Journal of Hydrology 489 (2013) 108–123

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Trends in the suspended-sediment yields of coastal rivers of northern California, 1955–2010

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ARTICLE INFO

Article history:
Received 7 September 2012
Received in revised form 11 February 2013
Accepted 24 February 2013
Available online 7 March 2013
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Peter W. Swarzenski, Associate Editor

Keywords:
Suspended-sediment discharge
River
Time series analysis
Northern California

SUMMARY

Time-dependencies of suspended-sediment discharge from six coastal watersheds of northern California – Smith River, Klamath River, Trinity River, Redwood Creek, Mad River, and Eel River – were evaluated using monitoring data from 1955 to 2010. Suspended-sediment concentrations revealed time-dependent hysteresis and multi-year trends. The multi-year trends had two primary patterns relative to river discharge: (i) increases in concentration resulting from both land clearing from logging and the flood of record during December 1964 (water year 1965), and (ii) continual decreases in concentration during the decades following this flood. Data from the Eel River revealed that changes in suspended-sediment concentrations occurred for all grain-size fractions, but were most pronounced for the sand fraction. Because of these changes, the use of bulk discharge-concentration relationships (i.e., "sediment rating curves") without time-dependencies in these relationships resulted in substantial errors in sediment load estimates, including 2.5-fold over-prediction of Eel River sediment loads since 1979. We conclude that sediment discharge and sediment discharge relationships (such as sediment rating curves) from these coastal rivers have varied substantially with time in response to land use and climate. Thus, the use of historical river sediment data and sediment rating curves without considerations for time-dependent trends may result in significant errors in sediment yield estimates from the globally-important steep, small watersheds.

1. Introduction

The small coastal watersheds of northern California (Fig. 1) drain an active tectonic margin and are recognized to discharge sediment at relatively high yields compared to global averages (Holeman, 1968; Milliman and Syvitski, 1992; Milliman and Farnsworth, 2011). Because of these high rates of sediment discharge, the Eel River has been the focus of large multi-investigator research programs to characterize the supply, dispersal and sedimentation of river suspended-sediment in the sea (Nittrouer, 1999; Wheatcroft, 2000; Wheatcroft and Sommerfield, 2005; Leithold et al., 2005; Nittrouer et al., 2007; Sommerfield and Wheatcroft, 2007). In this manner the northern California coastal rivers are used as representative watersheds of the numerous, active margin watersheds throughout the world that discharge a disproportionate amount of sediment to the ocean relative to their watershed area and – combined – are the largest supply of sediment to the ocean (Milliman and Farnsworth, 2011).

Sediment budget and yield investigations within catchments and tributaries of these northern California coastal watersheds have shown that the rates of sediment supply are related to the region's tectonics, lithology, climate, and history of land use (Kelsey, 1980; Nolan et al., 1995; Madej and Ozaki, 1996; Ziemer, 1998). Grazing and logging are primary land uses in the region, and widespread clearing and road building occurred in the region during the 1950s to 1970s as a result of mechanized logging (Best, 1995; Leithold et al., 2005). These land-use changes increased sediment supplies to these rivers by at least several fold over longer-term background rates and likely increased the rates of stormwater discharge (Kelsey, 1980; Ziemer et al., 1991; Best et al., 1995; Nolan and Janda, 1995). The combination of these land use changes and the intense rainfall of December 1964 resulted in record flooding, widespread river channel morphologic change, and the greatest sediment discharge rates recorded for these rivers (Anderson, 1970; Brown and Ritter, 1971; Waananen et al., 1971; Brown, 1973; Knott, 1974; Kelsey, 1980; Lisle, 1982; Madej and Ozaki, 1996, 2009).

Because there is considerable evidence that land use effects increased sediment supply from these northern California watersheds during the mid-20th century, there should be evidence of

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0022-1694/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.jhydrol.2013.02.041

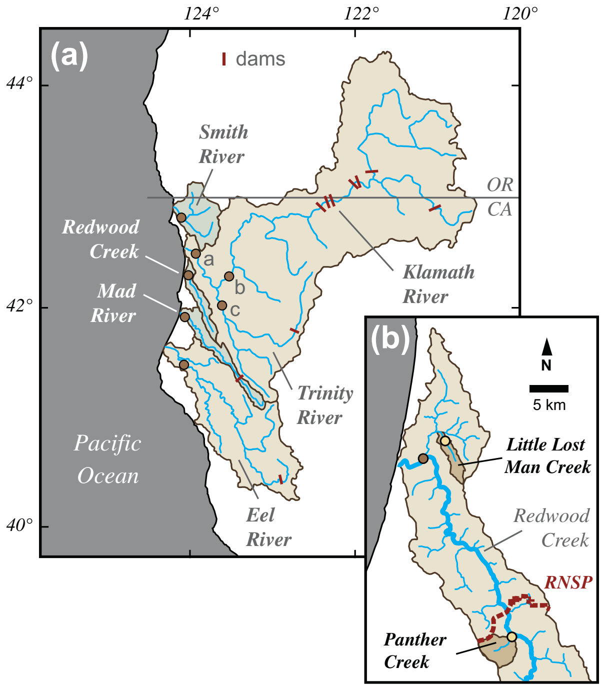


Fig. 1. Map of the northern California study area showing river watersheds and sampling stations (filled symbols). The six large coastal watersheds are shown in (a). Subwatersheds of Redwood Creek utilized in this study are shown in (b). The Redwood National and State Park (RNSP) boundary is shown with a dashed line.

these changes in the suspended-sediment discharge properties of these rivers. In fact, the work of Anderson (1970), Brown and Ritter (1971), Brown (1973), Knott (1974), Kelsey (1980), Sommerfield et al. (2002) and Morehead et al. (2003) have shown independently that suspended-sediment discharge properties changed after the December 1964 floods, and that increases in sediment yield ensued. Furthermore, marine sedimentary deposits offshore of the northern California coastal watersheds record increased sedimentation rates beginning in the 1950s that have been attributed to the effects of mechanized logging and the high flows of December 1964 (Sommerfield et al., 2002; Leithold et al., 2005; Sommerfield and Wheatcroft, 2007). These results are consistent with a growing consensus that humans have had substantial effects on sediment discharge properties of rivers throughout the world (Douglas, 1967; Meade, 1969; Dunne, 1979; Syvitski et al., 2005; Walling, 2006; Kettner et al., 2007).

Unfortunately, little work has focused on how sediment discharge of the northern California coastal rivers changed with time after the record floods of water year 1965 (WY1965). Most recent investigations of sediment discharge from these northern California watersheds have used bulk sediment rating curve techniques that utilize all available suspended-sediment data without consideration for time dependence in the rating-curve parameters (e.g., Milliman and Syvitski, 1992; Wheatcroft et al., 1997; Syvitski and Morehead, 1999; Willis and Griggs, 2003; Wheatcroft and Sommerfield, 2005; Farnsworth and Warrick, 2008; Andrews and Antweiler, 2012). In contrast to these studies, Morehead et al. (2003) used Eel River data from 1959 to 1979 to provide an example for how sediment rating curve parameters can exhibit time-dependent trends, and more recently Klein and Anderson (2012) have identified decreasing suspended-sediment concentrations in Redwood Creek and Klamath River between 1970 and 2009 that were related to reduced sediment supply and not changes in discharge regime.

The broad use of time-constant rating curves is consistent with sediment yield studies of other coastal watersheds in the California region (Brownlie and Taylor, 1981; Inman and Jenkins, 1999; Farnsworth and Warrick, 2008) and throughout the world (e.g., Asselman, 2000; Syvitski et al., 2000). Although rating curve techniques may be useful for estimating general sediment discharge patterns, these techniques may grossly over- or under-estimate sediment discharge for rivers with significant time-dependence in these relationships (Porterfield, 1972; Trimble, 1997; Morehead et al., 2003; Warrick and Rubin, 2007; Hu et al., 2011; Warrick

Table 1
USGS river gaging stations and suspended-sediment samples utilized in this study.

Station name (this study)	USGS station no.	USGS station name	Drainage area (km^2)	Portion of drainage area captured by dams (%)	Water years with suspended-sediment sampling	Number of suspended-sediment samples	Water years with suspended-sediment load estimates
Large rivers							
Smith River	11532500	Smith R. near Crescent City	1590	No dams	1955–1956, 1978–1993[a]	94	1979, 1981
Klamath River (mouth)	11530500	Klamath R. near Klamath	31,340	44.0%	1958, 1975–1995[a]	137	None
Klamath River (upstream)	11523000	Klamath R. at Orleans	21,950	54.7%	1957–1959, 1967–1979[b]	172	1968–1979
Trinity River	11530000	Trinity R. at Hoopa	7390	24.2%	1957–1979	244	1957–1979[f]
Redwood Creek	11482500	Redwood C. at Orick	717	No dams	1971–2010	382[e], 803[e]	1971–1987
Mad River	11481000	Mad R. near Arcata	1256	24.7%	1966–1974[c]	102	1958–1974[g]
Eel River	11477000	Eel R. at Scotia	8063	9.3%	1955–1998[a,d]	460	1960–1980
Small subwatersheds							
Little Lost Man Cr.	11482468[h]	Little Lost Man Cr. at Site No. 2	9.1	No dams	1976–1989[i], 1991–2010[j]	91[i], 948[j]	None
Panther Cr.	11482125[h]	Panther Cr. near Orick	15.4	No dams	1980–1990[i], 1991–2010[j]	62[i], 1282[j]	None

[a] No sampling was conducted during WY 1990.
[b] No sampling was conducted on the Klamath River (upstream) during WY1977.
[c] No sampling was conducted on the Mad River during WY1968 and WY1970.
[d] No sampling was conducted on the Eel River during WY1996–1997.
[e] Sampling conducted by both the USGS (382 samples) and NPS (803 samples), see text for details.
[f] WY1957–1959 and 1961 provided by Knott (1974).
[g] WY1958–1965 provided by Brown (1973) using additional samples not in the USGS NWIS database.
[h] These stations were retired by the USGS and operated by Redwood National and State Park (RNSP) since 1991.
[i] Manual samples by USGS.
[j] Pumped samples by RNSP.

et al., 2012). Time-dependence in discharge-sediment concentration relationships can be exhibited in flood event or seasonal hysteresis (e.g., Walling, 1977; Asselman, 1999) or in multi-year trends (e.g., Warrick and Rubin, 2007).

The goals of this paper are to: (i) evaluate whether relationships between discharge and suspended-sediment concentrations of the northern California coastal rivers (Fig. 1) have significant time-dependent trends over the available records, (ii) characterize whether trends were related to altered rates of sediment discharge, and (iii) investigate the potential causes of trends. Although the effects of the December 1964 floods on suspended-sediment discharge have been documented, much of this work has focused on tributaries or small catchments within these watersheds (e.g., Anderson, 1970; Brown, 1973; Knott, 1974; Kelsey, 1980; Nolan and Janda, 1995) or was focused on sediment discharge from the Eel River (Sommerfield et al., 2002; Morehead et al., 2003). It is not known whether these elevated rates of suspended-sediment discharge have continued to the present day, even though geomorphic investigations have shown that channel changes induced during the 1964–1965 winter have had long-lasting effects (Madej and Ozaki, 1996; Madej and Ozaki, 2009) and that land-use effects on sediment supply have lasted several years to decades (Grant and Wolff, 1991; Ziemer et al., 1991). Six watersheds were considered in this work, representing a cumulative drainage area of approximately 43,000 km^2 (Table 1; Fig. 1). Analyses focused on suspended-sediment concentration samples collected by the U.S. Geological Survey (USGS) and Redwood National and State Parks (RNSP) at river gaging stations at or near the river mouths of these watersheds.

2. Study area

The coastal watersheds of northern California drain steep landscapes of the Northern Coast Range and Klamath Mountains with several peaks higher than 2000 m. Watershed sizes of this rugged landscape are generally less than 10,000 km^2, and there are numerous small coastal creeks with watershed sizes less than 1000 km^2 (Fig. 1). The largest watershed is the Klamath River, which drains an extensive inland region of the Cascade Range.

The region's climate is dominated by dry summers and wet winters, and the coastal valleys experience cool, foggy conditions during much of the year. The majority of precipitation occurs as rainfall during passage of winter frontal systems from the northern Pacific Ocean, so called 'atmospheric rivers' (e.g., Ralph et al., 2006). Annual average precipitation ranges from over 300 cm in the steep mountains adjacent to the coast to less than 25 cm in the inland portions of the upper Klamath River basin (Rantz, 1969). This gradient in precipitation is caused by orographic enhancement near the coast and rainshadows east of the coastal mountains. The upper Klamath River basin experiences the hottest, driest conditions of the study area.

Winter rainfall results in punctuated river discharge, and floods commonly rise and last for several days at most. Variability in annual precipitation and storm intensities results in over an order-of-magnitude range in annual peak discharges for each of the rivers studied (e.g., Fig. 2). The highest measured peak discharges for all rivers occurred during the storms of December 1964 and are chronicled and reviewed by Waananen et al. (1971) and Waananen and Crippen (1977). Although these floods of WY1965 were the greatest recorded, a few study-area rivers (e.g., Klamath, Redwood, Mad) have had similar-magnitude peak discharges before and after these floods (Fig. 2). Earlier floods, such as 1955, may have induced similar erosional and geomorphic responses throughout this landscape, but unfortunately they occurred before USGS river sampling.

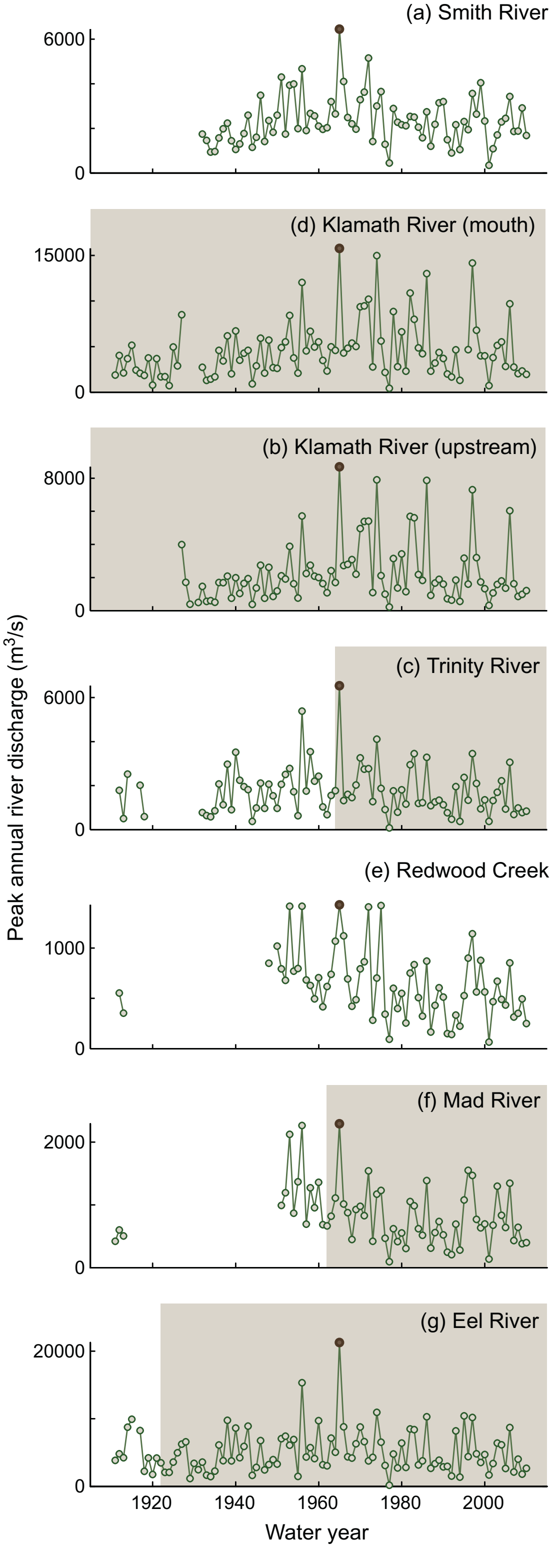


Fig. 2. Peak annual river discharge for the USGS gaging stations of the study area. The maximum measured discharge of all stations occurred in water year 1965 and is highlighted with a filled symbol. The intervals of time with large dams on these rivers are highlighted with shading.

The land cover of the region is largely undeveloped and consists of mixed coniferous forests, oak woodlands, chaparral, non-native grasslands, and scrub (Davis et al., 1998). The primary land uses include logging of the forests and grazing within the grasslands.

Mechanized logging, which involves extensive road building and clear cutting, accelerated post WWII reaching peak logging rates in the 1950s and 1960s (Best, 1995; Leithold et al., 2005). Livestock grazing was introduced and expanded in the middle 19th century and has been relatively steady with time (Pulling, 1944; Jelinek, 1979).

Sediment production with these northern California watersheds is primarily attributed to erosion of hillslopes, with lesser contributions from channel banks (Brown and Ritter, 1971; Kelsey, 1980; Madej and Ozaki, 1996). Mass movements, such as slumps and landslides, in the hillslopes provide the primary contributions to the sediment yield of these watersheds, and the occurrence of these mass movements increases with heavy precipitation and land changes related to logging (Brown and Ritter, 1971; Kelsey, 1980).

There are several large dams within the study area (Fig. 1) that have captured river sediment and reduced downstream rates of sediment discharge (Willis and Griggs, 2003; Minear and Kondolf, 2009). The largest river – the Klamath – has the most extensive and largest damming project, which was built between 1902 and 1962 and captures roughly half of the watershed area sampled by the two USGS gages utilized in this study (Fig. 1; Table 1). Roughly a quarter of the watershed areas of the Trinity and Mad Rivers and less than ten percent of the Eel River watershed are captured by dams (Fig. 1; Table 1). Smith River and Redwood Creek do not have large dams.

While there has been limited channelization throughout these rivers, there were widespread channel changes induced by the floods of December 1964 that resulted in net aggradation of gravel in most channels (e.g., Lisle, 1982), and persistence of this sediment on channel morphology for decades (e.g., Madej and Ozaki, 2009).

3. Data

3.1. Coastal watersheds

The primary focus of this study is an evaluation of suspended-sediment concentrations, grain-size distributions, and discharge at the river mouths of the study area. Suspended-sediment samples have been collected by the USGS at a number of stations in the area, and here we utilize the downstream most USGS stations of each river considered (Table 1). We included three stations within the Klamath River: one near the river mouth and one at the mouths of each major tributary, because these tributaries were as large or larger than the other study area watersheds, and because these tributary data extended the duration of Klamath River observations (Fig. 3).

Suspended-sediment concentrations were obtained from the USGS National Water Information System (NWIS; http://waterdata.usgs.gov/nwis), which is the primary source of USGS water-resources data. For these analyses, we utilized measured suspended-sediment samples for each station (USGS Parameter Code 80154 from the Water Quality Field/Lab Samples) with coincidental river discharge measurements. We did not utilize the daily suspended-sediment concentrations when they were available (USGS Parameter Code 80154 from the Time Series: Daily Data), largely because these data have been interpolated from the measured samples (Porterfield, 1972). Suspended-sediment samples were all obtained by standard, isokinetic, depth- and flow-integrated techniques of the USGS, which have not changed during the data collection interval presented herein (Edwards and Glysson, 1999). Grain-size information from the suspended-sediment concentration samples was obtained if available and summarized into the following classes: percent sand (greater than 0.063 mm) and percent mud (less than 0.063 mm) as measured by wet-sieving. Summaries of the suspended-sediment samples available for each USGS station are included in Table 1, and histograms of annual sampling rates are shown in Fig. 3. The majority of sampling in the study area occurred during the 1970s with limited sample collection during the most recent two decades.

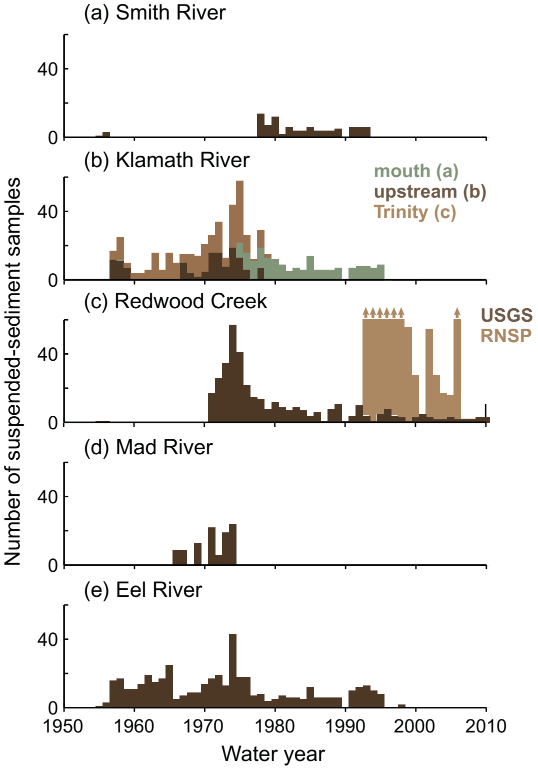


Fig. 3. Annual frequency of river suspended-sediment sampling by the USGS and RNSP at the study sites. Arrows indicate years with over 50 samples.

To supplement the USGS data we incorporated additional samples of Redwood Creek by Redwood National and State Parks (RNSP). Beginning in 1992, RNSP sampled the Redwood Creek at Orick (station 11482500) during high flows using a fixed D-49 depth-integrated sampler mounted above the centroid of flow (Fig. 3; Table 1). Several RNSP samples were collected coincidentally with USGS flow-integrated samples, and mean difference and r.m.s.e. between the measured discharges and concentrations were low (e.g., 4 samples were collected within an hour of each other, and the mean difference in these suspended-sediment concentrations was less than 1% with an r.m.s.e of 10%). Thus, the RNSP samples were combined with the USGS samples for the analyses of Redwood Creek below.

Annual mean discharge, peak discharge, and suspended-sediment discharge measurements available from USGS NWIS were also used in analyses. It was found that there were USGS sediment discharge data for the Mad and Trinity Rivers in addition to those provided from USGS NWIS in tables of Brown (1973) and Knott (1974), respectively (Table 1). USGS measurements of water and suspended-sediment sediment discharge were made using a combination of streamgage samples as described in Porterfield (1972). Finally, estimates of suspended-sediment discharge were made for years without USGS data using the techniques described in the Analysis Section below.

3.2. Small tributaries

Suspended-sediment concentrations collected by the USGS and RNSP in two tributaries of Redwood Creek were also used to evaluate time-dependent changes in source regions with different land uses. Little Lost Man Creek is a 9.1 km^2 catchment with pristine old growth redwood forest that was never logged. Panther Creek is 15.4 km^2 catchment that has been logged consistently since the 1930s (Fig. 1). Suspended-sediment samples were collected by both manual and pumped techniques for both of these watersheds (Table 1). Here we evaluate the pumped samples, because they are more numerous than the manual samples, and because no coincidental samples exist to compare these techniques and evaluate potential bias from these different techniques.

4. Analyses

Suspended-sediment concentrations were strongly related to discharge, largely because both river discharge (primarily from overland flow) and suspended-sediment supply (primarily from mass movements in the landscape) occurs during and following precipitation (e.g., see Fig. 4). For variables with strong discharge dependence, Helsel and Hirsh (1991) recommend the analyses of the residuals (i.e., the differences) between measured concentrations and those expected from fit relationships through the discharge-concentration data to evaluate changes with time. These techniques can reveal when river sediment concentrations are greater or lesser than the average conditions described by the fitted relationship.

Here we use this approach with the recommended fitting process of locally-weighted scatter smoothing, or “LOWESS” (Cleveland, 1979; Helsel and Hirsh, 1991). The LOWESS fitting techniques are also recommended for situations in which curvature exists between the discharge and concentration data (Hicks et al., 2000) such as described for the Eel River by Williams (1989) and shown for all study area rivers in Fig. 4. The LOWESS fitting technique utilized log$_{10}$(discharge) and log$_{10}$(concentration) data and included two steps: (i) an initial linear least-squares regression over fractions (f) of the data ranked by discharge, and (ii) a final weighted least squares regression. As recommended by Cleveland (1979), we used a weighting equal to the product of polynomial functions of the vertical distance between each concentration and the initial linear regression and the horizontal distance of each sample from the LOWESS estimate. We also utilized the recommendations of Helsel and Hirsh (1991) of adjusting f so that monotonic relationships are derived that include data curvature patterns. Values of f used here were inversely related to sample size (Table 2), although the statistical results reported below were not sensitive to the range of f values used (0.1–0.2). The LOWESS curves are shown in Fig. 4.

Suspended-sediment concentration residuals were computed between measured sample concentrations and expected concentrations from the LOWESS functions using logarithmic transformations of each variable. Residuals were summarized by both events and water year, the latter of which were summarized into annual percentiles and tested for time-dependence using nonparametric Mann–Kendall tests. Such tests are only useful for evaluating monotonic trends in data, so these analyses were applied to both complete sets of residuals and subsets of these residuals with apparent monotonic trends.

Time-dependence in the annual USGS suspended-sediment discharge data were evaluated with comparisons with annual river discharge, and Mann–Kendall tests were used for the mean annual suspended-sediment concentration, which was computed from the ratio of sediment discharge and river discharge.

The USGS computed suspended-sediment loads only through the mid-1970s to mid-1980s, even though suspended-sediment

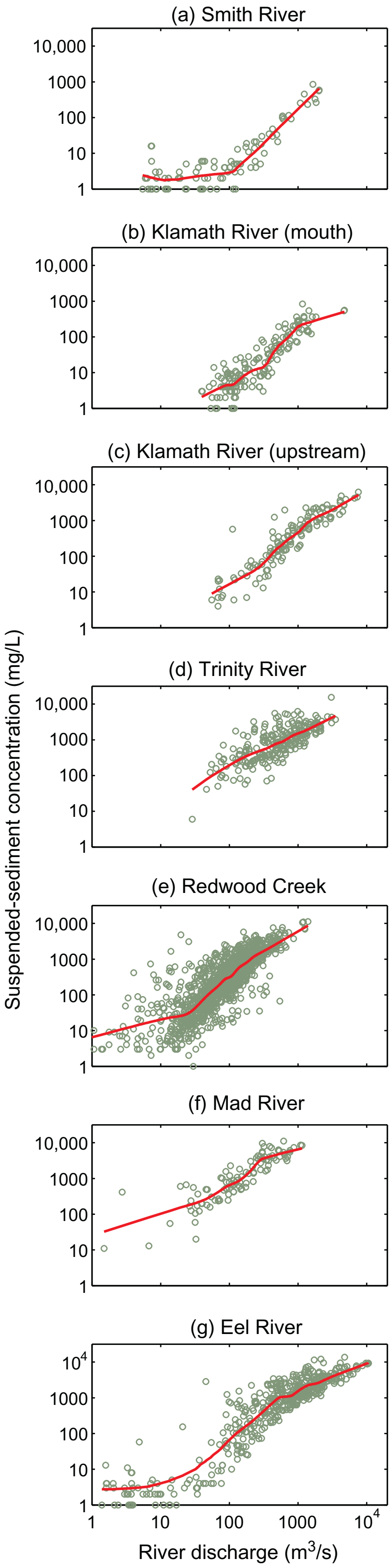


Fig. 4. The relation between river discharge and suspended-sediment concentrations for the study rivers. The LOWESS-fit curve through each data set is shown with a red line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Analyses statistics for the river stations utilized in this study.

Station name	LOWESS smoothing factor	R.M.S.E. about LOWESS ($\log_{10}$ units)	Kendall tau rank correlation – all LOWESS residuals	Kendall tau rank correlation –only post-1964 LOWESS residuals	Trend in post-1964 LOWESS residuals ($\log_{10}$ units/yr)
Large rivers					
Smith River	0.20	0.294	−0.252[**]	−0.231[*]	−0.0149[*]
Klamath River (mouth)	0.15	0.286	−0.438[**]	−0.435[**]	−0.0255[**]
Klamath River (upstream)	0.15	0.281	−0.187[*]	−0.298[**]	−0.0360[**]
Trinity River	0.15	0.318	−0.0373[N.S.]	−0.355[**]	−0.0386[**]
Redwood Creek	0.10	0.389	−0.373[**]	−0.375[**]	−0.0240[**]
Mad River	0.20	0.281	−0.198[*]	−0.198[*]	−0.0214[*]
Eel River	0.10	0.365	−0.272[**]	−0.382[**]	−0.0232[**]
Small subwatersheds					
Little Lost Man Cr.	0.15	0.405	+0.098[**]	+0.098[**]	+0.006 [N.S.]
Panther Cr.	0.15	0.423	−0.153[**]	−0.153[**]	−0.019[**]

[N.S] Not statistically significant at $p > 0.05$.
[*] Statistically significant at $p < 0.05$.
[**] Statistically significant at $p < 0.001$.

concentrations for some of these rivers (Redwood and Eel) were sampled for much longer intervals of time (Table 1). We extended the USGS suspended-sediment load estimates for the Eel River, which had the longest suspended-sediment sampling records, through the suspended-sediment record interval by using daily mean water discharge records and LOWESS-based daily suspended-sediment concentration estimates. Two types of calculations were made and compared. First, daily suspended-sediment concentrations were estimated from the LOWESS-fit relationship using all sampling data. This technique assumed that the discharge-concentration relationship did not change with time, and thus we termed this technique “time-constant.” Second, time-dependence of the suspended-sediment concentration relationship was included by applying the median residuals between the logarithmic-transformed concentrations and the LOWESS relationship for each water year. This technique was termed “time-dependent.”

For both techniques, daily suspended-sediment discharge (Qs) was calculated by the same general techniques of Wheatcroft and Borgeld (2000) following Cohn (1995), namely:

$$Qs(t) = Q(t) * Cs(t) * r(y) * e \tag{1}$$

where Q is daily mean water discharge, Cs is daily mean suspended-sediment concentration, r is the concentration correction for the “time-dependent” estimates based on the median residuals for each water year (y; r is unity for the “time-constant” technique), e is the bias correction associated with logarithmic transformation equivalent to half of the squared error of the residuals about the LOWESS functions, and t is time in days. For the Eel River, e was calculated to be 1.069.

5. Results

5.1. Coastal watersheds – overview

River suspended-sediment concentrations ranged from 1 to over 10,000 mg/L (Fig. 4). The highest measured concentrations were observed in the four most southern rivers (Trinity, Redwood, Mad and Eel), while the concentrations in the Smith and Klamath (both the mouth and upstream stations) were measurably lower. All rivers exhibited positive relationships between suspended-sediment concentrations and river discharge as shown by the fitted LOWESS relationships (Fig. 4). The root mean squared errors (r.m.s.e.) about the LOWESS relationships ranged between 0.28 and 0.39 $\log_{10}$ units, and the highest variability about these relationships occurred for Redwood Creek and the Eel River, which had the largest and longest sample records (Table 2; Fig. 4e and g).

5.2. Coastal watersheds – hysteresis

Examination of the suspended-sediment concentrations during high flow events that had multiple samples revealed hysteresis patterns in the discharge-concentration relationships (e.g., Fig. 5). However, consistent hysteresis patterns were not observed in any of the rivers. For example, while sediment concentrations revealed both clockwise and counterclockwise hysteresis patterns during high flow events (Fig. 5a and b), the most common condition was that of no hysteresis (Table 3). Furthermore, while clockwise hysteresis was observed more frequently than counterclockwise hysteresis (Table 3), the highest flow rates with multiple samples had either counterclockwise or no hysteresis (e.g., Fig. 5b; Table 3). Thus, no simple, consistent hysteresis patterns were observed in any of the rivers.

There were also subtle changes in discharge-sediment concentration relationships over the winter flood season, and the largest differences existed between early and late flood season samples (Fig. 5c). Early in the flood season (October–November), river discharges were generally low while suspended-sediment concentrations were comparable with later season concentrations (March–April; Fig. 5c). The differences in discharge-concentration relationships between the early and late flood season were greatest for low discharge rates but negligible for the highest discharge rates (Fig. 5c). Thus, although there were measurable hysteresis patterns over the flood season, they were most pronounced during the lowest flow rates when sediment concentrations were low and of little consequence for the annual sediment loads. Further, because the distribution of river sampling throughout the flood season remained constant throughout the years, seasonal hysteresis had a negligible effect on multi-year trends reported below.

5.3. Coastal watersheds – multi-year trends

The residuals between suspended-sediment concentrations and the LOWESS relationships revealed several significant multi-year trends (Fig. 6). Overall, most stations had significant decreasing trends in the residuals over the sample record as shown by negative Kendall tau values (Table 2). The only river station without a

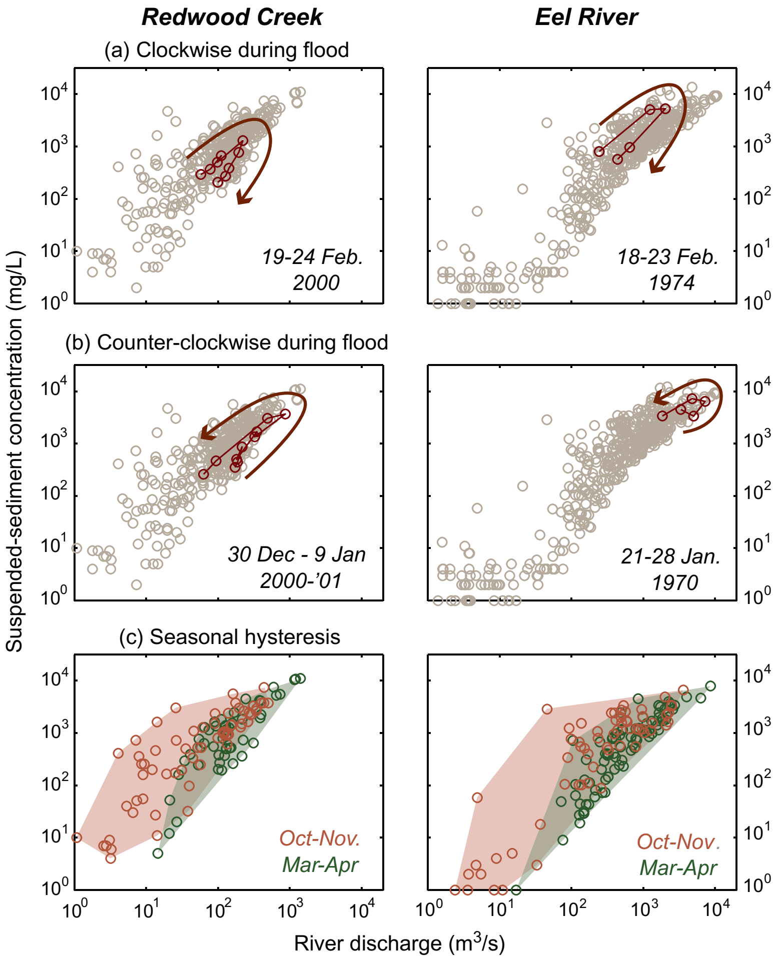


Fig. 5. Examples of hysteresis in the discharge-sediment concentration relationships for two northern California rivers, Redwood Creek (lefthand column) and Eel River (righthand column). (a) Clockwise hysteresis during floods; (b) counter-clockwise hysteresis during floods; and (c) a comparison of early (October–November) and late (March–April) flood season samples showning seasonal differences. The complete sampling data for each river is shown with light tan symbols in (a) and (b). Shading in (c) bounds the distributions of each sample group.

Table 3
Hysteresis characteristics for the two rivers with the greatest number of sampled high flows.

Station Name[a]	Number of high flows adequately sampled[b]	Clockwise hysteresis[c] (%)	Counterclockwise hysteresis[c] (%)	No hysteresis[c] (%)
Redwood Creek	68	44	6[**]	50
Eel River	28	36	7[**]	57
Trinity River	24	46	0	54[**]
Klamath River (upstream)	10	60	10[**]	30
Mad River	8	38	0	62[**]
Smith River	1	0	100[**]	0
Klamath River (mouth)	None	–	–	–

[a] Stations listed in the ranked order by number of high flow observations.
[b] "Adequately sampled" defined to be three or more samples collected over both rising and fall limbs of a single high flow event.
[c] Hysteresis defined to be a twofold or greater difference in suspended-sediment concentrations between rising and falling limbs of the high flow event.
[**] Highest measured discharge in hysteresis data set.

significant temporal trend at $p < 0.05$ was the Trinity River (Table 2), although data from this station had other temporal trends as noted below.

The Kendall statistics reported above test only for monotonic trends, and many of the time series of suspended-sediment concentration residuals suggested that changes were not monotonic (Fig. 6). For example, both the Trinity and Eel Rivers had samples collected before, during and after the record floods of December 1964, and these residuals suggested that suspended-sediment concentrations were substantially higher during and after this year of record flooding (Fig. 6d and g). The mean suspended-sediment concentration residuals during and prior to WY1964 and those during WY1965 differed by a factor of 0.51 $\log_{10}$ units for the Trinity River and 0.36 $\log_{10}$ units for the Eel River, and these differences were equivalent to increases in suspended-sediment concentrations of 3.2 and 2.3-fold, respectively. The differences in these two groups of residuals (pre-1965 and 1965) were significant when compared by two variable *t*-tests ($p = 0.0008$ and $p = 0.00006$, respectively).

Following the increases in suspended-sediment concentrations during WY1965, all stations revealed significant decreases with time. This was shown by the significant, negative Kendall tau

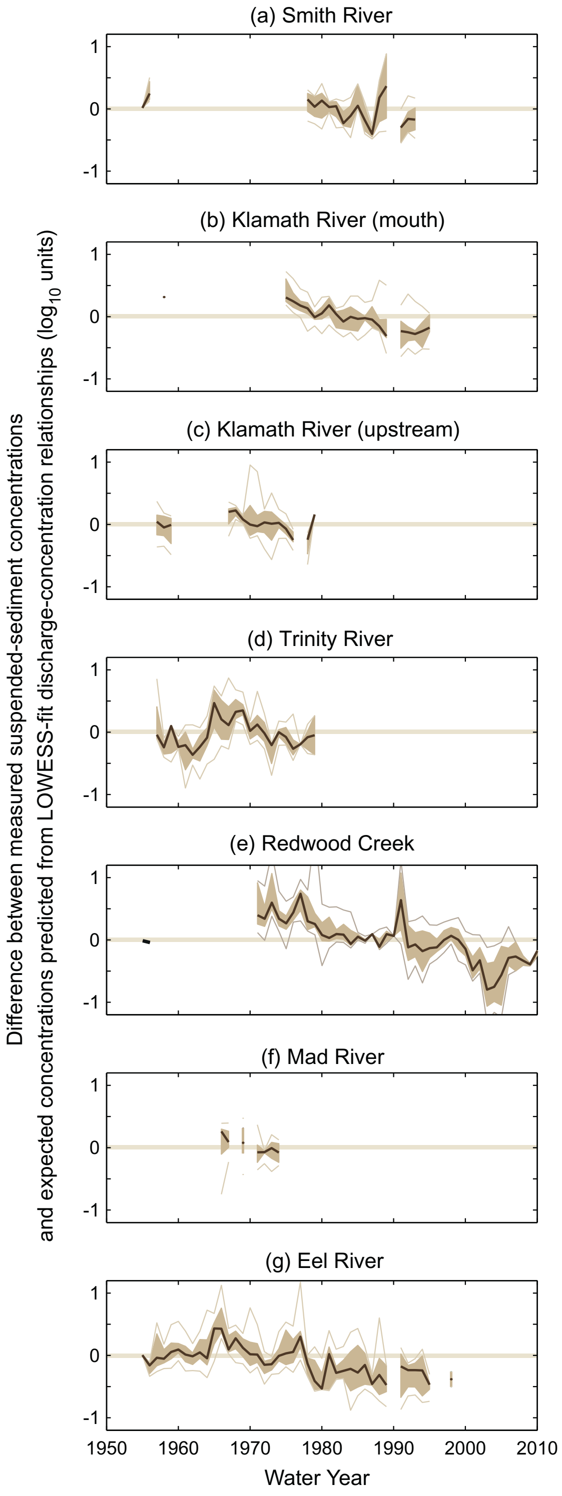


Fig. 6. Suspended-sediment concentration residuals about the LOWESS-fit curves shown in Fig. 4. Residuals are summarized by percentiles for all samples in each water year. The median and interquartile range are shown with the thick line and shading, respectively. Thin lines are the 10th and 90th percentiles.

values for tests on data collected after WY1964 (Table 2). For example, the suspended-sediment concentration residuals of the Eel River decreased by almost an order or magnitude (one $\log_{10}$ unit) between 1965 and the end of its sampling record in 1998 (Fig. 6g). Linear trends were calculated for each river from the post-1964 residuals, and these values ranged between −0.015 and −0.039 $\log_{10}$ units/yr with a mean of −0.030 $\log_{10}$ units/yr (Table 2). These rates of decrease are equivalent to exponential decay functions in which suspended-sediment concentrations are reduced by half every 8–20 yrs, with a mean of 10 yr.

The statistical analyses described above suggest that substantial changes occurred with time for the suspended-sediment concentrations of each river. These patterns can also be shown graphically with plots of the discharge and suspended-sediment concentrations. For example, the measured suspended-sediment concentrations in the Trinity River were generally lower than the LOWESS relationship before the December 1964 floods (Fig. 7a). During and for several years after WY1965, the Trinity River concentrations were higher than the LOWESS relationship (Fig. 7b), whereas in the final decade of sampling (WY1970–1980), suspended-sediment concentrations were much closer to the LOWESS relationship (Fig. 7c). Similar plots for the Redwood Creek and the Eel River – the two rivers with the longest and largest sampling records – are shown in the Supplemental information section available online.

5.4. Suspended-sediment grain size – Eel River

The Eel River had numerous grain-size analyses of the suspended-sediment samples, and these samples were used to inves-

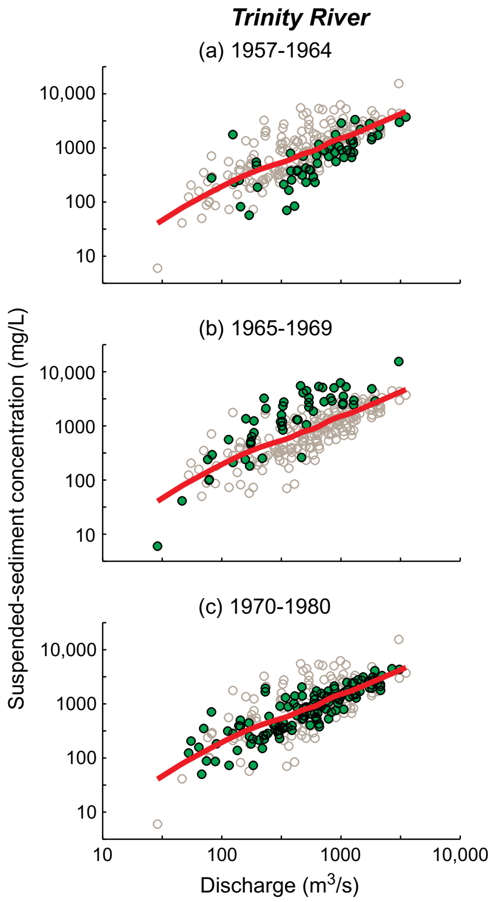


Fig. 7. Time dependence in the discharge – suspended-sediment concentration relationships for the Trinity River at Hoopa (USGS 11530000). The complete set of samples (unfilled symbols) and lowess fit through these samples (red line) are shown in each figure. Samples collected during 1957–1965, 1965–1969 and 1970–1980 are shown in (a) through (c), respectively, with filled symbols. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

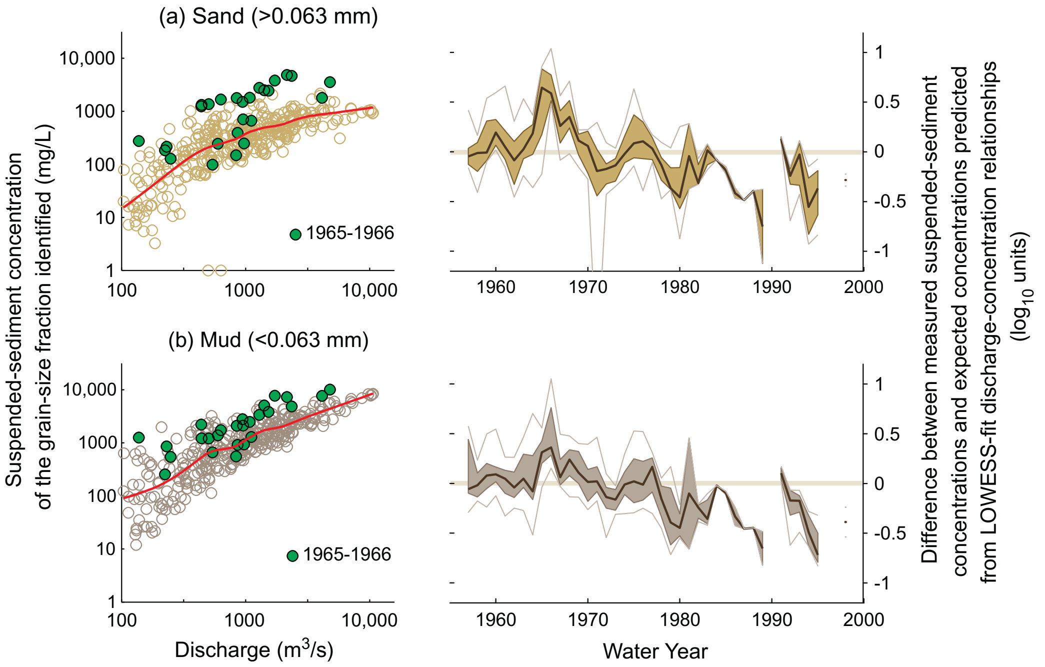


Fig. 8. Grain-size dependence in the discharge - suspended-sediment concentration relationships for the Eel River at Scotia (USGS 11477000) for samples collected at discharges greater than or equal to 100 m^3/s. The complete set of sand and mud (unfilled symbols), LOWESS-fit curves through these samples (red line), and samples collected during 1965–1966 (filled symbols) are shown in the righthand panels. Time-dependent suspended-sediment concentration residuals about the LOWESS-fit curves are presented by water year the lefthand panels as median (thick line), interquartile range (shading), and 10th and 90th percentiles (thin lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tigate grain-size patterns in the concentration data. The concentrations of each major grain size fraction were positively related to discharge (Fig. 8). LOWESS relationships were fit through each grain-size fractions (red lines, Fig. 8), and consistent with results reported above the majority of concentrations from WY1965–1966 were higher than these fitted functions. The greatest divergence between the 1965–1966 concentrations and the LOWESS functions were found for the sand fraction of suspended sediment (mean difference = 0.60 $\log_{10}$ units; Fig. 8).

The time dependencies of the grain-size fractions of the suspended sediment were evaluated from the residuals between measured concentrations and the LOWESS functions shown in Fig. 8. The sand-fraction residuals had greater variations with time than the mud fraction even though these increases were sustained for roughly 4 years for both fractions (Fig. 8). The residuals for both grain-size fractions decreased significantly with time following WY1965 (Kendall tests, $p < 0.05$). Thus, while changes occurred in time for all grain-size fractions, the largest and most sustained changes in the Eel River occurred for the sand fraction.

5.5. Suspended-sediment discharge – USGS measurements

Suspended-sediment discharge measurements by the USGS revealed significant time-dependent trends (Fig. 9). For the three rivers with WY1965 measurements, sediment discharge during that year was several times greater than all remaining years. The sediment discharge from the other two rivers (Klamath and Redwood) varied considerably but decreased with time (Fig. 9).

To evaluate time-dependencies in the suspended-sediment discharge measurements, annual measurements of water and sediment discharge were compared (Fig. 10). These comparisons revealed that suspended-sediment discharge was generally greater during years with high precipitation and elevated river discharge. However, unusually high rates of sediment discharge occurred during and after WY1965. For example, for the three rivers with sediment discharge measurements before WY1965 (Trinity, Mad, Eel), power-law relationships were derived between annual water discharge and annual sediment discharge (solid lines in Fig. 10b,d, and e). During WY1965, suspended-sediment discharge from these three rivers were 16, 6, and 5-times greater than the expected sediment discharge estimated using the pre-1965 regressions. After WY1965, suspended-sediment discharge generally showed decreases with time (lighter symbols; Fig. 10). For example, Redwood Creek sediment discharge during wet years (mean river discharge greater than ~30 m^3/s) was generally several times less in the 1980s than it was in the late 1970s (Fig. 10c).

These time-dependent changes are examined further in the lefthand column of Fig. 11, where the ratio between measured suspended-sediment discharge and the expected sediment discharge using the pre-1965 relationships from Fig. 10 are shown. These data show all rivers exhibited rates of sediment discharge that that increased during WY1965 and decreased with time after WY1965. The increases in Trinity River were greater and longer lasting than those for the Mad and Eel Rivers (Fig. 11).

These ratios can be compared to the variations in mean annual suspended-sediment concentrations, computed from the ratio of the annual discharge of sediment and water (Fig. 11, right column). Two patterns were observed in these mean concentration data. First, several-fold to order-of-magnitude increases occurred during WY1965. Second, all stations had decreasing concentrations with time after WY1965 as revealed by downward trends in these data (Fig. 11), which were all found to be significant, negative trends from Kendall tests (all $p < 0.05$).

5.6. Suspended-sediment discharge – LOWESS-based estimates

LOWESS-based suspended-sediment discharge calculations allowed for an extension of the USGS results presented above. Here we present results from the Eel River, which has the longest and most consistent sampling records of those studied (Fig. 3). A

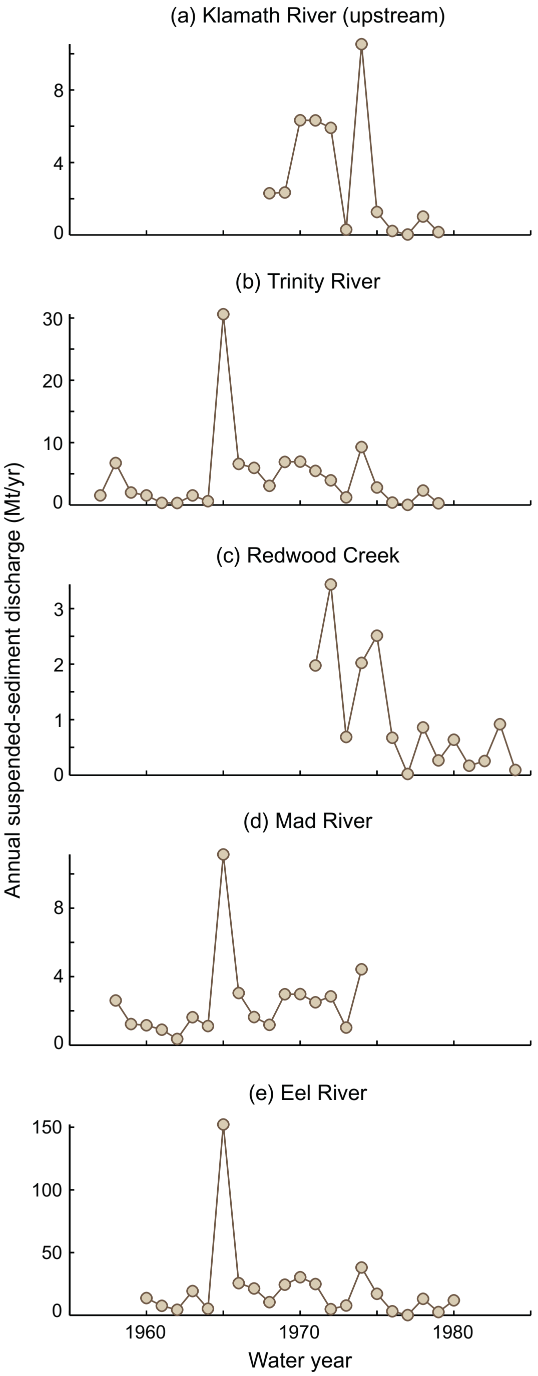


Fig. 9. Annual suspended-sediment discharge measured by the USGS for the study area rivers.

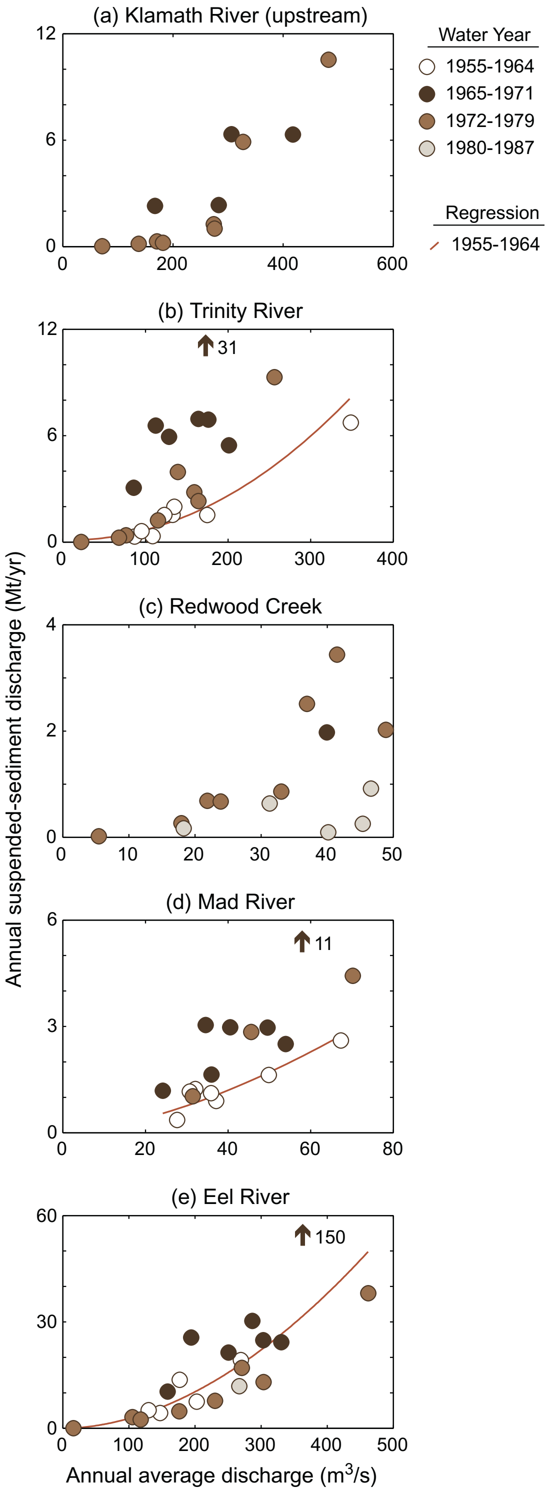


Fig. 10. Comparison of annual average river discharge and annual suspended-sediment discharge from the study area. Symbols are colored according to water year. Arrows represent exceptional sediment discharge events beyond the limits of the axes all occurring during water year 1965. Powerlaw regressions through the 1955–1964 are shown for the three rivers with these data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

comparison of the suspended-sediment discharge estimates using the two LOWESS-based techniques – "time-constant" and "time-dependent" – are shown in Fig. 12. Both techniques produced sediment discharge estimates that varied considerably year to year, consistent with the USGS measurements (cf. Fig. 9). However, the load estimates from the two LOWESS-based techniques differed substantially with time (Fig. 12). For example, these load estimates differed by almost 3-fold in WY1965 and WY1966 (Fig. 12b). During the 1980s and 1990s the ratio between "time-constant" and "time-dependent" load estimates averaged 0.42, which suggests that the time-constant estimates of sediment loads were 2.5 greater than the time-dependent estimates.

Because the "time-constant" and "time-dependent" LOWESS-based sediment discharge estimates differed substantially, we compared these with USGS sediment discharge measurements to evaluate which LOWESS technique provided better estimates.

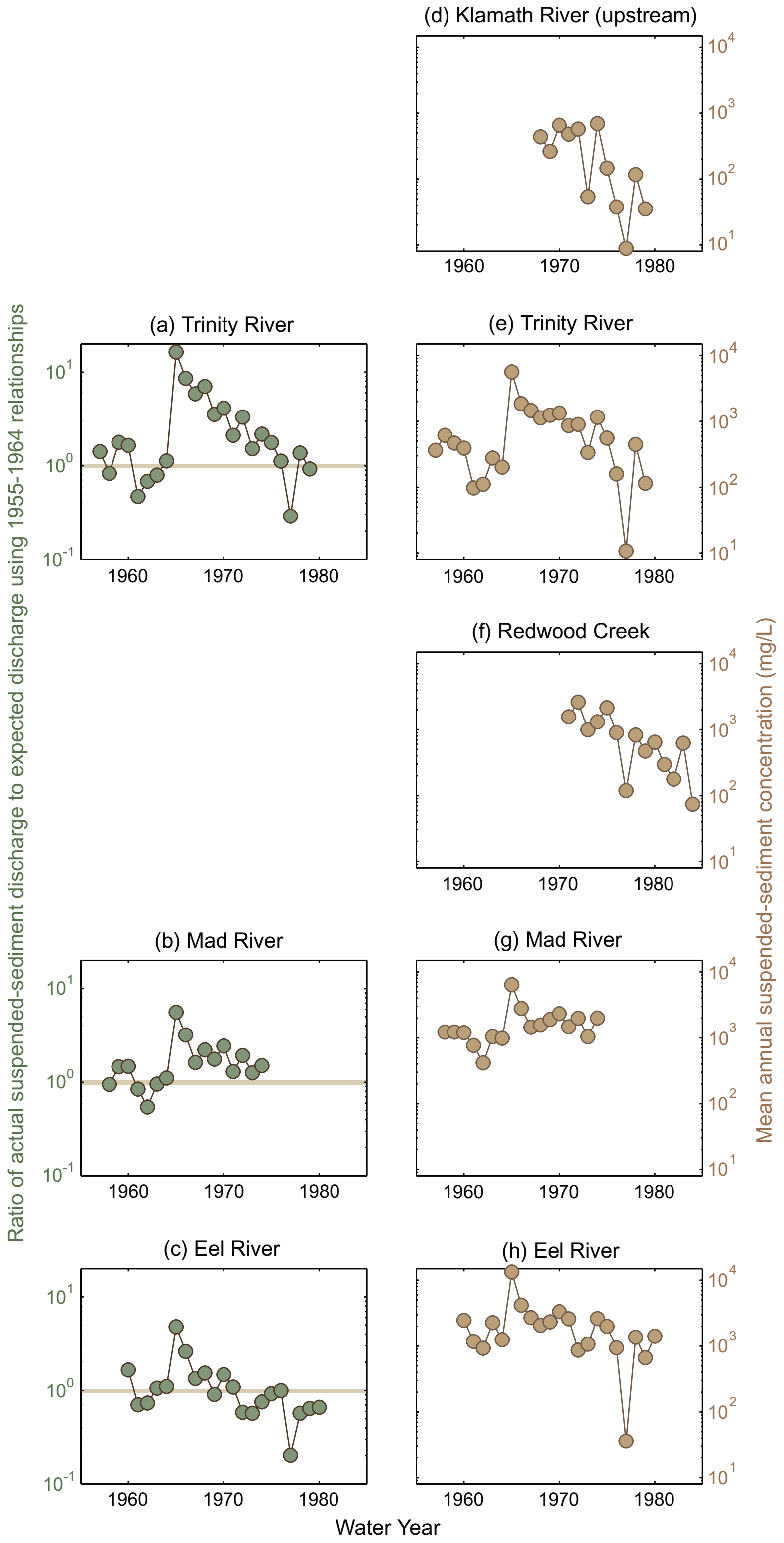


Fig. 11. Annual changes in suspended-sediment discharge relative to 1955–1964 (right column) and mean suspended-sediment concentrations (left column) for the study area rivers. The relative increases in sediment discharge computed from the ratio of actual sediment discharge to the expected sediment discharge from the 1955–1964 regressions shown in Fig. 12. Mean suspended-sediment concentrations computed from the ratio of annual average river discharge and annual suspended-sediment discharge.

The USGS measured 152 Mt of sediment discharge during WY1965 and 153 Mt during the combined eleven years from 1970 to 1980 (Table 4). The time-dependent LOWESS technique provided excellent estimates of the USGS measurements as shown by differences of less than 10% (Table 4). The suspended-sediment loads estimated by the time-constant LOWESS technique, in contrast, had

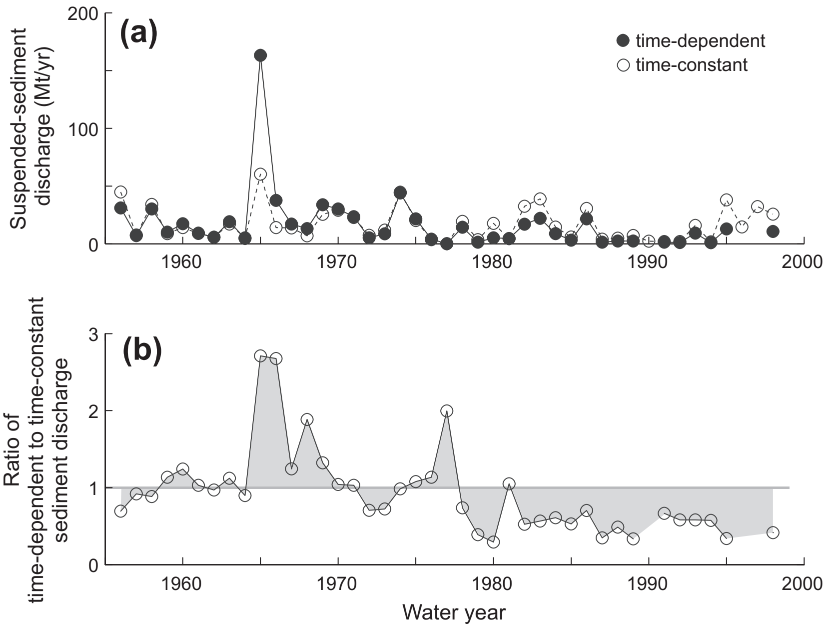
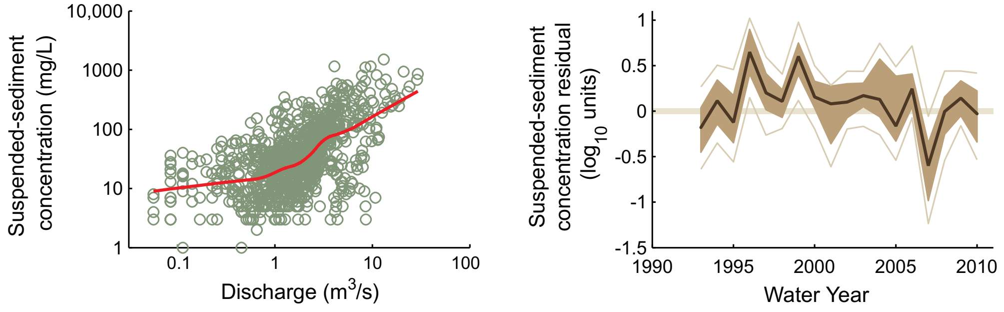


Fig. 12. Comparison of the two LOWESS-based estimates of annual suspended-sediment discharge from the Eel River. (a) Annual estimates using time-dependent and time-constant suspended-sediment concentration relationships. (b) The ratio between these two sediment load estimates. Shading in (b) represents the deviation between the two sediment discharge estimates. Time-dependent sediment loads were not calculated for water years without USGS suspended-sediment sampling.

Table 4
Comparison of suspended-sediment discharge (Qss) calculations for the Eel River and Scotia from the USGS and the time-constant and time-dependent LOWESS techniques used here.

Water year	USGS Qss (Mt)	Time-constant LOWESS Qss (Mt)	Error[a] (%)	Time-dependent LOWESS Qss (Mt)	Error[a] (%)
1965	152	60	*−61*	163	*+7*
1970–1980	153	180	*+18*	158	*+3*

[a] Error computed as (LOWESS Qss − USGS Qss) ÷ USGS Qss.


(a) Little Lost Man Creek *(not logged)*

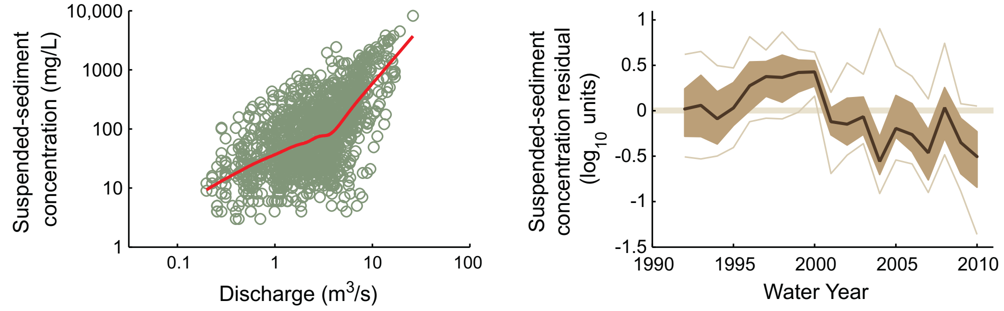

(b) Panther Creek *(regularly logged)*

Fig. 13. The relation between river discharge and suspended-sediment concentrations from automated samplers in the two subwatersheds of Redwood Creek. The LOWESS-fit curve through each data set is shown with a red line, and the residuals about this curve are shown in the right panels. Residuals are summarized by percentiles for all samples in each water year, including the median (black line), interquartile range (shading) and the 10th and 90th percentiles (thin lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

much more error and were substantially less than the WY1965 USGS measurements and greater than the combined 1970–1980 loads (Table 4).

5.7. Small tributaries

Because strong time-dependence was observed in the suspended-sediment concentrations and loads, we compared two small tributaries of Redwood Creek – one never logged (Little Lost Man Creek), the other regularly logged (Panther Creek) – to assess the potential causes of the suspended-sediment changes. Suspended-sediment concentration data from both tributaries are shown in Fig. 13. While these concentrations had the greatest amount of variability about the LOWESS-fit relationships of all of the study area stations (Table 2), there were measurable differences and time-dependencies in the concentrations. For example, the logged-watershed (Panther Creek) exhibited suspended-sediment concentrations that were roughly 10-times greater than the unlogged Little Lost Man Creek for discharges greater than 10 m^3/s (Fig. 13). The Panther Creek suspended-sediment concentrations also revealed significant decreasing trends in time with respect to discharge, as shown by statistical analyses of concentration residuals (Table 2) and annual compilations of these residuals (Fig. 13). Little Lost Man Creek, in contrast, revealed somewhat weak increases to no change to concentrations with time (Table 2; Fig. 13). Thus, the logged Panther Creek exhibited decreasing trends in concentrations similar to those in the larger coastal watersheds, whereas Little Lost Man Creek did not. The time-dependent trends in Panther Creek – including slight increases during 1995–2000 and greater decreases following 2000 (Fig. 13a) – were also consistent with the trends exhibited in Redwood Creek (Fig. 6e), even though Panther Creek represents only 2% of the Redwood Creek watershed area.

6. Discussion and conclusions

Suspended-sediment concentrations and discharge of the coastal rivers of northern California have varied widely over the past five decades. Systematic multi-year changes were observed for all rivers evaluated here, including: (i) increases in suspended-sediment concentrations and loads during the 1965 water year, and (ii) decreases in concentrations and loads during the decades following 1965. The most marked changes were observed for the Trinity River, which had time-dependent sediment concentration variations of over an order-of-magnitude (Fig. 6) and a sediment discharge response to the 1965 WY that lasted about a decade (Fig. 11a and e). Although more moderate responses were observed for the other rivers, all showed decreases in suspended-sediment concentrations and discharge that averaged a halving of these measurements approximately every decade since 1965 (Table 2; Fig. 11). Data from the Eel River provided evidence that these changes were not uniform with grain size, but were most pronounced for the sand fraction and least pronounced for mud (Fig. 9).

Unfortunately the reduced sampling of these rivers by the USGS during the past two to four decades limits our ability to track these changes to the present day. Redwood Creek is the only river that has been sampled regularly since 1998 largely through an effort led by RNSP (Fig. 3), and these data suggest that decreases in suspended-sediment concentrations have continued throughout this record (e.g., Fig. 6f). Other sampling of the Eel River has been conducted by Geyer et al. (2000) and our own efforts (Goñi et al., 2013), and these data suggest that decreases in suspended-sediment concentrations have also persisted with time (see Supplemental information).

The massive increases in suspended-sediment concentrations and discharge during WY1965 are consistent with geomorphic observations of exceptional landscape erosion and river channel aggradation and change during this year. For example, Kelsey (1980), Nolan and Marron (1995), and Madej and Ozaki (1996) provided observations of meter-scale aggradation of river channels during the record high flows of WY1965. As noted by many, the increases in sediment supply to the region's rivers was a response of barren logged slopes and unstable logging roads to the intense rainfall of December 1964 that may have been conditioned by another significant flood in 1955 (Anderson, 1970; Brown, 1973; Knott, 1974; Kelsey, 1980; Best et al., 1995; Nolan et al., 1995; Nolan and Janda, 1995; Weaver et al., 1995; Madej and Ozaki, 1996; Ziemer, 1998). These land-use practices have improved with time (Madej et al., 2012; Klein and Anderson, 2012), which combined with smaller hydrologic events since 1965 (Fig. 2), have resulted in decreased supplies of sediment to the river channels. These changes were evident in both the larger coastal watersheds and the smaller tributaries compared here (Table 2; Fig. 13). Thus, the combined effects of erosion-prone land uses and an exceptionally large storm were likely responsible for the increases in suspended-sediment discharge reported here.

Dams on these coastal watersheds have certainly disrupted the flow of water and sediment through these systems (Willis and Griggs, 2003; Minear and Kondolf, 2009). Unfortunately, the sampling histories of these watersheds do not provide many opportunities to evaluate the effects of dams on suspended-sediment discharge (Fig. 2). One exception is the damming of the Trinity River in 1962, which occurred near the middle of over two decades of suspended-sediment sampling. However, the Trinity River exhibited massive increases in suspended-sediment loads in 1965 (Fig. 6), which is inconsistent with the expectations of reduced sediment discharge following damming. In fact, the increases in sediment discharge from the Trinity River were much greater than the Eel River, which did not have a similar damming project during this interval of time (Fig. 11). Thus, although the dams in the northern

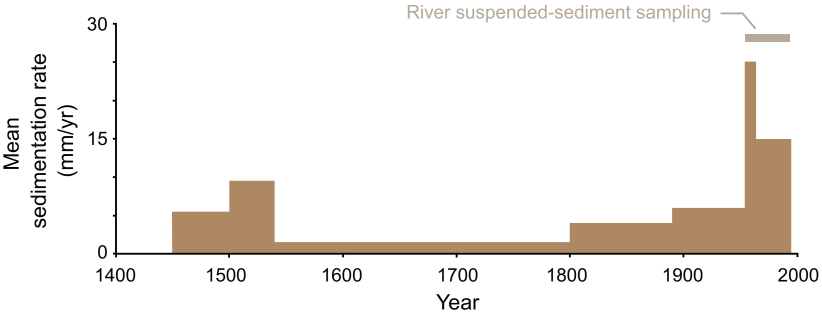


Fig. 14. Mean sedimentation rate on the continental shelf offshore of the northern California rivers between 1450 and 1995 after Sommerfield et al. (2002).

California watersheds certainly reduced sediment discharge in these rivers (Willis and Griggs, 2003; Minear and Kondolf, 2009), these effects appear to be secondary to the primary effects of land use and climate.

The increases in sediment discharge from these northern California coastal watersheds to the Pacific Ocean has been noted by marine geological investigations of continental shelf sedimentation (Sommerfield et al., 2002; Wheatcroft and Sommerfield, 2005; Leithold et al., 2005; Sommerfield and Wheatcroft, 2007). For example, the average sediment accumulation rate on the mid-continental shelf was computed for this region from data presented in Sommerfield et al. (2002; Fig. 14). The marine records suggest that marked increases in sedimentation occurred during the latter half of the 20th century, which coincides with the USGS data presented here. However, the marine records suggest that the most marked increases occurred ca. 1955 (Leithold et al., 2005; Sommerfield and Wheatcroft, 2007), which is before the initiation of any of the USGS sampling records (cf. Fig. 3). This finding suggests that the changes to suspended-sediment concentrations and discharge reported here may only be part of longer-term changes that occurred in these coastal watersheds. The marine sediment records (Fig. 14) and other geomorphic studies within the California coastal watersheds (e.g., Mudie and Byrne, 1980; Cole and Liu, 1994; Pinter and Vestal, 2005; Constantine et al., 2005) suggest that the humans increased sediment supplies to these rivers during the 19th and 20th centuries by altering land cover and land use of these watersheds (cf. Pulling, 1944). In addition, decadal and longer fluctuations in the hydroclimate of northern California (e.g., Wheatcroft and Sommerfield, 2005, Fig. 10) introduces another axis of variability that could oppose or amplify land use changes depending on their phasing. Unfortunately, none of these changes can be tracked from the river suspended-sediment data presented here.

However, the changes in river suspended-sediment discharge shown here suggest that sediment load calculations are highly sensitive to time-dependencies in sediment concentrations. For example, our calculations of Eel River sediment loads suggest that excluding time-dependence will result in substantial errors compared to the USGS measurements (Table 4). Thus, studies attempting to close sediment ‘source-to-sink’ budgets on event and centennial time scales (e.g., Wheatcroft et al., 1997; Sommerfield and Nittrouer, 1999) may need to be re-evaluated in light of this additional source of uncertainty.

Combined, the results presented here provide evidence that the rates and yields of sediment discharge from small mountainous river systems can vary substantially over decadal-scales, and that human-induced land-use changes and hydroclimatic variability can drive these changes. Because these land-use changes can alter suspended-sediment concentrations to similar scales of urbanization and wildfire (e.g., Warrick and Rubin, 2007; Warrick et al., 2012), there is great need to incorporate these changes in assessments of watershed and coastal sediment budgets (e.g., Inman and Jenkins, 1999; Willis and Griggs, 2003; Farnsworth and Warrick, 2008). Furthermore, regular and sustained river sampling will be needed to track the continued progress of the present changes and to characterize changes to come in the future. Unfortunately sediment discharge measurements have been sustained for only one Northern California river (Fig. 3), and similar rivers in many other parts of the world have essentially no sediment data.

Thus, the rates of sediment discharge from small coastal watersheds such as those in northern California can change markedly with time. These results suggest that approaches that assume stationary discharge-sediment concentration relationships (i.e., sediment rating curves) with time can provide erroneous results in areas like these, even though these techniques have found wide popularity (e.g., Brownlie and Taylor, 1981; Inman and Jenkins, 1999; Syvitski and Morehead, 1999; Willis and Griggs, 2003; Wheatcroft and Sommerfield, 2005; Farnsworth and Warrick, 2008). Extending the suspended-sediment sampling results from one interval of time to another may introduce large errors in sediment load estimates because of human- or climate-induced changes to the sediment-discharge relationships. These results are consistent with the findings and suggestions of Porterfield (1972, p.20), who emphasized that the relation between water discharge and sediment concentration is “not fixed” and that changes in time can be caused by natural availability of sediment from events such as “forest fires, channel changes, landslides, and mass wasting” and also by human-derived changes from “road construction, dam construction, river diversions, land-use changes, logging, urbanization, and gravel mining.” Because of the potential effects of these natural and human-caused changes, Porterfield (1972) warned against extrapolating sediment concentration relationships over gaps in time that range between 10 s of minutes to multiple days.

Because of the widespread inhabitation and history of landscape modification by humans throughout the world, our results suggest that sediment yield studies in the numerous and important steep, small coastal watersheds of the world should carefully consider time-dependent changes (cf. Syvitski et al., 2005; Walling, 2006; Milliman and Farnsworth, 2011). While the sediment yields from these small basins are critically important to coastal sediment budgets – especially local littoral budgets during the present time of accelerating seal level rise – we suggest that caution in applying historic river data to estimate modern or future rates of sediment yield. Our results reveal that these sediment yields can be altered greatly by land-use and climatic changes, which reinforces the need for renewed river sampling efforts along these margins.

Acknowledgements

We are thankful for the USGS river sampling programs that sustained river gaging stations utilized in this research. In the face of shrinking stream gaging networks in California, we appreciate the support of Redwood National and State Parks (RNSP) in continuing the monitoring of water and sediment loads in several north coastal watersheds. This work was also supported through a National Science Foundation Award number 0628487 – “Collaborative Research: Delivery and Burial of Particulate Organic Carbon (POC) on Ocean Margins Dominated by Small, Mountainous Rivers: the Role of Effective Discharge”, and the USGS Coastal and Marine Geology Program.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2013.02.041.

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