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History, Causes, and Significance of Changes in the Channel Geometry of Redwood Creek, Northwestern California, 1936 to 1982

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

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CONTENTS

ILLUSTRATIONS

TABLES

HISTORY, CAUSES, AND SIGNIFICANCE OF CHANGES IN THE CHANNEL GEOMETRY OF REDWOOD CREEK, NORTHWESTERN CALIFORNIA, 1936 TO 1982

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ABSTRACT

The configuration and behavior of the Redwood Creek stream channel changed markedly between 1936 and 1982. Increases in bank-to-bank width in excess of 100 percent and channel fill in excess of 4.5 m were observed. These changes, which occurred primarily in response to major storms in 1964 and 1972, adversely affected riparian resources of Redwood National Park. Timber harvest in the area may have exacerbated effects of these storms but did not trigger processes other than those that occur in the basin naturally. Effects of the 1964 and 1972 storms were still evident in the channel in 1981, but changes in channel geometry and grain size of alluvium indicate that some basinwide recovery may have begun.

Major storms can produce catastrophic changes in channel geometries in the study area because they trigger landslides throughout the unstable terrain. The resulting landslides introduce volumes of sediment sufficient to overload channel transport capacities for decades. In addition to channel fill, gravel berms deposited by floodflows persist because moderate flows do not rise high enough to erode them. Study of the Redwood Creek channel has shown that, as a result of naturally occurring processes, major storms strongly affect channel geometry for long periods of time. Channel geometry reflects the length of time since major storms and the levels of moderate flows that modify flood-related effects.

INTRODUCTION

The configuration and behavior of the Redwood Creek stream channel have changed markedly since the mid-1950's. The most apparent changes have been major increases in channel width and decreases in channel depth. These changes occurred in response to (1) a sequence of major storms and (2) large-scale timber harvest throughout the basin. Concern regarding the effects of these channel changes on riparian resources of Redwood National Park prompted numerous studies aimed at characterizing the magnitude and cause of the changes. Preliminary data collected in many of these studies are presented and discussed in papers by Iwatsubo and others (1975 and 1976), Janda and others (1975), Harden and others (1978), Nolan and Janda (1979), and Nolan (1980). Although recent channel changes similar to those observed in the Redwood Creek watershed have been noted in nearby watersheds (Ritter, 1968; Hickey, 1969; Kennedy and Malcolm, 1978; Kelsey, 1980; and Lisle, 1981), studies along the main channel of Redwood Creek have produced the longest and most complete basinwide record of channel response in the region.

PURPOSE AND SCOPE

The purpose of this paper is to summarize, update, and augment existing literature describing the history, causes, and significance of the changes in the main channel of Redwood Creek during the period 1936 to 1982. Channel behavior during this period, which was observed by using a variety of qualitative and quantitative methods, is described. The role that interactions of active physical processes in the basin played in producing the observed changes is discussed. Finally, the geomorphic significance of the channel changes is assessed.

THE STUDY AREA

Redwood Creek drains an elongate 725-km^2 drainage basin in the Coast Ranges of northwestern California (fig. 1). The main channel of Redwood Creek roughly bisects the drainage basin. Slopes in the watershed, which are naturally susceptible to mass wasting and fluvial erosion, have an average gradient of 26 percent (Janda and others, 1975). Total basin relief is 1,615 m.

Most of the Redwood Creek drainage basin is underlain by sedimentary and metasedimentary rocks of the

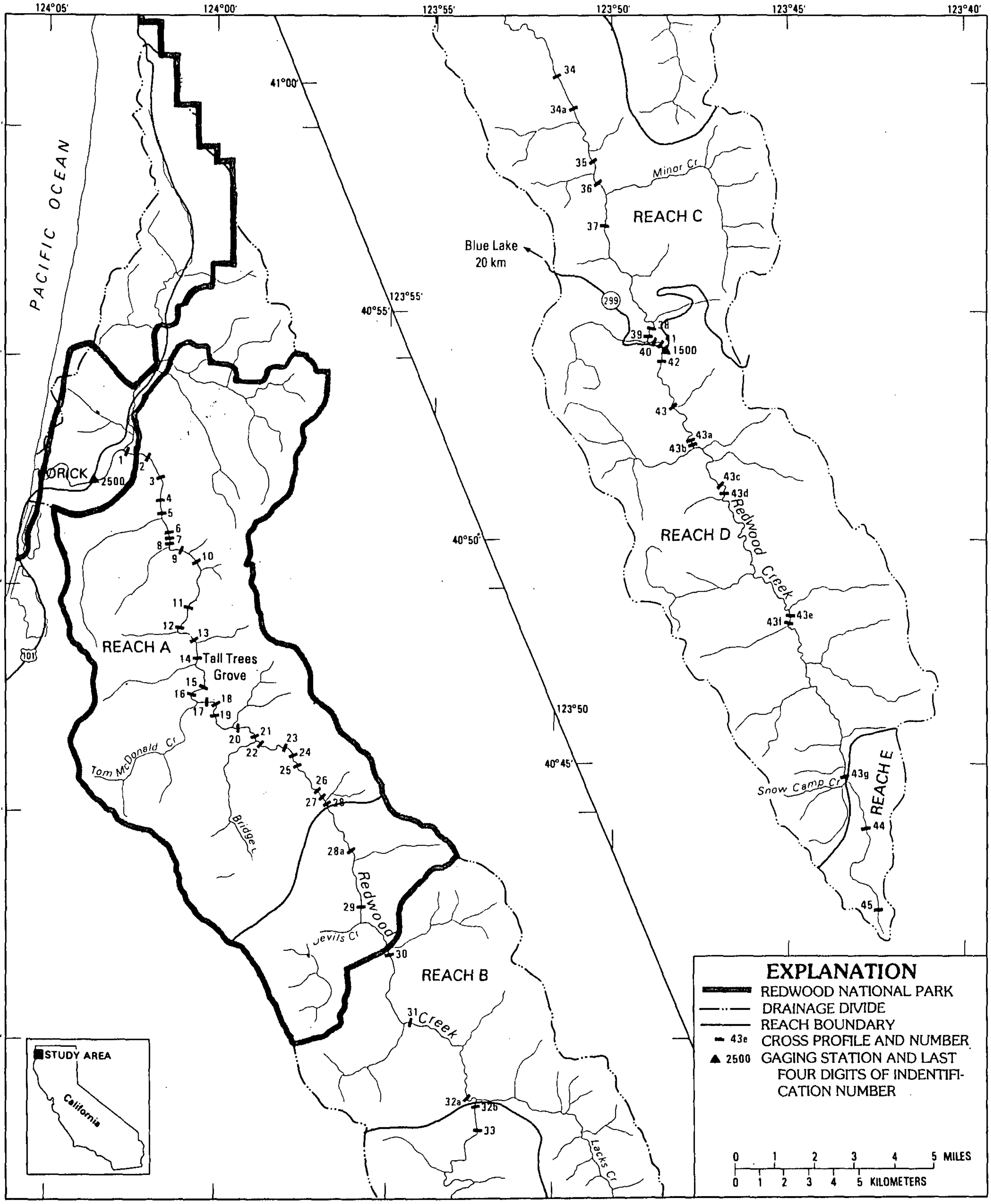

FIGURE 1.—Location of the Redwood Creek drainage basin and stream-channel cross profiles.

Franciscan assemblage of Late Jurassic and Cretaceous age (Bailey and others, 1970; Harden and others, 1982). Dominant rock types include unmetamorphosed, interbedded sandstone and shale and fine-grained, well-foliated quartz mica schist. The main channel of Redwood Creek roughly coincides with the Grogan fault, which separates the sandstone and schist units. Sandstone and related unmetamorphosed rocks dominate on the eastern side of the basin, whereas schist dominates the western half. Sandstone and shale in the basin are pervasively sheared at most localities.

The Redwood Creek watershed has a Mediterranean climate—warm, dry summers and cool, wet winters. Basinwide average rainfall is approximately 2,000 mm, 80 percent of which falls between the months of October and March. Regional storms of light to moderate intensity produce much of this precipitation. Approximately 66 percent of the annual precipitation appears as runoff, producing an average daily flow of 29.51 m^3/s (cubic meters per second) at Orick.

Forest, chiefly coastal redwood and Douglas-fir, covers most slopes in the Redwood Creek watershed. Prairies of grass and shrubs are also common on slopes. On most stream terraces and upper flood-plain surfaces in the lower part of the basin are stands of redwood and redwood mixed with Douglas-fir, whereas Douglas-fir dominates on these surfaces upstream and farther inland. Alder thickets are common throughout the basin where soil and rock have been exposed by overbank deposition, bank erosion, mass movement, or timber harvest.

During periods of moderate flow, Redwood Creek flows within a lower gravel flood plain that varies in width between 30 and 130 m. During periods of low flow, the channel is contained within a low-flow channel that is typically 0.1 to 0.5 times as wide as the lower flood plain and is incised 0.5 to 2.0 m into the lower flood plain (figs. 2, 3). Low-flow channels alternate in pattern from meandering to braided along the unvegetated lower flood plain. The entire lower flood plain is inundated for long periods during normal winters.

Along most of the length of Redwood Creek, the lower flood plain abuts directly against colluvial hillslopes (Nolan and others, 1976). Bedrock along streambanks, although present in some locations, is not common. Along some reaches, a narrow upper flood plain consisting of 2 to 5 m of unweathered, fine sandy loam and silt loam borders the lower flood plain. Its surface is commonly 1 to 2 m above the lower flood-plain surface. Inundation of upper flood plains during a single major storm commonly results in 0.15 to 0.30 m of deposition (Janda and others, 1975). Upper flood-plain surfaces are most prevalent along wider downstream reaches of the channel. Large, flood-deposited gravel berms, which resemble those found elsewhere in northwestern California by Stewart and LaMarche (1967) and Helley and LaMarche (1973), are found throughout the basin. These berms, which commonly consist of a 1- to 2-m thickness of gravel, are located on the insides of channel bends or in reaches characterized by abrupt increases in channel width or decreases in gradient (figs. 4, 5). Vegetation on these berms is distinguished by even-aged stands of young conifers that date to recent storms. A schematic representation of a typical cross section of the flood plain of Redwood Creek is shown in figure 6.

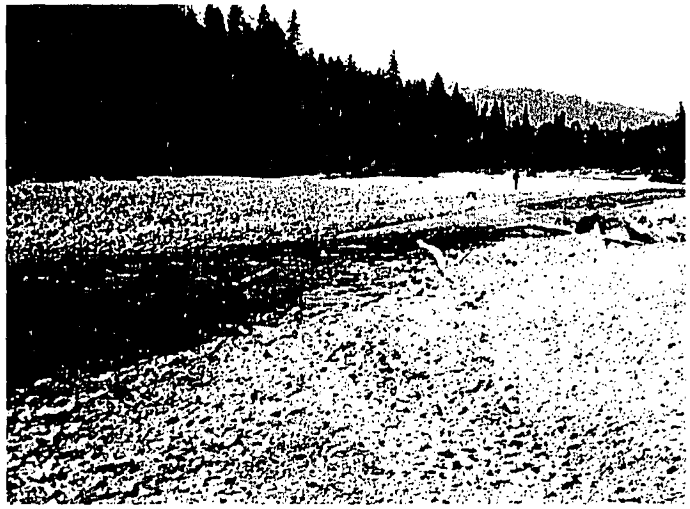

FIGURE 2.—Low-flow conditions along midbasin reach of Redwood Creek below mouth of Minor Creek. Photograph taken August 1975.

FIGURE 3.—Low-flow conditions along a lower reach of Redwood Creek near cross profile 3. Photograph taken August 1975.

BACKGROUND

Beginning in the mid-1950's, the Redwood Creek basin experienced five flood-producing storms (Harden and others, 1978); widespread clearcut timber harvesting took place as well. Major storms, which occurred in 1953, 1955, 1964, 1972, and 1975, were associated with rainfall totals of up to 500 mm. Peak discharges associated with the storms ranged between 1,283 and 1,430 m^3/s at the gaging station on Redwood Creek near Orick (table 1). Prior to 1964, a peak discharge of 1,416 m^3/s was considered to have a recurrence interval of 50 years. Concurrently with the major storms, nearly 65 percent of the basin was logged, and much of this logging was by tractor-yarded clearcutting, which was highly disruptive to the ground surface (Harden and others, 1978; Nolan and Janda, 1981).

The combination of inherently unstable bedrock, extensive timber harvest, seasonally intense precipitation, and moderately steep slopes in the Redwood Creek basin produces one of the highest annual sediment yields in the conterminous United States (Janda and Nolan, 1979). The long-term average annual suspended-sediment discharge for Redwood Creek at Orick (fig. 1) has been estimated at 2,100 Mg/km^2 (J.M. Knott, U.S. Geological Survey, written commun., 1975) and 2,540 Mg/km^2 (Anderson, 1979). When the discharges of bedload and suspended sediment were measured simultaneously, bedload was 20 to 60 percent of the total sediment discharge (Janda, 1978).

FIGURE 4.—Surface of gravel berm deposited (along a midbasin reach of Redwood Creek) during flood of December 1964. Photograph taken in August 1978. Alders in foreground are 1 to 1.5 m tall. Note small pack for scale.

FIGURE 5.—Gravel berm deposited (along midbasin reach of Redwood Creek) during flood of 1972. Photograph taken August 1975.

TABLE 1.—*Instantaneous peak discharge and runoff measured at the Redwood Creek gaging stations near Blue Lake and Redwood Creek at Orick during recent major floods*

[Runoff data are from Harden and others (1978). (—), no data]

Date	Peak discharges				Date	Runoff	
	Redwood Creek near Blue Lake[1]		Redwood Creek at Orick[2]			Redwood Creek near Blue Lake[1]	Redwood Creek at Orick[2]
	(m^3/s)	[(m^3s)/km^2]	(m^3/s)	[(m^3s)/km^2]		(cm)	(cm)
Jan. 18, 1953	—	—	1,416	1.97	Jan. 16–20, 1953	—	35.3
Dec. 22, 1955	342	1.96	1,416	1.97	Dec. 15–23, 1955	37.3	32.5
Dec. 22, 1964	464	2.66	1,430	1.99	Dec. 18–24, 1964	—	41.4
Jan. 22, 1972	195	1.11	1,283	1.78	Jan. 19–24, 1973	—	28.7
Mar. 3, 1972	387	2.22	1,407	1.96	Mar. 1–4, 1972	—	18.0
Mar. 18, 1975	345	1.97	1,422	1.98	Mar. 15–24, 1975	28.2	24.9

[1] Station 11481500.
[2] Station 11482500.

TABLE 2.—*Description of study reaches along the main channel of Redwood Creek*

Reach	Length (km)	Average gradient (m/m)	Average bank-to-bank width of surveyed profiles (m)	Boundaries[1]		Cross profiles included
				Upstream	Downstream	
A	28.0	0.003	85.4	Mouth	Cross profile 28	1–28
B	15.4	.005	51.6	Cross profile 28	Lacks Creek	29–32
C	26.0	.003	54.8	Lacks Creek	Highway 299	32a–41
D	23.0	.009	56.5	Highway 299	Snow Camp Creek	42–43g
E	6.3	.15	13.0	Snow Camp Creek	Cross profile 45	44–45

[1] Locations of various features are shown in figure 1.

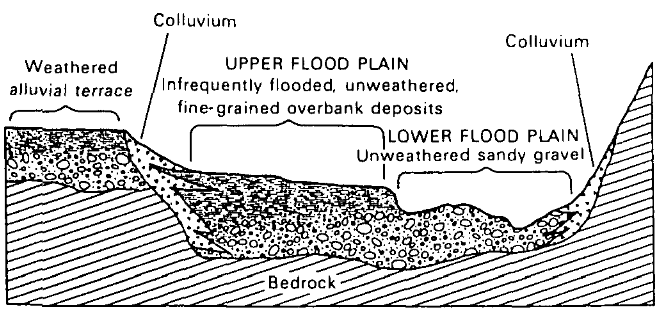

FIGURE 6.—Schematic representation of a typical cross section of the Redwood Creek flood plain. Cross section is not to scale.

CHANNEL HISTORY

The behavior of the Redwood Creek channel between 1936 and 1982 was observed by a variety of methods. Channel history between 1936 and 1973 was documented by using time-sequential aerial photographs, records from stream-gaging stations operated by the U.S. Geological Survey (USGS), and interviews with long-term residents of the area. These observations documented major increases in channel width and significant channel aggradation. Beginning in 1973, channel behavior was observed by repeated surveys of channel cross profiles and measurements of the size and composition of bed material at selected locations. In general, these more detailed observations have documented the persistence of the earlier channel changes. However, data collected during the last 2 years of study indicate that some channel recovery from these major changes may have begun.

For the purpose of analysis, the main channel has been separated into five reaches characterized by distinctive morphologies. Each reach is described briefly in table 2.

CHANNEL CONDITIONS IN 1936

Early documentation of the nature of the Redwood Creek stream channel is provided by aerial photographs taken in 1936 and 1947. Photographs taken in 1936 depict the part of the Redwood Creek basin north of the mouth of Minor Creek (fig. 1), and the 1947 photographs depict the part of the basin south of the mouth of Devils Creek. Basin conditions in 1947 were assumed to resemble closely those in 1936 because (1) weather records indicate that no major storms occurred between 1936 and 1947, (2) the history of land use indicates that no major disturbances occurred during the period, and (3) no significant changes in channel width or patterns were noted in areas where the two sets of photographs overlap. Channel conditions depicted on these photographs are therefore subsequently referred to as 1936 conditions.

In 1936, study reach A (table 2) was characterized by a predominantly braided pattern on a lower flood plain generally devoid of vegetation. Around this time the low-flow channel within this lower flood plain probably shifted frequently. Land surveys done during low flow at several locations below Bridge Creek showed that the low-flow channel migrated up to 30 m between 1946 and 1951 (Janda and others, 1975). Through reach B, the channel was alternately narrow and wide. Narrow subreaches within reach B were bounded by steep, V-shaped valley walls, whereas wider areas displayed morphology similar to that of reach C. Through reach C, the channel was mostly sinuous and moderately incised into a wide alluvial flood plain. Examination of aerial photographs suggests that this flood plain had numerous conifers 3 to 7 m high, many of which lined the narrow, active channel. Study reaches D and E, those above State Highway 299, were characterized by a narrow sinuous channel. A closed vegetation canopy existed along most of the length of these reaches. The canopy was broken only occasionally by a streamside landslide or a wide alluviated reach.

VARIATIONS IN CHANNEL GEOMETRY BETWEEN 1936 AND 1982

VARIATIONS BETWEEN 1936 AND 1974

Recollection of local residents, examination of aerial photographs taken in 1968 and 1974, records from the stream-gaging station on Redwood Creek near Blue Lake, and field observations of streambank stratigraphy and riparian vegetation indicate that, beginning in the mid-1950's, the lower gravel flood plain of Redwood Creek began to aggrade and widen and to shift across large parts of the former upper flood plain. Aerial photographs indicate that the lower flood plain in many areas of reaches D and E was more than twice as wide in 1974 as in 1947 (Harden and others, 1978). Stereograms in figure 7 show conditions of the channel in 1947 and 1973 near cross profiles 43e and 43f. Many of the 3- to 7-m-high conifers on the upper flood plain of reach C in 1947 were removed by 1973 (fig. 8). The only location where systematic increases in channel width did not occur was through reach A (fig. 9).

Data from the stream-gaging station on Redwood Creek near Blue Lake (USGS gaging station 11481500; fig. 1), together with interviews with local residents, indicate that the rapid changes in channel width were accompanied by major increases in streambed elevation. Evidence for as much as 4.5 m of channel fill near the mouth of Minor Creek and 3.0 m of fill near the mouth of Tom McDonald Creek (fig. 10) has been given by residents and local forest workers (Janda and others, 1975). Records from the stream-gaging station near Blue Lake indicate that the mean streambed elevation of Redwood Creek rose at least 1.5 m (fig. 11) and that the channel increased significantly in width between 1958 and 1973.

TABLE 3.—*Variations in channel geometry and velocity for Redwood Creek at the gaging station near Blue Lake*

[Station no. is 11481500. Values shown are those predicted by hydraulic geometry formulas developed for individual periods and applied to water-discharge values for the mean daily flow (7.45 m^3/s) and the 2-year flood (174 m^3). Station was discontinued in 1958 and reactivated at the same location in 1973]

Period	Channel geometry and velocity during mean daily flow			Channel geometry and velocity during 2-year flood		
	Width (m)	Depth (m)	Velocity (m/s)	Width (m)	Depth (m)	Velocity (m/s)
1956–58	19.2	0.43	0.92	32.0	2.06	2.68
1973–74	24.1	.29	1.06	41.4	1.33	3.18
1975–82	19.1	.37	1.03	35.9	1.55	3.13

Aggradation in this reach was probably anomalously low relative to reaches upstream and downstream because the channel is confined at this gaged site and because fill deposited in 1964 may have been removed prior to 1973.

Aerial photographs, botanical evidence, and interviews with local residents indicate that, although some changes began in the mid-1950's, the most dramatic changes occurred in response to major storms in December 1964 and March 1972 (Janda and others, 1975). The relatively minor changes observed by residents in the mid-1950's probably resulted from the flood of January 1953 and (or) the flood of December 1955. The locus of maximum erosion and deposition associated with the 1964 flood was concentrated in upper parts of the watershed, and that associated with the 1972 flood was concentrated in the lower part of the basin (Harden and others, 1978). Along upper Redwood Creek, stands of young conifers on flood-deposited gravel berms are even-aged and in 1984 were about 18 years old, suggesting that these berms are related to the December 1964 flood (fig. 4). Along downstream reaches, the ages of recently established conifers indicate that the flood berms in those reaches are primarily related to the 1972 flood (fig. 5).

The magnitude of channel changes that occurred between 1956 and 1974 at the gaging station near Blue Lake can be seen in table 3. This table shows the channel width and depth and stream velocity determined by applying hydraulic geometry formulas (Leopold and Maddock, 1953) to streamflow measurements made at the gaging station during three separate periods. The first period, 1956 to 1958, illustrates conditions just prior to the station's discontinuance and shows channel conditions prior to major storms of 1964 and 1972; the second period, 1973 to 1974, provides the earliest data available after the floods.

The channel changes resulting from the floods of 1964 and 1972 had adverse impacts on riparian vegetation along many reaches. Bank undercutting toppled many old-growth redwood trees (fig. 12). Elsewhere, gravel deposition completely filled the former lower flood plain and spilled onto extensive areas of the former upper flood plain. This gravel deposition killed numerous trees,

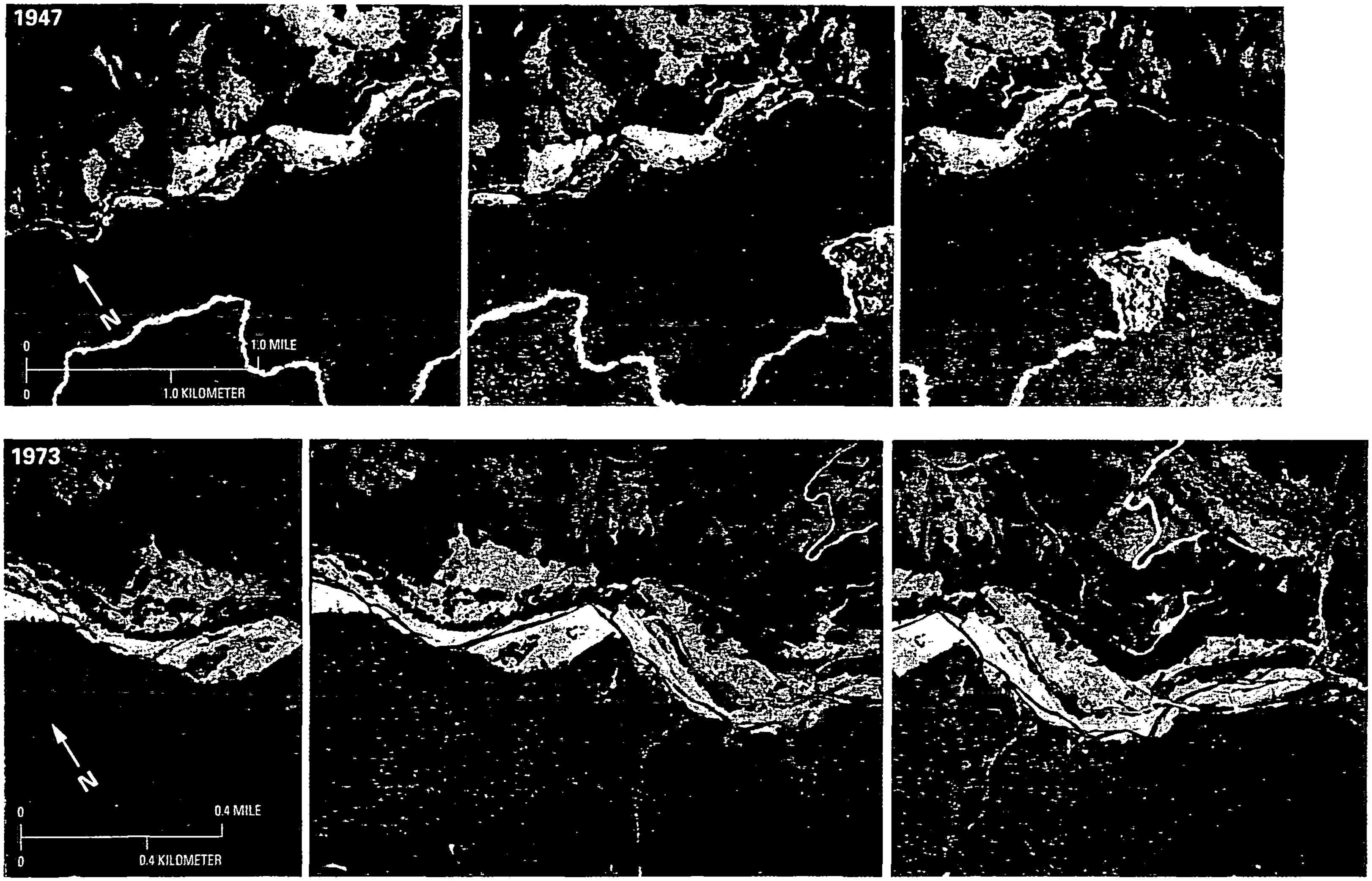

FIGURE 7.—Stereograms showing conditions of the Redwood Creek channel in 1947 and 1973 near cross profiles 43e and 43f (reach D). Arrows point to identical location on each set of photographs. Note large increases in streamside landslides and removal of vegetation canopy between 1947 and 1973.

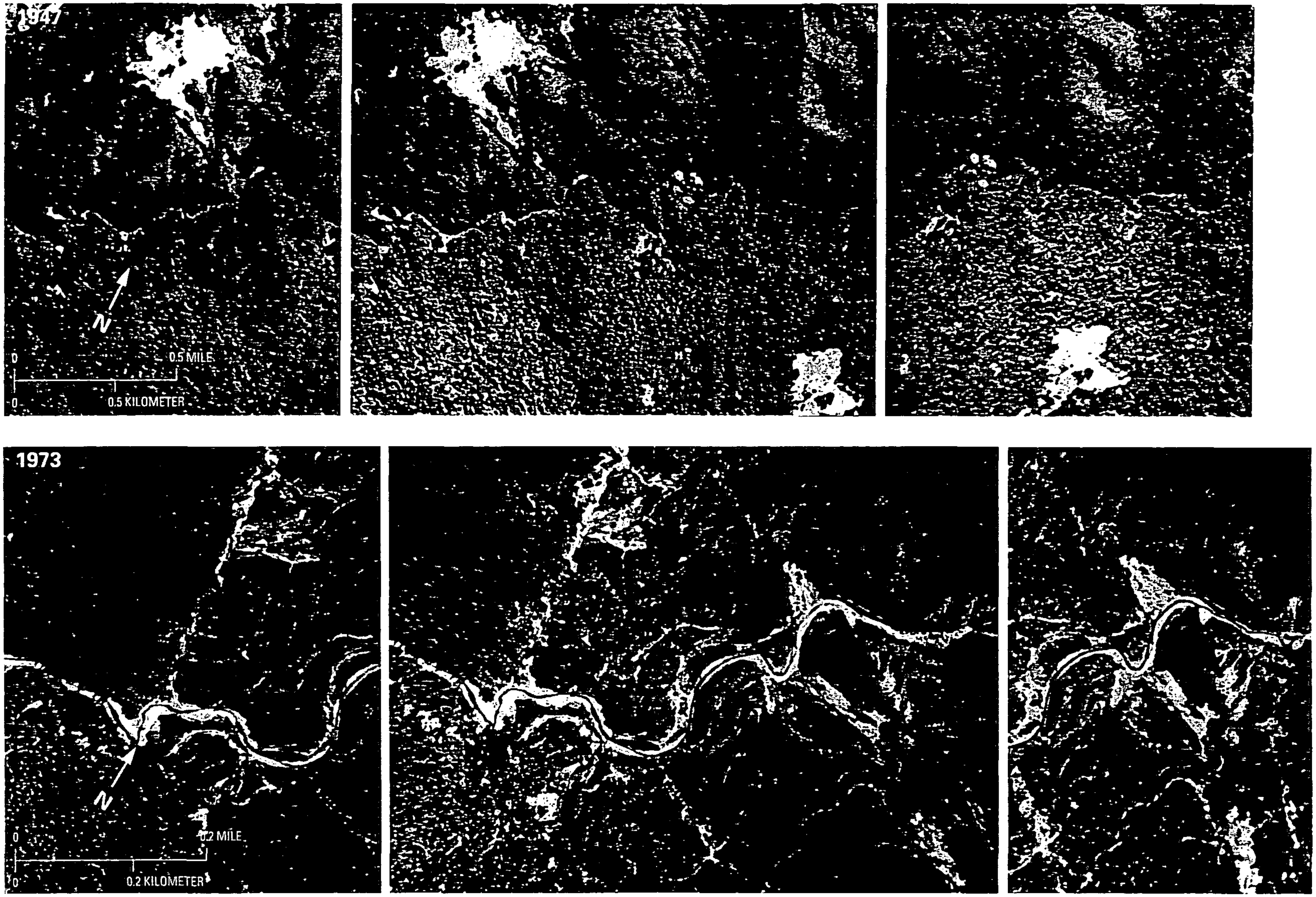

FIGURE 8.—Stereograms showing conditions of the Redwood Creek channel in 1947 and 1973 near cross profiles 35 and 36 (reach C). Arrows point to identical location on each set of photographs. Note removal of large amounts of midchannel vegetation by 1973.

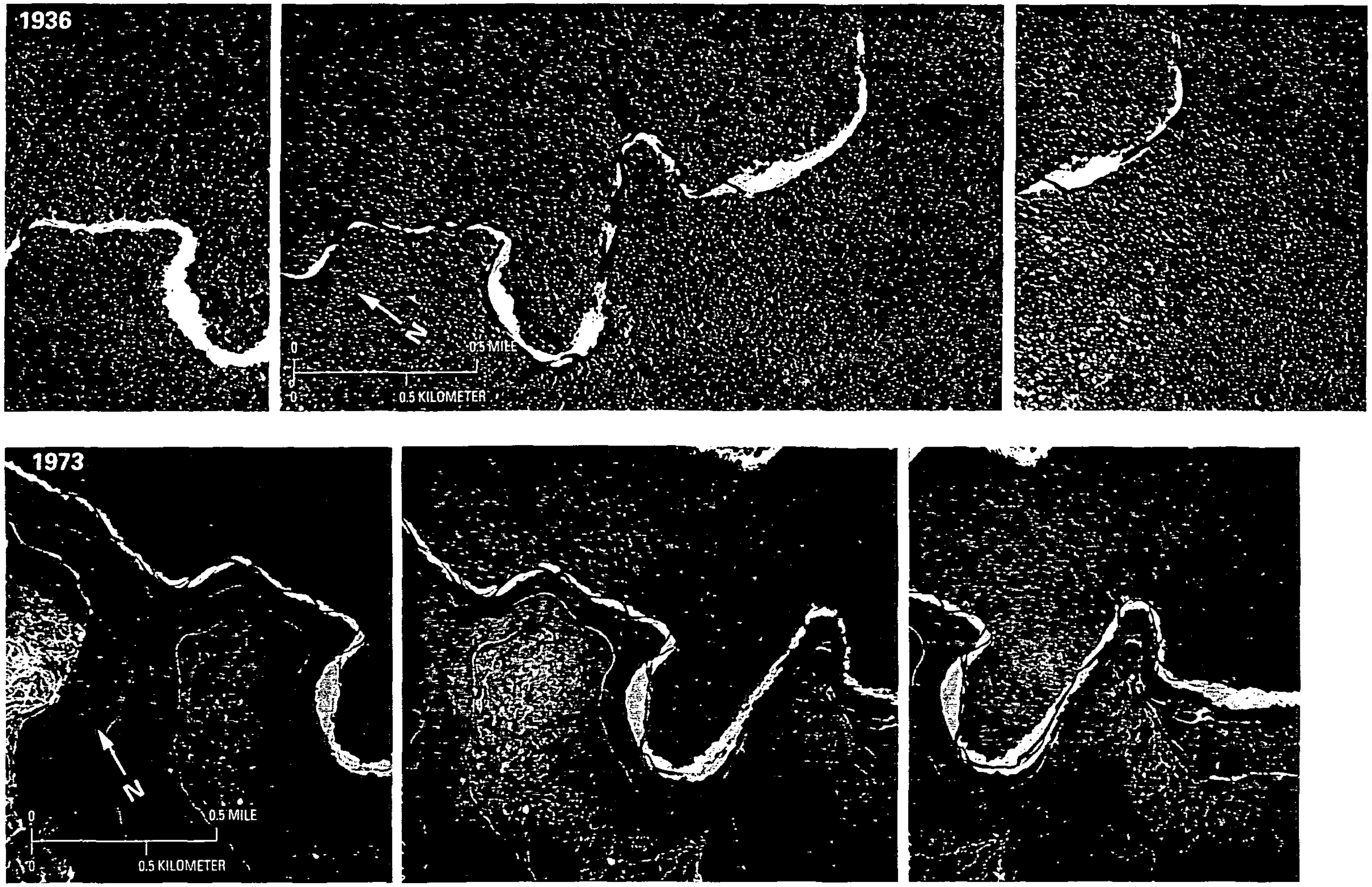

FIGURE 9.—Stereograms showing conditions of the Redwood Creek channel in 1936 and 1973 near the Tall Trees Grove in reach A. Note lack of significant changes in these reaches. Both sets of photographs are at approximately the same scale.

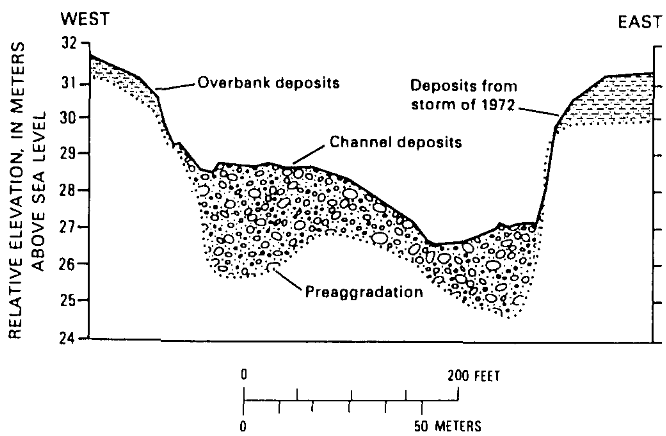

FIGURE 10.—Recent changes in the geometry of Redwood Creek at the mouth of Tom McDonald Creek. Preaggradation configuration was estimated from reports of local forest workers and road construction records. Configuration in 1972 is from ground surveys.

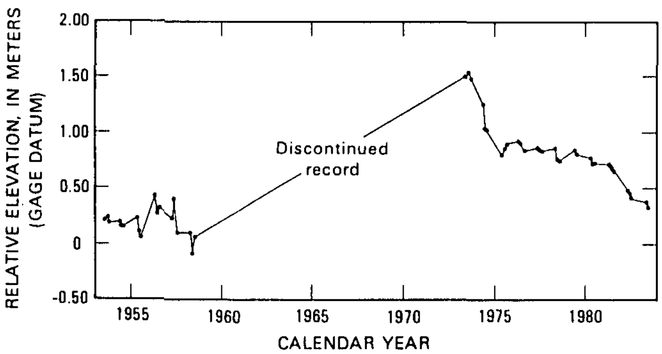

FIGURE 11.—Variation in mean elevation of the low-flow channel of Redwood Creek at the gaging station near Blue Lake (11481500). Mean streambed elevations were determined by using methods described by Hickey (1969).

FIGURE 12.—Trees toppled by bank erosion immediately downstream of the Tall Trees Grove. Photograph taken March 1976.

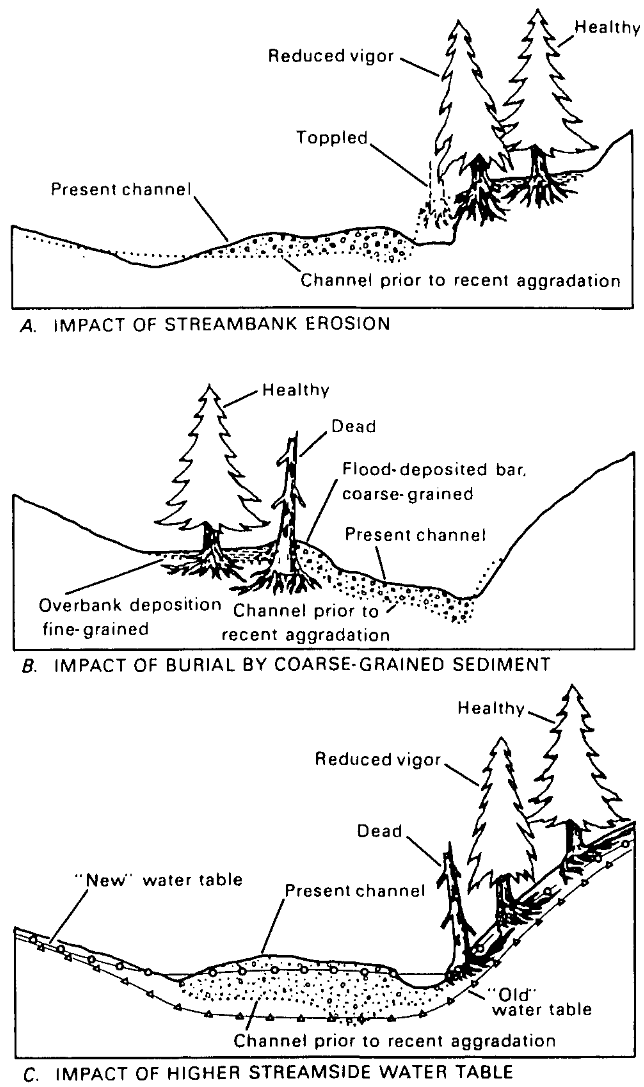

FIGURE 13.—Schematic representation of observed impacts of channel aggradation on riparian vegetation.

many of which were 200–300 years old (Janda and others, 1975), on the flood plains. Coarse, gravel-sized sediment may limit the supply of nutrients to the shallow root systems common to redwood trees and increase desiccation during warm, dry summer months (Zinke, 1981). Elevated water tables associated with channel aggradation also affected the health of many streamside trees (fig. 13).

VARIATIONS BETWEEN 1974 AND 1982

Changes in the cross-sectional area of Redwood Creek between October 1973 and August 1981 were monitored by a network of surveyed cross profiles (figs. 1, 14). This

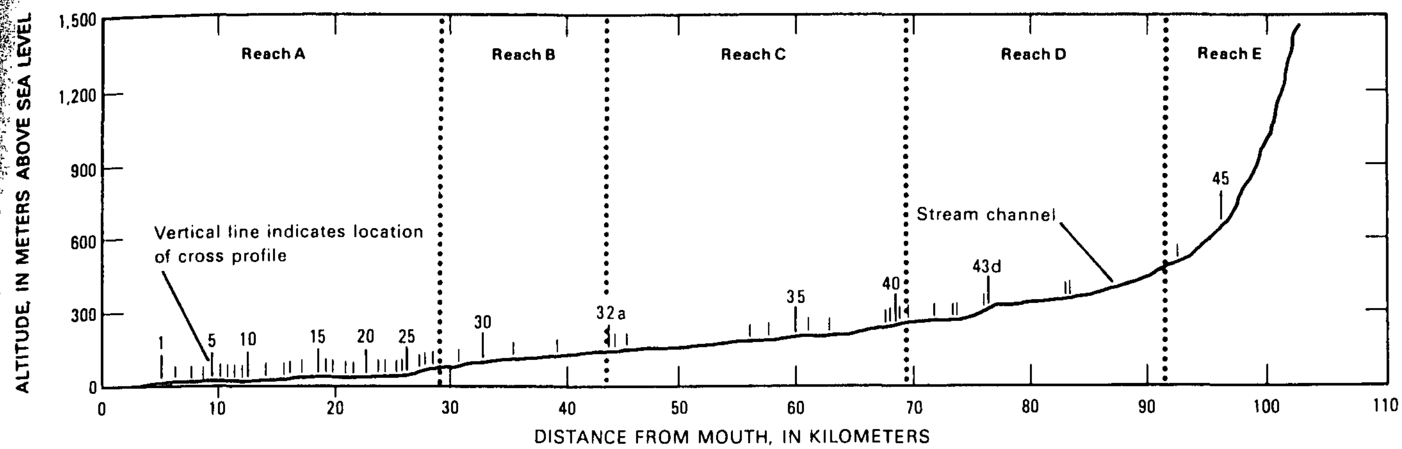

FIGURE 14.—Longitudinal profile of Redwood Creek showing location of study reaches and surveyed stream-channel cross profiles.

network, which consisted of 43 profiles in 1973, was expanded to include 53 profiles by 1978. End points were monumented by a 12.5-mm reinforcing bar, and profiles were determined by using a self-leveling level and stadia measurements. The slow recovery process following the floods of 1964 and 1972 is also illustrated by hydraulic geometry data for the period 1975 to 1982 (table 3).

Generalized channel behavior in each of the five study reaches from water years 1974 to 1981 is summarized in figure 15 and tables 4 and 5. Figure 15 presents changes in streambed area at all cross profiles for each study reach. Data in this figure have been normalized by dividing changes in cross-sectional area by bank-to-bank channel width to provide a better measure of the impact of the change at a given cross profile. Table 4 lists the number of cross profiles in each study reach that showed either scour, fill, or no change in streambed and streambank areas. Table 5 presents a brief description of channel behavior as indicated by data presented in earlier text, as well as in figure 15.

Although some annual variations occurred, the channel geometry data indicate a general pattern of channel scour in upstream reaches and channel fill in lower reaches between the 1974 and 1981 water years. Channel scour was particularly pervasive in reaches C, D, and E, and channel fill was generally found in reaches A and B. Channel fill was particularly prominent directly downstream of the steep rocky gorge that marks the upstream end of reach A. The magnitude of channel changes in 1974 and 1975 was relatively high, probably owing, at least in part, to relatively high streamflow during these years (table 6). The relatively minor changes recorded during the 1977 water year probably reflect the relatively low streamflow that occurred during that year.

The general pattern of channel behavior changed markedly in 1981 when 17 of 24 sections in reach A showed channel scour. This year was characterized by streamflow that was slightly below normal. Scour occurred at 31 of the 48 cross sections surveyed in 1981 at reach A. Streambank erosion was generally more common than streambank deposition throughout the period of resurveys (table 4).

GRAIN-SIZE DISTRIBUTION OF BED MATERIALS

The size distribution and lithologic composition of the bed material of Redwood Creek were determined by grid sampling of surficial material. Bed material was sampled at all 45 cross profiles surveyed in 1976 and was resampled at 13 of those sites during the summers of 1979 and 1982. The 13 resampled sections were chosen to represent conditions along major reaches that have distinctively different channel characteristics.

Field methods used for grid sampling follow those suggested by Wolman (1954). Five transects perpendicular to the channel were established at each survey site. One transect was on the survey line, while the others were spaced at distances equal to one-quarter and one-half the channel width upstream and downstream of the survey line. The median axis and lithology of bed-material clasts were noted at 30 points on each transect to sample a total of 150 points at each cross-profile site.

For all data, size-class frequency distributions and weight percentages per size class were determined by following methods presented by Leopold (1970). Size-class frequency distributions indicate the percentage of streambed area covered by various sizes, whereas weight percentages provide data roughly comparable to those obtained by sieve analysis. Phi values of D_{16}, D_{50}, and D_{84} were determined from cumulative curves of weight percentages (D refers to median diameter and the subscripts 16, 50, and 84 refer to the percentage of sediment with median diameters smaller than those values). Mean values were determined by summing phi

TABLE 4.—*Number of cross profiles showing either scour, fill, or no change of streambed and streambanks from water years 1974 to 1981*

Year and reach	Streambed			Streambanks		
	Scour	Fill	No change	Scour	Fill	No change
1974:						
A	7	18	0	19	3	3
B	5	2	0	3	4	0
C	8	1	0	4	0	5
D	1	0	0	1	0	0
E	None established			None established		
1975:						
A	8	17	0	9	14	2
B	0	7	0	5	2	0
C	5	7	0	9	1	2
D	2	0	0	0	0	2
E	1	1	0	1	1	0
1976:						
A	8	17	0	14	5	6
B	6	1	0	4	0	3
C	11	1	0	6	2	4
D	2	0	0	0	1	1
E	1	1	0	1	1	0
1977:						
A	11	13	0	5	4	15
B	5	2	0	3	0	4
C	6	6	0	2	1	9
D	0	2	0	1	0	1
E	0	1	0	0	0	1
1978:						
A	9	15	0	14	9	1
B	5	1	1	3	4	0
C	10	2	0	5	5	2
D	2	0	0	2	0	0
E	1	1	0	1	1	0
1979:						
A	9	14	0	6	3	14
B	4	3	0	5	0	2
C	4	5	0	4	1	4
D	1	1	0	0	0	2
E	2	0	0	1	0	1
1980:						
A	8	16	0	8	16	0
B	4	3	0	0	7	0
C	3	5	0	3	4	1
D	3	2	0	3	2	0
E	Not surveyed			Not surveyed		
1981:						
A	17	6	1	14	1	9
B	4	3	0	4	0	3
C	5	4	0	4	1	4
D	4	3	0	2	1	4
E	2	0	0	1	0	1

values of D_{16}, D_{50}, and D_{84} and dividing by 3, as suggested by Folk and Ward (1957).

The lithologic composition of the bed material was assessed by assigning clasts to one of the two major rock units in the basin (unmetamorphosed rocks or schist) or to an "others" category for rock types not diagnostic of either unit or for clasts too small to identify lithologically. Weight percentages of unmetamorphosed clasts include clasts identified as shale, siltstone, sandstone, or conglomerate, whereas weight percentages of schist include schist and metavolcanic clasts (Harden and others, 1982).

BED MATERIAL CHARACTERISTICS IN 1976

In 1976 the bed of Redwood Creek was dominated by gravel-sized clasts (phi=−2 to −6). Longitudinal variations in mean grain size reflected gross channel morphology and distance from the mouth. Steep, incised reaches such as B, D, and E had relatively large mean grain sizes. Wider reaches, such as A and C, which flow through well-defined alluvial flats, were characterized by relatively small grain sizes (fig. 16). Generally, mean grain size decreased in a downstream direction (fig. 16).

The lithologic composition of the clasts sampled in 1976 indicates that disproportionately high percentages of recognizable clasts on the bed of Redwood Creek were derived from terrane underlain by unmetamorphosed rocks relative to terrane underlain by schist. Even though roughly similar amounts of the basin above Bridge Creek are underlain by unmetamorphosed rocks and schist (Harden and others, 1982), the pebble-count data indicate that unmetamorphosed rocks consistently constituted greater percentages of the streambed in reaches B–E (fig. 17). The percentage of schist in the streambed clasts about equaled that of unmetamorphosed rocks only in reach A, which is mostly below the mouth of Bridge Creek, where schist begins to underlie a large percentage of the drainage area. The disproportionate contribution of unmetamorphosed rocks to the alluvium of Redwood Creek most likely reflects the fact that more area characterized by recent mass-movement activity is underlain by unmetamorphosed rocks than by schist (Harden and others, 1978). However, since the fine-grained, foliated schist clasts may be more easily broken down by abrasion during transport within the channel, a greater proportion of small, unrecognizable clasts may be derived from schist, so that the discrepancy may appear greater than it actually is.

BED MATERIAL CHANGES BETWEEN 1976 AND 1982

Mean grain size increased between 1976 and 1982 at 11 of the 13 cross profiles at which pebble counts were repeated (fig. 18). Increases in D_{16} were generally greater than in D_{84} (fig. 19), which suggests that the winnowing out of fine material was largely responsible for the increases in mean grain size. The selective removal of fine material is also suggested by the fact that, at 11 of the 13 cross profiles, the percentage of area covered by sand, silt, and clay decreased between 1976 and 1982 (fig. 20).

From 1976 to 1982, the ratio of weight percentages of unmetamorphosed clasts to weight percentages of schist clasts increased at all of the resampled cross profiles (fig. 21). This increase may be related to the sorting and weathering processes that were responsible for increases in mean grain size, as the schist clasts are commonly

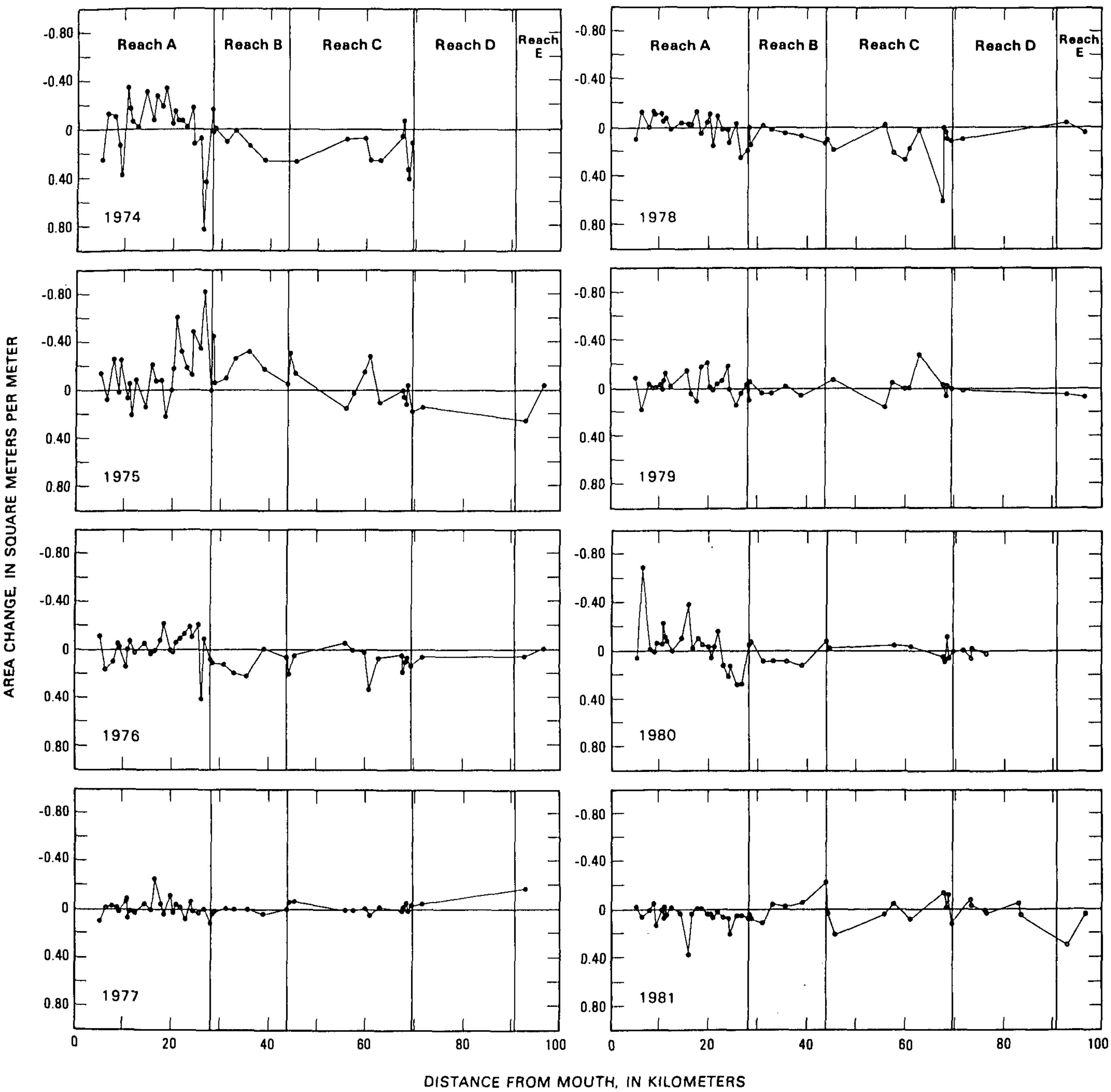

FIGURE 15.—Change in area of the streambed at cross profiles between water years 1974 and 1981. Area change is expressed in square meters of change per meter of bank-to-bank width. Channel scour is indicated by a positive change in area, and channel fill by a negative change. The lines connecting data points have no physical significance. They are presented only to aid in interpreting the data.

more breakable and consequently smaller than unmetamorphosed clasts in the streambed. The increase also may indicate that between 1976 and 1982 processes contributing sediment to Redwood Creek continued at more rapid rates on slopes underlain by unmetamorphosed rocks than on those underlain by schist.

Although net changes between 1976 and 1982 show pervasive increases in mean grain size as well as in the ratio of unmetamorphosed rock to schist bed material, these trends were not everywhere continuous. At two sites in reach B, a decrease in mean grain size was noted from 1976 to 1979, followed by an increase in mean grain

TABLE 5. *Summary of observed behavior of the Redwood Creek channel*

[Observations prior to 1974 are from a combination of aerial photograph interpretation, interviews with long-term residents, and gaging-station records. Observations after 1974 are from repetitive surveys of channel cross profiles]

Period	Reach A	Reach B	Reach C	Reach D	Reach E
1936–50	Wide gravel flood plain; inner channel shifted frequently.	Alternately narrow and wide gravel channel; narrow reaches bounded by steep valley walls.	Sinuous channel moderately incised into wide alluvial flood plain; channel lined with conifers.	Narrow sinuous channel with closed vegetation canopy.	Same as D.
1950–74	Wide gravel flood plain; inner channel shifted frequently; some increase in width of flood plain; channel fill in excess of 1.5 m noted; some riparian trees damaged by battering and burial.	Alternately narrow and wide gravel channel; some riparian vegetation damaged.	Channel filling in excess of 4.6 m noted; most conifers on flood plain removed.	Channel widening in excess of 100 percent noted; closed canopy gone due to abundant streamside debris slides.	Same as D.
1974	Channel fill dominant; some widening.	Channel scour dominant	Channel scour dominant	Channel scour dominant	Not surveyed.
1975	Pervasive channel fill accompanied by bank deposition.	Channel fill dominant	Channel filling slightly more prevalent than scour.	Channel scour dominant	Scour equal to fill.
1976	Minor fill	Minor scour	Minor scour at nearly all profiles.	Minor scour	Scour equal to fill.
1977	Minor fill	Scour equal to fill	Scour equal to fill	Minor scour	Minor fill, but only one profile surveyed.
1978	Minor fill	Minor scour	Scour about equal to fill	Minor scour	Channel scour dominant.
1979	Minor fill	Minor scour	Scour about equal to fill	Minor scour	Minor scour.
1980	Pervasive fill	Pervasive scour	Scour about equal to fill	Scour about equal to fill	Not surveyed.
1981	Scour at nearly all profiles	Minor fill	Scour about equal to fill	Scour about equal to fill	Scour.

TABLE 6.—*Summary of streamflow recorded for Redwood Creek at Orick during period of channel cross-profile surveys*

[Average annual runoff for 30 years of record was 1,290 mm. Peak of record was 1,430 m³/s on December 22, 1964. Peak discharges listed are those above a base of 255 m³/s. Gaging station no. is 11482500]

Water year	Total runoff (mm)	Date of peak discharge	Peak discharge (m^3/s)
1974	2,141	Oct. 23	459
		Nov. 8	303
		Nov. 12	306
		Nov. 30	422
		Jan. 16	445
		Feb. 19	314
		Mar. 30	377
		Apr. 1	702
1975	1,618	Jan. 8	340
		Feb. 13	276
		Feb. 19	558
		Mar. 18	1,422
		Mar. 25	569
1976	1,048	Dec. 4	286
		Feb. 28	343
1977	238	No peak above 255 m^3/s	
1978	1,448	Nov. 22	265
		Nov. 24	273
		Dec. 14	600
		Jan. 17	300
1979	785	Jan. 11	399
1980	1,374	Nov. 24	357
		Jan. 12	405
		Mar. 14	549
1981	801	Dec. 2	256

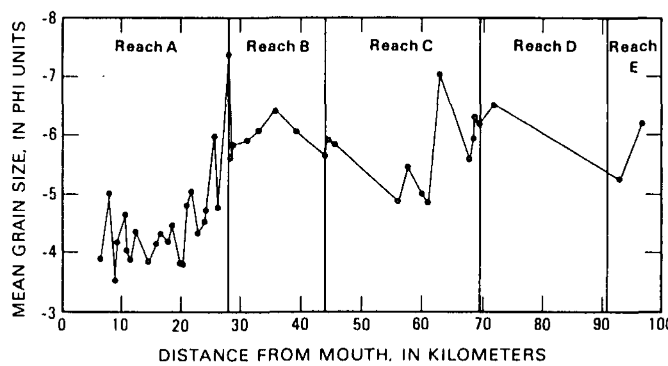

FIGURE 16.—Mean grain size of bed material at cross profiles during the summer of 1976.

size from 1979 to 1982 (fig. 18). In addition, most cross-profile sites in reaches B and C and in the downstream half of reach A showed an increase in the ratio of weight percentage of unmetamorphosed clasts to weight percentage of schist clasts from 1976 to 1979 followed by a decrease in that ratio between 1979 and 1982 (fig. 21).

CAUSES OF CHANGES IN CHANNEL GEOMETRY

Major changes in streambed elevation and width of the Redwood Creek channel coincided with major storms

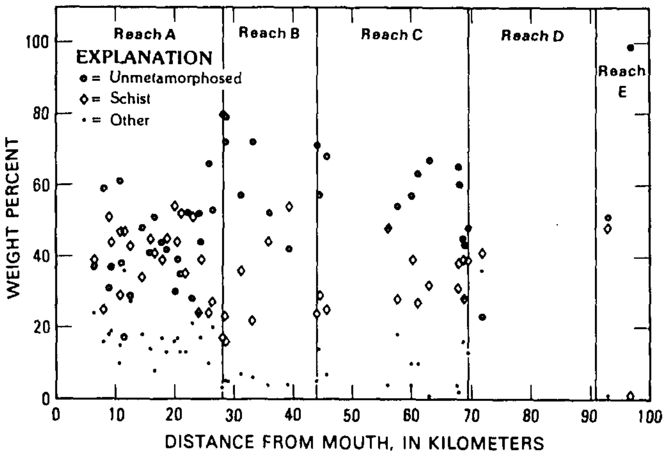

FIGURE 17.—Lithologic composition of bed material at cross profiles during the summer of 1976. "Unmetamorphosed" refers to conglomerate, sandstone, and mudstone clasts. "Schist" refers to schist and foliated metavolcanic clasts. "Other" refers to quartz and unfoliated greenstone clasts, and clasts too small for lithologic identification.

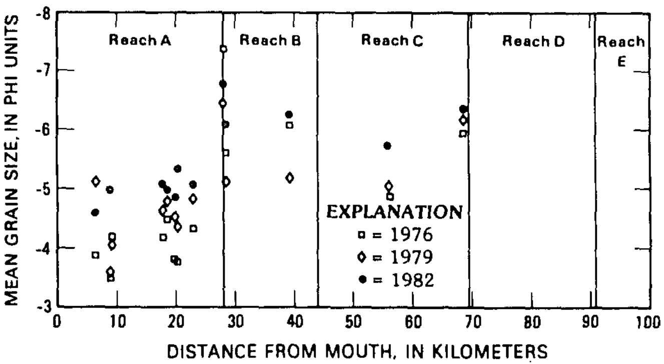

FIGURE 18.—Mean grain size at selected cross profiles in summers of 1976, 1979, and 1982.

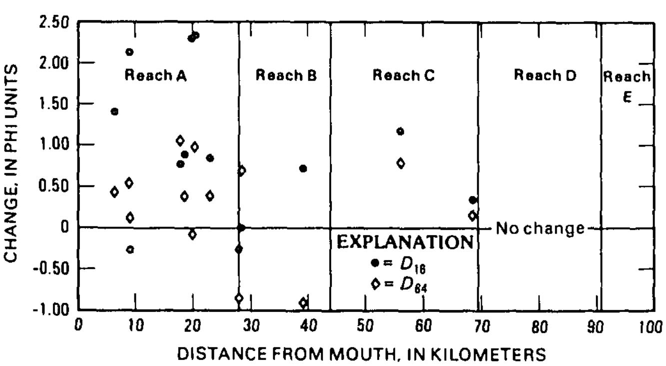

FIGURE 19.—Changes in D_{16} and D_{84} at selected cross profiles between the summers of 1976 and 1982. See p. XX for an explanation of D_{16} and D_{84}.

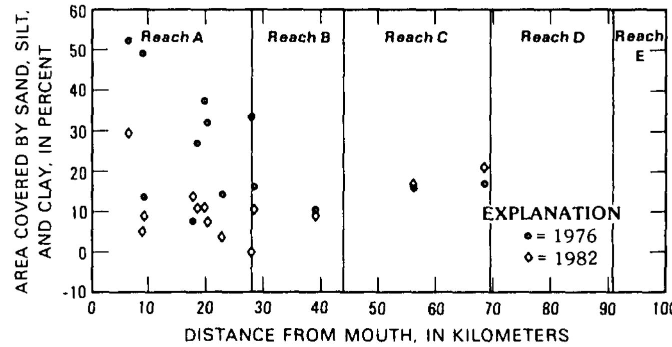

FIGURE 20.—Percentage of streambed area covered by sand, silt, and clay at selected cross profiles, summers of 1976 and 1982.

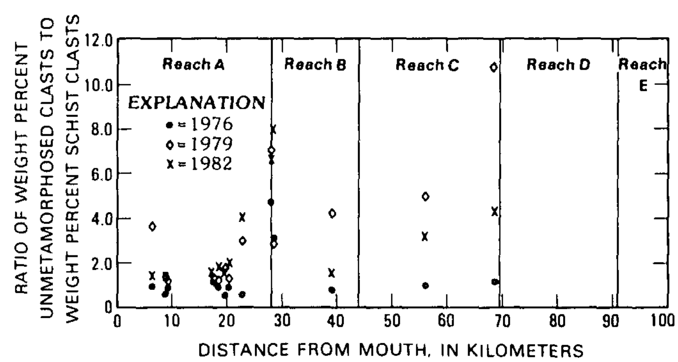

FIGURE 21.—Ratio of weight percent unmetamorphosed rocks to weight percent schist in bed material at selected cross profiles, summers of 1976 and 1982.

and with large increases in the percentage of the basin subjected to timber harvesting (fig. 22). These storms and land use greatly accelerated erosion and sediment-transport processes that were already active before the study period (Janda and others, 1975). Large increases in sediment supply, caused by the storms and the widespread timber harvesting, overloaded channel transport capacities. Channels filled and widened to accommodate this increase in sediment. In addition, increases in runoff caused by timber harvest probably accelerated channel widening. The observed causal relation between increased sediment supply and runoff and increased channel instability has been documented by several field and laboratory studies (Gregory, 1977; Schumm, 1977; Lisle, 1982).

The 1964 storm caused the most dramatic of the observed changes in channel geometry. The effects of this storm were far greater than those associated with either earlier storms in 1953 and 1955 or with later storms in 1972 and 1975, even though all of these storms were associated with roughly similar peak streamflow

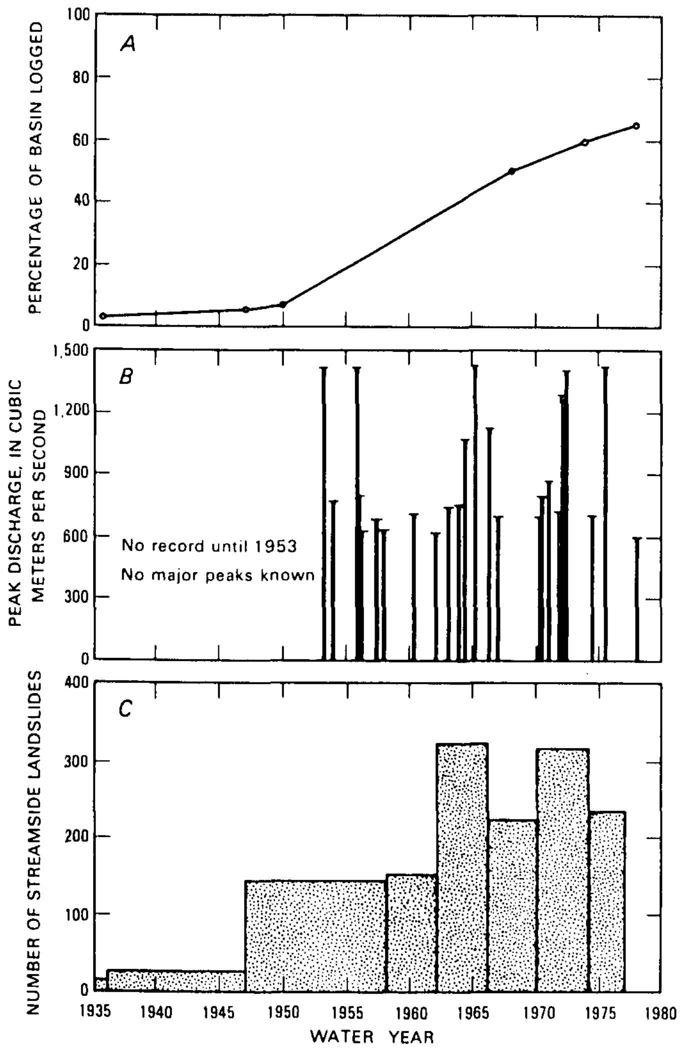

FIGURE 22.—Summary of storms, land use, and streamside landsliding in the Redwood Creek basin, 1936 to 1981. *A*, The percentage of the basin logged; logging history information is from Janda and others (1975), Iwatsubo and others (1975 and 1976), and Harden and others (1978). *B*, Peak discharge above a base of 600 m^3/s as measured at the gaging station, Redwood Creek at Orick (11482500). *C*, Number of streamside landslides mapped by Nolan and others (1976) and Harden and others (1978).

(table 1). The second most damaging storm, which occurred in January 1972, produced some channel filling and widening, particularly along downstream reaches. Vegetation established on gravel flood berms along downstream reaches dates to the 1972 storm. Channel filling in downstream reaches during 1972 also may reflect the downstream transport of sediment stored along upper reaches as a result of the 1964 storm.

The channel filling and widening related to these storms appear to have been primarily the result of large volumes of colluvium introduced to channels by streamside landslides during the storms. Observations of time-sequential aerial photographs indicate that the number of streamside landslides adjacent to the main channel of Redwood Creek approximately doubled around the time of the 1964 storm (fig. 22*C*). The fairly unstable colluvial streamside hillslopes commonly found adjacent to the Redwood Creek channel fail easily when undercut by high streamflow. Similar undercutting appears to have triggered many of the storm-related landslides (Colman, 1973; Harden and others, 1978).

INTERACTION OF HILLSLOPE AND CHANNEL PROCESSES

The ability of major storms to trigger exceptionally large numbers of landslides throughout the drainage basin may be related to the manner in which physical processes operating in stream channels interact with those operating on hillslopes in this highly erosive terrane. Colman (1973) suggested that a positive feedback loop exists between these two sets of processes in the Redwood Creek watershed. A single landslide along the naturally unstable hillslopes may trigger additional landslides downstream by deflecting streamflow or causing local channel fill, which raises water levels and undercuts banks (fig. 23). Such interaction leads to abundant landslides throughout entire watersheds and results in the introduction of large volumes of colluvium directly into high-order channels.

IMPACTS OF TIMBER HARVEST

Investigators have found it difficult to quantify the extent to which timber harvesting has increased the amount of sediment introduced to the channel of Redwood Creek. The increase appears to be due primarily to the superimposition of timber harvesting effects on an erosional system that is extremely active naturally. Colman (1973), Janda and others (1975), and Harden and others (1978) have all found that timber harvesting and related road construction are associated with a higher than normal incidence of landsliding. Nolan and Janda (1981) found that the massive ground disruption and rearrangement of natural drainage systems caused by timber harvest accelerated fluvial erosion in harvested basins. As much as 80 percent of the ground surface insome areas of the watershed was disturbed by harvesting activities (Janda, 1978), and bare soil was exposed in over 40 percent of some tributary basins (Nolan and Janda, 1981). Figure 24 shows the results of particularly disruptive practices near the mouth of Bridge Creek. Synoptic sediment sampling reported by Nolan and Janda (1981) indicates that tributaries subjected to large-scale harvesting were characterized by sediment yields as much as 10 times greater than those from comparable

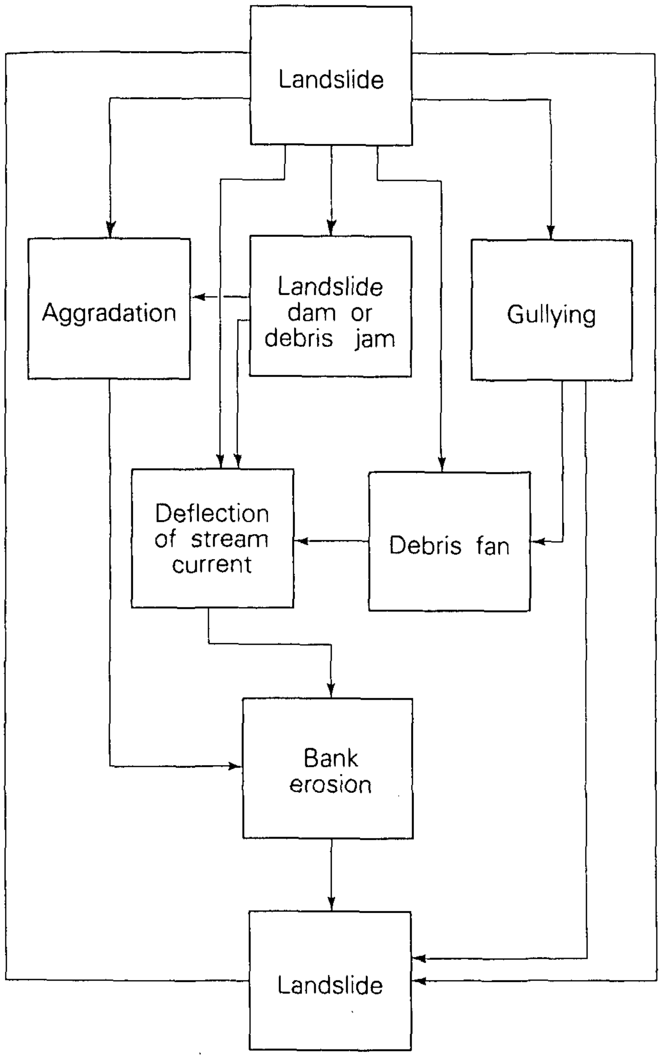

FIGURE 23.—Positive feedback loop, proposed by Colman (1973), between physical processes.

unharvested basins. Sediment introduced either directly by fluvial erosion or from harvest-related landslides may have helped trigger the positive feedback loop described by Colman (1973) among physical processes. This observation prompted Harden and others (1978) to suggest that timber harvesting caused the 1964 and 1972 storms to have impacts disproportionate to storm magnitude. Perhaps without timber harvesting these storms would have had effects similar to those of the 1953 and 1955 storms.

In addition to the effects on sediment yield, timber harvesting also is related to increased storm runoff throughout the basin, probably because of increases in the area of impervious surfaces. Lee and others (1975) suggested that timber harvesting increased storm runoff throughout the basin by about 20 percent. Nolan and Janda (1981) reported that runoff from harvested basins

TABLE 7.—*Relation between behavior of the streambed and streambanks at surveyed cross profiles*

[Numbers indicate the number of measurements in which a relationship was found. Streambank behavior reflects net change at both banks. Numbers in parentheses indicate frequencies to be expected if no relationship exists between streambed and streambank behavior. Total chi square=6.41]

Streambed behavior	Streambank behavior		Total
	Erosion	Deposition	
Fill	123 (134)	58 (47)	181
Scour	148 (137)	38 (49)	186
Total	271	96	

during synoptic storm sampling was between 1.3 and 12 times greater than that from comparable unharvested basins.

Analysis of stream-channel behavior during the period of resurveys (1973–82) indicates some of the effects of this increased runoff. Table 7 presents the distribution of streambank erosion and deposition relative to the behavior of the channel bed. This contingency table indicates the dominance of streambank erosion over deposition. In addition, a chi-square analysis (Dixon and Massey, 1969) indicates that, at the 95-percent confidence level, streambank behavior depends on streambed behavior. The numbers in parentheses in table 7 are the expected frequencies of occurrence if there were no association between streambank and streambed behavior. These data indicate that streambank erosion was associated with streambed scour more frequently than expected, and conversely that streambank deposition was associated with streambed filling more frequently than expected. This association between streambank and streambed deposition suggests that much of the observed streambank erosion resulted from general enlargement of channel cross-sectional area rather than from channel widening that resulted from streambed filling. These data indicate that general channel enlargement was important enough to cause an unexpectedly high frequency of streambank erosion relative to that associated with channel filling. Such general channel enlargement was most likely caused by the increases in basinwide runoff noted by Lee and others (1975). The observed channel behavior was clearly not the result of normal channel migration because under such conditions streambank erosion is about equal to streambank deposition.

DISPROPORTIONATE IMPACTS OF THE 1964 STORM

In addition to possible effects of timber harvest, the seemingly disproportionate impacts of the 1964 storm may be related to the sequencing of storms, the greater severity of the 1964 storm along inland parts of the basin, and the duration of high streamflow associated with the

FIGURE 24.—Highly disruptive timber-harvest practices along lower reaches of Bridge Creek. Photograph taken April 1975.

storm. Harden and others (1978) suggested that the 1955 storm may have slightly destabilized streamside hillslopes and left them more susceptible to future failure. Their report also suggests that, inasmuch as the 1972 storm was most severe along downstream reaches of Redwood Creek, it may not have triggered as many landslides because those downstream reaches contain less steep streamside slopes and because hillslopes are commonly buffered from the channel in these areas by wide flood plains. Although the 1972 storm reactivated many of the landslides triggered by the 1964 storm, it did not produce an increase in slide occurrence (fig. 22) (Harden and others, 1978), possibly because most of the likely sites for landslides had failed during the 1964 storm and additional failure sites did not have time to develop before the 1972 storm. Many of these sequencing effects are similar to those described by Bevin (1981). One more factor that may help explain the catastrophic impacts of the 1964 storm relates to the length of time high stream stages were maintained during the storm. As table 1 shows, the 1964 storm was associated with 41.4 cm of runoff, much more than that associated with any of the other storms, so that stream stages would have been elevated for longer periods of time than during the other storms and thus more bank erosion could have occurred. Bank erosion in turn destabilized hillslopes and thus resulted in more streamside landslides.

INDICATIONS OF CHANNEL RECOVERY, 1974 TO 1982

CHANGES IN CHANNEL GEOMETRY

The patterns of channel change noted at channel cross profiles between 1974 and 1982 appear to reflect the general removal of sediment from upstream reaches and redeposition of at least some of this sediment in downstream reaches. Net removal of sediment from upstream reaches is also illustrated by preliminary sediment-budget data presented by Kelsey and others (1981). According to these data, 16,728,000 Mg of sediment entered the channel above the gaging station near Blue Lake between 1956 and 1980, and 15,800,000 Mg of that material had been transported past the gaging station as of the 1980 water year.

The decrease in the magnitude of channel changes starting in 1976 and the widespread channel scour that occurred during 1981 may mark the beginning of a basinwide recovery from the large volume of introduced material. Weather patterns and improved land use practices between 1976 and 1980 probably helped to initiate the apparent channel recovery. No major storms hit the Redwood Creek basin during this period, peak streamflows were not exceptionally high, and timber harvesting proceeded at a slower rate and under stricter controls than during earlier years.

BED MATERIAL CHANGES

In addition to changes in channel geometry, the trend toward increasing mean grain size of bed material with time also may indicate that some recovery has occurred from a previous period of rapid erosion and aggradation. Because the earliest available data describing grain-size distribution in Redwood Creek were collected in 1976—subsequent to the period of major channel aggradation—no data are available to quantify the effects of channel aggradation on the size of alluvium in Redwood Creek. However, interviews with residents in the Redwood Creek basin (Janda and others, 1975), together with studies in nearby areas (Ritter, 1968; Kelsey, 1980; Lisle, 1981), suggest that aggradation is accompanied by a decrease in mean grain size. These observations suggest that, following the storms of 1964 and 1972, the channel of Redwood Creek was characterized by anomalously small grain sizes. The impacts of these storms persisted to an unknown degree until 1976, and the increases documented after 1976 reflect continued recovery from the earlier period of rapid erosion and channel aggradation. Reduction in the rate at which sediment entered Redwood Creek has apparently allowed winnowing of fine-grained alluvium from the bed, so that mean grain sizes increased.

The degree to which the grain-size data represent significant recovery in channel geometry is not clear. Attempts to correlate changes in cross-sectional area with changes in grain size at individual cross sections over a 1- to 2-year period were inconclusive. Trends in geometric changes were less consistent than those in grain size, and no meaningful correlations were found between the two data sets. Changes in grain-size distribution may represent incipient changes in channel geometry that are presently too subtle to distinguish in cross-sectional surveys.

Although the degree to which recent changes in bed material composition signal changes in channel geometry is questionable, the observed decreases in the percentage of streambed area covered by sand, silt, and clay do indicate considerable improvement in the aquatic habitat. The induration of streambed gravels with sand, silt, and clay impedes the construction of redds by spawning fish and affects emergence of young fry (Phillips, 1971). By reducing circulation of water through gravels, fine sediments also reduce the supply of oxygen to eggs and young fry, as well as the rate at which toxic waste products are removed.

PERSISTENCE OF CHANNEL CHANGES

Data presented in this paper indicate that the major changes in channel geometry that began in 1964 have persisted for decades and may persist for decades longer. All data available indicate that the channel of Redwood Creek did not show signs of widespread recovery from the recent period of rapid changes until the 1981 or 1982 water year. Although total recovery time depends upon the magnitude and sequencing of future storms, complete recovery will probably require at least several decades. The sediment budget presented by Kelsey and others (1981) suggests that, even without additional inputs of sediment, about 30 additional years are needed to transport sediment stored above the 1947 thalweg out of the basin. Recovery will probably take longest in downstream reaches.

It is difficult to judge whether the persistence of the channel filling and widening noted should be measured from 1964 or from 1972. Although the 1972 storm did not initiate large numbers of landslides, it did reactivate many of the 1964 landslides and no doubt added significant volumes of sediment to the channel. At least, the 1972 storm delayed basinwide recovery from the 1964 storm.

Basinwide recovery from the introduction of storm-related sediment has probably also been delayed by cumulative effects of timber harvesting. Often, new logging was begun adjacent to already logged areas in basins that had not been allowed enough time to recover from the increased water discharge, increased sediment yield, and hillslope instability triggered by the initial logging (Janda, 1978). As progressively larger parts of drainage basins were logged, basinwide impacts on runoff and sediment yield accumulated in a downstream direction. Impacts in downstream locations were therefore greater than at individual sites upstream or upslope.

Despite the uncertain effects of the 1972 storm and the timber harvesting, examination of the physical processes operating in the basin suggests that major storms exert long-lasting controls on channel geometries. The large volumes of sediment introduced by storm-related landslides are sufficient to overwhelm channel transport capacities for decades (Kelsey and others, 1981). Long periods of moderate flow are required to remove this sediment from the basin, as was indicated by analysis of sediment-transport relations reported by Nolan and Janda (1981) and by the observation of storm effects within the basin. The analysis and observations indicate that periods of high streamflow are associated with channel fill in the main channel of Redwood Creek and with scour along tributary channels. Conversely, periods of moderate flow are associated with scour along the main channel and fill in tributary channels.

Besides the need for long periods of moderate flow to transport storm-related sediment from the basin, the complex interaction between stream-channel and hillslope processes seems to dictate that long periods of slight erosion are needed for recovery. If landslide scars are not healed and channels remain filled with storm-related sediment, subsequent high flow may trigger the positive feedback loop and reactivate many of the original landslides, as apparently happened in the 1972 storm. Recovery from the period of exceptionally severe channel changes caused by the 1964 storm has apparently begun along many reaches of Redwood Creek. However, if the basin is subjected to a major storm before recovery is complete, the persistence of this apparent recovery is uncertain.

GEOMORPHIC SIGNIFICANCE OF RECENT EVENTS

The persistence of channel changes caused by recent storms in the Redwood Creek basin suggests that such storms play an important role in shaping channel morphology in the region. The use of persistence of impacts as a measure of geomorphic effectiveness was suggested by Wolman and Gerson (1978). Other measures of effectiveness such as the "most work" concept of Wolman and Miller (1960) do not appear to be as appropriate as the persistence of impacts in the Redwood Creek system. The "most work" hypothesis, which appears to hold in many stream systems, suggests that stream discharges with moderate return frequencies transport the most sediment over long periods of time and therefore have the greatest effect on channel morphology. In the Redwood Creek system, as well as in some other steep and highly erosive terranes (Stewart and LaMarche, 1967; Helley and LaMarche, 1973), however, the amount of sediment introduced during and after major storms totally overwhelms channel systems. Channel morphology during the long recovery period following major storms reflects flood effects in combination with effects of more moderate flows. The geometry of the channel is strongly dependent on the length of time since a major flood and on the level of postflood flows available to modify flood effects and to transport flood-deposited alluvium. Some features that are out of reach of moderate flows, such as the gravel flood berms, may be modified only by another major flood. The need to consider the effects of both high and moderate flows has recently been noted by Gupta (1983).

Timber harvest does not appear to cause fundamental changes in the response of the channel to major storms. Harden and others (1978) have shown that all the erosional processes triggered by the 1964 and 1972 storms and the manner in which these processes interacted occur naturally in the area. By initiating streamside landslides and increasing runoff, however, timber harvesting may have exacerbated effects of the 1964 and 1972 storms by triggering the positive feedback loop discussed on page XX.

The key to assessing whether or not the 1964 and the 1972 storms were truly significant in the geomorphic sense lies in knowing whether or not effects generated by these storms will persist longer than the expected recurrence interval of the storms themselves (Wolman and Gerson, 1978). Such an assessment is complicated in the Redwood Creek basin because of the close succession of the 1964 and 1972 storms and the uncertain role played by timber harvesting. The sequencing of the 1964 and 1972 storms raises questions as to whether channel recovery should be measured from 1964 or from 1972. Since timber harvesting appears to have caused the storms to have impacts disproportionate to storm magnitude, it is difficult to determine the recurrence interval against which to measure storm impacts. The 1964 storm may have produced effects that would have occurred only during a storm with a much longer recurrence interval under natural conditions. Despite this difficulty, the 1964 and 1972 storms provided the opportunity to study the processes triggered by major storms and the interaction of processes operating in stream channels with those operating on hillslopes. Considering the observed operation of these processes and the effects produced by the 1964 and 1972 storms, major storms can be expected to produce long-lasting effects on the main channel of Redwood Creek. Storm-related effects persist along the channel for long periods of time, during which those effects are modified by more moderate flows.

CONCLUSIONS

Study of the historical behavior of Redwood Creek suggests that major storms play an important role in shaping the morphology of the channel. These events introduce exceptionally large volumes of sediment that totally overwhelm channel transport capacities. Long periods of slight erosion are necessary for channel configurations to return to prestorm conditions.

Time-sequential aerial photographs, gaging-station records, and interviews with local residents all indicate that beginning in the mid-1950's the main channel of Redwood Creek began to aggrade and widen. Channel aggradation as much as 4.5 m and width increases of more than 100 percent occurred. Initiation of nearly all major changes in geometry coincided in general with the initiation of large-scale timber harvest and more specifically with the occurrence of major storms in 1964 and 1972.

Monitoring of channel configurations between 1973 and 1982 has documented a general pattern of channel scour in upstream areas and fill along lower reaches. This pattern probably reflects the removal of large volumes of sediment deposited in upstream areas as a result of the major storm in 1964 and the redeposition of at least part of this sediment along downstream reaches. Bank erosion was common throughout this period owing to the combined effects of increased sediment supply and increased runoff. Resurvey of channel cross profiles in 1981, and measurements of the grain size of channel bed material in 1982, indicates that channel recovery may have started basinwide. Scour was pervasive along downstream reaches for the first time in 1981, and mean grain sizes increased significantly in 1982.

The catastrophic impacts of major storms on channel geometry originate, at least in part, from the delicate balance between physical processes operating in stream channels and those operating on adjacent hillslopes. Undercutting of inherently unstable hillslopes causes many landslides, which introduce large volumes of sediment throughout long channel reaches. Human activity can affect this delicate balance. The landslides and increased storm runoff caused by timber harvesting may have helped trigger the positive feedback loop between physical processes, causing the 1964 storm to have a much greater impact than it would have had under natural conditions. In addition to the effects of timber harvesting, the particularly dramatic channel changes associated with the 1964 storm may have been related to the length of time that high stream stages were maintained, the sequencing of storms, and the location of maximum rainfall within the basin.

The relative importance of factors that may have caused the 1964 storm to be so significant in relation to other major storms is speculative, but the evidence given in this report illustrates the complex association of events and processes that must be considered when assessing the types of climatic events most responsible for shaping the main channel of Redwood Creek. In view of the long-lasting nature of storm impacts, channel geometries at any given time probably bear a strong imprint of the effects of major storms, even though those effects may have been modified by the effects of moderate flows.

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