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RECENT CHANNEL ADJUSTMENTS IN REDWOOD CREEK, CALIFORNIA

REDWOOD NATIONAL PARK

RESEARCH AND DEVELOPMENT

TECHNICAL REPORT 18

DECEMBER 1986

SEDIMENT BUDGET PROJECT

In 1978, the National Park Service initiated a study project to formulate a sediment budget for the Redwood Creek basin. This investigation documents and quantifies sediment source areas in the watershed, changes in sediment storage in tributary and mainstem stream channels, and sediment transport out of the basin.Results are presented in a series of Technical Reports and Data Releases, and condensed versions will be published in scientific journals.

NOTICE

This document contains information of a preliminary nature, and was prepared primarily on an interim basis. This information may be revised or updated.

RECENT CHANNEL ADJUSTMENTS
IN REDWOOD CREEK, CALIFORNIA

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Redwood National Park Research and Development

Technical Report Number 18

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ABSTRACT

The shape of Redwood Creek's channel has changed dramatically since the early 1950's. Several large storm events accelerated erosional processes and contributed large amounts of sediment to the mainstem of the creek. Since 1974, annual surveys of channel cross sections have documented channel response to storm events and changes in sediment load in the system. Cross section data indicate that the 1975 flood (RI = 25 years) caused the upstream third of the channel to degrade substantially while the lower 20 km of Redwood Creek severely aggraded. The 1975 storm contributed a pulse of sediment to the lower two-thirds of the channel. Following this brief period of sedimentation, the river has continued to downcut, particularly in wide areas in the middle reach.

Longitudinal profiles of the downstream 22 km, surveyed in 1977 and 1983, and channel cross sections document the movement of an aggradational wave of sediment in the lower third of Redwood Creek. In 1977, a wave of sediment began to move below the base of the gorge and by 1984 it had moved 6 km downstream. Following the passage of this wave, degradation of the streambed occurred, resulting in decreased channel gradients, increased pool-riffle morphology, and channel incision. The downstream reach has experienced aggradation since 1974 and probably since 1964. Active gravel bar surfaces above the elevation of bankside vegetation indicate that the elevation of bankfull discharge has increased in recent years due to streambed aggradation. Low flow channels in aggraded reaches typically shift position annually.

The magnitude of degradation in the lower 20 km indicates that reaches that are presently aggrading should begin to consistently downcut within the next decade under moderate flow conditions. This assumes no large sediment loads are introduced to the system. Recovery of Redwood Creek from recent erosional and flood events will be accelerated if streamside landslides remain dormant. Also, the present decrease of timber harvest activities should result in significantly less sediment contribution from fluvial hillslope erosion. Data from gaging stations located in the upstream third of the watershed and near the mouth indicate that present sediment transport rates have decreased about 40 percent from pre-1978 conditions.

ACKNOWLEDGEMENTS

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ΔA_s	Net streambed area change
ΔE_c	Change in mean cross-sectional streambed elevation
ΔE_ℓ	Change in mean longitudinal streambed elevation
Q_{base}	Baseflow discharge (235 m^3/s)
Q_{bd}	Bedload discharge
Q_{ss}	Suspended sediment discharge
Q_w	Water discharge
RI	Recurrence interval
ΔT	Change in thalweg elevation
W_b	Bankfull width
WY	Water Year, extends from October 1 to September 30

I. INTRODUCTION

Channel configuration and flow characteristics of Redwood Creek in north coastal California have changed greatly since the mid-1950's (Janda and others, 1975). A series of intense storms and the advent of widespread timber harvest in highly erodible terrain during this time have been recognized as major sources of these changes in Redwood Creek and other nearby north coast streams (Hickey, 1969; Denton, 1974; Kelsey, 1977; Kennedy and Malcolm, 1979; Lisle, 1981). Consequently, suspended sediment discharge rates in the late 1960's and early 1970's for Redwood Creek were probably at least seven times greater than the natural erosion rate (Anderson, 1976; Janda, 1978). The volume of stored sediment in the mainstem of Redwood Creek has increased 45 percent since 1947 (Madej, 1984a). Channel characteristics reflecting this increase in stored sediment include increased channel width, increased elevation of the streambed, increased channel braiding, and decreased streambed material sizes (Janda and others, 1975). These changes reflect the tendency of the stream to reestablish equilibrium to convey the load supplied to it by a given discharge. This paper addresses the channel adjustments in Redwood Creek over the past three decades through a study of cross-sectional and longitudinal profile surveys.

Redwood National Park encompasses the lower 40 percent of the Redwood Creek basin. Some of the world's tallest known trees grow on alluvial flats within the park and Redwood Creek historically supported large runs of anadromous salmonids. However, increases in channel stored sediment resulted in a drastic decline in anadromous fish populations and habitat. Extensive aggradation, bank erosion and streamside landsliding caused infilled pools, siltation, loss of streamside canopy, increased water temperature, loss of streamside shelter for fish, and decreased summer flows (Anderson and Brown, 1983). Also, loss and injury of streamside vegetation occurred along the main channel of Redwood Creek from abrasion, burial, undermining by deflected stream flow, and drowning by elevated water tables (Nolan and Janda, 1979).

In 1973, the National Park Service, in cooperation with the U.S. Geological Survey (USGS), initiated sediment studies in Redwood Creek to help formulate management priorities directed at preserving park resources (Janda and others, 1975). Between 1973 and 1978, a total of 58 cross sections were installed along the entire length of Redwood Creek, producing the most extensive basin-wide record of channel response available in the region (Nolan and Marron, in press).

The purpose of this study is to compare the state of the Redwood Creek channel in Water Years 1983 and 1984 to the previous years of record and to evaluate the possibility of damage to park resources. (Note: A water year extends from October to September, that is, Water Year (WY) 1984 is October 1, 1983 to September 30, 1984). This study attempts to document channel geometry changes, to explain how and when stream recovery occurs, and to identify where bank erosion and aggradation threaten park resources.

II. PREVIOUS STUDIES

The physical condition of the Redwood Creek drainage basin as of 1973 was described in detail by Janda and others (1975). Their report identifies processes that were modifying or threatening to modify the ecosystem of Redwood National Park. Major uncertainties and inadequacies in the available data were identified and have been the subject of continuing studies by both the USGS and the National Park Service.

USGS gaging stations have been used to monitor water discharge in the mainstem of Redwood Creek on a regular basis since 1953. They are located at Orick, above Panther Creek, and near Blue Lake (Figure 1). Records from these stations include measurements of continuous water discharge (Q_w), daily or periodic suspended sediment discharge (Q_{ss}), and periodic bedload discharge (Q_{bd}).

Monitoring the sediment in Redwood Creek began with the establishment of a channel cross section network in the summer of 1973. Iwatsubo and others (1976) published data on main channel cross sections for WY 1974. Nolan and Janda (1979) interpreted cross section data from 1973 to 1978. Nolan and Marron (in press) provided and interpreted data from cross sections between 1973 and 1981. Varnum (1984) reported WY 1982 data and, with data provided by Nolan and Marron (in press), made interpretations on cross section data collected between 1973 and 1982.

In the summer of 1977, the USGS surveyed a 22 km longitudinal profile of the streambed between the U.S. Highway 101 bridge at Orick and the mouth of Slide Creek. This provided the base for a resurvey of the longitudinal profile by National Park Service staff in 1983.

The timing and magnitude of hillslope erosion is critical to understanding processes affecting stream channel geometry. Harden and others (1978) analyzed precipitation and runoff records of major storms affecting the basin and documented the spatial and temporal distribution of landslides. Kelsey and others (1981 and in press) determined the volume of sediment contributed to the main channel by streamside landsliding relative to the occurrence of major storms. The timing and magnitude of tributary landsliding was documented by Pitlick (1982). Florsheim (NPS, personal communication) described changes at selected tributary cross sections in the Redwood Creek basin measured between 1976 and 1983.

Madej (1984a) quantified the volume of sediment stored on the valley floor of Redwood Creek for three time periods spanning 35 years (pre-1947, 1964 and 1980). Factors controlling deposition and subsequent erosion of flood deposits were described, and the persistence of sediment problems was estimated. Finally, Hagans and others (1986) summarized Redwood Creek studies to demonstrate that the watershed continues to experience long-term cumulative impacts brought about by land use and storms.

III. STUDY AREA AND BACKGROUND

Redwood Creek drains 720 km^2 in northwestern California (Figure 1). The basin is strongly elongate with a northwesterly aspect. The main channel is 108 km long with an average gradient of 1.4 percent. Tributaries to the main channel are less than 12 km long with gradients ranging from 6 to 32 percent (Pitlick, 1982). Total basin relief is 1,615 m.

The Redwood Creek basin is underlain by two distinct rock types of the Franciscan Assemblage (Bailey and others, 1964; Harden and others, 1981). The Franciscan Assemblage is a Mesozoic to early Cenozoic accumulation of pervasively sheared continental margin deposits, which are highly susceptible to fluvial erosion and mass wasting. The eastern side of the basin in underlain by unmetamorphosed sandstones and siltstones while the western side is underlain by quartz-mica schist. For the upstream 74 percent of its length, Redwood Creek closely follows the trend of the Grogan Fault Zone which juxtaposes the two rock types.

Vegetation in the basin is strongly influenced by elevation and proximity to the Pacific Ocean. Prior to the advent of commercial timber harvesting, 82 percent of the basin was covered by coniferous forests. The northern one-third of the basin supported mixed stands of Redwood and Douglas-fir. The southern two-thirds of the basin supported mixed stands of Douglas-fir and hardwood. Oak woodlands and prairie grasslands account for the remaining vegetative cover.

The vegetative landscape of the Redwood Creek basin has changed dramatically since the 1950's (Best, 1984). By 1966 approximately 33 percent of the drainage area of the lower basin, 58 percent of the middle basin, and 40 percent of the upper basin had been logged. Much of the pre-1966 logging and road building in the upper basin had occurred in the inner canyons of the mainstem and tributaries. After the late 1960's, logging declined in the upper and middle portions of the basin and increased in the lower basin. By 1978, 62 percent of the total basin area and 76 percent of the coniferous forest had been logged. Between 1979 and 1984 another 7 percent of the basin was logged, with two-thirds occurring in the middle basin and one-third in the upper basin. Well over half of this logging was reentry into previously cutover areas (Hagans, NPS, personnel communication). No logging occurred in the lower basin after 1978 because it was located within the newly expanded National Park boundaries.

The basin has a moist, mild climate characteristic of the northern California Coast Ranges (Janda and others, 1975). Basin-wide average rainfall is approximately 2000 mm, 80 percent of which falls between October and March.

The first half of the 20th century was relatively benign in terms of major storms, but six major storms have occurred in the basin since 1953 (Table 1). Investigations by Harden and others (1978) and Coghlan (1984)

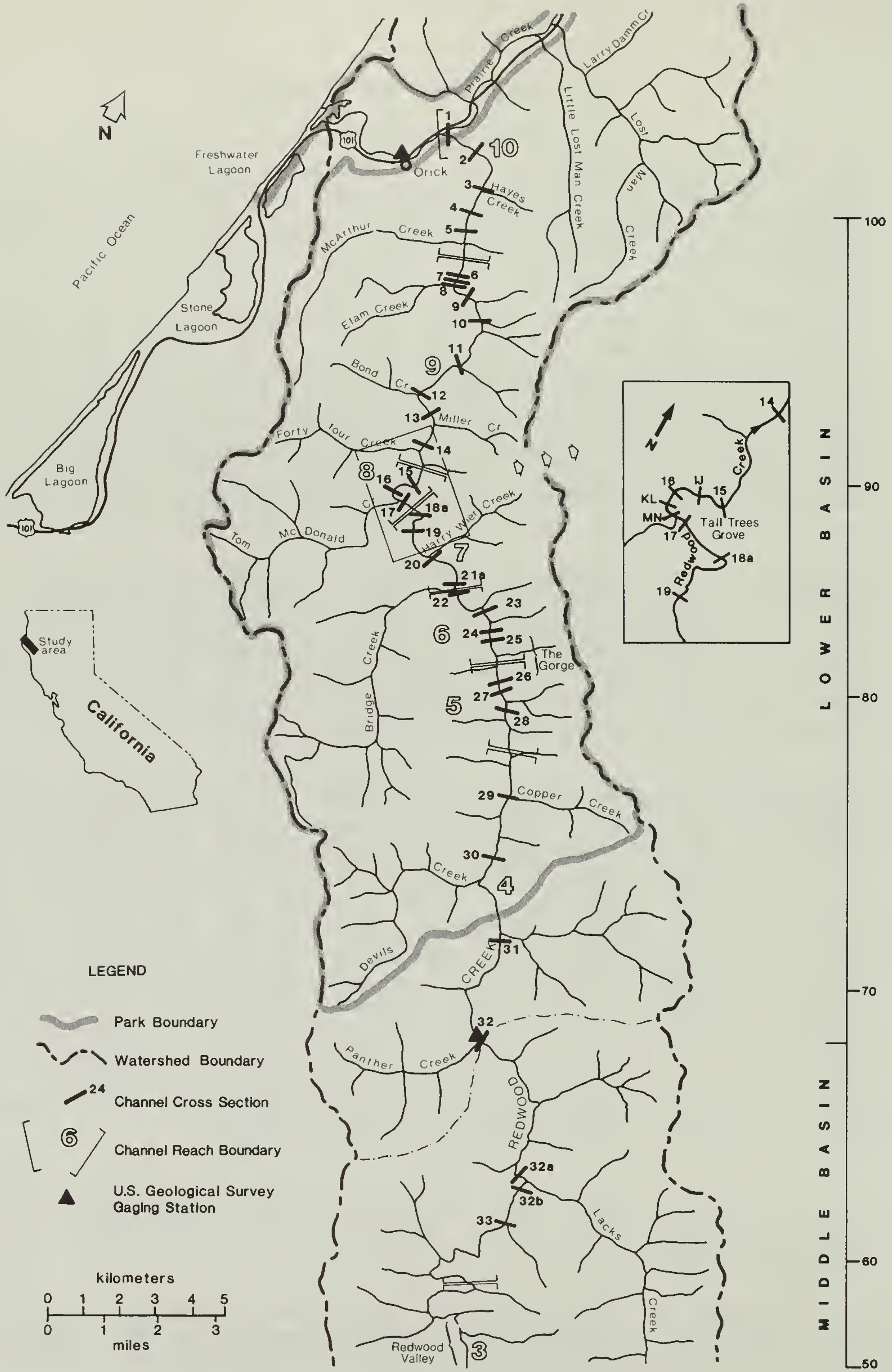


Figure 1. Location of channel cross sections, study reaches, and USGS gaging stations on Redwood Creek, California.

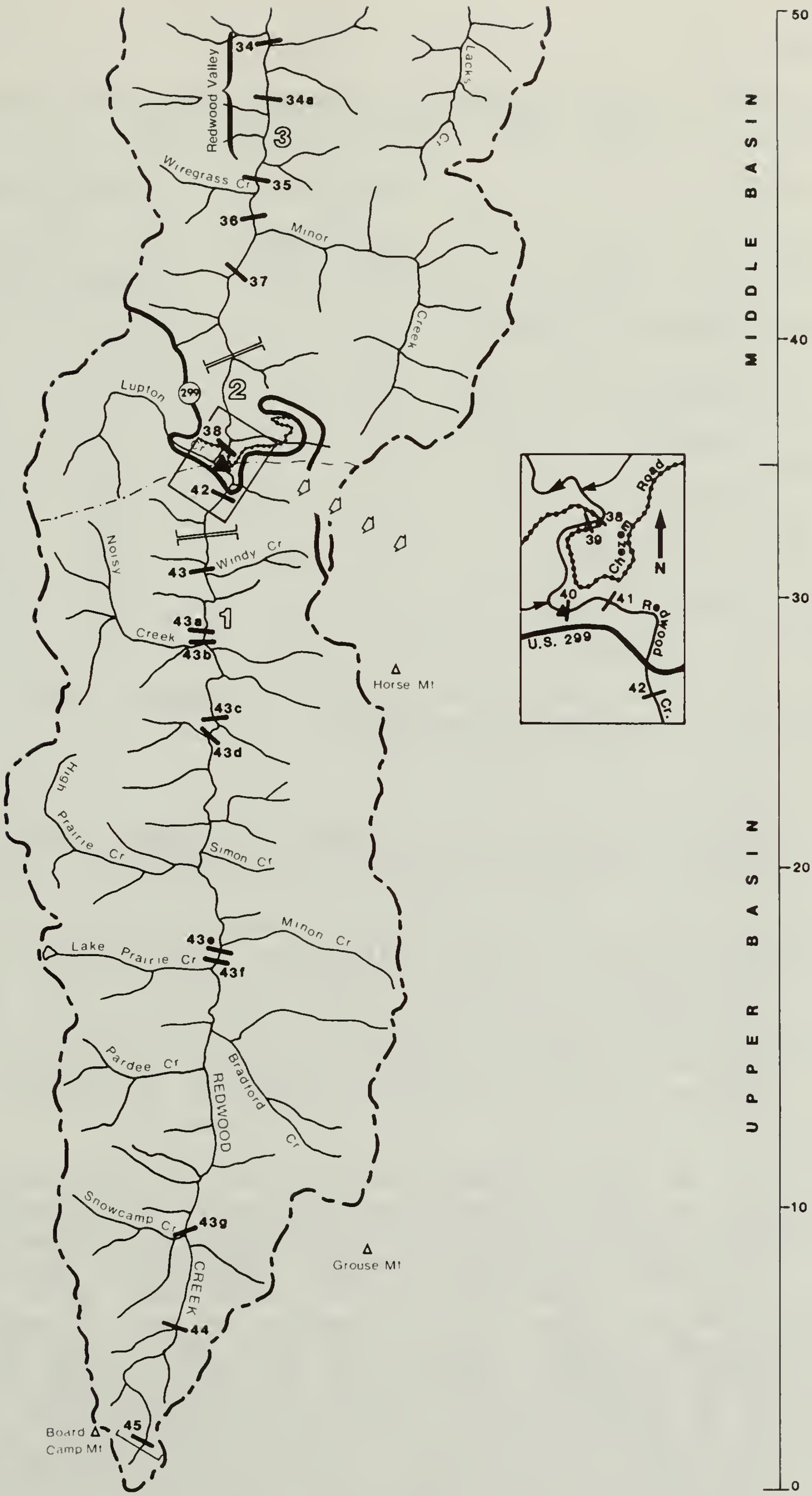


Figure 1. Location of channel cross sections, study reaches, and USGS gaging stations on Redwood Creek, California.

Table 1: Peak Discharges During Major Storms in the Redwood Creek Basin, 1950 - 1980* (Harden and others, 1978)

Date	Redwood Creek near Blue Lake cms**	Redwood Creek near Blue Lake cms/km²	Redwood Creek at Orick cms	Redwood Creek at Orick cms/km²	RI***
January 18, 1953	-	-	1416	2.0	25-30
December 22, 1955	343	1.9	1416	2.0	25-30
December 22, 1964	464	2.6	1430	2.0	40-50
January 22, 1972	195	1.1	1282	1.8	10
March 3, 1972	389	2.2	1407	2.0	10
March 18, 1975	346	2.0	1422	2.2	25-30

* - This table supercedes Table 1 in Varnum (1984).
** - cubic meters per second.
*** - From Coghlan, 1984.

indicate that events such as those in December 1964 and the winter of 1972 are a normal and permanent part of the area's climate.

The storms of 1955 and 1964 both produced regional flooding with similar peak discharges at Orick, California. The 1964 storm, however, was of longer duration and apparently more intense at higher elevations. This is evidenced by relatively higher discharge at the Blue Lake gaging station (monitoring the upper third of the basin). Major storms also occurred in 1972 and 1975. Precipitation and stream discharge records indicate that the middle and lower part of the basin received more rainfall during these storms than the upper basin.

Since the 1950's, streamside landsliding along the mainstem of Redwood Creek and its tributaries has contributed to widespread aggradation of Redwood Creek. Figure 2 illustrates the timing and volume of landsliding along the mainstem and tributaries in relationship to timber harvesting and peak flows in the Redwood Creek basin. Most landslides in the basin occur along streamsides and deliver sediment directly to perennial channels during large storm events (Kelsey and others, in press). The vast majority of the pre-1966 landslide volume entered the channel during the 1964 storm. The uppermost third of the basin was most affected by landsliding during the 1964 flood and it contributed approximately 55 percent of the total landslide-derived sediment entering Redwood Creek (NPS, unpublished data). Only 18 percent of the mainstem and tributary landsliding between 1948 and 1980 occurred after 1966, primarily in the 13 km reach of the middle basin between Lacks

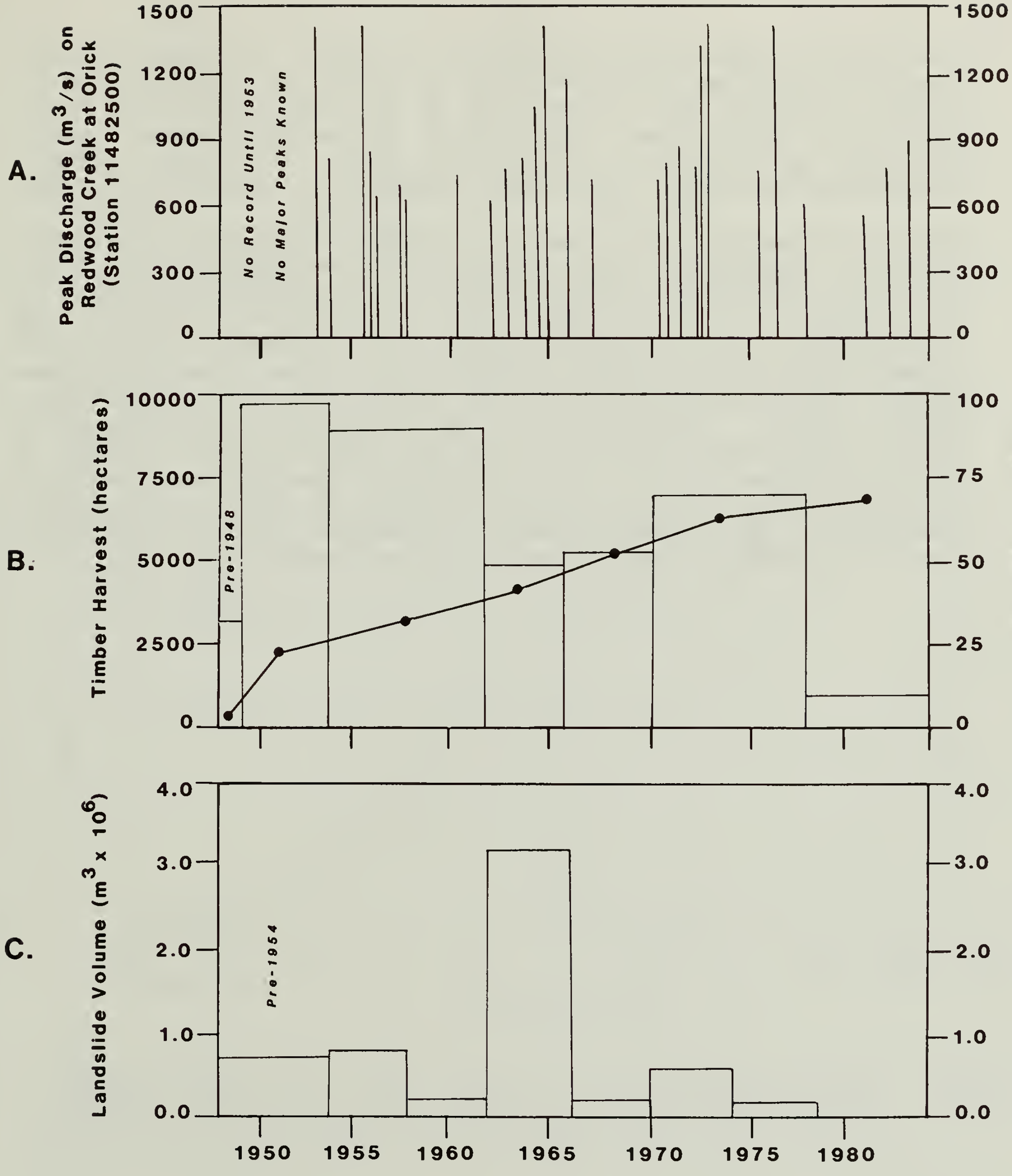


Figure 2. Summary of floods, timber harvest history, and streamside landsliding in the Redwood Creek basin, 1948-1984. Figure A depicts peak discharges above a base of 600 m^3/s measured at the Redwood Creek gaging station at Orick. Figure B depicts amounts of timber harvest for different time periods and the cummulative percent of the basin logged. The timber harvest data is from Best (1984). Figure C describes streamside landslide volumes for different time periods since 1948 (RNP, unpublished data).

Creek and the gorge (Kelsey and others, in press). The majority of this landsliding occurred during the 1972 storms (Harden and others, 1978). Timber harvest activity, concentrated in the upper basin prior to the 1964 storm and the lower basin prior to the 1972 storms, clearly increased the incidence of landsliding during those storms (Colman, 1973; Harden and others, 1978; Kelsey and others, in press; Best, 1984).

These recent major floods dramatically changed the quantity of sediment stored in the mainstem of Redwood Creek. As a result of the 1964 flood, the total volume of stored sediment in the mainstem increased to 16×10^6 m^3, 1.5 times greater than the sediment stored in 1947 (Madej, 1984a). Due to redistribution of 1964 sediments and additional sedimentation during the 1972 and 1975 floods, the volume of sediment measured in the mainstem in 1980 was slightly higher than 1964 volumes (Madej, 1984a). The spatial distribution and cumulative volumes of total stored sediment for 1947, 1964 and 1980 are shown in Figure 3. The center of mass of total stored sediment shifted upstream from km 64 (Lacks Creek) in 1947 to km 61 in 1964. By 1980 it had shifted downstream to km 78 (Maneze Creek). (Kilometers refer to the distance from the headwater divide of Redwood Creek as shown in Madej 1984b).

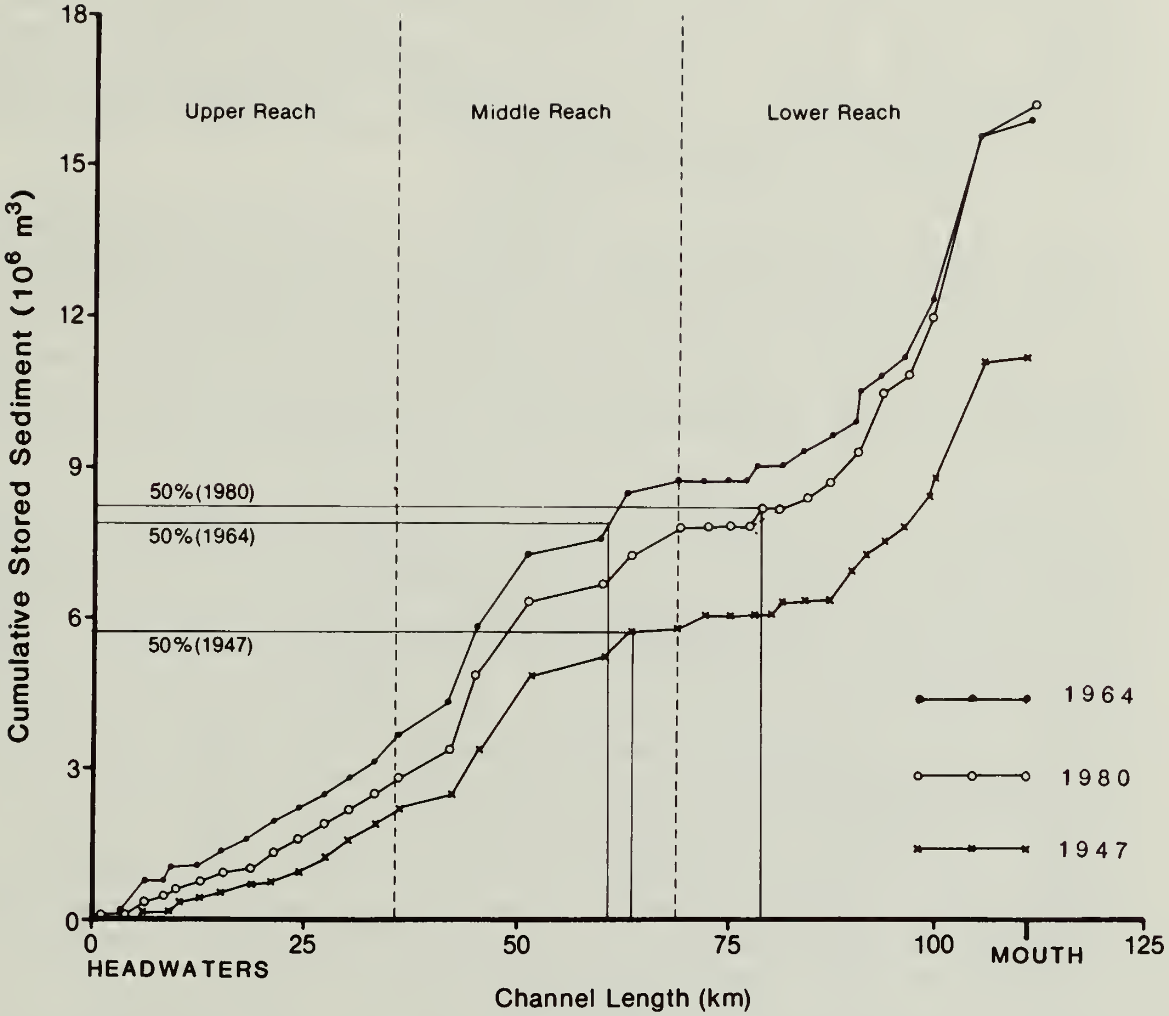


Figure 3. Cumulative volumes and spatial distribution of stored sediment in Redwood Creek as of 1947, 1964, and 1980 (from Madej, 1984a). Center of mass for each time period is indicated by the '50%' line.

IV. METHODS AND TERMINOLOGY

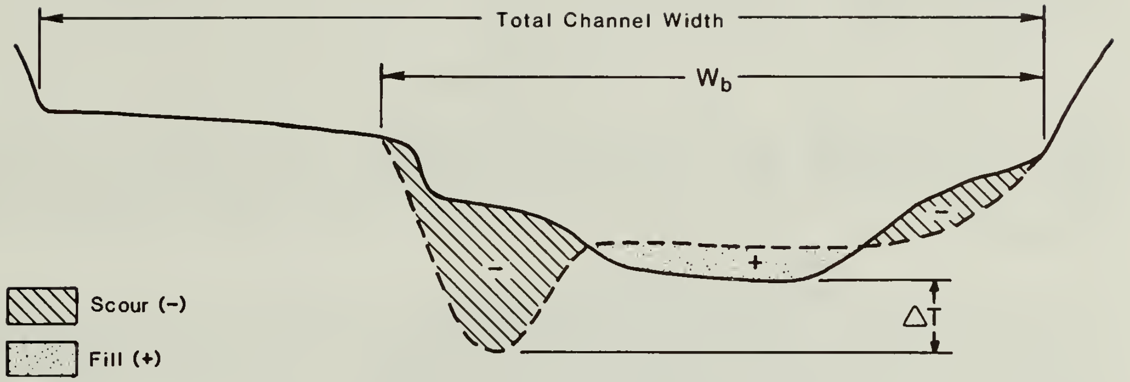
A. Cross Section Surveys

A technique commonly used to measure stream channel changes is a cross section survey between two permanently mounted end points (Emmett, 1974). Annual resurveys of cross sections determine changes in channel width, bed elevations, and thalweg position. This provides basic data needed to quantify channel response to hydrologic and physical variables and the movement of streambed sediment.

Currently, 58 monumented cross sections are distributed along the entire channel length of Redwood Creek. Two cross sections were established at the beginning of WY 1973 along lower Redwood Creek by the National Park Service, 40 additional cross sections were established early in WY 1974, and six more cross sections were established by WY 1975 by the U.S. Geological Survey (Nolan, 1979). By WY 1978, an additional ten cross sections had been established by the U.S. Geological Survey and the National Park Service.

Cross sections were monumented with 1.2 m lengths of 9.5 mm steel bar or by reference marks on concrete bridge abutments. The steel bars were driven 1 meter into the ground, reinforced with concrete, and referenced to at least two other triangulation points. Relative altitudes between end points were established by leveling (Nolan, 1979; Emmett, 1974). Cross sections were surveyed during the summer months with either an automatic level and stadia rod or a theodolite and electronic distance meter. Cross Section plots and calculations of scour and fill for the 1983 and 1984 surveys were accomplished with the assistance of the U.S. Forest Service Pacific Southwest Laboratory's computer facilities. Some error (<5 percent) is inevitable while surveying long distances or during poor weather conditions. Information and photographs on the condition of survey monuments, specific erosional or depositional features, bed forms, and bed material were obtained while surveying to assist in the interpretation of cross-sectional changes.

Figure 4 illustrates the symbols and terms used in describing changes at the cross sections. The thalweg is the lowest point in the streambed in cross-sectional profile. The streambed is completely inundated by winter flows. The width of the streambed may vary from year to year, depending on the magnitude of winter flows and bank erosion. In Redwood Creek, the streambed represents 80 to 90 percent of the entire cross-sectional profile and therefore is the most important factor in defining changes at a cross section. Net change in streambed area (ΔA_s) is the net difference between fill and scour in the streambed. The net change in area is the sum of streambed and streambank changes.



————	Cross section profile at time of initial survey
- - - - -	Cross section profile at time of resurvey
W_b	Bankfull width
ΔT	Change in thalweg
ΔA_s	Net change in streambed area is the sum of scour (-) and fill (+) at a cross section. (not shown)
ΔE_c	Change in mean streambed elevation $\Delta E_c = \Delta A_s / W_b$ (not shown)
Absolute change	Absolute change in area is the sum of the absolute value of scour (-) and fill (+). (not shown)

Figure 4. Terms and symbols used to describe changes at cross sections.

The streambed can be divided into several units. Low flow channels are those associated with the thalweg and carry summer flows. High flow back channels are formed during winter flows and abandoned as flows recede. Mid-channel bars are sediment bars in the center of the channel inundated during winter flows but not summer flows. Inactive gravel bars have surfaces that are only occasionally covered or partially covered by high winter flows and typically support annual and perennial vegetation. Major floods are capable of modifying inactive gravel bars.

The exact boundary between the streambed and streambank is sometimes subjective. Criteria for locating this boundary include vegetation breaks, highwater marks, breaks-in-slope, and upper floodplain surfaces. The horizontal distance between this boundary on both sides of the cross section is termed the bankfull width (W_b). Total channel width is the distance that would be inundated by large flows (RI = 10-50 years).

Another characteristic used to describe variation at a cross section is change in the mean streambed elevation (ΔE_c). This normalized value compares the relative importance of change at cross sections of different widths and is derived by dividing net change in streambed area (ΔA_s) by bankfull width (W_b):

$$\Delta E_c = \Delta A_s / W_b$$

Thus, a lowering of the mean streambed elevation of 0.15 m (ΔE_c = -0.15 m) has the same percent change in a 10 m wide cross section as it has in a 100 m wide section, even though more material moves through the wider cross section.

To evaluate the magnitude of change at a cross section, the absolute value of streambed area change was normalized. This value was derived by summing the absolute value of scour and fill at a cross section and dividing by the bankfull width. The absolute values reported in the text refer to normalized absolute values of change.

Excessive sediment loads often move downstream in a wave-like form. Gilbert (1917) studied the effects of hydraulic mining debris in the Sierra Nevada. He found that "...the flood of mining debris is analagous to a flood of water in its mode of progression through a river channel. It travels in a wave..." Cross section surveys in Redwood Creek suggest a wave-like mode of sediment loads as well. In this study, the leading edge of aggradation refers to the downstream end of the 'wave'; the trailing edge refers to the upstream end.

B. Longitudinal Profile Surveys

A longitudinal profile of the lower 22 km of Redwood Creek (between the gorge and the U.S. Highway 101 bridge at Orick, California) was surveyed by the U.S. Geological Survey in the summer of 1977 and resurveyed by Redwood National Park in the summer of 1983. The longitudinal profiles of the channel from 1977 and 1983 were compared to delineate net changes in bed elevation of Redwood Creek over these seven years.

Two different methods were used to survey the mainstem of Redwood Creek in 1977 and 1983. The 1977 survey measured distances along the center line of the channel. Elevations of the thalweg and water surface were measured using a self-leveling level and stadia rod (John Palmer, USGS, personal communication). The 1983 survey used the same techniques except that distances were measured along the thalweg of the low flow channel with a tape. Both surveys were tied into reference marks on staff plates at gaging stations 19 km apart. The total error in elevation between the two surveys was 0.2% (0.08m).

The two surveys generated different channel lengths along Redwood Creek; a mid-channel length (1977 profile) and a thalweg length (1983 profile) (Figure 5). Total channel lengths for the 1977 and 1983 surveys were 22,246 m and 22,850 m respectively. The 1983 survey was divided into 9 sections, and the section lengths from the 1983 survey were adjusted to 1977 survey length values. The adjustment value was derived by subtracting the 1977 section length from the 1983 section length and dividing by the number of survey points in the 1983 survey. The resulting adjustment value was applied to the 1983 survey distances. As a result, the two profiles were equal in length. The assumption used in this adjustment is that the center line of the channel did not change between 1977 and 1983. Aerial photographs of the channel taken in 1978 and 1981 show no discernable changes in the length, which suggests this assumption is valid.

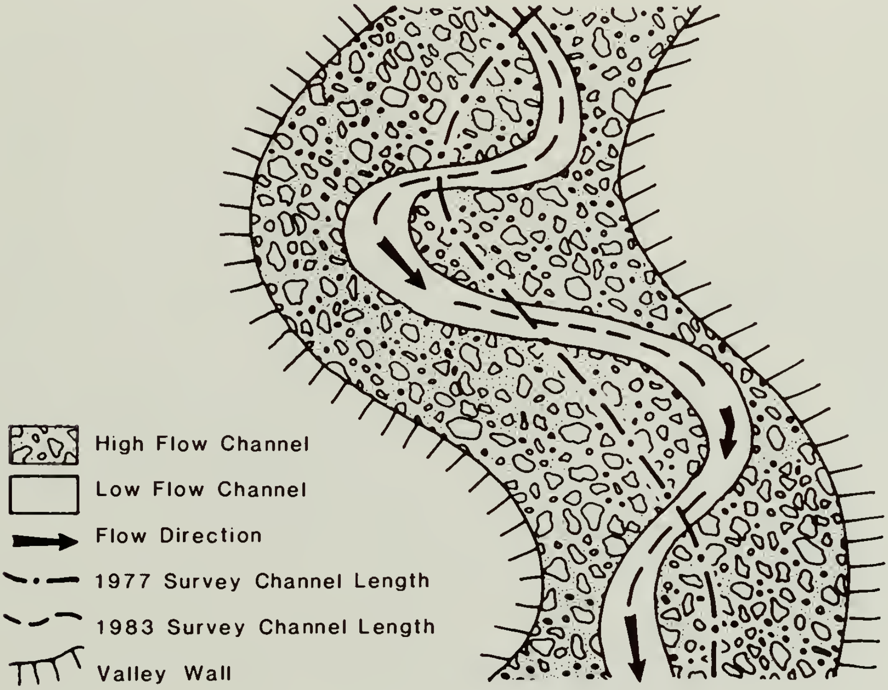


Figure 5. Schematic diagram of the Redwood Creek channel showing the different channel lengths surveyed for the 1977 and 1983 profiles.

Channel bed degradation has occurred where the 1983 longitudinal profile is at a lower elevation than the 1977 profile; aggradation has occurred where the converse is true.

Mean change in streambed elevation (ΔE_{ℓ}) of the longitudinal profile was determined for 72 300-m intervals. 'ΔE_{ℓ}' was derived by dividing the net area change between the 1977 and 1983 profiles by 300 m.

Water surface and thalweg gradients for 1977 and 1983 were calculated by regression analyses. Best fit lines were computed for water surface elevations and thalweg elevations in 1500 m intervals and the resulting slope coefficients were considered the slope of the interval.

An F-test (α=.05) was used to statistically define a significant increase in streambed variance for each reach. In 1977, the streambed profile was relatively flat and pool-riffle sequences were poorly defined (John Parker, USGS, personal communication). The increase in variance of the streambed since 1977 is assumed to be related to an increase in bed morphology. The F-statistic ratio was the residual variance for the 1983 profile over the residual variance for the 1977 profile with a Critical $F_{.05, \nu_1, \nu_2}$. (ν_1 is degrees of freedom for the variance for the 1983 profile; ν_2 is degrees of freedom for the 1977 profile).

V. RESULTS OF THE WY 1983-1984 CROSS SECTION SURVEYS

A. Cross-Sectional Changes in Study Reaches

The morphology of Redwood Creek changes drastically along its 108-km length. Varnum (1984) divided the channel into 10 study reaches (Figure 1). Classification of the reaches was based on channel morphology, channel gradient and locations of cross sections. Figure 6 is a longitudinal profile of Redwood Creek showing the locations of the cross sections and major tributaries.

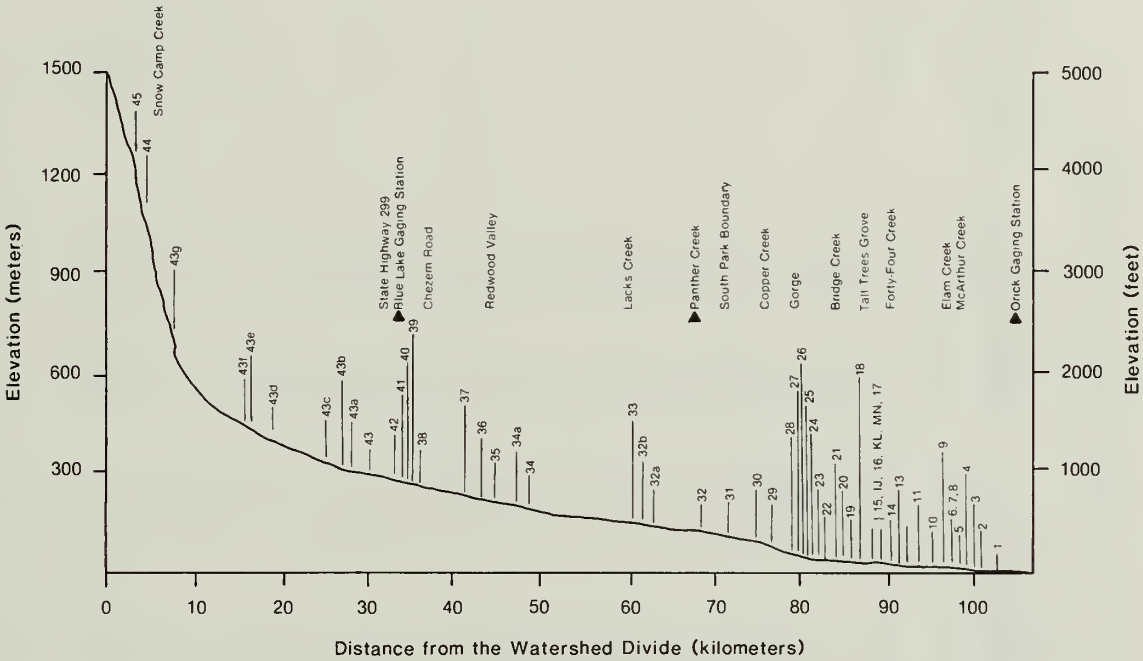


Figure 6. Longitudinal profile of Redwood Creek showing location of stream channel cross sections, major tributaries, roads, and stream gaging stations.

During the summers of 1983 and 1984, all 58 cross sections were surveyed along the mainstem of Redwood Creek and a longitudinal streambed profile of the lower 22 km was surveyed in 1983. Bankfull width, streambed and bank area changes, and the net area change for cross sections in WY 1983 and WY 1984 are summarized in Appendix A. Table 2 presents the calculated values for ΔT, ΔE_c, absolute value of streambed area change at cross sections, ΔE_ℓ, and the percent channel length aggrading or degrading along the longitudinal profile. A comparison of water surface slopes and mean change in longitudinal streambed elevations between the 1977 and 1983 for the lower 22 km of Redwood Creek are presented in Figure 7. Three of the cross sections are not included in the WY 1983

TABLE 2: Calculated Values of Channel Changes from Channel Cross Sections in WY 1983 and 1984 and Longitudinal Profiles in 1977 and 1983.

REACH	CROSS SECTION NUMBER	CHANGE IN THALWEG ELEVATION WY 1983 ΔT(m)	WY 1984 ΔT(m)	CHANGE IN MEAN CROSS-SECTIONAL STREAMBED ELEVATION WY 1983 ΔE_c(m)	WY 1984 ΔE_c(m)	NORMALIZED ABSOLUTE VALUE OF STREAMBED CHANGE WY 1983 (m)	WY 1984 (m)	CHANGE IN MEAN LONGITUDINAL STREAMBED ELEVATION 1977-1983 ΔE_ℓ(m)	PERCENT CHANNEL LENGTH 1977-1983 DEGRADING	AGGRADING
Prairie Ck	1	-0.1	0.4	.04	.09	.46	.59			
to Elam Ck	2	0.0	0.2	-.20	.08	.33	.31			
	3	0.0	0.0	.20	.04	.29	.34	-.08	64%	36%
10	4	-0.1	0.3	.18	-.14	.36	.44			
	5	0.4	-0.3	.07	.09	.23	.36			
Elam Ck to	6	0.3	-0.2	-.02	.11	.31	.16			
Forty four Ck	7	-1.5	0.8	.14	-.05	.46	.42			
	8	0.3	-0.5	-.04	.14	.40	.35			
	9	0.7	-0.1	.14	.14	.22	.33			
9	10	-0.2	0.1	-.04	.12	.04	.34	.13	35%	64%
	11	-0.1	-0.5	.08	-.19	.27	.30			
	12	0.2	0.6	-.04	.05	.25	.28			
	13	0.0	0.0	.08	-.10	.17	.20			
	14	-1.0	0.3	-.25	.07	.49	.51			
Tall Trees	15	-1.4	1.7	-.06	.05	.43	.44			
Grove	IJ	1.0	0.4	-.01	.16	.71	.91			
	16	-0.2	0.6	.16	-.30	.31	.32	-.27	62%	38%
	KL	0.2	-1.4	.29	-1.32	.86	1.33			
8	MN	-0.1	-0.2	-.10	-.05	.35	.18			
	17	0.2	-2.0	.24	-.22	.26	.41			
Elbow Ck to	18a	-0.2	-0.6	-.04	-.15	.30	.26			
Bridge Ck	19	-0.2	-0.6	.02	-.05	.44	.20	-.88	99%	1%
7	20	-0.7	-0.6	-.27	-.20	.29	.28			
	21a		-0.4		-.23		.23			
Bridge Ck to	22	0.3	-0.9	-.01	-.32	.14	.33			
Base of the	23	0.2	-0.5	-.22	-.07	.33	.20			
Gorge	24	-0.3	-0.6	-.21	-.12	.21	.26	-1.23	100%	0%
6	25	0.0	0.0	-.26	-.16	.48	.22			
Slide Creek	26	0.0	0.0	.05	.00	.18	.25			
5	27	-0.7	0.3	-.44	.19	.47	.24	NA		
	28	0.0	-0.2	.06	-.07	.15	.10			

TABLE 2: Calculated Values of Channel Changes from Channel Cross Sections in WY 1983 and 1984 and Longitudinal Profiles in 1977 and 1983.

REACH	CROSS SECTION NUMBER	CHANGE IN THALWEG ELEVATION		CHANGE IN MEAN CROSS-SECTIONAL STREAMBED ELEVATION		NORMALIZED ABSOLUTE VALUE OF STREAMBED CHANGE		CHANGE IN MEAN LONGITUDINAL STREAMBED ELEVATION	PERCENT CHANNEL LENGTH
		WY 1983	WY 1984	WY 1983	WY 1984	WY 1983	WY 1984	1977-1983	1977-1983
		ΔT(m)	ΔT(m)	ΔE_c(m)	ΔE_c(m)	(m)	(m)	ΔE_ℓ(m)	DEGRADING AGGRADING
Copper Ck to	29	0.3	-0.6	.00	-.28	.32	.57		
Stover Ck	30	0.1	-0.3	.04	-.04	.08	.14		
	31	0.0	0.1	-.04	.07	.07	.09		
4	32	-0.1	-0.1	-.04	-.06	.10	.07	NA	NA
	32a	-0.2	0.2	-.02	.23	.21	.45		
	32b		-0.4		-.07		.15		
	33	-0.1	-0.4	-.03	-.06	.20	.20		
Redwood	34	-0.1	0.0	-.04	.01	.26	.03		
Valley	34a	0.0	-0.2	-.28	-.10	.39	.14		
	35	-0.3	0.0	-.04	-.03	.14	.12	NA	NA
3	36	0.4	-0.2	.01	-.04	.20	.10		
	37	-0.3	-0.2	-.06	.02	.09	.09		
Chezem Rd to	38	0.5	-1.2	-.14	-.12	.23	.28		
State Hwy 299	39	0.0	0.0	.03	-.01	.12	.05		
	40	-0.2	0.0	-.14	-.01	.18	.05	NA	NA
2	41	-0.1	-0.1	-.02	-.01	.09	.06		
	42	-0.2	0.0	-.13	-.03	.14	.08		
Upstream of	43	0.5	0.0	-.05	-.03	.26	.07		
State Hwy 299	43a	-0.2	0.1	-.08	.07	.10	.12		
	43b	0.0	0.0	-.03	.00	.23	.07		
	43c	0.2	-0.2	-.45	-.03	.66	.24		
1	43d	0.2	0.0	-.19	-.01	.30	.06	NA	NA
	43e	0.0	-0.4	.02	-.01	.09	.07		
	43f	0.2	-0.2	.09	.00	.38	.11		
	43g	0.0	0.0	.00	.00	.10	.20		
	44		0.0		.00		.13		
	45	0.0	0.0	.02	.01	.04	.03		

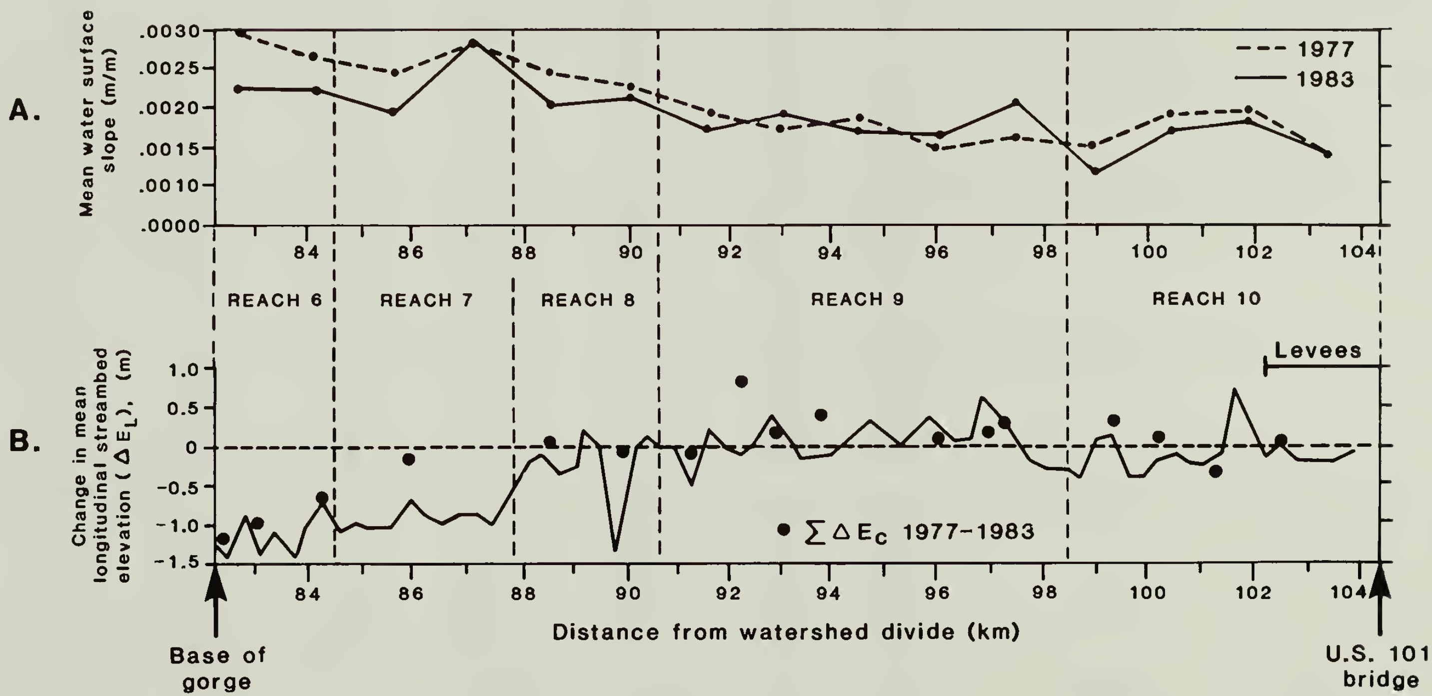


Figure 7. Comparison of mean water surface slopes and change in mean longitudinal streambed elevations between 1977 and 1983.

analyses due to either surveying inconsistencies (Cross Sections 21a and 44) or bulldozing in the channel (Cross Section 32b). Cross Section data prior to WY 1982 were provided by Nolan and Marron (in press).

The change in mean streambed elevation (ΔE_c) at the cross sections was used to characterize trends for each reach. If $\Delta E_c \leqq .05$, the ΔE_c was considered to be within survey error and reflected insignificant change in the reach. For $.05 < \Delta E_c \leqq .10$, the ΔE_c values reflected minor changes in the reach and for $\Delta E_c > .10$, the ΔE_c reflected significant changes.

In addition to the above, it is necessary to consider the absolute value of streambed area change because the values of ΔE_c reflect net change in elevation and not magnitude of change at the cross section. Thus ΔE_c may show minor changes in streambed elevation; however, streambed scour and fill may be quite large. Therefore, the normalized absolute value of area change is used to characterize the magnitude of scour and fill across the entire cross section. Figures 8 and 9 summarize the change in mean streambed elevation and absolute values of change for the cross sections in WY 1983 and WY 1984 respectively.

Reach 1. Upstream of State Highway 299:
Cross Sections 45 (4.7 km) - 43 (31.6 km)

This reach is 33.0 km long with 10 cross sections. Channel characteristics vary considerably in this long reach (Figure 10). Bankfull widths at cross sections range from 12 to 59 m. The stream gradient averages 0.030 m/m and ranges from 0.006 to 0.125 m/m. Cross Section 44 is not used in the WY 1983 analysis due to surveying inconsistencies.

In WY 1983, the upstream half of the reach reflected no change in mean streambed elevation. The lower section generally scoured with maximum scour occurring at Cross Sections 43c and 43d. The large ΔE_c values observed at these two cross sections were due to lateral erosion of gravel bars. In WY 1984, no change in mean streambed elevation occurred at cross sections. Six cross sections had no change in thalweg elevation (ΔT), three of which have shown no ΔT since 1982.

The channel upstream of the USGS gaging station near Blue Lake (1 km downstream of State Highway 299) was the most severely affected by the December 1964 storm. Over 600 streamside landslides have been identified in this reach and most were attributed to this storm (Kelsey and others, 1981). 1954 and 1966 air photos show that channel widths increased by 150 to 350 percent (Figure 11) as determined by the width between streamside vegetation. Up to 9 m of channel fill was deposited above the present thalweg elevation as demonstrated by terrace remmants. Roughness elements, such as large bed material, riparian vegetation, pool and riffle sequences, and channel obstructions, were greatly reduced. The 1964 storm caused a 90 percent increase in channel-stored sediment in this reach. Between 1965 and 1980, 50 percent (800,000 m³) of the added sediment had been removed (Madej, 1984a).

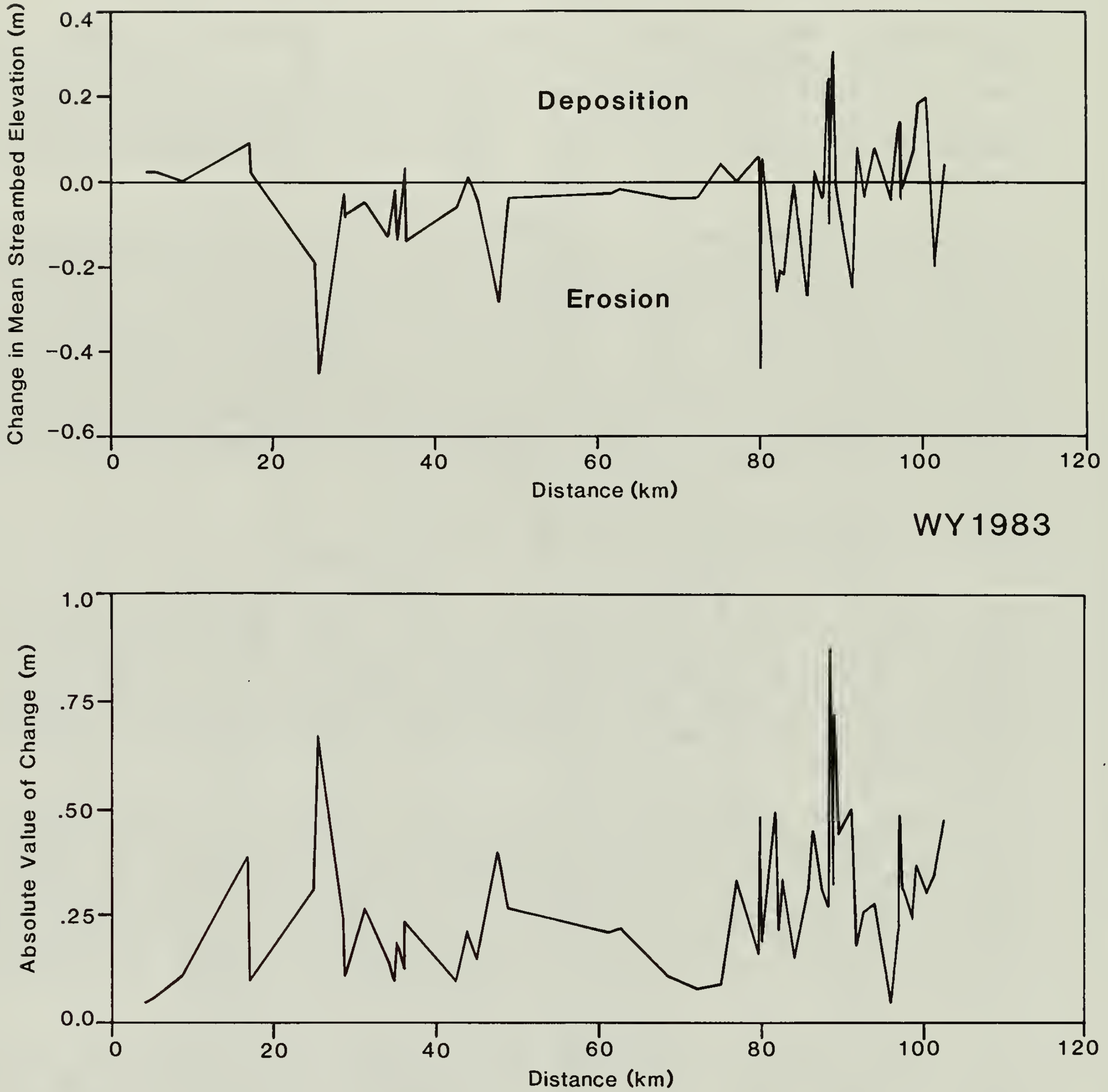


Figure 8. Summary of the change in mean streambed elevation and absolute values of change at cross sections along Redwood Creek for WY 1983.

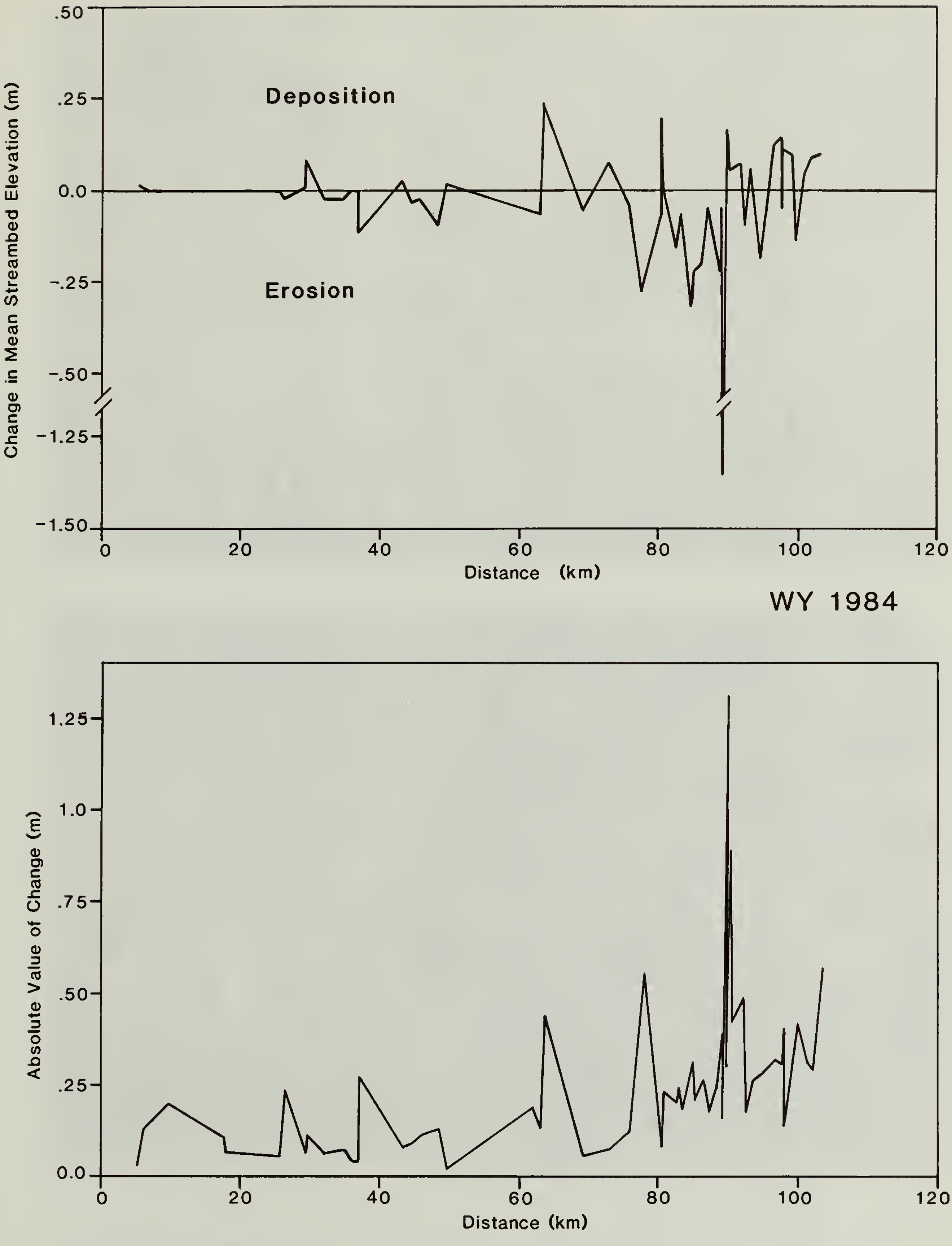


Figure 9. Summary of the change in mean streambed elevation and absolute value of change at cross sections along Redwood Creek for WY 1984.

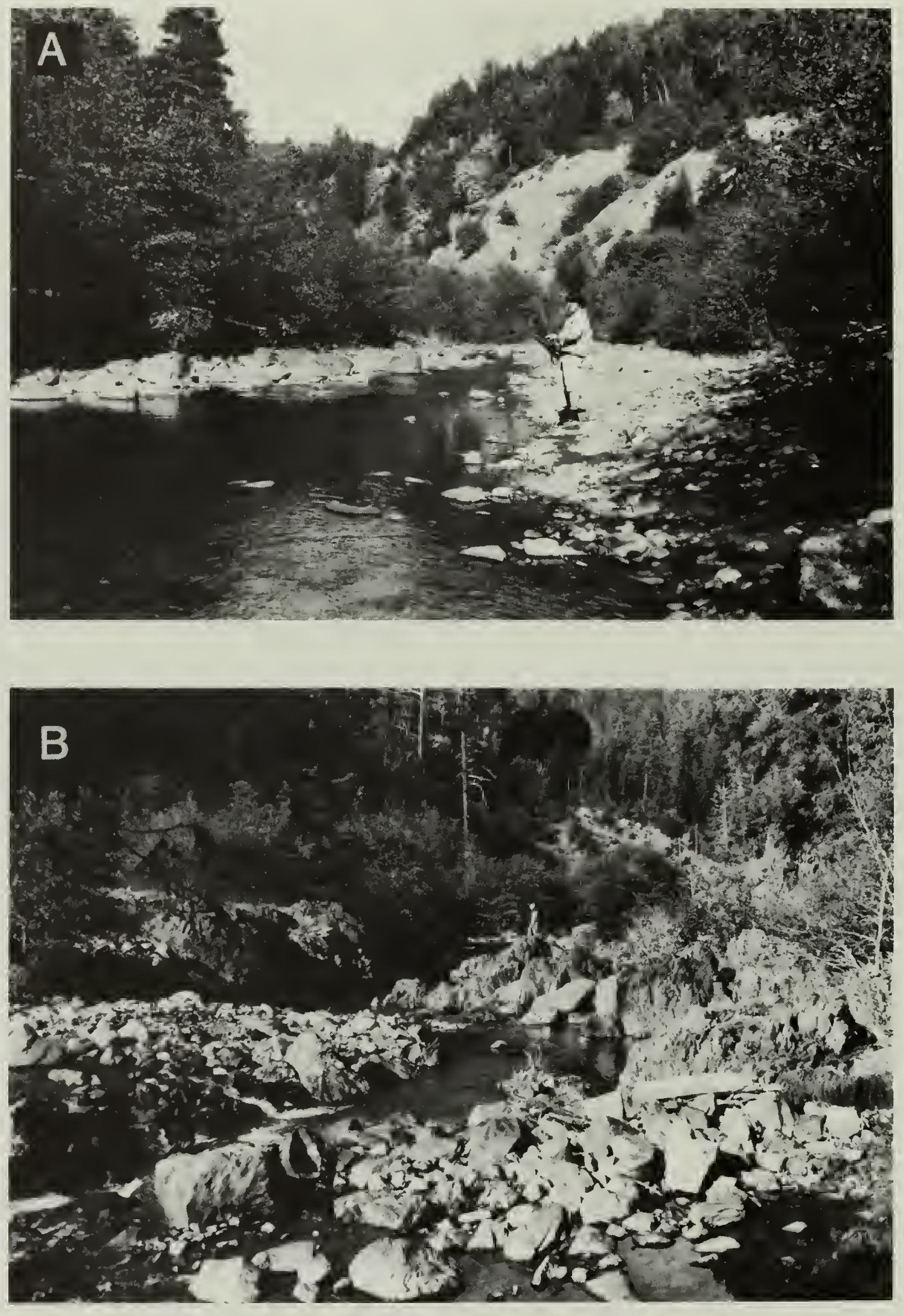


Figure 10. The stream channel in Reach 1 above State Highway 299 varies from small valleys with low gradients (A) to steep, narrow channels with exposed bedrock and boulders (B). In general, bed material is large and channel widths narrow.

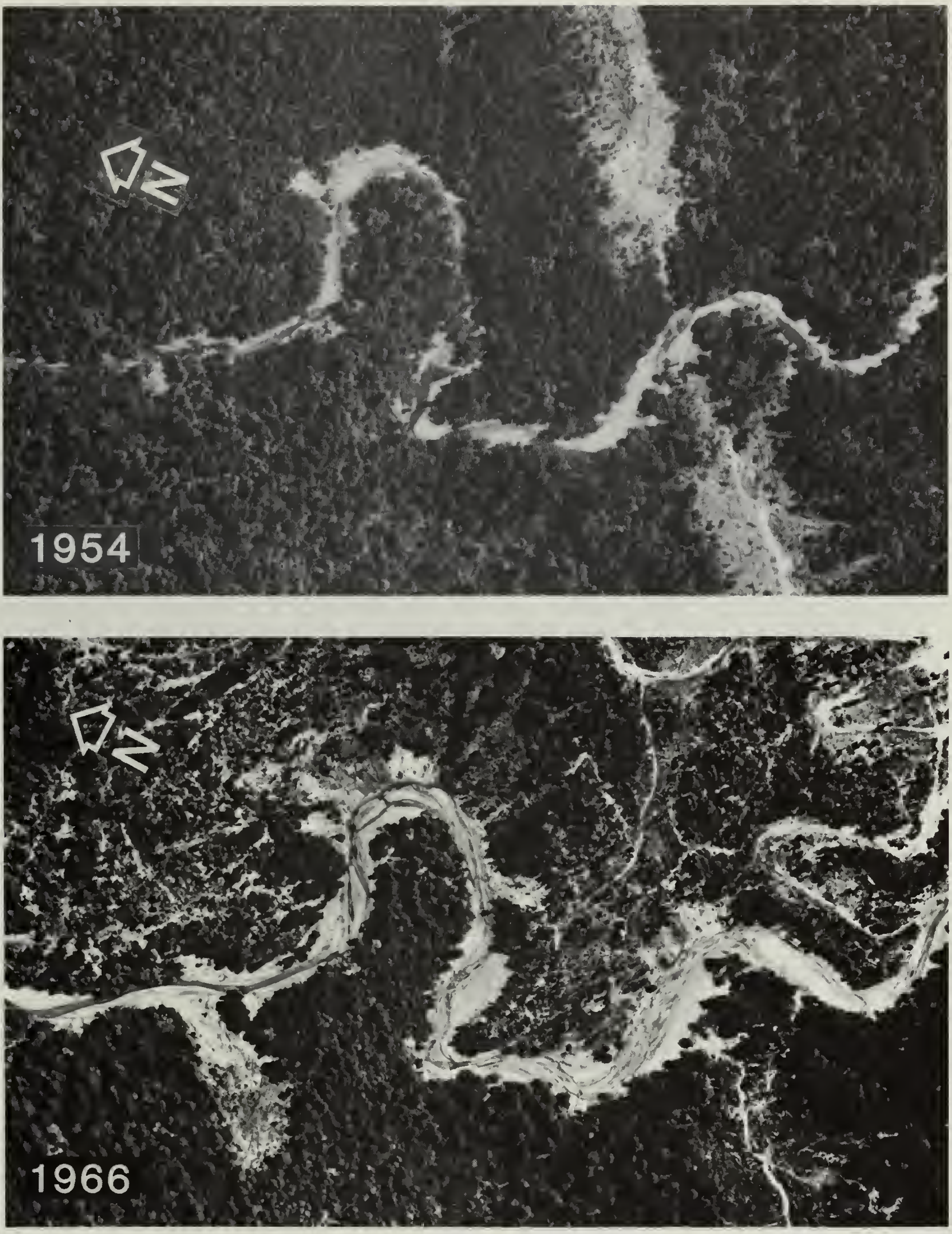


Figure 11. 1954 and 1966 aerial photographs of the main channel about 5 km upstream of State Highway 299. In 1954 photographs, slopes adjacent to this reach were undisturbed with the exception of the powerline right-of-way. Channel widths at cross sections upstream of State Highway 299 increased significantly between 1954 and 1966.

During the period of cross-sectional record, the bankfull width of the channel generally occupied one third or less of the total channel width occupied by the 1964 flood waters. The present channel is deeply incised into surrounding gravel bars and 1964 terrace remnants (Figure 12). At cross sections with WY 1975 records (Cross Sections 43, 44 and 45), W_b had not changed significantly between 1975 and 1984.

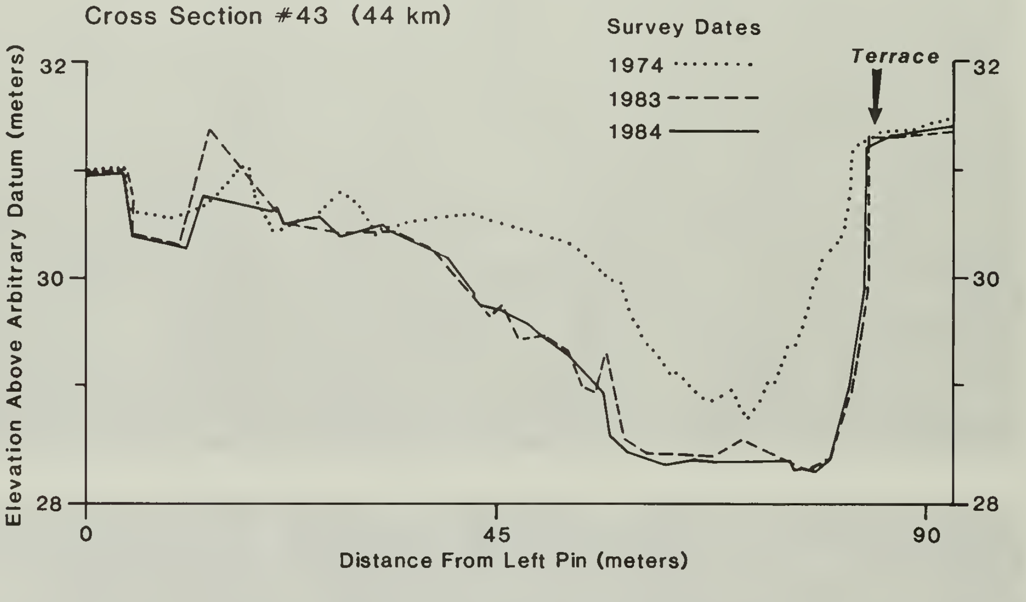


Figure 12. Plot of Cross Section 43 (located 2.7 km upstream of State Highway 299). Little change has occurred in the last few years at this cross section. The gravel berm on the left was deposited during the 1964 storm.

The most obvious consequences of post-1964 channel adjustments have been the development of a low flow channel and the reestablishment of roughness elements, including riparian vegetation and pronounced pool and riffle sequences. In many areas bedrock is exposed in the streambed near cross sections. The relatively low magnitude of cross-sectional changes which have occurred since WY 1975 and especially since WY 1982 indicates that the channel is adjusted to the moderately low peak flows that have occurred in those years (RI < 4 years).

Reach 2. State Highway 299 to Chezem Road:
Cross Sections 42 (34.4 km) - 38 (36.5 km)

Five cross sections are in this 6.7 km long reach. This reach is typified by a narrow channel and high and steep streambanks. Bankfull widths range from 30 to 40 m (Figure 13) and the channel gradient averages 0.005 m/m.

Figure 13. Between State Highway 299 and Chezem Road, the channel is typically narrow with bankfull widths of 30-40 m. Records from the USGS gaging station near Blue Lake (Cross Section 40) and cross section data indicate that degradation has occurred since 1973 in this reach and upstream reaches.

In WY 1983, cross sections alternated between significant amounts of scour (ΔE_c > .10 m) and no changes in the mean streambed elevation. In WY 1984, ΔE_c reflected little or no changes throughout the reach. The exception to this trend was Cross Section 38 which is located on the downstream edge of the Chezem Bridge. The changes at this cross section are influenced by the bridge and showed significant amounts of scour during both years.

Absolute values of streambed change indicate relatively limited movement of streambed material at cross sections in both years. WY 1983 had relatively higher magnitudes of streambed change than in WY 1984, but this reach reflected the lowest values of absolute change recorded for the entire stream in WY 1984.

Changes in channel morphology following the 1964 flood were similar to those that occurred upstream. A comparison of aerial photographs taken in 1958 and 1966 show large increases in channel width as well as decreases in channel depth and in the number of large roughness elements.

Cross section information from WY 1958 and WY 1973 from USGS stream gaging records at the Blue Lake gaging station on Redwood Creek (Cross Section 40), showed that between 1958 and 1973 ΔE_c increased more than 1.0 m and that ΔT rose more than 1.2 m (Nolan and Janda, 1979). (Note: The total amount of aggradation following the 1964 flood may have been considerably greater than this, but documentation is lacking since gaging station records were discontinued between 1958 and 1973 (Nolan and Janda, 1979)).

Cumulative ΔE_c from WY 1974 to 1984 reflected scour for three of the cross sections (38, 40 and 42). ΔE_c ranged from -0.48 to -1.13 m. Cumulative ΔE_c for Cross Sections 39 and 41 was about -0.30 m between WY 1974 and 1979, followed by filling to within 0.10 m of WY 1974 levels by WY 1984. At the Blue Lake gaging station (Cross Section 40), the thalweg lowered to within 0.3 m of the 1953 level (Figure 14). Most increases in channel depth occurred over the entire width of the cross section in these narrow channels. The reach also experienced notable increases in roughness elements, such as riparian vegetation and exhumed boulders.

The close spacing of cross sections and the long record at the Blue Lake gaging station probably best documents the trend of channel scour observed throughout the creek upstream of the Blue Lake gaging station since WY 1974. In recent years, the magnitude of change has become less, and in some cases, minor trend reversals have occurred. This suggests that the channel geometry has adjusted to moderately low peak flows (1 - 4 year recurrence intervals) that have occurred within the last 3 years (USGS, unpublished data). Discharge measurements taken at the USGS gaging station near Blue Lake demonstrate that these flows are capable of including changes at cross sections. Those measurements show

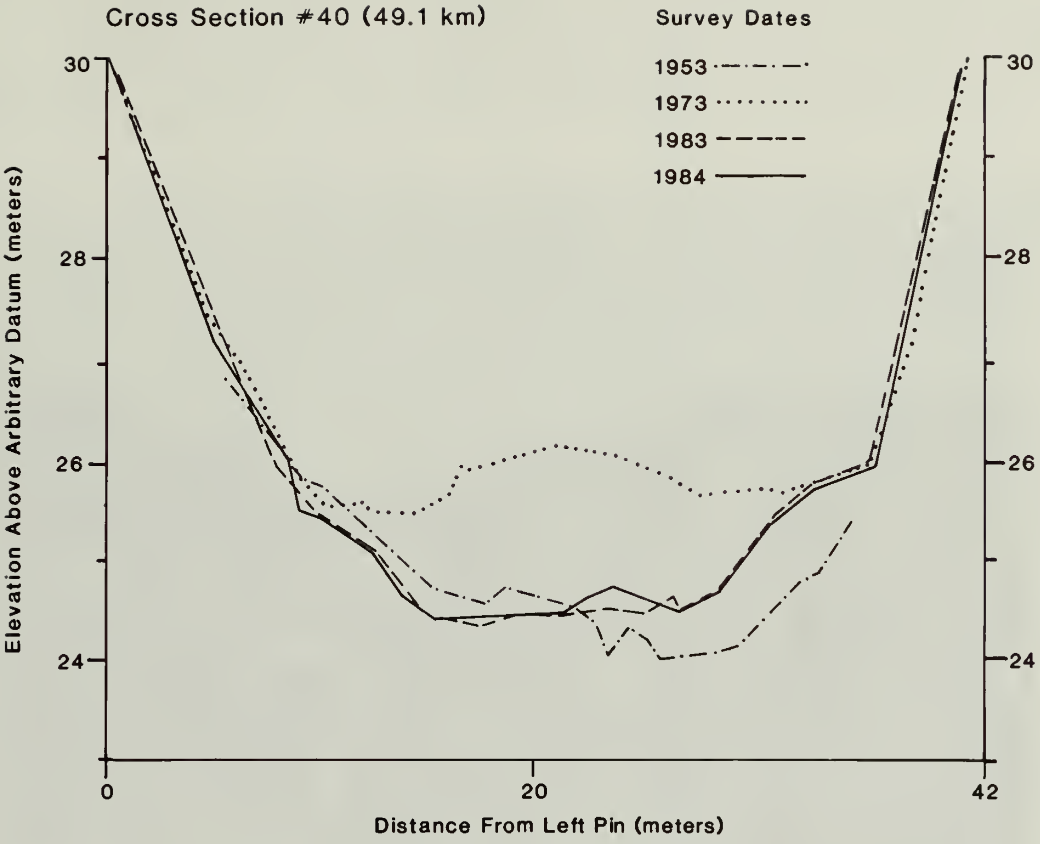


Figure 14. Plot of Cross Section 40. This cross section is located at the Redwood Creek gaging station near Blue Lake. Since 1973, the streambed has lowered to near 1953 levels.

at least 0.15 m of scour and fill occurs at flows above 85 m^3/s (less than bankfull) (Madej, 1984a).

Reach 3. Redwood Valley:
Cross Sections 37 (42.8 km) - 34 (49.1 km)

Five cross sections are in this 15.6 km long reach. Bankfull widths range from 38 to 85 m. Since some of the older gravel bars are only affected by extreme flows, bankfull widths are typically up to 100 m narrower than total channel widths (Figure 15). Extensive vegetated gravel bars and elevated stream terraces are common in this reach. The channel gradient in this reach is 0.004 m/m.

With the exception of Cross Section 34a, the cross sections showed no changes in WY 1983 and WY 1984. A significant decrease in mean streambed elevation (ΔE_c = -.28 m) occurred at Cross Section 34a due to localized scour. This cross section continued to scour (ΔE_c = -.10 m) in WY 1984. The absolute values of streambed area change at the cross sections were small in both years.

Figure 15. The channel in Redwood Valley is typically wide and alluviated. Bankful widths up to 150 m are common. The stream gradient is gentle in this reach and the lack of older vegetation on the gravel bars indicate recent inundation by high flows.

The 1964 flood drastically changed channel patterns in Redwood Valley. Aerial photographs show that the 1964 flood completely interchanged the position of the thalweg and gravel bars in parts of the channel (Figure 16). Subsequent floods did not significantly alter channel patterns established in 1964. Since 1964, vegetation on the gravel bars has grown to 5 m high.

Between 1947 and 1964, channel stored sediment increased 27 percent between Minor Creek (km 43.6) and Weepy Bend (km 52.5) (Madej, 1984a). By 1980, only 18 percent of the material (117,500 m^3) added between 1947 and 1964 had been removed. This, together with the lack of significant channel changes in the recent years, accounts for the persistence of large gravel bars typical of the reach.

Total channel widths are large in this reach (up to 200 m) and did not change considerably with the 1964 flood. Figure 17A illustrates a typical cross section in Redwood Valley with the total channel width much larger than W_b. Although the total channel width was inundated by the 1964 storm, aerial photographs indicate that W_b at cross sections are presently similar to what they were prior to 1964. Numerous wide terraces adjacent to the channel indicate that wide channels have been a persistent geomorphic feature in this reach.

Most of the changes that have occurred at cross sections since WY 1974 were increases in the low flow channel depth. Here, 86 percent of all ΔT has been associated with scour (averaging -0.2 m). A plot of cumulative ΔE_c at Cross Section 35 (Figure 17B) shows that the channel in this reach has generally continued to degrade since 1975 and has scoured minor amounts since 1981.

Reach 4. Stover Creek to Copper Creek:
Cross Sections 33 (61.4 km) - 29 (77.2 km)

This 23.3 km long reach has seven cross sections. The channel in this reach is located within a steep inner gorge and channel widths are typically narrow (Figure 18). Bankfull widths range from 25 to 94 m and the channel gradient averages 0.004 m/m. Cross Section 32b was not included in the 1983 analysis because the channel had been disturbed by bulldozers.

Cross-sectional changes in WY 1983 generally reflected little or no change. Minor scour in the reach occurred in WY 1984 with the exception of Cross Sections 32a and 29. 'ΔE_c' increased 0.23 m due to the downstream migration of a sand bar on the left bank of Cross Section 32a, and widening of the low flow channel at Cross Section 29 resulted in a decrease of -0.28 m in the mean streambed elevation.

Due to the narrow channel in this reach, only 3 percent of the total channel stored sediment of Redwood Creek is located between Lacks Creek and Copper Creek (15 percent of the total channel length) (Madej, 1984a).

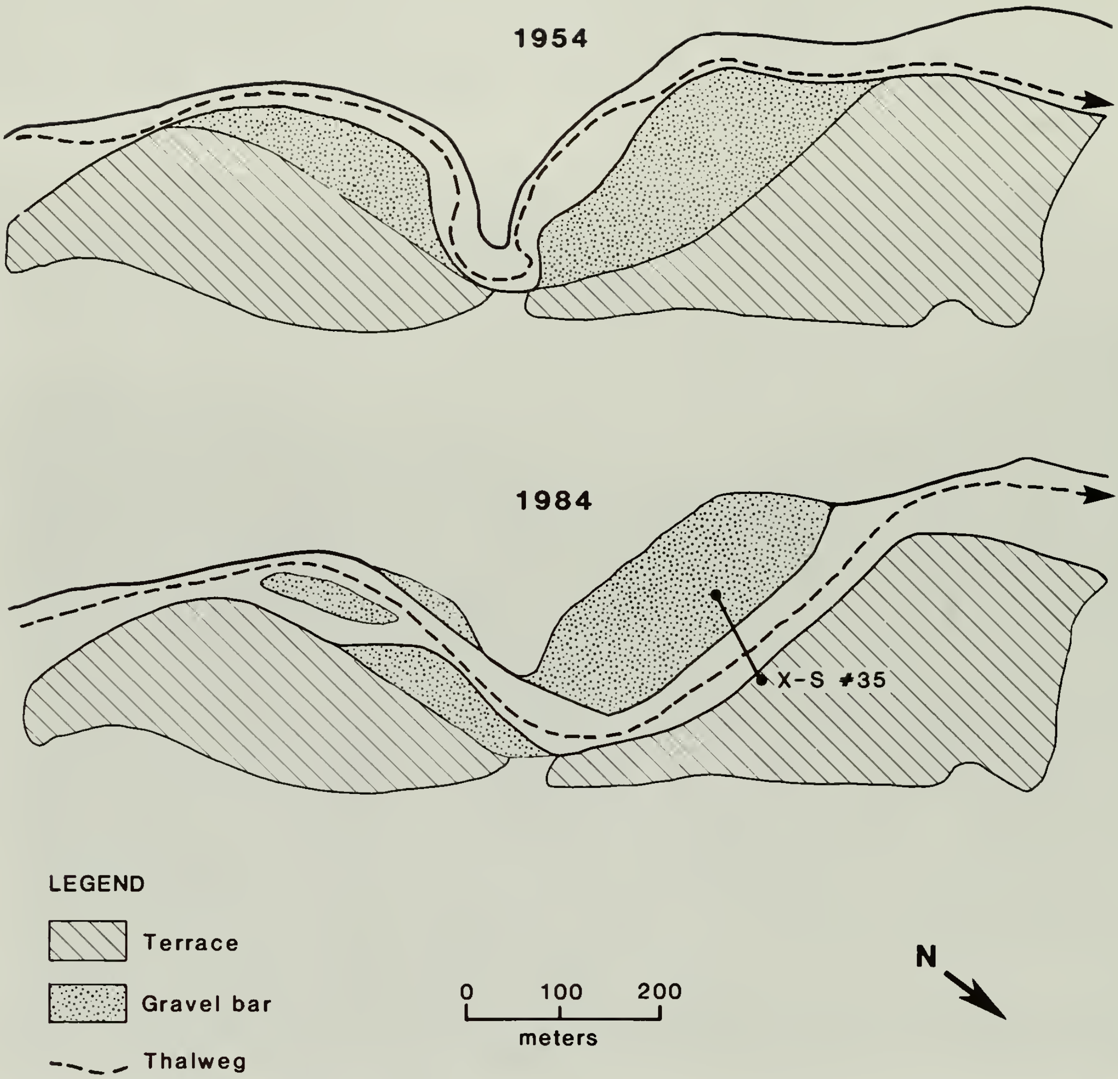


Figure 16. Changes in the position of the thalweg and adjacent gravel bars near Cross Section 35 occurred during the 1964 storm. The channel maps were drawn from 1954 and 1984 aerial photographs.

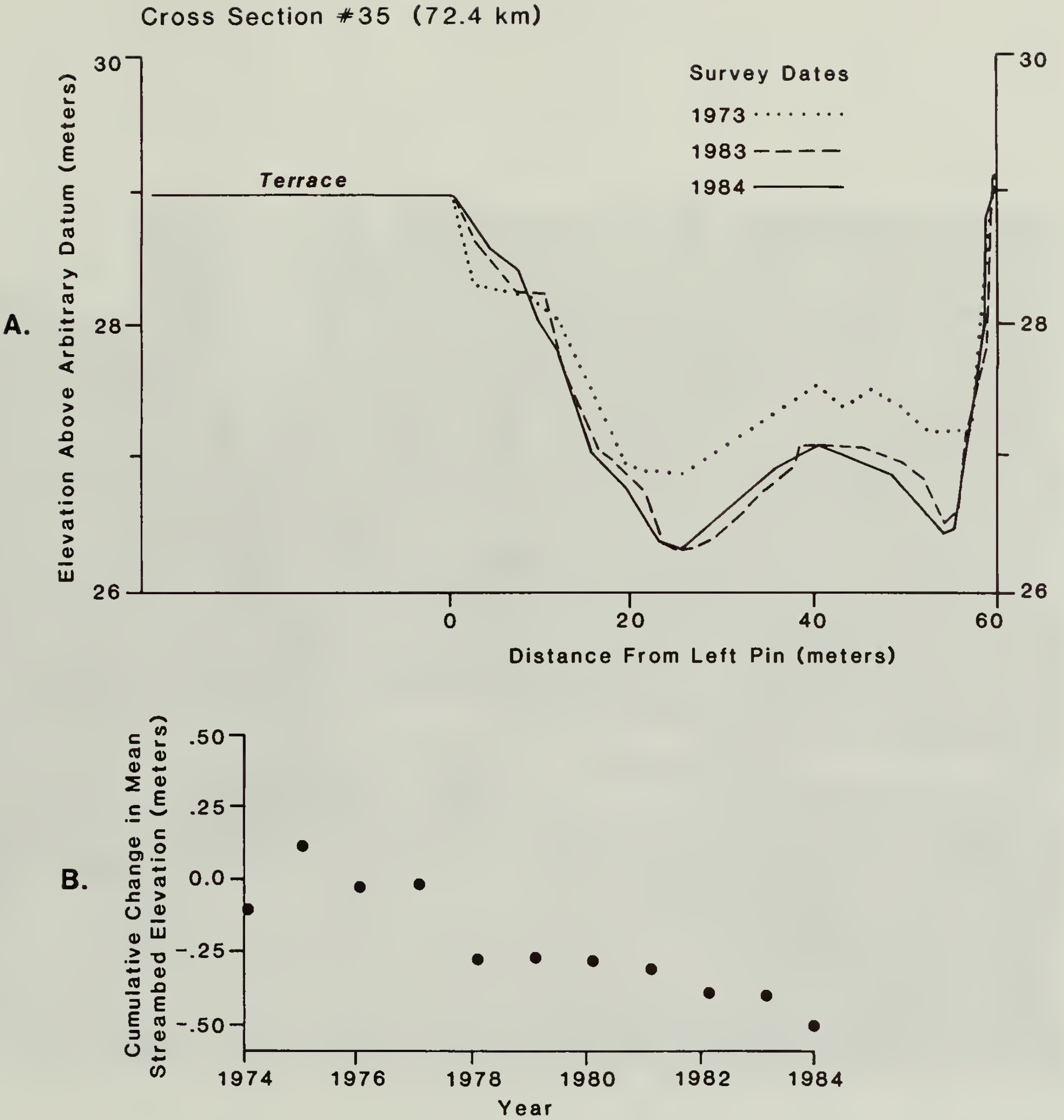


Figure 17. A: Plot of Cross Section 35. The channel is well incised into the adjacent 1964 terrace on the left bank. B: Cumulative change in mean streambed elevation shows that the channel has scoured since 1975.

Figure 18. Redwood Creek looking upstream from Cross Section 32. In the reach between Stover and Copper Creek, the channel again becomes narrow. Valley walls are steep with little room for extensive gravel bars.

The effect of large flows on the limited sediment supplies of tributaries appears to be documented by the effect of the 1975 flood on the main channel in this reach. The flood of 1975 resulted in fewer and smaller landslides than any other 20th century flood of comparable magnitude (Harden and others, 1978). However, most of the cross sections between Lacks Creek and the Tall Trees Grove filled in WY 1975. A major source of sediment supplied to these reaches appears to be sediment which was introduced to tributary streams during the 1972 storms and then redeposited in the mainstem by the 1975 storm. Cross section data for WY 1975 show exceptionally high values of filling in reaches where tributaries most affected by the 1972 floods enter Redwood Creek. The ability of steep tributaries in the Redwood Creek basin to rapidly transport sediment is described by Pitlick (1982): "Tributaries (in the Redwood Creek basin) represent streams in which the sediment transport regime is limited by sediment supply and residence time of sediment is necessarily short."

In addition to sediment contributed from tributaries, the transport of channel sediment from upstream reaches also had a significant impact on this and downstream reaches in WY 1975. Cross sections located upstream of this reach scoured with relatively high magnitudes in WY 1975 compared to magnitudes observed since about 1980. In addition, sediment transport was significantly higher at the Blue Lake gaging station in years prior to 1977 than in following years (Crippen, USGS, unpublished data).

A plot of cumulative ΔE_c illustrates that cross sections in this reach have generally scoured since WY 1975 (Figure 19B). Streambed lowering usually occurred over the entire bankfull width in these narrow channels (Figure 19A).

Reach 5. Slide Creek:
Cross Sections 28 (80.0 km) - 26 (80.3 km)

Three cross sections are in this 2.6 km long reach. Large earthflows entering the creek from the east side result in a narrow, extremely rocky channel with a steep gradient. Bankfull widths range from 45 to 90 m and become narrower in the downstream direction. These cross sections reflect an atypically wide section of the reach (Figure 20). Cross Sections 25 and 26 are separated by a narrow, rocky gorge 1.5 km long which is typically 40 - 50 m wide with a steep channel gradient (0.012 m/m).

Cross Sections 26 and 28 both experienced minor changes in WY 1983 and WY 1984; the absolute value of streambed area change was small. The thalweg of Cross Section 27 scoured significantly near the left bank in WY 1983 (ΔT = -0.7 m, ΔE_c = -0.44 m). In WY 1984, the left bank failed, aggrading the cross section (ΔT = 0.3 m, ΔE_c = 0.19 m).

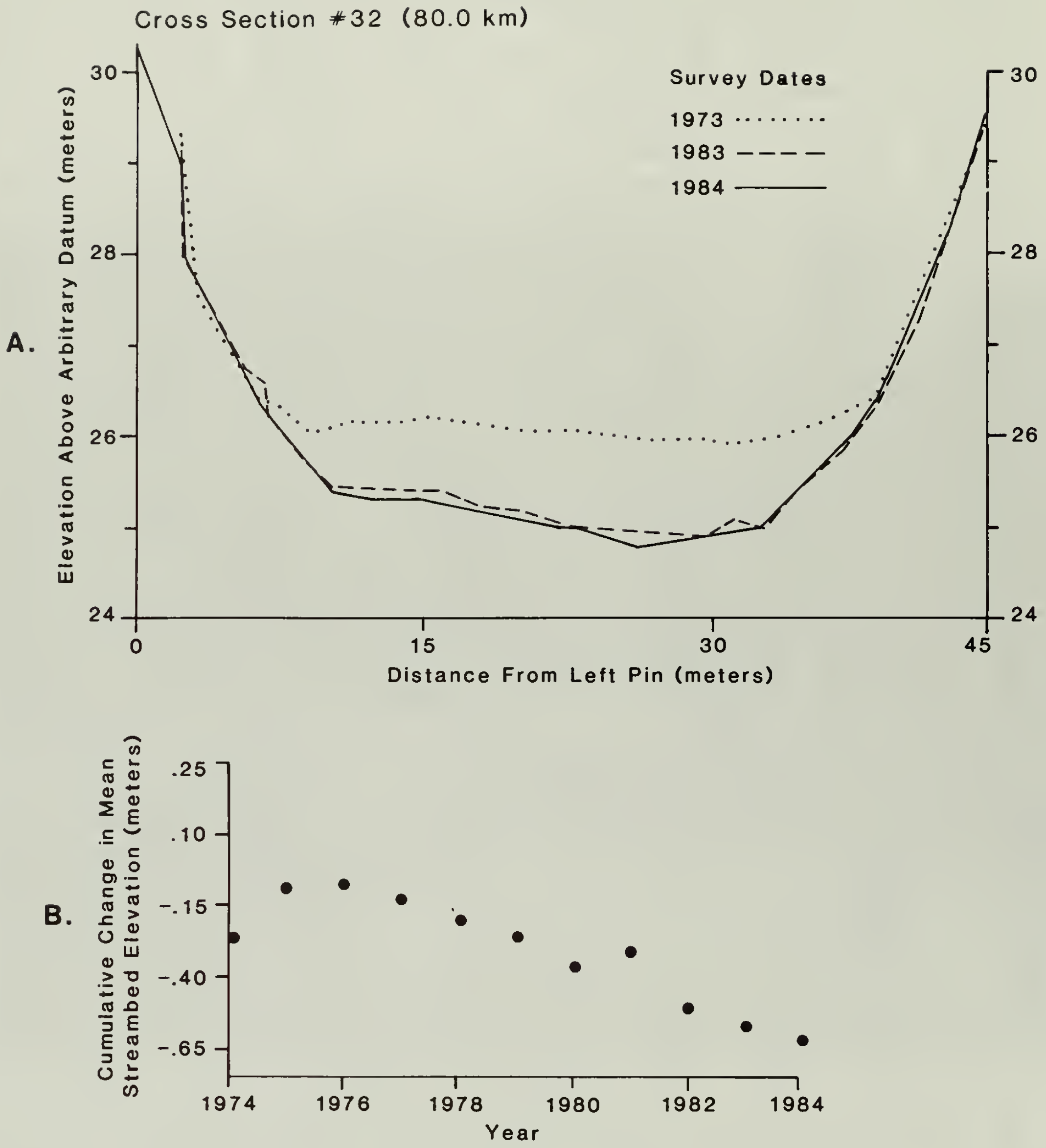


Figure 19. A: Plot of Cross Section 32. The low flow channel in this reach occupies the entire channel. B: Cumulative changes in mean streambed elevation show that after the 1975 aggradational event, the streambed scoured and has changed relatively little in the last three to four years.

Figure 20. This reach provides a temporary sediment storage site for material from earthflows (left) entering from the east side of the channel. This photograph is looking upstream from Cross Section 28.

General channel characteristics of this reach are similar to the reach upstream. The channel lies in an inner gorge, and the streambed gradient is steep. A notable difference is a pronounced constriction in the channel immediately downstream of the reach. A consequence of this constriction is a backwater effect which is responsible for the presence of several large gravel bars in the reach. Aerial photographs taken between 1954 and 1973 show the thalweg at Cross Section 28 moved from the left to the right side of the channel and a large gravel bar formed on the left side of Cross Section 28 and on the right side of Cross Section 27. Cross section profiles show that these bars enlarged between 1973 and 1975 and have since retained their configurations (Figure 21A). The presence of 2 m high brush and alder indicates that the surfaces of the bars have been modified more recently than those in Redwood Valley. The low flow channel is presently incised about 4.0 m into the adjacent gravel bars. Cumulative ΔE_c for cross sections in this reach indicates the mean streambed elevation lowered 0.20 to 0.82 m since WY 1975 (Figure 21B).

Except for localized bank instability at Cross Section 27, the low magnitude of changes since WY 1982 suggest that the channel in this reach is nearly adjusted to recent annual peak flows (RI = ≦ 4 years).

Reach 6. Base of the Gorge to Bridge Creek:
Cross Sections 25 (82.1 km) - 22 (84.3 km)

The mainstem of Redwood Creek downstream of the gorge differs dramatically from upstream reaches. At the base of the gorge, the stream leaves the trace of the Grogan fault and flows entirely through schist bedrock. Notable differences in channel characteristics include increased channel widths and decreased channel gradient. The base of the gorge marks the beginning of the wide alluvial channel typical of lower Redwood Creek (Figure 22).

There are four cross sections in this 3.3 km long reach. Bankfull widths range from 45 to 81 m with total channel widths up to 245 m. The average channel gradient is 0.0030 m/m.

All four cross sections reflected scour in WY 1983 and WY 1984. In WY 1983, with the exception of Cross Section 22, cross sections scoured significantly ($\Delta E_c \geq -.21$m) and scour occurred across the entire channel. In WY 1984, ΔE_c for the cross sections reflected scour, but were of a lesser magnitude than the previous year. In contrast to WY 1983, changes at most of the cross sections were related to shifting and scour along the thalweg.

Longitudinal profiles surveyed in 1977 and 1983 show that the entire length of this reach scoured an average of 1.2 m (Figure 7). The stream gradient lowered slightly between 1977 and 1983 (0.0030 to 0.0023 m/m). Leopold and Wolman (1957) showed that stream gradients generally decrease with degradation and increase with aggradation. An F-test on the residual variance of the longitudinal profiles from 1977 and 1983 indicate that there has been a significant development of bed morphology

A.

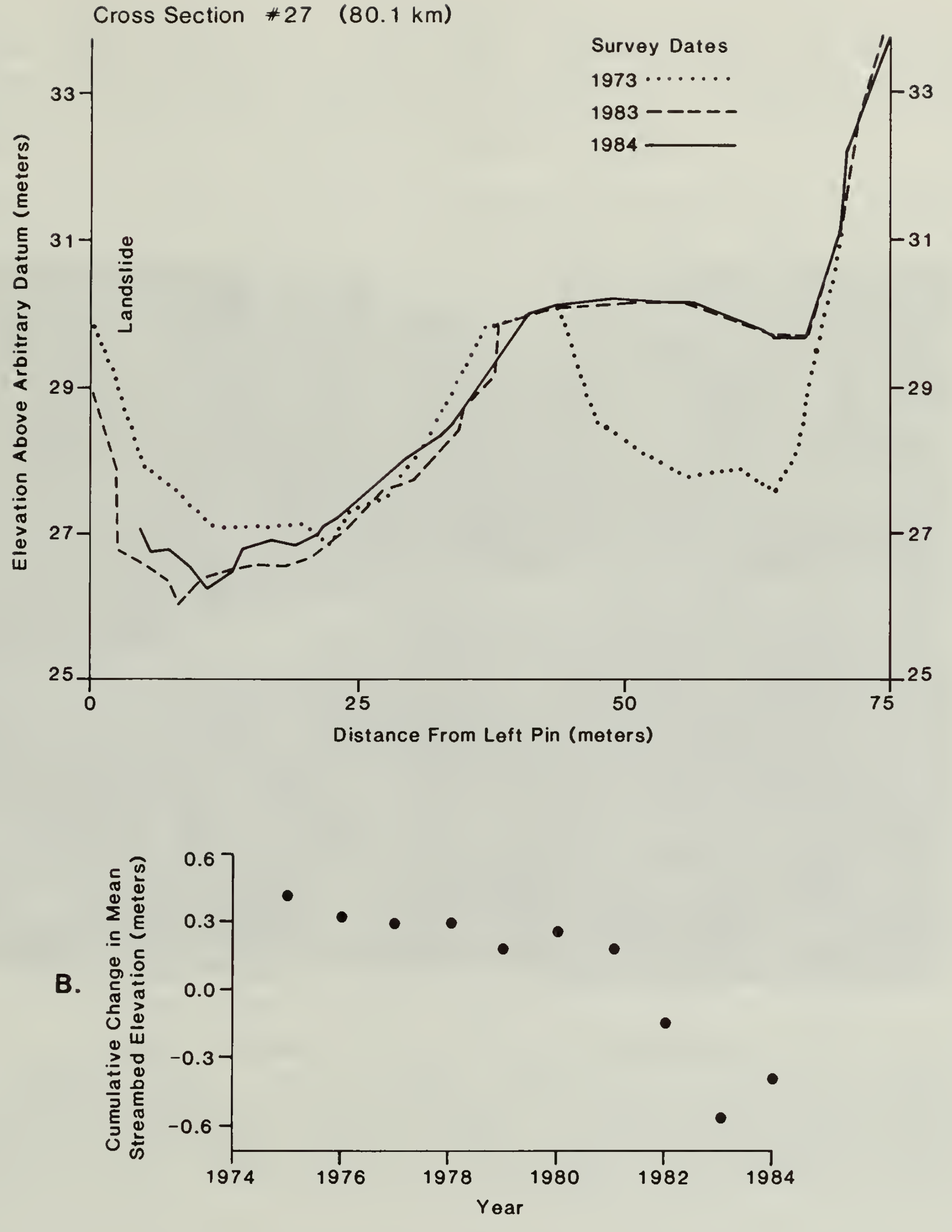


Figure 21. A: Plot of Cross Section 27. A large portion of the gravel bar on the right side was emplaced during the 1975 storm. B: Cumulative changes in mean streambed elevation at Cross Section 27 show that the majority of degradation has occurred since 1981.

Figure 22. Downstream of the gorge, the riparian vegetation of Redwood Creek is typically old growth redwood forest. The streambed is also characterized by a wide alluviated channel. Between the base of the gorge and Bridge Creek, ΔE_c values have been the highest recorded in the basin. Presently, the streambed is scouring here.

since 1977. Qualitative field observations indicate that pools have become larger and deeper since 1982. Most of these are scour holes around large roughness elements such as boulders, root wads, and bedrock outcrops. Moses (1984) showed that 89 percent of the pools in lower Redwood Creek form around large roughness elements.

Channel morphology in this reach responded dramatically to changes in discharge and sediment load. Aerial photographs from 1954 show a boulder-bedded reach between Cross Sections 25 and 23 and no gravel bars. Following the 1964 storm event, the boulder-bedded stream was buried by a finer alluvium. In response to the 1972 storms, extensive filling had occurred throughout the reach, and by 1973 a large gravel bar was deposited in an exceptionally wide portion of the channel at Cross Section 23. By WY 1974, the inflection point below which most downstream cross sections filled and upstream cross sections scoured was located near Bridge Creek. Measured values of cross- sectional changes in WY 1974 ranged up to ΔE_c = -0.44 m and ΔT = -0.8 m. Following the 1975 storm, major filling again occurred in this reach with measured values ranging up to ΔE_c = 0.83 m and ΔT = 1.2 m. Nolan and Janda (1979) considered this reach the locus of maximum aggradation in 1976.

Since WY 1977, this reach has scoured consistently, generally with higher magnitudes than the rest of the channel. Net difference in ΔE_c and ΔT agree with the trends and magnitude of scour seen in the longitudinal profile and indicate that by 1984, the streambed had scoured 0.5 m below the 1974 level. The most important change in channel morphology has been the incisement of the low flow channel (Figure 23A). The position of the low flow channel and adjacent gravel bars has not changed significantly since 1976. The low flow channel is presently incised about 1.5 to 2.5 m into gravel bars which are annually inundated by high flows. A cumulative plot of ΔE_c for Cross Section 23 (Figure 23B) demonstrates progressive scour has occurred since WY 1977.

Reach 7. Bridge Creek to Elbow Creek:
Cross Sections 21a (84.6 km) to 18a (87.8 km)

Four cross sections are in this 3.7 km long reach. Bankfull widths range from 57 to 120 m and the average channel gradient is 0.0024 m/m. Cross Section 21a was not included in the WY 1983 analyses due to surveying errors.

In WY 1983, the lower two cross sections (Cross Section 18a and 19) showed no change. However, the absolute value of change recorded at the cross sections indicate the stream sediment is quite mobile. At Cross Section 19, streambed scour and fill were both nearly 27 m². Cross Section 20 scoured significantly in WY 1983. At this cross section, the entire streambed lowered evenly (-.27 m) with slightly more material removed from the thalweg than the rest of the channel. In WY 1984, Cross Section 19 showed minor change and the remaining cross sections scoured significantly. The ΔT indicates this reach experienced the greatest thalweg lowering (-0.6 m) of the entire channel in WY 1983 and 1984. During this time period there were no major shifts in low flow channel position in this reach.

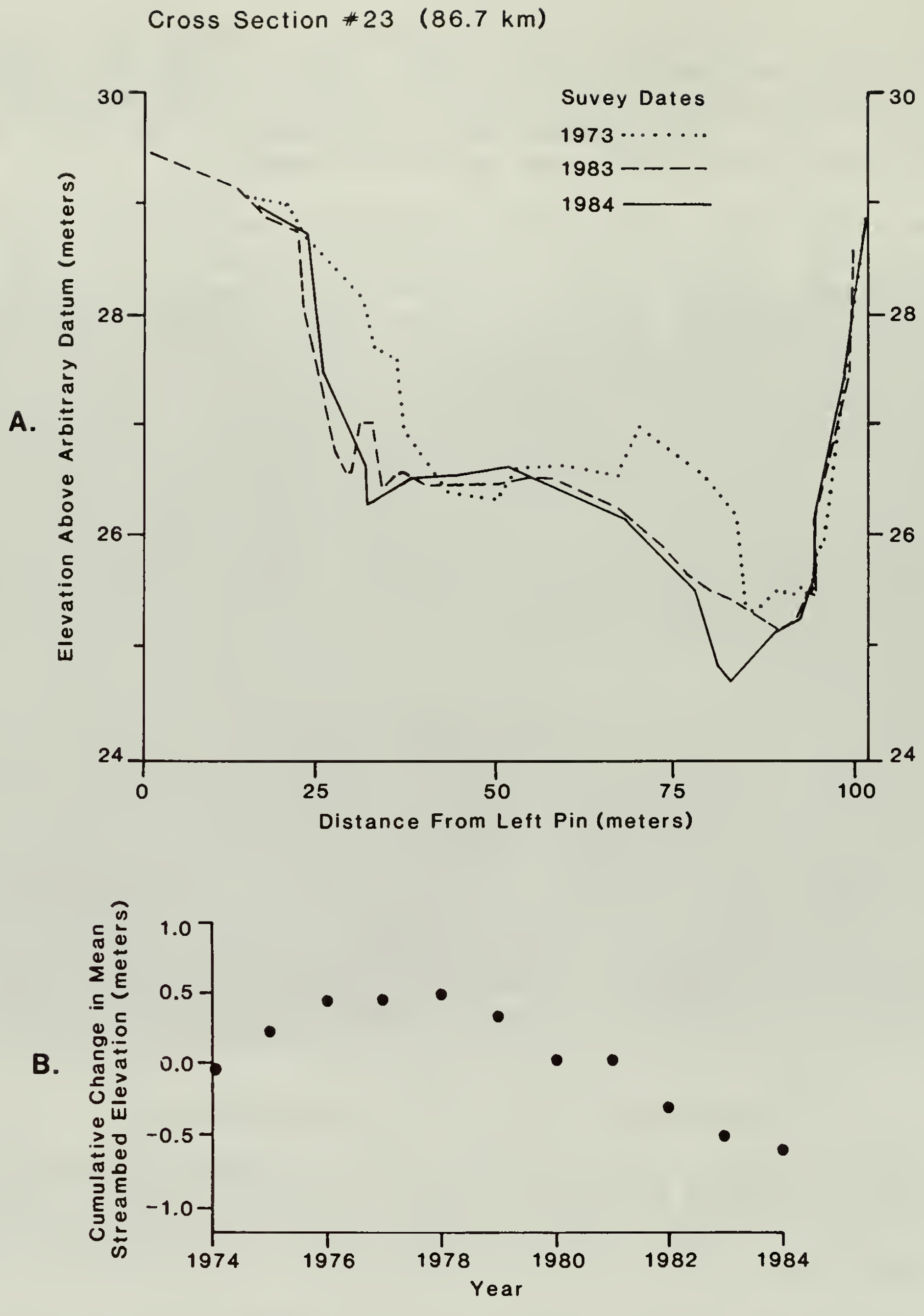


Figure 23. A: Plot of Cross Section 23. The gravel bar on the left was emplaced between 1970 and 1975. B: Cumulative changes in mean streambed elevation show that the channel is continuing to downcut after filling in 1975.

Longitudinal profiles show the entire thalweg scoured between 1977 and 1983, with scour decreasing in the downstream direction from about 1.00 m to 0.60 m (Figure 7). The mean ΔE_{ℓ} was -0.88 m. Slope gradients decreased from 0.0027 to 0.0024 m/m, and based on F-tests, pool and riffle development increased significantly since 1977.

Cumulative plots of ΔE_c indicate that Cross Section 21 aggraded in response to the 1975 flood until WY 1979 and then began to scour. Cumulative ΔE_c for Cross Section 19 show that significant scour did not occur until WY 1982. The data agree well with longitudinal profile data which also show decreasing degradation in the downstream direction (Figure 24). Large channel widths may contribute to the relatively slow rate of vertical downcutting near Cross Section 19 (Figure 25). Madej (1984a) showed that the most important variable in sediment storage is channel width. This suggests that greater storage capacities in exceptionally wide reaches retard the stream's ability to scour across the entire cross section.

The migration of scour downstream from the gorge to this reach appears to be accompanied by the depletion of the upstream sediment supply. The lack of significant changes in channel morphology in cross sections upstream of the gorge, with the exception of Redwood Valley, since 1981 suggests that the channel between Reaches 1 and 5 have not been a major source of sediment for downstream reaches. Sediment transport in the reaches upstream of the gorge has been limited to annual sediment supply from hillslope erosion during recent years of low to moderate flows. Gaging station records indicate that these recent flows are capable of transporting bedload. As excess sediment supply decreased in the upstream reaches, the more recently aggraded reaches (as of WY 1975) below the gorge began to scour, beginning at the base of the gorge and progressing downstream.

Reach 8. Tall Trees Grove:
Cross Sections 17 (88.5 km) - 15 (89.8 km)

Six cross sections monitor this 2.5 km long reach. In this reach, the creek flows around a large terrace that supports the Tall Trees Grove (Figure 26). Bankfull widths are large (up to 150 m), and the streambed gradient averages 0.0021 m/m.

In WY 1983, there were no consistent trends in ΔE_c between cross sections in this reach. The filling cross sections were higher in magnitude than scouring cross sections. In WY 1984, the upstream four cross sections reflected significant amounts of scour. ΔE_c at Cross Section KL was -1.32 m, the largest ΔE_c ever recorded.

Lateral shifting of the low flow channel is characteristic of this reach (Figure 27A). Although ΔE_c may reflect minor changes, values for streambed scour and fill are large, indicating fluctuation of sediment distributed across the entire cross section. At Cross Section IJ, in WY 1983, ΔE_c was only -0.01 m (Figure 27B). However, streambed scour and fill were both nearly 50.0 m². Absolute values of streambed area change

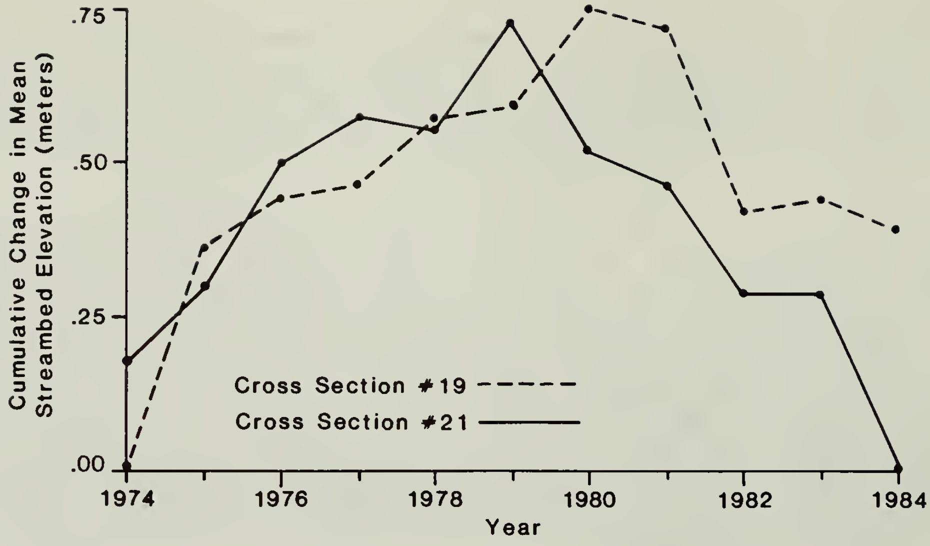


Figure 24. A plot of cumulative ΔE_c for Cross Sections 19 and 21 show that scour progressed in the downstream direction between WY 1975 and 1984.

Figure 25. Plot of Cross Section 19. The extreme width of the channel at this location has probably slowed the recent rate of scour.

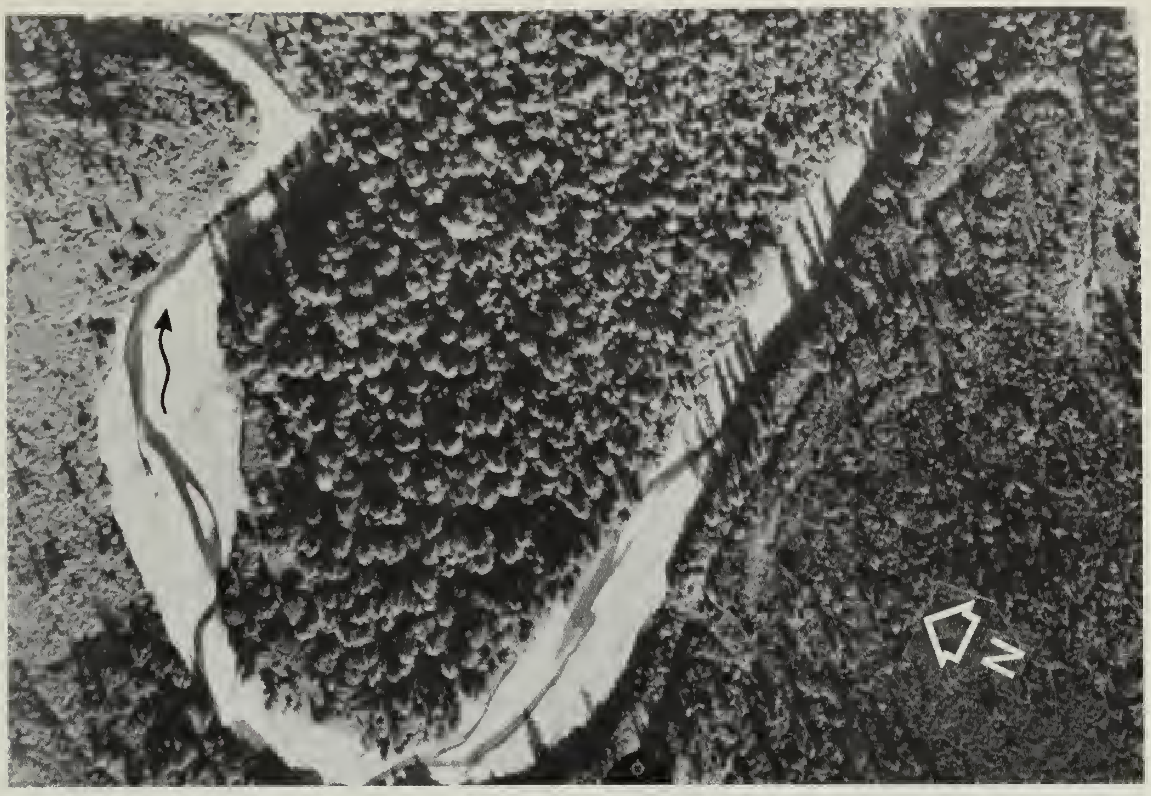
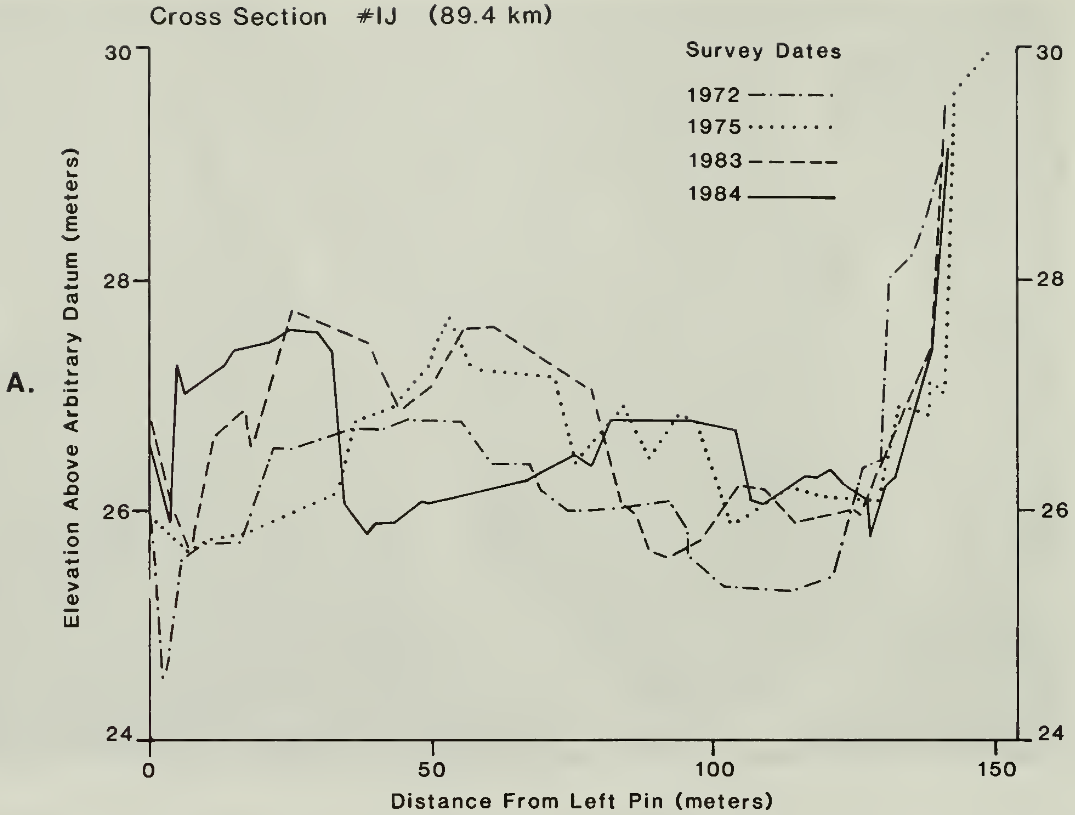


Figure 26. 1981 aerial photograph of the Tall Trees Grove. Redwood Creek flows around a terrace that supports the grove. The terrace is occasionally flooded during high flows (RI > 10 years) and was modified in 1986 by bank erosion. Channel widths are up to 150 m wide.

at the cross sections in this reach are consistently high, with the highest values of absolute change for the stream occurring in this reach in the past two years. This indicates the stream sediment in this reach is very mobile.

The first occurrence of aggradation noted in the longitudinal profile is located immediately downstream of Cross Section 18a (Figure 7). The longitudinal profile shows that 38 percent of the channel length has aggraded in this reach between 1977 and 1983. About half of the aggradation in the reach occurs downstream of Cross Section 16, corresponding to the portion of the reach with the largest channel width ($\geqq$ 160 m). The ΔE_ℓ for the reach was -0.27 m and since 1977, the channel gradient for the reach decreased from 0.0024 to 0.0022. Field evidence and F-tests on the residual variance of the two longitudinal profiles indicate significant development in pool-riffle sequence since 1977.

Figure 28 shows that the entire north side of the terrace has undergone extensive modification in the last thirty years. Major bank accretion deposits laid down between 1954 and 1965 have been eroded. In some areas, the terrace edge has eroded beyond the 1954 edge. Past



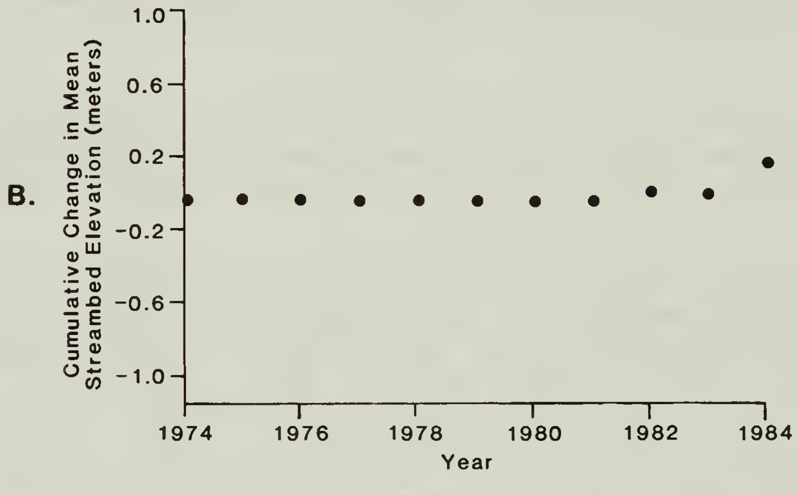


Figure 27. A: Plot of Cross Section IJ. Lateral shifting is common in the wide channel near the Tall Trees Grove.
B: Cumulative change in mean streambed elevation at Cross Section IJ shows no change since 1974.

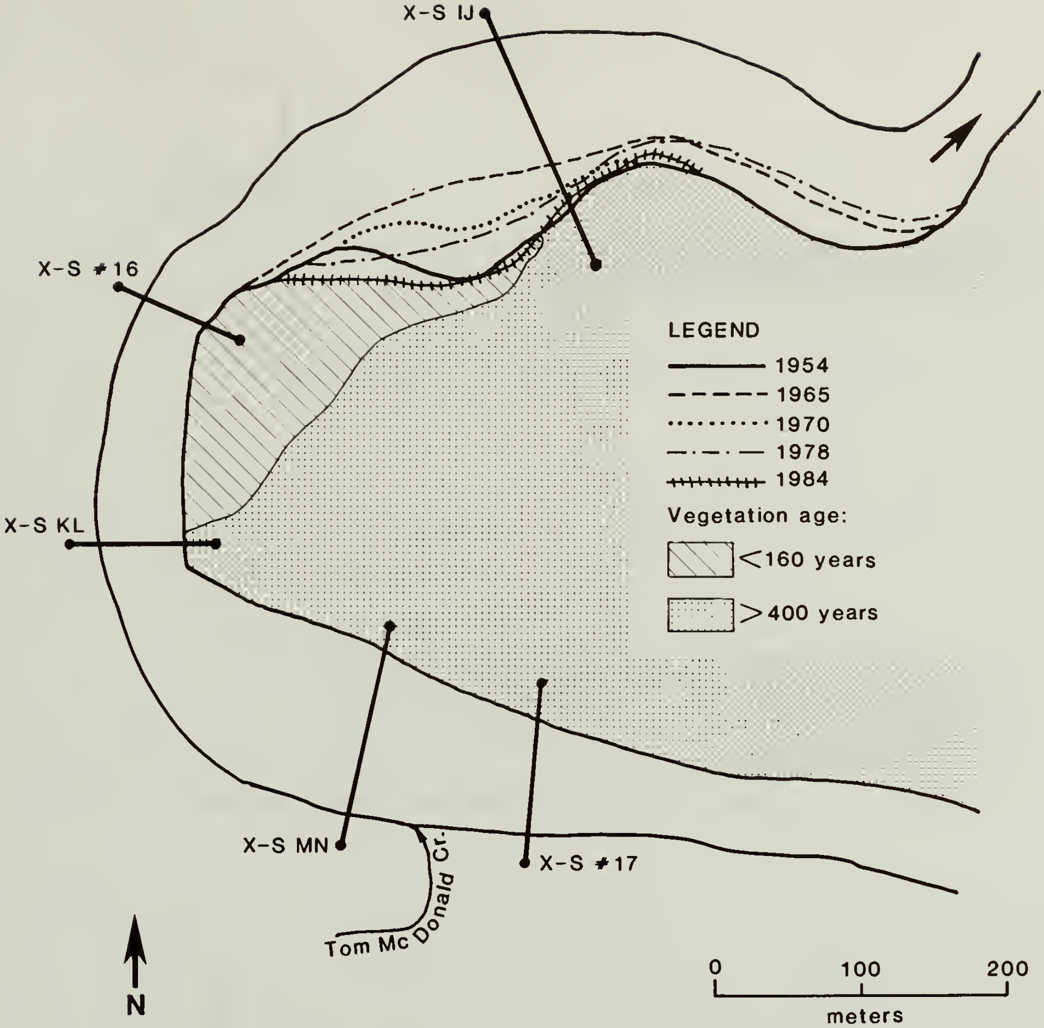
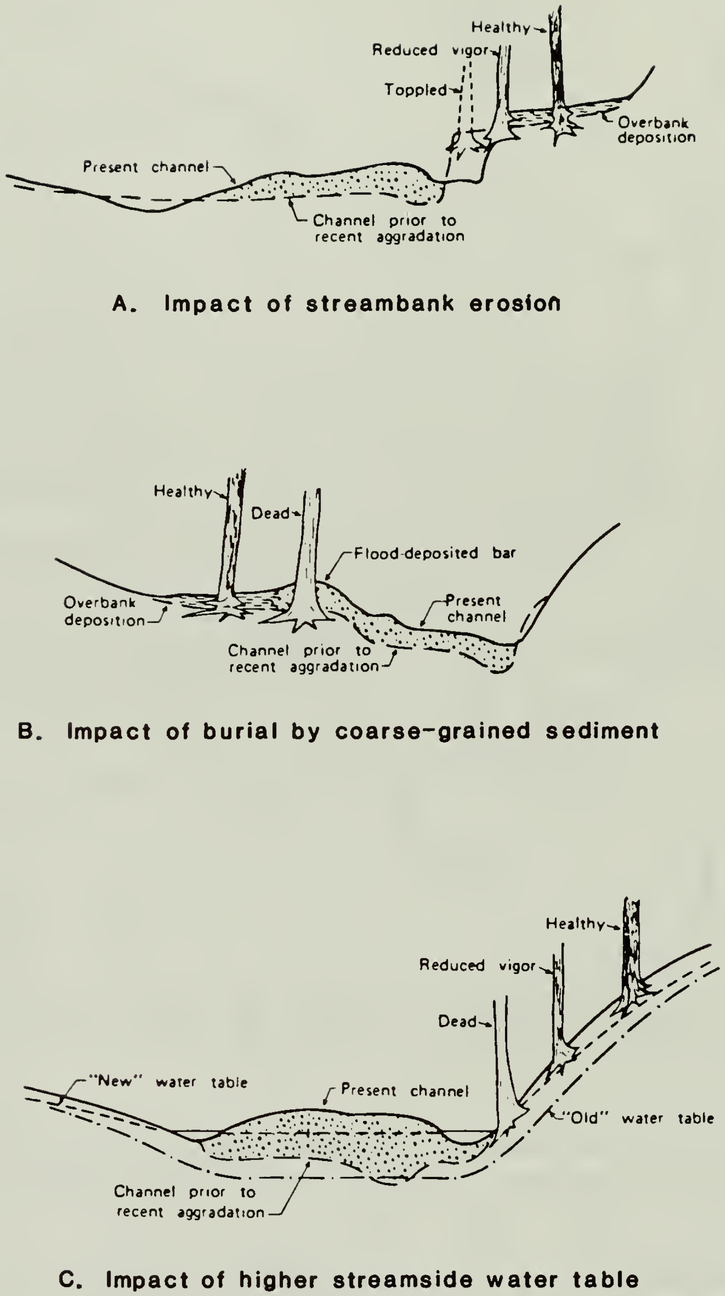


Figure 28. Bank modification along the north side of the terrace supporting the Tall Trees Grove, 1954-1984.

instability of the northwestern edge of the terrace is demonstrated by a stand of large trees less than 160 years old (S. Veirs, NPS, personnel communication).

Streambed aggradation poses a potential threat to old growth redwood forests growing on low-lying alluvial flats such as the Tall Trees terrace (Figure 29). Potential threats to the old growth redwoods include bank erosion, sustained elevated groundwater levels, and gravel deposition on the terrace. Severe examples of these problems have been described in the Bull Creek basin located 90 km south of the study area (Jager and LaVen, 1981; Zinke, 1981). Aggradation of the channel around the Tall Trees Grove may have begun as early as 1955. The flood of 1955 flushed the channel of vegetation visible on 1936 and 1954 aerial



A. Impact of streambank erosion

B. Impact of burial by coarse-grained sediment

C. Impact of higher streamside water table

Figure 29. Adverse impacts of recent channel aggradation on streamside vegetation (from Nolan and Janda, 1979).

photographs. Channel filling under the bridge at the mouth of Tom McDonald Creek indicated that extensive filling had occurred in the channel by the early 1970's. Since 1975, only minor changes in thalweg and gravel bar surface elevations have been observed.

Cross section and longitudinal profile data indicate that channel scour has migrated 6 km downstream since the aggradational event of 1975. The movement of the channel sediment is analogous to a wave. In WY 1984 the trailing edge of the aggradational wave was downstream of Cross Section 16 (Figure 7). This reach around the Tall Trees Grove has been a historic sediment storage site on Redwood Creek. A channel constriction downstream at Cross Section 15 and large channel widths typical of this reach facilitate sediment storage. However, the streambed has recently experienced aggradation above historic levels and the channel fill around the Tall Trees Grove may be a remnant of the passing aggradational wave. If this is the case, significant scour of the channel can be expected to begin within the next five years, provided annual peak flows do not exceed moderate values (RI < 10 years) and no large influx of sediment occurs.

The high magnitude of scour (ΔE_{ℓ} = -1.4 m) that occurred in the longitudinal profile immediately downstream of Cross Section 15 to Cross Section 14 was due to an abrupt decrease in channel width. At Cross Section 15 the channel turns approximately 90° and the channel width decreases 40 percent. This fairly straight and narrow section of stream is efficient at transporting stream sediment.

Overbank flooding of the Tall Trees Grove apparently occurs with every major flood (RI ≧ 10 years). The basal flanges of many of the Tall Trees have been buried by approximately a meter of deposition. Several redwood stumps located on the south edge of the grove support 120 year old sprouts. Axe marks on the top of the stumps are 0.3 to 0.6 m above ground level. If these trees were cut at breast height, at least 1.0 m of deposition of fine-grained material has occurred since the 1860's. Zinke (1981) showed that overbank siltation has a 900+ year history in alluvial flats of the Bull Creek basin and that periodic siltation contributes to growth vigor of redwood trees. However, overbank deposition of coarse materials, such as streambed gravels has resulted in the death of trees on those alluvial flats. So far, no gravels have been deposited on the surface of the Tall Trees Grove.

Reach 9. Forty-four Creek to Elam Creek:
Cross Sections 14 (91.4 km) - 6 (97.5 km)

This 6.5 km reach is monitored through nine cross sections. Bankfull widths range from 61 to 112 m (Figure 30). The channel gradient averages 0.0018 m/m.

Changes in mean streambed elevation alternated between minor scour and fill at cross sections in WY 1983. Filling cross sections showed a higher magnitude change than scouring ones with the exception of Cross

Figure 30. Redwood Creek between Forty-four and Elam Creeks is wide and alluviated. The presence of multiple channels may reflect high sediment loads.

Section 14 (ΔE_c = -0.25 m). Here, a large root wad caused a deep scour hole in the thalweg. Cross Section 7 had one of the largest values for net fill (ΔE_c = 0.14 m), even though it experienced one of the largest streamwide negative thalweg changes (-1.5 m). Thalweg lowering was due to a low flow channel shifting against a bedrock outcrop, causing subsequent scour.

WY 1984 generally showed filling trends in the downstream part of the reach. The magnitude of both filling and scouring cross sections was fairly high, with ΔE_c often greater than ±0.10 m.

For both years, the absolute values of streambed area change are relatively high and indicate fairly mobile stream sediments at the cross sections. The low flow channel in this reach alternated between a single, wide meandering channel and multiple channels. Lateral shifts in low flow channels and mid-channel bars occurred at every cross section except Cross Section 13. Remnants of high flow channels were often present. Local incidences of bank erosion occurred throughout the reach resulting in toppled riparian vegetation, generally alders.

Aerial photographs taken in 1954 show a low flow channel that is typically split and flowing within a wide alluviated channel. Low and high flow channels appear to be well incised around mid-channel bars that commonly support alders and other vegetation. The depth of low flow channel incision around the gravel bars is difficult to estimate, but probably does not exceed 3 m. Photographs in 1965 show the channel completely devoid of the alders and other vegetation that were growing along the channel margins in 1954. Stream crossings and tonal variations in the alluvium on aerial photographs suggest that a fair amount of relief still existed between mid-channel bars and low flow channels. By 1970, the streambed appeared nearly flat by the lack of tonal variations and discernable relief between low flow channels and mid-channel bars in the photos.

The longitudinal profile survey shows that 64 percent of the channel length aggraded between 1977 and 1983. The mean change in longitudinal streambed elevation was 0.3 m and the magnitude of aggradation generally increased in the downstream direction. Cumulative ΔE_c for cross sections in this reach all show a general trend of aggradation with mean streambed elevation rising from 1976 to 1984 (Figure 31B).

Increases in slope gradient with aggradation have been described by Mackin (1948) and Leopold and Wolman (1957). In Redwood Creek, between 1977 and 1983, the upstream half of this reach exhibited minor changes in slope gradient and actually decreased slightly in some areas. In the downstream half, where aggradation appears to be most dominant, slope gradients increased significantly (Figure 7).

An F-test of the residual variance in the longitudinal profiles indicate that sections in this reach have had no significant development of pools and riffles since 1977. This is the only reach to show no increase in bed morphology.

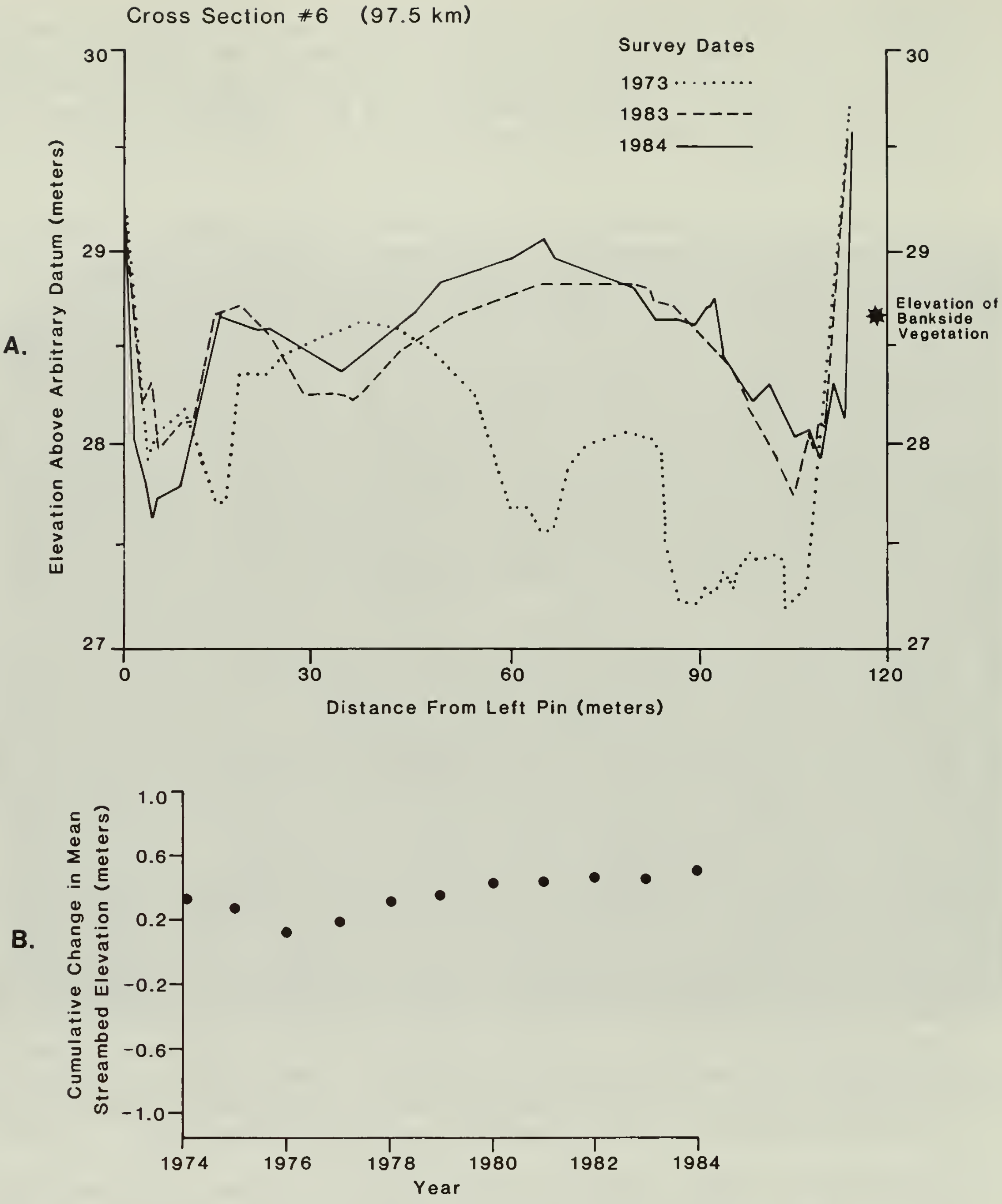


Figure 31. A: Plot of Cross Section 6. Bankside vegetation lines are lower than gravel bar surfaces. This suggests a new higher bankfull elevation has been established due to higher streambed elevations in this reach. B: Cumulative change in mean streambed elevation at this cross section shows the channel has filled since 1976.

Superimposed on many gravel bars downstream of the Tall Trees Grove, and especially in this reach, was a smaller bedform similar to the 'gravel waves' described by Church and Jones (1982). Typically these 'gravel waves' were 0.3 to 0.5 m high at their downstream face, 30-40 m long, and 10-30 m wide. They consisted of well-sorted pea-sized (or larger) gravel and overlay the surface of coarser, more poorly sorted gravel bars. The process of formation of these 'waves' is presently unknown; however, in Redwood Creek they were only found in wide, gentle aggraded reaches with a large sediment supply.

Downstream of Cross Section 11, mid-channel bar surfaces commonly occurred above the elevation of perennial bankside vegetation. During the period of cross-sectional record, bar surface elevations typically varied up to 0.3 m annually above vegetation lines. In WY 1983, bar surfaces were often 0.75 m above vegetation lines (Figure 31A). The surfaces of gravel bars formed by moderate flows (that is, bankfull) must be lower than the bankfull water surface elevation. Therefore, the existing vegetation lines may correspond to an older bankfull level, and it appears that a new, higher bankfull elevation exists due to higher streambed elevation. Elevated gravel bar surfaces above bankside vegetation are only found in wide gentle reaches that are currently experiencing aggradation.

Reach 10. Elam Creek to Prairie Creek:
Cross Sections 5 (98.8 km) - 1 (102.8 km)

This reach is 4.6 km long and monitored with five cross sections. Bankfull widths are between 108 to 141 m at cross sections (Figure 32). Channel gradient averages 0.0015 m/m.

With the exception of Cross Section 2, the reach aggraded in WY 1983. The high magnitude of scour at Cross Section 2 (ΔE_c = -.20 m) was due to scouring of the gravel bar on the right side of the channel. Minor aggradation occurred in WY 1984. Large scour (ΔE_c = -.14 m) at Cross Section 4 is associated with scour of a gravel bar that was emplaced the previous year. In WY 1983 and WY 1984, consistently high values for the absolute change at cross sections in the reach indicate that the stream sediment is mobile throughout the reach. Cumulative change in mean streambed elevation documents aggradation of the streambed following the 1975 storm (Figure 33B). Since 1976, a general trend of aggradation has occurred.

Longitudinal profiles show 64 percent of the channel length degraded between 1977 and 1983 with the mean ΔF_c = -0.08 m. The water surface slope decreased from 0.0017 to 0.0015 m/m since 1977. With the exception of the uppermost part of the reach, the F-test indicates that pools and riffles have significantly increased since 1977.

The majority of aggradation in this reach occurred immediately upstream of the left bank of the flood control levees (Figure 7). Aggradation extended for 600 m upstream. Channel constriction (caused by the

Figure 32. Channel shifting is common in the wide, alluvial reach between Elam and Prairie Creek. This photograph is looking upstream from Cross Section 4.

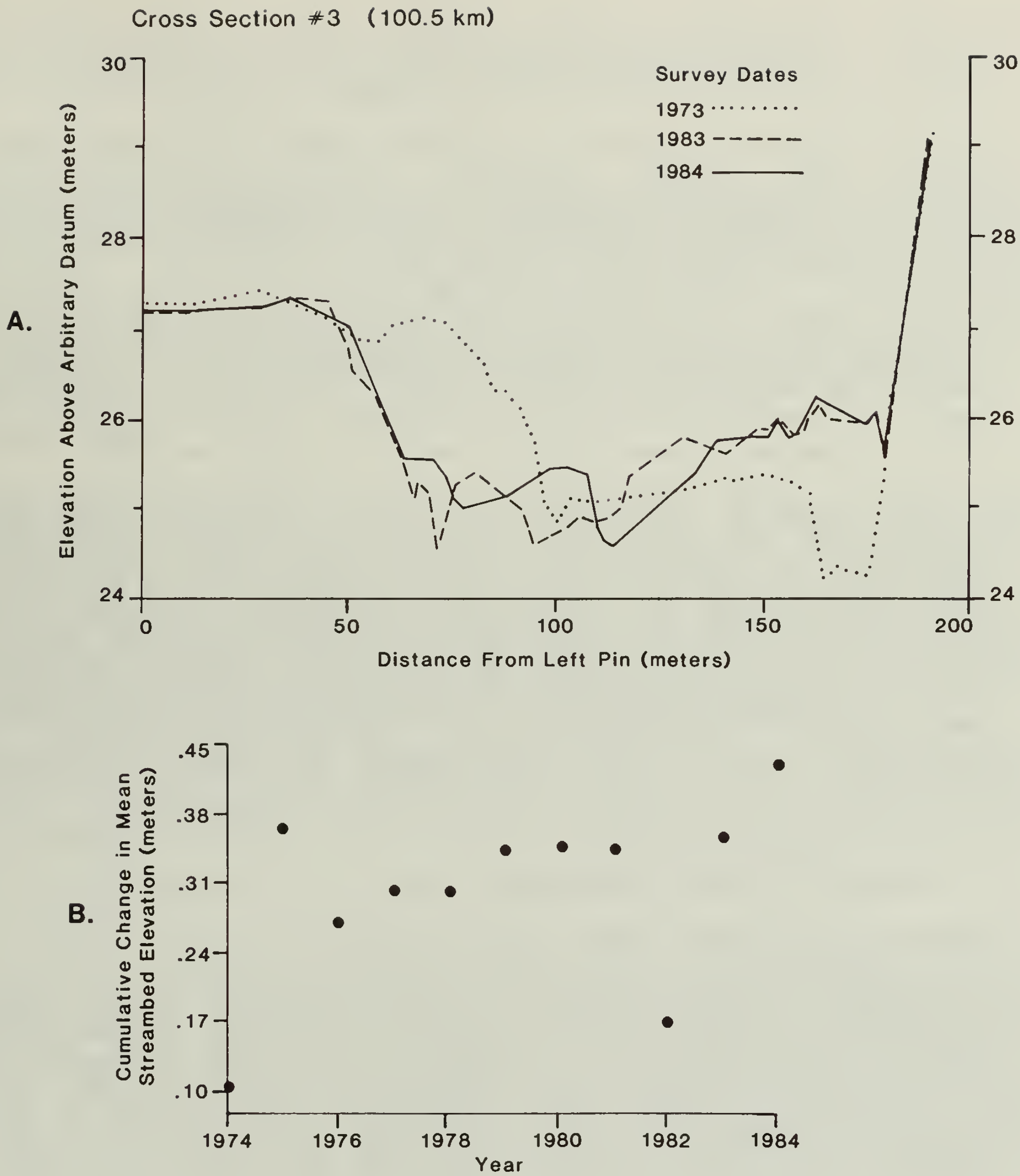


Figure 33. A: Plot of Cross Section 3. Low flow channel shifting is common in wide channels downstream of Elam Creek. B: Cumulative changes in mean streambed elevation show that there has been a general trend of aggradation in this reach since 1974.

levees), tributary inflow, and a sharp bend in the channel created backwater effects and contributed to aggradation here.

Local bank erosion occurred on the right bank of the reach along the base of a large terrace. Incidences of minor bank erosion along this terrace have occurred throughout the cross-sectional record, and in many cases, is related to low flow channel shifting, also a common characteristic of this reach (Figure 33A).

At Cross Sections 4 and 5, the elevations of mid-channel bar surfaces were higher than those of perennial vegetation lines on the banks. In Reach 9 bar elevations varied up to 0.3 m above vegetation lines. However, no significant increase or decrease in the maximum elevation at these bars was determined for this reach in WY 1983 or 1984.

The leading edge of the aggradational wave is less well defined and more difficult to determine than the trailing edge which has migrated downstream 6 km from the base of the gorge since 1977. Near the leading edge, cross section data show high variability from year to year. Longitudinal profile data and field observations, such as mid-channel bar elevations in the upstream portion of the reach and the return of channel vegetation in the lower portion of the reach, suggest that the leading edge of aggradation has moved downstream no more than 2-3 km since 1974, if at all, and is now between the Elam and McArthur Creek confluences.

B. Summary of Channel Adjustments

Headwaters to Chezem Road (Reach 9 and 10)

The channel reaches upstream of Chezem Road were the most severely affected by the 1964 storm. Channel adjustments to the increased sediment load introduced by the 1964 storm included: increased channel widths, decreased channel depth, decreased roughness elements, and loss of riparian vegetation. The cross-sectional record since WY 1974 has generally showed scour, and since WY 1983, no significant changes have been observed in these reaches. Long-term records at Cross Section 40 indicate that the streambed has returned to near pre-aggradation levels. Degradation in these reaches was associated with the incisement of the low flow channel into surrounding gravel bars and 1964 terrace remnants and the return of pool-riffle sequences and riparian vegetation.

Redwood Valley

Redwood Valley is characterized by significantly larger channel widths than reaches located upstream or immediately downstream. Present channel patterns in Redwood Valley were established in the 1964 flood and not modified by subsequent high flows. Between 1975 and 1982, the cross-sectional record indicates the channel in this reach was degrading. In WY 1983 and WY 1984, no significant changes were observed at cross sections. Present bankfull widths are similiar to those observed prior to the 1964 flood in this reach.

Stover Creek to Copper Creek

The channel in this reach is located in a steep, narrow inner gorge. Cross section records indicate significant aggradation occurred as a result of the 1975 storm in this and downstream reaches. Primary sediment source areas in WY 1975 were local tributaries and redistributed channel sediment from upstream areas. The cross-sectional record indicates the reach scoured since 1975. In WY 1983 and WY 1984, changes at cross sections were minor and usually resulted in scour.

Slide Creek

Channel characteristics of this reach are similar to the reach immediately upstream except locally the channel is wider and contains large gravel bars. Cross section records, aerial photographs, and vegetation ages indicate that these gravel bars were largely implaced by the 1972 and 1975 storms. The existence of these gravel bars can be attributed to large sediment inputs and the backwater effect of a major channel constriction immediately downstream (the gorge). Cross section records indicate the channel has been degrading since 1975.

The low flow channel has downcut approximately 4 m into adjacent gravel bars. Cross-sectional changes since WY 1982 have been relatively minor and suggest the channel is adjusted to recent annual peak flows.

The Base of the Gorge to Bridge Creek

The base of the gorge differs dramatically from upstream reaches and marks the beginning of the wide alluvial reaches typical of lower Redwood Creek. Analysis of cross sections showed that major aggradation occurred after the 1975 flood. Since 1977, the entire length of this reach has been degrading. Longitudinal profile and cross section data indicate that by 1984 the channel had degraded 0.5 m below 1974 levels. Changes in channel morphology associated with degradation have been the incision of low flow channels, decreased channel gradients, and increased pool-riffle development.

Bridge Creek to Elbow Creek

Cross sections in this reach aggraded in response to the 1975 flood until around 1979. In following years the streambed scoured and changes in channel morphology in response to degradation were similar to those observed upstream.

Tall Trees Grove

In this reach the channel flows around a large terrace. Active bank erosion along the terrace edge and lateral channel shifting is characteristic of this reach. Channel filling under the bridge of Tom McDonald Creek indicated that major aggradation had occurred by the early 1970's. Cross section data from 1974 to 1983 showed no discernable trends in either aggradation or degradation. However, longitudinal profile data indicate that the upper half of this reach degraded between 1977 and 1983. Sediment accumulations around the Tall Trees Grove may be a remnant of the aggradational wave that has passed through this reach. Longitudinal profile and cross-sectional data indicate that channel scour moved 6 km downstream from the gorge since 1975.

Forty Four Creek to Elam Creek

Aerial photographs indicate that this reach had aggraded by the early 1970's. This trend continued and cross section data showed that the channel rose 0.2 to 0.7 m between 1974 and 1984. Longitudinal profile surveys demonstrated that 64 percent of the channel length in this reach had risen an average of 0.13 m between 1977 and 1983. Aggradation in this reach was associated with frequent shifting and splitting of the low flow channel, mid-channel bar surfaces above the elevation of perennial bankside vegetation, gravel waves, and increased channel gradients. Portions of the streambed in this reach experienced no significant increase in pool-riffle development. This is one of the only sections of the channel to show no pool-riffle sequences.

Elam Creek to Prairie Creek

Cross section data reflected streambed aggradation from 1975 to the present. However, longitudinal profile surveys showed that 64 percent of the thalweg in this reach generally degraded and bed morphology had significantly increased. The leading edge of aggradation between Elam and McArthur Creeks and did not move significantly since 1974.

Successive discharge measurements at the Orick gaging station indicate that the streambed is extensively mobilized at flows ≧235 m^3/s, a flow that is exceeded only about 1.4 percent of the time (Figure 34). Appendix B lists the peak flows between WY 1974 and WY 1984 at the Orick Station that exceeded 235 m^3/s, providing an index of how often the streambed is extensively mobilized. Since the last major flood in 1975, Redwood Creek has experienced eight years of moderately low peak flows (RI < 4 years) (USGS, unpublished data).

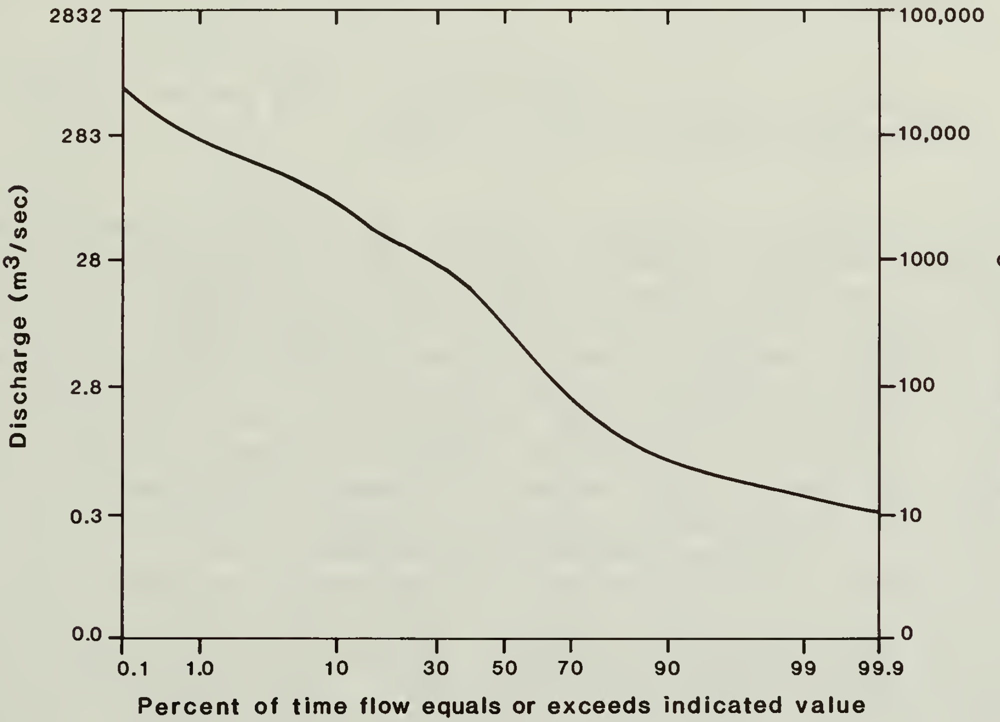


Figure 34. Flow duration curve of daily data for Water Years 1954-1981. Redwood Creek near Orick (USGS, unpublished data).

Suspended sediment and bedload discharge rating curves for the three gaging stations monitoring the main channel have been developed by the USGS (unpublished data). Bedload curves developed for WY 1982 and WY 1983 indicate that for flows with RI = 1.5 years, bedload discharge ranges from 18 percent of the total load at the Blue Lake and Panther Creek stations to 14 percent at the Orick station. These estimates agree with estimates of 15 to greater than 20 percent for other north coast streams (Knott, 1971, 1974; Janda and Nolan, 1979). The long-term (1954 to 1980) annual bedload sediment discharge estimates for the mainstem gaging stations are listed in Table 3. McClelland (personal communication) estimated the accuracy of bedload estimates at the mainstem gaging stations to be within 20 to 30 percent.

Table 3: Long-term Bedload Discharge for Mainstem Gaging Stations on Redwood Creek

Station	Annual Bedload Discharge*		
	m^3**	Tonnes	Tonnes/km^2
Redwood Creek near Blue Lake	49,000	93,500	535
Redwood Creek at Panther Creek	101,000	193,000	500
Redwood Creek at Orick	91,000	173,000	240

*Estimates are for the 1954-1980 water year period (Crippen, 1981)
**Assuming a bulk density of 1.9 g/cm^3.

Bedload discharge estimates are less certain than suspended sediment estimates due to: incomplete calibration of the Helley-Smith bedload sampler, uncertain bedload formulas used for Redwood Creek (Janda and Nolan, 1979), and logistical problems in sampling bedload at high flows. The suspended sediment discharge rating curves for the three main channel gaging stations are shown in Figure 35. For flows with RI = 1.5 years, the Orick and Blue Lake gaging stations had an approximately 40 percent reduction in suspended sediment discharge in WY 1983-1984 compared to the pre-1978 record. Although the Panther Creek gaging station has an incomplete data set, records indicate only an 8 percent reduction in suspended sediment. Cross Section data upstream of this gaging station (with the exception of Redwood Valley) show little change in stream bed morphology after 1978. Since 1977, timber harvest activity has been more intense in the vicinity of this gaging station than in other areas of the basin (Best, 1984; Hagans, NPS, personal communication). This land use activity might partially explain the persistent high suspended sediment concentration at the Panther Creek Station. Nolan and Janda (1981) showed suspended sediment discharge can be up to 10 times greater from harvested terrain than in unharvested terrain in the Redwood Creek basin.

The cross section record partially reflects the relationship between storm events and sediment transport. Table 4 shows that the number of cross sections that experience significant change ($\Delta E_c \geqq 0.15$ m) is generally higher in years that have a large number of flows with mean daily flows exceeding 235 m^3/s.

In 1977 and 1983, volumetric changes in streambed sediment were estimated for reaches downstream of the gorge. Estimates were made using average channel widths, channel lengths, average depth of scour or fill from longitudinal profile, and cross section data. A major constraint with this method is the irregular spacing of cross sections. The volume of sediment removed in actively scouring areas (Cross Sections 25-18a) was estimated to be about 300,000 m^3 and the volume of sediment deposited in actively filling areas (Cross Sections 14-6) was about 200,000 m³. The resulting net loss of 100,000 m³ between 1977 and 1983 is well within the limits of 550,000 m³ of bedload sediment transported past Orick during the same time period (Table 3).

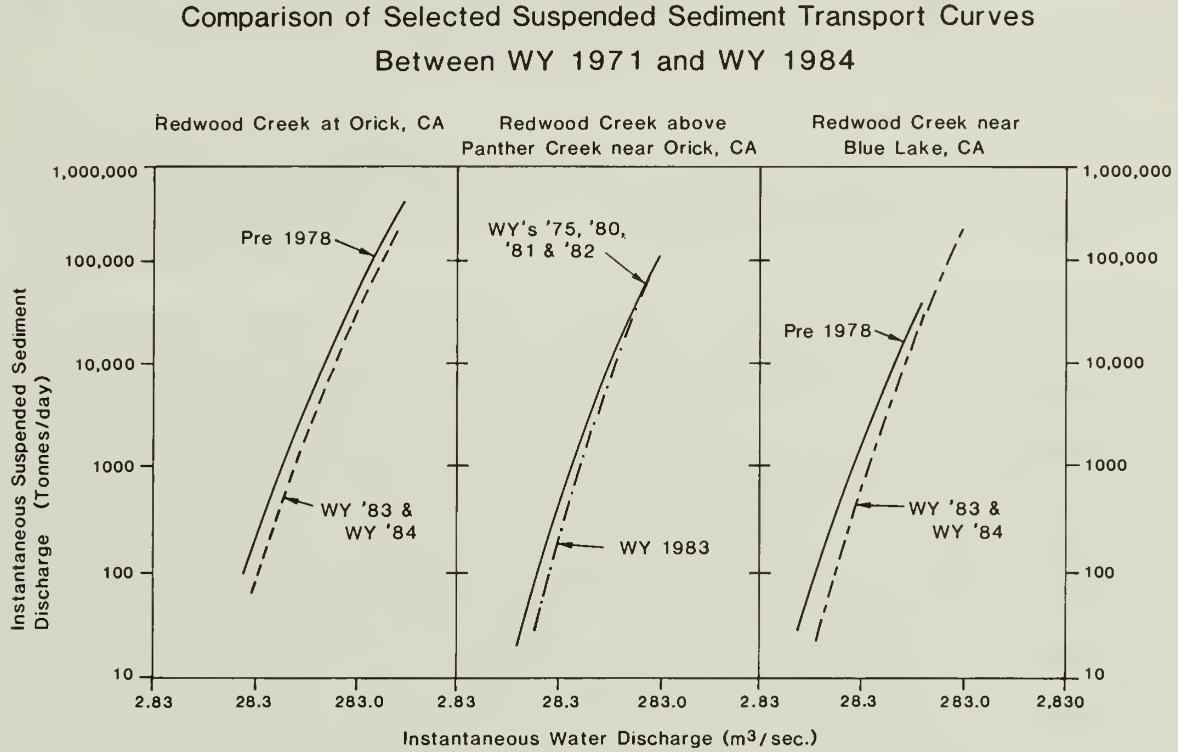


Figure 35. Suspended sediment transport curves for gaging stations, Redwood Creek at Orick (Station #11482500), Redwood Creek at Panther Creek (Station #11482125), and Redwood Creek near Blue Lake (Station #11481500). Significant drops occurred in suspended sediment discharge rates at Orick and near Blue Lake after 1978.

Table 4: Comparison of the Percent of Cross Sections Experiencing Major Changes to the Number of Days Mean Daily Flow Exceeded 235 m^3/s (8,300 ft^3/s) at Orick, California.

Year	Number of Days Mean Daily Flow Exceeded 235 m^3/s*	Percent** of Cross Sections Showing ΔE_c of ≥ 0.15 m
1974	8	47
1975	5	42
1976	2	22
1977	0	6
1978	4	6
1979	1	14
1980	3	12
1981	1	15
1982	5	47
1983	6	27
1984	5	21

* - From U.S. Geological Water Resources Data (1983).

** - The total number of cross sections analyzed each year varied from 40 in 1974 to 55 in 1982.

VII. DISCUSSION

Since 1975, channel changes in Redwood Creek have been largely dependent on the frequency and magnitude of storms and on the availability and character of transportable sediment.

The cross section record shows the magnitude of scour declining since 1977 in reaches upstream of the gorge regardless of the magnitude of flow. Below the gorge, degradation progressed downstream 6 km from the base of the gorge to near the Tall Trees Grove. This has resulted in a 30-40 percent reduction in the length of the streambed experiencing aggradation below the gorge. The leading edge of the aggradational wave has remained near the same location since 1977. The relatively higher flows since 1982 do not appear to correspond to increased aggradation in these reaches.

The primary source of sediment since 1977 for aggrading reaches below the gorge (km 90.2 to km 97.5) appears to be streambed materials eroded from the actively degrading reaches immediately upstream (km 82.1 to km 90.2) and possibly from Redwood Valley. As noted above, volume estimates for actively scouring areas downstream of the gorge were within 30 percent of the volume estimates for actively filling reaches from 1977 to 1983. The low magnitude of change in the cross sections above the gorge indicate that these reaches are not a major source of sediment. Suspended sediment discharge, although an uncertain indicator of bedload discharge, is apparently a sensitive indicator of hillslope erosion (Janda and Nolan, 1981). The major decrease in suspended sediment discharge after 1978 implies a reduction in hillslope contribution to the main channel since WY 1975. Studies of hillslope gully erosion also indicate that most fluvial erosion in the last two decades occurred during the storms of 1964, 1972, and 1975. Sediment yields from gullies have diminished significantly since then (Weaver and others, in press).

The magnitude of geomorphic events has been described by Wolman and Gerson (1978) as: "...a time scale for effectiveness may relate the recurrence interval of an event to the time required for a landform to recover the form existing prior to that event." Lisle (1981) indicated in a stream channel, "complete recovery would include the net displacement of the volume of flood debris out of the channel and the reshaping of the channel to its former morphological characteristic."

Coghlan (1984) showed that recent 20th century floods had a recurrence interval of 50 years or less based on studies of regional climatology and the regional record of past major flooding. However, using recurrence intervals of hillslope erosional events is probably a better measure of geomorphic effectiveness. High sediment loads from landslides and gullies were more directly responsible than high streamflow for channel changes observed in the mainstem of Redwood Creek.

Erosional events associated with recent flooding appear to have a much longer recurrence interval than the floods themselves. Harden and others (1978) showed that recent 20th century storms resulted in more streamside landslides than storms of comparable frequency and magnitude occurring in the late 19th century. Streamside landslides and gully erosion contributed the majority of sediment to the stream during major storm events in the last three decades. In the lower basin streamside landslides have been estimated to contribute 52 percent of the total sediment load between 1954 and 1980 (Hagans and others, 1986). Figure 2 shows that streamside landsliding declined substantially following the 1964 storm, despite the continuation of widespread timber harvesting and major flooding. Most of the inherently unstable streamside hillslopes failed during previous storms, resulting in a low number of new slides during the 1975 flood (Harden and others, 1978). Many main channel and tributary streamside landslide scars in the upper basin expose bedrock (Kelsey and others, 1981), indicating that much of the material available to floods with RI $\leq$ 50 years has been removed. At these sites, the time required to develop a regolith that would be susceptible to renewed landsliding could be hundreds of years or more.

Another significant source of channel sediment in the past 30 years has been fluvial hillslope erosion. Recent studies of tributaries in the middle and lower reaches of the basin (Best and others, in press; Weaver and others, in press) indicate that 45 to 65 percent of the sediment delivered to the stream channel in recent years was derived from gully erosion on the hillslopes. While 90 percent of the sediment is directly related to logging road and skid trail construction. Prior to the 1975 storm, 65 percent of the commercial forest in the basin had been harvested (Best and others, in press). The majority of the gully erosion had occurred during or prior to that storm. Since 1975, timber harvesting and associated road construction have declined substantially. As a result, sediment contributions from gully erosion should also decline significantly despite the occurrence of large storms. However, recent studies have shown that abandoned road networks are a continual and potential sediment source to the stream channel. In addition, future timber harvest practices and road construction on second growth stands may increase fluvial hillslope erosion.

Channel recovery after aggradation may be envisioned by a model for channel development proposed by Hey (1979) that describes the interaction between erosional and depositional phases. Following a major triggering mechanism such as the 1975 flood, Hey argues that erosional and depositional phases oscillate and that the oscillations are dampened through time and space (Figure 36). The cross section record indicates that the original 1975 flood deposits located between Lacks Creek and Bridge Creek were quickly eroded and deposited immediately downstream. Sediment output from the basin declined with successive years of moderate flows and resulted in secondary downstream aggradation of a smaller magnitude. It also seems reasonable that as these oscillations continue, aggradational phases will be accompanied by

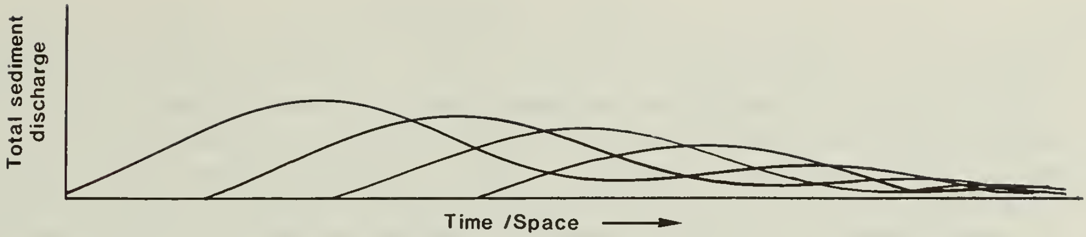


Figure 36. Interactions between erosional and depositional activity in time and space (from Hey, 1979).

coarser bed materials as the original flood deposits are reworked by the erosional phases. As the magnitude of the oscillations decline through time, they become more frequent and have a decreasing spatial effect. In Redwood Creek, an example of this last point may be the 30-40 percent reduction in the length of the streambed experiencing aggradation since 1979. Hey (1979) also showed a decreasing oscillation process could be responsible for river terraces. Stream incisement and streambed scour result in abandoned remnants of inactive sediment. In Redwood Creek, this process may be responsible for high, inactive gravel berms in upper reaches and flights of unvegetated gravel berms in the recently degraded portions of the lower reaches.

The length of time that it will take for aggraded reaches to begin to degrade will depend largely on future years of moderate to low flows and sediment supply. Years with flows of RI $\leqq$ 1.5 years appear to have a greater tendency for low magnitude scour in normally aggrading reaches. As streambed materials become larger in the actively degrading reaches, higher flows are needed to transport sediment to aggrading reaches. If the recurrence interval of flows needed to transport material out of degrading reaches increases, then the recurrence interval of flows that cause deposition in normally aggrading reaches will also increase. This of course assumes that the channel bed is the major sediment supplier to aggrading reaches. Changes in land use may make this assumption invalid.

Recent flows have produced channel changes in Redwood Creek which are beginning to restore the channel to its pre-1950 configuration. If the long term time scale of recovery is related to the recurrence interval of the erosional event rather than that of flood events, then the probability of complete recovery in Redwood Creek is considerably increased.

VIII. CONCLUSIONS

Analysis of channel cross sections from WY 1983 and WY 1984 documented recent channel changes and movement of sediment in the system. Cross sections in the upper two thirds of the basin (upstream of the Gorge) showed minor channel changes. This indicates that the channel is relatively stable and is not providing significant amounts of sediment to downstream reaches. In contrast, degradation was fairly persistent between the gorge and the Tall Trees Grove. Around the Tall Trees Grove, no discernible trends in channel aggradation or degradation have been observed since 1974. Downstream of the Tall Trees Grove, the channel has been generally aggrading. The primary sediment source for the aggrading reaches in recent years were the actively degrading reaches downstream of the gorge.

Hey's model of dampening oscillations of erosional and depositional phases seems to apply, in a general sense, to Redwood Creek. Aggradation of the streambed occurred in the lower Redwood Creek during the 1975 storm. Since 1977, channel scour below the gorge migrated downstream 6 km while the leading edge of aggradation moved less than 2 - 3 km. The net result was a 30 - 40 percent reduction in the length of streambed experiencing aggradation. The model suggests that given no major perturbations in the system, magnitude of aggradation will become less and the channel length experiencing aggradation will become smaller in the future.

The magnitude of degradation observed downstream of the gorge since 1977 suggests that presently aggrading reaches could begin to scour within the next decade. This will depend on continued years of moderate flows and no large sediment input to the system.

Streamside landslides and gully erosion were a predominant source of sediment to Redwood Creek during major storm events in the last three decades. Recent 20th century storms resulted in more streamside landsliding than storms of comparable magnitude and frequency that occurred in the late 19th century. Bedrock exposed in streamside landslide scars in the upper basin indicate that much of the material available to flood waters has already been removed. Gully erosion also delivered a significant amount of sediment directly to the stream channel. Most of the gully erosion occurred during or prior to the 1975 storm. Since that time timber harvesting and the associated road construction has been substantially reduced. As a result of these land use changes and the absence of major storm events, the amount of sediment contributed by gully erosion has declined significantly in recent years. However, gully erosion associated with existing and abandoned logging roads and remobilization of channel stored sediment remain potential sediment sources to the channel during large storm events.

High sediment loads from streamside landslides and gullies are probably more responsible for recent channel changes on Redwood Creek than high streamflow. Therefore, recurrence intervals for erosional events are probably a more appropriate measure of the time required for complete channel recovery than flood recurrence intervals. The recurrence interval of the hillslope erosional events associated with storm events in the last 30 years appears to be significantly longer than the recurrence intervals of the flood producing storms (RI = 10 - 50 years). If a prediction of complete channel recovery is based on the recurrence interval of the erosional event rather than the flood event, the probability of complete recovery is considerably increased.

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APPENDIX A Measured Changes at Channel Cross Sections.
Refer to Figure 4 for an explanation of terms.

			WATER YEAR 1983				WATER YEAR 1984			
			CHANGE IN STREAMBED AREA		CHANGE IN STREAMBANK AREA*	NET CHANGE IN AREA	CHANGE IN STREAMBED AREA		CHANGE IN STREAMBANK AREA*	NET CHANGE IN AREA
REACH	CROSS SECTION NUMBER	BANKFULL WIDTH (m)	FILL (+) (m^2)	SCOUR (-) (m^2)	(m^2)	(m^2)	FILL (+) (m^2)	SCOUR (-) (m^2)	(m^2)	(m^2)
Prairie Ck	1	133	33.5	27.8	0	5.7	45.6	33.1	0.0	12.5
to Elam Ck	2	141	9.0	37.7	0	-28.7	27.3	16.0	0.0	11.3
	3	127	31.2	5.3	1.6L	27.5	24.2	18.8	0.0	5.4
10	4	139	37.7	12.6	0	25.1	21.5	40.2	0.0	-18.7
	5	108	16.2	8.6	0	7.6	24.3	14.7	0.0	9.6
Elam Ck to	6	112	16.3	18.3	0	-2.0	13.3	4.7	-3.0R	5.6
Forty four Ck	7	62	18.6	10.2	0	8.4	11.4	14.4	0.0	-3.0
	8	88	16.1	19.5	0	-3.4	21.6	9.5	0.0	12.1
	9	111	20.0	4.9	0	15.1	26.3	10.4	0.0	15.9
9	10	94	0.0	3.4	0	-3.4	21.2	10.4	0.0	10.8
	11	65	11.5	6.2	0	5.3	3.5	15.7	0.0	-12.2
	12	75	7.9	11.2	0	-3.3	12.2	8.5	0.0	3.7
	13	70	8.7	3.3	RIGHT BANK SLIDE	5.4	3.5	10.6	0.0	-7.1
	14	61	7.4	22.7	0	-15.3	17.5	13.5	0.0	4.0
Tall Trees	15	60	11.0	14.5	0	-3.5	14.6	11.8	0.0	2.8
Grove	IJ	137	47.9	49.6	0	-1.7	73.5	51.8	0.0	21.7
	16	85	20.1	6.5	LEFT BANK SLIDE	13.6	1.1	26.2	LEFT BANK SLIDE	-25.1
	KL	76	43.7	21.9	0	21.8	0.2	100.5	-11.2R	-111.5
8	MN	110	13.6	24.6	0	-11.0	7.4	12.9	0.0	-5.5
	17	79	19.6	0.8	.2L	19.0	7.5	24.8	LEFT BANK SLIDE	-17.3
Elbow Ck to	18a	53	6.7	9.0	0	-2.3	2.9	10.7	0.0	-7.8
Bridge Ck	19	120	27.6	25.6	-2.L	0.0	9.1	15.4	0.0	-6.3
7	20	57	0.6	16.0	0	-15.4	2.3	13.7	0.0	-11.4
	21a	69	DATA NOT AVAILABLE				0.1	15.9	0.0	-15.8
Bridge Ck to	22	58	3.9	4.2	0	-0.3	0.4	18.7	0.0	-18.3
Base of the	23	81	4.3	22.2	0	-17.9	5.3	11.2	0.0	-5.9
Gorge	24	67	0.1	14.2	0	-14.1	4.6	12.6	0.0	-8.0
6	25	45	5.0	16.6	0	-11.6	1.3	8.6	0.0	-7.3
Slide Creek	26	47	5.3	3.0	-2.1R	0.2	6.0	5.9	0.0	0.1
5	27	45	0.9	20.2	6.0L	-13.3	9.7	1.1	LEFT BANK SLIDE	8.6
	28	90	9.2	4.1	-11.2R	-6.1	1.4	8.0	0.0	-6.6

* L designates left bank change
R designates right bank change

APPENDIX A Measured Changes at Channel Cross Sections

			WATER YEAR 1983				WATER YEAR 1984			
			CHANGE IN STREAMBED AREA		CHANGE IN STREAMBANK AREA*	NET CHANGE IN AREA	CHANGE IN STREAMBED AREA		CHANGE IN STREAMBANK AREA*	NET CHANGE IN AREA
REACH	CROSS SECTION NUMBER	BANKFULL WIDTH (m)	FILL (+) (m^2)	SCOUR (-) (m^2)	(m^2)	(m^2)	FILL (+) (m^2)	SCOUR (-) (m^2)	(m^2)	(m^2)
Copper Ck to	29	66	10.4	10.6	0	-0.2	9.7	27.9	RIGHT BANK SLIDE	-18.2
Stover Ck	30	36	2.1	0.7	0	1.4	1.7	3.2	0.0	-1.5
	31	25	0.3	1.4	0	-1.1	1.9	0.3	0.0	1.6
4	32	35	1.1	2.3	0	-1.2	0.2	2.1	0.0	-1.9
	32a	71	7.0	8.2	0	-1.2	24.2	7.6	-0.9	15.7
	32b	94		BULLDOZED			3.7	10.5	0.0	-6.8
	33	43	3.8	4.9	0	-1.1	2.9	5.6	0.0	-2.7
Redwood	34	67	7.3	10.0	-1.7R	-4.4	1.3	0.9	0.0	0.4
Valley	34a	85	4.9	28.4	0	-23.5	2.0	10.1	0.0	-8.1
	35	48	2.4	4.3	0	-1.9	2.1	3.5	0.0	-1.4
3	36	41	4.1	3.9	0	0.2	1.2	3.0	0.0	-1.8
	37	38	0.6	2.8	0	-2.2	2.2	1.3	0.0	0.9
Chezem Rd to	38	23	1.0	4.2	0	-3.2	1.9	4.6	0.0	-2.7
State Hwy 299	39	30	2.2	1.3	0	0.9	0.6	1.0	0.0	-0.4
	40	32	0.6	5.2	0	-4.6	0.5	1.0	0.0	-0.5
2	41	27	1.0	1.5	0	-0.5	0.7	0.9	0.0	-0.2
	42	33	0.2	4.3	0	-4.1	0.8	1.7	0.0	-0.9
Upstream of	43	51	5.5	8.0	-4.0R	-6.5	1.1	2.6	-1.8	-3.3
State Hwy 299	43a	56	0.5	4.9	0	-4.4	5.3	1.5	0.0	3.8
	43b	59	6.0	7.6	RIGHT BANK SLIDE	-1.6	2.0	2.0	0.0	0.0
	43c	47	4.9	26.0	0	-21.1	4.8	6.3	0.0	-1.5
1	43d	40	2.3	9.8	0	-7.5	1.0	1.3	0.0	-0.3
	43e	48	2.7	1.5	0	1.2	1.5	1.9	0.0	-0.4
	43f	30	7.0	4.3	0	2.7	1.6	1.7	-3.0L	-3.1
	43g	33	1.7	1.7	0	0.0	2.6	4.0	0.0	-1.4
	44	15	DATE NOT AVAILABLE				1.1	1.0	0.0	0.1
	45	12	0.4	0.1	0	0.3	0.2	0.1	0.0	0.1

*L designates left bank change
R designates right bank change

APPENDIX B

Summary of Streamflow Recorded on Redwood Creek at Orick From WY 1974 to WY 1984

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 235 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

* Average annual runoff for 30 years of record was 1290 mm.

** Peak discharges listed exceed a baseflow of 235 m^3/s. The highest peak discharge recorded was 1,430 m^3/s on December 22, 1964.

APPENDIX B

Summary of Streamflow Recorded on Redwood Creek at Orick From WY 1974 to WY 1984

Water Year	Total Runoff (mm)	Date of Peak Discharge	Peak Discharge (m^3/s)
1982	1986	Nov. 15	425
		Dec. 20	750
		Dec. 26	329
		Feb. 16	357
		Apr. 14	320
1983	2039	Dec. 16	835
		Dec. 21	297
		Jan. 26	532
		Feb. 10	527
		Feb. 18	300
		Mar. 30	399
1984	1762	Nov. 24	267
		Dec. 7	442
		Dec. 11	422
		Dec. 14	507
		Feb. 13	263

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