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Persistence of effects of high sediment loading in a salmon-bearing river, northern California

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ABSTRACT

Regional high-magnitude rainstorms have produced several large floods in north coastal California during the last century, which resulted in extensive mass-movement activity and channel aggradation. Channel monitoring in Redwood Creek, through the use of cross-sectional surveys, thalweg profiles, and pebble counts, has documented the persistence and routing of channel-stored sediment following these large floods in the 1960s and 1970s. Channel response varied on the basis of timing of peak aggradation. Channel-stored sediment was evacuated rapidly from the upstream third of the Redwood Creek channel, and the channel bed stabilized by 1985 as the bed coarsened. Currently only narrow remnants of flood deposits remain and are well vegetated. In the downstream reach, channel aggradation peaked in the 1990s, and the channel is still incising. Channel-bed elevations throughout the watershed showed an approximate exponential decrease with time, but decay rates were highest in areas with the thickest flood deposits. Pool frequencies and depths generally increased from 1977 to 1995, as did median residual water depths, but a 10 yr flood in 1997 resulted in a moderate reversal of this trend. Channel aggradation generated during 25 yr return interval floods has persisted in Redwood Creek for more than 30 yr and has impacted many life cycles of salmon. Watershed restoration work is currently focused on correcting erosion problems on hillslopes to reduce future sediment supply to Redwood Creek instead of attempting in-channel manipulations.

INTRODUCTION

Many river channels have been disturbed by an increase in sediment loading from activities such as mining, grazing, agriculture, logging, and road construction. River restoration is an actively evolving field that seeks to improve channel conditions following disturbances. In order to effectively design

river-restoration projects, however, it is important to understand the persistence of the problem that requires mitigation and the time required for the system to recover. The feasibility of *passive restoration*, whereby a river system is allowed to heal itself, can best be evaluated if rates of recovery are well understood. Unfortunately, in many cases the expected duration of anthropogenic effects is unknown. To fully understand the persistence of

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sediment effects, a watershed level analysis is needed to identify the location and timing of sediment input as well as to route sediment through the river network.

Channel recovery following disturbances can be defined in several ways. Wolman and Gerson (1978) characterize recovery in terms of reestablishing channel form, especially channel width, following large storms and climatic variations. Reconstruction of floodplains (Hack and Goodlett, 1960) or a return to former channel-bed elevation (Gilbert, 1917), to grade (James, 1999) or to a pre-aggradation hydraulic geometry (Lisle, 1982) have also been used. Planform can change from a braided system to a single-thread channel as a river recovers from elevated sediment loads (Harvey, 2007). Regulatory agencies commonly employ a return to low sediment yields as a recovery target; other regulatory targets include specific pool depths, frequencies, and substrate particle size (California Regional Water Quality Control Board, 1998).

Understanding how increased sediment volumes in a river network are evacuated through time and routed downstream is key to predicting the persistence of sediment effects on a river system. In his classic study, Gilbert (1917) described transport of hydraulic mining debris in the Sierra Nevada. Incorporating the influence of sediment storage on transport capacity expands upon his study of channel adjustments. Sediment transport-storage relations for degrading gravel-bed channels from flume experiments and field studies show a general exponential decline of stored sediment as gravel beds become more strongly armored, but a constant rate of decline when armoring did not occur (Lisle and Church, 2002). Consequently, characterizing the interaction between channel substrate and channel adjustment is essential in determining the duration of sediment impacts in a gravel-bed river and the length of time needed for channel recovery.

Channel cross-sectional and longitudinal surveys have been conducted in Redwood Creek, north coastal California, since the 1970s. The residence time of sediment in various sediment reservoirs in Redwood Creek was modeled on the basis of sediment-storage volumes estimated in the early 1980s (Kelsey et al., 1987). Trends in channel-bed elevations and pool development, based on surveys through the late 1990s, were summarized (Madej and Ozaki, 1996; Madej, 1999). At that time the downstream reach of Redwood Creek was actively aggrading. Since that time, patterns in channel response have shifted. In the present study, 30 yr of cross-sectional and longitudinal channel morphologic surveys and measurements of substrate particle-size distribution along most of the length of a river channel are used to detect temporal and spatial trends of channel changes following disturbances from high sediment supplies.

BACKGROUND

The Redwood Creek basin drains an area of 720 km² in north coastal California (Fig. 1A) and flows into the Pacific Ocean near the town of Orick. The main channel is 108 km long. Channel gradient decreases from 12% in the headwaters to 0.10% near

the mouth (Fig. 1B). Total basin relief is 1615 m, and the average hillslope gradient is 26%. The basin receives ~200 cm of rainfall annually, most of which falls as rain between October and March.

The Redwood Creek watershed is underlain by the Franciscan Assemblage of Jurassic and Cretaceous age (Bailey et al., 1970) and is pervasively sheared and fractured. The basin is bisected by the Grogan Fault, which has juxtaposed different bedrock units on the east side (sandstones and siltstones) and west side (schist) of the watershed (Janda et al., 1975). Redwood Creek follows the trace of the Grogan Fault for most of its length. The combination of high precipitation, steep terrain, and fractured bedrock creates a landscape that is highly susceptible to mass movement and gullying. Annual suspended-sediment discharge of Redwood Creek (1000–2500 Mg km⁻¹ 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 show that prior to widespread commercial timber harvesting in Redwood Creek during the late twentieth century >80% of the basin was covered with old-growth redwood (*Sequoia sempervirens*) and Douglas fir (*Pseudotsuga menziesii*) forest, and the remaining areas were oak woodlands and prairie grasslands (Best, 1995). For much of its length, Redwood Creek was shaded by a thick canopy of large conifers, and the channel was narrow and sinuous in most reaches. The advent of large-scale timber harvesting began in the early 1950s, and by 1966, 55% of the coniferous forest had been logged. In 1968, Redwood National Park was established along lower Redwood Creek to preserve old-growth redwoods, and the park was subsequently expanded in 1978 to encompass the downstream one-third of the watershed. By 1978, 81% of the original conifer forests in the Redwood Creek basin had been logged (Best, 1995). Although timber harvesting ceased in the expanded park lands at that point, since 1978 about one-half of the land upstream of the park has been reentered for logging of second-growth trees and residual timber. During the last five decades, ~2000 km of logging roads and ~9000 km of skid roads were built throughout the watershed, with the vast majority having been built prior to forest-practice rules dealing with road standards (Best, 1995). A road removal program was initiated on park lands in 1978, and an erosion-control program on private lands in Redwood Creek began in the mid-1990s to correct the erosional problems associated with these roads. To date, ~350 km of road throughout the basin has been decommissioned.

Large floods occurred in 1953, 1955, 1964, 1972, and 1975 (Fig. 2). These floods, with peak discharges ranging from 1280 to 1420 m³s⁻¹, have a long-term recurrence interval of ~25 yr (Harden, 1995). Since 1975, annual peak flows measured on Redwood Creek near Orick have all been less than a 5 yr recurrence interval (895 m³s⁻¹), with the exception of a 10 yr flood in 1997. Floods in 1964, 1972, and 1975 initiated widespread road- and stream-crossing failures, gullying, and streamside landsliding throughout the basin. Hillslope disturbance from intensive logging and road building prior to these floods contributed to extensive geomorphic changes in

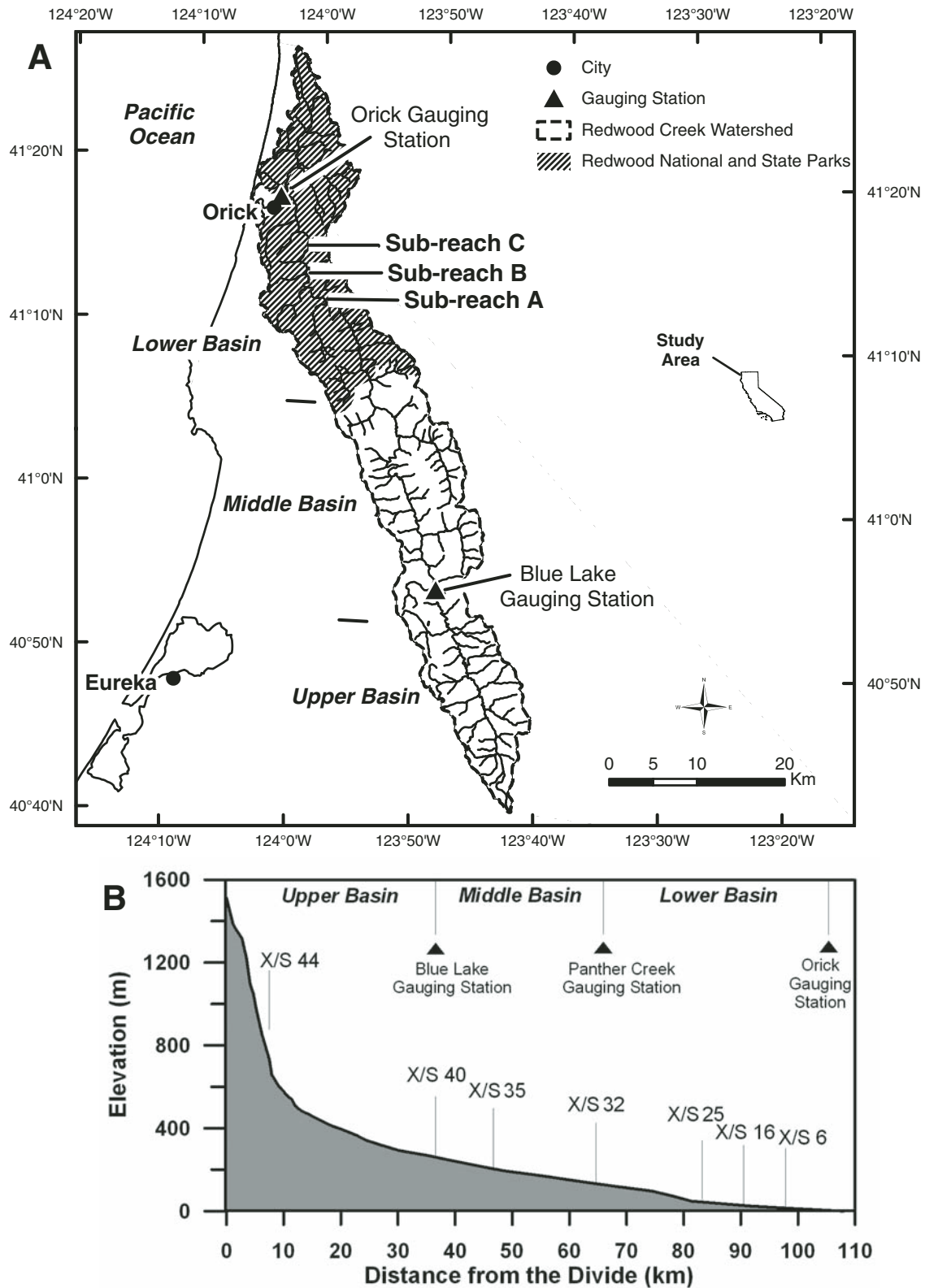


Figure 1. (A) Location of study reaches and gauging stations in the Redwood Creek basin. (B) Locations of cross-sectional transects (xs) along longitudinal profile of Redwood Creek.

the basin. In comparison with a large flood of equal or greater magnitude in 1861, the 1964 flood caused much more widespread mass movement (Harden, 1995). Landslides delivered $\sim 5.25 \times 10^6 \text{ m}^3$ to Redwood Creek during the 1964 flood, and an additional $1.17 \times 10^6 \text{ m}^3$ entered in 1972 and 1975 (Kelsey et al., 1995). Aerial photographs, field observations, and accounts by local residents documented that the channel widened, pools filled in, channel-bed material became finer, and the channel bed aggraded up to 9 m at some sites (Nolan and Marron, 1995; Madej, 1995). The 10 yr flood in 1997 initiated 250 landslides in the Redwood Creek basin and contributed an additional $0.42 \times 10^6 \text{ m}^3$ of material to Redwood Creek (Curry, 2007). Although this volume was $<10\%$ of the 1964 landslide input, it did cause localized channel aggradation in parts of Redwood Creek.

Sedimentation of the mainstem channel from mid-twentieth-century floods impacted aquatic habitat in Redwood Creek as the stream channel aggraded, causing loss of pools, bank erosion, and loss of riparian trees. Redwood Creek is listed as both sediment- and temperature-impaired under Section 303 (d) of the federal Clean Water Act. Logging, roads, erosion and sedimentation, floods, and loss of riparian vegetation have been listed as having contributed to the impairment of Redwood Creek (California Regional Water Quality Control Board, 1998). Currently, three out of four salmonid fish populations (Chinook salmon, *Oncorhynchus tshawytscha*; coho salmon, *Oncorhynchus kisutch*; and steelhead trout, *Oncorhynchus mykiss*) have declined in Redwood Creek to the degree that they are currently listed as threatened under the Endangered Species Act.

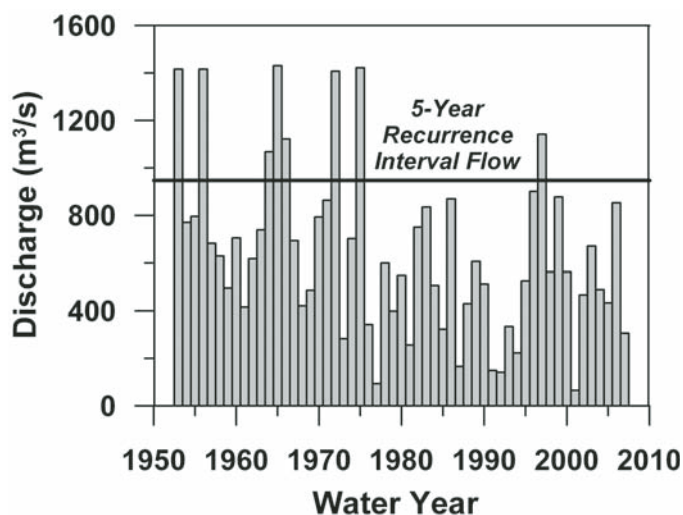


Figure 2. Annual peak flows on Redwood Creek at Orick from water years 1953–2007. A water year, WY, extends from 1 October to 30 September.

METHODS

Cross-Sectional Surveys

In 1973 the U.S. Geological Survey (USGS) established ~ 50 cross-sectional transects along the length of Redwood Creek (labeled XS in Fig. 1). Cross sections have been resurveyed by the USGS and Redwood National Park annually from 1973 to 1987, and periodically since then. Cross sections were monumented with steel rebars reinforced by concrete, and referenced to at least two other triangulation points. The cross sections were surveyed during the low-flow summer months with either an automatic level or an electronic total station. Changes in cross-sectional area from channel scour, fill, and bank erosion were calculated by comparing plots of successive cross-sectional surveys. The change in mean streambed elevation was calculated as the change in cross-sectional area, referenced to permanent endpoints, divided by bankfull width, which results in a stage-independent value. For each survey year, the cumulative change in mean streambed elevation was calculated to show trends at individual cross sections over time. Some transects have since been abandoned owing to lack of access or loss of monuments through bank erosion, but data from 23 cross sections span more than 30 yr and were used in the present analysis.

Thalweg Profiles

Thalweg profiles of lower Redwood Creek have been surveyed by the USGS and Redwood National Park since 1977. Subsequent profiles have been surveyed every 5 to 10 yr. Thalweg elevations and water depths were surveyed with an automatic level, or an electronic total station. All major morphologic features (i.e., top, middle, and base of pools, runs, and riffles) and breaks-in-slope were surveyed. Pools were characterized by slow-moving water with no surface disturbances. Runs had fast-moving water with a smooth surface and were typically ~ 1 m deep. Riffles had fast-moving, shallow water with surface disturbances. The average spacing of survey points was ~ 15 m in Redwood Creek, which is about one-fourth the bankfull channel width. The length of each surveyed profile was 20 to >30 channel widths, and survey distances were measured along the center line of the high-flow channel.

Residual pool depths were calculated for each thalweg profile. A residual pool depth is the difference in depth or bed elevation between the deepest part of a pool and the downstream riffle crest (Lisle, 1987). For this analysis, pools were defined as features that had residual depths of at least 1 m and a length or width of at least 10% of the bankfull channel width. Similar to the calculation of residual pool depths, the entire distribution of water depths below controlling riffle crests can be determined (Madej, 1999). In this case, thalweg elevations were interpolated between survey points to obtain bed-elevation values spaced 5 m apart. Consequently, each year's survey for a given reach had a similar sample size of bed elevations. Using

the elevation of the downstream riffle crest, we determined a residual water depth for each bed-elevation point. Points on a riffle were assigned a value of zero. Because water depths were not normally distributed, we tested differences in the medians rather than in the means, using the nonparametric Mann-Whitney two-sample comparison test.

Substrate Particle-Size Distribution

The particle-size distribution of the channel bed at selected cross sections was determined using the Wolman pebble-count methodology (Wolman, 1954). Five transects perpendicular to the stream channel were measured, with the center transect located on the cross section. The length of streambed sampled equaled the active channel width, and transects were spaced a quarter-channel width apart. The B or intermediate axis was measured for 20 particles selected at regular intervals along each transect, for a total of 100 particles. This standard grid spacing assured that the same area of channel bed was sampled in each survey.

Class sizes ranged from <2 mm (sand) to >256 mm (boulders) and were classified into half-phi size intervals.

RESULTS

Channel-Bed Elevation

The trends in mean bed elevation at representative cross sections along Redwood Creek showed a general decrease, following channel aggradation in the 1960s and 1970s (Fig. 3). Cross sections in Redwood Creek were already aggraded by past floods by the time monitoring began in 1973. In general, cross-sectional surveys in the upper basin documented that the Redwood Creek channel downcut to a stable bed elevation by 1985. The channel bed at cross section 40 is now at the same elevation as in 1953, based on gauging-station records at this location. In the middle reach, the channel attained a more stable bed elevation at most cross sections by 1995. In lower Redwood Creek, the channel continues to downcut and evacuate sediment from the channel bed.

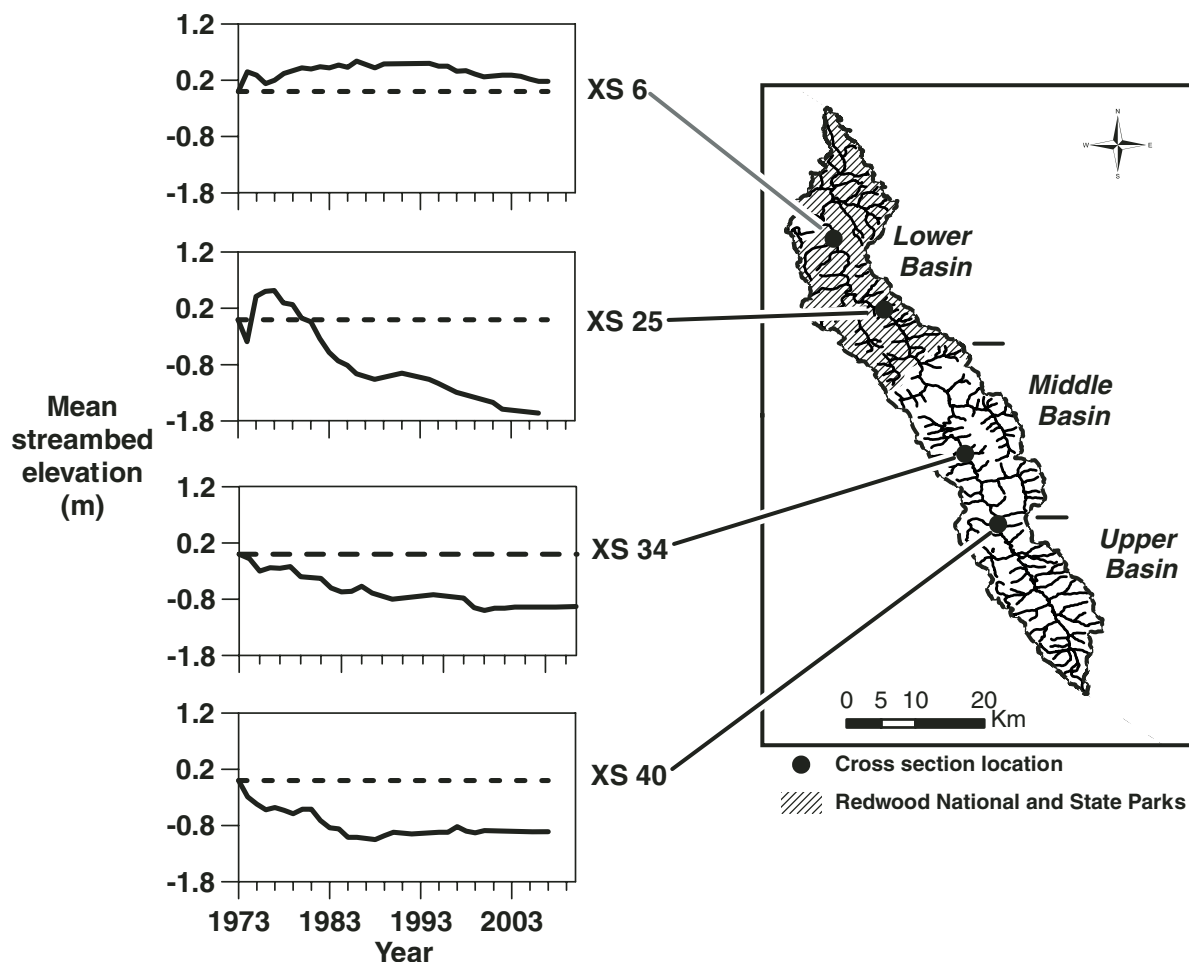


Figure 3. Change in E, mean streambed elevation, at four representative cross sections along Redwood Creek. Dashed line is zero; i.e., the bed elevation at the beginning of the surveys in 1973.

The most complete records of bed-elevation change were available for the downstream-most 26 km of Redwood Creek. Here, the timing of peak aggradation was delayed in a downstream direction. Channel aggradation at cross section 25, ~26 km upstream of the mouth, peaked in the early 1970s, whereas aggradation at cross section 6, 10 km upstream of the mouth, did not peak until the mid-1990s (Fig. 3). Following peak channel aggradation, the decrease in mean bed elevation ranged from 0.4 m near the mouth of Redwood Creek to 4 m at cross section 23, at km 25 (Fig. 4).

The decreases in mean channel-bed elevation as seen in Figure 3 were typical of most cross sections. These trends in channel incision were described by exponential decay functions in the form of:

$$E(t) = Ae^{-kt}, \quad (1)$$

where E = mean streambed elevation relative to a cross-section datum; t = time since peak aggradation, in years; and A and k , the decay rate, are coefficients determined for individual cross sections through the least-squares technique. Exponential decay functions modeled decreases in channel-bed elevation at the cross sections reasonably well, with r^2 values generally >70% (Table 1). One exception (cross section 40) had a better fit with a power function ($r^2 = 0.77$). We also tested whether the magnitude of peak flows during a survey period influenced the rate of channel incision; however, when added to the exponential decay model, peak flow was not a significant variable for any of the cross sections ($p > 0.40$). There was no obvious trend between decay rates, k , and either channel width or distance along the channel (Table 1) ($p > 0.40$, through simple linear regression). Some of the highest decay rates, though, were associated with cross sections 19 through 25. This reach is just downstream of a steep canyon, where the channel gradient changes abruptly from 1.4% to 0.3%, which was the site of extensive flood deposits in the early to mid-1970s. Here, narrow remnants of flood deposits along the valley walls are 7 m high.

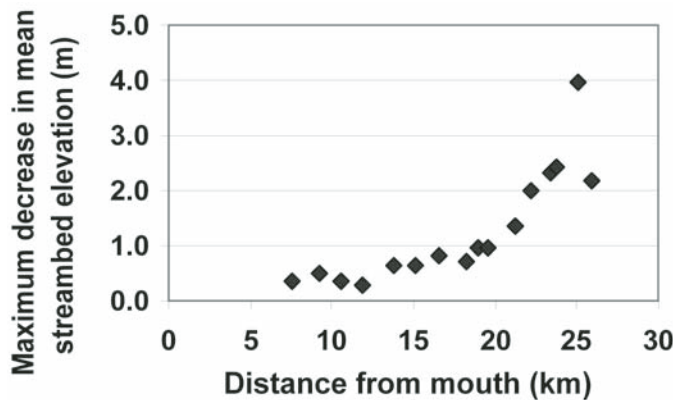


Figure 4. Maximum decrease in E , mean streambed elevation, since peak of aggradation in lower Redwood Creek.

Particle Sizes of Channel Substrate

Pebble counts have been conducted at selected cross sections since 1979. In addition, we compared on-the-ground photographs of the channel taken in 1980 and in 2003 along the upstream-most 20 km of Redwood Creek to confirm trends in that reach, which does not have many cross sections. The dominant particle size, D_{84} (the 84th percentile of the surface-bed particle sizes) is important in controlling bed mobility, and as it increases, bed mobility decreases for a given flow. D_{84} increased at most cross sections during the past 27 yr (Fig. 5). At many cross sections D_{84} doubled during this period. Based on 2006 data, D_{84} decreased in a downstream direction, from 165 mm in the headwaters to 40–60 mm in the lower river. In general, the channel bed has coarsened as the channel has downcut (Fig. 6).

Thalweg Profiles

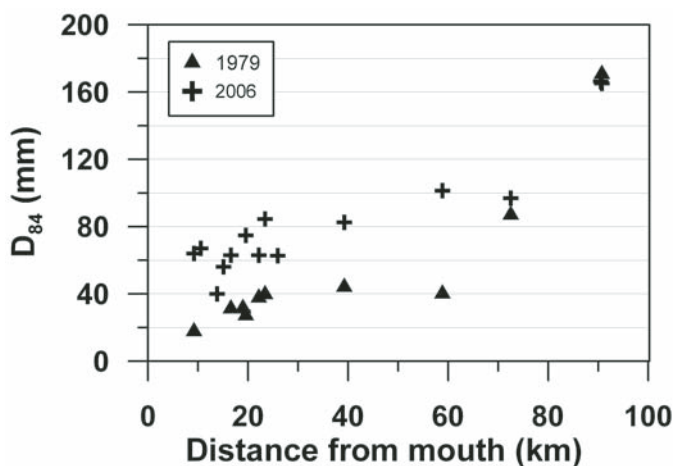
Pool frequencies and depths are important measures of aquatic habitat diversity. Comparisons of successive thalweg profiles showed that pool frequencies and depths on lower Redwood Creek have changed over time as the channel has responded to increases and decreases in coarse sediment supply. In general, pool frequency has increased in lower Redwood Creek since 1977. However, a comparison of three channel segments in lower Redwood Creek with differing lengths of time since peak aggradation showed different levels of pool development. Sub-reaches A and B (Fig. 1), the channel sub-reaches with the most recovery time (30 and 25 yr since peak aggradation, respectively) had a greater number of pools per channel length than sub-reach C, which had less recovery time (17 yr since peak aggradation) (Fig. 7). In sub-reach A the number of pools increased from 1977 to 1995, but following the 1997 flood the number of pools decreased by more than one-third (36%), and by 2007 there were still 14% fewer pools than prior to the flood. Pool frequency in sub-reach B has increased continually through time. In sub-reach C, the reach with the least recovery time, response was similar to that of sub-reach A, with a 50% decrease in pools following the 1997 flood. By 2006 the number of pools had not recovered to pre-flood frequency (25% fewer pools). In 2007 the average pool spacing for sub-reaches A and C was ~3.5 channel widths, and for sub-reach B the average pool spacing was 2.5 channel widths.

The dominant pool-forming mechanism in all three reaches was scour around bedrock outcrops or large boulders (59%, 54%, and 77% in sub-reaches A, B, and C, respectively). In addition, the deepest pools in each reach were associated with bedrock or boulders. As the channel has incised, bedrock blocks and boulders became exhumed, and pools were scoured around these obstructions. The size of the boulders decreased downstream. In sub-reaches A and B, several in-channel boulders were >10 m in diameter, whereas in sub-reach C, boulders were generally <2 m in diameter (Figs. 8A, 8B). About one-quarter of the pools were formed by scour around large woody debris. There were no channel-spanning logs in lower Redwood Creek, and pools were

TABLE 1. BANKFULL CHANNEL WIDTHS, DISTANCE DOWNSTREAM, AND EXPONENTIAL DECAY RATES FOR MEAN STREAMBED ELEVATIONS MEASURED AT CROSS SECTIONS

Cross section	Distance from mouth (km)	Width of channel (m)	Number of surveys*	Decay rate, k	Correlation coefficient, r^2	Significance (p-value)
3	7.5	127	9	-0.01	92.84	<0.0001
5	9.2	114	14	-0.01	84.83	<0.0001
6	10.5	112	16	-0.05	79.94	<0.0001
10	11.8	99	7	-0.04	85.60	0.0028
11	13.8	71	18	-0.02	72.38	<0.0001
12	15.1	75	18	-0.03	69.50	0.0005
14	16.6	61	15	-0.01	78.19	<0.0001
15	18.2	62	15	-0.03	82.56	<0.0001
16	18.9	85	17	-0.04	77.49	<0.0001
17	19.5	87	15	-0.02	80.80	<0.0001
19	21.3	128	16	-0.07	95.39	<0.0001
20	22.2	58	18	-0.07	87.53	<0.0001
21a	23.4	71	16	-0.05	92.12	<0.0001
22	23.7	58	17	-0.12	64.04	0.0001
23	25.1	119	14	-0.09	93.96	<0.0001
25	25.9	49	18	-0.06	95.06	<0.0001
32	44.9	35	23	-0.02	77.64	<0.0001
32a	45.4	69	9	-0.01	65.29	0.0008
34	58.9	67	25	-0.02	89.26	<0.0001
34a	60.0	127	25	-0.02	80.16	<0.0001
35	62.7	51	23	-0.02	89.35	<0.0001
40	72.5	34	29	-0.01	52.64	<0.0001
44	102.4	15	16	-0.04	84.22	<0.0001

*Number of channel-bed surveys since peak of aggradation. Owing to access and crew constraints, not all cross sections were surveyed each year.

Figure 5. D_{84} , calculated from pebble counts conducted at cross sections in 1979 and 2006. See text for further explanation.

generally scoured around individual pieces of wood that were either anchored on the bank and dipped steeply into the river bed or around large (>2 m in diameter) redwood rootwads. Exhumation of in-channel wood also enhanced pool depths through time. The flow contribution from tributaries is small relative to the mainstem Redwood Creek, and confluence pools were small and few in number.

Pool frequency is only one aspect of aquatic habitat, and changes in pool depths were also analyzed. Channel recovery, if defined by greater pool depths, followed a similar trend as that for pool frequency. In 1977, following a series of large floods and massive landslide inputs to the channel, no pools were >0.6 m deep in lower Redwood Creek, and the channel lacked a well-defined pool-riffle morphology. By 1983 several pools had formed in sub-reaches A and B (Fig. 9), and from 1983 to 1995 pool depths increased in all sub-reaches. In the early 1980s, residual pool depths were skewed toward shallower pools, but by 1995 the number of deeper pools had increased. However, a moderate flood in 1997 (10 yr recurrence interval) and associated landslide activity filled in pools and set back pool recovery to pool depth distributions similar to those of the mid-1980s. Since 1997, it has

taken more than a decade for pool depths to recover, and there are still fewer deep pools in sub-reaches A and B than prior to the flood. Sub-reach C, which was still actively aggrading in 1983 but is presently degrading, now has several deep pools.

Distribution of Residual Water Depths

An assessment of individual pools does not address other habitat units such as runs and riffles. To examine this aspect, we assessed the population of all residual water depths in a reach. For example, a reach with a greater length in riffles than in pools or runs will have a smaller value for median water depth. In the reach with the longest recovery time (sub-reach A), median residual water depth increased through time until 1997, when conditions after the flood reverted to those of 1983 (Table 2). By 2007, median water depth again increased and had almost doubled over the 1997 values. In contrast, sub-reach B did not show a large increase in median residual water depth through time, and conditions in 2006 were similar to those of the 1980s. Median water depths in sub-reach C increased greatly from 1983 to 1995 during a transition between peak aggradation in the channel and the initiation of channel incision. Here, water depths decreased by more than half following the 1997 flood, and the median of residual water depths in sub-reach C has not changed significantly since then.

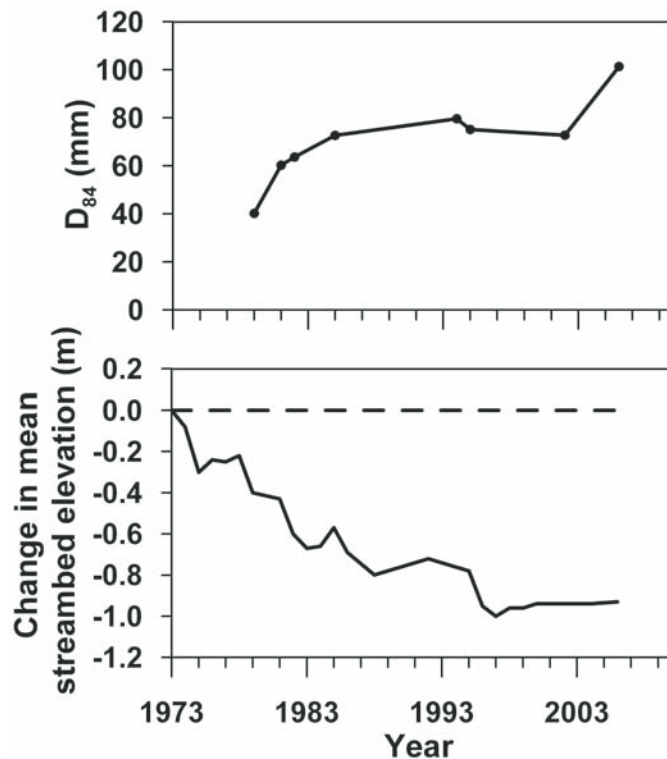


Figure 6. Changes in D_{84} and mean streambed elevation documented through field surveys at cross section 34.

DISCUSSION

Redwood Creek affords a unique opportunity to evaluate channel recovery from large floods and sediment input events. Since the last large flood in 1975, the stream has undergone only low to moderate peak flows. The monitoring data set covers >30 yr of channel adjustments without the influence of another major disturbance.

In the upstream two-thirds of Redwood Creek, where the average channel gradient ranges from 0.5% to 3%, the channel bed degraded rapidly following large sediment inputs and channel aggradation in the 1960s and 1970s. Subsequently, the rate of incision decreased as D_{84} increased, and presently the channel is strongly armored. Taking cross section 40 as representative of the upper basin, little change in mean streambed elevation has occurred since 1985, and a moderate flood in 1997, which initiated >100 landslides in this reach, only resulted in localized deposition.

In lower Redwood Creek, where the average channel gradient is 0.2%, cross-sectional surveys illustrated a somewhat different trend. The highest rates of sediment evacuation occurred 26 km upstream of the mouth of Redwood Creek in a channel reach that attained peak aggradation in the late 1970s. Similar to upstream reaches of Redwood Creek, the channel initially incised rapidly and then slowed as bed material coarsened through time. However, peak aggradation did not occur in the lower 10 km of Redwood Creek until the mid-1990s, and the channel bed is still incising in this area.

Exponential decay functions effectively modeled the rate of decrease in mean channel-bed elevations along the length of Redwood Creek. Such trends in sediment evacuation were consistent with other studies of geomorphic adjustment following disturbances (Graf, 1977; Gran, 2005) where channel response was rapid at first but slowed through time. In Redwood Creek the magnitude of channel-bed elevation decrease was not significantly related to peak flows, perhaps because the magnitude of

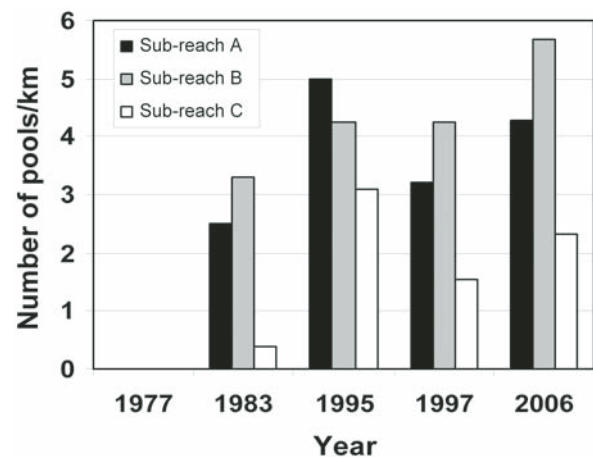


Figure 7. Frequency of pools >1 m deep by sub-reach in lower Redwood Creek, 1977–2007. Sub-reach A was surveyed in 2007; sub-reaches B and C were resurveyed in 2006.



Figure 8. (A) Large (16-m-diameter) boulder and associated pool in sub-reach A. Large wood is commonly trapped on such obstructions but is not the primary mechanism for pool scour. Flow is to the right. (Person on gravel bar on right, for scale.) (B) Channel in sub-reach C, showing relative lack of in-channel wood, bedrock outcrops, or large boulders. View is looking downstream.

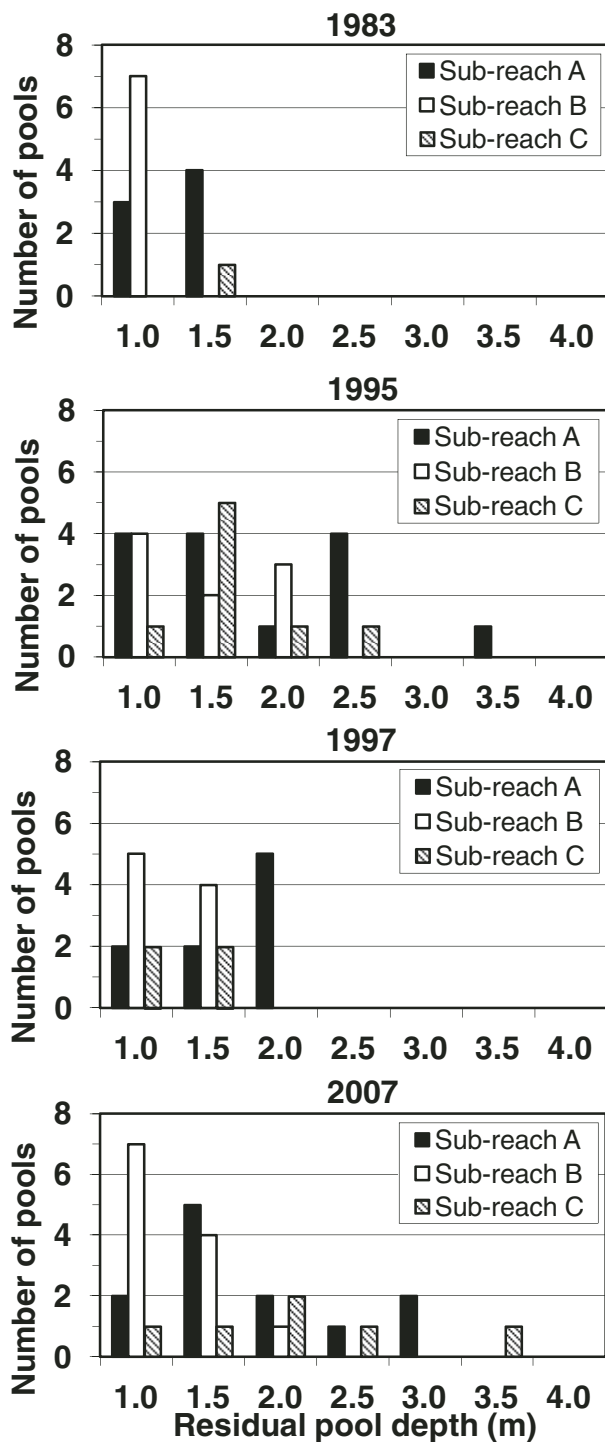


Figure 9. Distribution of pool depths through time in three sub-reaches of lower Redwood Creek. Class sizes represent the lower class boundaries.

TABLE 2. MEDIAN RESIDUAL WATER DEPTHS IN REDWOOD CREEK SUB-REACHES A, B, AND C

Survey date	Sub-reach A	Sub-reach B	Sub-reach C
1977	0	0	
1983	0.36 a	0.16 c	0.06
1986	0.46 b		
1995	0.51 b	0.24 d	0.30
1997	0.32 a	0.22 d	0.16 e
2006/2007	0.61	0.20 cd	0.15 e

Note: Median residual water depths in years not sharing a common letter were statistically different from one another ($p < 0.05$).

peak flows during the monitoring period was not high (all flows were less than a 12 yr return interval). This too is consistent with other studies, such as in Japan, where the exponential decay rate of channel-stored sediment removal was not strongly related to the magnitude of the peak flows (Maita, 1991). There, in the steep (~10% gradient) stream channel, sediment was evacuated quickly, and sediment storage returned to pre-flood levels within 3 years; however, the rate of decrease was somewhat slower in wide valley segments. In Redwood Creek, though, there was not a clear relationship between decay rates determined from cross-sectional data and channel width or distance along the channel. The highest decay rates were associated with a reach of river downstream of a canyon where flood deposits were at least 7 m thick, on the basis of the height of remnants of flood terraces. The thick deposits would have caused a local steepening of channel gradient, increasing sediment transport capacity and presumably sediment evacuation rates. A high transport capacity related to high storage volume is consistent with the concepts put forth by Lisle and Church (2002).

Net erosion between surveys at these cross-sectional transects indicates that as channel-stored sediment was evacuated from a reach, it was not completely replaced, owing to reduced sediment supply to the channel. Sediment supply was reduced over time through several mechanisms. Streamside landslides delivered much less material to the channel in the post-1980s than in the previous two decades. Channel-stored sediment in tributaries was evacuated rapidly after the 1970s floods, where 60%–100% of recent flood deposits was evacuated in 5 to 10 yr (Madej, 1987). Thus, the role of tributaries as a source of sediment diminished through time. The Redwood Creek channel bed became more strongly armored as the bed incised, which then required higher shear stresses to mobilize the bed particles over time. As the channel bed incised and flood deposits were eroded, the remaining deposits became more isolated from the main flow. Although not quantified in the present study, the establishment of woody vegetation at the base of flood deposits probably hindered erosion as well, as it has been shown to stabilize streambanks in other aggraded systems (Hupp, 1992). Since 1978, hillslope restoration activities, focused on the roads with the highest erosion risk, have removed about one-fifth of the road network in Redwood Creek, further reducing sediment contributions from hillslopes.

Pool frequencies varied among reaches with different lengths of time since peak aggradation. Pool spacing in lower Redwood

Creek was 2.5–3.5 channel widths apart. This is a closer spacing than the five to seven channel widths generally reported for pool-riffle rivers formed in alluvium (Leopold et al., 1964). In Redwood Creek, most of the stream length has streambanks composed of bedrock or coarse colluvium, however, and large in-channel wood also induces bed scour. Pool spacing reflects the importance of such obstructions in pool formation in this system (Lisle, 1986). Exhumation of buried boulders and, to a lesser extent, buried logs, has led to higher pool frequency through time and plays an important role in recovery of this habitat feature.

Considering that coastal redwood trees are the tallest trees in the world, one might expect that large woody debris would have a stronger influence on pool formation in this system. Nevertheless, the lower Redwood Creek channel is wide enough (60–130 m) so that no fallen trees span the channel. We have observed that even old-growth trees that fall into the channel have floated out of the system during average winter flows. Upstream, where the channel is narrower, streambanks have been logged, so presently there is not a source of large trees. Currently, only when wood becomes lodged against boulders or bedrock, or is firmly anchored on the streambank, is it effective in forming or enhancing pools.

Trends in pool depths and median residual water depths were not necessarily the same as trends in pool frequency. For example, over time sub-reach B developed more pools per channel length than sub-reach A (the reach with the longest time since peak aggradation), but pools were not as deep in sub-reach B, and the median residual water depth was less than that in sub-reach A.

In general, both pool frequencies and depths were sensitive to a 10 yr flood in that fewer deep pools occurred in lower Redwood Creek after the 1997 flood. In sub-reach A, median residual water depths have increased greatly from 1997 to 2007, although pool frequency and pool depths are still somewhat reduced from 1995 levels. This trend suggests that sediment persists in pools even as the runs are becoming deeper as the channel incises. In sub-reaches B and C, pool frequencies and pool depths have increased in the 10 yr following the flood, whereas median residual water depths in 2006 are about the same as they were immediately post-flood. This suggests that scour of pools is localized and that runs and riffles along most of the channel length have not become deeper. These are sub-reaches where mean bed elevations have not decreased nearly as much as in sub-reach A. These trends also illustrate both the need to consider more than just pool frequency when assessing channel response, and the susceptibility of pools to filling even in moderate-sized floods.

The biological linkage to these habitat changes is not yet well established, but biological monitoring is beginning to assess the effects of sediment on aquatic biota in Redwood Creek. Salmon and steelhead trout have about a 4-year life cycle, and juvenile steelhead can rear in the mainstem of Redwood Creek for several years before migrating out to the ocean. Sediment impacts in Redwood Creek have persisted for several decades and consequently have reduced the quality and availability of aquatic habitat for many generations of anadromous salmonids. Population estimates for 1- and 2-year-old steelhead in Redwood Creek

have decreased for the past 8 years, or ~50% since the beginning of biological monitoring in 2000 (California Department of Fish and Game, 2007). Although Redwood Creek has been incising and coarsening through time, there has not yet been a positive response in steelhead populations. Anadromous salmonids spend most of their life cycle outside the freshwater environment and are affected by ocean conditions. This highlights the difficulty of using salmonids as biological indicators of stream health.

Freshwater mussels also can be used as bioindicators of stream condition (Young et al., 2003). In 2007, western pearlshells (*Margaritifera falcata*) were discovered in lower Redwood Creek in sub-reach A. Young subadult mussels were found in the mussel beds, indicating reproductive success over the last decade (Benson, 2007). The last known sighting in Redwood Creek was >50 yr ago, prior to the 1955 and 1964 floods. Pearlshell mussels live up to 100 yr, and the population in Redwood Creek has survived decades of sedimentation >2 m deep since peak aggradation in the 1970s, and channel incision has exposed bedrock substrate along streambanks that are colonized by mussels.

In contrast to extensive channel widening documented in the nearby Eel River basin (Sloan et al., 2001), the Redwood Creek channel responded to large floods and sediment inputs primarily through channel aggradation and subsequent incision. Lateral erosion of flood deposits was limited to the few unconfined reaches of river with wide valleys and floodplains, which account for only ~15% of the length of Redwood Creek. Although remnants of flood deposits from the 1960s and 1970s remain plastered against the valley walls at a few localized sites, the toes of these deposits are well vegetated and seem to be stabilized.

The removal of channel-stored sediment influences interpretations of sediment-yield measurements from a basin. For example, the degree of channel incision measured in sub-reach C (0.5 m) was much less than the 2–4 m of incision in sub-reach A. Because sub-reach C has just recently begun to incise, it is likely that sediment evacuation will continue in this area for many more years and affect sediment-transport rates measured at the downstream Orick gauging station. Erosion of in-channel stored sediment accounted for ~25% of the total sediment load and 95% of the bed load exported from Redwood Creek from 1980 to 1990 (Madej and Ozaki, 1996). Since that time the channel bed in upper Redwood Creek has coarsened, and bed elevations have stabilized. As a result, removal of in-channel stored sediment will probably play a lesser role in bed-load transport at the upstream gauging station (Redwood Creek at Blue Lake). Nevertheless, sediment yields, which are used as a target to document watershed recovery by regulatory agencies, should be used with caution because of the time lag in routing channel-stored sediment through the river network.

Although the magnitudes of peak flows in floods of 1964 and the 1970s were not unusual, the geomorphic effectiveness of those floods was great because streamside landslides contributed large volumes of material to the river channel during the floods. Channel aggradation that resulted from those floods has persisted in lower Redwood Creek for >30 yr. If channel recovery is

defined as a return to a former streambed elevation, a coarser bed substrate, more frequent and deeper pools, and greater median residual water depth, the Redwood Creek channel has been on a trajectory of recovery. However, if we assume that channel-bed elevations will continue to decrease exponentially by the decay rates listed in Table 1, it will take until the year 2016 for the bed in lower Redwood Creek to return to the elevation of the mid-1970s. Because the probability of a 25 yr flood occurring within a 40 yr period (1975–2015) is 80% (Dunne and Leopold, 1978), it is highly likely that another large flood will occur before the flood deposits in lower Redwood Creek are fully evacuated.

Whereas the recent discovery of fresh-water mussels is encouraging and may signal a shift to improved fresh-water aquatic conditions, and long-term monitoring indicates that Redwood Creek is currently on a recovery trajectory from past floods, the stream still lacks improvement in some fundamental stream-habitat and water-quality components necessary to support a healthy aquatic ecosystem. Stream temperatures, large woody debris in the stream, and large conifer trees in the riparian zone have not recovered to a functional level to support anadromous salmonids (Madej et al., 2006). Evacuation of channel-stored sediment probably affects the Redwood Creek estuary at the mouth of Redwood Creek, which is an important rearing habitat for salmonids. Future research will examine the magnitude, distribution, rate, and source of estuarine deposition, and evaluate possible management actions. Restoration of the Redwood Creek estuary will play a critical role in the recovery of threatened salmon and steelhead trout (Cannata et al., 2006).

The persistence of sediment impacts has implications for river restoration. Once sediment enters a channel it can take decades to be routed through the system. In steep, confined mountain channels, in-channel restoration opportunities are limited because hillslope and channel processes are closely linked. In the case of Redwood Creek, restoration work has focused on ameliorating hillslope-erosion problems rather than attempting to modify the channel by such actions as installing channel structures, dredging sediment, or reshaping the channel. The goal of hillslope erosion-control work is to reduce sediment supply to Redwood Creek in future storms, but the effectiveness of this work in preventing road failures, landslides, and gullyng has not yet been tested by a large (25 yr) event.

CONCLUSIONS

A series of 25 yr floods in the 1960s and 1970s resulted in channel aggradation in Redwood Creek, northwestern California. The temporal histories of this newly deposited sediment differed between upstream and downstream reaches of the river. Aggradation was especially severe in the upper basin, but by the mid-1980s the channel had incised to pre-disturbance levels; the dominant particle size of the bed, D_{84} , had doubled in size; and remnants of flood deposits along valley walls were becoming well vegetated and stabilized. In this reach, recovery time was similar to the recurrence interval of the floods that caused aggra-

dation. In contrast, in lower Redwood Creek, channel aggradation continued through the 1980s as sediment was redistributed downstream and did not peak until the 1990s. Here, the channel bed is still in the process of downcutting, and D_{84} is increasing in size. The decline in channel-bed elevations was initially rapid but slowed as the channel became more strongly armored. The decline can be modeled by exponential decay functions, and the magnitude of peak flows was not significant in defining the decrease in bed elevation.

As the channel has incised, pool frequencies and depths have increased. The degree of pool development differs among reaches with different lengths of time since peak aggradation. Highest pool frequencies were found in reaches for which 25–30 yr has elapsed since peak aggradation, in contrast to a reach for which only 17 yr has elapsed since peak aggradation. From 1983 to 2007 the reach with the greatest amount of channel incision consistently had the highest number of deep pools and the highest median residual water depth. In 1997 a 10 yr flood, with associated streamside mass-wasting activity, resulted in the loss or partial filling of some pools but did not have a large effect on mean streambed elevation. By 2007, median residual water depth had again increased to pre-1997 levels in the reach with 30 yr since peak aggradation, but had not significantly increased in downstream reaches. Pool depths have not recovered to pre-1997-flood values in any of the surveyed reaches.

The duration of sediment impacts in Redwood Creek has affected multiple lifecycles of salmon and steelhead, and channel aggradation has persisted longer than the recurrence interval of the flood that originally emplaced the deposits. Nevertheless, a 10 yr flood somewhat reversed the trend of recovery, and it is likely that the Redwood Creek channel will be impacted by another large flood (25 yr recurrence interval) before it fully evacuates all the recent in-channel flood deposits.

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