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CHANNEL RESPONSE TO SEDIMENT WAVE PROPAGATION AND MOVEMENT, REDWOOD CREEK, CALIFORNIA, USA

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ABSTRACT

Redwood Creek, north coastal California, USA, has experienced dramatic changes in channel configuration since the 1950s. A series of large floods (in 1955, 1964, 1972 and 1975) combined with the advent of widespread commercial timber harvest and road building resulted in extensive erosion in the basin and contributed high sediment loads to Redwood Creek. Since 1975, no peak flows have exceeded a 5 year recurrence interval.

Twenty years of cross-sectional survey data document the downstream movement of a 'sediment wave' in the lower 26 km of this gravel-bedded river at a rate of 800 to 1600 m a^{-1} during this period of moderately low flows. Higher transit rates are associated with reaches of higher unit stream power. The wave was initially deposited at a site with an abrupt decrease in channel gradient and increase in channel width. The amplitude of the wave has attenuated more than 1 m as it moved downstream, and the duration of the wave increased from eight years upstream to more than 20 years downstream.

Channel aggradation and subsequent degradation have been accommodated across the entire channel bed. Channel width has not decreased significantly after initial channel widening from large (> 25 year recurrence interval) floods. Three sets of longitudinal surveys of the streambed showed the highest increase in pool depths and frequency in a degrading reach, but even the aggrading reach exhibited some pool development through time. The aggraded channel bed switched from functioning as a sediment sink to a significant sediment source as the channel adjusted to high sediment loads. From 1980 to 1990, sediment eroded from temporary channel storage represented about 25 per cent of the total sediment load and 95 per cent of the bedload exported from the basin.

KEY WORDS channel adjustment; sediment transport; sediment storage; pool–riffle morphology; channel recovery

INTRODUCTION

River channel morphology can adjust to changes in the water and sediment loads imposed upon it. Channel adjustments may be immediate or lag temporally after disturbance. They may lead to a re-establishment of previous conditions or to a new state. The response times and mechanisms of channel adjustments after disturbance depend on the magnitude of the imposed change and stream power available to effect changes (Knighton, 1984).

When sediment input into a river reach is greater than sediment output, rivers respond by aggradation, channel widening, or other changes in hydraulic geometry. Aggradation and degradation can occur over different time scales, from the variations in channel bed elevation during a single flood event to adjustments which span centuries (10^3 to 10^4 years) due to factors such as tectonic or climatic changes. However, documentation of long-term channel response to a disturbance can be obscured by annual variations of erosion and deposition. Thus, a monitoring programme on the same time scale as the response time is necessary to discriminate between annual variations and long-term trends in channel adjustments.

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During the last three decades, large floods and extensive logging in the Redwood Creek basin in northern California caused widespread aggradation and bank erosion, which killed or damaged many old-growth redwood trees along the river (Janda *et al.*, 1975). Critical salmonid habitat was also severely impacted by the sedimentation. Because Redwood National Park was established to protect this reserve of the tallest trees in the world, the US National Park Service, in cooperation with the US Geological Survey (USGS), has conducted a monitoring and evaluation programme since 1973 to study channel response to fluctuating high sediment loads. The monitoring programme includes detailed channel cross-sectional and longitudinal surveys and discharge and sediment transport measurements spanning two decades. This long-term monitoring programme has provided a unique opportunity to document the distribution and transit times of an aggradational wave of sediment initiated by land use and floods.

Other studies have examined sediment waves generated from channel-side disturbances. Gilbert (1917) recognized that increases in sediment input from hydraulic mining caused a wave of sedimentation to propagate downstream from mining sites in California, USA. James (1991) also studied effects of hydraulic gold mining in California on channel geometry, and Pickup *et al.* (1983) and Knighton (1989) analysed channel changes induced by alluvial tin mining in New Guinea and Tasmania, respectively. Nevertheless, measurements of specific channel response to basin-wide disturbance, with concurrent sediment transport measurements, are rare.

There were three purposes to this study. The first was to quantify the mechanisms and timing of channel response along a 100 km length of river following a major increase in sediment load. Channel response can be defined in several ways, and in this paper we use channel-bed elevation, channel width, pool–riffle morphology and sediment transport rates as measures of response. A second purpose was to define the

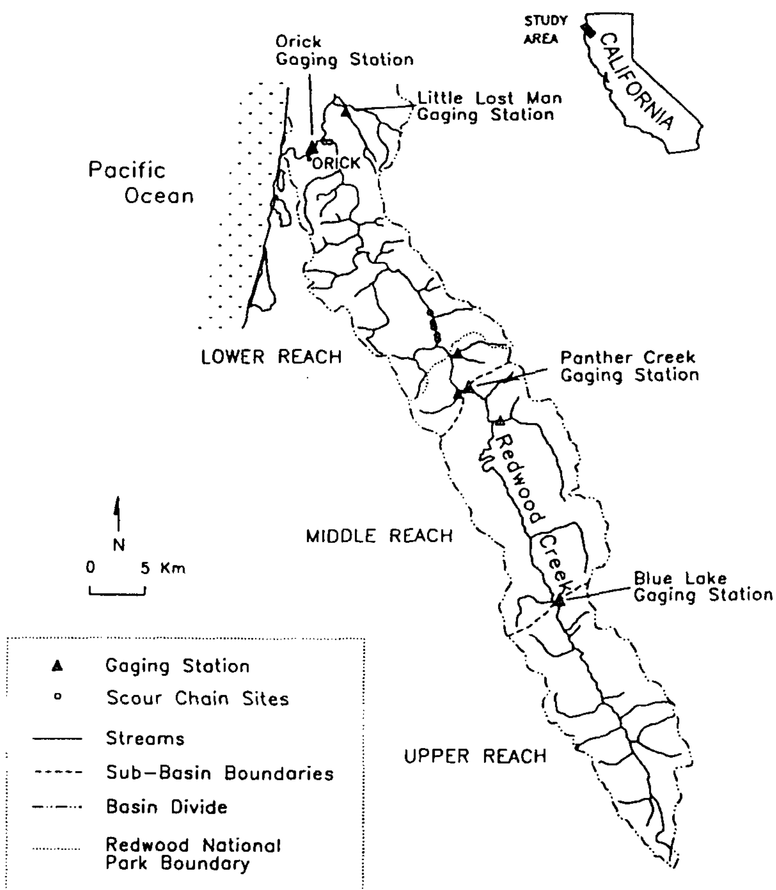

Figure 1. Location map showing Redwood Creek drainage basin, study reaches and gauging stations

magnitude and transit rates of an aggradational wave of sediment during a sequence of moderate peak flows. The third objective was to compare and quantify changes in the mass of channel-stored sediment to sediment yields in the drainage basin.

THE STUDY AREA

Redwood Creek drains a 720 km^2 basin in northern California, USA (Figure 1). The basin receives an average of 2000 mm of precipitation annually, most of which falls as rain between October and March. Total basin relief is 1615 m; average hillslope gradient is 26 per cent. Channel gradient decreases from 12 per cent in the headwaters to 0·10 per cent near the mouth of Redwood Creek.

For most of its length, Redwood Creek follows the trace of the Grogan Fault, which juxtaposes sandstones and siltstones on the east side of the basin against schist on the west side. The bedrock is part of the Franciscan Assemblage of Jurassic and Cretaceous age (Bailey *et al.*, 1970), and is pervasively sheared and fractured. As a result of the high precipitation and fractured bedrock, the terrain is highly susceptible to mass movement and gullying. Annual suspended-sediment discharge of Redwood Creek (1000 to 2500 $Mg\,km^{-2}\,a^{-1}$) is among the highest measured in the United States for basins of this size, apart from rivers draining active volcanoes or glaciers.

Aerial photographs from 1936 and 1947 show that prior to the advent of commercial timber harvesting the basin was covered with old-growth redwood and Douglas fir forest and a few areas of oak woodlands and prairie grasslands. Redwood Creek was narrow and sinuous in most reaches, with a thick canopy of trees over much of its length. Large-scale timber harvesting began in the early 1950s. By 1966, 55 per cent of the coniferous forest had been logged, and by 1992 about 80 per cent of the forest was logged, largely by clearcutting. Thousands of kilometres of logging roads were built during the last 40 years, resulting in increased sediment supply from surface erosion, gullying, road crossings and road-fill failures.

Large floods in 1964, 1972 and 1975 (recurrence intervals of 20 to 50 years (Coghlan, 1984)) initiated widespread road failures, gullying, and streamside landsliding in the basin. These floods caused extensive aggradation and bank erosion in Redwood Creek. Channel changes were most extensive in the upstream half of the basin, where both the storms and previous logging activity had been most intense. Aerial photographs, field observations and accounts by local residents document that the channel widened, pools filled in, channel-bed material became finer, and the channel bed aggraded up to 9 m at some sites (Madej, 1992).

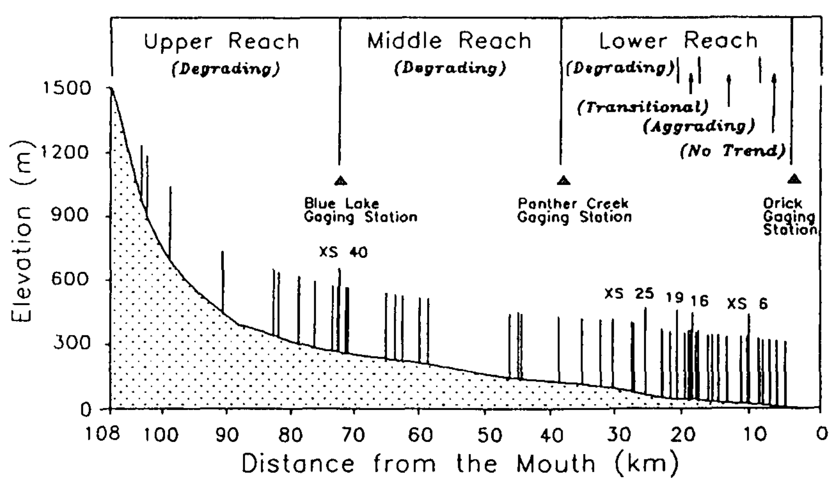

Figure 2. Longitudinal profile of Redwood Creek indicating the major bed elevation trends in three major study reaches, based on cross-sectional surveys from 1973 to 1991. Cross-section locations are represented by vertical lines on the profile

METHODS

Since the USGS initiated a monitoring programme in 1973, 58 cross-sections located on Redwood Creek between the headwaters and the mouth (Figure 2) have been surveyed annually or after major flows. While the USGS attempted to sample representatively all reaches of the river, cross-section locations are controlled by physical access to the river, and the monitoring network is not based on a random sample. Cross-sections are located primarily on straight reaches with alternate bars. Cross-sections were monumented with 1·2 m lengths of steel bar reinforced with concrete, and referenced to at least two other triangulation points. Relative elevations between end points were established by levelling (Emmett, 1974). Cross-sections were surveyed during summer low flows with an automatic level and stadia rod or theodolite and electronic distance metre. In this paper, cross-sections are referenced to channel distance (in km) from the mouth of Redwood Creek.

Figure 3 shows the terminology used in this study. The thalweg (T) is defined as the lowest point in the streambed in cross-sectional profile. Channel width (W) is defined as bankfull width, identified by high-water marks, vegetation changes and breaks in slope between banks and floodplains. Net change in streambed cross-sectional area (ΔA_s) is the difference between fill and scour in the streambed between successive surveys. Mean change in streambed elevation (ΔE_c) is a normalized value computed by dividing the net change in streambed area (ΔA_s) by bankfull width (W):

$$\Delta E_c = \Delta A_s / W$$

ΔE_c shows the relative magnitude of changes at cross-sections of different widths. Thus, lowering the mean streambed elevation by 0·15 m ($\Delta E_c = -0{\cdot}15$ m) represents the same per cent change in a 10 m wide cross-section as it does in a 100 m wide cross-section, even though ten times more sediment has moved out of the wider cross-section. The accuracy of ΔE_c is $\pm 0{\cdot}05$ m, based on the computed error in surveying.

A longitudinal profile of the downstream 28 km of Redwood Creek was surveyed by the USGS in 1977, and portions were resurveyed by Redwood National Park in 1983 and 1986. Thalweg elevations were surveyed using an automatic level and stadia rod, or theodolite and electronic distance metre. Surveys were referenced to staff plates at gauging stations 19 km apart, and to cross-sectional monuments. The total vertical error in elevation between the surveys was 0·2 per cent (0·08 m). All pools with residual depths (Lisle, 1987) of greater than 1·2 m were tabulated. The number of pools per kilometre and average pool depth were calculated for the three surveys.

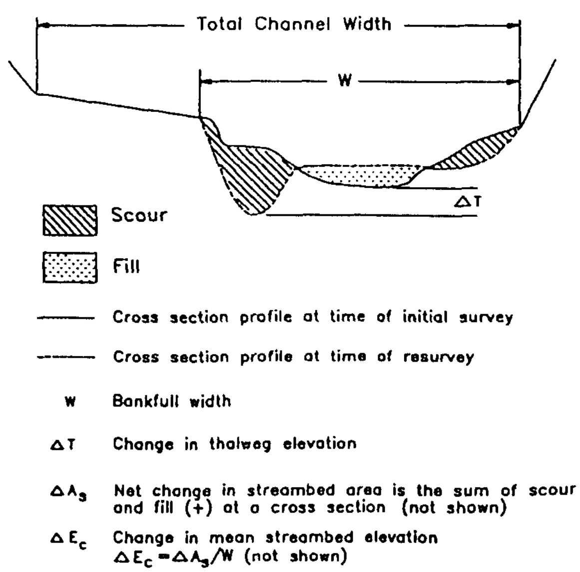

Figure 3. Definitions of cross-sectional terminology used in this paper

Water discharge has been monitored continuously at several gauging stations since 1971 by the USGS (Figure 1) and the Orick and Blue Lake stations have daily suspended-sediment-discharge records. During floods, bedload discharge was measured up to several times a day, whereas bedload sampling frequency decreased to monthly intervals during low-flow periods.

RESULTS

Overview of channel response

Annual cross-sectional survey results from 1973 to 1991 are tabulated elsewhere (Varnum, 1984; Varnum and Ozaki, 1987; Potter *et al.*, 1987; Nolan and Marron, 1995; Ozaki, 1991, 1992). The average change in channel-bed elevation based on all the annual surveys at all cross-sections is $-0{\cdot}02$ m ($n = 657$, SD $= 0{\cdot}17$ m). Cumulative changes in mean streambed elevation at channel cross-sections from 1974 to 1988 are plotted in Figure 4 and indicate the long-term channel response along the length of Redwood Creek. The following discussion summarizes channel changes in Redwood Creek that occurred in response to large floods and altered sediment loads of the last three decades. The three reaches used in this discussion are defined by the location of USGS gauging stations (Figure 1).

Upper reach. The 35 km long upper reach extends from the headwaters of Redwood Creek to the Blue Lake gauging station. Thirteen cross-sections are located in this reach and have bankfull widths ranging from 12 to 84 m. Stream gradient ranges from 12 per cent to 0·6 per cent, and averages 3 per cent. This reach was the most adversely affected by the 1964 flood. Kelsey *et al.* (1981) mapped over 600 streamside landslides in this reach, most of which failed in 1964 and which contributed over 5×10^6 m^3 of sediment to the channel. A comparison of aerial photographs in 1954 and 1966 reveals that channel widths increased by 150 to 300 per cent. Up to 9 m of channel fill were deposited above the 1994 thalweg elevation (Figure 5). The presence of roughness elements, such as boulders, riparian vegetation, and pool–riffle sequences, was greatly reduced. The 1964 flood increased channel-stored sediment in this reach by $1{\cdot}5 \times 10^6$ m^3 (a 90 per cent increase), and over half of the added sediment (800 000 m^3) was subsequently eroded from this reach between 1965 and 1980 (Madej, 1992).

Long-term records at the Blue Lake gauging station (cross-section 40, or XS 40) indicate that between 1958 and 1973 the increase in main streambed elevation was at least 1 m, and the thalweg rose more than 1·2 m (Nolan and Janda, 1979). The total amount of aggradation following the 1964 flood was probably

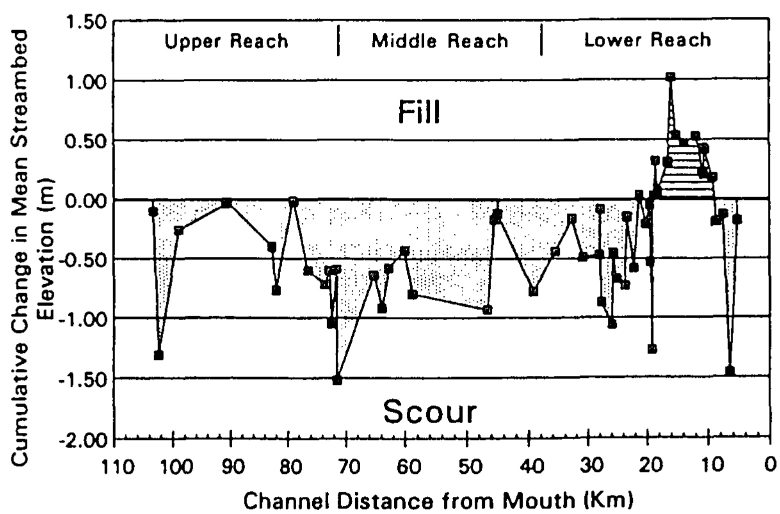

Figure 4. Cumulative bed elevation changes from 1973 to 1988 plotted against channel distance. Each point represents the net change for the period of record for an individual cross-section. Aggradation is presently confined to the downstream-most 18 km of Redwood Creek

ADDED BED SED. 1980 LOSS
UPPER: 1,500,000 .5
MIDDLE: 1,400,000 .62

Figure 5. Remnants of channel fill deposited in the 1964 flood which buried and killed riparian vegetation. Downcutting since that time has exposed the dead trees, large volumes of sediment have been eroded, and channel-bed elevation has regained its previous level

greater than this, but documentation is lacking because the gauging station was discontinued between 1958 and 1973. The channel bed in this reach has degraded since 1974 (Figure 4). By 1992, the streambed at cross-section 40 had returned to near 1958 levels. Concurrently, the low-flow channel has incised into remnants of the 1964 flood deposits, and bedrock is now exposed locally in the streambed.

Middle reach. Between the Blue Lake and Panther Creek gauging stations Redwood Creek flows through a wide valley floor at the upper end, and a narrow gorge at the downstream end, but channel gradient is about the same in both portions (0·4 per cent). There are 11 cross-sections in this 34 km long reach. In the upper portion bankfull widths range from 23 to 127 m, and floodplain widths extend up to 200 m. The channel pattern here was dramatically modified during the 1964 flood and has not been changed by subsequent high flows. Bankfull widths in the downstream portion range from 25 to 35 m, and the floodplain is generally < 50 m wide. Channel-stored sediment in the middle reach increased by $1{\cdot}4 \times 10^6\ m^3$ after the 1964 flood, a 32 per cent increase over previous levels. By 1980, 62 per cent of those flood deposits had been eroded (Madej, 1992). Cross-sectional surveys display similar channel response as in the upper reach; that is, the channel widened and aggraded as a result of the 1975 flood and has degraded since then (Figure 4).

Lower reach. Between the Panther Creek and Orick gauging stations, the Redwood Creek channel shows four patterns of channel response (Figure 2). In the upstream portion, km 39·1 to 20·2 (14 cross-sections) bankfull widths range from 28 to 128 m and average channel gradient is 0·31 per cent. The location km 26 marks the beginning of a wide alluvial channel typical of lower Redwood Creek. Channel gradient decreases abruptly from 1·4 per cent to 0·3 per cent, and channel width increases from 30 m to 50 m. The channel in this portion of the river aggraded > 1 m after the 1975 flood. Since 1980 the river has degraded, and by 1994 the channel bed was an average of 0·7 m lower than 1974 levels.

A second type of response occurred from km 20·1 to 18·2 (six cross-sections). Here, bankfull widths are large (up to 150 m) and channel gradient is 0·21 per cent. The channel bed fluctuated between periods of aggradation and degradation. Although the net change in recent years has been a lowering of the bed elevation, streambed elevations have not recovered to 1974 levels and this portion of the streambed is considered a transitional reach, between the upstream degrading and downstream aggrading portions of the channel bed.

Farther downstream, from km 18·1 to 9·2 (ten cross-sections), Redwood Creek responded in a third way, by continual aggradation since 1973. In this aggrading reach, bankfull widths range from 61 to 114 m, and channel gradient averages 0·18 per cent. Aerial photographs show that this area had aggraded between 1964 and the early 1970s, and cross-sectional surveys show that the streambed had increased an average of 0·6 m in elevation from 1973 to 1994. Aggradation was accompanied by frequent shifting of the low-flow channel and formation of mid-channel bars. The elevations of the mid-channel bar surfaces are higher than the elevation of rooting sites of perennial vegetation on the streambanks, an observation that is also consistent with a rapid rise in streambed elevation.

The fourth type of response is apparent in the 4 km reach immediately downstream of cross-section 5 to the Orick gauging station, where the river has fluctuated between aggradation and degradation. Several factors influence river behaviour there: the river becomes unconstrained at this point, and valley widths are > 500 m; however, construction of flood levees in 1968 artificially confined part of the channel reach. In addition, extraction of gravel from the streambed in recent years artificially lowered streambed elevations in some areas. The results of cross-sectional surveys in this area are not considered typical of the lower reach, and are not used in calculating transit times, but they are used in computing the sediment balance (volumes eroded or deposited) in the reach (discussed below).

In all the reaches described above, the channel aggraded and degraded across the entire active channel width (including the thalweg and low, unvegetated bars) rather than becoming incised and narrower. There was no significant difference between the change in thalweg elevation and the change in mean streambed elevation (two-sided p value = 0·66).

Timing and duration of aggradation in Lower Redwood Creek

In order to determine transit rates of a wave of sediment in Redwood Creek, the following discussion focuses on the downstream-most 26 km of the river where the most frequent surveys and closely spaced cross-sections are concentrated. Aerial photographs show that channel aggradation downstream of km 26 (XS 25) had begun prior to 1974 in response to large floods in 1964 and 1972. However, the cross-sectional network was not installed until 1973 on Redwood Creek and survey data are not available before 1973. As a result, the data presented here represent a minimum amount of aggradation in the lower channel.

Cross-sectional surveys for four cross-sections that are representative of the lower reach are plotted in Figure 6. Figure 6 also plots the cumulative bed elevation change at these cross-sections (XS 25, 19, 16 and 6) for the period of record. These plots clearly illustrate that the streambed did not aggrade uniformly, but that aggradation lagged both in time and space as a sediment 'wave' moved downstream.

The shape of the cumulative bed elevation curves indicates the persistence of channel-stored sediment in the river. The duration of the sediment impact on lower Redwood Creek was defined by the time needed for the average streambed elevation to return to 1974 levels. We recognize that the streambed was already in an aggraded condition by 1974 due to floods in 1964 and 1972, but no bed elevation data exist for those times. For that reason this value is a measure of the minimum duration of sediment impact. The channel at km 26 recovered to 1974 channel-bed elevations in 8 years, but 4·7 km downstream (XS 19) recovery time increased to 15 years. Downstream from cross-section 14 the channel bed continues to aggrade or has maintained its aggraded elevation since 1974, so the persistence of the sediment impact in this area is at least 20 years.

We can also examine the variation in the timing of peak aggradation at cross-sectional stations. The channel between km 26 and 22·2 (XS 25 and XS 20) filled with sediment in 1975, with peak aggradation occurring in 1977 (Figure 6). By 1980 the peak of streambed aggradation was near km 21·3 (XS 19) and by 1983 it had moved downstream to between km 19·0 to 16·6 (XS 16 and XS 14). Downstream of km 16·6 (XS 14), the streambed has continuously aggraded since 1974 and remains an average of 0·6 m higher than 1974 bed elevations (i.e. XS 6 in Figure 6).

Transit rates of the aggradational wave

By tracking the timing of peak aggradation at individual cross-sections, we can calculate transit rates of

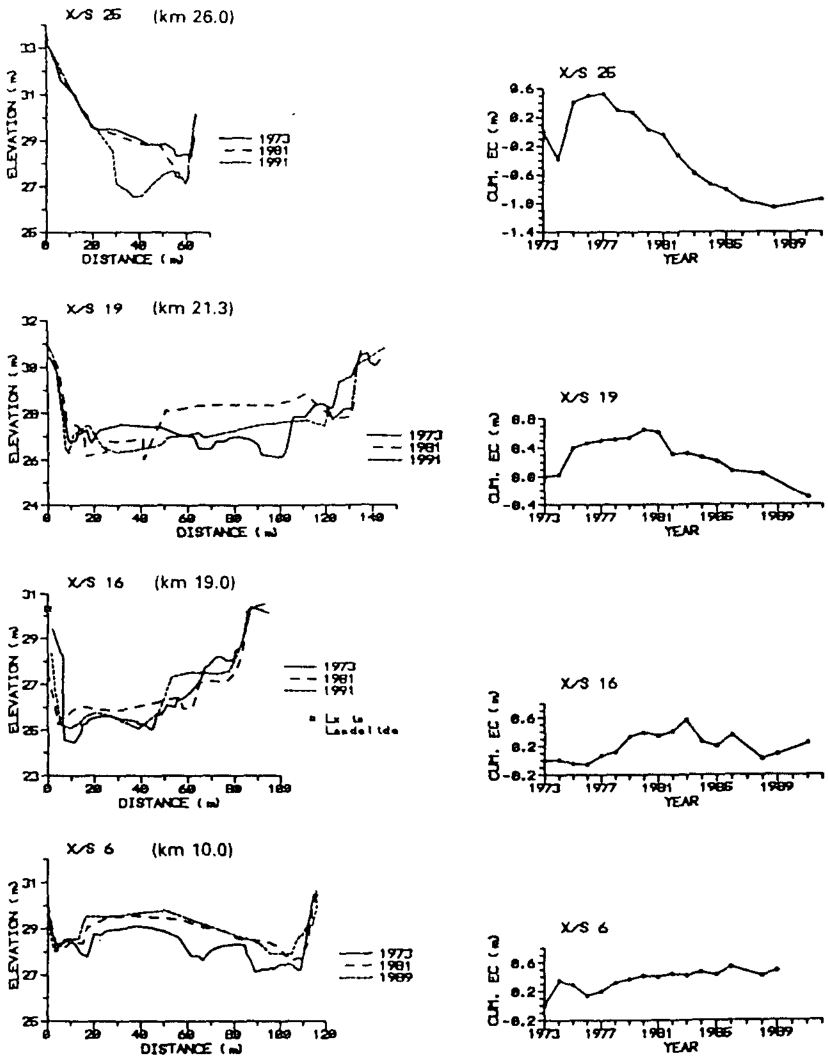

Figure 6. Plots of cross-sectional surveys from 1973, 1984 and 1994 for four lower-reach cross-sections. Each cross-section is accompanied by a plot of the cumulative bed-elevation change, which summarizes annual survey results for the period of record

the sediment wave downstream. Transit rates based on peaks shown in Figure 6 decrease from 1600 m a^{-1} near km 26 to 770 m a^{-1} near km 19 and 820 m a^{-1} downstream at cross-section 6 (assuming the 1994 value for cross-section 6 is really a peak). However, the wave form has not moved noticeably during low-flow years from 1987 to 1994, and the true transit rate near cross-section 6 may be slower than 820 m a^{-1}.

Transit rates of the aggradational wave are roughly related to unit stream power, ω, defined by Bagnold (1966) as:

$$\omega = \gamma RSV$$

where γ is the specific weight of water (9810 N m^{-3} for flows with low sediment concentrations), R is the hydraulic radius, S is the slope of the energy gradient, and V is average flow velocity. Estimates of unit stream power at bankfull flow were based on values of bankfull discharge measured at km 20 and km 5 and extrapolated to intervening reaches. Mean depth was used in place of R, and surveyed channel-bed gradients were used to estimate S. The fastest transit rate (1600 m a^{-1} from km 26 to km 21·3) was in the reach with the highest unit stream power (227 W m^{-2} s^{-1} at $Q_{bankfull}$). Unit stream power decreased to 85 W m^{-2} at km 19, and to 55 W m^{-2} at km 10, where transit rates are slower (about 800 m a^{-1}). The magnitude of flows may also control transit rates, but because no large flows (> 5 year recurrence interval) occurred during the study period, the effect of flow magnitude cannot be evaluated fully.

Downstream decrease in sediment wave amplitude

The heights of peak aggradation measured at cross-sections 15 to 25 from 1973 to 1991 are plotted against channel distance in Figure 7. Peak aggradation is not plotted downstream of km 18 because a peak cannot be defined until bed elevations begin to decrease there. The downstream decrease in peak aggradation can be defined by an exponential decay function, $P = 1{\cdot}6\ e^{-0{\cdot}16x}$, where P is peak aggradation in metres, and x is channel distance in kilometres ($r^2 = 0{\cdot}96$). Based on this exponential function, the sediment wave would be undetectable (i.e. within one standard deviation of annual bed elevation change, or 0·17 m) at km 12. Interestingly, this channel distance corresponds with our field observations of where the sediment wave is difficult to define, although downstream gravel mining and levee construction complicate the picture here as well.

Peak aggradation can be expected to decrease downstream as channel width increases. However, channel width does not increase regularly downstream in Redwood Creek (Figure 7), and peak aggradation is 0·2 to 0·4 m less than 'expected' for cross-sections downstream of km 21, even after accounting for the distribution of a given volume of sediment at cross-sections of different widths.

Recovery of pool depth and spacing

A return to a former channel-bed elevation is only one measure of channel recovery. Another measure is the re-establishment of a previous channel morphology, specifically, well-developed pool–riffle sequences. Three surveyed reaches represent different states of channel response to an increase in sediment load: a recovering reach which has been degrading since 1975 (from km 25·9 to km 21·3), a transitional reach (from km 20·1 to km 18·2), and an aggrading reach (from km 10·6 to km 9·2).

In 1977, no residual pools greater than 1·2 m deep were measured in the three reaches. Surveys in 1983 and 1986 documented that pools in all three reaches deepened through time, although the distribution of pool depths was distinctly different. In 1986, residual pool depths were distributed normally in the degrading reach where the median depth class was 1·5–2·0 m (Figure 8). In contrast, the distribution of residual pool depths in the aggrading reach showed that most pools were less than 1 m deep. Pre-disturbance pool

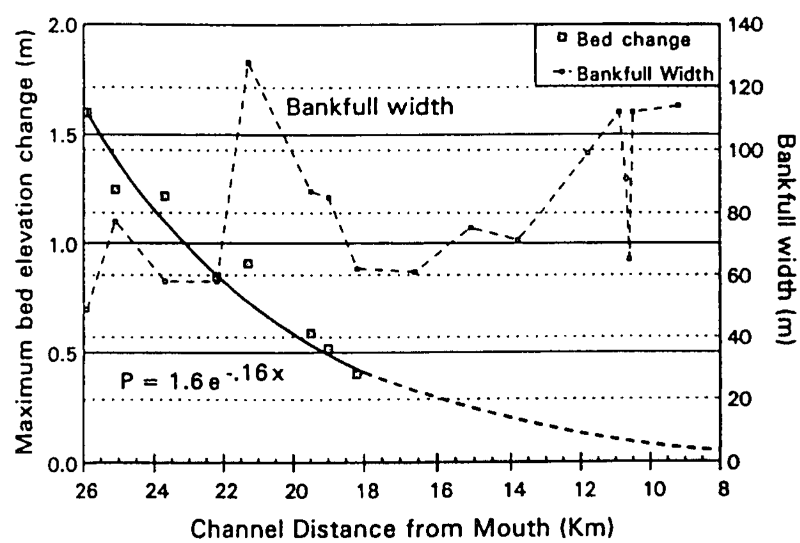

Figure 7. Exponential decrease of peak aggradation downstream (solid and heavy dashed line) and values of bankfull (light dashed line), Redwood Creek

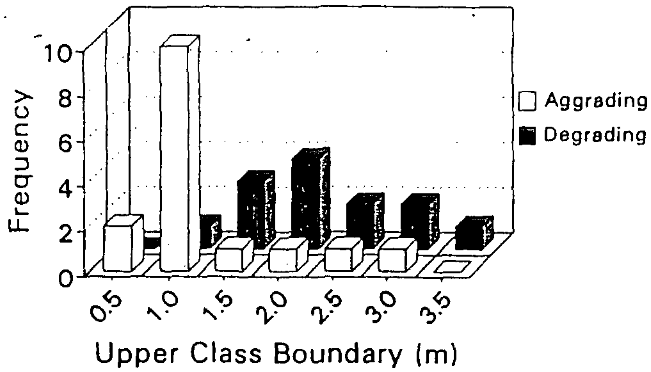

Figure 8. Distribution of residual pool depths in the aggrading and degrading reaches based on 1986 surveys

depths are not known, but local residents have reported swimming in a few pools 3 m deep or more in these areas.

Longitudinal profiles also indicate that since 1977 a better defined pool–riffle morphology has developed in all three reaches. Pool spacing has significantly decreased from 1983 to 1986 in all three reaches (two-sided p value $< 0{\cdot}024$ for all comparisons) (Figure 9); however, pool spacings in 1983 and 1986 were significantly closer in the degrading reach than the aggrading reach (two-sided p value $< 0{\cdot}004$). (Riffle spacing was essentially the same as pool spacing, so was not plotted separately in Figure 9.) Pre-disturbance pool spacing is not known. Nevertheless, the longitudinal profiles show that presently pool spacing in all three areas is similar to the spacing of five to seven channel widths proposed by Leopold *et al.* (1964) for alluvial rivers. Although pool depths have not achieved their probable pre-disturbance values, the present pool spacing appears to be approaching the pre-disturbance spacing. It is not unexpected that pool spacing would recover more quickly than pool depth, as locations of pools in this region are fixed somewhat by scour around bedrock outcrops and large woody debris accumulations (Lisle, 1986).

Magnitude and frequency of flows

In a study of channel adjustments, flow magnitude and frequency must be considered. Peak flows in 1964, 1972 and 1975 produced large channel changes in Redwood Creek. Those floods initiated extensive streamside landsliding, bank erosion and channel-bed aggradation. Since 1975, no flows have exceeded a 5-year recurrence interval (895 $m^3 s^{-1}$, Figure 10A), and bankfull flow (560 $m^3 s^{-1}$) was exceeded only five times.

Although there have been no large flows during the last two decades, several lines of evidence indicate that

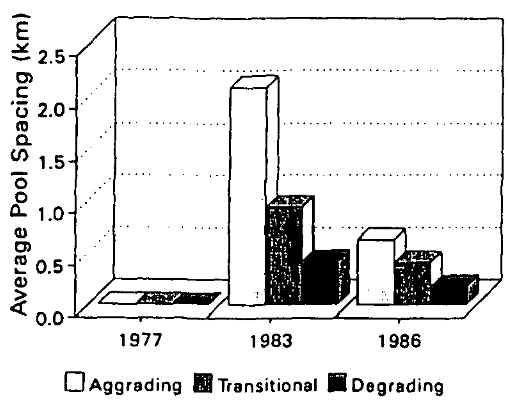

Figure 9. Changes in pool spacing from 1977 to 1986 in three reaches in lower Redwood Creek

the moderate flows during the study period were capable of bed mobilization. Past analyses of effective discharge for Redwood Creek, based on suspended-sediment measurements (Nolan *et al.*, 1987), indicated that 425 $m^3 s^{-1}$ (1·8 year recurrence interval) was the magnitude of flow at which the product of sediment transport rate and flow frequency reached a maximum (Wolman and Miller, 1960). From 1976 to 1994, that flow was met or exceeded 15 times although peak flows did not exceed a 5 year recurrence interval flow (Figure 10A and B). While this effective discharge may be important in controlling the channel shape over the long term, on Redwood Creek even lower, more frequent flows are capable of adjusting the channel and can influence channel storage of sediment. The bedload transport rating curve generated by the USGS indicates that movement of bedload is initiated at 10 $m^3 s^{-1}$ and significant amounts of bedload (3000 Mg/day, or about 5 per cent of the annual bedload) were transported at 115 $m^3 s^{-1}$ at the Orick gauging station. In most years, this flow was met or exceeded many times (Figure 10B). Even at these relatively low flows, bed material was observed in transport at the gauging stations, and the channel bed both scoured and filled.

Significant bed movement at less than bankfull flows is in contrast to the phases of transport that Carling (1988) observed in two gravel-bedded streams in Great Britain, where only slight channel adjustment was possible until flows were greater than bankfull. One reason for the frequent mobilization of the Redwood

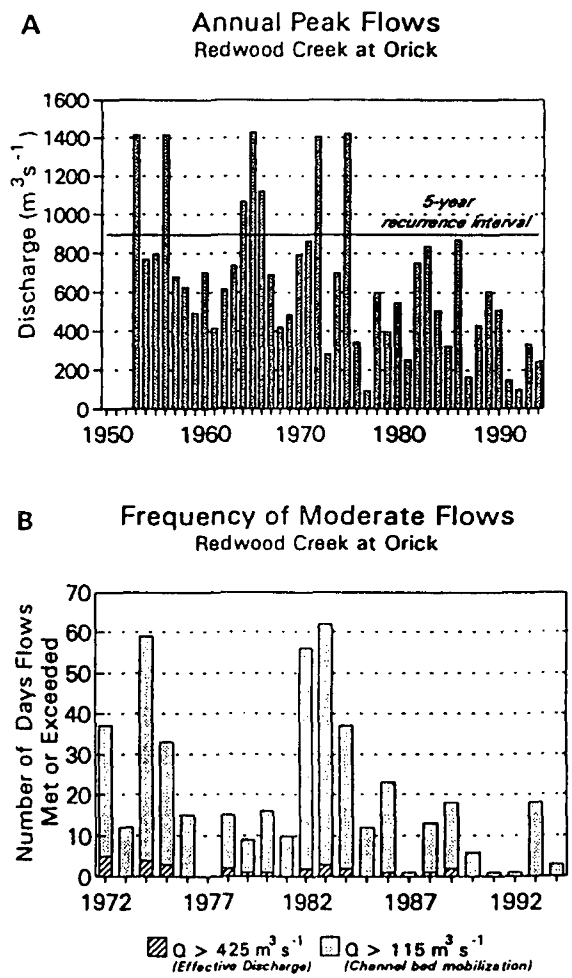

Figure 10. Plots of annual peak flows (A) and frequency of flows (B) measured near the mouth of Redwood Creek, 1972 to 1994

Creek bed may be the lack of widespread channel-bed armouring. The D_{50} (median grain size) of bed-surface material ranged from 22 mm at cross-section 20 to 15 mm at cross-section 6. The ratio of the D_{50} size of bed surface to subsurface material in Redwood Creek was also low, only 1·2 and 1·6 at those cross-sections, respectively (Lisle and Madej, 1992), compared to the ratio of > 3 in well-armoured beds (Dietrich *et al.*, 1989).

Two other lines of evidence point to frequent bed mobility. Scour chain sets installed at seven sites in Redwood Creek between km 31 and km 6 (Figure 1) showed 0·3 to 1·2 m of scour under less-than-bankfull flows (Madej, 1992). In addition, during discharge measurements, the depth to the channel bed below an arbitrary datum is recorded. Discharge measurement notes were used to reconstruct the magnitude and location of channel-bed scour and fill during moderate flood flows at seven gauging locations in Redwood Creek. At flows with a recurrence interval of less than 1·2 years (i.e. 290 $m^3 s^{-1}$ at Orick), Redwood Creek scoured 0·3–0·9 m (Madej, 1992).

Although large floods caused the initial influx of large sediment loads and the resultant changes in channel form, moderate flows are capable of adjusting the channel by changing the elevation of the thalweg and bar surfaces. James (1991) found this to be the case in Bear River, California, as well. The volume of material represented by these channel adjustments is significant in terms of sediment yield measured over the period of adjustment, which will be illustrated in the next section.

Relationship of channel adjustments to sediment yields

Changes in channel-stored sediment can affect sediment yields measured from the drainage basin. In the case of Redwood Creek, after the 1964 flood, the upper reach buffered lower Redwood Creek from the total amount of sediment delivered to the channel by storing sediment (aggrading its bed). As the river remobilized sediment stored upstream and transported it downstream, the channel bed itself became an important sediment source to reaches farther downstream. In this respect, analysis of cross-sectional survey data can give insight to basin-wide sediment production, storage and transport.

The volume of sediment eroded from or deposited in the Redwood Creek channel can be calculated by transforming the cross-sectional data (a two-dimensional view of channel change) to a three-dimensional perspective (changes in volume of sediment in reaches of river channel). We used the longitudinal profile to divide Redwood Creek into sub-reaches that responded similarly in terms of the amount of aggradation or degradation. Colour aerial photographs (1 : 6000 scale) from 1978 to 1992 were used to verify that areas within a channel reach were indeed responding similarly, and to define reach boundaries where longitudinal data were not available. Redwood Creek was divided into 42 sub-reaches for these volume calculations. We then multiplied the average net change in channel area $((\Delta A_{s1} + \Delta A_{s2})/2)$ measured from adjacent cross-sections within that reach by the channel length between cross-sections to calculate a change in sediment volume for the period of interest. Volume was converted to mass using bulk density data determined from bed material sampling (1·92 $Mg\,m^{-3}$ of bed material).

The mass of bed material eroded from a reach during a given time period can then be compared to the total sediment load measured from that reach (Figure 11). In this study, total load is assumed to be the sum of suspended load and bedload, although Hubbell (1964) discusses why this may not always be the case. Sediment discharge measurements represent the movement of sediment derived from all sources (hillslopes, tributaries and main-channel contributions) being transported past a point in the channel. Sediment loads presented in Figure 11 refer to sediment contributed and transported in only that portion of the basin; i.e. the load from the middle basin includes only sediment generated and transported in the middle basin and does not count sediment coming in from the upper reach.

For the period of Water Years 1974 to 1979 cross-sectional data in the upper reach are limited, and the change in storage is a conservative estimate of what was probably eroded from the channel. Sediment yields were higher in the upper and middle reaches (2160 and 2360 $Mg\,km^{-2}\,a^{-1}$, respectively) than in the lower reach (1040 $Mg\,km^{-2}\,a^{-1}$), which reflects both high erosion during the 1975 flood in the upstream parts of the basin and channel aggradation in the lower reach (Figure 11).

More extensive cross-sectional data for Water Years 1980 to 1990 allow a closer examination of the role of channel-bed storage. From 1980 to 1990 sediment yields in all parts of the basin were less than during the

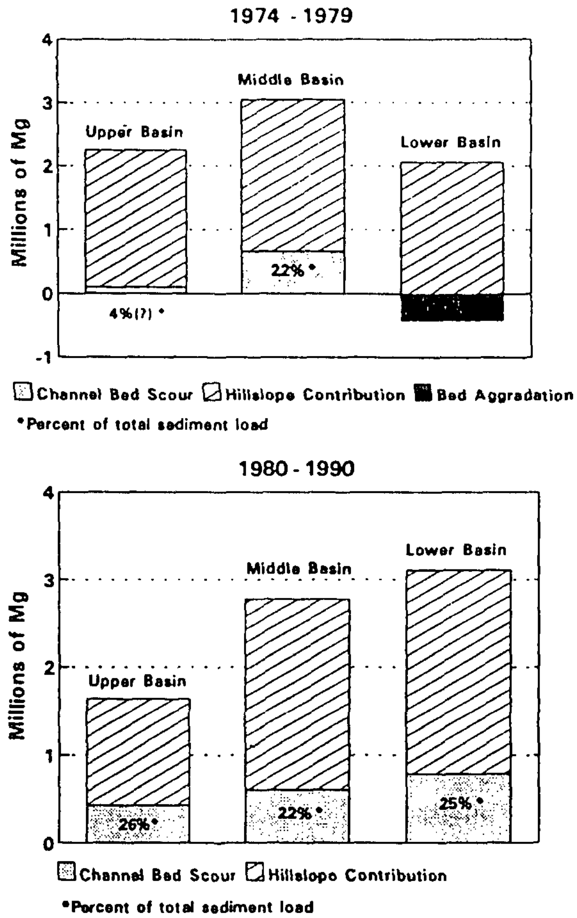

Figure 11. Comparison of sediment loads and changes in channel-stored sediment during two time periods in the three study reaches of Redwood Creek

higher flow period of the 1970s (860, 1180 and 850 $Mg\,km^{-2}\,a^{-1}$ for the upper, middle and lower basins respectively). A series of drought years and decreased timber harvesting and road construction reduced the overall sediment yields during the 1980s. Although channel-bed aggradation was still occurring in the lower 20 km of Redwood Creek, the net change in sediment storage in the 35 km long lower reach was negative (degradation exceeded aggradation in terms of volume of sediment). Channel-bed degradation is only one aspect of basin-wide sediment production, but it represents one-quarter of the total sediment load measured in Redwood Creek from 1980 to 1990, and 95 per cent of the bedload export measured at the Orick gauging station during this period. Other sediment sources, such as mass movement, gullies, road-fill failures, surface erosion on unpaved roads, and bank erosion, contribute mostly to the suspended-sediment load (Madej, 1992). Floodplain dynamics can affect channel storage on a longer time scale, but during this study period, channel and floodplain interaction was negligible.

In Figure 11, the mass of eroded bed sediment was compared to total load rather than just the bedload fraction for several reasons. First, bedload was measured less frequently than suspended load, and we consider bedload measurements to be an order-of-magnitude estimate of true bedload transport. In contrast, suspended sediment was measured daily, and the USGS estimates the accuracy of these sediment measurements to be ± 15 per cent (Crippen, USGS, unpublished memorandum). Bedload generally constitutes 20 to 25 per cent of the total load in Redwood Creek.

Second, bedrock in the Redwood Creek basin is highly sheared and very friable. Breakdown of bed material to suspended-sediment size along the 100 km course of transport is probably very high. In a tumbling experiment, Madej (1992) reported that nearly two-thirds of samples of bed material from Redwood Creek broke down to the 'less than 2 mm' fraction after 13 'tumble kilometres'.

Finally, a significant amount of material stored in the channel bed can be transported as suspended sediment during moderate flows. For example, extensive sampling of bed material by Lisle and Madej (1992) showed 9 to 25 per cent of the subsurface bed material was less than 1 mm in diameter. Particle-size analyses of suspended-sediment samples by the USGS determined that sediment up to 2 mm in diameter was frequently transported as suspended sediment (US Geological Survey, 1974–1993).

DISCUSSION AND CONCLUSIONS

Long-term monitoring of channel cross-sectional changes illustrates channel response to a major increase in sediment supply. Cross-sectional survey data chronicle aggradation and subsequent degradation of the Redwood Creek streambed as sediment was routed downstream. The surveys document the downstream shift of the locus of aggradation from km 26·0 in 1976 to about km 10·5 in 1994. Although there is some annual variation in the amount of scour or fill observed at cross-sections, the pattern of a sediment 'wave' moving downstream is clearly visible. The wave form has become less clearly defined as it moved downstream, however.

The aggradation wave was a result of sediment from many dispersed sources in the upper basin being routed quickly through the steeper upstream reaches and concentrated by valley morphology in the downstream reach. The initial depositional site at km 26 was downstream of an abrupt decrease in channel gradient and increase in channel width. The amplitude of the sediment wave attenuated as it moved downstream (Figure 7). Close to the initial deposition site at km 26, peak aggradation was at least 1·6 m, but decreased to 0·4 m downstream at km 18.

Pickup *et al.* (1983) and Hey (1979) also noted an attenuation of a sediment wave, which they attributed to selective transport of different particle sizes, and different probabilities of distance moved even for particles of the same size. There is not strong evidence of selective transport in Redwood Creek, although median particle size, D_{50}, decreases from 22 mm at km 26 to 15 mm at km 10. The attenuation of the wave in Redwood Creek is probably due to the different probabilities of particle movement, based on a bed particle's lateral and vertical position in a cross-section. However, the specific mechanism of propagation and movement of sediment waves is a topic for future field and experimental research.

The downstream decrease in peak aggradation in Redwood Creek suggests that there is a point downstream where aggradation will be undetectable, in this case downstream of km 12. This attenuation is significant because channel-bed aggradation has been used as one indicator of off-site cumulative watershed effects from land-use disturbances (Reid, 1993). To document such effects it is important to monitor areas of expected change, and to know where the effects will become masked by local variations downstream.

In addition to an attenuation of the size of the wave, the arrival of the aggradational peak was delayed in a downstream direction, from 2 years after disturbance at km 26 to more than 20 years at km 10. The transit times of the wave, defined by the shift of peak aggradation downstream, ranged from 800 to 1600 m a^{-1}. These transit rates are slightly less than those predicted in models by Kelsey *et al.* (1987) and Madej (1992) (of about 2000 m a^{-1}), but the flows from 1976 to 1994 have been considerably below average as well. The wave form is not as clearly defined downstream at km 10 and so exact transit rates are difficult to measure. The surveys show that it took 20 years to route most of the 'sediment wave' from km 26 to km 18·2. Based on the transit rates measured near km 10, we predict it will take an additional 20 to 25 years for the sediment wave to move through the downstream-most 18 km to the Pacific Ocean, assuming a similar flow regime as in the past two decades. Pitlick (1993) describes rapid recovery (within 5 years) of a mountain stream after a catastrophic flood and its associated sediment input. In contrast, the present study shows much longer recovery times (> 20 years) following less catastrophic events.

Wolman and Gerson (1978) suggested that after a channel widened in a large flood, it might recover to its former width in several years under a temperate climate. However, channel width has not decreased significantly in Redwood Creek after initial channel widening during the 1964, 1972 and 1975 floods. Channel aggradation and degradation have been accommodated across the entire channel bed. This is in contrast to the Bear River, which became successively narrower with degradation (James, 1991). The lack of well-developed bed armouring and frequent channel-bed mobilization in Redwood Creek may contribute to the distribution of channel changes across the width of the channel bed.

Since the 1975 flood, responsible for the most recent large influx of sediment to the Redwood Creek channel, no flows greater than a 5 year recurrence interval have occurred. However, flows capable of transporting significant quantities of bedload ($115\,m^3\,s^{-1}$) were exceeded 300 times during the last 19 years. Even without large floods, the channel bed responded to material already in the channel system by eroding channel-bed sediments to attain the 1974 bed elevation in upstream reaches and by depositing that reworked sediment farther downstream.

If channel recovery is defined as a return to a former channel-bed elevation, recovery time ranged from 8 years at km 26 to 15 years at km 21·3, and no recovery is seen downstream of km 18. Timing of recovery for the downstream-most 18 km of Redwood Creek will depend on future sediment inputs and flow magnitudes, as well as the transport rates of sediment presently in storage in the channel.

Channel recovery can also be defined as the return to a pre-existing pool–riffle morphology. Pool spacing decreased and depths increased in Redwood Creek from 1977 to 1986. Pool depths have not achieved their probable pre-disturbance depths, but the present pool spacing may be approaching the pre-disturbance spacing, even in reaches that are still aggrading.

Another definition of recovery, described by Pitlick (1993), is a return to previous sediment transport rates. Few sediment measurements before drainage-basin disturbance are available for Redwood Creek, but the present sediment yields ($1000\,Mg\,km^{-2}\,a^{-1}$) are still several times higher than the sediment yields measured during the same period in the unlogged tributary basin of Little Lost Man Creek ($250\,Mg\,km^{-2}\,a^{-1}$).

The comparison of material scoured from the streambed to sediment yield measurements reveals the importance of the channel bed as a sediment source in basin sediment yields. From 1974 to 1979, which includes the 1975 flood, the Redwood Creek channel degraded in the upper and middle reaches, and bed scour contributed almost one-quarter of the measured sediment load from the middle reach (Figure 11). Channel storage through aggradation buffered the amount of total sediment exported at the mouth of Redwood Creek; that is, sediment output at Orick would have been almost 500 000 Mg higher during this period if not for channel aggradation.

In contrast, during the lower flow period of 1980–1990, with low hillslope-sediment contributions, removal of previously deposited sediment accounted for about 25 per cent of the total load measured at all three mainstem stations, and about 95 per cent of the bedload exported from Redwood Creek. Thus the present sediment yields are indicators of channel adjustments rather than a reflection of hillslope erosion. Trimble (1977) also noted such disequilibrium between rates of hillslope erosion and measured sediment yields in the midwestern and southeastern United States.

Although there was a net decrease in the volume of sediment in the entire lower reach from 1980 to 1990, aggradation in the lowermost 18 km amounted to 260 000 Mg. This represents 1·5 times the long-term annual bedload transport rate calculated for Redwood Creek at Orick (Knott, USGS, unpublished memorandum). Thus aggradation is still buffering the sediment load measured at the mouth of Redwood Creek.

As a result of land-use disturbances, the recurrence interval of recent floods may be different from the recurrence interval of their associated erosion events (Nolan and Marron, in press). Consequently, it is difficult to compare channel recovery times with the recurrence interval of the initial hydrologic events triggering disturbance. In some reaches, channel adjustments have restored previous streambed elevations and the probable pool spacing on the scale of 20 years after damage from floods with 20 to 50 year recurrence intervals, but recovery of Redwood Creek in terms of pre-existing channel width, pool depth and sediment yields will take much longer. If the recovery of damaged riparian and aquatic biota depend on the restoration of their pre-existing physical habitat, their recovery times following disturbance in Redwood Creek will likewise take several decades.

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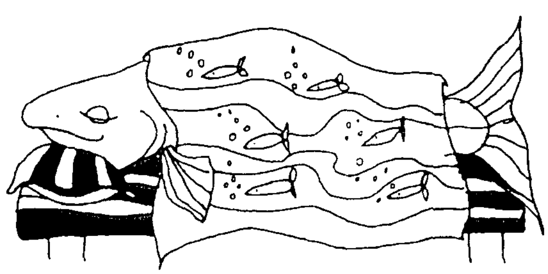
Aquatic Habitat and Watershed Approaches

Rick Kattelmann
Guest Editor

Conservation of fish and other water-borne critters has been a critical driving force in many of our watershed-based efforts. Maintenance and enhancement of aquatic habitat is usually one of the main rationales (along with water quality and soil conservation) for "watershed work". Fisheries biologists are often the primary partners of hydrologists and soil scientists on interdisciplinary teams within land-management agencies. Until recently, these associations have generally been implicit (but obvious to the professionals) rather than explicit (and known to administrators and the public). In the past decade, aquatic conservation programs have become more holistic and wide-ranging. Declines of many aquatic species have been widely recognized as consequences of habitat degradation, and that degradation has been increasingly recognized as a cumulative result of human disturbances within, adjacent to, and upslope from a stream and its tributaries. Thus, river basins and watersheds have become part of the essential framework of many of these recent and current efforts. This issue of the Networker provides a cursory overview of a few of the high-profile species-recovery and habitat-conservation programs that use a watershed approach and are making news in 1999.



Salmon Recovery

In the Pacific Northwest, the March listing of eight species of salmon and steelhead as threatened and one as endangered brought a long-simmering watershed-and-aquatic-habitat issue to network newscasts and national magazines. The complex relationships between landscape degradation, water management, and endangered species as well as a host of other associated issues are becoming more common topics of conversation in the affected region. In the Colorado River basin, efforts at recovery of four endangered species of fish may produce major changes in reservoir operations and land management. A systematic review of options for restoring the habitat of these fish is underway throughout the Upper Colorado River basin. In northern California, a joint state-federal purchase of a red

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What Can Thalweg Profiles Tell Us?

A Case Study from Redwood Creek, California

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In recent years, many land management and regulatory agencies have searched for various indices of stream health, which can be used to assess watershed conditions. The Environmental Protection Agency, through its Water Quality Attainment Strategy and Implementation Plan (commonly know as the Total Maximum Daily Load, or TMDL process) is required to use in-stream targets to evaluate the status of sediment and temperature-impaired watersheds. The use of in-stream targets is confounded by the lag time between hillslope erosion and channel response, as well as the history of disturbance in a watershed. However, in-stream measurements can be used as a trend monitoring tool to show changes in streambed conditions through time. Redwood National and State Parks and the U.S. Geological Survey have been evaluating the usefulness of several in-stream measurements to describe and quantify stream channel changes, based on monitoring started in the early 1970s. This article will focus on our results of using thalweg profiles to document changes in river conditions.

Disturbances such as major floods and large sediment inputs can modify channel bed topography, and so influence aquatic habitat. In gravel-bed rivers, low gradient (<2%) reaches commonly display a pool-riffle morphology, and disturbances can decrease the size and frequency of deep pools. Following the introduction of large sediment loads, a river channel will adjust and evolve. The trajectories and timing of this adjustment ("recovery") are of interest to both geomorphologists and aquatic ecologists. Disturbances in riffle-pool channels which result in aggradation lead to more extensive riffles; smaller, shallower pools; and finer textures of the bed material (Lisle, 1982; Jackson and Beschta, 1984).

Several methods of quantifying longitudinal channel bed patterns, especially the presence of pools, have been developed in previous research. A frequently used technique in the United States to determine the distribution of pools is "habitat typing"

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What Can Thalweg Profiles Tell Us? A Case Study from Redwood Creek

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in which an observer walks the channel with a tape and measures the length of pools, riffles and other features. There are several problems with habitat typing, including high operator variability, lack of replicability, and discharge dependency. Hogan and Church (1989) suggested, instead, using depth and velocity distributions across the entire channel area for more complete habitat assessment; however, these distributions will change with increasing discharge, and are difficult to measure for high flows.

Peterson et al. (1992) attempted to set target conditions for pool frequency, but they admitted that criteria used to define pools varied considerably among studies used in their analysis. Another method that has been used is to determine the best fit regression line of the thalweg profile survey points, compute the residuals from that regression, and use the sum of residuals as an indication of channel roughness. In forested, mountain regions, log jams or bedrock can form major irregularities in a thalweg profile, which violates the assumption that the channel bed can be characterized by a linear relationship. O'Neill and Abrahams (1984) show why this method may not accurately define pools because of channel bed nonlinearities, and suggested an objective method of determining pools. However, their method determines only numbers of pools and riffles, and it is still based on a single threshold measure of the deepest part of the pool.

The problem with these approaches is that they assume the pool is the only feature of interest in channel spatial structure, and that a pool can be objectively and consistently identified. In addition to pools, the degree of variation of channel bed elevations is an important component of aquatic habitat, which cannot be derived simply from an analysis of maximum pool depths. In practice, two pools with equal maximum depths may have very different bed morphologies and be formed by different fluvial processes.

To monitor pool depths independently of discharge, Lisle (1987) adapted the concept of residual water depths introduced by Bathurst (1981). A residual pool depth (d_r) is the depth of water in the pool below the elevation of the downstream riffle crest. This can be thought of as the water depth that would be present in the pool if there were no flow in the stream. Considering the distribution of residual water depths along the entire longitudinal profile, which incorporates all thalweg topography, would provide more useful information than an analysis of pools alone.

What is a Thalweg Profile?

A thalweg profile is constructed by surveying the elevation of the channel bed in a downstream direction along the deepest part of the channel. Typically, bed elevation, water surface elevation, bar height, and substrate size is recorded at each surveyed point, as well as comments on the local channel feature (pool, riffle, run, presence of large woody debris, etc.). Where possible, high water marks are also surveyed. In-stream points are surveyed at all breaks-in-slope, riffle crests, maximum pool depths, and tails of pools. It is essential that the spacing of survey shots be close enough to define the bed features of interest. The length of channel surveyed should be at least 20 channel widths long, and we usually survey a length of 30 to 40 channel widths. Channel distance is measured down the centerline of the high flow channel. Different levels of precision have been used in various channel types, from hand levels and tapes in steep channels, to surveying with laser equipment in low gradient reaches. Surveys have been conducted at various time intervals as well. Ramos (1996) gives a detailed description of survey techniques to construct thalweg profiles.

What Do Thalweg Profiles Tell Us?

Longitudinal profiles have been used for years by geomorphologists to determine channel gradient in a stream reach. Stream gradient is an important variable in determining stream power and sediment transport relationships in streams. However, longitudinal profiles used to measure general channel gradient are not necessarily surveyed in enough detail to define channel bed topography and bedforms. In this paper the term 'thalweg profile' is used to distinguish between the two types of surveys. The thalweg profile can show the number of pools, depths of pools, pool-riffle spacing, and the spatial pattern of pool distribution. Successive thalweg profiles can document trends in aggradation or degradation. Thalweg profiles are also useful in combination with cross-sectional profiles or channel planform analysis to determine the vertical dimension of channel morphologic features.

The "bumpiness" of the thalweg profile can be used an indicator of channel roughness. For example, in Redwood Creek, we observed that the channel bed was almost flat and featureless following an aggradational episode in 1975. Since that time bar forms and pools have developed as the channel reorganized its sediment load. The development of bed forms is most pronounced in reaches where the stream has degraded after 1975, but some increased pool development has occurred even in reaches that are still aggraded. These observations led to the development of a method to quantify these changes (Madej and Ozaki, 1994). The underlying assumption is that the increases in the variation of channel bed elevations increases the complexity of the aquatic habitat and the degree of channel roughness.

Field Area

The Redwood Creek watershed is located in the northern Coast Ranges of California. The Redwood Creek basin is underlain by rocks of the Franciscan Assemblage, mostly sandstones, mudstones and schist. Redwood Creek is a gravel-bedded river that drains 720 km^2, and the channel gradient ranges from 12 percent in the headwaters to 0.01 per cent in the lower reaches. The catchment receives an average of 2000 mm of precipitation annually, most of which falls as rain between October and March. Total basin relief is 1615 m, average hillslope gradient is 26 per cent. About 80 km of its 100 km length is characterized by a pool-riffle morphology. Most of its tributaries are steep (> 4%), but the four largest tributaries have low-gradient reaches with well developed pool-riffle morphology as well. Two tributaries, Lost Man and Bridge Creeks, are included in this study.

Following a 25-year flood in 1975, the channel beds of Redwood Creek and Bridge Creek were almost flat and featureless in many areas. Between 1977 and 1997 longitudinal thalweg profiles of several reaches of Redwood Creek and its tributary Bridge Creek were surveyed several times to determine the changes in pool distribution and depths following the sedimentation events. The depth and frequency of pools in Redwood Creek increased from 1977 to 1995 (Madej, 1996; Madej and Ozaki, 1996), and pools are presently spaced at three channel widths apart in most of the study reaches. Channel cross-sectional changes have also been monitored, which have shown patterns of bank erosion, aggradation and subsequent degradation (Madej and Ozaki, 1996). From 1977 to 1996, no flow exceeded a five-year recurrence interval, and channel changes were moderate. In 1997, a 12-year flood occurred, initiating many debris flows that contributed large volumes of sediment to the rivers and renewed aggradation in several areas.

Study reaches were chosen to represent a range of channel conditions and types. Three reaches of Redwood Creek, three in Bridge Creek, and one in Lost Man Creek were analyzed in the present study. Upstream reaches of Redwood Creek aggraded after the 1975 flood, and have subsequently degraded (Madej and Ozaki, 1996). Redwood Creek at Weir Creek represents this degrading section of river, and has degraded 1.2 to 1.6 m since 1977, with localized 0.2 m of aggradation following the 1997 flood (Ozaki and Jones, Redwood National Park, personal communication). Farther downstream, Redwood Creek at Bond Creek and Redwood Creek at Elam Creek are two reaches that aggraded 0.4 m to 0.9 m from 1975 to 1986, and subsequently degraded from 0.1 to 0.6 m from 1986 to 1995 (Madej and Ozaki, 1996). Much of the channel length in this part of the basin aggraded slightly (0.1 m) after the 1997 flood.

7410 ac.

Three reaches of Bridge Creek are also analyzed. Bridge Creek is a gravel-bed stream draining 30 km^2. The reaches range in gradient from 1.1 to 1.7 percent. In 1954 and 1971 large woody debris was removed from the channel of Bridge Creek to salvage merchantable timber (Klein et al., 1987). Since 1971, the input of new large woody debris has been limited and, due to the extensive harvesting of streamside trees, the present debris loading is lower than it would be under pristine conditions. Upper Bridge Creek received high sediment inputs in 1975 (as detected from aerial photographs and field observations), but longitudinal profile surveys were not conducted until 1986. Cross section monitoring showed that by 1986 much sediment had been transported out of the upper reach and only 0.2 m of degradation occurred between 1986 and 1995. In 1997 a debris flow delivered 13,000 m^3 to the channel upstream of the upper surveyed reach and the channel aggraded locally.

A narrow canyon, in which large woody debris, boulders and bedrock outcrops are common, separates the upper and lower reaches of Bridge Creek. In Lower Bridge Creek the channel degraded two metres between 1975 and 1986, but the rate of downcutting had decreased to 0.1 m by 1996. In 1986 woody debris loading was low in Lower Bridge Creek, but landslides from the 1997 flood contributed many new pieces of woody debris to this reach.

Lost Man Creek drains an area of 20 km^2, and has a channel gradient of 0.7 percent. The basin underwent timber harvesting and road construction in the 1950s and 1960s, but has not experienced land use disturbances since then. This stream is used as a point of comparison with other study reaches.

Field Methods

Three to five sets of surveys document the development of channel bed pattern, especially pools and riffles, in many sections of the channel network during two decades after the 1975 flood (1977 to 1997). A longitudinal thalweg profile of the downstream-most 22 km of Redwood Creek was surveyed by the U.S. Geological Survey in the summer of 1977. The author resurveyed selected reaches of this area in 1983, 1986, 1995 and 1997. Surveys in Bridge Creek were conducted by Klein and others (1987) in 1986, and by the author in 1995 and 1997. Survey transects began and ended at riffle crests and survey distances were measured along the centerline of the high-flow channel. Elevations of the thalweg and water surface were surveyed with an automatic level and stadia rod, or electronic distance meter and target. The spacing of survey points averaged 15 m in Redwood Creek and 4 m in Bridge Creek. In Redwood Creek, surveyors used staff plates at three gaging stations and twenty permanent bench marks established for channel cross-sectional monitoring as a control on survey accuracy. The total error in elevation between the surveys was less than 0.2% (0.08 m). The length of each survey transect was 20 to 55 channel widths (400 to 2500 m long, depending on the stream reach).

Analysis

For each thalweg survey, a distribution of residual water depths was calculated. First, bed elevations between survey points were linearly interpolated (at a 5 m spacing for Redwood Creek and a 3-m spacing for Bridge and Lost Man Creeks) to obtain a common base from which to compare profiles for different years. Because channel widths vary from 60 to 110 m in Redwood Creek, and 12 to 23 m in the tributaries, this spacing of points defined all but the finest features of longitudinal bed topography. A computer program was written to plot the profiles, convert the surveys into standardized data sets, calculate the distribution, mean and standard deviation of residual water depths, and compute the percent of channel length occupied by riffles (i.e., point on the channel bed having a residual depth = 0). Figure 1 shows an example of a surveyed thalweg profile (a) and the transformation of the profile data into a set of residual water depths (b). Variability in bed elevations was evaluated using the standard deviations of residual water depth for each student reach. To test for differences in the means, medians, and distributions of successive thalweg profiles, the t-test, Mann-Whitney test, and Kolmogorov-Smirnov test were used, respectively, on the sets of residual water depths.

In addition to the depths of pools, the spatial distribution of pools and riffles is also of ecological and geomorphological interest, and the above measures do not contain information on the spatial ordering of the fluvial system. Spatial statistics are an objective technique to look for channel structures, such as pools or bar units. To analyze the spatial pattern of pool distribution and channel bed elevations, residual water depths were analyzed by the use of a spatial autocorrelation coefficient (Moran's I). The relationship of pool frequency to large woody debris loading, bedrock outcrops, etc. can also be explored. A discussion of spatial statistics is beyond the scope of this paper, but results using Redwood Creek data do show the development of regularly spaced bedforms following disturbance (Madej, in press), but with significant differences in streams with high woody debris loading.

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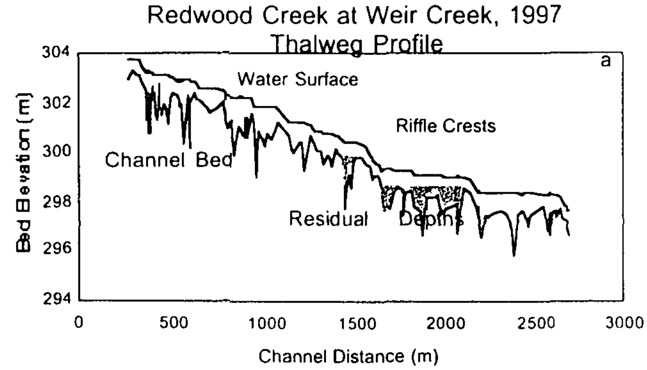


Figure 1: Examples of a longitudinal thalweg profile plot (a) showing how residual water depths are calculated, and the corresponding residual water depth plot (b) for Redwood Creek at Weir Creek.

Results

Figure 2 is a typical box-and-whisker plot of residual water depths in Redwood Creek. In all study reaches of Redwood Creek, the mean water depth was low immediately following the 1975 flood, and mean and maximum depths increased, until 1995. After the flood of 1997, mean and maximum residual water depths decreased to approximately 1983 levels. Although the mean residual depths were not significantly different between some surveys, distributions for all reaches are significantly different from one another (Kolmogorov-Smirnov test, 95% confidence levels). A consideration of the entire distribution of residual water depths may thus give a more detailed picture of trends in the channel bed status than just the means and maxima alone.

Figure 3 is a plot of mean residual depth of the study reaches over the period 1977 to 1997. Mean depth increased rapidly from 1977 to 1986, but the rate of change has been moderate since 1986. Mean residual depths in all study reaches decreased slightly after the 1997 flood (recurrence interval = 12 years). A reduction in residual water depth is consistent with the finding of increases in fine bed material in pools (V.) in high sediment load streams (Lisle and Hilton, 1992).

Figure 4 shows the percent of channel length classified as riffle (residual depth = 0) in all study reaches. Trends in percent riffle are the inverse of those in residual depths: the percent of

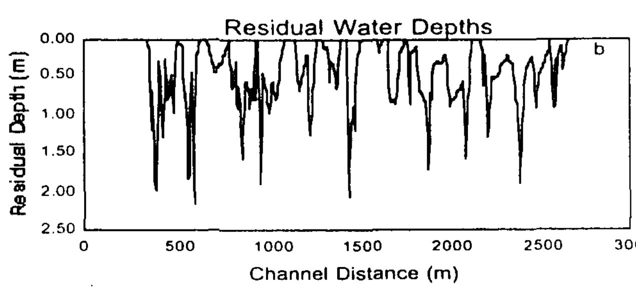


Figure 2: Box plots of residual water depths for 'Redwood Creek at Weir Creek' study reach for the period 1977 to 1997. The upper and lower lines of the box are the 75 and 25 percentiles of the residual water depth distribution, the notches and centerline show the median values, and the "" sign is the mean of the distribution. Values that fall beyond the whiskers, but within three interquartile ranges are plotted as individual points (outliers).*

channel length occupied by riffles decreased in the years following the 1975 flood, until 1997 when the percent increased again slightly.

The variance of bed elevations was evaluated by using the standard deviation of the population of residual water depths (Figure 5). The underlying assumption is that increased variance in bed elevations reflects increased morphologic diversity in the channel bed. In Redwood Creek, standard deviations increased rapidly in the 10 years following the 1975 flood. Since the mid-1980s, standard deviations have increased only slightly. This flattening of the curve may indicate a probable

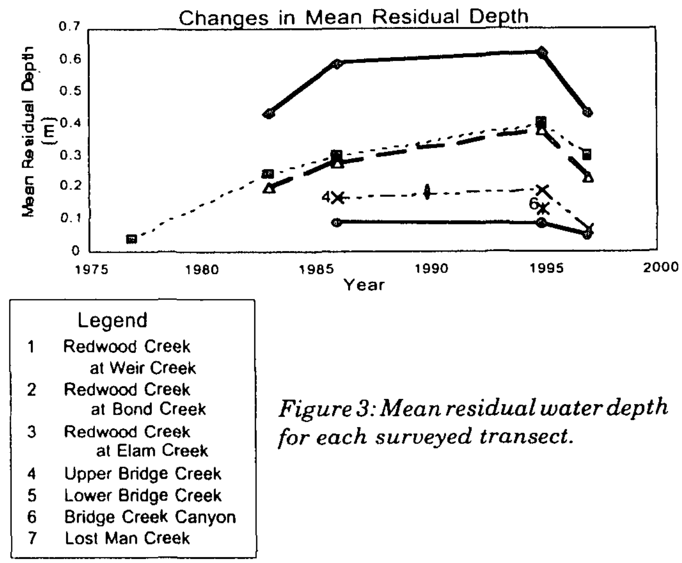


Figure 3: Mean residual water depth for each surveyed transect.

upper limit to the degree of bed variation that can develop in this river under the present sediment regime. The standard deviations decreased in all reaches after the 1997 flood, but none decreased to the 1977 level (immediately following the larger 1975 flood).

If one wants to compare measurements over a range of stream sizes, a standard index is needed. The commonly used statistic of coefficient of variation [(standard deviation/mean) * 100] did not show any obvious pattern except that the magnitude of

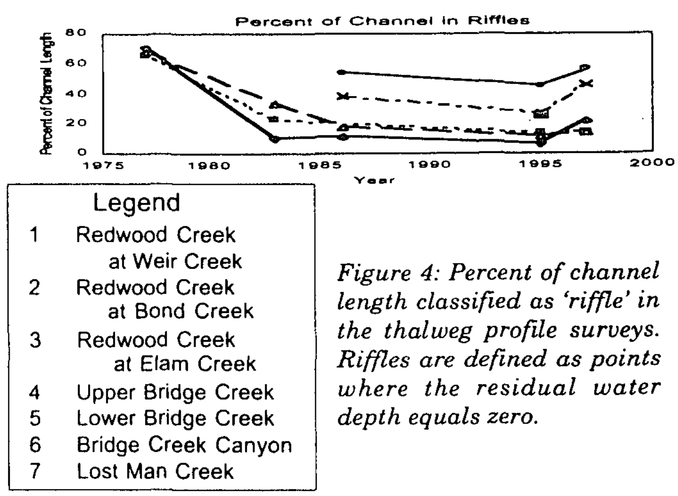
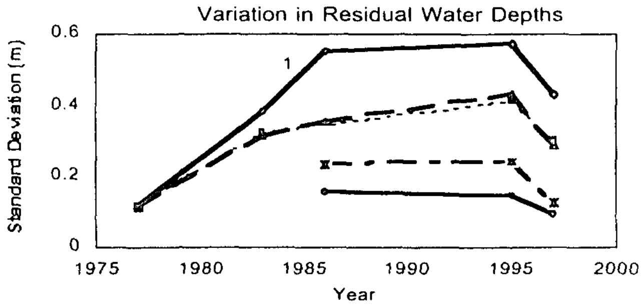


Figure 4: Percent of channel length classified as 'riffle' in the thalweg profile surveys. Riffles are defined as points where the residual water depth equals zero.

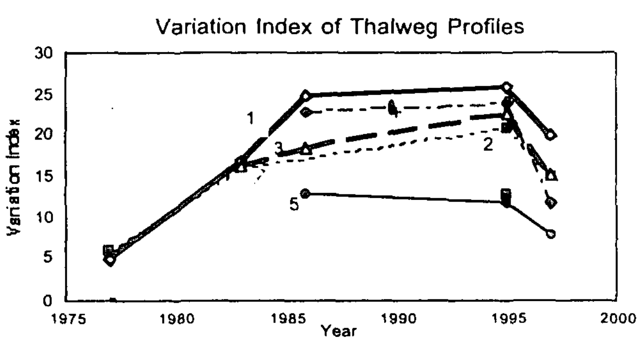
the standard deviation is frequently the same as the mean residual depth. Both mean residual depth and standard deviation change through time, but not necessarily at the same rate. As an alternative method, bankfull depth was used to normalize residual depths. Although bed topography was changing through time, the reach-averaged bankfull depth was consid-



Legend
1 Redwood Creek at Weir Creek
2 Redwood Creek at Bond Creek
3 Redwood Creek at Elam Creek
4 Upper Bridge Creek
5 Lower Bridge Creek
6 Bridge Creek Canyon
7 Lost Man Creek

Figure 5: Variation in residual water depths in the thalweg profile surveys. The standard deviation of the population of residual water depths is plotted against time for the individual reaches.

ered to be constant during this period. In some cases, bankfull indicators are not always obvious (Ramos, 1996), and a careful determination of bankfull depth is needed. Figure 6 shows this new variation index [(standard deviation/bankfull depth) * 100]. A general trend emerges in which index values are higher at sites with better habitat conditions. The stream reaches with the smallest amount of remaining flood deposits (Upper Bridge Creek, Redwood Creek near Weir Creek, and Lost Man Creek) all plot above a value of 20. The values for all surveyed reaches dropped after the 1997 flood.



Legend
1 Redwood Creek at Weir Creek
2 Redwood Creek at Bond Creek
3 Redwood Creek at Elam Creek
4 Upper Bridge Creek
5 Lower Bridge Creek
6 Bridge Creek Canyon
7 Lost Man Creek

*Figure 6: Variation index for study reaches plotted against time. The variation index is defined as [(standard deviation of residual water depths / bankfull depth) * 100].*

Conclusions

Thalweg profiles are easy to survey, and can be used to show trends in the development of channel bed topography through time. An analysis of thalweg profiles in the Redwood Creek basin surveyed between 1977 and 1997 showed there were statistically significant differences in the distributions of residual water depths and the variation of channel bed elevations in streams impacted by high sediment loads. (Of course, more interdisciplinary work is necessary to evaluate if statistical significance of change is equivalent to biological significance). In the 22 years following the 1975 flood, mean residual water depth and variation of depths increased and the length of channel in riffles decreased. The method for analysis of thalweg profiles presented here provides an objective way of quantifying changes in channel bed topography in low gradient streams in north coastal California. Further work is needed to determine the applicability of this method in different channel systems.

If one wants to compare thalweg profile data from different streams, the survey results need to be normalized. For this purpose, a variation index was developed to compare the variation of residual water depths in streams of different sizes. Increased variation of residual water depths is indicative of increased spatial heterogeneity of the physical environment, which is assumed to contribute to increased diversity in biological communities. The variation index [(standard deviation of residual water depths/bankfull width) * 100] was highest (> 20) in stream reaches with the least amount of remaining flood deposits. Results from the variation index on the study streams corresponded to field observations of improved fish habitat and shows promise as a trend monitoring tool to indicate more favorable stream habitat conditions. This index, like any in-channel measure, cannot by itself determine habitat quality, but must be used in conjunction with other information on watershed conditions.

An issue of concern in the Pacific Northwest regarding management of forested lands is the range of variability in natural systems. Variability in the magnitude and frequency of many processes has not been adequately quantified. The results of the present research provide a base upon which to compare variability of longitudinal profile patterns in different sized streams and in response to large floods and sediment loads. The method presented here is relatively easy to implement, yet can yield useful information for both biologists and geomorphologists.

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NRC Looking for Some Grand Ideas

The National Research Council (NRC) has been asked by the National Science Foundation (NSF) to identify grand challenges in the arena of environmental sciences. NSF places a high value on interdisciplinary and multidisciplinary approaches because it believes many interesting environmental problems transcend traditional science disciplines, although those disciplines are essential components of any research program. Therefore, the NSF is seeking advice from the scientific community on research initiatives and programs that would address scientific (not management) uncertainties in environmental science. These initiatives will likely involve researchers from a variety of disciplines and will likely be relevant to the research mandates of several federal agencies. Policy implications of scientific research are of course important, because public funding of research is based at least in part on the premise that there will be benefits to the public. However, because NSF is a science agency, its motivation is primarily scientific.

The study will identify and describe the few grand challenges that appear to have the greatest scientific importance and research potential with a clear effort to set priorities and to document the scientific reasons for its choices. A specific effort will be made to identify multidisciplinary approaches to identifying and researching the questions.

The anticipated result of the project is a report containing findings and recommendations regarding grand challenge research priorities in environmental sciences. The report will describe the criteria for identifying and describing a few major scientific questions, document the reasons for choosing them, and prioritize them in terms of research. More information is available at www.nas.edu/gces

USFS Committee of Scientists Report Released

Advice on National Forest policy from an independent scientific panel was released in March. The report, "Sustaining the People's Lands", suggests that sustainability—ecological and social—should be the first priority in managing Forest Service natural resources. Other general recommendations included conservation of critical species and habitats, greater use of science, more flexibility in forest plans, and consideration of greater geographic scope than individual forests when updating forest plans. The report provided several recommendations regarding watershed management: develop a strategy for conserving and restoring watersheds; maintain and restore the natural composition, structure, and processes of watersheds, including their flow regimes; provide conditions for the viability and native riparian and aquatic species; recognize watersheds in assessment and planning; develop an overall strategy for setting priorities for restoration and use; energize the people of the watershed to help provide stewardship; and monitor watershed conditions over time as part of adaptive management.

The team was appointed by the Secretary of Agriculture in December 1997. The group of 13 scientists held forums in each region of the country, gathering information from Forest Service employees, tribal representatives, members of state and local governments, other federal agencies and the public.

Although many of the recommendations are already Forest Service policy, the report will serve as the basis for new planning guidelines under the National Forest Management Act.

The full report is available at

www.fs.fed.us/news/science

Additional background information is available at

www. cof.orst.edu/org/scicomm

The May 1999 issue of the Journal of Forestry (volume 97, number 5) was devoted to articles about the Committee of Scientists report.