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EROSION AND SEDIMENTATION IN THE PACIFIC RIM

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Proceedings of an international symposium held
at Oregon State University, Corvallis, Oregon,
USA, 3-7 August 1987. This symposium was
organized by the US Department of Agriculture,
Forest Service, Pacific Northwest Research
Station; College of Forestry, Oregon State
University; and the National Council of the Paper
Industry for Air and Stream Improvement, Inc.

IAHS Publication No. 165

Residence times of channel-stored sediment in Redwood Creek, northwestern California

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ABSTRACT Floods in 1964, 1972 and 1975 resulted in streambed aggradation in Redwood Creek and its tributaries. Sixty to 100% of the sediment stored in steep, low-order tributaries was transported out of the channels in 5 to 10 years, except where trapped by debris jams. In the mainstem of Redwood Creek, recovery after aggradation (i.e., removal of flood-deposited sediment) varies from 0 to 70%, depending on the "activity level" of the sediment. Calculated residence times for the remaining sediment range from decades for active and semi-active sediment to centuries for inactive and stable sediment.

INTRODUCTION

Much of the north coast of California is underlain by highly fractured rocks of the Mesozoic to early Cenozoic Franciscan Assemblage (Bailey *et al.*, 1964). A combination of rapid uplift, pervasively sheared bedrock, high seasonal rainfall (2000 mm year⁻¹) and disturbance by timber harvest and road construction activities since the 1950's has resulted in exceptionally high sediment yields in this region (>2000 t km⁻² year⁻¹) (Judson & Ritter, 1964).

Severe flooding on the north coast of California in 1964, 1972, and 1975 resulted in widespread channel bed aggradation and channel widening. In the 720 km² Redwood Creek basin, the 1964 flood was estimated to have a recurrence interval of 50 years, and 10-25 years for the 1972 and 1975 floods (Coghlan, 1984). Several regional studies documented extensive landsliding, bank erosion, gullyng and sedimentation occurring during the 1964 and 1970's floods (Stewart & LaMarche, 1967; Hickey, 1969; Janda *et al.*, 1975; Kelsey, 1980; Hagans and Weaver, this volume). Stream channel recovery from major floods involves the removal of flood-deposited sediment and the return to pre-flood channel morphology. Lisle (1981) documented that elevated channel beds after 1964 flood aggradation lasted 5-15 years at nine gauging stations in northern California and southern Oregon. The purpose of this study is to document changes in the volume of stored sediment in Redwood Creek and its tributaries after major flooding and to estimate residence times for remaining sediment.

Severe aggradation occurred in Redwood Creek during the 1964 flood, especially in the headwater areas. Seven years of moderate flows (less than five-year recurrence interval) after 1964 removed roughly half the flood-deposited sediment stored in steeper reaches of the channel and deposited much of it farther downstream. The 1972 and 1975 floods resulted in additional aggradation in

downstream reaches, and again some sediment was removed in subsequent years by moderate flows. The location and rate of sediment removal, and residence times of remaining sediment, are functions of: where sediment was originally stored, its height above and proximity to the main channel, channel gradient, sediment size, and the presence or absence of debris jams.

STUDY AREA

Redwood Creek drains an elongate 720 km² basin (Fig. 1). For much of its length it flows along the trace of the Grogan Fault, which juxtaposes unmetamorphosed Franciscan sandstones and siltstones to the east against a quartz-mica schist to the west. Total basin relief is 1615 m; average hillslope gradient is 26%, and channel gradient ranges from 12% in the headwaters to 0.1% at its mouth. In its pristine, unlogged condition the Redwood Creek basin supported old-growth redwood and Douglas fir forests, with scattered grassland areas. Timber harvest began in earnest in the mid-1950's, and by 1978 81% of the old-growth forest had been logged (Best, 1984).

Redwood Creek changes drastically in character from steep and narrow in headwater reaches to wide and gently sloping in downstream reaches. For this study Redwood Creek was split into an upper, middle and lower reach (35.3, 33.3, and 35.6 km in length respectively) with a U.S. Geological Survey (USGS) stream gauging station located at the downstream end of each reach (Fig. 1).

Seventy-four tributary basins are drained by second-order or higher streams, and range from 0.7 to 44 km². Most tributaries are low order, high gradient (5-30%) streams having narrow, discontinuous flood plains. Tributary streams are nearly equally divided between those draining sedimentary and metamorphic basins (Pitlick, 1982).

METHODS

Volumes of main channel alluvium under pre-1950 conditions were estimated from aerial and historical photographs and old surveys. Field evidence (remnant fill terraces, exhumed trees and artifacts), bridge surveys, discussions with local residents and aerial photographs from 1962-1965 were used to estimate sediment volumes deposited in Redwood Creek by the 1964 flood. Sediment volumes present in the 1980 Redwood Creek channel were determined by field measurements and air photo analysis. Gravel bar and terrace heights were surveyed with a hand level and stadia rod. In addition, all bars were described in terms of age and type of vegetation growing on them, size characteristics of the deposited material (boulder, cobble, pebble, sand) and the presence of partially buried trees or artifacts. Fifty-eight streambed cross sections, surveyed annually from 1973-1986, document changes in bed elevation and width (Nolan, 1979; Varum, 1984).

A thick canopy of trees obscures most tributary channels from view on aerial photographs. Pitlick (1982) mapped the location of tributary stored sediment and estimated the total volume to be $1.05 \times 10^6 \text{ m}^3$. Tributary cross sections were surveyed by the USGS and the National Park Service from 1974 to 1986. Although the

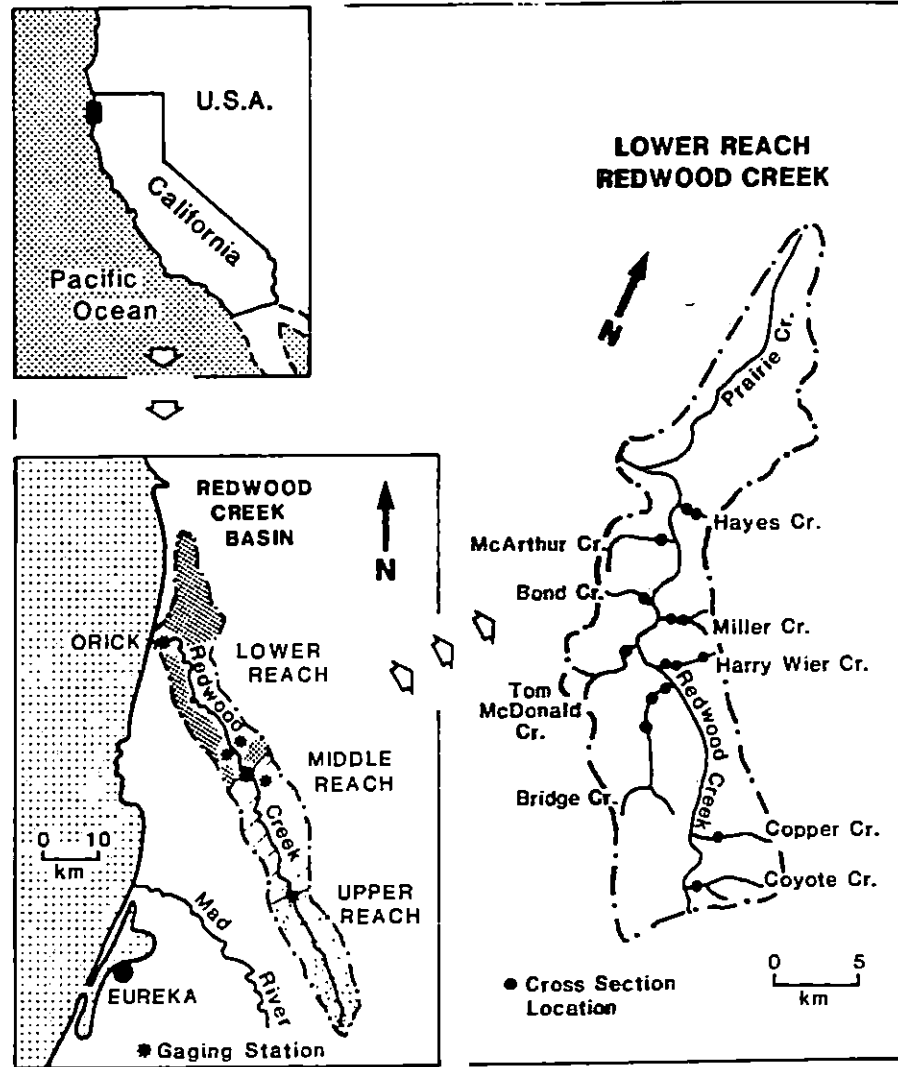


FIG. 1 Location map of the Redwood Creek basin showing study reaches, major tributaries, gaging stations, and cross-sectional locations.

effects of the 1964 and 1972 floods in tributary streams can be generally described, detailed field measurements only permit a more quantitative analysis of channel recovery after the 1975 flood.

RELATIVE AGE ESTIMATES OF SEDIMENT

In order to evaluate the length of time stored sediment will remain on a valley floor, it is first necessary to know the age of the deposit (that is, the time since the sediment entered the deposit) (Dietrich *et al.*, 1982). Because the absolute age of many alluvial deposits in Redwood Creek is unknown, a relative age scale was used to categorize deposits. Relative age estimates were based on the "activity level" of a deposit, ranging from easily mobilized to stable. The four categories defined within this range were active, semi-active, inactive, and stable (Madej, 1984).

Several lines of evidence were used to determine relative ages of stored sediment. Trees growing on deposits were dated wherever possible to obtain a minimum sediment age. The presence of annuals, shrubs, and other perennials indicated whether or not sediment moved recently. Time-sequential aerial photographs showed in which time period a new feature was deposited, or an old feature was eroded. Scour chains and successive discharge measurements at gauging stations indicated to what depth the channel bed was active during flood flows.

Using these indicators, the following definitions were developed. Active sediment is channel bed sediment transported during moderate flood flows with a recurrence interval (RI) of one to five years. Vegetation is absent or sparse on active sediment. In contrast, semi-active sediment is mobilized during flows with RI=5-20 years. At such flows, sediment covered with shrubs and young trees as well as some cobble and boulder deposits are mobilized. Inactive sediment is stationary until 20- to 100-year floods occur. In addition to mobilizing more active sediment, such flows may mobilize inactive sediment found in coarse lag deposits, three-to five-meter high fill terraces, and coherent log jams. Stable sediment comprising flood plain and low-lying terrace deposits has not been mobilized historically. The majority of sediment stored in alluvial terraces covered with old-growth forests is not in transport in the short term. Nevertheless, lateral erosion of the terraces occurs and a fresh veneer of fine sediment may be deposited on them at high flows (RI>10 years).

CHANGES IN STORED SEDIMENT IN THE REDWOOD CREEK CHANNEL

As a result of the 1964 flood, total volume of stored sediment in the Redwood Creek channel increased from $11.0 \times 10^6 \text{ m}^3$ to $16.0 \times 10^6 \text{ m}^3$ (Madej, 1984). After the 1964 flood, several years of moderate flows eroded roughly half the sediment from aggraded reaches in the upper basin (Figure 1). Much of this eroded material was deposited in downstream reaches, where cross-sectional surveys show recent aggradation (Varnum, 1984).

Floods in 1972 and 1975 caused little deposition in upper reaches of Redwood Creek, but did leave thick flood deposits downstream. Unit discharges computed from gaging station records indicated that the 1972 and 1975 floods were more severe downstream (Harden *et al.*, 1978). Recent timber harvest and road construction in those downstream areas accelerated hillslope erosion rates (Hagans & Weaver, this volume). In 1980 the total amount of sediment stored

in Redwood Creek was estimated to be $16.1 \times 10^6 \text{ m}^3$. Cross-sectional and longitudinal profile surveys showed degradation in lower Redwood Creek from 1980-1986 (Varnum and Ozaki, in press), suggesting the total amount of stored sediment in 1986 was roughly $15.8 \times 10^6 \text{ m}^3$.

RESIDENCE TIMES OF STORED SEDIMENT IN THE REDWOOD CREEK CHANNEL

A critical part of describing the dynamics of channel-stored sediment is defining the residence time, or persistence, of stored sediment. In this study, calculations of residence times for active, semi-active, inactive and stable sediment were based on the approach of Dietrich and Dunne (1978). Residence time was defined as volume of sediment per unit channel length (V_s) divided by bedload discharge rate (Q_B). Bedload discharge rates were based on measurements from USGS gauging stations on three tributaries and at three mainstem sites (Fig. 1). ' V_s ' and ' Q_B ' were then defined as power functions of drainage area (A), and drainage area (A) was defined as a power function of mainstem channel length (X):

$$V_s = aA^m \quad (1)$$

$$Q_B = bA^n \quad (2)$$

$$A = cX^p \quad (3)$$

where a , b , c , m , n and p are constants. Madej (1984) discussed this technique more completely.

Combining equations (1) - (3) yielded the following relationships between residence time (V_s/Q_B) and the power function equations:

$$\frac{dt}{dx} = \frac{V_s}{Q_B} = \frac{a(cX^p)^m}{b(cX^p)^n} = \frac{a}{b} c^{(m-n)} X^{p(m-n)} \quad (4)$$

Integration of Equation 4 allowed calculation of residence times for a reach of channel length $x_2 - x_1$:

$$\int_{t_1}^{t_2} dt = \int_{x_1}^{x_2} \frac{a}{b} c^{(m-n)} X^{p(m-n)} dx \quad (5)$$

(Dietrich and Dunne, 1978).

Table 1 lists results of residence time calculations for Redwood Creek. Active and semi-active sediment have the shortest residence times, and residence times decrease downstream. Residence times increase by about an order of magnitude for each level of increasing stability. Madej (1984) and Kelsey et al. (1986) discussed results and implications of these calculations further.

Results suggest that material deposited in active and semi-active sediment categories is likely to be flushed out of a reach rapidly (10-50 years). Cross-sectional data confirm this. Field evidence and aerial photographs show that severe aggradation of

TABLE 1 Residence times for sediment stored in each of four sediment categories in each of the three reaches.

Storage Category	Residence Time (years)		
	Redwood Creek Reaches		
	Upper	Middle	Lower
ACTIVE	26	11	9
SEMI-ACTIVE	50	19	15
INACTIVE	104	99	100
STABLE	700	3100	7200

Redwood Creek occurred upstream of the Bridge Creek confluence in the 1972 and 1975 floods. Sediment was deposited in the thalweg and on low-lying unvegetated bars (active and semi-active categories). Figure 2 illustrates rapid channel degradation occurring at a cross section in the following decade. In contrast, in wider areas of Redwood Creek, where sediment was deposited on flood plains and low-lying terraces (inactive and stable categories), the volume of sediment removed has been much less. The sediment remaining will take decades to centuries to be flushed out of the stream (Table 1). Thus, complete mainstem recovery (i.e., removal of flood-deposited sediments) may take centuries.

Channel recovery in the mainstem of Redwood Creek channel varied from 4-70% in the upper reach to typically 0-13% in the middle and lower reaches. Only in localized areas in the middle or lower reaches where active and semi-active sediment dominates did recovery exceed this amount (Fig.2). Dating trees that are growing at the base of eroded flood deposits suggests that locally much of the

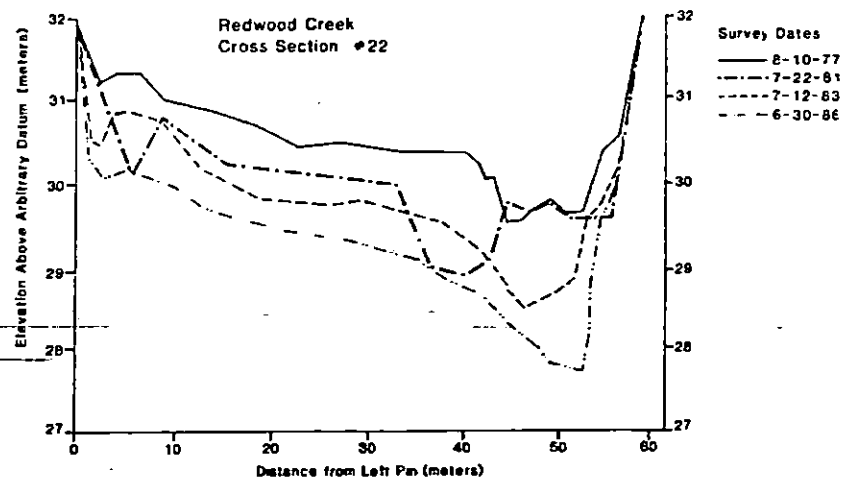


FIG. 2 Plot of Redwood Creek Cross Section 22. Note rapid degradation of thalweg and low-lying gravel bars after major aggradation occurred in 1972 and 1975.

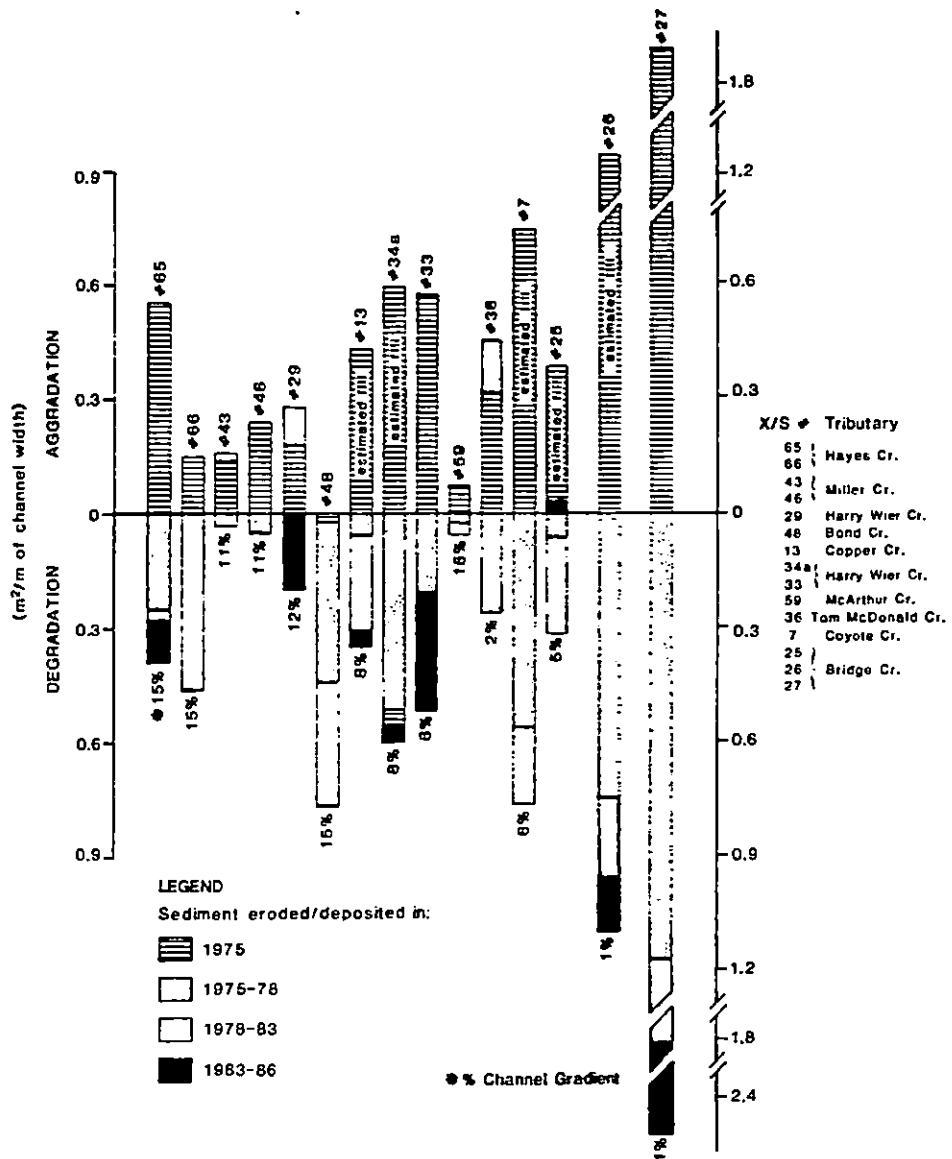


FIG. 3 Summary of cross-sectional survey results from nine tributaries of Redwood Creek. Normalized values of sediment deposited or eroded during a given time period are shown by bar graphs. Channel fill is designated by bars above the base line; channel scour by bars below the line. Channel gradients at the cross sections (in percent) are listed under the bar graphs.

22. Note
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recovery in the upper reach had occurred by the early 1970's. Most of the sediment removed had been stored as active or semi-active sediment.

RECOVERY TIME OF TRIBUTARY CHANNELS

The data base necessary to similarly compute residence times of stored sediment in the tributaries was not available. Instead, changes in channel-stored sediment following the 1975 flood were examined from cross-sectional surveys. Figure 3 shows results from 15 tributary cross sections affected by the 1975 flood. The change in each cross-sectional area was divided by bankfull width to compare relative changes from tributary to tributary. Not all tributaries were surveyed each year. Five tributaries had not been surveyed before the 1975 flood, but field evidence (remnants of fill terraces, buried boulders, trees and artifacts) allowed reasonable estimates of the pre-1975 channel geometry.

Recovery of tributaries shown in Figure 3 refers to the total removal of sediment deposited by the 1975 flood. Figure 4 illustrates a typical pattern of recovery. Most tributaries exhibited 60-100% recovery in 10 years (Fig. 3). The only exceptions (Cross Sections 36, 43, and 46) were locations where debris jams trapped sediment. Keller and Tally (1979) estimated that log jams in a redwood environment may remain intact and stable for up to 1000 years. Thus sediment trapped behind these log jams may also persist in the channels for centuries.

Channel recovery did not occur simultaneously in all tributaries or uniformly in response to specific flow events. It varied from tributary to tributary. Flows from 1975 to 1986 did not exceed the five-year recurrence interval. In tributaries, much of the recovery had occurred by 1983, and most sediment was gone by 1986 (Fig. 3). Figure 3 shows tributaries in order of increasing drainage area. There is only a rough relationship between the volume of flood

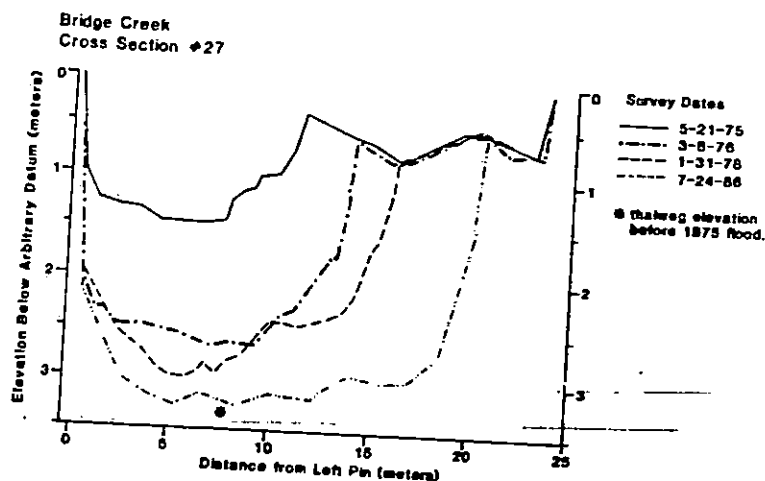


FIG. 4 Plot of Bridge Creek Cross Section 27. Note rapid removal of sediment deposited by 1975 flood.

deposits or degree of recovery (on a normalized basis) and drainage area.

The degree of tributary channel recovery corresponds roughly with channel gradient. All tributary reaches steeper than 12% showed substantial recovery, but even relatively low gradient streams (1%) showed good recovery if no log jams were present.

A few streams showed in excess of 100% recovery from the 1975 flood. These streams were most likely eroding underlying sediments deposited by the 1972 flood. Unfortunately no pre-1974 cross-sectional data were available to confirm this.

CONCLUSIONS

Much of the recovery of Redwood Creek and its tributaries after major flooding and associated aggradation occurred within 10 years of the event. In the mainstem of Redwood Creek, sediment stored in active and semi-active categories is easily mobilized and has a residence time of 10-50 years per reach. Sediment still remaining from the flood events of 1964, 1972 and 1975 is commonly stored in inactive and stable categories as fill terraces and overbank flood-plain deposits. The calculated residence time of this remaining sediment (>100 years) exceeds the recurrence interval of the floods which deposited it. Thus, total channel recovery (i.e. total removal of 'excess' sediment) may only occur over geologic time periods.

In contrast, steep, small tributaries of Redwood Creek are more efficient sediment transporters, and they flush themselves clean of sediment rapidly. Within 10 years under moderate flow conditions, recovery is almost complete in most basins, except where log jams trapped sediment. The residence time of sediment upstream of debris jams is dependent on the stability of the jam.

ACKNOWLEDGEMENTS I am grateful to K.M. Nolan, D. Marron and J. Pitlick for the use of their data. J. Florsheim, D. Best, V. Ozaki, N. Varnum, T. Walter, C. O'Sullivan, K. O'Dea and S. Potter surveyed and plotted most cross sections. S. Potter drafted the figures.

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