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Suspended-sediment rating curve response to urbanization and wildfire, Santa Ana River, California

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[1] River suspended-sediment concentrations provide insights to the erosion and transport of materials from a landscape, and changes in concentrations with time may result from landscape processes or human disturbance. Here we show that suspended-sediment concentrations in the Santa Ana River, California, decreased 20-fold with respect to discharge during a 34-year period (1968–2001). These decreases cannot be attributed to changes in sampling technique or timing, nor to event or seasonal hysteresis. Annual peak and total discharge, however, reveal sixfold increases over the 34-year record, which largely explain the decreases in sediment concentration by a nonlinear dilution process. The hydrological changes were related to the widespread urbanization of the watershed, which resulted in increases in storm water discharge without detectable alteration of sediment discharge, thus reducing suspended-sediment concentrations. Periodic upland wildfire significantly increased water discharge, sediment discharge, and suspended-sediment concentrations and thus further altered the rating curve with time. Our results suggest that previous inventories of southern California sediment flux, which assume time-constant rating curves and extend these curves beyond the sampling history, may have substantially overestimated loads during the most recent decades.

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1. Introduction

[2] Sediment flux measurements from rivers are important for evaluating terrestrial organic and inorganic material export, landscape denudation, geomorphic change, habitat and water quality, and inputs to reservoir and coastal systems. Rates of sediment discharge are related to the sources, transport and storage of sediment within a watershed, which are in turn related to tectonic regime, climate, land cover, land use, and river setting [*Milliman and Syvitski*, 1992; *Dinehart*, 1998; *Trimble*, 1997, 1999; *Burbank and Anderson*, 2001; *Yang et al.*, 2005]. Global inventories of river discharge suggest that both accelerated rates of soil erosion and trapping of sediment by dams have altered these fluxes during recent decades [*Walling and Fang*, 2003; *Syvitski et al.*, 2005].

[3] The finest fraction, and commonly the majority, of river sediment flux is transported below theoretical transport capacities, which necessitates the development of site-specific, empirical relationships to compute flux [*Colby*, 1963; *Porterfield*, 1972; *Walling*, 1977]. These empirical relationships between river discharge and suspended-sediment concentration respond to patterns of sediment production, availability and transport capacity throughout a watershed, which may include sediment-production variability of river tributaries [*Meade et al.*, 1990; *Hicks et al.*, 2000; *Lenzi and Marchi*, 2000], changes in bed sediment grain size [*Rubin and Topping*, 2001], flow rate dynamics and event hysteresis [*Walling*, 1974; *Williams*, 1989; *Rubin and Topping*, 2001], and seasonal to interannual changes in sediment supply [*Leopold*, 1968; *Walling*, 1974; *Van Sickle and Beschta*, 1983; *Dinehart*, 1998; *Asselman*, 2000; *Topping et al.*, 2000]. Thus simple sediment rating curve relationships (e.g., power law) may not adequately reproduce the variability in sediment production, and hence flux, owing to nonlinear or time-dependent effects [e.g., *Van Sickle and Beschta*, 1983; *Hicks et al.*, 2000; *Hovius et al.*, 2000; *Horowitz*, 2003]. Further, a comprehensive analysis of North American suspended-sediment rating curves suggests that water discharge also plays a controlling factor in the curve variability [*Syvitski et al.*, 2000], although little work has examined the effects of hydrologic change on rating curves.

[4] The rivers of southern California drain a semiarid landscape that has been subject to periodic wildfire, extensive population and urban growth, and channel modifications including large dams [*Brownlie and Taylor*, 1981; *Inman and Jenkins*, 1999; *Lave and Burbank*, 2004]. These rivers are also recognized to be highly event-driven, producing the majority of long-term discharge and sediment flux during brief, intense winter events [*Kroll*, 1975; *Warrick and Milliman*, 2003]. Thus, owing to their small size, high relief, active tectonics, and history of human development, southern California rivers serve as examples of high-sediment-yield, small, mountainous rivers with considerable human modification [*Milliman and Syvitski*,

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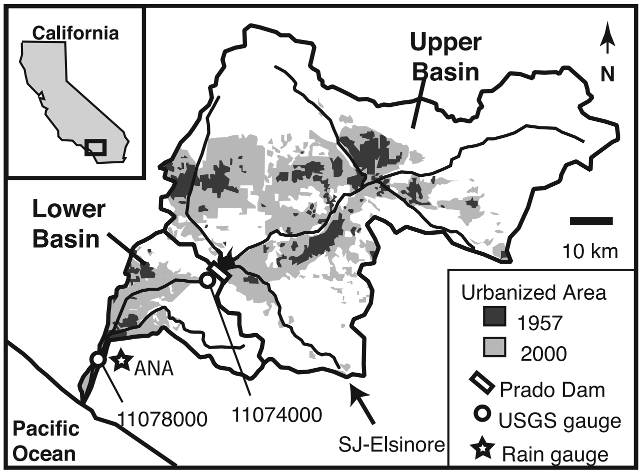

Figure 1. Santa Ana River watershed, including urbanized areas in 1957 and 2000 (see Figure 2 for data sources), Prado Dam, USGS gauging stations, and NWS rain gauge at Santa Ana (ANA).

1992]. The Santa Ana River is unique for southern California in that through a multidecadal period of land use change and multiple wildfires, the U.S. Geological Survey (USGS) continued stream gauging and event-based suspended-sediment sampling operations at a station near the river mouth. These data prove to be exceptionally valuable, because they clearly reveal that order-of-magnitude changes in suspended-sediment concentrations occurred over the three-decade sampling period. We show here that these changes were largely caused by altered rates of water discharge, rather than the more commonly cited sediment supply modifications discussed above. Trends and variability in discharge rates were strongly correlated with the landscape changes in urbanization and wildfire.

2. Santa Ana River

[5] The Santa Ana River drains a 4406 km^2 basin that includes the San Gabriel and San Bernardino Mountains (maximum relief = 3500 m) and a large flood control structure, Prado Dam (Figure 1). Built in 1941, Prado Dam traps discharge from 3859 km^2 (or 87.6%) of the watershed, with the primary purpose of regulation of winter stormflow for downstream flood control and groundwater recharge in Orange County Water District (OCWD) percolation basins [*U.S. Army Corps of Engineers*, 1994]. Thus the "upper watershed" (above Prado Dam) drains the steep inland mountains and a flat inland plain, while the "lower watershed" (below Prado Dam) drains the lower lying Santa Ana Mountains (maximum relief = 1730 m) and a portion of the coastal plain of Orange County (Figure 1).

[6] The Santa Ana River has urbanized rapidly since the mid-20th century, and the location of this development has largely occurred in lowlands that were previously used for agriculture (Figure 1) [*California Department of Water Resources*, 1960] (also California Department of Conservation (CADC) Farmland Mapping and Monitoring Program—Standard and custom map products, http://www.consrv.ca.gov/DLRP/fmmp/map_products/index.htm, accessed 11 August 2003) (hereinafter referred to as CADC online data). By 2000, approximately 40% of the basin had been developed into urban land uses, a rate consistent in both the upper and lower basins and coincidental with rapid population increases (Figure 2).

[7] Water and sediment discharge in the Santa Ana River is dominated by brief runoff events during wet winter storms occurring mostly in December–March. On average, half of the annual discharge and ~90% of the sediment flux to the ocean occurs during just 3 days per year, while the river discharges nothing to the ocean during ~70% of the time [*Kroll*, 1975; *Warrick and Milliman*, 2003]. These discharge patterns are similar to the event-based discharge patterns of unregulated rivers of southern California due to Prado Dam operations: The majority of upper basin water is captured by Prado Dam and diverted to groundwater recharge facilities immediately downstream of the dam [*U.S. Army Corps of Engineers*, 1994]. Some upper watershed discharge is released to the river mouth during storms, however, as reservoir storage is drained during or soon after floods to provide for maximum reservoir storage and to drain riparian habitats behind the dam [*Izbicki et al.*, 1998]. Owing to the high variability of annual precipitation, discharge in the Santa Ana River can vary by many orders-of-magnitude from year to year and can be excep-

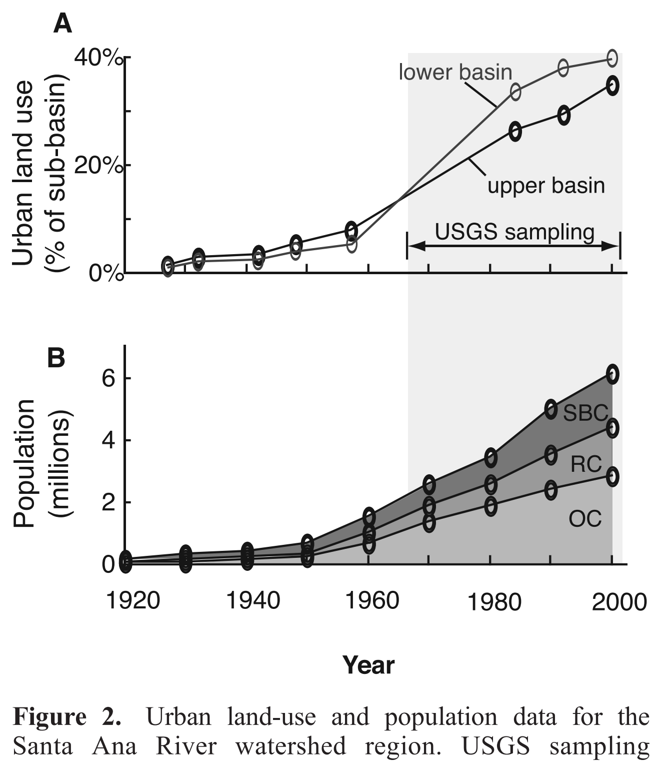

Figure 2. Urban land-use and population data for the Santa Ana River watershed region. USGS sampling (1968–2001) shown with gray shading. (a) Urban land use for both the upper and lower basins of the Santa Ana River after *California Department of Water Resources* (*CADWR*) [1960], CADC (online data), and unpublished CADWR data (provided by G. I. Bergquist, personal communication, 2003). (b) Total population of the three counties of the watershed from *U.S. Census Bureau* [2003]. SBC, San Bernardino County; RC, Riverside County; OC, Orange County. Portions of each county population live outside of the watershed.

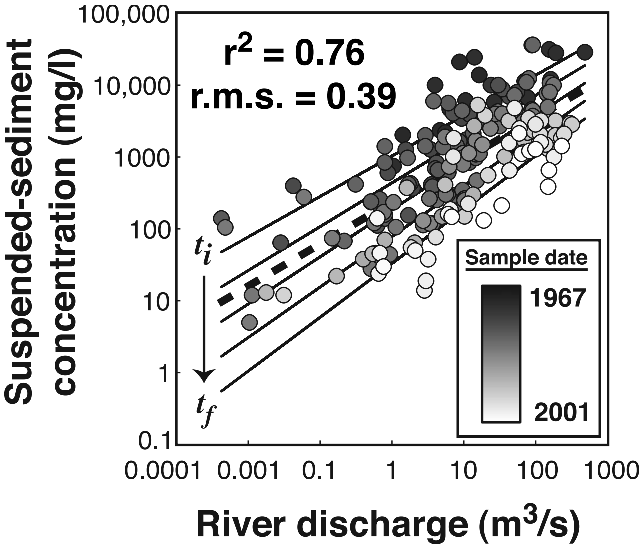

Figure 3. Suspended-sediment concentration measurements from the Santa Ana River at Santa Ana (USGS 11078000). Symbols are shaded according to sample date (see inset). Data have been fit by a power law (thick dashed line, r^2 = 0.53) and a nonlinear, time-dependent function (series of black lines; r^2 = 0.76; see text for methods).

tionally high during El Niño−Southern Oscillation (ENSO) winters [*Inman and Jenkins*, 1999; *Warrick and Milliman*, 2003; *Andrews et al.*, 2004].

3. Suspended-Sediment Rating Curve

[8] The relationship between instantaneous discharge and suspended-sediment concentration at the last USGS station on the Santa Ana River (USGS 11078000; Figure 1) reveals a positive, yet somewhat weak relationship between discharge and concentration (Figure 3). Scatter about a power law regression relationship through these data is high (r^2 = 0.53), and the high error of this relationship (r.m.s.e. = 0.54 $\log_{10}$ units) represents over an order-of-magnitude spread about the fitted relationship. The large r.m.s. error cannot be attributed to changes in the sampling technique or sampling timing with respect to the event or annual hydrograph (Appendix A). Sampling has consistently focused on days of peak event discharge throughout the sampling record, and 77% of all samples have been taken within 1 day of peak discharge (Appendix A).

[9] Sample date, on the other hand, explains roughly half of the variability associated with the original power law relationship residuals (r^2 = 0.48; Figure 4). A fitted exponential function suggests that the residuals decreased by an average of 1.3 $\log_{10}$ units, or ∼20-fold, between 1968 and 2001 (Figure 4). Further, mean residuals for each water year reveal that this drop occurred somewhat gradually over time rather than abruptly (Figure 4b). This time-dependency of the Santa Ana River rating curve can be shown to be significant with other analyses. For example, the combination of discharge and date of sample in multiple-variable regression reveals that both variables are highly significant ($p < 0.01$) producing an improved correlation coefficient (r^2) of 0.75 and r.m.s. error of 0.40 $\log_{10}$ units.

[10] The combined analyses above assume that concentration changes were consistent across the range of measured discharge rates. To test this, we conducted two time-dependent, nonlinear regressions, the first of which both power law slope (b) and offset (a) were allowed to change with time according to

$$\begin{aligned} Css &= a(t)Q^{b(t)}, \\ \text{such that} \quad a(t) &= a_i\, e^{-m_a t}, \\ b(t) &= m_b\, t + b_i, \end{aligned} \tag{1}$$

where t is time in days since 10/1/1967, a_i and b_i are the initial values at $t_i = 0$, and m_a and m_b are the rates of change with time. Results of this analysis are shown with a series of thin lines in Figure 3, and both a and b were significantly related to time ($p < 0.01$ and $p < 0.05$, respectively). This nonlinear, time-dependent relationship explained only 1% more variance in the concentrations (r^2 = 0.76, r.m.s.e. = 0.39; Figure 3) than the linear relationships discussed above. Secondly, we conducted moving-window power law regressions through the data and allowed the regression sample window to vary between 5 and 100 samples. Complete significance (all regression $p < 0.05$) occurred for sample windows of 21 to 100 samples. Highly significant ($p < 0.01$) time-dependence was shown for both the power law offset (a) and slope (b) across the complete record, and total offsets were −1.2 (±0.1) and 0.17 (±0.05), respectively, for the range of window lengths. Values of a and b did not change abruptly with time.

[11] Hence all analyses suggest that concentration changes on the order of 20-fold have occurred across the broad range of sampled discharge rates. Although a slight increase in power law slope was found with time (e.g., Figure 3), this change explains little of the variance in the concentration data. The main change in the rating curve is a gradual downward shift with time. There is thus a highly significant, decadal-scale time-dependency in the suspended sediment concentrations for the lower Santa Ana River. Below we examine hydrologic variables from the USGS gauging station to evaluate the source(s) of this time-dependent relationship.

4. Analysis of Hydrologic Change

[12] Four variables from the Santa Ana River were evaluated for change with respect to time: precipitation, annual peak discharge, annual water discharge, and annual sediment discharge. Four precipitation stations near or within the Santa Ana River watershed were found to span the 1968−2001 record, a monthly recording National Weather Service precipitation gauge at the Santa Ana Fire Station (ANA in Figure 1; http://cdec.water.ca.gov/) and three daily recording stations in the U.S. Historical Climatology Network (049087-Tustin Irvine Ranch, 047306-Redlands and 046719-Pasadena [*Williams et al.*, 2004]). The ANA data were shown to correlate best with the Santa Ana River discharge data, as discussed below, and are generally used in our analyses.

[13] Discharge variables for the water years sampled (1968−2001) were obtained from the USGS Surface Water Database (http://waterdata.usgs.gov/nwis/sw) for stations 11078000 (Santa Ana River at Santa Ana) and 11074000

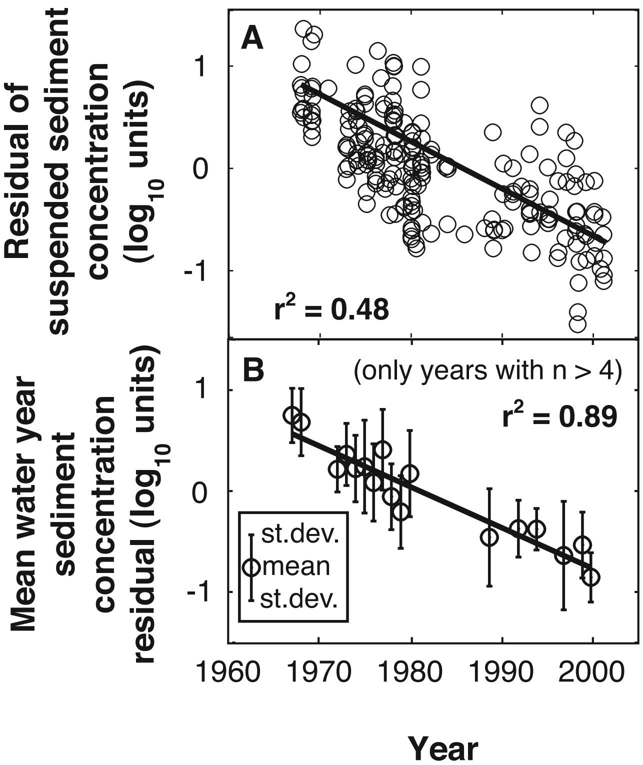

Figure 4. Suspended-sediment concentration residuals for the Santa Ana River at Santa Ana (USGS 11078000). Residuals are calculated as the difference between measured concentration and the calculated concentration from the best-fit power law rating curve relationship (dashed line in Figure 3). Solid lines are best-fit exponential relationships ($p < 0.01$).

(Santa Ana River below Prado Dam). The USGS also estimated and published daily suspended-sediment flux rates for the Santa Ana River during water years 1968–1985 using the techniques of *Porterfield* [1972] (data available at: http://co.water.usgs.gov/sediment/). We used these 19 years of USGS sediment discharge estimates to compare with our sediment flux computations for the entire 34-year record.

[14] Suspended-sediment discharge (Q_{ss} in t/d) was computed as the product of average daily water discharge data (Q in m^3/sec) and time-dependent discharge-suspended-sediment concentration (C_{ss}) relationships,

$$Q_{ss} = Q(t)C_{ss}(t). \qquad (2)$$

Because sediment concentrations were not related to event or seasonal hysteresis (Appendix A), sophisticated techniques for including sediment supply limitations were not employed [e.g., *Van Sickle and Beschta*, 1983]. Rather, we evaluated the decadal-scale changes with three different rating curves. These rating curves included: (1) the power law fit corrected for the exponential, time-dependent residual decrease (Figure 4a),

$$C_{ss} = 841.3Q^{0.65}exp(-0.0002446t), \qquad (3)$$

where C_{ss}, Q, and t have units of mg/l, m^3/s, and days since 1 October 1967, respectively; (2) the power law (Figure 3) corrected with individual water year mean concentration residuals $n > 4$ (Figure 4b) or the trend in residuals when $n < 4$; and (3) the best-fit nonlinear rating curve using equation (1) (thin lines, Figure 3). Concentration estimates were corrected for logarithmic-transformation biases using daily corrections suggested by *Hicks et al.* [2000], because the rating curve errors were discharge dependent (Figure 5). Bias correction resulted in total mass discharge increases of only 4–5% for the three rating curves techniques.

[15] Comparison of the rating-curve results and USGS estimates of sediment flux during 1968–1985 are shown in Figure 6. There is general agreement between the methods over the many orders-of-magnitude of annual sediment discharge, and r.m.s. differences are 0.22 to 0.26 log_{10} units for each method. The rating-curve techniques, however, generally underpredict USGS estimates at the lowest fluxes (<100 kt/yr; Figure 6), and there is a mean systematic bias for each method of −0.16 to −0.19 log_{10} units. There is no time-dependence ($p < 0.05$), however, in the biases of any of the rating curve methods, which suggests that both the rating curve and USGS techniques are consistent in including the time-dependent sediment concentration relationships discussed above. For the results presented below, we chose to present results from rating curve method 2: annual offsets, because (1) it resulted in low log_{10} r.m.s. errors and biases and the lowest linear r.m.s. errors and biases with respect to the USGS results, (2) it includes annual variability in concentrations (Figure 4b) that may be related to actual sediment source variability, and (3) it does not include the potential, or apparent, biases of the flexible USGS methodologies detailed by *Porterfield* [1972]. We note, however, that although the three rating-curve techniques produce slightly different estimates of flux, they all produce the same statistical relationships and conclusions presented below.

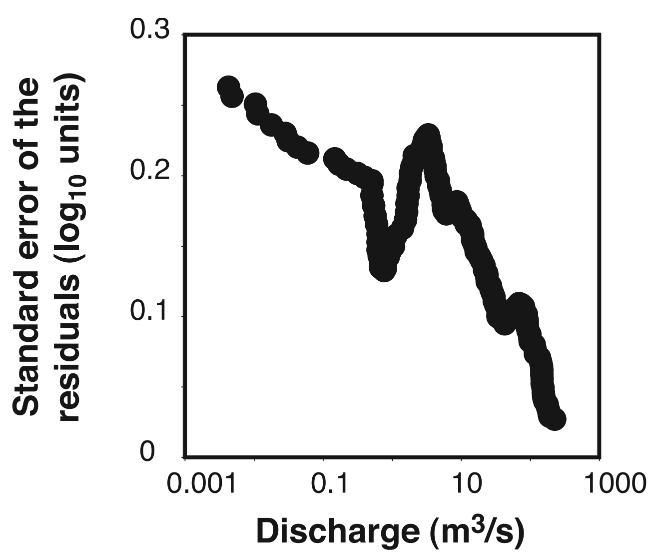

Figure 5. Running local mean standard error of the residuals between measured suspended-sediment concentration and the time-dependent rating curve.

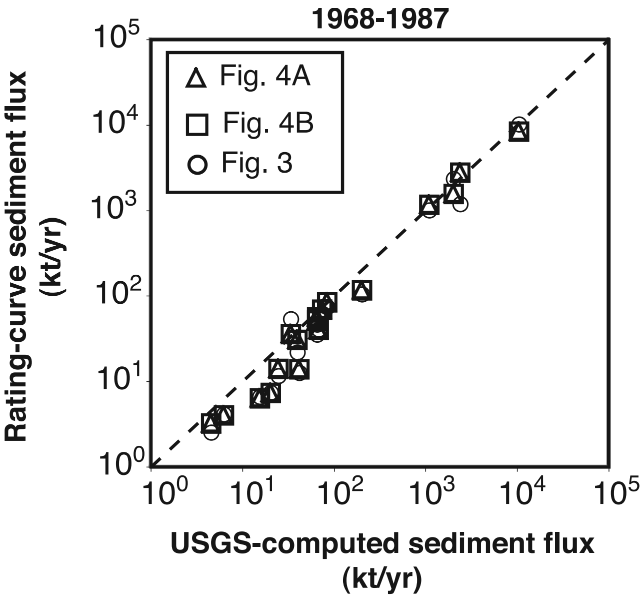

Figure 6. Comparison of USGS suspended-sediment flux computations with flux results from three time-dependent sediment rating curves: exponential decrease in offset (triangles), annual concentration residuals (squares), and nonlinear time dependence (circles).

[16] Time series of the four hydrologic variables over the period of suspended-sediment sampling (1968–2001) are shown in Figure 7. There is both substantial year-to-year variability in the data and multiyear periods of high and low precipitation and discharge. For example, two well-recognized multiyear periods of low precipitation and discharge occur during 1970–1977 and 1984–1991 [*cf. Inman and Jenkins*, 1999] (Figure 7).

[17] To evaluate time-dependence in discharge we used precipitation as a dependent variable in a series of statistical tests [*cf. Alley*, 1988]. Owing to the semiarid climate of southern California, winter precipitation clearly provides the primary condition for river discharge variability [*cf. Brownlie and Taylor*, 1981]. Others researchers [see, e.g., *Lave and Burbank*, 2004] have noted that precipitation intensity rather than total annual precipitation better explains water and sediment discharge rates, such that precipitation index (*PI*),

$$PI = \Sigma P_t^A, \tag{4}$$

better correlates with discharge measurements, where P_t is a t-hour precipitation intensity, A is a fitted coefficient typically >1, and P_t^A are summed over a hydrologic year or storm series. We utilized equation (4) with data from three USHCN daily precipitation stations in close proximity of the watershed (stations 049087, 047306, and 046719) and found that annual *PI* correlated significantly ($p < 0.05$) with annual water and sediment discharge measurements under the conditions $1 < A < 3.6$. However, peak correlation for all analyses occurred for A values of 1.0 to 1.4, and negligible benefit was exhibited for $A > 1$ (maximum r^2 improvement for $A \neq 1$ was 0.006). Thus we present all results below with respect to annual precipitation values (i.e., $A = 1$).

[18] Positive relationships are exhibited between annual precipitation and all discharge measurements (Figures 8a–8c). Residuals about these relationships reveal that both annual and peak water discharge are significantly correlated with time, while sediment discharge was not significantly correlated with time (Figures 8d–8f). The rates of increase suggest a 280% (±170%) increase in total annual water discharge and a 350% (±150%) increase in peak discharge with respect to precipitation over the 34-year record. Of all of the years in the record, 1969 is clearly unique: Not only does it have high water and sediment discharge (accounting for approximately half of the total 1968–2001 sediment flux; Figure 7), but also the water- and sediment-discharge

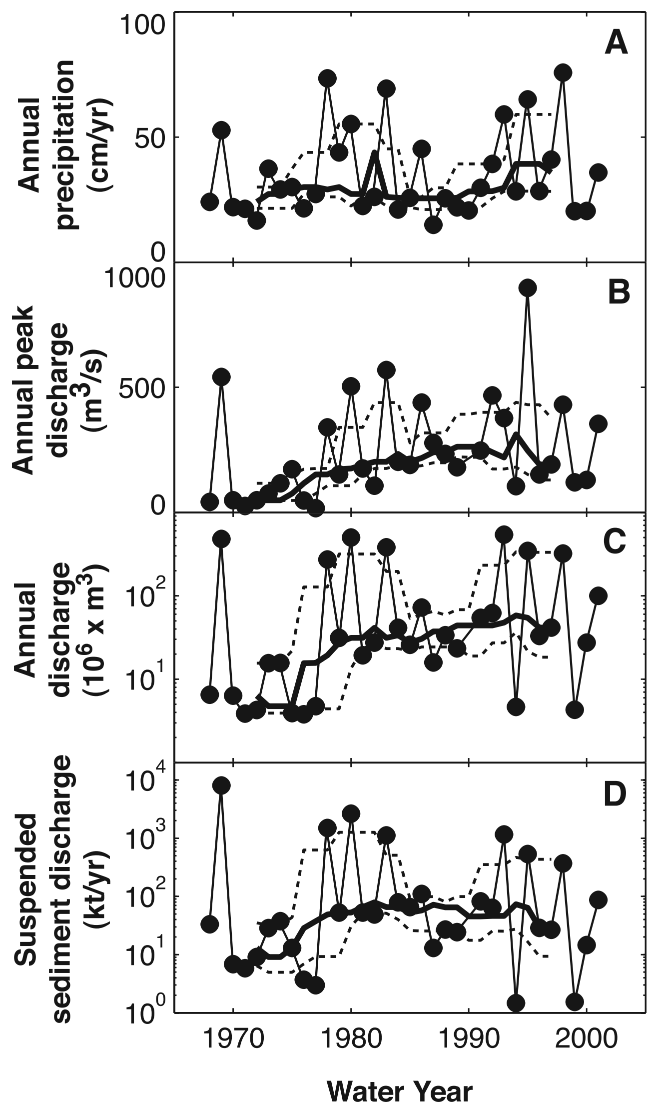

Figure 7. Hydrologic data for the Santa Ana River at Santa Ana (USGS 11078000) during the period of suspended-sediment measurements. Thick line is the 10-year running median value, and dashed lines are 10-year running 20 and 80 percentile values. (a) Annual precipitation at NWS Santa Ana station (ANA). (b) Annual peak discharge. (c) Total annual discharge. (d) Annual suspended-sediment discharge.

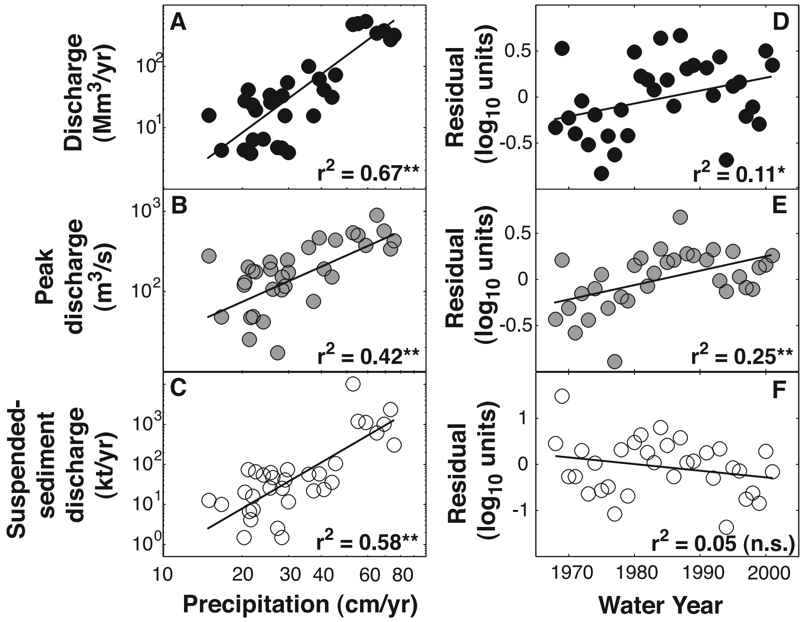

Figure 8. Relationship between annual precipitation and (a) total annual discharge, (b) annual peak discharge, and (c) suspended-sediment discharge for USGS 11078000. Best-fit power law relationships (solid lines) and correlation coefficients are shown. (d, e, f) Time-history of the $\log_{10}$ residuals about these relationships, with best-fit linear relationships (solid lines). Regression significance is shown by: **($p < 0.01$), *($p < 0.05$), and n.s. ($p > 0.05$).

residuals were unusually large with respect to the general trends in the remaining data (Figures 8d–8f). Below we show evidence that these anomalously high fluxes are related to a large wildfire.

[19] We then evaluated whether scale-dependent temporal changes existed in the data using the time-dependent, nonlinear model found in equation (1). For these analyses, C_{ss} was replaced with the three hydrologic variables and Q was replaced with annual precipitation. Results suggest that all variables reveal some scale dependence in the temporal changes, and all b and a are highly significant with respect to time ($p < 0.01$; Figure 9). Both annual discharge and peak discharge show order-of-magnitude increases during the driest years, while having negligible temporal change during the wettest years (Figures 9a and 9b). Although suspended-sediment flux did not show significant temporal changes in the scale-independent results presented previously (Figure 8f), the scale-dependent analyses suggest that decreases were exhibited for the high-rainfall years (Figure 9c).

[20] Summarizing, although linear models significantly fit the time-dependent changes for total and peak discharge (Figure 8), we note that highly significant, scale-dependent and nonlinear changes are exhibited in all data (Figure 9). These changes are not in the same direction with respect to precipitation, however, water discharge increased through time whereas sediment discharge decreased. Below we show that these changes are strongly correlated with the wildfire and urbanization history of the basin.

5. Sources of Change

[21] Results presented above suggest that significant changes occurred in suspended-sediment concentrations, water discharge and sediment flux. Below we examine the processes that may have caused these changes before integrating these findings into a suspended-sediment conceptual model for the Santa Ana River.

5.1. Upper Watershed

[22] The upper watershed of the Santa Ana River (Figure 1) cannot be overlooked as a potential source of the change exhibited. Discharge through Prado Dam captures these upper watershed inputs, and USGS gauging and sampling records at 11074000 (Figure 1) capture the time-history of discharge at this site. Peak discharge records below Prado Dam reveal increases in peak discharge with time that are similar in magnitude to the lower watershed gauge (data not shown). However, these rates of peak discharge were consistently twofold to fourfold lower than those measured at the river mouth (Figure 10). This suggests that although rates of upper basin water discharge increased with time, they do not represent the majority of discharge during event peaks, when suspended sediment sampling has dominantly been conducted (Appendix A).

[23] The influence of upper basin sediment fluxes on the suspended-sediment results was evaluated with a sediment mass balance. For this mass balance we examined: sedimentation behind Prado Dam, sediment discharge immediately downstream of Prado Dam, and lower basin contributions of sediment (Figure 11). Total sedimentation behind Prado Dam was estimated from U.S. Army Corps of Engineers surveys of the reservoir conducted during 1960, 1975 and 1988, which suggest that sedimentation has been 0.927 million m^3/yr since dam construction, although this rate fluctuated (0.389–1.567 million m^3/yr) between the three surveys [*U.S. Army Corps of Engineers*, 2003] (also Greg Peacock, USACE, personal communication, 2004).

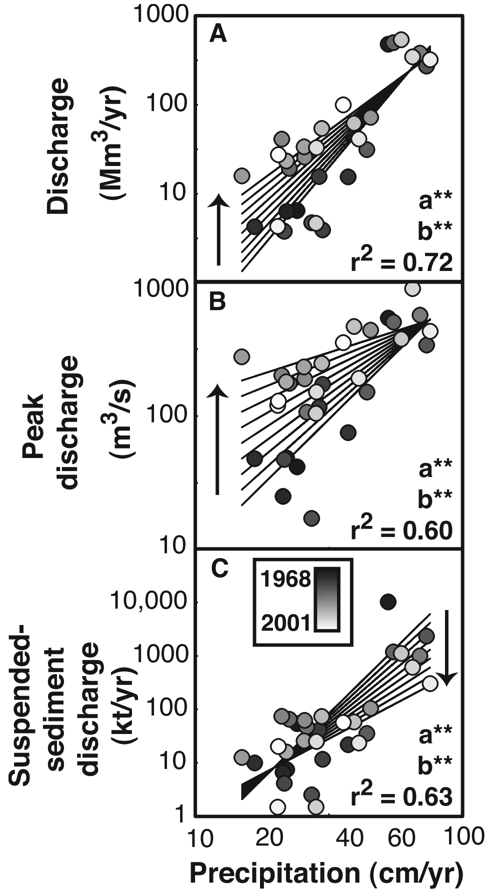

Figure 9. Nonlinear, time-dependent relationships of annual discharge, peak discharge and suspended-sediment discharge with respect to precipitation for USGS 11078000. Arrows identify the direction of significant, time-dependent relationships in (a) power law offset and (b) slope. Significance level is shown by **($p < 0.01$), *($p < 0.05$) and n.s. ($p > 0.05$). Best-fit lines are shown at 4-year intervals.

Unfortunately the survey dates do not coincide with the period of river monitoring (1968–2001), thus we estimated that the total sedimentation behind the dam during 1968–2001 to be ~10^6 m^3/yr (or ~1.6 Mt/yr assuming a bulk density of 1600 kg/m^3; Figure 11).

[24] Suspended-sediment discharge through Prado Dam was computed with daily discharge records and the suspended-sediment concentrations from the USGS 11074000 station (Figure 1). These sediment concentrations did not correlate with discharge ($r^2 = 0.009$, n = 448) nor significantly change with time (best $r^2 = 0.04$, exponential function) even though a wide range of discharge conditions were sampled. Therefore we used the average concentration of 490 mg/l (st.dev. = 290 mg/l) for all discharge measurements. During the period 1968–2001, total suspended-sediment discharge below Prado Dam was calculated to be 1.6 ± 1.0 Mt or ~0.05 Mt/yr (Figure 11), which is only ~3% of the approximated sedimentation behind Prado Dam, consistent with the high trap efficiency (>95%) reported by *Brownlie and Taylor* [1981].

[25] Total flux to the Pacific Ocean was calculated from the average annual suspended-sediment discharge past the lower gauging station during 1968–2001 (0.54 Mt/yr) plus an additional 10% bedload transport, an amount recommended by *Brownlie and Taylor* [1981] and *Inman and Jenkins* [1999]. Thus the mass balance (Figure 11) shows that the majority (~92%; potential range = 81–97%) of the total sediment (suspended and bedload) discharged at the mouth can be attributed to sediment production in the lower basin landscape.

[26] Thus, with so little sediment passing through Prado Dam and with no changes in concentration identified with time, it is highly unlikely that upper basin sediment discharge influenced the observed shifts in the suspended-sediment fluxes downstream. Further, although water discharge rates from Prado Dam appear to have changed in a manner consistent with those measured downstream, the lower watershed produces much more event-based discharge to the river mouth (twofold to fourfold on average). These results are consistent with the high trap efficiency and flood control procedures of the dam, described above.

5.2. Lower Watershed

[27] We therefore look to the lower watershed for evidence of the changes in water discharge and/or suspended-sediment production. The lower watershed main stem channel shows little evidence for influence, because the bed material is much coarser than the suspended sediment. For example, on average only 2% of the bed material is finer than 0.125 mm (n = 18), while over 75% of the suspended-sediment mass (n = 134) is finer than 0.125 mm (USGS 11078000). Thus, although the main stem channel bed downstream of Prado Dam has been shown to degrade during flood events and aggrade during years with moderate flow [*Brownlie and Taylor*, 1981; *Nelson*, 1982], it cannot be the dominant source of suspended sediment. Further, the bed material grain-size does not show coarsening or fining trends with time (n = 18; 1967–1987), either of which may suggest alteration of the bed erodibility and hence sediment production potential.

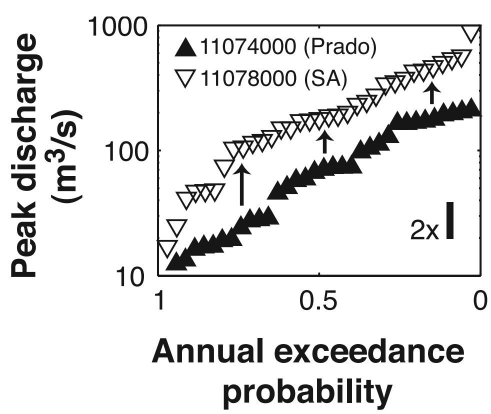

Figure 10. Comparison of annual peak discharge data from the Santa Ana River below Prado Dam (11074000) and at Santa Ana (11078000) during 1968–2001. Doubling scale (2×) is shown with vertical bar. Annual peak discharge at Santa Ana (SA) is consistently 2–4 times higher than at Prado.

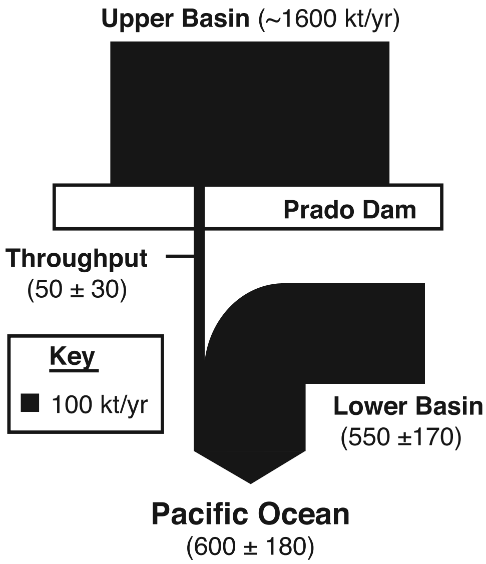

Figure 11. Total sediment budget for the lower basin of the Santa Ana River watershed based on 1968–2001 suspended-sediment measurements, estimates of bedload discharge, and measurements of Prado sedimentation (see text). Thickness of the flow diagram is a function of average annual sediment flux values, which are presented in parentheses. Errors for lower basin inputs are calculated assuming independent random errors in measurements.

[28] The landscape of the lower watershed is therefore the likely source of change exhibited in the suspended-sediment rating curve. Here we evaluate two recognized means of altering water discharge and sediment production with time within southern California: wildfire [*Taylor*, 1981; *Rice*, 1982; *Florsheim et al.*, 1991] and land use change [*Trimble*, 1997; *Pinter and Vestal*, 2005].

[29] Wildfire has been reported to produce a multiyear response in landscape erosion and runoff that is greatest in the immediate year and decays with time. We found that runoff, erosion rate and sediment concentration data from burned areas of semiarid Spain [*Cerdá*, 1998] and the San Gabriel Mountains of southern California [*Lave and Burbank*, 2004] closely fit exponential decay models during the first 5 years following wildfire (r^2 = 0.91 to 0.98) and that response half-life ($t_{1/2}$) ranged between 0.3 and 1.2 years. Therefore, to evaluate the effects of the wildfire in the lower watershed, we computed an annual "effective" wildfire area using wildfire areas mapped by California Department of Forestry and Fire Protection (CAFRAP) (Fire perimeters—map, 2004, http://frap.cdf.ca.gov/projects/fire_data/fire_perimeters/, website accessed 7 July 2004) (hereinafter referred to as CAFRAP website) and an exponential decay model with variable $t_{1/2}$ (Figure 12).

[30] Annual assessments of land cover were not available, but decadal inventories show monotonic increases in both urban land cover and population (Figure 2). This expansion of urban areas was largely at the expense of agricultural lands such as citrus orchards and rangeland (CADC online data). These types of landscape changes have been shown to induce increases in rainfall-runoff discharge and complex responses in sediment production [*Wolman*, 1967; *Leopold*, 1968; *Hollis*, 1975; *Booth*, 1990; *Trimble*, 1997; *Nelson and Booth*, 2002]. No significant alteration in grazing practices was identified for the Santa Ana River rangeland, which would similarly induce sediment production changes [*cf. Pinter and Vestal*, 2005]. Thus, because better land use data were not available, we used water year as a proxy for urban land change effects due to the monotonic increase in urban land cover with time.

[31] Both effective wildfire area and water year provided significant ($p < 0.05$) correlations with peak and annual discharge and annual sediment concentration residuals when evaluated with stepwise, multiple variable correlations (Table 1). Wildfire was shown to significantly increase annual total and peak discharge, sediment discharge, and sediment concentration. Significant $t_{1/2}$ were found between 0.4 and 14 years with peak correlations occurring at 1–3 years. An example of the relationship of effective wildfire area and sediment flux is shown in Figure 13. A linear model explains roughly 31% of the remaining sediment flux variance ($p < 0.01$) after the precipitation-relationship, and this model suggests a 10-fold increase between no wildfire and a large (200 km^2) wildfire.

[32] We then reevaluated the scale-dependent temporal relationships (Figure 9) without the influence of wildfire by correcting the annual time series with the best-fit linear relationships of effective wildfire area with optimal $t_{1/2}$. All analyses produced much higher correlation coefficients than previous tests without wildfire (Figure 14). Highly significant ($p < 0.01$) scale-dependence changes continue to be exhibited in total and peak discharge (Figures 14a and 14b). The average magnitude of these discharge changes was sixfold during the 34-year record. Suspended-sediment discharge, however, does not exhibit significant changes with time (Figure 14c), which is counter to the previous scale-dependent analyses (Figure 9c). These results suggest that: (1) although wildfire significantly increased total and

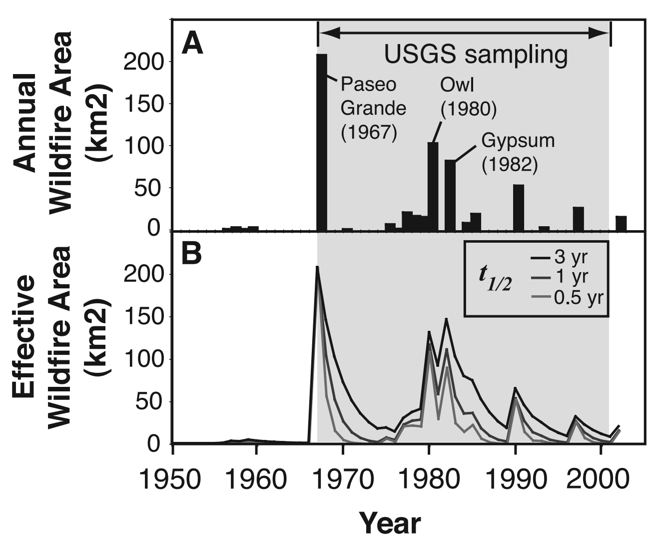

Figure 12. Wildfire history for the lower basin of the Santa Ana River watershed. (a) Annual wildfire area (1950–2003) within the lower watershed from fire boundaries mapped by CAFRAP (website). (b) "Effective" burn area computed with an exponential function with various half-lives ($t_{1/2}$, see text).

Table 1. Multiple-Variable Correlation Matrix for Water Year Variables During the Suspended Sediment Sampling Record (1968–2001) at USGS 11078000[a]

Water Year Variable	Annual Precipitation ($\log_{10}$)	Time	"Effective" Wildfire Area	$t_{1/2}$, years	r^2	σ_E ($\log_{10}$)
Suspended-sediment concentration residuals ($\log_{10}$)	n.s.	−0.036[b]	0.0015[c]	0.5–5	0.91	0.15
Total annual discharge ($\log_{10}$)	2.87[b]	0.024[b]	0.0043[b]	1.5–10	0.78	0.34
Annual peak discharge ($\log_{10}$)	1.27[b]	0.023[b]	0.0027[b]	2–14	0.69	0.24
Computed annual sediment flux ($\log_{10}$)	3.69[b]	N.S.[d]	0.0069[b]	0.4–12	0.72	0.50

[a]Each variable was tested with stepwise, linear regression, and the linear slope of significant variables are shown with t-test significance levels (see footnotes below). The range of each effective wildfire area half-life ($t_{1/2}$) that was significant ($p < 0.05$) is also given. The Final two columns present the multivariable regression coefficient (r^2) and the standard error of the estimate (σ_E).
[b]Significance level $p < 0.01$.
[c]Significance level $p < 0.05$.
[d]N.S. denotes significance level $p > 0.05$.

peak discharge rates (Table 1), there are very strong temporal relationships in discharge irrespective of wildfire (Figures 14a and 14b); and (2) temporal variability of sediment flux can largely be explained by precipitation and wildfire rather than from a general trend with time, whether scale dependent or independent (Table 1 and Figure 14).

5.3. Rating-Curve Conceptual Model

[33] It was shown above that highly significant temporal changes were observed in both the suspended-sediment rating curve and discharge variables of the Santa Ana River. Here we show how these changes are coupled using a rating curve conceptual model based on power law formulations,

$$C_{ss} = a\,Q^b \tag{5a}$$

$$Q_{ss} = C_{ss}Q = aQ^{1+b}, \tag{5b}$$

where both suspended-sediment concentration (C_{ss}) and flux (Q_{ss}) are functions of discharge (Q) based on rating curve relationships (a, b). Although we use the power law formulation here for its mathematical simplicity and general applicability to the Santa Ana River, the general principles

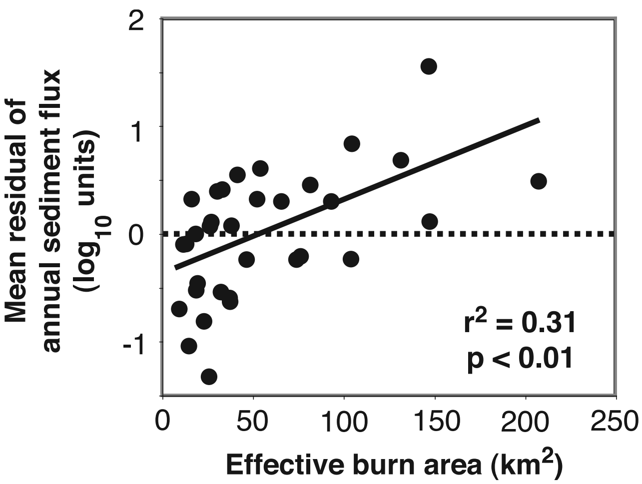

Figure 13. Relationship between effective wildfire burn area ($t_{1/2}$ = 2 years) and residual annual suspended-sediment discharge. Flux residuals computed as the difference between rating curve computations and flux estimated with the best-fit relationship with precipitation (Figure 8c). Effective wildfire $t_{1/2}$ = 2 years provided the best linear correlation with the residuals.

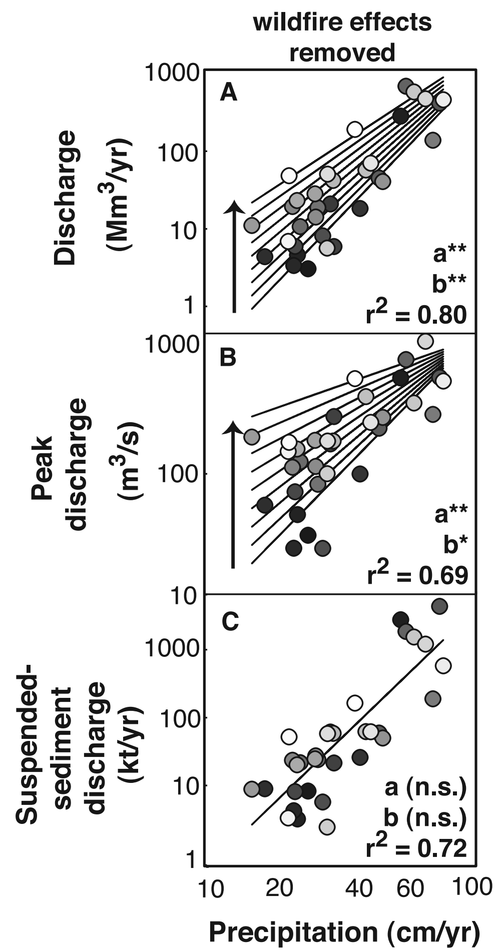

Figure 14. Identical to Figure 9, except wildfire effects have been removed by subtracting the best-fit linear relationship between effective wildfire area and the respective discharge residuals. Single line in Figure 14c represents nonsignificant (n.s.) temporal relationships ($p > 0.05$).

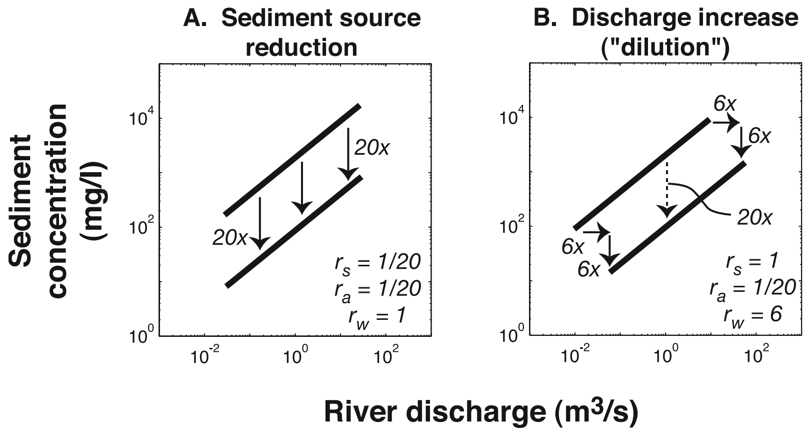

Figure 15. Conceptual model of sediment rating curve changes induced by sediment source reductions and water discharge increases. Note that similar results are predicted for very different forcing. Shown are changes induced by the linear conceptual model (equation (6)) with b equal to 0.65.

presented below are applicable to a broad range of rating curve statistical functions [e.g., *Hicks et al.*, 2000; *Horowitz*, 2003].

[34] The changes in the Santa Ana River rating curve resulted largely from decreases in offset (a) with time (Figure 3). Thus we first simplify the conceptual model by assuming rating curve slope (b) is constant with time, i.e., changes in water and/or sediment discharge exhibit linear changes in magnitude-frequency relationships. For this framework, two periods of time (subscripts 1 and 2) with different water and/or sediment discharge rates can be compared by

$$r_s = r_a r_w^{1+b}, \qquad (6)$$

where r_s is the ratio of sediment flux (Q_{ss1}/Q_{ss2}), r_a is the ratio of the sediment rating curve coefficients (a_1/a_2), and r_w is the ratio of water discharge (Q_1/Q_2). Application of this conceptual model is provided in Figure 15. Twenty-fold decreases in sediment rating curves such as exhibited in the Santa Ana River can be produced by either reductions in sediment source (Figure 15a) or by increases in water discharge (Figure 15b). The latter condition can be understood as a dilution-like process, and can occur only if the discharge increases are independent of sediment production. This dilution process results in a nonlinear relationship between r_w and r_a (equation (6)). For example, for the mean Santa Ana River b of 0.65, an increase in discharge of only sixfold will cause a 20-fold reduction in the rating curve offset (Figure 15b). This simple conceptual model shows how somewhat moderate increases in discharge can cause much larger decreases in rating curve offset.

[35] We next apply this simple conceptual model to the most significant time-dependent results for the Santa Ana River, namely that the discharge increases averaged approximately sixfold and were slightly scale dependent, and the sediment flux modifications were related to wildfire (Figure 14). The water discharge modifications would

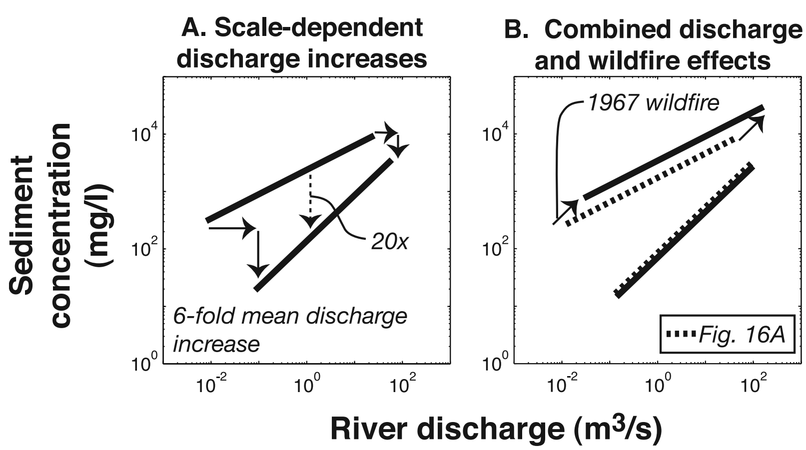

Figure 16. Conceptual model of sediment rating curve changes for the Santa Ana River. (a) Inversely proportional discharge changes with respect to event size (see Figures 14a and 14b). (b) The combined effects of Figure 16a and water and sediment flux changes from wildfire, simplified to show only the largest wildfire, the Paseo Grande of 1967.

produce a rating curve that shifts as shown above and also increases slightly in slope with time (Figure 16a). The resulting rating curve change is equivalent to the dominant changes exhibited in the Santa Ana River (see Figure 3). Wildfire correlated with increases in both water and sediment discharge with a net effect of moderate increases sediment concentrations (a 200 km^2 wildfire would double concentrations; Table 1). A simplified representation of how wildfire further modified sediment concentrations is shown in Figure 16b, where the largest wildfire (summer of 1967) is shown to cause a shift up and to the right with moderate effects on the curve offset. Hence, although wildfire modified watershed fluxes of water and sediment, it does not explain the large temporal shifts exhibited in the rating curve. Thus the conceptual model shows how water discharge, rather than sediment flux, produced a time-shifting rating curve in the Santa Ana River (Figure 16a).

6. Discussion and Conclusions

[36] Large changes in sediment rating curves are typically attributed to alterations in river suspended-sediment fluxes, which are in turn related to watershed sediment production [e.g., *Van Sickle and Beschta*, 1983; *Reid and Dunne*, 1996; *Hovius et al.*, 2000]. Here we show how hydrologic changes can be major processes in forcing order-of-magnitude alterations in suspended-sediment rating curves, especially for systems with minor suspended-sediment contributions from the river channel. For these conditions, water discharge scales nonlinearly with concentration reductions, and the power law slope of this relationship, $1 + b$ (equation (6)), will commonly range between 1.5 and 3 [cf. *Syvitski et al.*, 2000]. For these conditions, many-fold alterations in discharge will produce order-of-magnitude changes in concentration.

[37] Addition of dilute water to a channel is a necessary condition for the proposed dilution model, but it is not sufficient to cause reduced suspended-sediment concentrations or to maintain a constant long-term sediment flux. If sediment were available locally in the channel, inputs of dilute water could be expected to erode and suspend sediment, thereby increasing concentrations back to past levels (if channel sediment and geometry remained constant). As shown above, however, the main stem channel of the Santa Ana River effectively behaved as a pipe rather than an alluvial channel with respect to the suspended-sediment.

[38] Large changes in precipitation-discharge relationships are first-order characteristics of hydrologic responses to urbanization [e.g., *Leopold*, 1968; *Gregory*, 1974; *Hollis*, 1975]. As noted by hydrologic analyses of *White and Greer* [2006], urbanization in southern California of the same scale (from 10% to 40% urbanized) induced order-of-magnitude increases in the low-magnitude (1- to 2-year recurrence) peak and annual discharges and more moderate to negligible increases for the largest (>10-year recurrence) events, which is consistent with the data presented here (Figures 14a and 14b) and within other southern California watersheds [e.g., *Trimble*, 1997]. Although the Santa Ana River discharge rates were surely influenced by the upper basin, these contributions were secondary compared to the discharge generated in the lower basin. Stated simply, Santa Ana River discharge increased in a manner coherent and consistent with other urbanizing southern California watersheds. We therefore suggest an urban hydrologic response for the Santa Ana River during the period considered.

[39] Once the effects of wildfire were removed, no time-dependent relationship was found between sediment discharge and time (Figure 14 and Table 1). This suggests that the land use changes with time had little effect on the total sediment flux from the basin. Urbanization has been noted to alter rates of sediment production, although this sediment production response may be complex owing to increases and/or decreases in landscape erosion and channel scour and/or armoring, all which may be related to the hydrologic changes of the basin [*Keller*, 1962; *Wolman*, 1967; *Wolman and Schick*, 1967; *Booth*, 1990; *Trimble*, 1997]. We hypothesize that the steady rate of sediment discharge during a time of urbanization could have been a result of: (1) continual disturbance by the relatively constant land use conversion, or (2) sediment production dominance in the rural uplands above the urban regions.

[40] Wildfire effects were evident in water discharge, sediment flux and sediment concentrations, which is consistent with other semi-arid regions [*Los Angeles County Flood Control District*, 1959; *Taylor*, 1981; *Rice*, 1982; *Florsheim et al.*, 1991; *Cerdá*, 1998; *Moody and Martin*, 2001; *Lave and Burbank*, 2004]. Although wildfire was shown to significantly correlate with both water and sediment discharge, the net effect was an increase in suspended-sediment concentrations (Table 1 and Figure 16). This suggests that the relative increase of sediment production was greater than that of discharge, consistent with the results of *Cerdá* [1998]. Wildfire effects also fit exponent decay models with peak correlations occurring with $t_{1/2}$ of 1–3 years. These values were somewhat larger than those computed from other research (0.3–1.2 years, see above), which supports the hypothesis of *Lave and Burbank* [2004] that larger watersheds (such as the Santa Ana River) would exhibit a longer time delay compared to the landscape and first-order drainage basins cited in the wildfire literature. The 1967 Paseo Grande fire, which was the largest wildfire on record (Figure 12a), was responsible for elevated discharge and sediment production during the beginning of the 1968–2001 sampling record, including the year of largest discharge, 1969.

[41] If modifications to the Santa Ana River are representative of changes in other southern California rivers, most of which have urbanized at similar rates [*cf. White and Greer*, 2006], we estimate that present-day loads would be overpredicted by an order-of-magnitude owing to the effects of increases in discharge (Figures 14a and 14b) and outdated rating curves. This is especially important because river sampling has been dramatically reduced or eliminated on most coastal rivers during the past two decades when massive development and population growth has occurred. Although extending rating curves beyond the sampling history is generally not accepted [*Porterfield*, 1972], we note that sediment flux inventories for southern California use such techniques owing to data limitations [*Brownlie and Taylor*, 1981; *Inman and Jenkins*, 1999; *Willis and Griggs*, 2003]. Thus inventories of southern California coastal littoral and margin-wide sediment budgets, which are dominated by river suspended-sediment fluxes [*Inman and*

Jenkins, 1999; *Schwalbach and Gorsline*, 1985], may be substantially overestimated.

[42] This pattern of landscape modification coupled with reduced sampling of rivers is not limited to the southern California region, but is endemic of watersheds globally as pointed out by *Vörösmarty et al.* [2001], *Shiklomanov et al.* [2002] and *Beach* [2002]. We suggest that reinvigorated sampling efforts will be needed not only to characterize land use impacts such as described here and by *Vörösmarty et al.* [2004] and *Syvitski et al.* [2005], but also to evaluate the hydrologic effects of future climate change, which may be great [*Inman and Jenkins*, 1999; *Vörösmarty et al.*, 2000; *Peterson et al.*, 2002].

[43] Thus the 34-year sampling record examined here was extremely valuable for identifying not only the magnitude of suspended-sediment concentration changes but also the landscape causes of these changes. We emphasize that land use and landscape changes can alter both sediment fluxes and water discharge in rivers, both of which can have large effects in altering suspended-sediment concentration relationships. Without careful consideration of these effects, order-of-magnitude errors can be made in flux calculations.

Appendix A: Evaluation of Sampling Technique and Timing

[44] We evaluated the possibility that the changes observed in the suspended-sediment data were not caused by geomorphic or hydrologic process, but rather were an artifact of a change in sampling technique or timing. However, the sampling technique of flow-weighted, depth-integrated sampling was not altered during the record. Such a change would likely produce a step-function in the residuals with respect to time, rather than the gradual change observed (Figure 4b).

[45] There did appear to be a change in the timing of the sample collection with time, however. For example, if samples were split into two equal-length, sequential groups, the latter group had 26% less samples on days of peak discharge (Figure A1a). The latter period made up for this deficit with samples both on days prior to and following peak discharge. This suggests that although sampling has consistently focused on event discharge, sampling was less likely to sample on a day of peak discharge in the latter portion of the record.

[46] This change in sampling timing could influence temporal patterns in the rating curve if there were significantly lower concentrations measured on the nonpeak discharge days. However, very little difference was observed in the sediment concentration residuals (actual minus best-fit power law curve in Figure 4) for the different days of sampling (Figure A1b). Box plots of these groupings had substantial overlap, and t-test comparisons of the residuals suggested that the mean values of most groups were not significantly different ($p < 0.05$). The only significantly different groups ($p < 0.05$) were the samples obtained 5+ days following peak discharge (mean residual = −0.44), which were lower than the samples obtained on the day before peak (mean residual = 0.08; $p = 0.04$) and the day of peak discharge (mean residual = 0.10; $p = 0.015$). If the mean residuals (Figure A1b) were weighted by the sampling histograms (Figure A1a), however, total difference in the two sampling periods was only 0.056 $\log_{10}$ units, equivalent to a change by a factor of 1.14. This is equivalent to a ~30% reduction during 1968−2001 if continuous (equivalent to 1.14^2), considerably less than the ~2000% average change observed.

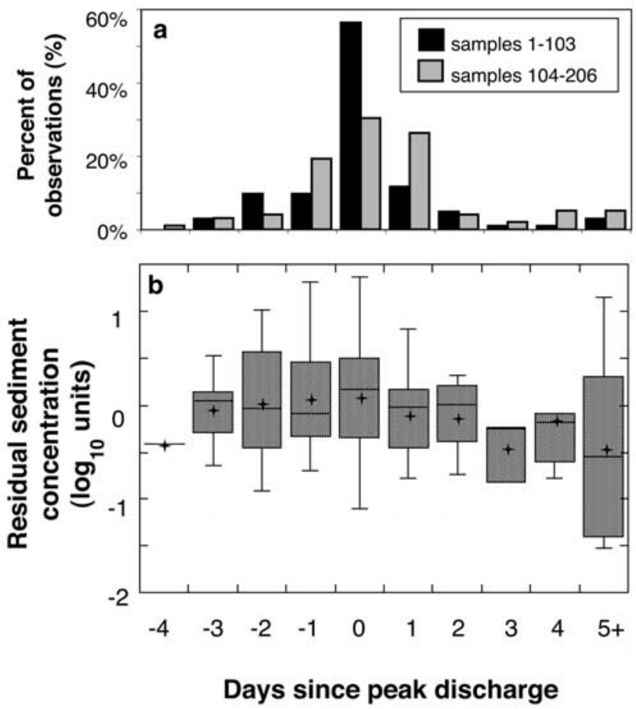

Figure A1. Evaluation of sample timing on suspended-sediment concentrations for the Santa Ana River at Santa Ana (USGS 11078000). (a) Histogram of the timing of suspended sediment sampling. Data have been separated into six groups based on number of days since a peak discharge (zero defined to be the day of peak discharge). The first half of the samples (1−103) were obtained from November 1967 to January 1980, the second half (104−206) from January 1980 to March 2001. (b) Relationship between timing of suspended-sediment sample and suspended-sediment concentration. Residuals are based on the logarithmic difference between concentration and best-fit power regression from Figure 3. Box plots are defined by the quartiles, and the whiskers are the minimum and maximum values if within 1.5 times the interquartile distance. Points are outliners of these whiskers, and pluses are mean values.

[47] Last, the results above (Figure A1b) suggest that consistent event hysteresis patterns may not exist. This is supported by hydrologic events with multiple samples (Figure A2). Of the 7 events with multiple samples, 2 show clockwise, 4 show counterclockwise and one shows no distinguishable hysteresis (Figure A2). Thus no consistent event hysteresis was identified. Further, an analysis of seasonal effects on sediment concentrations reveals that concentration residuals were not significantly different from zero during the months with the majority of sampling (Figure A3).

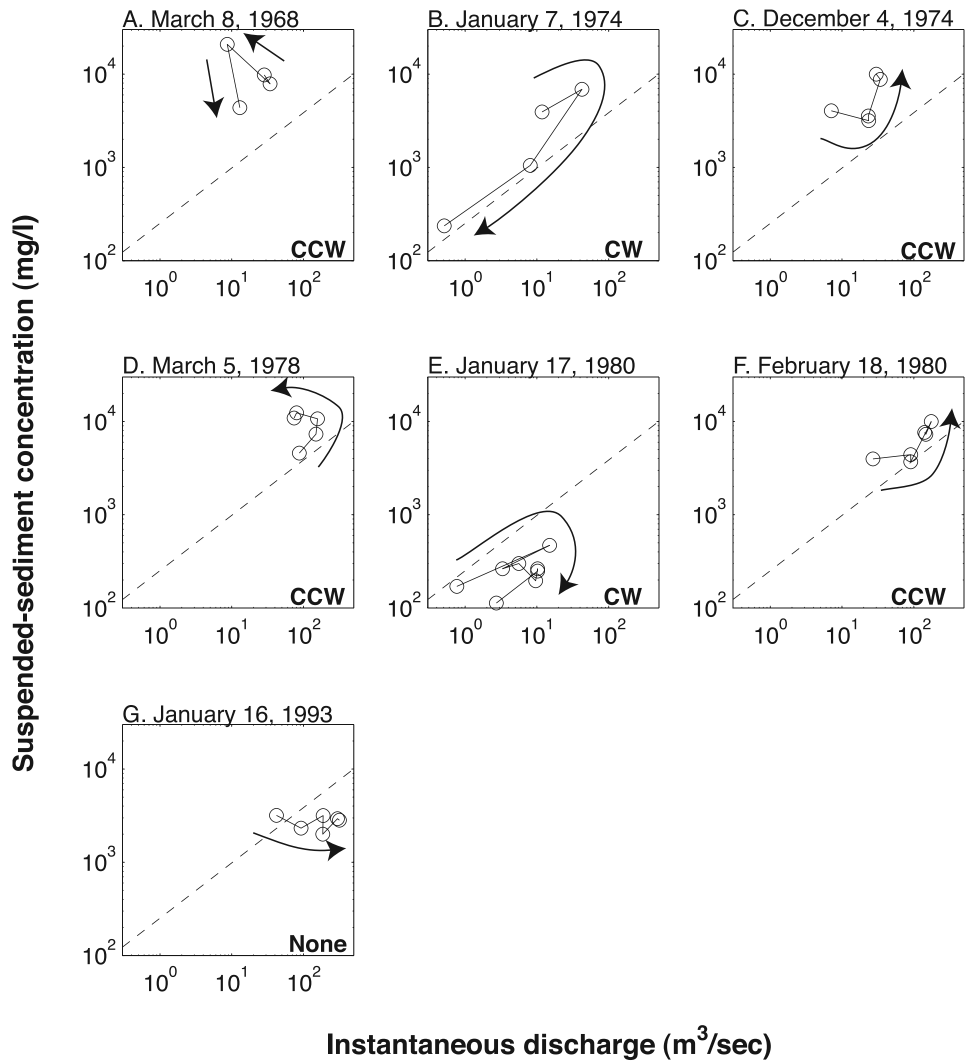

Figure A2. Event rating curves to evaluate hysteresis for the Santa Ana River at Santa Ana (USGS 11078000). Direction of hysteresis is labeled on each plot as clockwise (CW), counterclockwise (CCW), or neither (none). Each plot is labeled with the date of peak discharge and includes the best-fit power relationship through all data (dashed line). No consistent hysteresis pattern is observed in these data.

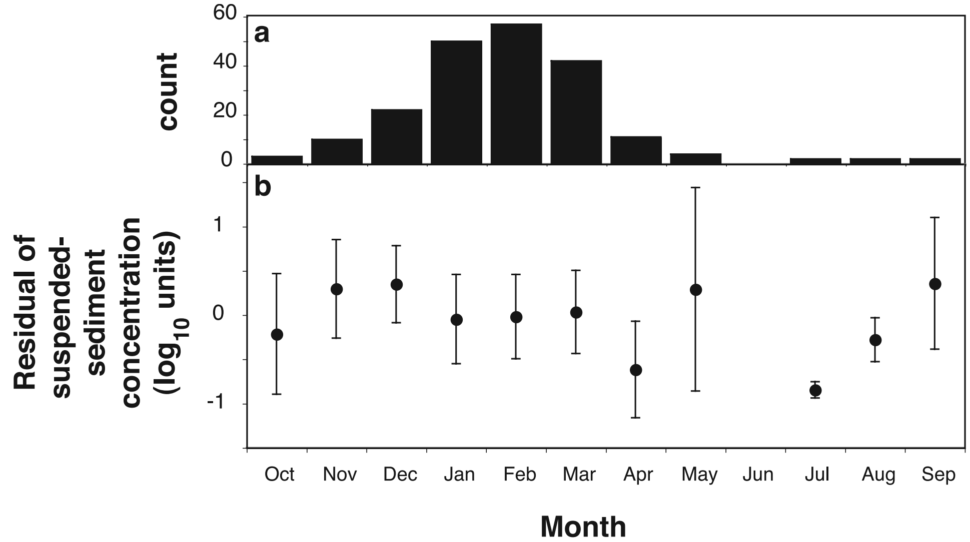

Figure A3. Monthly residuals of suspended-sediment concentrations with respect to the power law rating curve presented in Figure 3. (a) Number of samples during each calendar month. (b) Mean and standard deviation (bars) concentration residuals.

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References

Alley, W. M. (1988), Using exogenous variables in testing for monotonic trends in hydrologic time series, *Water Resour. Res.*, *24*(11), 1955–1961.
Andrews, E. D., R. C. Antweiler, P. J. Neiman, and F. M. Ralph (2004), Influence of ENSO on flood frequency along the California coast, *J. Clim.*, *17*(2), 337–348.
Asselman, N. E. M. (2000), Fitting and interpretation of sediment rating curves, *J. Hydrol.*, *234*, 228–248.
Beach, D. (2002), Coastal sprawl— The effects of urban design on coastal ecosystems in the United States, report, 40 pp., Pew Ocean Comm., Arlington, Va.
Booth, D. B. (1990), Stream-channel incision following drainage-basin urbanization, *Water Resour. Bull.*, *26*(3), 407–417.
Brownlie, W. R., and B. D. Taylor (1981), Sediment management for Southern California mountains, coastal plains and shoreline; Part C, coastal sediment delivery by major rivers in southern California, *Rep. 17-C*, 314 pp., Environ. Qual. Lab., Calif. Inst. of Technol., Pasadena.
Burbank, D. W., and R. S. Anderson (2001), *Tectonic Geomorphology*, 274 pp., Blackwell Science, Malden, Mass.
California Department of Water Resources (1960), Upper Santa Ana River Drainage Area Land and Water Use Survey, 1957, *Bull. 71*, 51 pp., Sacramento, Calif.
Cerdá, A. (1998), Post-fire dynamics of erosional processes under Mediterranean climatic conditions, *Z. Geomorphol.*, *42*(3), 373–398.
Colby, B. R. (1963), Fluvial sediments—A summary of source, transportation, deposition, and measurement of sediment discharge, *U.S. Geol. Surv. Bull., 1181-A*, 47 pp.
Dinehart, R. L. (1998), Sediment transport at gaging stations near Mount St. Helens, Washington, 1980-90, *U.S. Geol. Surv. Prof. Pap.*, *1573*, 111.
Florsheim, J. L., E. A. Keller, and D. W. Best (1991), Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Ventura County, southern California, *Geol. Soc. Am. Bull.*, *103*(4), 504–511.
Gregory, K. J. (1974), Streamflow and building activity, in *Fluvial Processes in Instrumented Watersheds*, edited by K. J. Gregory and D. E. Walling, *Spec. Publ. 6*, 107–122, Inst. of Brit. Geogr., London.
Hicks, D. M., B. Gomez, and N. A. Trustrum (2000), Erosion thresholds and suspended sediment yields: Waipaoa River basin, New Zealand, *Water Resour. Res.*, *36*, 1129–1142.
Hollis, G. E. (1975), The effect of urbanization on floods of different recurrence interval, *Water Resour. Res.*, *11*(3), 431–435.
Horowitz, A. J. (2003), An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations, *Hydrol. Processes*, *17*(17), 3387–3409.
Hovius, N., C. P. Stark, H.-T. Chu, and J.-C. Lin (2000), Supply and removal of sediment in a landslide-dominated mountain belt: Central Range, Taiwan, *J. Geol.*, *108*, 73–89.
Inman, D. L., and S. A. Jenkins (1999), Climate change and the episodicity of sediment flux of small California rivers, *J. Geol.*, *107*, 251–270.
Izbicki, J. A., G. O. Mendez, and C. A. Burton (1998), Stormflow chemistry in the Santa Ana River below Prado Dam and at the diversion downstream from Imperial Highway, southern California, 1995–98*, U.S. Geol. Surv. Water Resour. Invest. Rep., 00-4127,* 98 pp.
Keller, F. J. (1962), Effect of urban growth on sediment discharge, northwest branch Anacostia river basin, Maryland, *U.S. Geol. Surv. Prof. Pap.*, *450C*, 129–131.
Kroll, C. G. (1975), Estimate of sediment discharges, Santa Ana River at Santa Ana and Santa Maria River at Guadalupe, California, *U.S. Geol. Surv. Water Resour.*, 40–74.
Lave, J., and D. Burbank (2004), Denudation processes and rates in the Tranverse Ranges, southern California: Erosional response of a transitional landscape to external and anthropogenic forcing, *J. Geophys. Res.*, *109*, F01006, doi:10.1029/2003JF000023.
Lenzi, M. A., and L. Marchi (2000), Suspended sediment load during floods in a small stream of the Dolomites (northeastern Italy), *Catena*, *39*, 267–282.
Leopold, L. B. (1968), Hydrology for urban land planning: A guidebook on the hydrologic effects of urban land use, *U.S. Geol. Surv. Circ.*, *554*, 18 pp.
Los Angeles County Flood Control District (1959), Report on debris reduction studies for mountainous watersheds of Los Angeles County, report, 164 pp., Los Angeles, Calif.
Meade, R. H., T. R. Yuzyk, and T. J. Day (1990), Movement and storage of sediment in rivers of the United States and Canada, in *Surface Water Hydrology,* vol. 0–1, edited by M. G. Wolman and H. C. Riggs, pp. 255–280, Geol. Soc. of Am., Boulder, Colo.
Milliman, J. D., and J. P. M. Syvitski (2001), Geomorphic/tectonic control of sediment discharge to the ocean; the importance of small mountainous rivers, *J. Geol.*, *100*(5), 525–544.
Moody, J. A., and D. A. Martin(2001), Initial hydrologic and geomorphic response following a wildfire in the Colorado front range, *Earth Surf. Processes Landforms*, *26*, 1049–1070.

Nelson, C. R. (1982), The Santa Ana River in Orange County, California: A case history in sediment transport, in *National Research Council and California Institute of Technology, Storms, Floods, and Debris Flows in Southern California and Arizona 1978 and 1980: Proceedings of a Symposium*, pp. 177–190, Natl. Acad. Press, Washington, D. C.

Nelson, E. J., and D. B. Booth (2002), Sediment sources in an urbanizing, mixed land-use watershed, *J. Hydrol.*, *264*(1–4), 51–68.

Peterson, B. J., R. M. Holmes, J. W. McClelland, C. J. Vorosmarty, R. B. Lammers, A. I. Shiklomanov, I. A. Shiklomanov, and S. Rahmstorf (2002), Increasing river discharge to the Arctic Ocean, *Science*, *298*(5601), 2171–2173.

Pinter, N., and W. D. Vestal (2005), El Niño-driven landsliding and post-grazing vegetative recovery, Santa Cruz Island, California, *J. Geophys. Res.*, *110*, F02003, doi:10.1029/2004JF000203.

Porterfield, G. (1972), *Techniques of Water-Resources Investigations of the U.S. Geological Survey,* vol. 3, *Computation of Fluvial-Sediment Discharge*, *Applications of Hydraulics,* 7 pp., U.S. Gov. Printing Off., Washington, D. C.

Reid, L. M., and T. Dunne (1996), *Rapid Evaluation of Sediment Budgets*, 167 pp., Catena Verlag, Reiskirchen, Germany.

Rice, R. M. (1982), Sedimentation in the chaparral: How do you handle unusual events?, in *Sediment Budgets and Routing in Forested Drainage Basins,* edited by F. J. Swanson et al., *Gen. Tech. Rep. PNW-141*, pp. 39–49, Pac. NW For. and Range Exp. Stn., Portland, Oreg.

Rubin, D. M., and D. J. Topping (2001), Quantifying the relative importance of flow regulation and grain size regulation of suspended-sediment transport α and tracking changes in grain size of bed sediment β, *Water Resour. Res.*, *37*, 133–146.

Schwalbach, J. R., and D. S. Gorsline (1985), Holocene sediment budgets for the basins of the California Continental Borderland, *J. Sed. Petrol.*, *55*, 829–842.

Shiklomanov, A. I., R. B. Lammers, and C. J. Vorosmarty (2002), Widespread decline in hydrological monitoring threatens Pan-Arctic research, *Eos Trans. AGU*, *83*(2), 13, 16–17.

Syvitski, J. P. M., M. D. Morehead, D. B. Bahr, and T. Mulder (2000), Estimating fluvial sediment transport: The rating parameters, *Water Resour. Res.*, *36*, 2747–2760.

Syvitski, J. P. M., C. J. Vorosmarty, A. J. Kettner, and P. Green (2005), Impact of humans on the flux of terrestrial sediment to the global coastal ocean, *Science*, *308*, 376–380.

Taylor, B. D. (1981), Sediment management for southern California mountains, coastal plains and shoreline: Part B. Inland sediment movements by natural processes*, Environ. Qual. Lab. Rep. 17-B*, Calif. Inst. of Technol., Pasadena.

Topping, D. J., D. M. Rubin, and L. E. Vierra Jr. (2000), Colorado River sediment transport: 1. Natural sediment supply limitation and the influence of Glen Canyon Dam, *Water Resour. Res.*, *36*, 515–542.

Trimble, S. W. (1997), Contribution of stream channel erosion to sediment yield from an urbanizing watershed, *Science*, *278*, 1442–1444.

Trimble, S. W. (1999), Decreased rates of alluvial sediment storage in the Coon Creek basin, *Science*, *285*, 1244–1246.

U.S. Army Corps of Engineers (1994), *Water Control Manual, Prado Dam and Reservoir, Santa Ana River, California*, 83 pp., Washington, D. C.

U.S. Army Corps of Engineers (2003), *Interim Water Control Plan (During Construction), Prado Dam & Reservoir, Santa Ana River, Orange County, California*, Washington, D. C.

U.S. Census Bureau (2003), U.S. Census Bureau population data, http://www.census.gov, Washington, D. C.

Van Sickle, J., and R. L. Beschta (1983), Supply-based models of sediment transport in streams, *Water Resour. Res.*, *19*(3), 768–778.

Vörösmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers (2000), Global water resources: Vulnerability from climate change and population growth, *Science*, *289*, 284–288.

Vörösmarty, C. J., et al. (2001), Global water data: A newly endangered species, *Eos Trans. AGU*, *82*(5), 54–56.

Vörösmarty, C., et al. (2004), Humans transforming the global water system, *Eos Trans. AGU*, *85*(48), 509, 513–514.

Walling, D. E. (1974), Suspended sediment and solute yields from a catchment prior to urbanization, in *Fluvial Processes in Instrumented Watersheds*, edited by K. J. Gregory and D. E. Walling, *Spec. Publ. 6,* pp. 169–192, Inst. of Brit. Geogr., London.

Walling, D. E. (1977), Assessing the accuracy of suspended sediment rating curves for a small basin, *Water Resour. Res.*, *13*, 531–538.

Walling, D. E., and D. Fang (2003), Recent trends in the suspended sediment loads of the world's rivers, *Global Planet. Change*, *39*(1–2), 111–126.

Warrick, J. A., and J. D. Milliman (2003), Hyperpycnal sediment discharge from semiarid southern California rivers: Implications for coastal sediment budgets, *Geology*, *31*, 781–784.

White, M. D., and K. A. Greer (2006), The effects of watershed urbanization on the stream hydrology and riparian vegetation of Los Penaquitos Creek, California, *Landscape Urban Planning*, *74*, 125–138.

Williams, C. N., Jr., M. J. Menne, R. S. Vose, and D. R. Easterling (2004), United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data, *ORNL/CDIAC-118, NDP-070*, http://cdiac.ornl.gov/epubs/ndp/ushcn/usa.html, Carbon Dioxide Inf. Anal. Cent., Oak Ridge Natl. Lab., Oak Ridge, Tenn.

Williams, G. P. (1989), Sediment concentration versus water discharge during single hydrologic events in rivers, *J. Hydrol.*, *111*, 89–106.

Willis, C. M., and G. B. Griggs (2003), Reductions in fluvial sediment discharge by coastal dams in California and implications for beach sustainability, *J. Geol.*, *111*, 167–182, doi:10.1086/345922.

Wolman, M. G. (1967), A cycle of sedimentation and erosion in urban river channels, *Geogr. Ann.*, *49A*, 385–395.

Wolman, M. G., and A. P. Schick (1967), Effects of construction in fluvial sediment, urban and suburban areas of Maryland, *Water Resour. Res.*, *3*, 451–464.

Yang, S. L., J. Zhang, J. Zhu, J. P. Smith, S. B. Dai, A. Gao, and P. Li (2005), Impact of dams on Yangtze River sediment supply to the sea and delta intertidal wetland response, *J. Geophys. Res.*, *110*, F03006, doi:10.1029/2004JF000271.

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