semiactive, inactive, and stable (fig. 5).

Active sediment is transported during moderate flood flows having a recurrence interval of 1 to 5 years. Vegetation on active sediment is absent or sparse. Cross-section survey data and scour-chain data show channel shifting, or scour and fill of active sediment, during moderate flows. Bed sediment that occurs 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 that are subject to collapse under moderate floodflows. Active sediment may also be found in bars less than 1 m high that are composed of pebbles, sand, and some cobbles.

Semiactive sediment is mobilized during higher flows, such as a 5- to 20-year flood. At such flows, sediment covered with shrubs and young trees is mobilized, as well as some cobble and boulder deposits.

Inactive sediment is stationary until 20- to 100-year floods occur. Such flows may mobilize inactive sediment

FIGURE 6.—Classification of sediment reservoirs shown on a vertical aerial photograph (1978; scale 1:6,000) of Redwood Creek, kilometer 100 near Orick; flow is from left to right. Classes are active (A), semiactive (Sa), inactive (Ia), and stable (S).

found in coarse lag deposits; gravel berms 3 to 5 m high; strong, coherent log jams; and flood-plain deposits.

Stable sediment has not been mobilized historically and constitutes some flood-plain and terrace deposits (fig. 6). Most 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 terraces are not abandoned flood plains (as terraces are defined by Leopold and others, 1964), 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 channels. 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.

In the flood plain near the mouth of Redwood Creek, great quantities of stable alluvium are stored, down to an unknown depth. However, flood levees built in 1968 isolate the flood plain from the channel, and no erosion or deposition has occurred on the flood plain since the levees were built. Because the flood plain has been artificially stabilized, it is not included in the analysis of the present distribution of stored sediment. Nevertheless, an estimated 23.4×10^6 m^3 of fine-grained alluvium is stored in the flood plain above the elevation of the present stream thalweg.

RELATION BETWEEN SEDIMENT MOBILITY AND SIZE

Physical characteristics of sediment in storage influence whether it will be transported as bedload or suspended load. The character of stream sediment reflects properties of the soil mantle, underlying geology, dominant hillslope erosion processes, and fluvial sediment transport processes. Size distribution analyses of sediment samples from Redwood Creek (Iwatsubo and others, 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 (chap. N, this volume). Bulk densities of stored sediment were measured with a Soiltest Volume Measurer at several sites in the drainage basin. Relative resistance of bed material to breakdown during transport was determined through an attrition experiment, as described below.

TEMPORAL CHANGES IN SEDIMENT STORAGE

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 (chap, N, this volume), Janda and others (1975), and Best (1984) describe undisturbed basin conditions in more detail. Measurements from aerial photographs indicate that under pristine conditions 11×10^6 m^3 of sediment was stored along Redwood Creek. Fifty percent of this sediment was stored in stable terraces. Differentiation of active, semiactive, and inactive sediment from early photographs was not feasible.

As a result of the 1964 flood, the total volume of stored sediment along Redwood Creek increased to 16×10^6 m^3, which is 1.5 times greater than the volume stored in 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 they 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 along Redwood Creek in 1980 was slightly greater than the 1964 total. The total volume of sediment in 1980 would have been even greater than it was, but approximately 1.15×10^6 m^3 (2.2×10^6 Mg) of gravel was excavated from the bed of lower Redwood Creek between 1953 and 1978 (Milestone, 1978). This amount represents 23 percent 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, 1980) are displayed in figure 7. In 1947, the center of mass of total stored sediment along Redwood Creek was at kilometer 64; in 1964 it shifted upstream to kilometer 61, and by 1980 it had shifted downstream to kilometer 78. Nolan and Marron (chap. N, this volume) describe how the locus of maximum aggradation has moved downstream in recent years, as inferred from cross-sectional data.

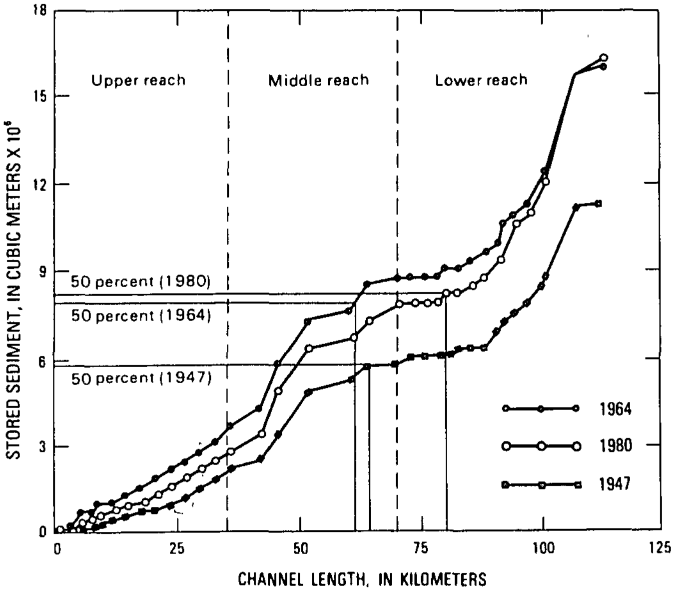

FIGURE 7.—Cumulative volumes and spatial distribution of stored sediment in Redwood Creek as of 1947, 1964, and 1980. Center of mass for each time period indicated by the "50%" line.

A comparison of the three curves in figure 7 shows some other differences between the three time periods. The slopes of the three curves increase sharply at kilometer 42 (near Redwood Valley). These increases indicate that Redwood Valley was a high-storage area in 1947 and has remained so. The reach between Lacks and Slide Creeks (kilometer 63 to kilometer 80) is narrow and stores relatively little sediment, as indicated by gentle slopes of the three curves. High storage areas downstream from the gorge (kilometer 80) show a rapid increase in storage volume, as indicated by the increase in slope of the curves. The rate of increase of stored sediment under pre-1947 conditions downstream from the gorge was less than in either 1964 or 1980.

Figure 8 shows that all individual study reaches stored more sediment in 1980 than in 1947, although storage in some areas was not much higher in 1980 than in 1947. All reaches upstream from reach 14 stored more sediment in 1964 than in 1980, and downstream reaches stored more in 1980 than in 1964. This increase in storage 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 the volume of material from landslides in the lower basin between 1966 and 1980 (chap. J, this volume, fig. 9).

Table 1 summarizes changes in stored sediment along the 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 4.7×10^6 m^3

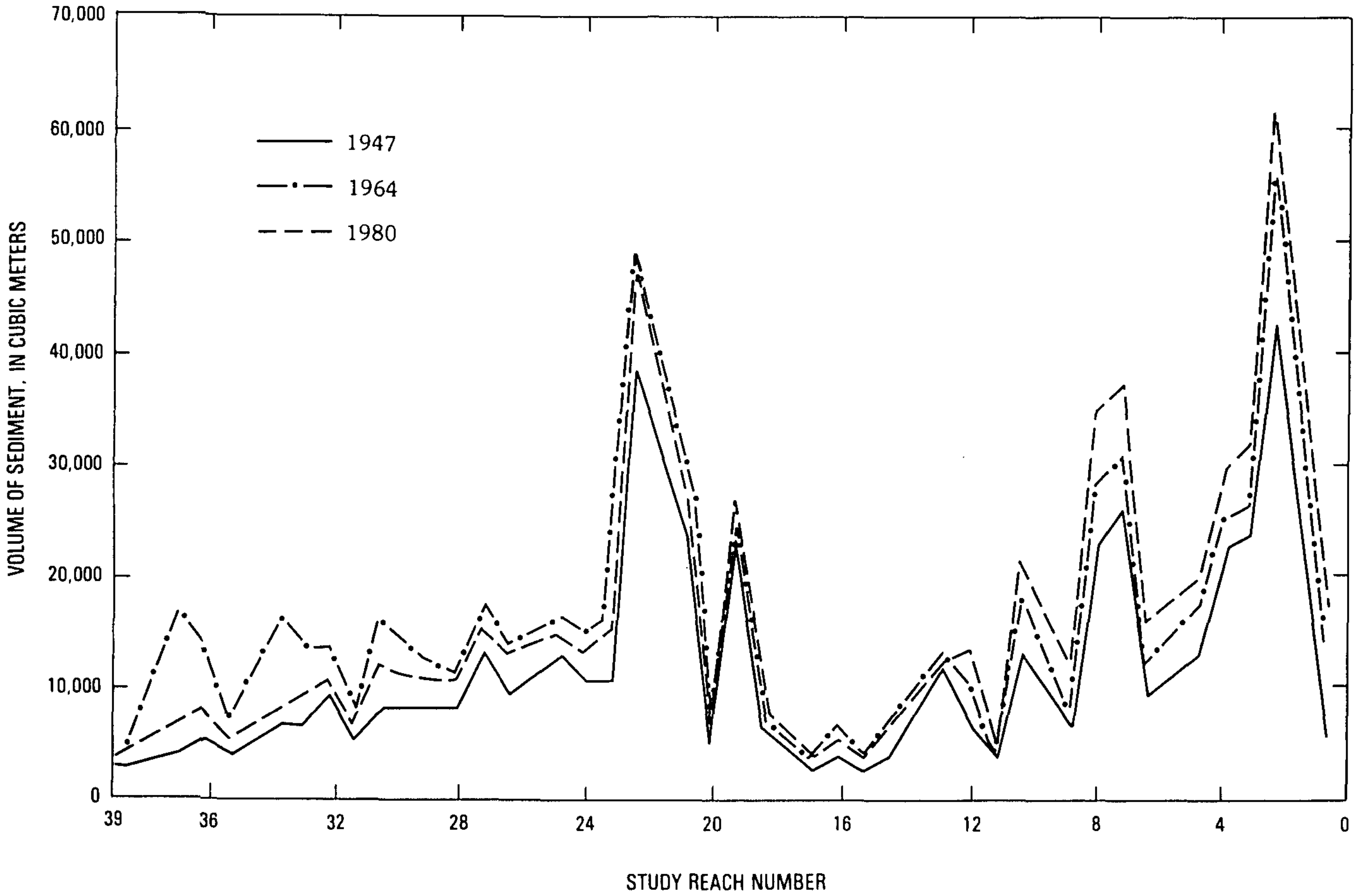

FIGURE 8.—Volumes of stored sediment in individual study reaches as of 1947, 1964, and 1980. Locations of study reaches shown on figure 1.

TABLE 1.—*Net changes in stored sediment at Redwood Creek, 1947–64, 1964–80, and 1947–80*

["+" indicates deposition; "−" indicates erosion]

Reach	Change in stored sediment (Mg)[1] 1947 to 1964	Mg/km^2	Change in stored sediment (Mg)[1] 1964 to 1980	Mg/km^2	Increase in 1980 stored sediment over 1947 levels (Mg)	Mg/km^2	Current bedload transport rates[2] [(Mg/km^2)/yr]
Upper	$+2.8\times10^6$	16,000	-1.5×10^6	−8,600	$+1.3\times10^6$	7,400	530
Middle	$+2.5\times10^6$	11,700	$-.3\times10^6$	−1,400	$+2.2\times10^6$	10,300	400
Lower	$+3.8\times10^6$	11,500	$+2.1\times10^6$	+6,300	$+5.9\times10^6$	17,800	240
Total channel	$+9.1\times10^6$	12,600	$+.3\times10^6$	+400	$+9.4\times10^6$	13,000	

[1] Assumes a bulk density of 1.92 g/cm^3.

[2] Based on sediment discharge measurements from 1971 to 1980.

(9.1×10^6 Mg) of "excess" sediment had been deposited. An excess of sediment over 1947 volumes still existed for all reaches of Redwood Creek in 1980 (table 1). The total volume of excess sediment was greatest in the lower reach (5.9×10^6 Mg). As of 1980, 1.3×10^6 Mg was still in the upper basin, which represents 46 percent of the 1947 to 1964 sediment increase.

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 Mg (or 65 percent) of the present excess sediment is stored in inactive gravel berms. The channel bed itself has degraded very slowly since 1977 (chap. N, this volume). Much of the excess sediment in the upper reach will probably persist for decades.

In contrast to the upper reach, the lower reach stored 5.9×10^6 Mg of excess sediment in 1980, and 70 percent of that amount is in the aggraded active channel bed. Here

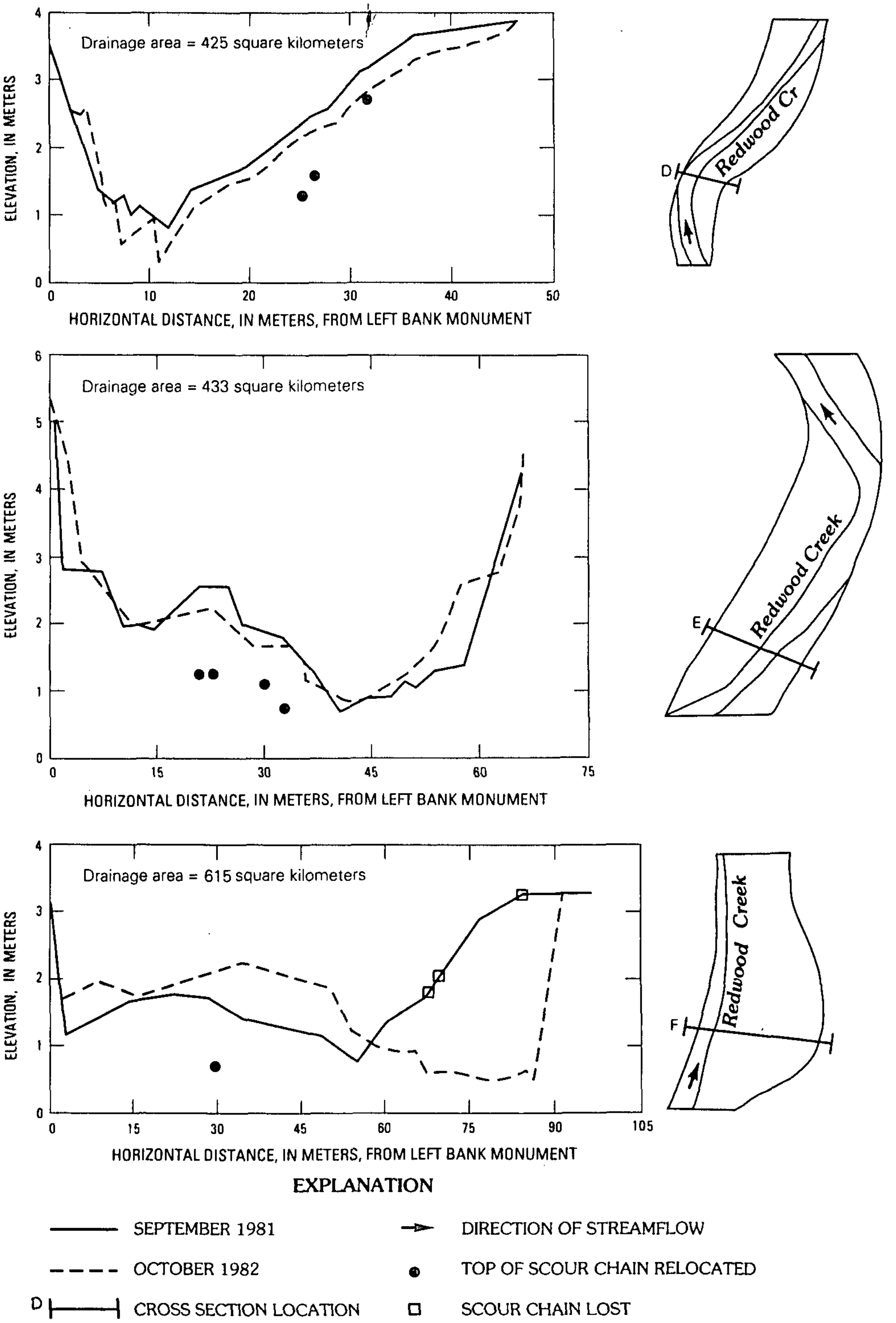

FIGURE 9.—Cross-sectional profiles of Redwood Creek for 1981 and 1982. Plan maps show relation of cross section to channel. Scour-chain sites are shown in figure 1.

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 (chap. N, this volume, fig. 15).

As of 1980, total stored sediment above the 1947 datum in Redwood Creek is equivalent to 13,000 Mg/km^2. This amount of storage represents a large in-channel sediment supply and indicates that bedload transport rates will be high in the future.

EFFECTS ON BEDLOAD TRANSPORT

An example of the strong effect channel-stored sediment can have on bedload transport can be seen by examining data from the upper reach. Between 1965 and 1980, 1.5×10^6 Mg of sediment (or 8,600 Mg/km^2) were eroded from the upper reach (table 1). Aerial photographs taken in 1972 and field evidence suggest that most of this sediment was eroded within 8 years of its initial deposition in 1964. This means that the bedload sediment yield due to erosion of flood deposits at the Blue Lake gaging station was probably 8,600 Mg/km^2, or 1,075 (Mg/km^2)/yr, for the first 8 years following the 1964 flood. Currently, the bedload transport rate measured at this station is only 530 (Mg/km^2)/yr (James Knott, USGS, written commun., 1981). Unfortunately no sediment discharge measurements are available before 1973 for this station. Stations on nearby rivers, however, showed large increases in sediment yield for several years after 1964 (Knott, 1974). On the Trinity River at Hoopa, for example, the long-term bedload transport rate is 100 (Mg/km^2)/yr. In water year 1965 (which includes the December 1964 flood), bedload transport was about 1,300 (Mg/km^2)/yr, and in the following 5 years bedload transport rates remained elevated at about 300 (Mg/km^2)/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, and bank erosion), as well as channel scour.

A similar comparison at the old South Park Boundary gaging station (kilometer 80) shows an estimated 1965–72 bedload sediment yield of 475 (Mg/km^2)/yr due to erosion of flood deposits, as opposed to the current measured value of 400 (Mg/km^2)/yr. These data suggest that erosion of the 1964 flood deposits in the period from 1965 to 1972 resulted in bedload transport rates as high as the total bedload sediment yield currently measured in Redwood Creek from all sediment sources. Because other sediment sources also were active from 1965 to 1972, total bedload sediment yield for that period was probably much higher than at present.

TABLE 2.—*Depths of scour and fill in channel bed at scour-chain sites*

[* = Chains not recovered. Scour depth listed is depth of hole dug at scour-chain sites without hitting chain. NA, not available]

Site	Chain number	Scour (m)	Fill (m)
A	1*	>0.2	NA
	2*	> .6	NA
B	1*	> .6	NA
	2*	> .6	NA
	3*	> .6	NA
C	1*	>1.2	NA
	2*	>1.2	NA
	3*	>1.2	NA
D	1	.9	.7
	2	.8	.4
	3	.3	.1
E	1	1.2	.8
	2	1.2	.7
	3	.7	.6
	4	.9	.8
F	1	1.0	1.3
	2	1.0	1.3
	3*	>1.8	NA
	4*	>1.8	NA
	5*	>1.8	NA
G	1*	>1.2	NA
	2*	>1.2	NA
	3*	>1.2	NA

Several other studies support the suggestion of high bedload transport rates for the period 1965 to 1972. Nearby rivers responded to an increase in sediment load from the 1964 flood with changes in channel geometry that resulted in high bedload transport rates (Lisle, 1982). Madej (1982) found that a stream in western Washington became wider and shallower and that bed shear stress changed to transport an increased sediment load. Redwood Creek responded similarly in that width increased and depth decreased, suggesting that the resulting distribution of bed shear stress should have permitted higher bedload transport rates after the 1964 flood.

DEPTHS OF SCOUR AND FILL

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

Figure 9 shows examples of scour and fill from three of the seven scour-chain sites (fig. 1). The depth at which chains were found indicates the depth of scour and subsequent fill during winter flows of 1981 to 1982. In table 2, the actual amount of scour and fill at each scour-chain location is given. At sites D and E, general cross-section 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 to 1.2 m deep. At sites D and E, the channel bed was mostly cobbles (D_{50}[2]=32 mm), but boulders 25 to 55 cm in diameter were deposited on top of the chains during the fill episode. Bed material below a coarse armor layer generally consisted of coarse sands and pebbles. At a depth of 1–2 m, however, there was generally a layer of large boulders (1–1.2 m in diameter). Scour did not extend 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 semiactive 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 toward the right bank. A scour chain near the left bank indicated 1.0 m of scour and 1.3 m of fill. Several other chains, 2 m in length, were lost because of 25 m of lateral erosion at 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 semiactive because of its vegetative cover of grasses and shrubs. Excavation of gravel from the bed downstream from 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 the magnitude and location of channel bed scour and fill during moderate to high floodflows (flows with recurrence intervals of 1 to 10 years). Discharge measurement notes were available for seven stations on Redwood Creek for various storms. Figure 10 shows examples of scour and fill at three stations during the flood of January 13–14, 1980, at discharges near bankfull. Station 11481500 (kilometer 35.5) 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 to 0.2 m with some fill at the right bank. Downstream at station 11482260 (kilometer 92), where the bed consists of sand and pebbles with a few cobbles (D_{50}=22 mm), the bed was scoured to a depth of 0.6 to 1.3 m at the peak of the flood and filled during receding flows. The postflood and preflood cross sections are similar. Successive cross-section surveying done only at low flows would not have indicated the depth of sediment movement at these sections.

TABLE 3.—*Scour depths estimated from U.S. Geological Survey current meter discharge measurements*

Date	Maximum depth of scour (m)	Discharge (m^3/s)	$Q/Q_{1.2}$[1]
Redwood Creek near Blue Lake, kilometer 35.5, $Q_{1.2}$=120 m^3/s			
2/19/75	0.6	180	1.5
2/26/76	.3	78	.7
2/26/76	.3	65	.5
2/28/79	.3	40	.3
1/13/80	.2	59	.5
1/14/80	.3	77	.6
12/22/81	.5	32	.3
1/26/83	.9	158	1.3
Redwood Creek above Harry Weir Creek, kilometer 85.8 ($Q_{1.2}$=224 m^3/s)			
4/01/74	1.6	379	1.7
2/26/76	.8	207	.9
2/26/76	.8	200	.9
12/14/77	1.0	456	2.0
12/15/77	.6	259	1.2
1/19/78	.6	136	.6
2/28/79	.4	140	.6
1/14/80	.8	231	1.0
1/14/80	.5	259	1.2
2/10/82	.6	270	1.2
2/16/82	.3	213	1.0
Redwood Creek at Orick, kilometer 104.4 ($Q_{1.2}$=289 m^3/s)			
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	.9	252	.9
12/15/77	.9	311	1.1
1/19/78	.4	171	.6
1/14/80	.5	328	1.1
12/14/81	.4	163	.6
12/22/82	1.3	195	.7
1/24/83	1.2	121	.4

[1] $Q/Q_{1.2}$ is a dimensionless index where $Q_{1.2}$ is the discharge with a 1.2-year recurrence interval.

Sediment at the sites of channel cross profiles shown in figure 10 was all classified as "active" 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 are located at bridge sites where the channel is confined, semiactive and inactive sediment are not likely to be represented at such sites.

U.S. Geological Survey current meter discharge measurement notes for 1972 to 1983 (table 3) were used to generalize the extent of scour at different flows at different gaging stations. To compare equivalent discharges for different stations, discharge data were transformed 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 Young and Cruff (1967, p. 12). The maximum depths of scour for several discharges were plotted for three

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[2] D_{50} is particle size representing the 50th percentile of the grain size distribution.

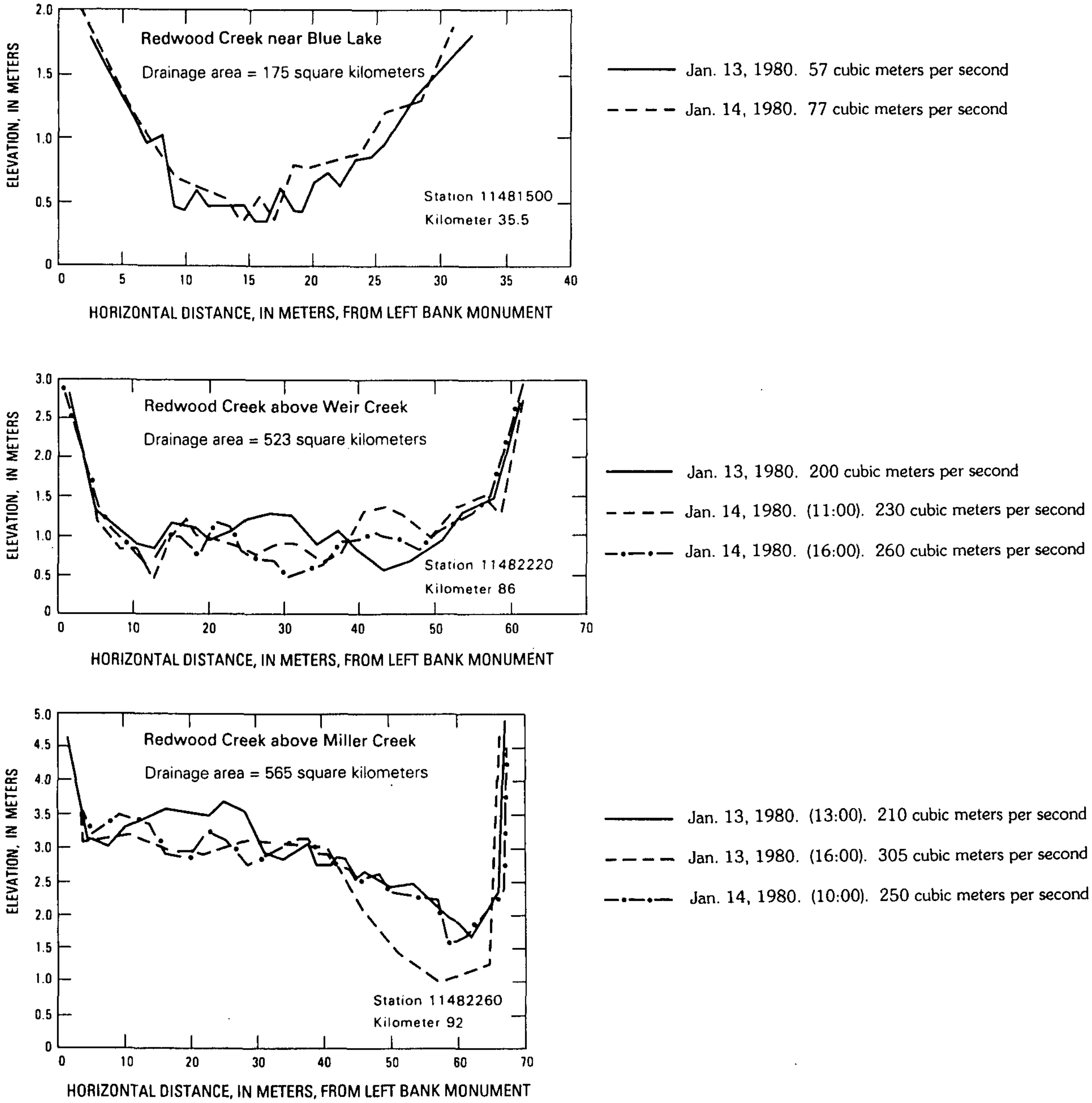

FIGURE 10.—Cross-sectional profiles of Redwood Creek at stream-gaging stations showing changes in bed elevation during flood of January 13–14, 1980.

stations (fig. 11). Best fit regression curves were computed for each station. The plotted points are scattered, but the correlations are significant at the 95-percent confidence level. In general, depth of scour increases downstream for equivalent discharges, and depth of scour increases with increasing discharge at a given station.

BREAKDOWN OF BED MATERIAL

Several lines of evidence indicate that bed material breaks down rapidly into smaller clasts in Redwood Creek. First, bedrock in the basin is highly sheared and fractured and in general is very friable. Preliminary data suggest that roundness of bed-material particles gener

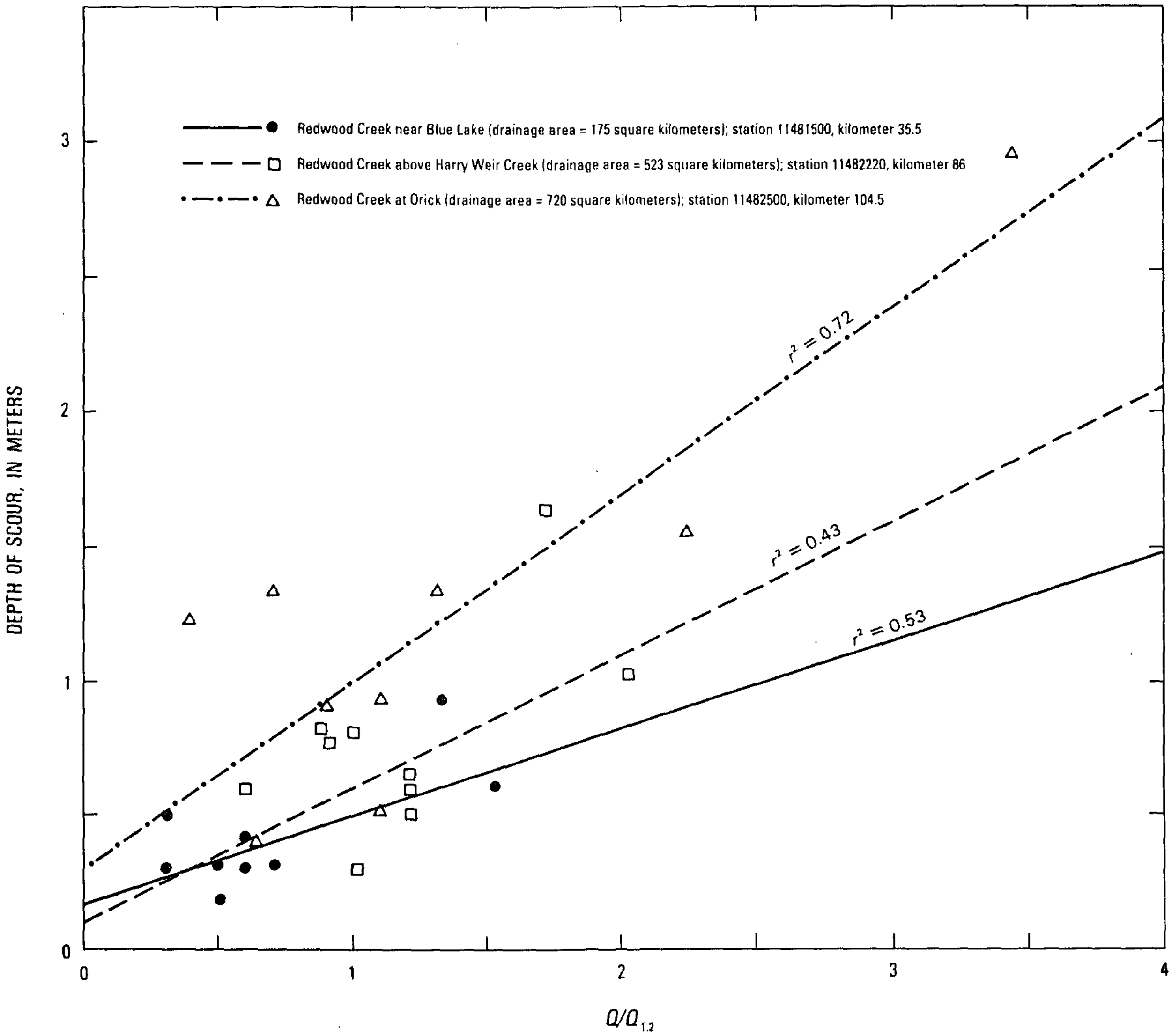

FIGURE 11.—Plot of maximum depths of scour versus dimensionless discharge index, $Q/Q_{1.2}$, for three gaging stations in Redwood Creek. Data include measurements from 1972 to 1983. Best fit regression lines ($\alpha=0.05$) shown for the three stations. $Q/Q_{1.2}$=a dimensionless index where $Q_{1.2}$ is the discharge with a 1.2-year recurrence interval for that station. r^2=coefficient of linear correlation.

ally increases downstream. In the upper basin, bedload makes up 20 percent of the total load; at the mouth, 11 percent (Knott, 1981, unpub. data). Suspended sediment discharge evidently increases slightly downstream, from 2,100 (Mg/km^2)/yr in the upper basin to 2,200 (Mg/km^2)/yr at the mouth (Knott, 1981, unpub. data). The incidence of cracked cobbles exposed at low flow on gravel-bar surfaces is high throughout the basin. Lastly, a tumbling experiment showed a high rate of reduction in weight for particles 2 to 90 mm in diameter.

The tumbling experiment used a Los Angeles Rattler Machine, a 0.7-m-diameter revolving steel barrel. Mounted on the interior wall was a steel shelf, 9 cm in width, which caused material to freefall in the cylinder during part of each revolution. Sediment was tested dry because water could not be used in the machine. 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. One core was collected upstream from Copper Creek at kilometer 77 (sample 1), and the other at kilometer 89 upstream from Tom

McDonald Creek (sample 2). These cores were analyzed for size distribution and lithology. Analyses of the samples showed 5 percent (sample 1) and 15 percent (sample 2) of the sediment particles by weight were 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 (sample 1, 64 percent; sample 2, 69 percent) had broken down into the less-than-2-mm size fraction (fig. 12).

Bed material greater than or equal to 8 mm in diameter used in the experiment was classified according to rock type: sandstone, schist, or other (chert, conglomerate, or metavolcanic). The size fraction greater than or equal to 8 mm composed over two-thirds (66 and 78 percent) of the original bed material. Schist originally made up 20 and 27 percent of the bed material by weight for samples 1 and 2, respectively, and sandstone, 63 and 67 percent. 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 either breakdown of schist particles is more rapid or that sandstone terrain contributes more coarse sediment.

The percentage of weight loss or attrition by size class, during the experiment, varied with lithology. At the end of the run, the percentage of schist material equal to or greater than 8 mm in diameter was reduced 83 to 85 percent, whereas the sandstone percentage was reduced only 46 to 52 percent. Although these specific attrition rates are not directly equivalent to those occurring in Redwood Creek, they do indicate that attrition is an important process in this basin and that schist breaks down more readily than sandstone. Results of this experiment are similar to those found by other investigators. Cameron and Blatt (1971) showed that sand-sized fragments of schist were mechanically destroyed by less than 25 km of transport in a stream in the Black Hills of South Dakota. By using rocks from New Zealand in a tumbler experiment, Adams (1978) also found that schist pebbles broke down much more readily than sandstone pebbles.

Schist is a fairly common bed material in the lower 20 km of Redwood Creek (chap. N, this volume) but, as described above, 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 provides a large fraction of the particles less than 8 mm in diameter and contributes greatly to the suspended load.

A high attrition rate for 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.

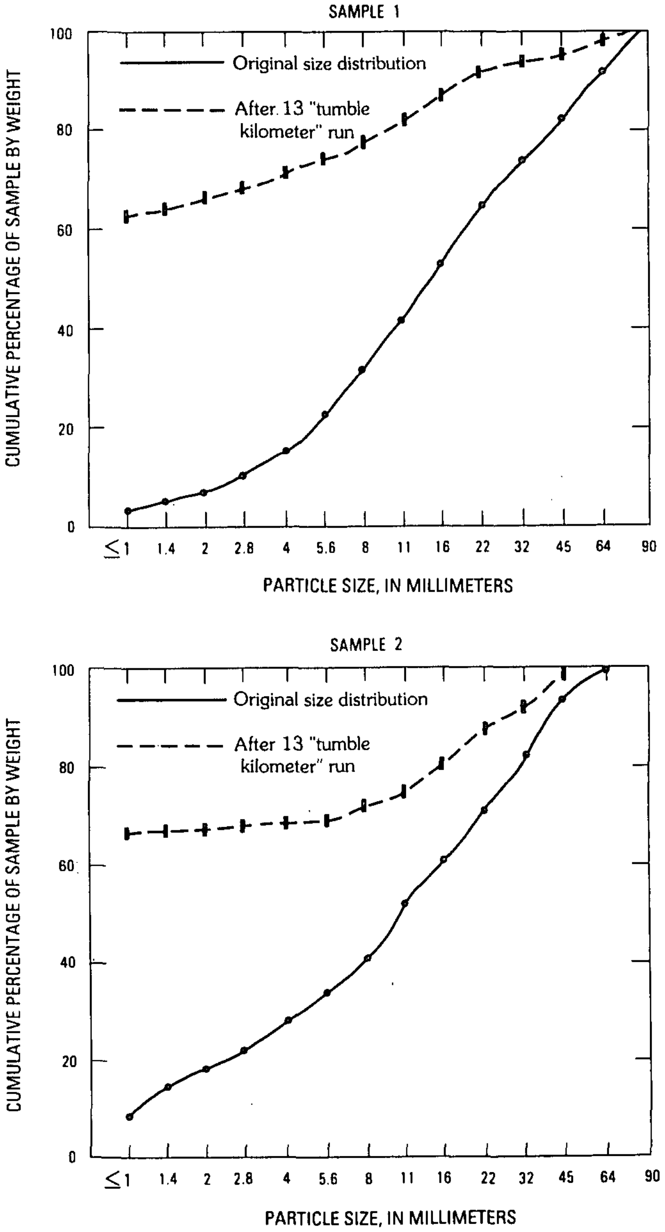

FIGURE 12.—Cumulative particle-size distribution curves for samples used in attrition experiment. Note that in both cases nearly two-thirds of the material broke down to the less-than-2-mm fraction after 13 "tumble kilometers." The tumbling experiment involved a Los Angeles Rattler Machine, which was used to determine attrition rates on dry sediment samples.

DISTRIBUTION AND QUANTITY OF CHANNEL-STORED SEDIMENT

Sediment is stored in the Redwood Creek channel in several types of storage features that differ from place to place along the channel. Stability and persistence of storage features also differ, according to the size and location of the features in the channel. Figure 13 shows the relative amount of sediment in each storage feature. It is interesting to note that 23 percent of the total sediment is stored in features that were not present in Redwood Creek before 1947 (flood-deposited gravel berms and aggraded channel bed). A single storage feature may consist of several different sediment reservoirs. For example, a point bar (storage feature) may have active, semiactive, and inactive sediment (sediment reservoirs) stored within it (fig. 5*B*).

Some kinds of storage features are found only in particular reaches of Redwood Creek (fig. 14). For example, terracelike gravel berms deposited by the 1964 flood (fig. 2) are found predominantly in the upper reach, and berms deposited during the floods 1972 and 1975 are found in the middle reach. They 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. In some berms, the gravel is very angular, indicating little fluvial transport before deposition. Also, some landslides that occurred during the 1964 flood (as documented in aerial photographs) have unmodified berm deposits at their toes. This indicates that, at least locally, major landslides occurred prior to the deposition of the berms and that no slide activity has occurred since.

Strath terraces as much as 60 m in height are common between kilometer 12 and kilometer 50 (fig. 14). The lower terraces in this reach have fresh deposits of sand and gravel from recent floods. Extensive alluvial terraces are located in the downstream third of the channel and are important in supporting stands of old-growth redwoods.

Although organic debris is important in storing channel sediment in Redwood Creek tributaries (chap. K, this volume), debris jams store less than 1 percent of the total stored sediment in the main stem of Redwood Creek. Jams that span the channel width, and thus form effective sediment traps, occur only where the drainage area is less than 65 km^2. Keller and Swanson (1979) also found that debris concentrations generally decrease in number downstream. Cut logs are a major component of debris jams, and so jams may have been even less numerous under natural conditions.

Even though woody debris does not directly trap much sediment in Redwood Creek, such debris does influence channel and flood-plain deposits. Large logs that lie parallel to the streambanks 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 becomes established around these jams sooner than elsewhere 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.

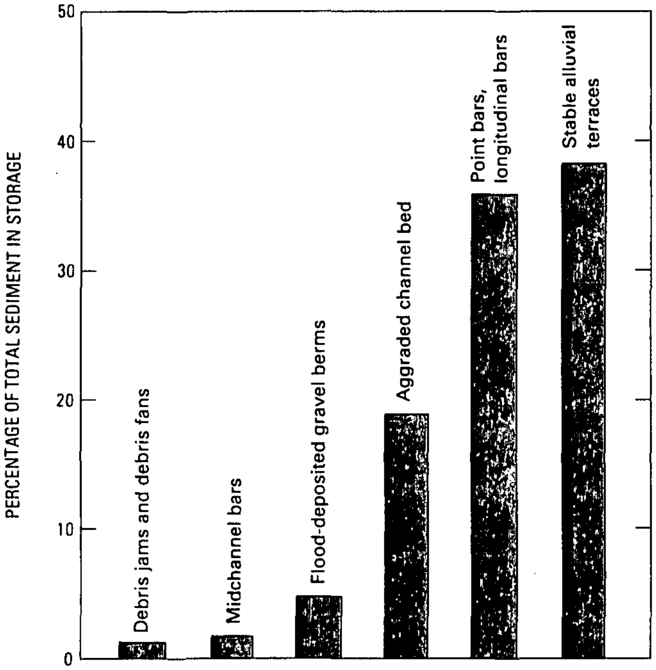

FIGURE 13.—Distribution of stored sediment in various features in Redwood Creek as of 1980.

A total volume of 16×10^6 m^3 of sediment is stored in the main Redwood Creek valley, and an additional 23×10^6 m^3 is stored in the flood plain at Orick. In tributaries, however, 95 percent of total sediment volume is stored in the lower 50 percent of their drainage lengths (chap. K, this volume), whereas alluvial storage in the main channel of Redwood Creek is spread over 85 percent of its length. Ninety-five percent of the total stored sediment in Redwood Creek is located in 65 percent of its drainage length.

The distribution of sediments of different relative mobility changes significantly along the length of the channel (fig. 15). Active sediment makes up a greater percentage of the total stored sediment in the upper 10 km than does any of the other classes. It decreases in relative importance in the midbasin and increases again downstream from the gorge (kilometer 80). The increase in mobile sediment in downstream reaches does not necessarily indicate that transport rates are higher or that the threshold of movement is lower than in

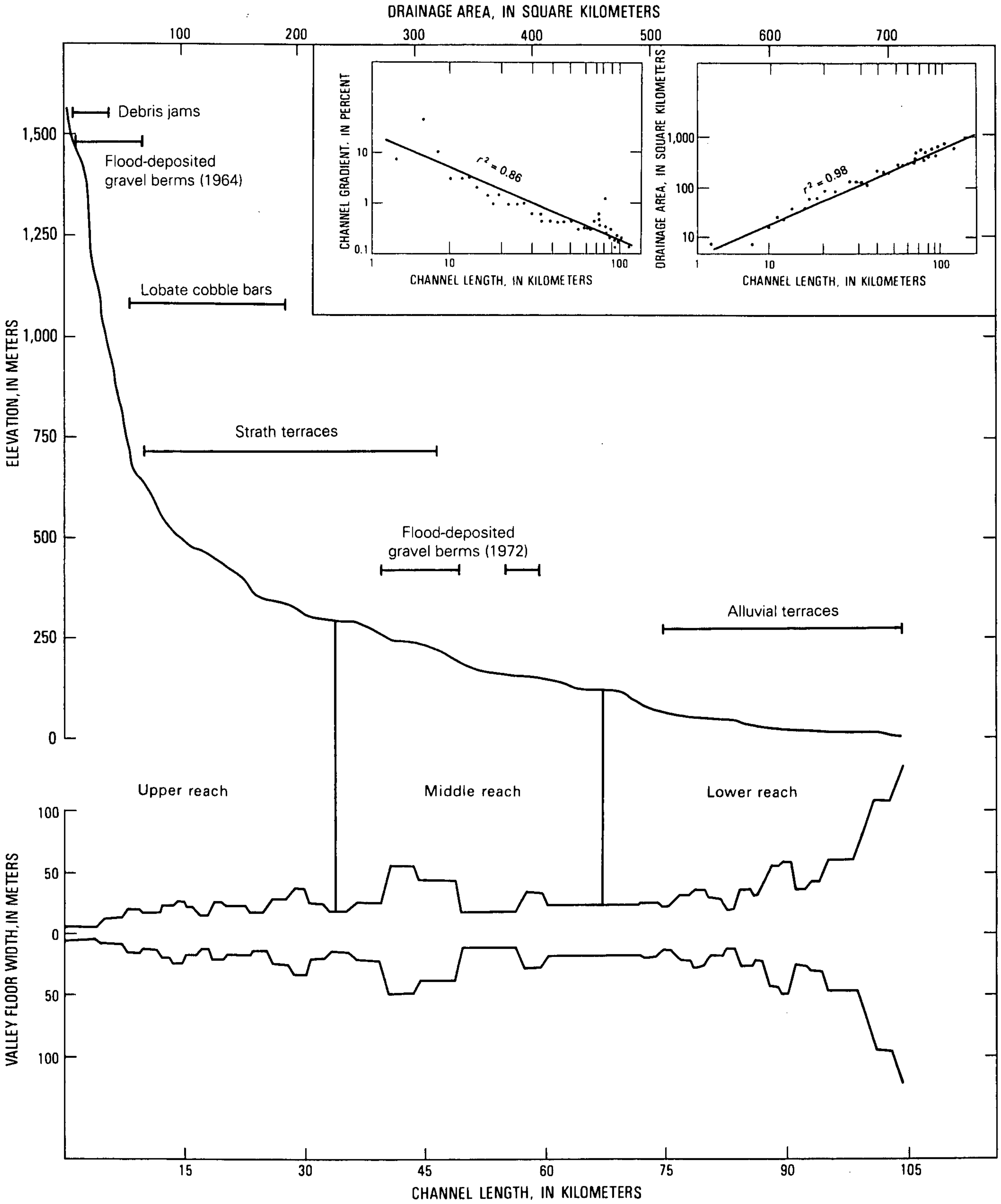

FIGURE 14.—Longitudinal profile of Redwood Creek showing distribution of localized features along certain reaches of the creek. Valley widths for Redwood Creek are drawn on the channel gradient and same horizontal scale as the profile. Strong relationships exist between channel length and between drainage area and channel length ($r^2=0.86$ and 0.98, respectively).

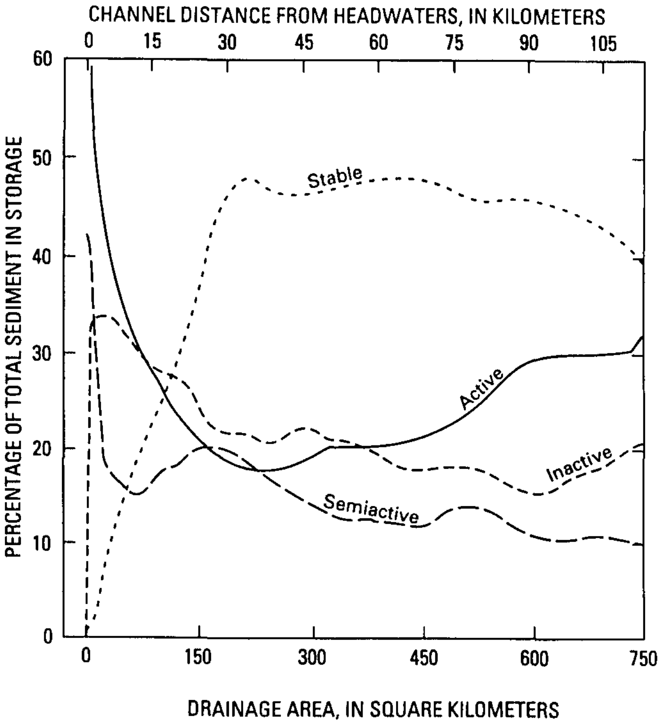

FIGURE 15.—Plot of distribution of sediments of different relative mobility (sediment reservoirs) versus drainage area, Redwood Creek basin.

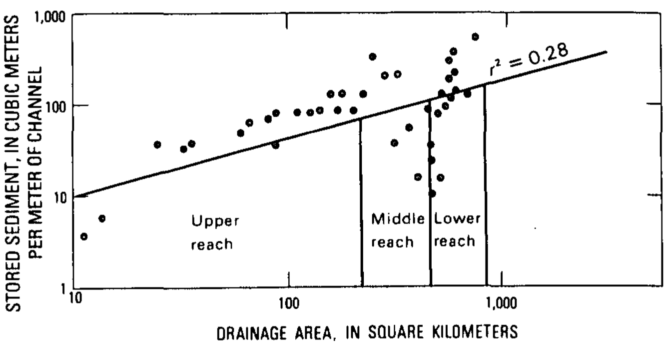

FIGURE 16.—Logarithmic plot of volume of stored sediment per unit distance (V_s) versus drainage area.

upstream reaches but rather that a higher percentage of sediment 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 reaches.

The percentage of semiactive sediment (fig. 15) generally decreases downstream, as does the percentage for inactive sediment. Inactive sediment increases in relative importance near the mouth of Redwood Creek where large areas of alluvial deposits occur.

Stable alluvial sediment is rare in steep headwater channels and becomes most important downstream of kilometer 30 (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 feature from kilometer 30 to the mouth. More than a third of all sediment in Redwood Creek is stable, and this stable sediment is a major component of alluvial storage for most of the drainage length.

CONTROLS ON SEDIMENT DISTRIBUTION

Stored sediment is not distributed uniformly along a channel; some reaches store more than others. This study identifies the factors controlling sediment distribution in stream reaches having different 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 (table 4). Because study reaches are not of equal length, sediment storage volumes in different reaches were compared on the basis of the index "cubic meters of sediment per meter of channel" (V_s). All correlations used in the following analysis are significant at the 95-percent 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 (fig. 16). 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 at a drainage area of about 475 km^2 (the gorge). The third degree polynomial $V_s=-3{,}992+227\ A-0.084\ A^2+0.0009\ A^3$ ($r^2=0.58$) describes the data better than a simple power function, but 42 percent of the variation in stored sediment is still left "unexplained" by that approach. Storage volume must be controlled by factors other than drainage area along much of Redwood Creek (table 4).

Large amounts of the sediment stored in Redwood Creek have come from landslides triggered during the 1964 storm. Kelsey and others (chap. J, this volume) describe sediment discharge by landslides into the main stem of Redwood Creek for the periods 1954 to 1966 and 1966 to 1980. In general, most pre-1966 landslides occurred during the 1964 storm. Total landslide input to the main stem of the Redwood Creek is the sum of main stem landslides and the estimated input from tributary landslides that reached the main stem. Figure 17 shows the cumulative volumes of total landslide input to the main stem (5.25×10^6 m^3; chap. J, this volume, table 1) and the deposition in Redwood Creek (4.74×10^6 m^3) resulting from the 1964 flood. Thus, the sediment that remained in the valley was 90 percent of the volume of

TABLE 4.—*Data for the 39 study reaches on Redwood Creek*

[Study reaches are shown in figure 1]

Study reach	Drainage area (km^2)	Channel length (km)	Stored sediment in study reach (1947) (m^3)	Stored sediment in study reach (1964) (m^3)	Stored sediment in study reach (1980) (m^3)	Valley width (m)	Channel gradient (percent)	Boundary sheer stress (dyn/cm^2)	Pre-1966 landslide volumes (m^3)
39	11	4.90	2,400	23,500	23,500	15.2	9.10	2,730	0
38	14	3.45	6,500	45,300	25,500	17.7	12.20	9,100	93,700
37	25	2.20	29,200	319,300	96,000	36.6	4.00	2,635	254,200
36	35	1.10	35,200	124,500	54,600	31.4	3.30	2,970	76,300
35	37	1.60	24,600	74,300	54,000	30.5	3.00	2,682	198,700
34	63	1.40	54,900	205,000	84,300	42.7	1.90	1,724	184,200
33	66	2.05	89,500	218,800	157,000	51.2	1.25	1,054	205,300
32	86	1.65	110,200	179,000	148,500	39.3	1.20	1,245	136,900
31	89	1.80	59,400	98,800	81,200	27.7	1.24	1,341	113,300
30	109	1.50	87,100	212,300	148,200	57.0	1.20	910	385,100
29	122	3.60	220,100	332,100	300,000	51.2	1.20	1,054	223,100
28	145	2.35	139,300	211,100	203,300	36.3	.90	1,293	70,100
27	159	3.00	355,100	457,000	407,900	51.2	.80	766	85,300
26	169	2.80	212,700	320,500	295,400	76.8	.60	527	277,100
25	176	2.35	268,500	325,800	302,300	45.7	.50	575	43,700
24	200	3.40	275,400	440,700	381,900	40.5	.50	445	41,800
23	216	4.45	398,500	626,300	604,500	48.8	.45	484	72,000
22	261	2.85	1,075,300	1,352,700	1,327,900	104.9	.44	460	325,100
21	292	5.95	1,303,700	1,670,000	1,577,300	85.3	.38	398	48,300
20	314	7.50	253,500	347,445	327,700	33.2	.35	364	31,200
19	319	2.80	614,700	682,000	724,600	61.0	.35	733	6,900
18	372	6.15	222,700	330,700	326,000	39.6	.30	718	696,000
17	410	3.65	22,100	69,400	65,100	42.7	.27	445	235,600
16	433	1.80	19,600	70,600	51,200	52.7	.48	656	213,000
15	454	1.10	7,000	16,000	10,700	39.6	.40	599	271,000
14	458	1.60	27,500	67,200	67,200	57.9	.32	671	42,400
13	468	1.75	170,000	185,500	178,600	76.2	.66	1,183	157,100
12	475	1.30	63,500	117,600	137,800	54.9	.31	833	56,600
11	479	1.65	20,000	20,300	21,000	33.5	1.40	3,760	181,300
10	485	1.50	166,500	255,500	286,400	76.2	.30	625	68,400
9	520	2.65	100,500	164,600	267,000	62.5	.26	625	162,300
8	531	1.80	376,800	475,800	605,000	106.7	.26	390	22,800
7	551	2.05	517,800	606,500	739,200	115.8	.23	412	61,700
6	562	2.10	142,200	211,700	280,000	65.5	.23	412	52,900
5	573	2.55	300,400	389,600	473,100	82.3	.20	390	58,500
4	584	2.95	610,000	713,200	829,800	111.3	.17	305	49,300
3	593	1.40	308,300	362,400	427,700	111.3	.14	290	25,200
2	719	5.70	2,426,900	3,198,700	3,483,200	213.4	.18	430	18,600
1	729	3.60	125,200	448,600	551,300	140.2	.12	290	0

sediment influx from landslides to the main stem. Kelsey (1977) showed that, in the nearby Van Duzen River drainage area (A=1,115 km^2) for the same time period, landslide input was 8.54×10^6 m^3, and the increase in valley storage was 64 percent 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 the sediment volume from these sources has not yet been quantified for Redwood Creek.

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

If the three general reaches of Redwood Creek are considered, a pattern of sediment input from landslides and deposition emerges (table 5). The areas with the highest landslide input showed the highest 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

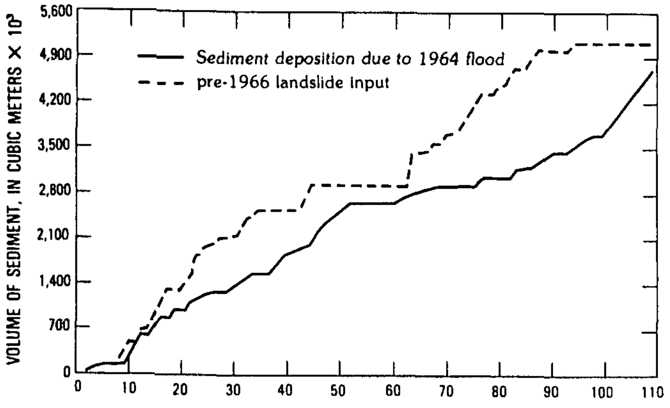

FIGURE 17.—Cumulative volumes of total landslide input to the main stem of Redwood Creek and the deposition in Redwood Creek resulting from the December 1964 flood. Landslide data are from Kelsey and others (chap. J, this volume, table 1).

TABLE 5.—*Comparison of landslide input and changes in channel-stored sediment due to the 1964 flood in the upper, middle, and lower reaches of Redwood Creek*

Reach	Reach length (km)	Landslide input[1] 1954–66 (m^3/km of channel)	Increase in stored sediment in 1964 (m^3/km of channel)	Increase in stored sediment 1947–64 (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

[1] Derived from Kelsey and others (chap. J, this volume, fig. 9).

channel and valley characteristics in a reach, rather than sediment input at a point, control where deposition occurs.

An important reach characteristic related to the storage and transport of sediment is channel gradient. Other studies (chap. K, this volume) have shown that deposition is generally confined to low-gradient reaches. In Redwood Creek, the amount of channel-stored sediment per unit channel length (V_s) in 1980 increased with decreasing channel gradient (S) (fig. 19). Channel gradient decreases with an increase in drainage area ($S=87A^{-0.9}$; $r^2=0.89$). Nevertheless, a comparison of figure 16 and figure 19 shows that, in Redwood Creek, V_s correlates better with channel gradient than with drainage area ($r^2=0.42$ 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 reaches (reaches 11 and 38).

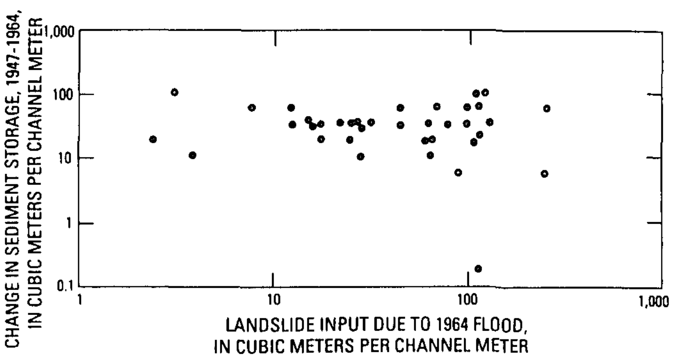

FIGURE 18.—Logarithmic plot of changes in stored sediment in Redwood Creek (due to the 1964 flood) versus input due to the same flood. No line was drawn because the regression analysis showed no relationship ($r^2=0.02$).

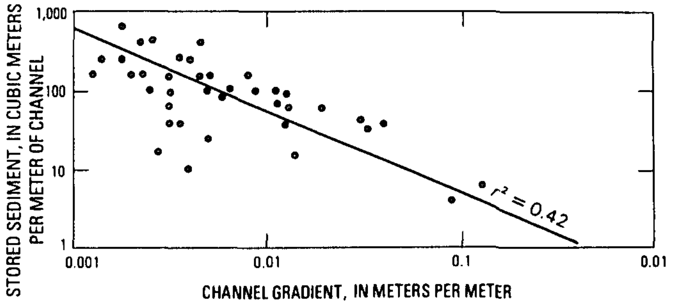

FIGURE 19.—Logarithmic plot of volume of stored sediment per unit channel length (V_s) versus channel gradient.

Deposition may also be related to the amount of tractive force available to move sediment on the streambed. In river channels, the average total tractive 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. This assumes that water surface slope is close to bed gradient S on the average over long reaches. Resistance to flow is generated by bank curvature and irregularities, bed topographic features such as bars, and stationary and moving sediment. If it is assumed that stationary roughness or resistance features of the channel changed little along Redwood Creek, then as τ_b decreases, less tractive force is available to move sediment, and deposition will tend to occur.

For reaches in Redwood Creek, τ_b was defined for bankfull discharge as determined from 1980 channel surveys. The relationship of V_s to τ_b is described by $V_s=4.5\times10^6\ \tau_b^{-0.94}$, for which $r^2=0.44$ (fig. 20). The fact that the relation is not stronger may be because much of

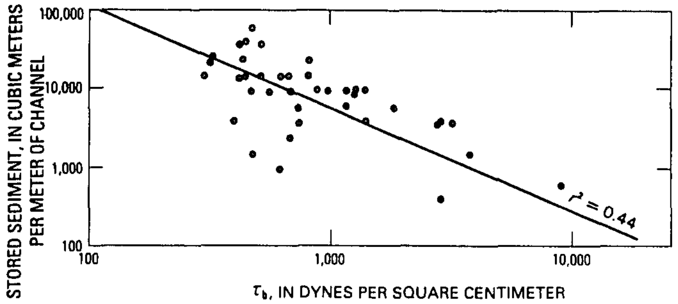

FIGURE 20.—Logarithmic plot of volume of stored sediment per unit distance (V_s) versus the boundary shear stress (τ_b) calculated for Redwood Creek at bankfull discharge.

the deposition of V_s occurred during different hydraulic geometry and flow conditions (and thus different τ_b conditions) than were present in 1980. Few data are available for determining accurate values of τ_b during the 1964 flood. Also, the assumption that resistance changes little along Redwood Creek may not be valid.

Of the parameters tried, V_s correlates best ($r^2=0.72$) with valley width (fig. 21). Valley width was defined as the average width in a study reach that was inundated by the 1964 flood, and valley widths are shown schematically in figure 14. V_s is highest in areas of large valley widths. In the Redwood Creek basin, geologic structure and bedrock influence valley width. Climate, tectonics, and general landscape evolution may affect 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, semiactive, and inactive sediment) should occur in the same reaches that ancient deposition (stable sediment) occurred. This is indeed the case, as is shown in figure 22.

Thus sediment deposition in a reach is most strongly controlled by valley width. 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 be predicted by considering sites of past deposition—that is, reaches with large valley widths and gentle stream gradients.

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. To do this, the volume of sediment in various reservoirs must be known, as must 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, semiactive, inactive, and stable) by dividing the volume of sediment per meter of channel length (V_s) by the bedload discharge rate (Q_B). Following the approach of Dietrich and Dunne (1978), the volumes of sediment and bedload discharge were defined as power functions of drainage area A: $V_s=aA^m$ and $Q_b=bA^n$ (table 6). Drainage area is defined as a function of channel length (X): $A=cX^p$. Then the residence time per meter of channel length, $\frac{dt}{dX}$, is:

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

A more complete discussion of this equation is given by Dietrich and Dunne (1978). Dietrich and others (1982)

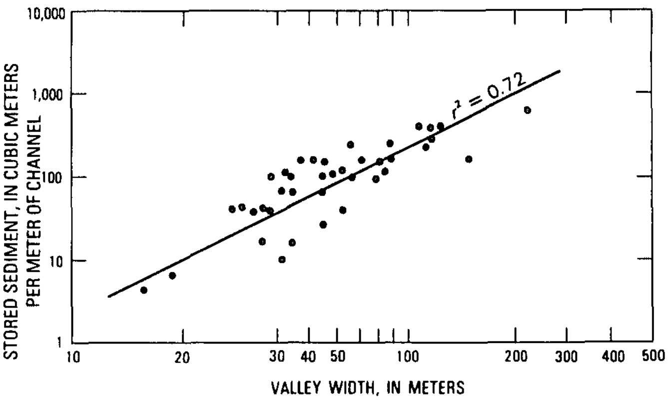

FIGURE 21.—Logarithmic plot of volume of stored sediment per unit channel length (V_s) versus valley width in a study reach.

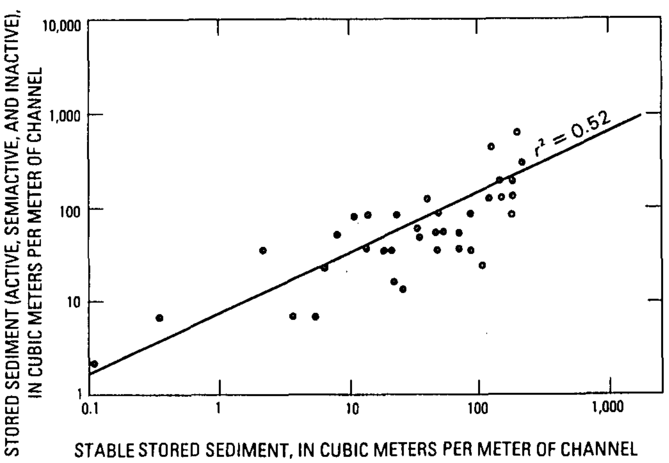

FIGURE 22.—Logarithmic plot of volume of active, semiactive, and inactive sediment per unit channel length (V_s) versus volume of stable stored sediment per unit channel length for study reaches in Redwood Creek.

TABLE 6.—*Definition of power functions for the four types of sediment reservoirs in Redwood Creek*

[Sediment reservoirs: A, active; Sa, semiactive; Ia, inactive; S, stable. See p. XX for explanation of symbols used]

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	.98
A sediment	$V_s=aA^m$	0.64			0.70			.49
A+Sa sediment	$V_s=aA^m$	1.29			.65			.47
A+Sa+Ia sediment	$V_s=aA^m$	.79			1.05			.45
A+Sa+Ia+S sediment	$V_s=aA^m$	.04			2.20			.45

have subsequently shown that this estimation of residence time is not dependent on the actual process of sediment transport through a given reservoir. A modified approach to this model is presented by Kelsey and others (1987).

The relations among drainage area, channel length, and volume of sediment 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) used in table 6 is based on bedload measurements made for 8 to 10 years at three gaging stations on Redwood Creek and for 3 years on three tributaries draining three types of terrain typical of the Redwood Creek basin:

Gaging station	Drainage area (km²)	Bedload as percent of total load	Bedload transport rate (Mg/yr)
	Main stem		
Blue Lake	175	20	93,500
South Park Boundary	474	16	193,000
Orick	720	11	173,000
	Tributaries		
Lacks Creek	44	35	11,000
Coyote Creek	20	23	15,000
Panther Creek	16	19	2,100

The relation defined by figure 23 is good (r^2=0.88) and is used in table 6; however, because the bedload data are based on different lengths of record, the relation may need to be modified slightly as more hydrologic data become available.

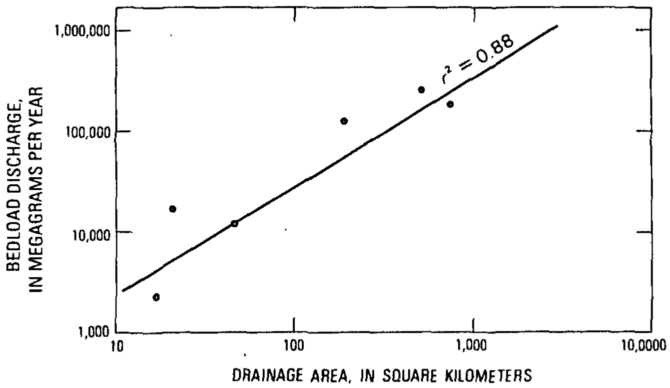

FIGURE 23.—Logarithmic plot of annual bedload discharge versus drainage area computed for six gaging stations on Redwood Creek.

Four separate power functions were computed to define the relations of the four types of sediment reservoirs to drainage area. As discussed previously, several factors contribute to considerable variance in the downstream increase of sediment in storage. To use a simple power function relation between sediment in storage and channel length, anomalously low values for reaches near kilometer 80 (the gorge) were omitted, and a least-squares regression through the remaining data was computed. The four power functions used for the four sediment reservoirs are listed in table 6. For active sediment, this relation is $V_s=0.64\ A^{0.70}$, for which r^2=0.49. When sediment in the active reservoir is mobilized, it moves down the channel through the active reservoir, and residence time is V_s/Q_B, as stated earlier. However, when sediment in the semiactive reservoir is mobilized, sediment moves into the active reservoir. Because the sediment moves down the channel through both semiactive and active reservoirs, the residence time is [V_s (active)+V_s (semiactive)]/Q_B. When sediment in the stable reservoir is mobilized, sediment is transported through all four reservoirs. In defining the "stable" power function, the stable sediment near the mouth that is now protected by flood levees was included because this sediment is 79 percent of the total amount of stable sediment in the basin. Integrating equation 2 between two points (x_1 and x_2) in a reservoir gives the residence time (t_2-t_1) through that section of the reservoir (Dietrich and Dunne, 1978):

$$\int_{t_1}^{t_2} dt=\int_{x_1}^{x_2} \frac{a}{b}\, c^{(m-n)}X^{(m-n)p}dX \qquad (3)$$

$$t_2-t_1=\frac{\frac{a}{b}\, c^{(m-n)}}{1+(m-n)p}\, X^{(1+(m-n)p)} \Big|_{x_1}^{x_2} \qquad (4)$$

By using this approach, residence times for active, semiactive, inactive, and stable sediment in the upper, middle, and lower reaches of Redwood Creek were computed (table 7). The three main channel reaches are approximately equal in length (35.5, 33.3, and 35.6 km,

TABLE 7.—*Residence times of sediment in storage reservoirs in the three main reaches of Redwood Creek*

[Approximate boundaries of reaches are shown in figure 1. x_1, x_2 are two points in a reservoir]

Reach	Equation for residence time	Number of years	Velocity (m/yr)
	Active		
Upper		26	1,365
Middle	$0.09\ [x_2^{\ 0.54} - x_1^{\ 0.54}]$	11	3,030
Lower		9	3,950
	Semiactive		
Upper		50	710
Middle	$0.33\ [x_2^{\ 0.48} - x_1^{\ 0.48}]$	19	1,750
Lower		15	2,370
	Inactive		
Upper		104	340
Middle	$2.63\times10^{-3}[x_2^{1.01}-x_1^{1.01}]$	99	335
Lower		106	335
	Stable		
Upper		700	50
Middle	$1.76\times10^{-9}[x_2^{2.55}-x_1^{2.55}]$	3,100	10
Lower		7,200	5

respectively). Velocity of sediment is simply defined as the length of the main channel reach in question divided by the residence time of a sediment reservoir in that reach (table 7). As expected, sediment in the active reservoir has the shortest residence time. For example, a particle entering the active channel bed at kilometer 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 residence time is of the same order of magnitude as estimated for gravel bars on Rock Creek by Dietrich and Dunne (1978). 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 adjustments (channel widening, decrease of depth) (chap. N, this volume) that would tend to increase sediment transport there. A velocity on the order of 3,000 to 4,000 m/yr, as predicted for active sediment in the middle and lower reaches, is much higher than the 234 m/yr reported by Milhous (1973) for Oak Creek and much higher than the estimated velocities in Rock Creek (Dietrich and Dunne, 1978), both of which are small streams transporting considerably less bedload than Redwood Creek. This rate is also supported independently by an analysis of changes detected through cross-section surveys.

Residence times for semiactive sediment, as with active sediment, decrease downstream. Semiactive sediment moves more slowly than active sediment in the upper reach, but the difference is negligible in the downstream reach. The velocities of both active and semiactive sediment are within the same order of magnitude. Scour and fill data indicate frequent erosion of semiactive sediment in the downstream reach. Because most sediment transport in north coast streams occurs at relatively high discharges (Ritter, 1968), at which both active and semiactive sediment are mobilized, the similarity in residence times is not unexpected.

The residence time for inactive sediment is an order of magnitude longer than for active or semiactive sediment. Residence times are approximately constant throughout the length of the channel. In the upper reach, sediment in the inactive reservoir consists of high, flood-deposited gravel berms in a narrow valley. Downstream, flood deposits are found on a wider flood plain removed from the inactive reservoir. This situation indicates that some effects of a large depositional event such as the 1964 flood will persist on the order of a century.

Stable sediment has the longest residence time—an order of magnitude greater than for 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 800 years old, and some of them may have sprouted from even older trees. The long residence times of inactive and stable sediment probably allow 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 to 20 years. The transport relationship defined in table 6 is probably accurate for discharges up to the 20-year peak flow. The above discussion of residence times, however, assumes that the volume of sediment in each reservoir and the bedload transport rates remain constant through time. Because Redwood Creek is not in a state of equilibrium, 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.

IMPLICATIONS FOR CHANNEL RECOVERY FROM MAJOR STORMS

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 present channel-forming discharge. Wolman and Gerson cited examples of rivers in temperate regions that regained their original width in a matter of months or years after the occurrence of channel-widening floods that had recurrence intervals 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 having 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 probably 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, recovery is lacking because a threshold of competence has not been exceeded (Wolman and Gerson, 1978). In Redwood Creek, however, particle sizes of stored sediment can be transported at 5- to 20-year peak discharges if they are located near the thalweg. Nonrecovery in Redwood Creek results from the inability of moderate flows to erode the vast amounts of "excess" sediment deposited throughout the valley width.

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 features (flat-topped gravel berms and an aggraded channel bed) were created. This stored sediment was responsible for exceptionally high bedload transport rates after the 1964 flood. Sediment input to a reach is related in a general way to increases in stored sediment, but characteristics of a specific reach control the local distribution of stored sediment. The volume of stored sediment is greatest in reaches having large valley widths and gentle channel gradients. The net amount of sediment stored in Redwood Creek in 1964 had decreased by 1980. Much of the active sediment originally stored in the upper basin had been transported and redeposited in lower reaches. Unless sediment input to Redwood Creek from hillslope processes increases in the future, the volume of stored sediment will slowly decrease through time. The residence time of deposits differs according to storage reservoirs. Residence times of sediment in active and semiactive reservoirs are on the order of a few decades; of sediment in inactive reservoirs, a hundred years. The residence time for sediment in stable reservoirs is thousands of years. These data indicate that recovery of the entire system from a major aggradational event is extremely slow. 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 residence time of sediment deposits.

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Long-Term Effects of Clearcutting and Short-Term Impacts of Storms on Inorganic Nitrogen Uptake and Regeneration in a Small Stream at Summer Base Flow

By FRANK J. TRISKA, VANCE C. KENNEDY, RONALD J. AVANZINO, *and* KENT C. STANLEY

GEOMORPHIC PROCESSES AND AQUATIC HABITAT IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

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By FRANK J. TRISKA, VANCE C. KENNEDY, RONALD J. AVANZINO, and KENT C. STANLEY

ABSTRACT

Uptake and regeneration of dissolved inorganic nitrogen (DIN) in forest streams are controlled by factors operating on time scales of less than 1 day to greater than 80 years. Flux of inorganic nitrogen, primarily nitrate, was estimated in Little Lost Man Creek, Humboldt County, Calif., between 1974 and 1982 and in experimental channels during 1979. Studies were conducted during low flow (May–November) over an approximately 1,500-m reach of the stream flowing through an area clearcut in 1965. The study period coincided with the development of a riparian canopy, dominated by alder (*Alnus rubra*), a nitrogen-fixing species.

Studies in experimental channels indicated a large diel fluctuation in DIN concentration. Nitrate uptake rates decreased as the community aged. Uptake rates varied with canopy cover. Experimental short-term nitrate enrichment of the stream (200 μg/L NO_3-N) in 1975 (open canopy) and 1979 (closed canopy) confirmed reduced uptake under closed canopy conditions.

Background DIN chemistry surveyed weekly to biweekly during 1974 (prior to canopy closure) indicated a maximum uptake of 77 percent available nitrate (NO_3-N) at summer base flow. In 1976 maximum uptake was 87 percent of available NO_3-N under a similar sampling regime. Nitrate concentration at the upstream station (1975) was highest at night (18 μg/L NO_3-N) and lowest at midafternoon (8 μg/L NO_3-N). Nitrate concentrations downstream simultaneously ranged from 5 to 8 μg/L NO_3-N, indicating uptake within the reach. Four years later after canopy closure (1979), a diel study indicated regeneration (6–10 μg/L NO_3-N) rather than uptake in a 265-m section of the same reach. Regeneration was confirmed in June–November 1982.

Laboratory studies of stream sediments using an inhibitor of nitrite oxidation (sodium chlorate) indicated a potential for nitrate regeneration. Nitrate regeneration (measured by difference in upstream-downstream nitrate concentration) was also observed in a 92-percent-shaded experimental channel when the epilithon was senescent.

Development of the alder riparian zone is of long-term importance in nitrogen cycling of Little Lost Man Creek. We hypothesize gradual decline of instream production related to reduced synthesis of protein from inorganic nitrogen thus reducing passage of nitrogen to higher trophic levels. Biotic production will remain low until the canopy is reopened by natural mortality of riparian trees.

INTRODUCTION

Of the major dissolved elements in fluvial environments, nitrogen is especially valuable for studying biotic impacts on element transport. Nitrogen is useful as an indicator because most nitrogen chemistry is biologically mediated in nature, and nitrogen is rare in the mineral structure of sediments. In mountain streams, the biotic interface with solute chemistry is primarily associated with communities attached to benthic surfaces (epilithon). High gradients and current velocity, however, often prevent planktonic water-column communities from having a major impact on nutrient cycling. The instantaneous pool of dissolved elements in the surface water of a reach is usually insignificant; rather, the timing of nitrogen input determines the magnitude of potential chemical-biological interactions.

A myriad of factors, operating on different time scales, determines nitrogen uptake and transport properties of a stream under pristine conditions (table 1). Daylight uptake by photosynthetic algae can produce a diel fluctuation in nitrogen concentration during low flow. Small storms can reset the benthic community during the growing season by partially scouring sediment surfaces. Scouring is often followed by vigorous growth and rapid nitrogen uptake. Seasonal light and temperature fluctuations, due to such factors as spring leafout, bed stability, and fluctuations in discharge, introduce variability within a reach. Finally, canopy development in the riparian zone can control solar input to a reach (and thus uptake by photoautotrophs) for extended periods (Swanson and others, 1982).

This paper examines uptake and transport of dissolved inorganic nitrogen (DIN) from a variety of time perspectives. Biotic control of nitrate transport between storm-induced resets is examined daily and seasonally with

TABLE 1.—*Biological and physical factors that influence nitrate uptake on a stream reach over specified time scales*

<24 hours	1 to 30 days	30 days to 1 year	1 year to <100 years
Increase uptake (decrease transport)			
Diel photoperiod (daylight hours).	Epilithon in early successional stage (active growth).	Seasonal increase in daylight hours (spring-summer).	Canopy opening due to natural or storm-induced mortality.
Small storms that cause slight scour and elevate nitrogen concentration.	Moderate consumption of epilithon by grazing invertebrates.	Seasonal increase in temperature.	
Existing high bed roughness and porosity.		Seasonal discharge pattern: low base flow, high bed contact, high bed stability.	
Decrease uptake (increase transport)			
Diel photoperiod (hours of dark).	Epilithon in late successional stage (senescence).	Seasonal decrease in daylight hours (autumn, winter).	Canopy closure due to development of riparian vegetation.
	Extremely low or high consumption of epilithon by grazing invertebrates.	Seasonal decrease in temperature.	
	Major storms that cause high scour and high discharge.	Seasonal discharge pattern: high base flow, low bed contact, high bed disturbance.	
		Spring leafout of riparian canopy.	

respect to growth, maturity, and senescence of epilithon during summer low flow. The influence of canopy cover is examined in flumes in which shading, discharge, nutrient concentration, and channel geometry can be controlled. Observations from these controlled experiments are used to interpret long-term field variations in dissolved nitrogen (1974–82) during development of a riparian canopy.

STUDY SITE

The study was conducted at Little Lost Man Creek, a third-order pool-and-riffle stream located in Humboldt County in northwestern California (fig. 1). The site is approximately 5 km east of the Pacific Ocean. Soils on the watershed, derived from the rocks of the Franciscan assemblage (Bailey and others, 1964), are unstable, and numerous dormant landslides have been reported along the banks (Iwatsubo and others, 1975). The watershed is 9.4 km^2 and ranges in altitude from 24 to 695 m (387 m mean altitude). The channel gradient if 66 m/km (Iwatsubo and others, 1975; Iwatsubo and Averett, 1981). The area is characterized by cool, wet winters and warm, dry summers. Approximately 92 percent of the vegetation is old-growth, coastal redwood forest (*Sequoia sempervirens*) including associated Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga hetrophylla*). Between 1962 and 1965, and prior to incorporation into Redwood National Park, 8 percent of the watershed was clearcut at two sites. Following clearcutting, alder (*Alnus rubra*), a nitrogen-fixing species, has dominated the riparian vegetation.

Summer streamwater temperature typically varies between 14 and 20 °C. Summer background dissolved inorganic nitrogen and orthophosphate concentrations, which were determined colorimetrically with a Technicon II AutoAnalyzer, were approximately 20 to 40 μg N/L and 10 μg P/L. Summer and early autumn storms can increase DIN concentration to 150 to 175 μg N/L and orthophosphate concentration to 25 μg PO_4-P/L (Kennedy and Malcolm, 1977).

The summer epilithon community is dominated by diatoms including *Achnanthes lanceolata*, *Diatoma vulgare*, *Gomphonema angustatum*, and *Melosira varians*. (For a more complete species list, see Iwatsubo and others, 1976.) A full range of invertebrate functional groups (Cummins, 1973; Merritt and Cummins, 1978) is represented in the benthos with a predominance of collector organisms (Iwatsubo and Averett, 1981). Common fishes include steelhead trout (*Salmo gairdneri gairdneri*), coho salmon (*Oncorhynchus kisutch*), threespine stickelback (*Gasterosteus aculeatus*), and the coast-range sculpin (*Cottus aleuticus*) (Iwatsubo and Averett, 1981).

MATERIALS AND METHODS

FLUME STUDIES: SHORT-TERM NITROGEN UPTAKE AND REGENERATION

Determinations of short-term inorganic nitrogen uptake and regeneration were made in one set of six clear acrylic plastic channels, or flumes, between August 17 and September 20, 1979 (fig. 2; baseline water chemistry and channel characteristics are listed in tables 2 and 3). A header box with separate mixing chambers and separate V-notched weirs regulated flow (10 L/min) to each channel. Water was supplied through PVC (polyvinyl

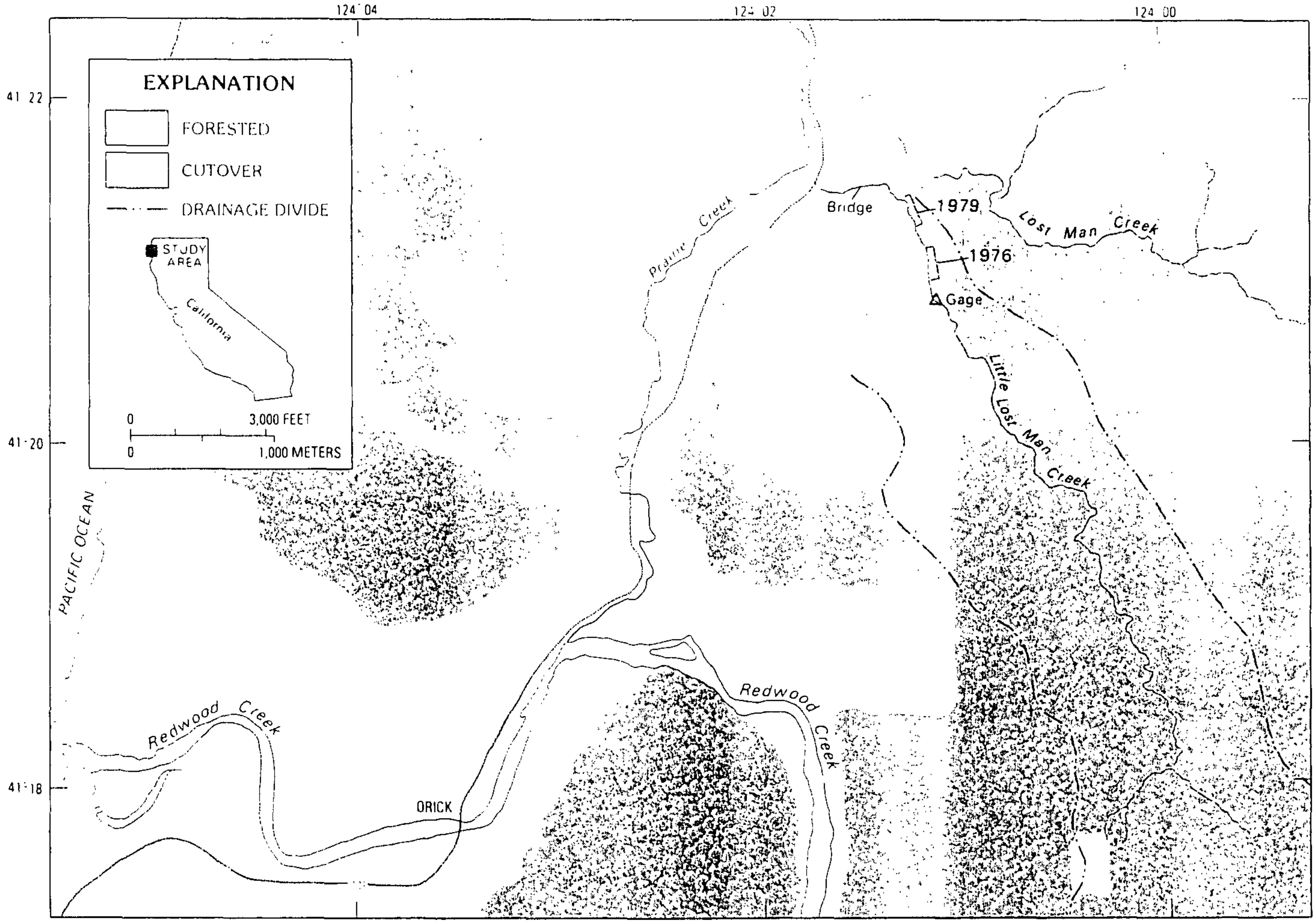


FIGURE 1.—Location of study area and sampling sites along Little Lost Man Creek. Most upstream-downstream dissolved inorganic nitrogen chemistry is compared between sites labeled "Gage" and "Bridge." Flume experiments occurred at the downstream end of the reach labeled "1979." Data from other upstream-downstream studies (1976, 1979) are labeled by year and indicate the approximate reach length. For all studies, the reach passed through an area clearcut on one bank in 1965.

chloride) pipe by gravity and passed through a 300-μm-pore-size filter. Nutrient solutions, when added, were pumped from a common source by using a separate pump for each channel. Nutrient enrichment was targeted at 100 μg/L NO_3-N and 25 μg/L PO_4-P except in the control channel. The nutrient concentrations in enriched channels were 2 to 3 times baseline concentrations (night) and typical of concentrations observed in summer and early autumn storms. Chloride was added with the nutrient solution at an accurately known flow rate and concentration. Since it is conservative with respect to biological uptake and sediment sorption, dilution of the added chloride after mixing was used as a measure of waterflow through the channel. Change in the ratio of chloride to nutrients during transport, which served as the measure of nitrogen flux, was calculated as follows:

$$\text{DIN uptake } (\mu\text{g/h}) = [N_o + (Cl_x - Cl_o \times N_T / Cl_T - N_x] \times Q$$

where:

N_o = DIN upstream concentration,
Cl_x = downstream flume concentration of chloride,
Cl_o = upstream flume concentration of chloride,
N_T = DIN concentration solute tank,
Cl_T = chloride concentration solute tank,
N_x = DIN concentration downstream, and
Q = discharge.

Discharge was determined daily from either daily injection pump rates and ΔCl or by using a calibrated bucket and stopwatch. Nutrient injection began August 24 and ended September 11, 1979.

Light input was estimated by a Licor 500 integrating light meter with a LI 190S sensor, which measured photosynthetically active radiation. Water temperature was measured by a continuous recording sensor placed in the stream.

TABLE 2.—*Channel properties and average background water chemistry (± standard deviation) in 1979 for the experimental acrylic plastic channels set in Little Lost Man Creek*

[DON=dissolved organic nitrogen; DOC=dissolved organic carbon]

Properties of the channel reach studied		Background water chemistry	
Length	9.75 m	DON	62.6±10.5 σ μg nitrogen per liter
Width	152.5 mm	NO_3	41.1±7.3 σ μg nitrogen per liter[1]
Depth	100.0 mm	NO_2	<3.0 μg nitrogen per liter
Volume	148.7 L	NH_4	<4.0 μg nitrogen per liter
Flow	9.5 L/min	PO_4	12.8±1.0 σ μg phosphorus per liter
Surface area (including slides).	12.4 m^2	DOC	1.1±.28 σ mg carbon per liter
Water surface area	1.48 m^2		
Water traveltime through reach.	15–20 min		

[1] Diel fluctuations in nitrate concentration were approximately 25 percent.

TABLE 3.—*Light and temperature data for selected sampling dates at Little Lost Man Creek*

[Light input was estimated by a Licor 500 integrating light meter with a LI 190S sensor that measures photosynthetically active radiation. Water temperature was measured by a continuous recording sensor placed in the stream]

Date (1979)	Temperature (°C)		Light [(μE/m^2)/s] 24-hour average
	Maximum	Minimum	
Aug. 24–25	16.7	15.5	468
Aug. 28–29	16.9	15.6	317
Sept. 6–7	17.2	15.6	363
Sept. 12–13	17.2	16.7	372
Sept. 18–19	15.6	14.4	294

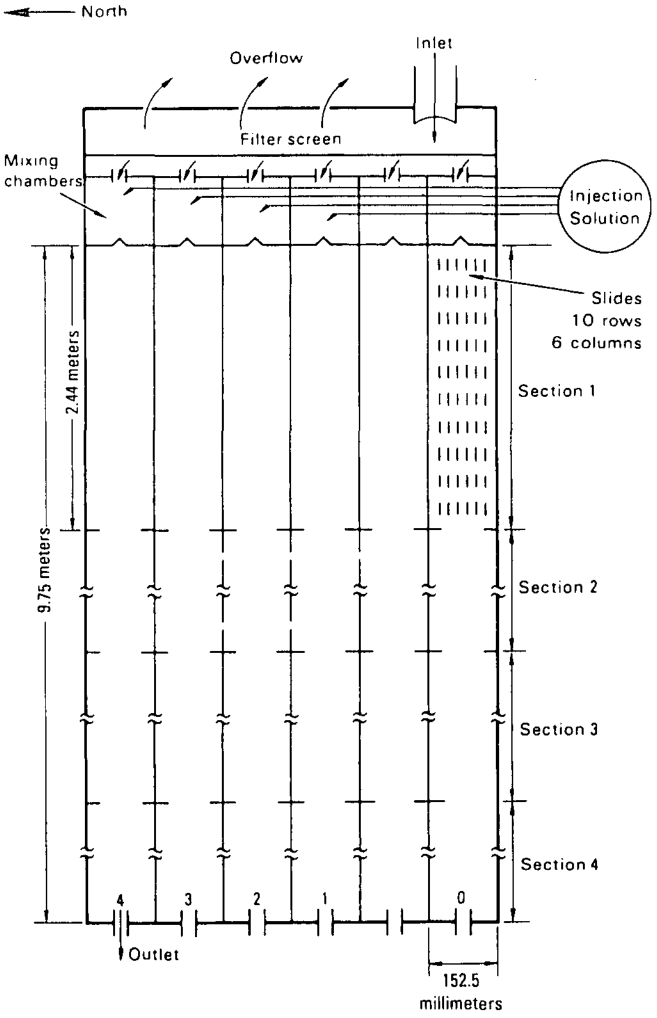


FIGURE 2.—Experimental flumes used to estimate short-term nitrogen flux by the epilithon community. Physical dimensions and arrangement of slides are illustrated.

Each experimental channel consisted of four successive longitudinal sections (fig. 2), and each section contained 10 rows of 102×152-mm clear plastic slides roughened by sandblasting and mounted perpendicular to the bottom. Each row contained six slides spaced 25 mm apart. Each channel contained 240 slides, and the total surface area of each flume was 12.4 m^2. Potential access to nutrients by epilithon was identical in each channel. Slides were placed in various streambed habitats 5 days before mounting in the channels, then acclimated 4 additional days prior to nutrient enrichment. Experimental treatments with regard to nutrient enrichment and canopy were as follows: channel 0 (control)—background nutrient, full sunlight; channel 1—nutrient amendment, full sunlight; channel 2—nutrient amendment, 30 percent shade; channel 3—nutrient amendment, 66 percent shade; channel 4—nutrient amendment, 92 percent shade. Shading was provided by woven nylon greenhouse screen of variable mesh size to produce the respective shade treatments. On each sampling date, 18 slides (6 percent of channel surface area) were randomly removed from each channel, and no location was sampled more than once. Slides were placed in individual plastic bags and returned to a field laboratory where epilithon was harvested by scraping, placed in plastic bags, and frozen. Each sample yielded four subsamples. Scraped slides were returned to the channels. A detailed description of sampling procedures is presented elsewhere (Triska and others, 1983).

At the conclusion of the experiments, chlorophyll α was determined on one sample chosen from each section of each channel on each sampling date. (Three samples were collected per channel.) Chlorophyll α was determined by extraction of algae in 90 percent acetone shaken with magnesium carbonate. Absorbance was read at 665 nm for chlorophyll α and 750 nm to correct for turbidity. Readings were made before and after acidification to correct for phaeopigments (Wetzel and Westlake, 1974). Results were extrapolated from the known surface area of the sample (slide) to the total surface area of the plastic channel.

Biomass was determined by oven drying duplicate nonextracted samples at 50 °C. Ash content was estimated by ignition at 500 °C for 4 hours. From the amount of ash from the acetone-extracted sample and known percent ash from the unextracted samples, biomass was estimated for the acetone-extracted sample. Epilithon transported from the flume or deposited on the bottom was not included. The carbon:nitrogen ratio of epilithon was determined on a Carlo-Erba CHN analyzer at the laboratory of Dr. Wayne Minshall, Idaho State University.

Water was sampled five times daily for background concentrations of NO_3+NO_2, NH_4, PO_4, and Cl and for nutrient concentrations at the outlet of each flume. Samples were collected before sunrise (approximately 6:00 a.m.) and at 10:00 a.m. and 2:00, 6:00, and 10:00 p.m. After collection, samples were filtered (0.45 μm) at streamside. Samples for nitrogen and phosphorus were frozen (−20 °C) until the day of analysis, and samples for chloride were refrigerated. Analyses were made on a Technicon AutoAnalyzer II with a precision for NO_3-N+NO_2-N and NO_2-N of ±1 μg/L below 100 μg/L and ±1 percent above (Technicon Industrial Method no. 158–71W, December 1972). Analytical precision for orthophosphate was ±1 μg/L (Technicon Industrial Method no. 155–71W, January 1973). Analytical precision for chloride was ±1 percent at 5 mg/L and above (Technicon Industrial Method no. 99–70W/B, revised February 1976; O'Brien, 1962). Water samples frozen for extended periods did not show significant loss of nutrients compared to samples analyzed immediately. Nitrite and ammonium were always at or below the limits of detection; thus nitrate and DIN are essentially synonymous.

FIELD STUDIES: LONG-TERM NITROGEN UPTAKE AND REGENERATION

Field studies consisted of both daily and weekly to biweekly surveys of DIN. Samples were taken at midafternoon. When water was sampled more than once the same day, the samples collected closest to 2:00 p.m. were used for comparison. Weekly to biweekly surveys were made at low flow in 1974, 1976, and 1982. Water samples were taken at two sites: Gage, at a gaging station, and Bridge, downstream near the base of the clearcut. Diel fluctuations in chemical constituents were measured in 1975, 1979, and 1982. Diel sampling was conducted at Gage and Bridge and at two subreaches within the clearcut area (designated "1976" and "1979" in fig. 1).

Nitrification potential was estimated from bankside sediments collected at two sites in the clearcut area and at one site in the old-growth forest. Following the method of Belser and Mays (1980), sodium chlorate (10 m*M* final concentration) was added to shaken slurries of stream sediments (20 g fresh weight). Slurries were incubated at room temperature (23 °C) for 48 h. Chlorate inhibits enzymatic oxidation of nitrite to nitrate. Nitrification was estimated by comparing accumulations of nitrite in treated sediment slurries to untreated controls. Organic carbon content of sediments was determined on a Leco carbon analyzer by subtraction of inorganic carbon from total carbon.

RESULTS AND DISCUSSION

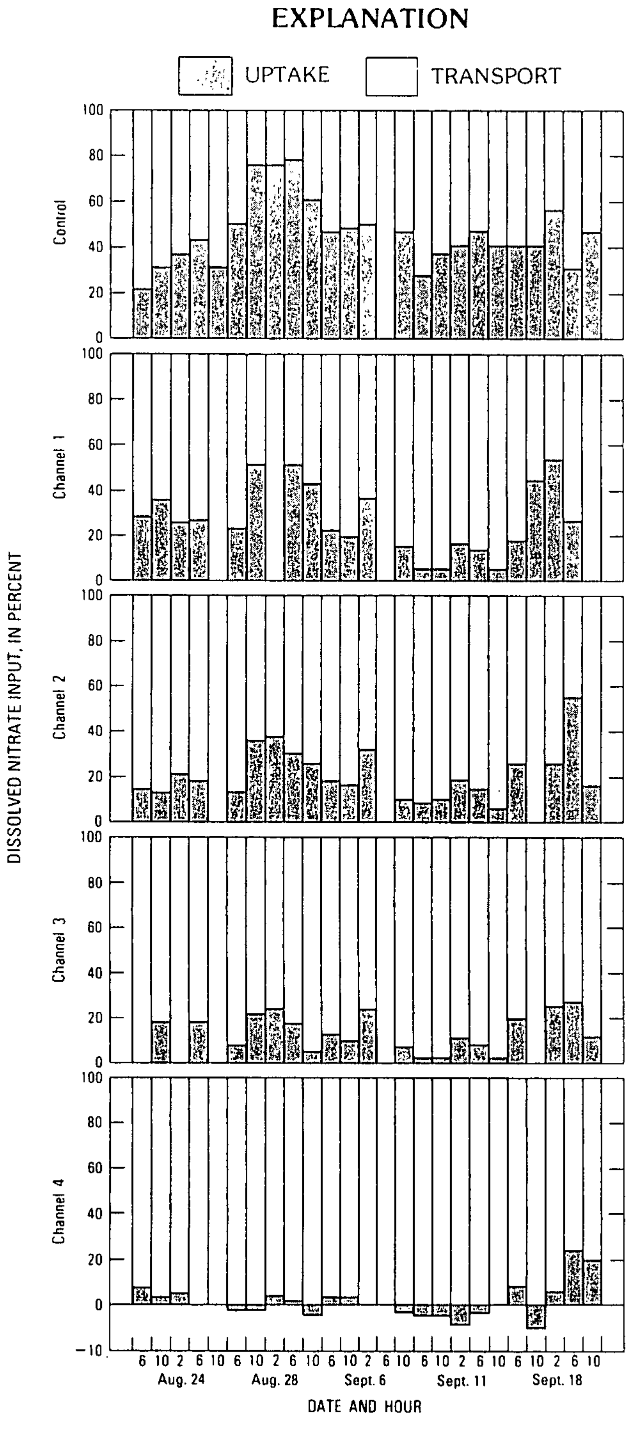
FLUME STUDIES: SHORT-TERM NITROGEN UPTAKE AND REGENERATION

Light and temperatures were regulated by climate, geomorphology, and vegetation of the watershed. Little Lost Man Creek flows through a long narrow valley that has steep slopes that reduce light intensity part of the day. Incident radiation input on sampling days varied from 294 to 468 $(\mu E/m^2)/s$ (table 3). Between August 28 and September 12, day length (light input) to the flumes was decreased by morning fog. Fog also helped to moderate temperature. The diel variation in water temperature was about 2 °C. Temperature throughout the experiment ranged between 14.4 and 17.2 °C.

Nitrate uptake, the difference between input and output (transport) concentrations in the channels, varied (fig. 3). Uptake was greatest in midafternoon and least after dark. The magnitude of fluctuation depended on nutrient concentration, shading, and the maturity of the biological community.

Nitrate uptake rates in the control channel and in channel 1 were similar prior to nutrient addition (fig. 4; 6:00 and 10:00 a.m., August 24). Once injection of nutrients began, nitrate uptake immediately increased in channel 1 (fig. 4; 2:00 p.m. and 6:00 p.m. samples, August 24). High rates of uptake continued through August 28, as the community grew rapidly. In the control channel, nitrogen uptake increased by 5 to 10 mg/h during daylight hours through August 28 but by an additional 20 to 30 mg/h in channel 1 as a result of nutrient amendment. Differences between the channels decreased as the community matured (September 11). On September 19, 1 week after the end of nutrient amendment, diel uptake patterns were similar in both channels.

Nitrogen uptake in the nutrient-amended channels was also controlled by shading (figs. 3, 5). Over the full experiment, algal uptake on an areal basis was linearly related (r^2=0.95) to shading in the nutrient-amended



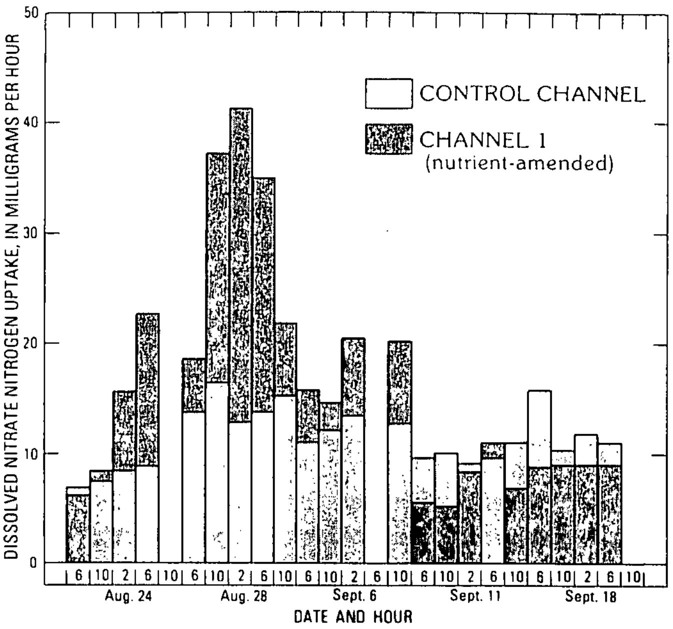


FIGURE 4.—Nitrate uptake in two channels exposed to full sunlight. The control channel had background nutrient concentrations, while nitrate and phosphate were added to channel 1.

◀ FIGURE 3.—Diel uptake versus transport as a percent of instantaneously available nitrate on five sampling dates during a 28-day experiment. Uptake is input minus output, and transport is equivalent to output. Nutrient concentration and shading were manipulated as follows: Control—background nutrients, full sunlight; channel 1—nutrient amendment, full sunlight; channel 2—nutrient amendment, 30 percent shade; channel 3—nutrient amendment, 66 percent shade; channel 4—nutrient amendment, 92 percent shade. Negative uptake indicates samples in which dissolved inorganic nitrogen concentration was higher in output than in input water. Nutrient amendment was 100 µg NO_3-N/L and 25 µg ortho PO_4-P/L. Nutrient amendment was cut off on September 12.

channels. Uptake was greatest in channel 1 (0.73 g N/m^2) and least in channel 4 (0.002 g N/m^2).

Transport, nitrate not removed biologically as uptake, was also linearly related (r^2=0.97) to percent shading over the total experiment. In the nutrient-amended flumes, average transport varied between 75 percent (channel 1) to more than 99 percent (channel 4) (fig. 3). In the control, transport was approximately 55 percent of input nitrate (fig. 3). Considering the short flume length (<10 m), small surface area (12.4 m), and continuous input of nitrate, a very short cycling distance under natural conditions is suggested.

Nitrate uptake also was related to community senescence. In both control and nutrient-amended channels, uptake of amended nitrate decreased as the community aged (fig. 3). Maximum nitrate uptake occurred when

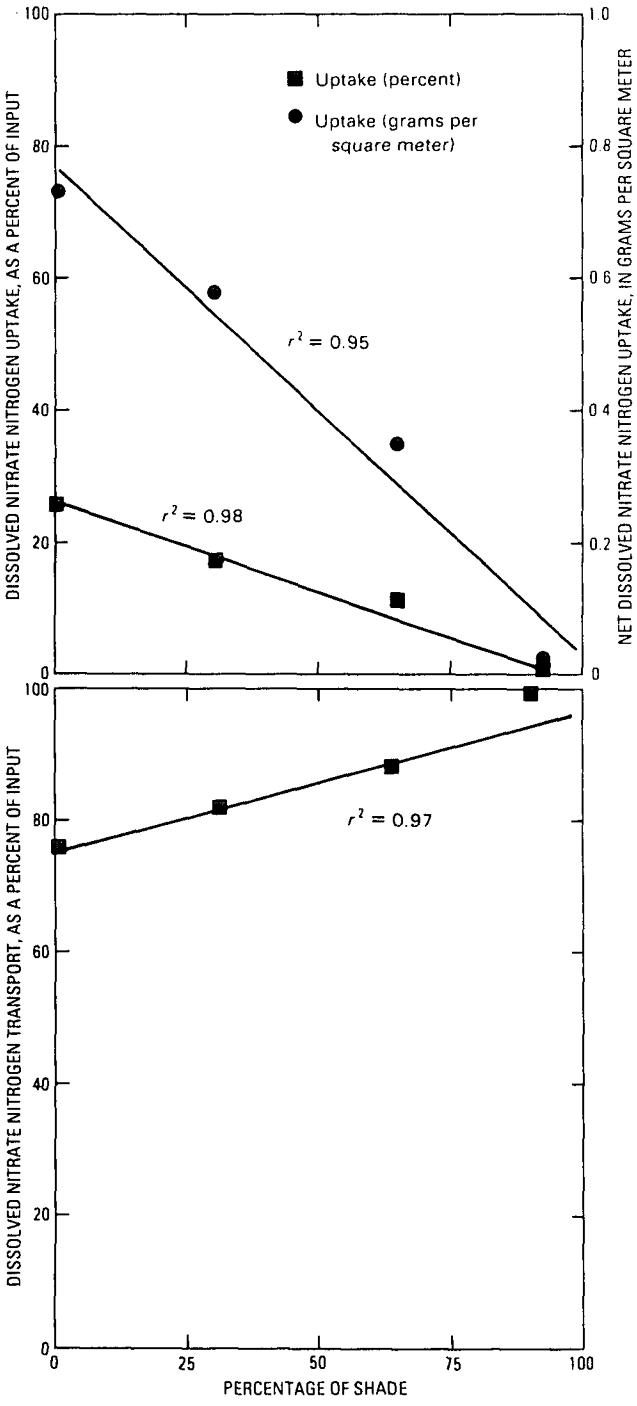


FIGURE 5.—Cumulative nitrogen uptake and transport for the full experiment in response to controlled levels of shading after 28 days of continuous nutrient amendment.

growth rate was greatest (August 28–31). After August 28, midafternoon uptake gradually declined at all levels of shading. By September 11, nitrate uptake in the nutrient-amended channels was less than at the beginning of the experiment, although epilithon biomass was maximum. On September 12, nutrient addition was cut off, thus the higher percentage uptake September 18 is of background nitrate. Net community primary production also declined as the community aged (Triska and others, 1983). Pryfogle and Lowe (1979) report that dead cells can constitute between 20 and 50 percent of the biomass in natural epilithon communities. Thus, dead and senescent tissue can represent a high proportion of organic matter that is physiologically inert to nutrient uptake.

In channel 4 (92 percent shade), many samples had higher output than input of nitrate concentration. Regeneration, 105 to 110 percent of input, is shown as negative uptake on figure 3. Regeneration occurred almost continually from September 6 to 12 (data shown for September 11 only) and is attributed to remineralization of organic detritus. By the end of the experiment, regeneration nearly equaled earlier uptake, explaining the low net uptake for all channels (fig. 5). This regeneration is considered in detail in Triska and others (1985). The influence of nitrate regeneration in flume experiments will be considered later in the discussion of field studies that examine the long-term influence of canopy development.

The relation of nitrate uptake to three measurements, biomass, chlorophyll, and carbon:nitrogen ratio, was also examined. When nutrient enrichment commenced, epilithon biomass (ash free) ranged from 2.43±0.5 to 7.77±0.68 g/channel (table 4). After 4 days of nutrient enrichment, the heavily shaded channel 4 (92 percent) had little biomass accumulation. Biomass in this channel thereafter remained significantly lower than that in channel 1 (student's *t*-test, $p < 0.01$). Two weeks after the nutrient amendment began, channel 1 was significantly higher ($p < 0.05$) in biomass than either the 30-percent-shaded or the 66-percent-shaded channels. On September 11, 19 days after nutrient addition began, biomass in all shaded channels was significantly lower than that in channel 1; (channel 2, $p < 0.05$; channel 3, $p < 0.01$). On September 12, nutrient addition ended, and nutrient concentration in all treated channels returned to background levels. Immediately before cutoff, both fully lighted channels supported nearly equal biomass (52.2±7.0 g/channel for the control channel vs. 49.0±2.3 g/channel for channel 1). After cutoff, biomass declined equally in both channels (17.6±2.6 g vs. 16.8±0.3 g biomass remaining, respectively, for channel 0 and channel 1).

Although the accumulation of biomass was nearly identical in the control and in channel 1, chlorophyll α content of the control channel at nutrient cutoff was less than half that of channel 1 (table 4). From a base of 31 mg, chlorophyll α increased to 182 mg/channel in the control. In channel 1, however, chlorophyll α rose from a base of 22 mg to a maximum of 403 mg/channel. Channel 2 (30 percent shade) produced slightly more chlorophyll α

TABLE 4.—*Biotic characteristics of the epilithon in the experimental flumes*

Date		Aug. 24	Aug. 28	Sept. 6	Sept. 11	Sept. 20
Channel treatment		**Biomass, in grams ash-free dry weight (± standard deviation)[1]**				
0	Control	7.77±0.68	13.34±0.60	31.27±4.53	52.15±6.99	17.63±2.64
1	0 shade	5.13±.55	14.82±2.36	40.50±2.94	49.02±2.34	16.83±.31
2	30 percent shade	4.76±.66	11.62±1.63	23.25±1.43	39.59±1.01	23.91±2.93
3	66 percent shade	3.71±1.23	9.72±1.08	21.33±2.80	28.18±4.70	25.53±3.36
4	92 percent shade	2.43±.50	3.27±.48	3.94±1.43	7.45±2.42	4.54±2.00
Channel treatment		**Chlorophyll α in milligrams [2]**				
0	Control	30.98	63.47	167.42	181.86	64.77
1	0 shade	21.59	135.20	270.87	402.52	104.34
2	30 percent shade	20.64	134.74	332.65	410.34	170.68
3	66 percent shade	20.10	132.85	178.32	278.05	130.06
4	92 percent shade	14.60	54.51	59.42	92.77	51.78
Channel treatment		**Carbon:nitrogen[3] (± standard deviation)**				
0	Control	11.58±0.67	14.06±0.26	10.56±0.62	8.11±0.21	7.18±0.07
1	0 shade	12.76±.29	8.21±.15	7.39±.22	7.79±.07	7.49±.02
2	30 percent shade	11.13±.48	9.15±.71	7.35±.55	6.83±.31	6.91±.01
3	66 percent shade	9.22±.14	7.74±.17	7.30±.07	7.47±.06	7.39±.06
4	92 percent shade	9.72±.11	9.19±.62	6.92±.06	8.47±.30	8.08±.06

[1] Biomass estimates for the total channel.

[2] Chlorophyll α in the total channel.

[3] Carbon:nitrogen is determined from samples taken at midflume.

than channel 1 but had approximately 20 percent less biomass, possibly indicating shade adaptation (Meeks, 1974; Lyford and Gregory, 1975). Chlorophyll α was lower in the 66-percent-shaded and 92-percent-shaded channels.

Carbon:nitrogen ratios varied between 9.2 and 12.8 when the experiment began (table 4). C:N was lower in most nutrient-amended flumes than in the control channel. Nutrient amendment resulted in reduction of C:N by August 28, and C:N generally continued to decline throughout the experiment. In the control flume, however, C:N increased when community growth was most rapid, indicating potential nitrogen limitation. By September 20, C:N was similar in all flumes.

After 1 week, the cumulative nitrate uptake in channel 1 (0.358 g NO_3-N/m^2) was 1.8 times higher than that of the control (0.198 g NO_3-N/m^2). This cumulative nitrate uptake is consistent with the observed lowering of C:N. Cuker (1983) reported an increase in chlorophyll α levels in the epilithic algal community of an arctic lake after addition of nutrients. Chlorophyll α may partially serve as a reservoir of nitrogen, because the chlorophyll molecule contains significant nitrogen. This possibility is also consistent with our own observations of chlorophyll α enhancement as a result of nutrient amendment. Rhee (1978) observed that protein was the major storage pool of cellular nitrogen. Protein also serves an important function in the structural arrangement of chlorophyll in chloroplasts. Wherever the intracellular location of nitrogen, however, the decline in C:N and high cumulative uptake indicate a rapid epilithon response to increased nitrate.

Although the highest rates of nitrate uptake occurred in midafternoon, indicating a primarily algal response, significant uptake also was observed afterdark. Afterdark uptake varied by shade treatment and was greatest during the period of most active epilithon growth, August 24 to 28. Afterdark uptake was maximum in the control channel at about two-thirds the uptake of daylight, possibly indicating nitrogen limitation. Eppley and others (1971) reported afterdark uptake of nitrate in nitrogen-limited chemostat cultures of two marine phytoplankton. Grant and Turner (1969) observed afterdark uptake but found light uptake was 23 times greater. This observation was presumably due to the fact that nitrate uptake and reduction by algae are energetically linked to photosynthesis (Eppley and Coatsworth, 1968; Eppley and others, 1971; Healy, 1973; Cloern, 1977), possibly through the reversible inactivation of nitrate reductase during light-dark cycles (Hodler and others, 1972; Griffiths, 1979). Nitrate reductase activity rapidly increases in *Chlorella* sp. cultures during the light period and may begin to fall even before the dark period begins. The rapid response following illumination may result from conversion of a preformed macromolecule into an active enzyme (Tischner and Hutterman, 1978). These previous studies on *Chlorella* sp. in chemostats used pure and synchronous algal cultures. Because afterdark uptake was proportionally higher in our field experiments, significant nitrogen flux also may occur through bacteria and fungi in natural epilithon.

The channel experiments illustrate how biological uptake can regulate the distance that a nitrate ion travels downstream. Temporally, uptake was controlled on a daily basis by irradiance and on a week-to-week basis by physiological senescence that reduced uptake at all levels of shading. In natural channels, physical factors, including sloughing, animal grazing, and small summer and early autumn storms, reset the community and partially mitigate the effect of senescence. Tissue removal, whether directly by consumption or indirectly by sloughing or scouring, may enhance both nitrogen passage to higher trophic levels and the DIN uptake per unit area.

Spatially, canopy cover (percent shading) controlled the overall magnitude of uptake. Under natural conditions canopy cover is a function of stream order, with almost complete coverage in lower order streams and less coverage downstream.

FIELD STUDIES: LONG-TERM NITROGEN UPTAKE AND REGENERATION

In this section, we will apply conclusions from the flume studies to longer term DIN chemistry by comparing years when the riparian canopy was open, 1974 to 1976, to years when it was largely closed, 1979 to 1982. We will approach canopy effects on inorganic nitrogen transport from a diel and seasonal perspective, as in the flume studies, and briefly speculate about the long-term impact of canopy closure on the structure of biological communities.

Diel nitrate patterns in September 1974 and 1982 are compared in figure 6 for two stations, Gage and Bridge. The Gage site was at the head of the clearcut area and indicates dissolved inorganic nitrogen input from the upstream virgin forest. The Bridge site was located about 1,500 m downstream near the base of the clearcut area and upstream of the junction of Little Lost Man Creek and Prairie Creek (fig. 1). Diel variation in background nitrate concentration at Gage was typically 10 to 20 μg NO_3-N/L in both 1974 and 1982 but was higher in 1982. The diel pattern of nitrate concentration at Gage was similar to the pattern seen in our experimental channels (highest after dark and lowest between noon and 4:00 p.m.). In 1974 (fig. 6), the riparian canopy was open, and full sunlight reached the stream. At the Bridge site, nitrate concentration was typically reduced to between 5 and 8 μg NO_3-N/L due to biological uptake. Absence of a diel pattern at Bridge is attributed to continuous biotic uptake. Uptake of approximately 77 percent of transported nitrate occurred between the two stations in 1974. Opposite results were observed at the same sites in 1982 (fig. 6). Rather than a reduction in nitrate concentration, a threefold increase in nitrate was observed at the downstream site. The canopy was nearly closed in 1982, except for a few large pool reaches that allowed light infiltration.

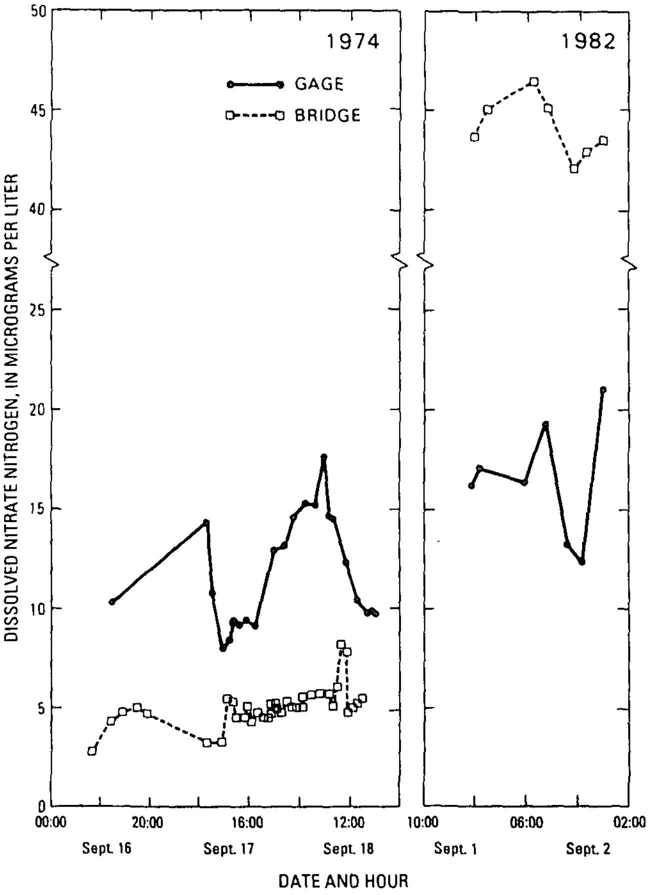


FIGURE 6.—Diel difference in NO_3-N concentrations during late summer between an upstream (Gage) and a downstream (Bridge) study site. Concentration differences prior to canopy closure (September 16–18, 1974) are indicated on the left, and differences after canopy closure (September 1–2, 1982) are indicated on the right. Location of the Gage and Bridge study sites is shown in figure 1.

By 1982, nitrate regeneration was observed over the whole summer-autumn period of declining discharge (fig. 7). Except for the mid-August sample, the pattern of background nitrate concentration at the Gage site was similar in both 1974 and 1982; DIN concentration was low during early summer (June and July), usually between 10 and 15 μg N/L in 1974 and 5 and 10 μg N/L in 1982. Maximum midday nitrate concentration at the Gage site was approximately 40 μg N/L during 1974 (mid-August sample) but less than 20 μg N/L during 1982. Concentrations at the Gage site during 1976 were intermediate, but as in 1974, the Gage site samples had a higher concentration in late summer. Comparison of data from the Bridge and Gage sites indicates nitrate disappearance during the late spring and summer in 1974 and 1976 but nitrate regeneration throughout the summer of 1982.

During the low-flow period, uptake in the reach was greatest during July in 1974 and in mid-July and early

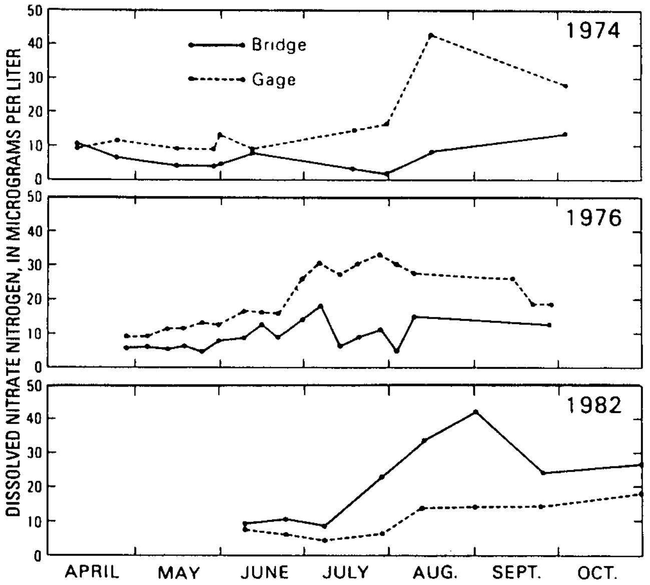


FIGURE 7.—Seasonal differences in midday NO_3-N concentration between an upstream study site (Gage) and a downstream study site (Bridge). The riparian canopy was open above the stream during 1974 and 1976 and closed by 1982. Study site locations are shown on figure 1.

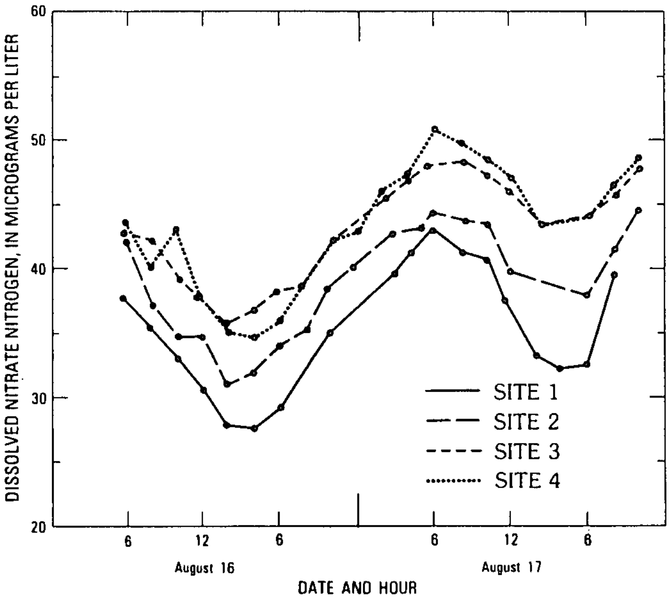


FIGURE 8.—Diel change in background NO_3-N concentration at four stations within a 265-m reach of Little Lost Man Creek under low-flow conditions, August 16 to 17, 1979. Distance between sites 1 and 2 is 64 m; between sites 2 and 3 is 58 m; and between sites 3 and 4 is 143 m. This 265-m reach is labeled "1979" on figure 1.

August in 1976. Differences between study sites were less in early summer, presumably because higher discharge and increased velocity shortened traveltime and lessened contact with the epilithon. Nitrogen uptake declined in September and October. Declines in uptake, despite low flow, may indicate community senescence as observed in the experimental channels. Possible causes of senescence include emergence of many grazer invertebrates by late summer and extremely low flows, which allow metabolites to accumulate and minimize physical sloughing. Nitrate regeneration also declined by mid-September in 1982.

The nitrate regeneration currently observed at Little Lost Man Creek is not uniform throughout the reach. A diel study at four sites in a 265-m section of the clearcut reach (labeled "1979" in fig. 1) indicated significant increase in nitrate concentration within short distances (fig. 8). For example, the distance between sites 1 and 2 was 64 m and between sites 2 and 3, 58 m. The greatest observed increase in nitrate concentration occurred between sites 1 and 3. The distance between sites 3 and 4 was 143 m but was characterized by net nitrate uptake during daylight and by slight nitrate regeneration after dark and until noon the next day. This reach contained one unshaded riffle and two long unshaded pools.

The flume studies indicate two potential sources of nitrate increase in 1979 and 1982: (1) regeneration within the bed and (2) decrease of algal uptake of nitrate from inflowing ground water as a result of canopy development (increase in shading). To test the hypothesis that nitrification was actually occurring in stream sediments, we collected submerged bankside soils at three sites along the stream: (1) adjacent to an alder stand where nitrogen-fixing nodules were not observed on roots, (2) adjacent to an alder tree where roots were definitely nodulated, and (3) adjacent to an old-growth maple tree. Nitrification potentials were measured as an increase in nitrite by inhibition of the enzyme that facilitates the final oxidation of nitrite to nitrate. Samples from all three sites indicated nitrification potential when compared to uninhibited controls (fig. 9). In conjunction with our observations in the experimental channels, this preliminary survey of bankside sediments indicates a biological potential for nitrate regeneration.

A second hypothesis for the observed nitrate increase is absence of nitrate uptake from inflowing ground water. If ground water is higher in NO_3-N than stream water due to upstream removal of NO_3-N during transit, then an apparent increase in NO_3-N in the shaded clearcut areas may result from lack of uptake from newly contributed ground water rather than from actual nitrification. To test this hypothesis, two experiments involving passage of a 3-hour midmorning pulse of nitrate in two reaches were compared between 1976 when the canopy was open and 1979 when it was closed (for location see fig. 1). Calculated nitrate uptake relative to nitrate concentration (based on chloride as a conservative tracer) is presented in figure 10. The results indicate

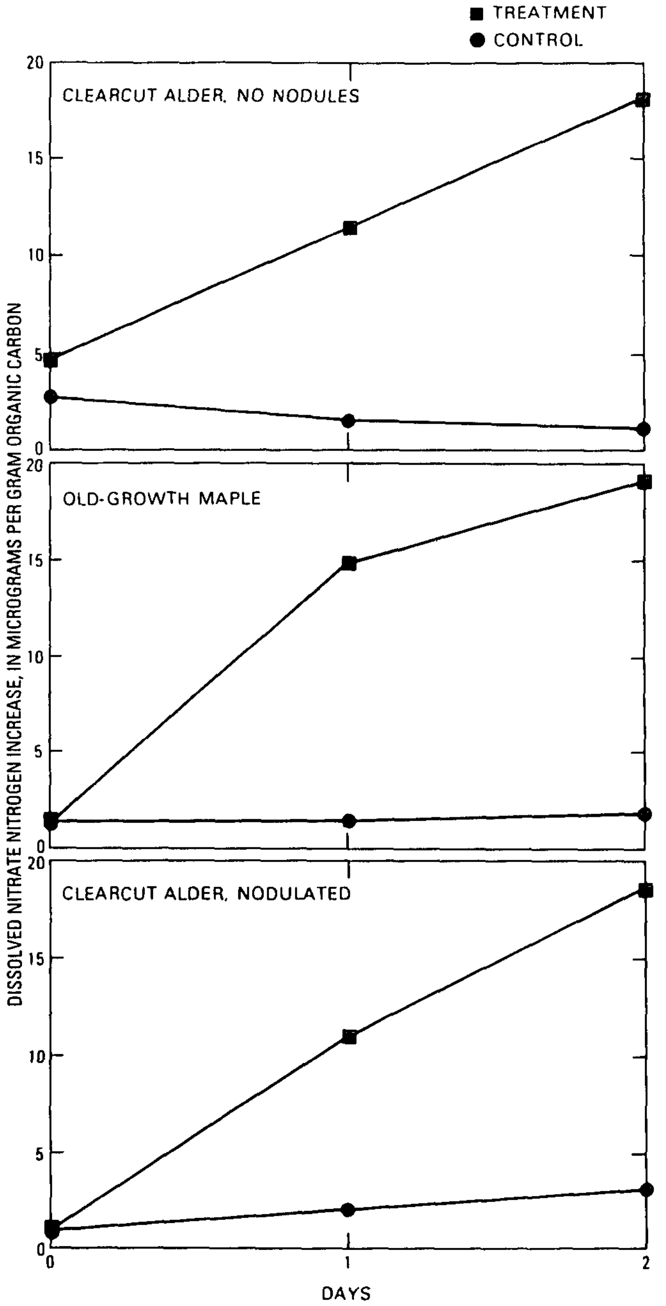


FIGURE 9.—Nitrification potential along Little Lost Man Creek, August 1981, measured by chlorate inhibition. Bankside sediments were collected adjacent to an alder tree where nitrogen-fixing nodules were not observed, adjacent to an old-growth maple, and adjacent to an alder tree where nitrogen-fixing nodules were observed on the roots.

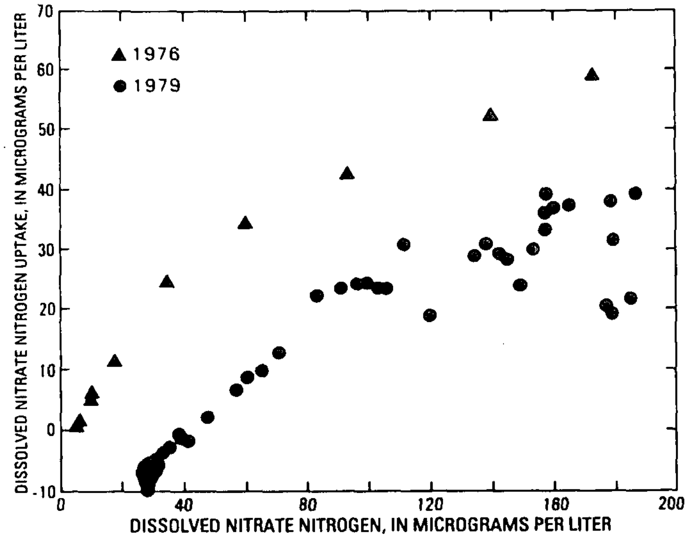


FIGURE 10.—Nitrate uptake at concentrations between 5 and 200 μg NO_3-N/L after passage through two reaches of Little Lost Man Creek (labeled "1976" and "1979" on fig. 1). Experimental injections of nitrate were conducted during 1976 when the riparian canopy was open and during 1979 after canopy closure. Concentration was varied by passage of a nitrate pulse down the channel; chloride was used as a conservative tracer to correct for dilution.

less nitrate uptake at all concentrations between approximately 30 and 180 μg NO_3-N in 1979. The negative uptake observed in 1979 around 30 μg NO_3-N/L is due to regeneration. Decreased uptake was observed in 1979 despite the fact that the minimum traveltime was shorter in 1976 (2.2 hours compared to 7 hours in 1979). The longer traveltime should have enhanced contact with periphyton in 1979. Even with better contact, less nitrate uptake after canopy closure indicates significantly reduced capacity for nitrogen uptake by biota. Thus both mechanisms, nitrification in the bed and reduced uptake by the epilithon, contribute to the current increase in DIN transport from the watershed.

At Little Lost Man Creek, the atomic N:P ratio (NO_3-N+NO_2-N)/ortho PO_4-P) was extremely low in 1974 (approx 1.75) but rose to approximately 7.8 by 1979. Although N:P has risen due to less nitrogen uptake and greater regeneration, both ratios indicate potential nitrogen limitation relative to phosphorus (Redfield and others, 1963; Rhee, 1978). Under the former (1974–76) conditions of high light input and nitrogen limitation, nitrate regeneration would have been difficult to observe in place, because nitrogen-limited algae can remove nitrogen both night and day (Conway and Whitledge, 1979; Triska and others, 1983; Sebetich and others, 1984), obscuring any potential contribution of nitrate regeneration. Since 1979, however, canopy shading has limited light infiltration, thereby lowering algal growth and nutrient uptake. At the same time, enhanced input of particulate organic matter (for example, alder leaf litter and decomposing root tissue) provides an additional source of organic nitrogen for regeneration. Dense shading also optimizes conditions for nitrate regeneration because nitrifying bacteria are inhibited by light (Olson, 1981; Ward and others, 1982). The result has been a change within the reach from a net loss of nitrogen in transit to a net gain.

SUMMARY AND CONCLUSIONS

The channel and stream studies in combination indicate that uptake and regeneration of inorganic nitrogen can be regulated on variable time scales in the stream. In experimental control, midafternoon nitrate uptake was up to 75 percent during the period of most active growth and approximately 40 percent by senescent communities under full sunlight. In the stream, maximum diel uptake was greater than 75 percent of the available nitrogen (77 percent in 1974, 87 percent in 1976) in an approximately 1,500-m open reach of Little Lost Man Creek. These levels of uptake indicate the potential of the biotic community to control diel nitrate transport under low-flow conditions.

Within longer term resetting periods (such as between storms), the epilithon community varied in its ability to influence nitrate transport in experimental channels. In an unshaded, nutrient-amended channel, the major factor controlling uptake was the maturity of the algal community. Actively growing epilithon had high nitrogen uptake per unit biomass compared to senescent films, under identical solute nitrogen concentration and channel discharge. In the control, a high C:N of periphyton during active growth presumably reflected nitrogen limitation. In the absence of periphyton removal, nitrogen uptake and C:N of periphyton generally decreased as the community aged. Under natural conditions of full sunlight in the stream, uptake increased from May through August. As discharge fell, background nitrogen concentrations rose, but nitrogen was effectively removed through most of the low-flow period. Toward late August and September, uptake declined although discharge was at its annual low. Community senescence was a possible cause.

Reduction in canopy density, such as from lower to higher order streams or through time as a result of canopy development, also influenced nitrate transport. The canopy increased solute nitrogen concentrations by at least two mechanisms: (1) by promoting nitrification in bankside sediments and (2) by decreasing algal uptake due to light limitation. In our experimental flumes, nitrate regeneration presumably occurred as benthic communities became senescent. However, the process could be verified only under highly darkened conditions, perhaps conditions simulating intragravel sites having high organic matter mineralization. Historically, nitrate regeneration did not produce an observable impact at Little Lost Man Creek until 14 years after clearcutting, when closure of the riparian canopy was nearly complete. The impact of nitrate regeneration was slight early in the growing season but increased throughout the summer to a peak in early September. Regeneration declined in late September, although discharge remained constant. The role of other sources and sinks, such as nitrogen fixed by riparian vegetation or lost via denitrification, is not known.

Experimental shading in the flume studies reinforced our conclusion that development of the riparian zone is of long-term importance in nitrogen cycling at Little Lost Man Creek and similar creeks. Our results suggest that canopy development will result in a long-term decline in epilithon production because of limitation of the synthesis of algal protein. Epilithon production is a major interface between DIN and the passage of nitrogen to higher trophic levels. Heterotrophic processes such as the decomposition of leaf litter will gain in importance due to greater litter input. However, nutrient flux associated with these heterotrophic processes is slow compared to nutrient flux associated with epilithic communities. As a result, animal species dependent on epilithic films are likely to decline in abundance. Other species that filter sloughed tissue from the water column or consume it as organic detritus are also likely to be affected. Decrease in protein synthesis low in the food chain may even extend to higher level carnivores such as fishes. Murphy (1979), who surveyed 20 small streams in Oregon, found trout biomass (g/m^2) to be lowest in streams covered by dense second-growth riparian cover, highest in open streams, and intermediate in the mixed canopy cover of old-growth forests. Thus the net result of lower DIN flux may be a large decline in biotic production until natural mortality in the riparian zone reopens the canopy (Triska and others, 1982). Development of an alder canopy is a typical response to clearcutting in coastal watersheds of northern California and the Pacific Northwest. As a result, more long-term data are needed for clearcut reaches like Little Lost Man Creek, to adequately assay the long-term impacts of current land management practices.

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