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

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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.

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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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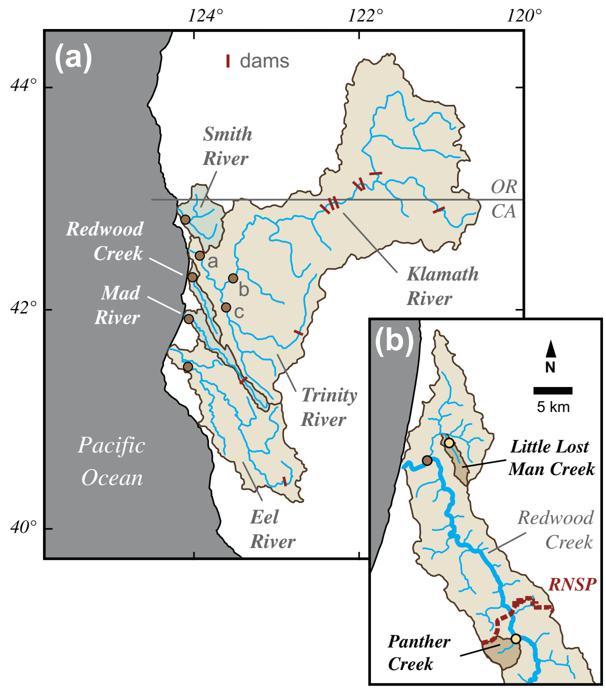

Fig. 1. Map of the northern California study area showing river watersheds and sampling stations (filled symbols). The six large coastal watersheds are shown in (a). Subwatersheds of Redwood Creek utilized in this study are shown in (b). The Redwood National and State Park (RNSP) boundary is shown with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