Declining Sediment Loads from Redwood Creek and the Klamath River, North Coastal California

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Abstract

River basin sediment loads are affected by several factors, with flood magnitude and watershed erosional stability playing dominant and dynamic roles. Long-term average sediment loads for northern California river basins have been computed by several researchers by several methods. However, characterizing the dynamic nature of climate and watershed stability requires computation of annual loads. We computed annual suspended and bedload loads for the 1950s through 2009 for both Redwood Creek and the Klamath River. Results show high sediment loads coincident with a period of widespread logging by destructive practices and large storms in the 1950s through 1970s followed by a dramatic decline in sediment loads through the present. Analyses of annual departures from mean and time trend tests indicated the decline in loads is not due solely to the lack of very large storms. We infer it can also be explained by the partial recovery of watershed erosional stability from the 1980s through the present due to reduced logging rate, use of lower impact logging practices, and implementation of treatment programs for reducing erosional threats from logging roads.

Key words: bedload, suspended load, watershed recovery, Redwood Creek, Klamath River

Introduction

Sediment yield, or load, consists of the total mass of sediment particles transported by streamflow past a location along a stream or river over a given time period. Sediment is transported either suspended in the water column (suspended load) or along the channel bed (bedload). Quantification of sediment loads can be important for a variety of management needs, such as evaluating land use impacts, reservoir design, coastal sediment budgets, and others. In oceanographic studies, the long term total or average annual sediment yield may suffice for correlation with sediment accretion on the continental shelf (Farnsworth and Warrick 2007, Willis and Griggs 2003), but for assessing effects of changing watershed conditions, annual time series sediment load estimates are required. The objective of this analysis was to characterize fluctuations in sediment loads for the period of record for Redwood Creek and the Klamath River and to relate changes in annual loads to watershed conditions affecting loads.

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Study area

The Klamath River and Redwood Creek drain lands in northwestern California, with the Klamath basin extending into eastern Oregon (*fig. 1*). The Redwood Creek basin area of 717 km^2 lies entirely within the Coast Range of California and is underlain by metamorphic and sedimentary rocks of the Franciscan assemblage (Nolan et al. 1995), relatively weak rocks subject to high erosion rates. Redwood Creek's Mediterranean climate is dominated by rainstorms rather than snowmelt runoff, with most of the average annual rainfall depth of about 150 cm falling during winter months (November through March). Occasional intense rainfall events produce large stormflow peaks at the basin outlet near Orick, California. Harden (1995) reported peak discharges in the 1950s through 1970s ranging from about 1300 to 1400 m^{3}s^{-1}, with recurrence intervals of approximately 25 years.

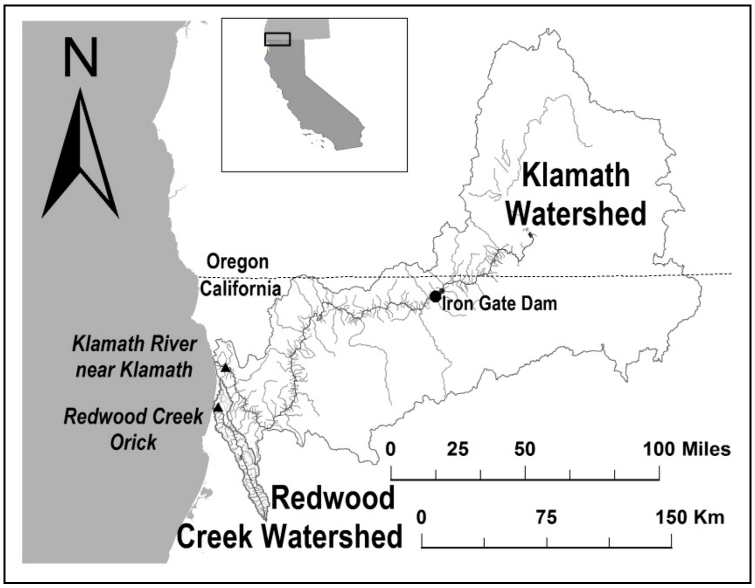

Figure 1—Location of the Redwood Creek and Klamath River watersheds, northern California and southern Oregon. Gaging stations near watershed outlets and location of Iron Gate Dam are also shown.

Due to its much larger size (40,720 km^2), the Klamath River basin contains broader ranges of both climates and lithologies than Redwood Creek. Ayers Associates (1999) report that mean annual precipitation ranges from about 280 cm in the upper reaches of tributaries near the coast to as little as 25 cm in the upper watershed near Tule Lake. Large floods are caused by both intense rainfall and rain on snow (Ayers Associates 1999) with several large storms having occurred over the past 50+ years. In the simplest terms, the basin can be subdivided geomorphically into the upper basin (above the Shasta River) and the lower basin based on bedrock geology and potential sediment delivery to streams. Hillslopes of the upper basin have generally lower sediment delivery potential due to more competent terrane and lower relief than the lower basin. Not far upstream of Cottonwood Creek, Iron Gate Dam traps much of the sediment load generated from the upper watershed. The Trinity River, the largest Klamath River tributary, is notable for its historically high sediment delivery to the lower river due, in part, to the presence of highly weathered granitic rocks (US Bureau of Land Management 1995). Elsewhere in the lower basin the Coast Range geology, similar to that of Redwood Creek, also creates high sediment delivery potential and sensitivity to land use disturbances.

The Redwood Creek watershed has been studied extensively since the 1970s, owing in part to the creation of Redwood National Park in 1968 and expansion of the park in 1978 due to concerns over erosion and sediment delivery originating on adjacent private timberlands (Nolan and Janda 1995). Stream gaging stations were established at key locations within the basin where water discharge and, for much of the period of record, suspended sediment and bedload transport rates were measured. Large increases in sediment yields due to widespread clearcut logging and tractor yarding were documented (Nolan and Janda 1995). The Klamath River has also had stream gaging stations operated on it for some time, several of which included periodic suspended sediment sampling. Together, water discharge and sediment transport samples at known discharges provide the information for making sediment load computations.

Best (1995) documents the post-World War II acceleration of logging in Redwood Creek when few regulations were in place to moderate effects on erosion and sediment delivery. Ayers Associates (1999) indicate that acceleration of logging began in the Klamath's lower basin at about the same time as in Redwood Creek. With passage of the Z'berg-Nejedly Forest Practice Act of 1973 the size of individual harvest areas in California was reduced along with other rules to limit damage to hillslopes and streams. In Redwood Creek logging rates fell abruptly after park expansion in 1978 excluded the downstream one-third of the watershed from commercial timber harvest.

The response to harsh land use and large floods in Northern California's redwood country in the 1960s through the 1970s caused persistent changes to hillslopes and channels. Madej and Ozaki (2009) document the export of channel-stored bed sediment in Redwood Creek from the 1970s through the present, with channel recovery process proceeding in a downstream direction. Recovery rate toward pre-aggradation channel bed elevations was dramatically slower in the gentler-gradient downstream reaches. Payne and Associates (1989) documented tributary delta growth in the lower Klamath River, indicative of elevated sediment delivery from these sub-basins reaching a maximum in the 1970s and persisting through the time of their analysis. Tributaries to the lower Klamath remain heavily aggraded, attesting to a high degree of prior land disturbance and persistent channel bed aggradation similar to that of Redwood Creek.

Methods

Annual sediment loads were computed for water years (WY) 1954 to 2009 for Redwood Creek at Orick (No. 11482500) and for WY1951 to 2009 for the Klamath River near Klamath (No. 11530500). The U.S. Geological Survey (USGS) has operated these stream gaging stations near the mouths of both rivers since the early 1950s and collected sediment samples for a portion of that time. Redwood Creek sediment data included both suspended sediment and bedload samples, but the Klamath dataset included only suspended sediment.

Suspended sediment

Redwood Creek suspended sediment sampling occurred from 1971 to 2009 during which 380 samples were collected. Klamath River suspended sediment sampling occurred from 1974 to 1995 with a total of 270 samples collected, of which 158 were used for estimating suspended load. To compute annual suspended sediment loads, we used the USGS program “LOADEST” (Runkel et al. 2004), a rating curve approach based on a multi-parameter log-linear model that accounts for the effects of discharge, time and seasonality on suspended sediment concentration (SSC). LOADEST contains a number of predefined log-linear models, and the best fit model based on the internally calculated Akaike Information Criterion is generally recommended. LOADEST automatically adjusts for log-space retransformation bias for determining average load estimates (Runkel et al. 2004). Review of log flow-adjusted SSC (as described later) showed a nonlinear trend with time for both rivers indicating potential SSC rating curve shifts. To overcome the nonlinearity we employed multiple log-linear models at obvious shifts.

Separate log-linear models were used on Redwood Creek for the periods of WY 1954 to 1970, 1971 to 1977 and 1978 to2009, and on the Klamath River for WY 1951 to 1964, 1965 to 1977 and 1978 to 2009. Load estimates for periods preceding data collection were based on a single-variable log-linear model of discharge using all available data. To improve the log-linear rating curves and better constrain Klamath River high flow load estimates for the pre-sampling (1951 to 1974) period, high flow data between 1957 and 1977 were used from two upstream stations composing 94 percent of the basin area draining to the lower Klamath: Klamath River at Orleans (No. 11523000) and Trinity River at Hoopa (No. 11530000). Mass balanced SSC values for the upstream stations and the corresponding mean daily flows for discharges greater than 1,800 $m^3 s^{-1}$ for the Klamath River near Klamath were then used in the Klamath River log-linear rating curves for the two periods. For the Klamath River, the selected multi-variable log-linear model was used beyond the data sampling period for the 1996 to 2009 load estimates. All selected log-linear models showed good fits to the data with coefficient of determination (R^2) values ranging from 89 to 99 percent.

Bedload

Annual bedload loads were determined for Redwood Creek and Klamath River using a recently published bedload transport formula (Recking 2010), which uses discharge, active channel width, slope, and surface particle size (D_{50} and D_{84}) as inputs. In general, loads were estimated by first developing log-linear rating curves using available streamflow measurement records, slope and surface particle sizes for each river with the Recking (2010) bedload formula. The rating curves were applied to the mean daily flow record and then summed by WY to produce annual bedload loads. We corrected for log-space bias by applying the correction factor exp ($s^2/2$) (Ferguson 1986) to estimated annual loads, where s is the standard error of a log-linear model of sampled bedload and discharge in Redwood Creek (correction factor = 1.29).

For Redwood Creek most of the necessary data were available for most of the period of record, with the exception of bed surface particle sizes prior to 2010. The USGS sampled bedload (150 samples) in Redwood Creek from 1972 to 2009, which included bedload particle size fractions. To estimate surface D_{50} and D_{84}, a relationship was developed between measured surface and bedload particle sizes. Adequate bedload particle size measurements were available to estimate changes in median surface D_{50} and D_{84} by decade. Although the ratios may have changed over smaller time scales, we felt this was a reasonable method for conditioning bed surface grain sizes through time, as suggested by comparison with USGS measured daily bedload rates for Redwood Creek: 96 percent of the predicted rates were within one order of magnitude of USGS measurements for the overlapping period (1971 to 1992).

Recking's (2010) model was also used to determine bedload annual loads for the Klamath River. Unfortunately, no data on bedload samples, channel bed material particle sizes or slope were available for the Klamath station, so field data were collected for this project in 2010. Particle sizes were determined by performing pebble counts (Wolman 1954) on a gravel bar near the gaging station and surveying the adjacent water surface slope. Lacking any prior data, we had to use the 2010 pebble count and slope data to estimate bedload loads for the entire period of record.

Time trends

Temporal trends in suspended sediment for the Klamath River and Redwood Creek were evaluated by two methods: 1) comparison of departures from period means of annual suspended sediment loads and peak flows, and 2) trends in SSC using the nonparametric Seasonal Kendall test (Helsel and Hirsh 2002). This test adjusts for seasonal variability by combining individual Mann-Kendall trend tests to seasonally grouped SSC. To increase the power of the Seasonal Kendall test, SSC data were adjusted for streamflow effects (flow-adjusted SSC) using a LOWESS smooth curve between SSC and streamflow (Helsel and Hirsh 2002). The residuals from the LOWESS curve were then used in the Seasonal Kendall test. Based on recommendations in Schertz et al. (1991) and the frequency of available SSC data, the Seasonal Kendall test was conducted on six seasons for the Klamath River, and three seasons for Redwood Creek. Monotonic trends in SSC are considered significant at the alpha < 0.05 probability level (p).

Results

The history of sediment loads delivered to the Pacific Ocean by Redwood Creek and the Klamath River is characterized by large inter-annual and decadal variability (*figs. 2A* and *2B*). Loads were highest during the largest storms of the 1950s through mid-1970s and have declined dramatically since.

As expected, annual average total suspended sediment loads for the periods were vastly different between the two rivers given the differences in watershed area. At 6,831,000 Mg yr^{-1}, the much larger Klamath River produced about seven times more suspended sediment over the long term (1950s to 2009) than Redwood Creek, which averaged 975,000 Mg yr^{-1}. However, the situation reverses when considered on an area-weighted basis: Redwood Creek produced about seven times more suspended sediment per unit area than the Klamath River.

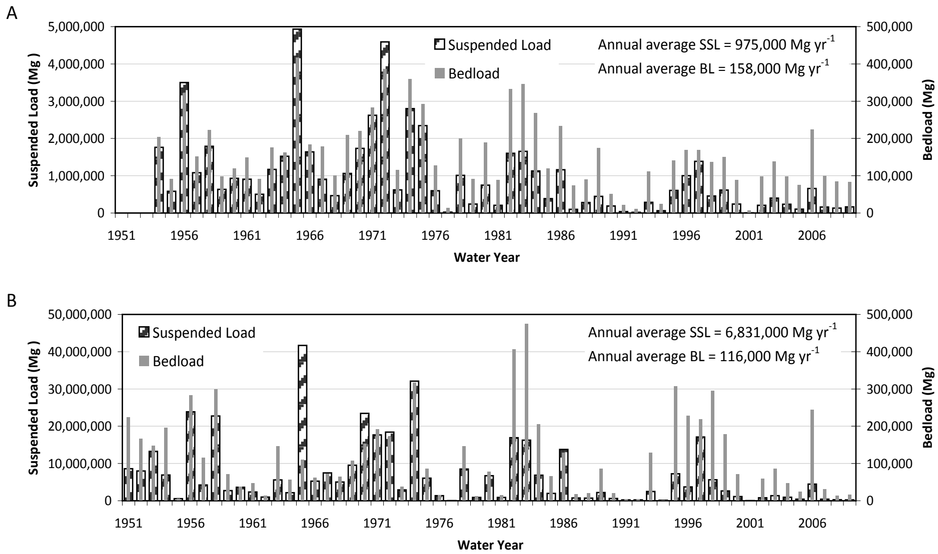

Figure 2—Annual suspended and bedload sediment loads for Redwood Creek (A) and Klamath River (B), 1951 to 2009. Note the difference in scales for suspended loads.

Unlike suspended loads, differences in bedload sediment loads were relatively small between the two rivers: 158,000 Mg yr^{-1} for Redwood Creek and 116,000 Mg yr^{-1} for the Klamath. Closure of Iron Gate Dam in 1961 on the Klamath River approximately 306 km upstream from the mouth (see *fig. 1*) reduced sediment fluxes from the upper one-third of the watershed. However, because area-weighted sediment delivery in the basin area upstream of the dam is much lower than that downstream (Ayers Associates 1999), reductions in basin yields to the Pacific Ocean would be less than the proportion of watershed area truncated by the dam. We note that bedload load estimates for the Klamath are based on a very limited data set for model inputs

Figures 3A and *3B* show departures in annual maximum instantaneous peak discharge and suspended load from their respective period means and trendlines for each. Large departures coincided with years of large sediment loads and floods. Declining trends since about 1975 characterize both variables for both rivers, but the trendline slopes of suspended load are steeper than those of peak discharge for both rivers, indicating loads have declined to a greater degree than peak flows. For Redwood Creek, the suspended sediment trendline is about three times steeper than that for peak discharge, and four times steeper for the Klamath River. For both rivers, the largest storms of recent decades (in WY1996 and WY1997 of roughly 10- and 15-years recurrence intervals, respectively) produced far less sediment than would be expected with similar sized stormflows before 1975.

Results from the Seasonal Kendall test (*fig. 4*) indicate that SSC significantly declined from 1975 to 1995 for the Klamath River ($p < 0.0001$), and from 1971 to 2009 for Redwood Creek ($p < 0.0001$). Trend results indicate a 5.9 mg L^{-1} yr^{-1} (0.7 percent yr^{-1}) decrease in SSC for the Klamath River, and a 3.5 mg L^{-1} yr^{-1} (4.4 percent yr^{-1}) decrease in SSC for Redwood Creek.

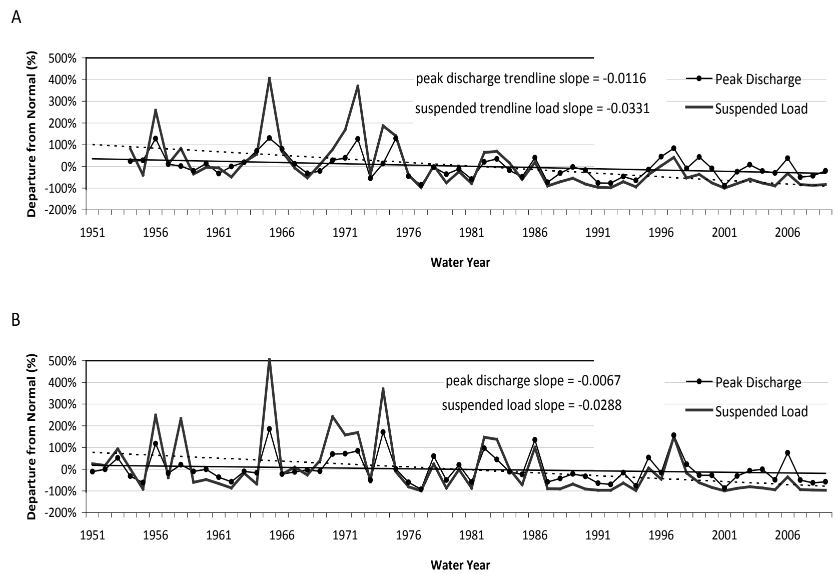

Figure 3—Suspended sediment load and annual peak discharge departures from normal for Redwood Creek (A) and Klamath River (B). Dashed line is trendline for suspended sediment load, solid line is trendline for peak discharge.

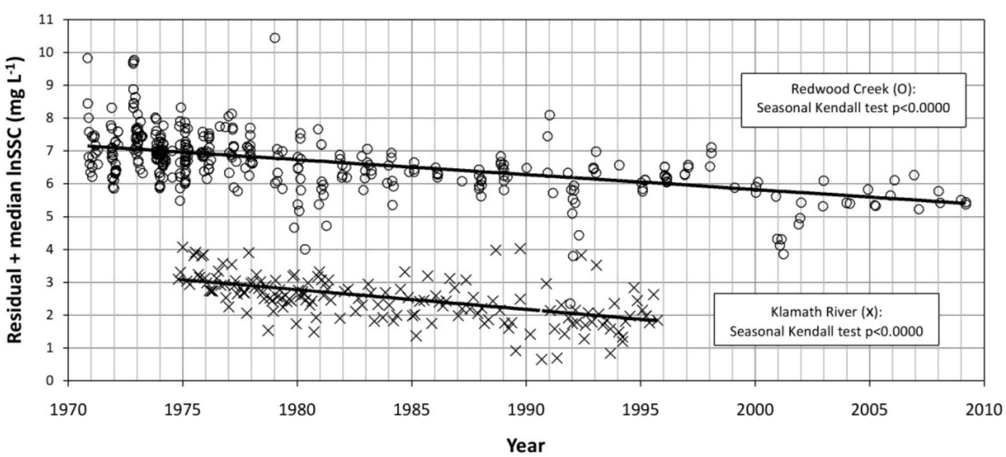

Figure 4—Suspended sediment concentration (SSC) residuals with flow effects removed and Seasonal Kendall test results.

Accompanying the reduction in loads, the proportion of bedload to suspended load has shifted in Redwood Creek and the Klamath River. Prior to 1976, the ratio of bedload to suspended load for Redwood Creek was 0.12, rising to over twice that (0.26) for the later period. The proportion of bedload to suspended load was much smaller for the Klamath River: the pre-1976 proportion was 0.012 and rose to 0.029 for the 1976 to 2009 period, although this should be viewed with caution considering that historical Klamath bedload loads were computed using model inputs collected only in 2010. This results in lower confidence in computed bedload loads with increasing time before present, although we believe this method to be superior to bedload computed as an assumed percentage of suspended or total load as others have done (e.g., Willis and Griggs 2003).

Discussion

Computing historic annual sediment loads necessitated the use of several methods and assumptions, however, use of a single sediment rating curve spanning decades, as done by other researchers (e.g., Farnsworth and Warrick 2007, Wheatcroft and Sommerfield 2005), cannot account for shifting relationships between water discharge and sediment transport that occur due to changing watershed conditions. Both the departures from normal analysis and the Seasonal Kendall trend tests indicated sediment loads are declining independent of lower peak flows. These declines highlight the importance of assessing temporal trends in sediment loads as opposed to average annual or period total loads. As watersheds become erosionally destabilized, sediment loads rise relative to flows, and as recovery to more stable conditions proceeds, loads decline relative to flows. Accordingly, sediment rating curves can be expected to shift upward or downward through time with the watershed disturbance regime.

Although no definitive causal link has been established, reduction in sediment loads since the mid-1970s probably can be attributed to natural watershed recovery processes, strengthened land use regulations, and watershed restoration programs. Watershed recovery processes such as vegetation re-growth and export of channel stored sediment as bedload have occurred throughout our study area even with ongoing timber harvest. Timber harvesting regulations that went into effect around 1980 in California, and have been continually refined since, reduced the allowable size of harvest units, elevated road construction standards, and extended riparian buffer requirements, all of which tend to reduce erosion and sediment delivery relative to earlier, more destructive practices.

In accordance Redwood National Park expansion legislation in 1978, a restoration program was initiated on Redwood Creek parklands focusing on the 700 km of logging roads that existed in 1978. To date, about 480 km (69 percent) of logging roads have been decommissioned (obliterated) such that their potential to deliver sediment has been greatly reduced. Road decommissioning has also occurred elsewhere in Redwood Creek on private timberlands, along with upgrading of logging roads to reduce their likelihood of sediment delivery. This type of work is also occurring in the lower Klamath River basin, but to a lesser degree than in Redwood Creek.

It remains to be seen how Redwood Creek and the Klamath River will respond to the inevitable recurrence of very large floods of magnitudes similar to those of 1950s through 1970s. However, our analyses suggest that the changing watershed conditions described above have provided the basins with a higher degree of resilience than that which led to the highly destructive erosion and sediment delivery events of the 1950s to 1970s.

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