The effects of wildfire on the sediment yield of a coastal California watershed

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ABSTRACT

The occurrence of two wildfires separated by 31 yr in the chaparral-dominated Arroyo Seco watershed (293 km^2) of California provides a unique opportunity to evaluate the effects of wildfire on suspended-sediment yield. Here, we compile discharge and suspended-sediment sampling data from before and after the fires and show that the effects of the postfire responses differed markedly. The 1977 Marble Cone wildfire was followed by an exceptionally wet winter, which resulted in concentrations and fluxes of both fine and coarse suspended sediment that were ~35 times greater than average (sediment yield during the 1978 water year was 11,000 t/km^2/yr). We suggest that the combined 1977–1978 fire and flood had a recurrence interval of greater than 1000 yr. In contrast, the 2008 Basin Complex wildfire was followed by a drier than normal year, and although suspended-sediment fluxes and concentrations were significantly elevated compared to those expected for unburned conditions, the sediment yield during the 2009 water year was less than 1% of the post–Marble Cone wildfire yield. After the first postfire winters, sediment concentrations and yield decreased with time toward prefire relationships and continued to have significant rainfall dependence. We hypothesize that the differences in sediment yield were related to precipitation-enhanced hillslope erosion processes, such as rilling and mass movements. The millennial-scale effects of wildfire on sediment yield were explored further using Monte Carlo simulations, and these analyses suggest that infrequent wildfires followed by floods increase long-term suspended-sediment fluxes markedly. Thus, we suggest that the current approach of estimating sediment yield from sediment rating curves and discharge data—without including periodic perturbations from wildfires—may grossly underestimate actual sediment yields.

INTRODUCTION

Wildfire alters the physical conditions of vegetation and soil, and these changes can modify the hydrologic and geomorphic processes within the burned landscape (Shakesby and Doerr, 2006). There are two primary hydrogeomorphic effects of wildfire: (1) an increase in runoff, primarily through increased overland flow from the combined effects of reduced water infiltration through soil hydrophobic layers, reduced surface roughness, and a reduction in evapotranspiration (DeBano and Krammes, 1966; Swanson, 1981; Brown, 1972; Rice, 1974; DeBano, 2000; Doerr et al., 2000; Martin and Moody, 2001; Neary et al., 2005), and (2) an increase in erosion through several mechanisms including dry ravel, rain splash erosion and transport, rilling resulting from surface-water flow, and mass movements (Osborn et al., 1964; Wells, 1981; Scott and Williams, 1978; Scott and Van Wyk, 1990; Inbar et al., 1998; Moody et al., 2005; Shakesby and Doerr, 2006). Although these two effects can be pronounced—runoff and erosion can increase by up to several orders of magnitude following wildfire—they commonly last only 3–8 yr and decay quickly over this time (Rowe et al., 1954; LACFCD, 1959; Swanson, 1981; Brown et al., 1982; Cerdà, 1998; Cerdà and Lasanta, 2005; Reneau et al., 2007; Warrick and Rubin, 2007). Even so, wildfire will increase long-term erosion rates from the landscape if the effects are marked and fire recurrence is sufficiently frequent (Swanson, 1981; Lavé and Burbank, 2004).

Increased runoff and erosion from burned landscapes often cause increased suspended-sediment discharge and sedimentation in downstream channels, reservoirs, and coastal landforms, which can alter landform morphology and aquatic habitats (e.g., Florsheim et al., 1991; Reneau et al., 2007; Malmon et al., 2007; Warrick et al., 2008). Postfire erosion also results in increased export of carbon and nutrients from burned watersheds, which can influence rates of primary production and carbon preservation in depositional settings (Johnson et al., 2004; Murphy et al., 2006; Hunsinger et al., 2008). Because of the rates and patterns of erosion following a fire, both hillslope morphology and sedimentary deposits within the geologic record will be influenced by periodic wildfire (Meyer et al., 1995; Mensing et al., 1999; Pierce et al., 2004; Roering and Gerber, 2005; Shakesby and Doerr, 2006).

The rate of erosion following a wildfire can vary widely, and differences have been attributed to prefire vegetation, landscape slope, wildfire burn intensity, postfire soil conditions, and precipitation rates (Shakesby and Doerr, 2006; Malmon et al., 2007). The prefire vegetation types and conditions will have important influences on the burn intensity and postfire soil hydrophobicity. For example, combustion of fire-prone chaparral produces marked water repellency in soils because of the low vegetation height and high burn temperatures (Rice, 1982; Wells, 1981).

Vegetation also inhibits downslope sediment transport during the years before a wildfire, resulting in hillslope storage of sediment (Fig. 1A; Rice, 1982; Florsheim et al., 1991). After a wildfire, this hillslope sediment will be released downslope as dry ravel on slopes greater than a critical angle of repose (Fig. 1B). Dry ravel is recognized as an important postfire sediment transport process in both wet and dry climates (e.g., Florsheim et al., 1991; Roering and Gerber, 2005), and Wells (1981) reported that annual net dry ravel transport rates increased

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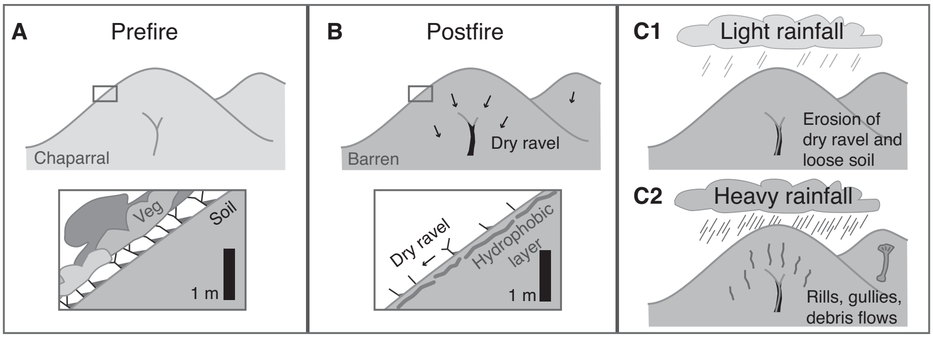

Figure 1. Illustration of the effects of wildfire on sediment yield from a steep, chaparral landscape. (A) Before a wildfire, the dense chaparral vegetation (veg) and organic debris retain sediment that had been mobilized downslope by diffusive processes. (B) During and immediately after a wildfire, the combustion of vegetation and organic debris above the ground reduces surface roughness and releases retained soil as dry ravel, which accumulates as talus in colluvial hollows, hillslope toes, and stream channels. The high temperature of chaparral fire also creates a hydrophobic layer beneath the soil surface. (C1) and (C2) Sediment erosion and transport processes during postfire rainfall are highly dependent upon rainfall intensity. Whereas light rainfall will result in the erosion of loose soil and dry ravel talus, heavy rainfall will generate overland flow at rates that can cut rills and gullies into the soil and potentially generate debris flows.

~30-fold during the first year following wildfires in southern California chaparral.

Once the postfire sediment supply has increased by dry ravel, the fate of this sediment and further erosion of hillslope soils will depend largely on the timing and intensity of rainfall (LACFCD, 1959; Keller et al., 1997; Lavé and Burbank, 2004; Shakesby and Doerr, 2006; Malmon et al., 2007). With increasing rainfall intensity and amounts, the rate of sediment eroded and transported downslope from overland flow increases. Overland flow can erode exposed soil, mobilize dry ravel talus, and—during heavy rainfall—cut rills and gullies into the landscape and activate debris flows (Fig. 1C; Rice, 1982; Wells, 1981; Florsheim et al., 1991; Cerdá, 1998; Inbar et al., 1998; Cannon, 2001; Moody and Martin, 2001; Gabet, 2003). Thus, it is common to find postwildfire erosion models incorporating strong rainfall dependencies (e.g., Rowe et al., 1954; LACFCD, 1959; Rice, 1982; Keller et al., 1997; Reneau et al., 2007; Malmon et al., 2007; SEAT, 2008).

There exists a great need to extend the understanding of these wildfire erosion effects to suspended-sediment discharge at watershed scales (>100 km^2). Shakesby and Doerr (2006) noted that watershed-scale studies are unfortunately rare because of the difficulty and costs of monitoring before and after a wildfire and the potential for loss or destruction of monitoring sites during wildfire. Much more effort has been placed in plot-scale experiments (1–10 m^2) or first-order drainage basin monitoring (~1 km^2; e.g., Scott, 1993; Cerdá, 1998; Scott et al., 1998; Moody and Martin, 2001), the results of which cannot be scaled directly to watersheds (Shakesby and Doerr, 2006; Walling, 2006). Perhaps the largest drainage basin with extensive pre- and postfire sampling of suspended-sediment discharge is the ephemeral mountain stream draining a 7 km^2 burn sampled by Malmon et al. (2007), in which suspended-sediment concentrations increased by two orders of magnitude after the fire.

Watershed-scale (>100 km^2) investigations of postfire sediment production have largely relied upon sediment accumulation behind debris basins and dams (e.g., Scott and Williams, 1978; Lavé and Burbank, 2004). While these studies have shown that wildfire can increase watershed sediment yield, the interpretation of these results must be balanced with the knowledge that dams and debris basins do not capture the full sediment load of the rivers, especially during high loads that follow wildfire (e.g., Keller et al., 1997). Furthermore, these sedimentation studies typically do not yield data on changes to water discharge from the watershed or sediment grain sizes (e.g., Lavé and Burbank, 2004). Thus, to evaluate the effects of wildfire on sediment yield at watershed scales (>100 km^2), one must attempt to extrapolate erosion rates or other findings from smaller plot-scale investigations, which is not straightforward (e.g., Walling, 2006), or use dam and debris basin sedimentation records results, which may not fully account for total sediment yield.

Two large wildfires within the Arroyo Seco watershed of central California (Fig. 2) provide an ideal opportunity to evaluate the effects of wildfire on hydrologic fluxes from a watershed. This is largely due to a river gauging and sampling program by the U.S. Geological Survey (USGS) that provided discharge and suspended-sediment data, which we supplemented with additional suspended-sediment sampling from 2008 to 2010. Using these data, we investigated whether the wildfires produced significant changes in water and suspended-sediment discharge rates. Our primary goals were to: (1) characterize the postfire changes in water and sediment yields, (2) use the two wildfires and postfire hydrologic conditions to compare and contrast postfire effects, and (3) use these data to provide insights into long-term (millennial) dynamics of watershed-scale denudation.

STUDY SITE

The Arroyo Seco watershed is a steep, 790 km^2 basin within the second largest watershed of California's coastal ranges, the Salinas River (11,000 km^2). Here, we focus on the upper Arroyo Seco watershed that drains into USGS gauging station 11151870 (site 1A in Fig. 2; Table 1) and has a drainage area of 293 km^2. The Arroyo Seco drains the steep Santa Lucia Range (maximum elevation 1784 m), which trends southeast from Monterey Bay to San Luis Obispo and forms the rugged Big Sur coastal setting. The Santa Lucia Range is part of the greater Coastal Ranges of California and is characterized by a Mesozoic granitic basement and widely distributed metamorphic and sedimentary (both marine and terrestrial) rocks (Hall, 1991; Table 1).

These steep and tall mountains orographically enhance precipitation, which is dominated by rainfall during winter (November to March) storms, resulting in average precipitation rates of ~90 cm/yr along the Big Sur coast, ~165 cm/yr along the peaks of the Santa Lucia Range, and ~30 cm/yr in the central Salinas River valley (Rantz, 1969). Because of the Arroyo Seco's steep slopes and high elevations—five peaks on its drainage divide exceed 1400 m elevation (Fig. 2B)—the Arroyo Seco has the highest average runoff rates of all of the Salinas River tributaries (Farnsworth and Milliman, 2003). There is considerable variability in annual precipitation, however, caused by the location of Pacific storm tracks and levels of atmospheric moisture, which in turn are influenced by El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) cycles (Gabet and Dunne, 2002; Andrews et al., 2004; Pinter and Vestal, 2005). The variability in precipitation results in annual water and sediment discharge rates that

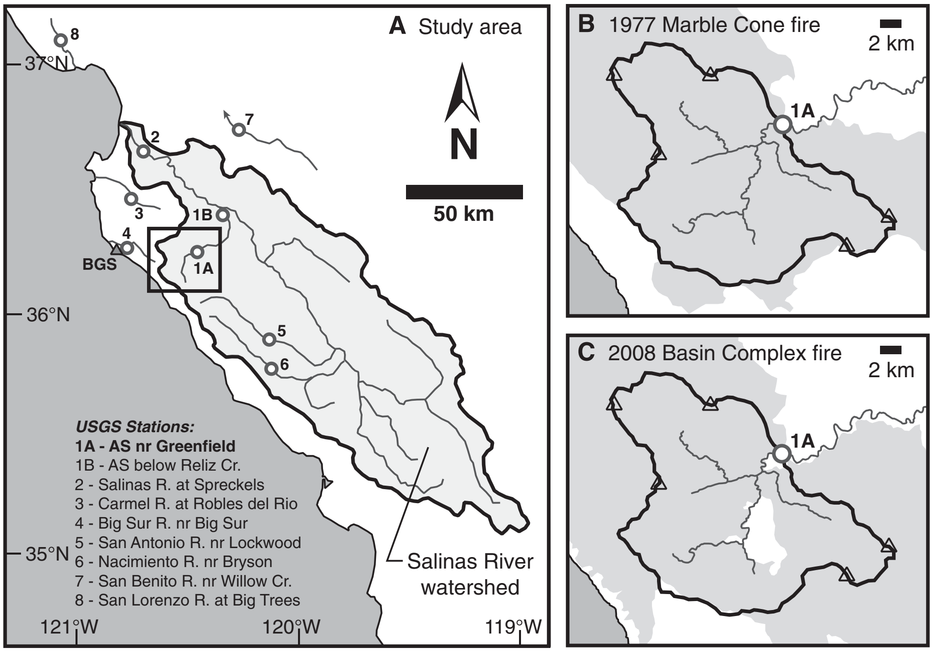

Figure 2. The central California study area and research stations. (A) Watershed map of the Salinas River (shaded) and the Arroyo Seco (AS). U.S. Geological Survey (USGS) gauging stations shown with numbered symbols (1–8), precipitation station at Big Sur (BGS) shown with triangle. (B–C) Fire maps from 1977 and 2008 focused on the Arroyo Seco watershed (shown with heavy line). Wildfire extent is shown with shading. Peaks over 1400 m are shown with triangles.

vary by over an order of magnitude (Farnsworth and Milliman, 2003).

The Arroyo Seco watershed is dominantly chaparral (Table 1), which is characterized by dense communities of fire-prone shrubby vegetation. It also lies wholly in the undeveloped lands of the Ventana Wilderness of the Los Padres National Forest and is thus not subject to grazing or other landscape disturbances (cf. Pinter and Vestal, 2005). Wildfire is a regular phenomenon in the chaparral-dominated watersheds of central and southern California, largely owing to the hot, dry summers and the abundant fuel from vegetation and plant litter (Wells, 1981; Rice, 1982; Greenlee and Langenheim, 1990; Keeley and Zedler, 2009). Because of the high temperatures and low burn heights of wildfire in chaparral, soil hydrophobicity is commonly observed after chaparral wildfires (Fig. 1B; Wells, 1981; Rice, 1982).

Recent Wildfires in the Arroyo Seco Watershed

Two recent wildfires—the 1977 Marble Cone fire and the 2008 Basin Complex fire—burned the majority of the Arroyo Seco watershed (Figs. 2B and 2C; Table 1). The ignition source of the 1977 wildfire was a lightning strike, and while the 2008 wildfire was similarly started by lightning, a second region of the 2008 burn was started by a human disturbance suspected to be arson. Both wildfires were noted to have burned at high intensities throughout the chaparral (Griffin, 1978; SEAT, 2008; Fig. 3).

The August 1977 Marble Cone wildfire burned the entire gauged portion of the Arroyo Seco watershed and parts of adjacent watersheds, including those of the Big Sur and Carmel Rivers (Fig. 2B). Prior to this fire, the Arroyo Seco watershed had not burned for 30–50 yr (Griffin, 1978). Accounts of this fire and its effects on the vegetation, soil conditions, and channel morphology are provided by Griffin (1978) and Hecht (1981). The 1977 fire burned intensely and uniformly throughout the chaparral, and these hillslopes were observed to have “suffered heavy soil erosion during the January-to-March storms of 1978” as described qualitatively by Griffin (1978, p. 10). Griffin (1978) observed that the upper layers of soil had been removed, and extensive networks of rills and small gullies had been cut into steep slopes during these 1978 storms. Hecht (1981) described the extensive filling and subsequent scour of sand and gravel from the channels in the Carmel River watershed following the 1977 Marble Cone wildfire and suggested that this fill-scour cycle transpired over an interval of 1–3 yr. Hecht (1981) also reported that sedimentation of the Los Padres Reservoir of the Carmel River during the first winter after the 1977 fire was 25 times greater than the average annual sedimentation rate during the previous 30 yr.

The July 2008 Basin Complex wildfire burned the majority (~93%) of the gauged Arroyo Seco watershed (Figs. 2C and 3). Field- and satellite-based analyses of this fire and its intensity were provided by consortia of state and federal agencies (BAER, 2008; SEAT, 2008), which noted thorough combustion of the chaparral, widespread occurrence of soil hydrophobicity, extensive dry ravel throughout steep slopes, and moderate to high burn intensity classifications for the majority of the Arroyo Seco watershed. Postfire erosion-control measures (e.g., hydromulching and seeding) were not performed because of concerns about native plant species and potential weed introduction into the wilderness area (BAER, 2008; SEAT, 2008). Combined, these factors indicated that the likelihood for flooding and debris flows in the burned region was “high to very high” (BAER, 2008, p. 1), although it was predicted that the “magnitude of

TABLE 1. WATERSHED CHARACTERISTICS OF THE ARROYO SECO

U.S. Geological Survey gauging station	11151870
Station name	Arroyo Seco near Greenfield
Drainage area	293 km^2
Maximum elevation	1789 m
Average landscape slope at 30 m resolution	0.53 m/m
Surficial geology*	52.0% schist 22.1% sandstone 21.3% granodiorite 3.3% mudstone 1.3% plutonic rock
Land cover†	66.8% shrub 28.5% hardwoods 3.9% conifer 0.6% herbaceous 0.1% barren/other
Percent burned in 1977	100%
Percent burned in 2008	93%

*From data provided from Jennings et al. (1977).
†From data provided from FRAP (2002).

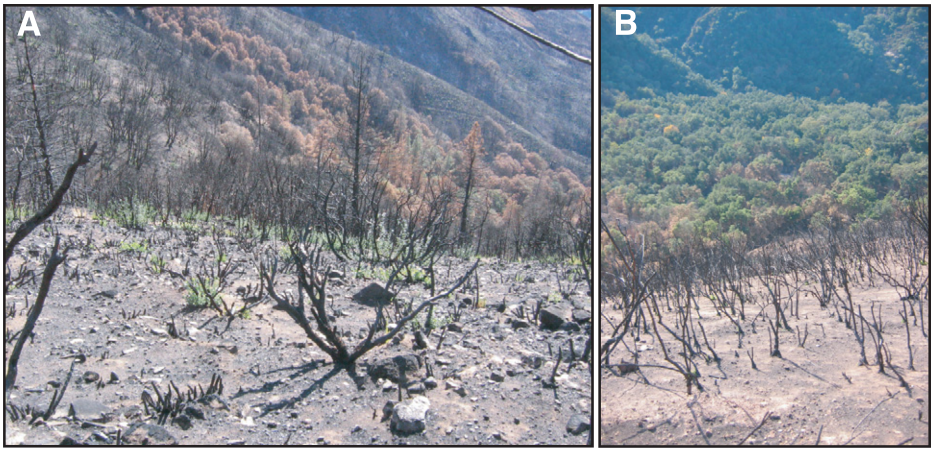

Figure 3. Photographs of the burned chaparral and bare soils in the upper slopes of the Arroyo Seco watershed following the 2008 Basin Complex wildfire. Also shown is rapid regrowth of chaparral from the roots (A), burned overstory of pine forest (A, background), and a region of riparian and oak woodland that was unburned (B, background). Photos were obtained on 17 November 2008 by J. Hatten. Burned chaparral in the foreground of each photograph is 0.5 to 1 m tall.

post-fire damage will ultimately be determined by the intensity and duration of storms that impact the burn area, particularly during the winter of 2008–09" (SEAT, 2008, p. 21).

METHODS

Data Collection

USGS River Data—Arroyo Seco

Our analyses focused on river discharge, suspended-sediment concentration, and suspended-sediment discharge data from the USGS gauging station 11151870 (Arroyo Seco near Greenfield; 293 km^2 drainage area). This station was designated site 1A for the purposes of this paper (Fig. 2; Table 2). Mean daily and annual peak discharge data were available for this site for water years 1962–1986. In addition, we utilized all USGS suspended-sediment concentration and grain-size distribution results from flow-integrated samples at this site, consisting of 65 samples collected during water years 1965–1983.

From these discharge and concentration data, the USGS estimated daily and annual suspended-sediment fluxes using the techniques of Porterfield (1972), and these estimates are available for water years 1963–1984 for site 1A. The uncertainties of these load estimates were not provided by the USGS, although we provide an assessment of these uncertainties in the "Data Analyses" section below. All data were obtained through the USGS Surface Water Database (http://waterdata.usgs.gov/nwis/sw).

River Sample Collection—Arroyo Seco

To characterize the effects of the 2008 wildfire, we collected suspended-sediment samples at two USGS gauging stations on the Arroyo Seco (sites 1A and 1B; Fig. 2A; Table 2). The purpose of this sampling was to collect samples for total suspended solids and organic chemistry analyses (e.g., Hatten et al., 2010). During the 2008–2009 winter, one sample was obtained during the low-flow conditions of November 2008, and the remaining 19 samples were obtained between 15 and 18 February 2009 during the highest rainfall and discharge event of the water year. Eleven samples were taken during the 2009–2010 winter, and all were taken during storms with elevated river discharge. Sampling dates, times, and results are provided in the GSA Data Repository.[1]

TABLE 2. U.S. GEOLOGICAL SURVEY (USGS) GAUGING STATIONS UTILIZED FOR THIS PAPER

Site no.	USGS gauging station	Station name	Drainage area (km^2)	Record interval (water years)
1A	11151870	Arroyo Seco near Greenfield	293	1962–2010*
1B	11152050	Arroyo Seco below Reliz Cr.	787	1996–2010
2	11152500	Salinas R. at Spreckels	10,770	1930–2010
3	11143200	Carmel R. at Robles del Rio	500	1957–2010
4	11143000	Big Sur R. near Big Sur	120	1951–2010
5	11149900	San Antonio R. near Lockwood	562	1966–2010
6	11148900	Nacimiento R. near Bryson	240	1972–2010
7	11156500	San Benito R. near Willow Cr.	645	1940–2010
8	11160500	San Lorenzo R. near Big Trees	275	1937–2010

*This site was operated as a continuous-record streamflow site during water years 1962 to 1986, after which operations were reduced to a partial-record program, for which instantaneous stage and limited flood-flow measurements were recorded.

Samples were obtained using a Wildco Horizontal Alpha Sampler that was lowered into the center of the main channel and tripped to capture water from just below the surface. Rouse calculations for these sampling sites suggest that the fine fraction of the suspended sediment (i.e., <0.063 mm) and some sand should be wash load (see part 2 of supplementary information [see footnote 1]). Hence, our near-surface samples of fine (<0.063 mm) suspended-sediment concentrations should be directly comparable to the depth-integrated fine suspended-sediment samples of the USGS, because uniform vertical concentration profiles would be expected for these grain sizes.

Water samples were passed through a 0.063 mm sieve to recover coarse suspended sediment, and fine suspended sediment was concentrated from the sieved water by centrifugation in 500 mL bottles at 3250 g for 10 min. After centrifugation, a 20 mL subsample of the overlying (i.e., supernatant) liquid was removed from each bottle and filtered through a combusted glass fiber filter (Whatman GF/A with a 0.7 µm pore diameter) to determine the portion of suspended sediment that did not settle during centrifugation. Sediments recovered from sieving, centrifugation, and supernatant subsampling were all oven-dried until constants weights were achieved (12–24 h for filters, 24–48 h for bulk samples). Suspended-sediment concentrations for each particle class (sieved, centrifuged, and supernatant) were calculated by dividing the dried mass of particles by the total volume of the water sampled, or subsampled in the case of the supernatant. The concentration of fine particles (<0.063 mm) was determined by adding the concentrations of centrifuged and supernatant particles, while the coarse fraction (>0.063 mm) was the concentration of sieved material.

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[1] GSA Data Repository item 2012140, tabulated river suspended-sediment sampling results from water years 2009–2010, a comparison of the USGS flow-integrated suspended-sediment samples and our near surface suspended-sediment samples, and a comparison of the suspended-sediment concentrations measured at the three sites sampled on the Arroyo Seco, is available at http://www.geosociety.org/pubs/ft2012.htm or by request to editing@geosociety.org.

For each suspended-sediment sample, we found an instantaneous river discharge from USGS gauging records. The USGS calculates discharge at 15 min intervals for the downstream gauge (site 1B). The primary gauge, site 1A, was maintained as a partially recording station between 1987 and 2010, for which instantaneous stage was recorded continually. The USGS does maintain a stage-discharge rating curve for this site (http://waterdata.usgs.gov/nwisweb/data/ratings/exsa/USGS.11151870.exsa.rdb), and we used this rating curve and the instantaneous stage measurements to estimate discharge at the time that our samples were collected. Our suspended-sediment sampling was conducted only during and immediately following rainfall, and we were able to sample both rising and falling limbs of these events, although no consistent hysteresis patterns were observed over flood hydrographs.

We were able to sample both Arroyo Seco sites during the 2009 water year but only site 1B during the 2010 water year. A comparison of suspended-sediment concentrations for the two Arroyo Seco sampling sites during the first year is presented in part 3 of the supplementary information (see footnote 1). This comparison reveals that the discharge-concentration relations did not vary significantly between these sites. Thus, for comparative purposes with the 1965–1983 USGS samples from site 1A, we present site 1A data from water year 2009 and site 1B data from water year 2010.

USGS Data—Other Rivers

For comparative purposes, we also evaluated water and sediment discharge records from other USGS gauges in the region. To evaluate whether wildfire influenced suspended-sediment fluxes from the larger Salinas River watershed, we obtained suspended-sediment concentration and daily and annual sediment flux estimates from the USGS station 11152500 (10,770 km^2; site 2; Fig. 2). For this station, the USGS collected 105 suspended-sediment samples during water years 1969–1986 and made flux estimates for water years 1970–1979. We also evaluated the effect of the two wildfires on peak and total water discharge in the Arroyo Seco using comparisons with six additional USGS stations listed as sites 3–8 in Table 2 and Figure 2.

Precipitation Data

Lastly, precipitation data were obtained from the California Department of Water Resources California Data Exchange Center (CDEC), which makes hydrologic data available from numerous state and federal agencies (http://cdec.water.ca.gov/). Although there is a weather station maintained by the U.S. Forest Service within the Arroyo Seco watershed (station ARY; 300 m elevation), these data are only available for June 1999–2010, which does not include the important pre-1977 and post-1977 intervals. The next nearest station with data available for the duration of our study is the monthly recording National Weather Service rainfall gauge at Big Sur (station BGS; 73 m elevation; Fig. 2A), which has been operated since October 1913, although these data were not collected for the majority of the 1981 and 1982 water years (Fig. 4). The annual rainfall values at stations BGS and ARY are correlated at $r^2 > 0.8$ using linear regression, although total rainfall at BGS averages 1.5 times that measured at ARY. Thus, for the purposes of this paper, we utilize BGS data to provide information about rainfall rates in the Arroyo Seco watershed.

Data Analyses

Sediment Discharge and Uncertainty Calculations

The USGS calculated suspended-sediment discharge for the Arroyo Seco for water years 1963–1984 and for the Salinas River for 1970–1979, although uncertainties for these discharge estimates were not provided. Uncertainty in these suspended-sediment discharge estimates can be evaluated by the scatter in the discharge and suspended-sediment concentration data from which these estimates were based. Following Hicks et al. (2000), the 95% confidence intervals of sediment discharge can be estimated as $2s/\sqrt{(N)}$, where s is the standard error in the rating curve (even though the USGS methods do not utilize simple rating curve techniques), and N is the number of samples. Assuming a power-law rating curve, the 95% confidence intervals for the Arroyo Seco are estimated at ±46% and ±50% for the loads estimated from the pre-1978 and 1978 water year data. Confidence intervals for the sediment discharge during subsequent water years (1979–1984) are much higher due to the smaller number of samples. Assuming a similar standard error as calculated for the 1978 water year, computed 95% confidence intervals range between ±68% and ±89% for water years 1979–1981 and are greatest for 1984 at ±250%. Confidence intervals in the Salinas River sediment loads are computed to be ±90% using the same methods.

Suspended-sediment discharge from the Arroyo Seco at site 1A was estimated for water years 2009 and 2010 using a combination of instantaneous discharge and suspended-sediment sampling data. A suspended-sediment rating curve was developed from the power-law fit between discharge and fine suspended-sediment concentrations. As shown in the "Results" section, the least-squares fits of the 2009 and 2010 data were not significantly different, so all sampling data were combined to produce one rating curve utilized for both years. Fine suspended-sediment discharge was estimated as the product of the instantaneous discharge values and concentrations of fine suspended-sediment derived from the rating curve. Because the log-transformed residuals about the power-law rating curve were not normally distributed (Kolmogorov-Smirnov test, $p = 0.13$), a correction factor to account for the logarithmic transform of the data was not utilized (cf. Ferguson, 1987; Cohn et al., 1989). The 95% confidence intervals for 2009 and 2010 were estimated using the techniques described previously and were found to be ±37%.

For the 2009 and 2010 sediment discharge estimates, discharge was estimated for intervals

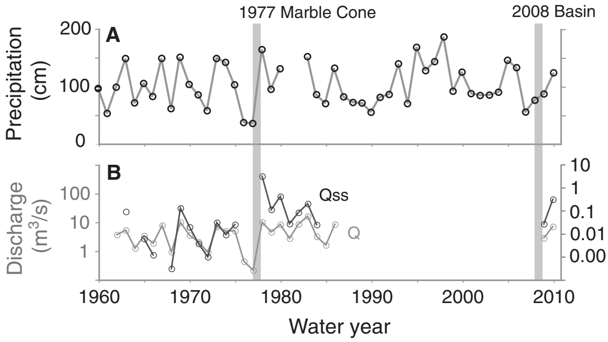


Figure 4. Annual water year (October–September) hydrological characteristics of the Arroyo Seco study area. (A) Precipitation at Big Sur, California (BGS). Mean annual precipitation during 1915–2010 was 103 cm. There was no data collection during water years 1982–1983. (B) Average annual discharge (Q, gray) and annual suspended-sediment discharge (Qss, black) for the Arroyo Seco (USGS 11151870). Watershed-scale wildfires are highlighted and named.

without stage measurements assuming exponential decreases in discharge with time between the two measured end points, and these data gaps occurred wholly during summer base flow and represented only 11% and 2% of the total annual water discharge for the two years, respectively.

Comparisons of Prefire and Postfire Data

The effects of the two wildfires were analyzed using the measurements and calculations of discharge, suspended-sediment concentrations, and sediment yield. Analysis techniques included comparisons of the deviations between sampled suspended-sediment concentrations and the river discharge–sediment concentration relationships (i.e., the "sediment rating curves"). First, a power-law regression ($Cs = aQ^b$, where Cs is suspended-sediment concentration, Q is discharge, and a and b are coefficients) was developed for the prewildfire interval of time. To evaluate whether the postfire data were significantly different from the prefire data, log-transformed residuals were computed between the measured concentrations and the expected concentrations from the prefire rating curve equation. The prefire and postfire residuals were compared using analyses of variance (ANOVA) because these data were normally distributed as shown by Kolmogorov-Smirnov tests ($p < 0.05$).

This framework for evaluating changes in pre- and postfire suspended-sediment concentration data was also followed for suspended-sediment discharge. Power-law regressions were developed between prefire annual suspended-sediment discharge and both annual discharge and annual precipitation. Residuals about these regressions were placed into prefire and postfire groups and compared with ANOVA when applicable. Lastly, the effects of wildfire on discharge were evaluated with similar comparisons of residuals about prefire regressions between precipitation and annual peak and total discharge.

Rating Curve Corrections

Patterns and trends in suspended-sediment rating curves are generally associated with the sediment load of rivers (e.g., Hicks et al., 2000; Hu et al., 2011). However, the river discharge rate can also play a significant role in rating-curve shapes and parameters (Syvitski et al., 2000). For example, an increase in river discharge with no change in sediment discharge will result in lower suspended-sediment concentrations because of dilution (Warrick and Rubin, 2007). The resulting suspended-sediment rating curve for this scenario will shift downward, even though no changes occurred to the sediment load. These concepts are applicable here because of the potential increases in river discharge relative to precipitation following a wildfire, which may cause dilution patterns in the discharge–sediment concentration relationships.

To produce an independent metric of sediment yield from a suspended-sediment rating curve, the river discharge–derived variables must be corrected for these effects of increased discharge. For the simple case in which suspended-sediment rating curves shift vertically in time without a change in the curve slope (b), Warrick and Rubin (2007) showed that the relative vertical shift in a rating curve ($r_a = a_1/a_2$, where a_1 and a_2 are the a coefficients for prefire and postfire intervals, respectively) is equivalent to a power function of the relative increases in both water (r_w) and sediment discharge (r_s), where $r_w = Q_1/Q_2$, $r_s = Qs_1/Qs_2$, and Qs is the suspended-sediment discharge. To convert a rating-curve change (r_a) into a sediment yield change (r_s), the following relationship is suggested:

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

Because we could not detect a significant change in b over the postfire record, Equation 1 was used to correct the r_a values derived from the rating curves for changes in sediment yield.

Similar corrections are needed when comparing annual water and suspended-sediment discharge values over time. For example, if the relative postfire increases in water and sediment discharge are equivalent (i.e., $r_w = r_s$), the relationship between these flux rates will not deviate from historical values, and the discharge-load rating curve will remain unchanged. Thus, the changes (or lack of changes) in a discharge-load rating curve over time may not provide an adequate index of sediment yield. In the case that sediment yield is altered to a larger scale than water yield (i.e., $r_s > r_w$) such as was the case here, r_s can be found by:

$$r_s = \frac{r_{sa}}{r_w}, \qquad (2)$$

where r_{sa} is the measured vertical offset in the water-versus-sediment discharge plot between prefire and postfire data (Warrick and Rubin, 2007).

Monte Carlo Simulations

Lastly, the millennial-scale influences of wildfire on suspended-sediment yield were investigated using Monte Carlo simulations of the Arroyo Seco watershed. These simulations were conducted on an annual basis with relationships and patterns derived from the results of this study presented in the "Results" section below. As detailed in the "Synthesis" section below, the model was tested for a range of wildfire recurrence intervals to evaluate the implications of stochastic wildfires and floods on total sediment yield.

RESULTS

Comparison of Postwildfire Rainfall

The two large wildfires in the Arroyo Seco were followed by considerably different hydrologic conditions. The first wet season after the 1977 Marble Cone wildfire was wetter than normal, with almost 170 cm of rainfall (Fig. 4A). This rainfall amount has a 25 yr annual recurrence interval over the 1915–2010 record at Big Sur (BGS). In contrast, the 2008 Basin Complex wildfire was followed by a much drier winter, during which 90 cm of rainfall fell in Big Sur (Fig. 4A). This is equivalent to 87% of the historical mean and to a 1.7 yr annual recurrence during the 1915–2010 record. Subsequent years after both wildfires were much closer to the long-term average rainfall (Fig. 4A).

Arroyo Seco Suspended-Sediment Concentrations

Suspended-sediment concentrations during the first winter after the 1977 Marble Cone wildfire were ~30 times greater than the previous 11 yr (Figs. 5A and 5B). These 30-fold increases in suspended-sediment concentrations were observed for both the fine and coarse fractions of the suspended sediment when compared to instantaneous discharge (Figs. 5A and 5B). The slopes (b) of least-squares regressions through the fine ($b = 1.2$) and coarse ($b = 2.2$) sediment data did not change significantly after the wildfire. During the subsequent years, suspended-sediment concentrations (total, coarse, and fine) decreased with respect to discharge, and by the seventh year after the wildfire, concentrations were approximately equivalent to the prefire values (Figs. 6A and 6B).

Suspended-sediment concentrations after the 2008 Basin Complex fire were only moderately higher than those without influence of wildfire (Fig. 5C). During the first year after the wildfire, the mean ratio of the measured fine suspended-sediment concentrations and those expected from the regression through prefire concentrations was only 2.3 (Fig. 5C). During the second postfire year, this ratio was 3.1 (Fig. 6C). Because these offsets were not significantly different ($p = 0.33$), there was not a fundamental decrease in fine sediment concentrations during the two years of postfire sampling after the 2008 Basin Complex fire.

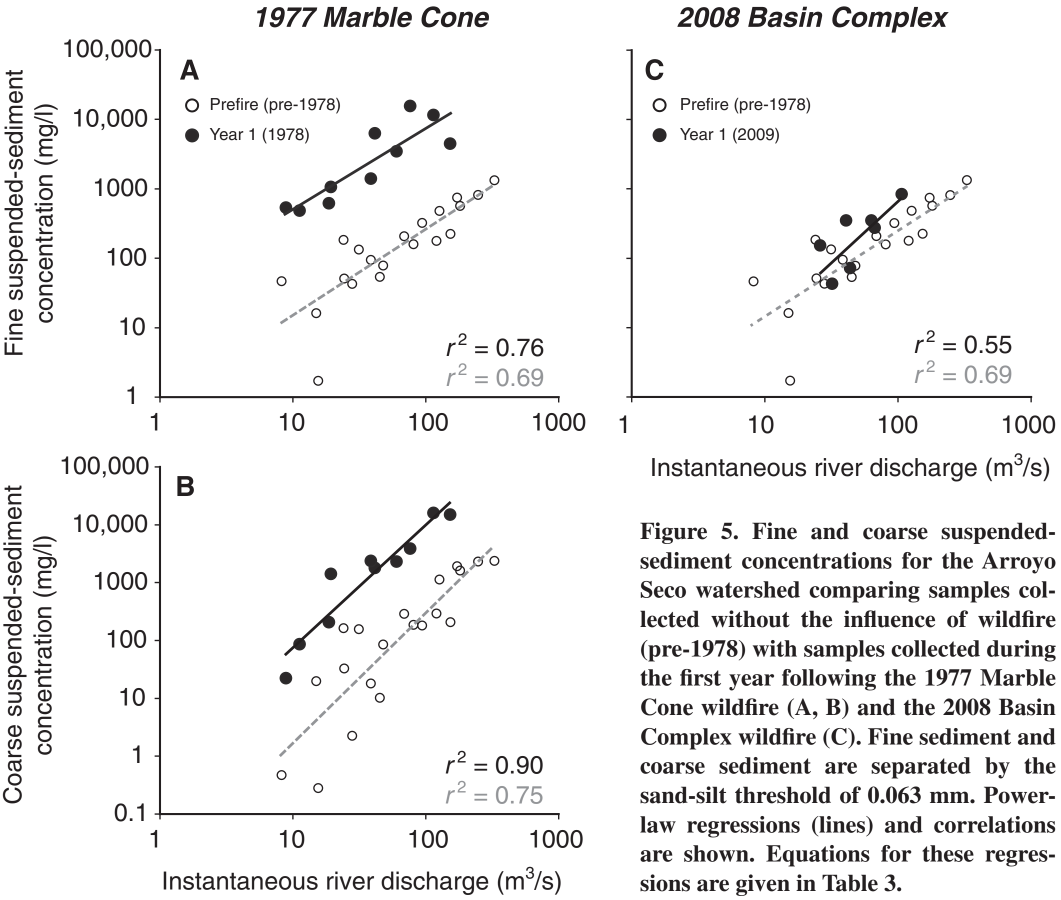


Figure 5. Fine and coarse suspended-sediment concentrations for the Arroyo Seco watershed comparing samples collected without the influence of wildfire (pre-1978) with samples collected during the first year following the 1977 Marble Cone wildfire (A, B) and the 2008 Basin Complex wildfire (C). Fine sediment and coarse sediment are separated by the sand-silt threshold of 0.063 mm. Power-law regressions (lines) and correlations are shown. Equations for these regressions are given in Table 3.

Combined, the two years of postfire concentrations averaged 2.8 times greater than the prefire regression. However, an unpaired Student *t*-test shows that the prefire (pre-1978) and postfire residuals about the prefire regression were significantly different at $p < 0.002$, suggesting that the concentrations after the 2008 wildfire were significantly elevated compared to unburned conditions.

Arroyo Seco Suspended-Sediment Discharge

Suspended-sediment discharge for the Arroyo Seco watershed reached unprecedented rates following the 1977 wildfire (Fig. 4B). The suspended-sediment discharge during water year 1978 was ~3.1 Mt, which greatly exceeded the previous maximum of 0.13 Mt during 1969. Averaged over the drainage area, the 1978 sediment discharge was equivalent to a suspended-sediment yield of 11,000 t/km^2/yr.

By comparing the estimates of suspended-sediment discharge with annual river discharge, it can be shown that sediment discharge from the Arroyo Seco watershed during the first year after the 1977 wildfire was 27-fold greater than the expected value from the discharge-flux relationship that existed during the 11 preceding years (Fig. 7A). Sediment discharge during the 2–4 yr after the 1977 fire was 5–6 times greater than the prefire relationship (Fig. 7A), and these values exceeded the maximum deviations from the prefire regression and the uncertainty in these estimates. The annual sediment discharge estimates after year 4—including those from the exceptionally wet 1983 water year—fall within the range of values observed during the prefire record (Fig. 7A).

The total suspended-sediment discharge after the 2008 wildfire was estimated by the sum of the fine and coarse suspended-sediment discharge. Fine suspended-sediment discharge was estimated using the best-fit power-law regression through the combined 2009 and 2010 data following this fire ($C_{fs} = 3.88Q_{\text{inst}}^{1.04}$; $r^2 = 0.74$). Coarse suspended-sediment discharge was estimated by assuming a 2.5-fold increase in the prefire regression shown in Figure 5B. These calculations resulted in estimates of 0.027 Mt during the first postfire year and 0.31 Mt for the second year (Fig. 4). Thus, our estimate of suspended-sediment discharge during the first year after the 2008 wildfire was 120-fold lower than the USGS estimates for the first year following the 1977 wildfire (Fig. 7B).

A more independent assessment of the effects of wildfire on sediment yield can be obtained with comparisons to precipitation because river discharge rates were likely influenced by the wildfires. The relation between annual precipitation and suspended-sediment discharge changed after both wildfires, and these changes were greatest following the 1977 Marble Cone wildfire (Fig. 8). Although annual precipitation was positively correlated with suspended-sediment discharge during the prefire record, there was substantial scatter in this relationship, as shown by the 0.40 log$_{10}$ units (or 2.5-fold) standard error about the power-law regression and by a maximum deviation of 0.66 log$_{10}$ units (or 4.6-fold). Sediment discharge values for years 1–3 after the 1977 Marble Cone wildfire were 37, 20, and 15 times greater, respectively, than the prefire regression, far exceeding the prefire variance (Fig. 8A). During the first year following the 2008 Basin Complex wildfire, the sediment discharge was 7.2 times greater than the prefire relationship, and during the subsequent year, this increased to 16 times (Fig. 8B).

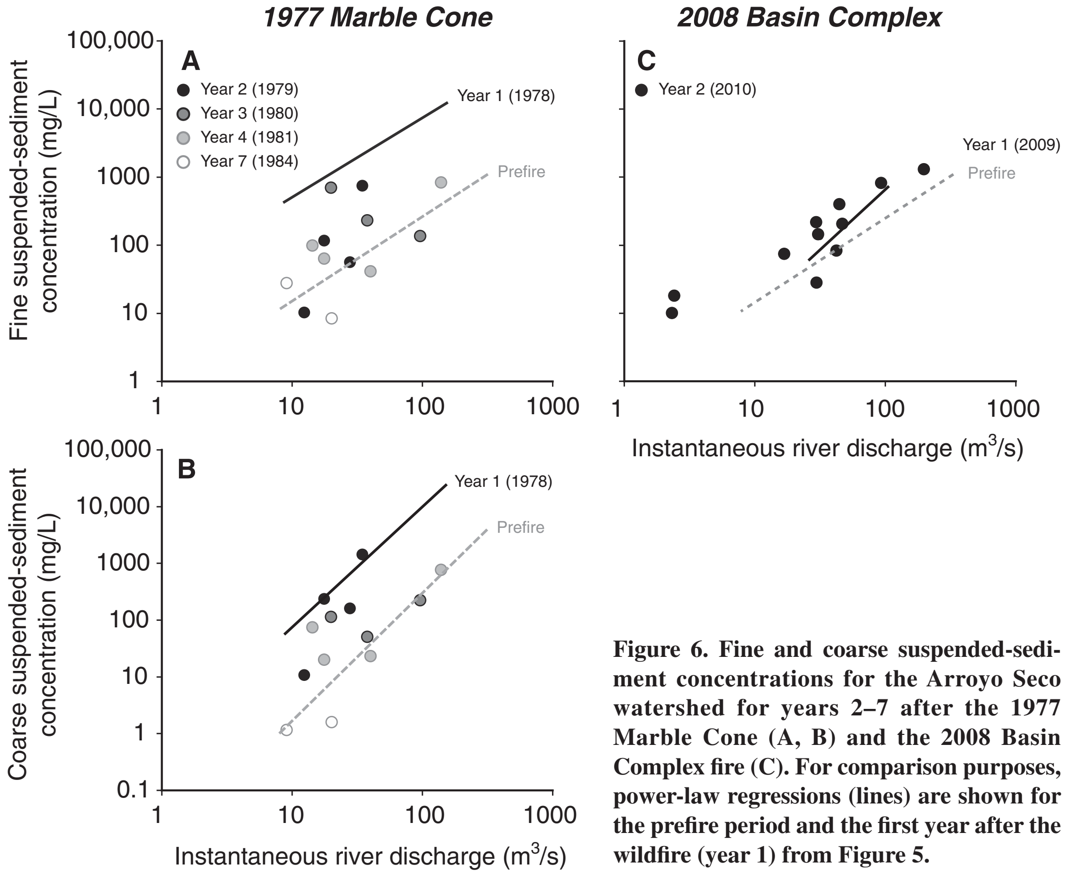


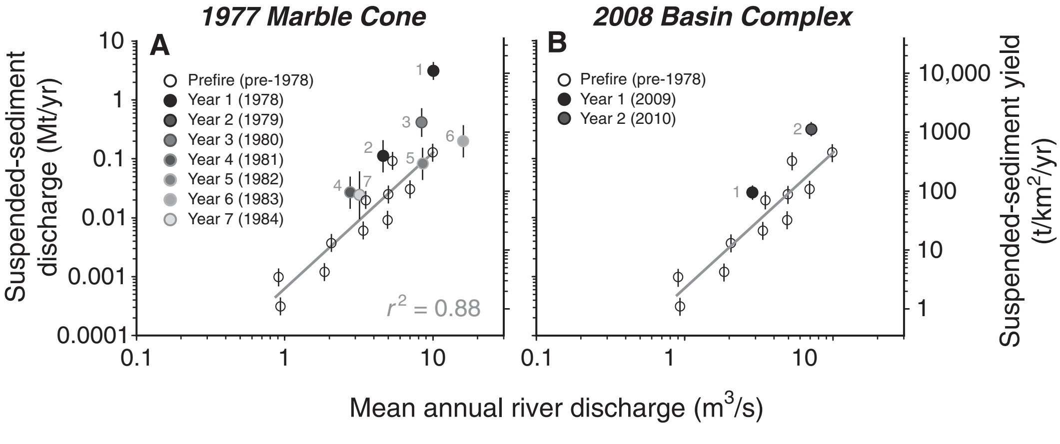
Figure 6. Fine and coarse suspended-sediment concentrations for the Arroyo Seco watershed for years 2–7 after the 1977 Marble Cone (A, B) and the 2008 Basin Complex fire (C). For comparison purposes, power-law regressions (lines) are shown for the prefire period and the first year after the wildfire (year 1) from Figure 5.

Arroyo Seco Water Discharge

Analyses of river discharge after each wildfire were made with mean and peak annual discharge records. Comparisons between precipitation and these discharge metrics reveal that although the postfire discharge was generally within the historical bounds of the prefire data, there were measurable increases in average river discharge (Figs. 9A and 9C). For example, the annual average discharge during the first three years after the 1977 fire was significantly higher with respect to rainfall (40% on average, $p < 0.02$), and this higher rate of discharge was observed through water year 1984 (Fig. 9A). Similarly, water discharge during the two years following the 2008 wildfire averaged 40% greater than expected rates extrapolated from prefire relationships (Fig. 9C), although the sample size ($n = 2$) does not allow for evaluation by ANOVA. In contrast, there were not statistically significant differences in peak discharge between pre- and postfire intervals of time (Figs. 9B and 9D).

Hydrological effects can also be assessed by comparing discharge records with those of similar unburned watersheds within the region (Fig. 2; Table 2). For the comparative watersheds that were simultaneously burned in 1977 (the Carmel, Big Sur, and San Antonio Rivers), the rates of annual total and peak discharge did not change between pre- and postwildfire intervals of time, suggesting that hydrologic responses were generally similar across these watersheds (data not shown). Comparison of the unburned watersheds (the Nacimiento, San Benito, and

Figure 7. Annual river water and suspended-sediment discharge for the Arroyo Seco near Greenfield (USGS 11151870) highlighting the effects of the 1977 and 2008 wildfires (A and B, respectively). A power-law regression (line; $r^2 = 0.88$) is shown through the prefire data. Vertical lines are 95% confidence intervals of the sediment discharge estimates.



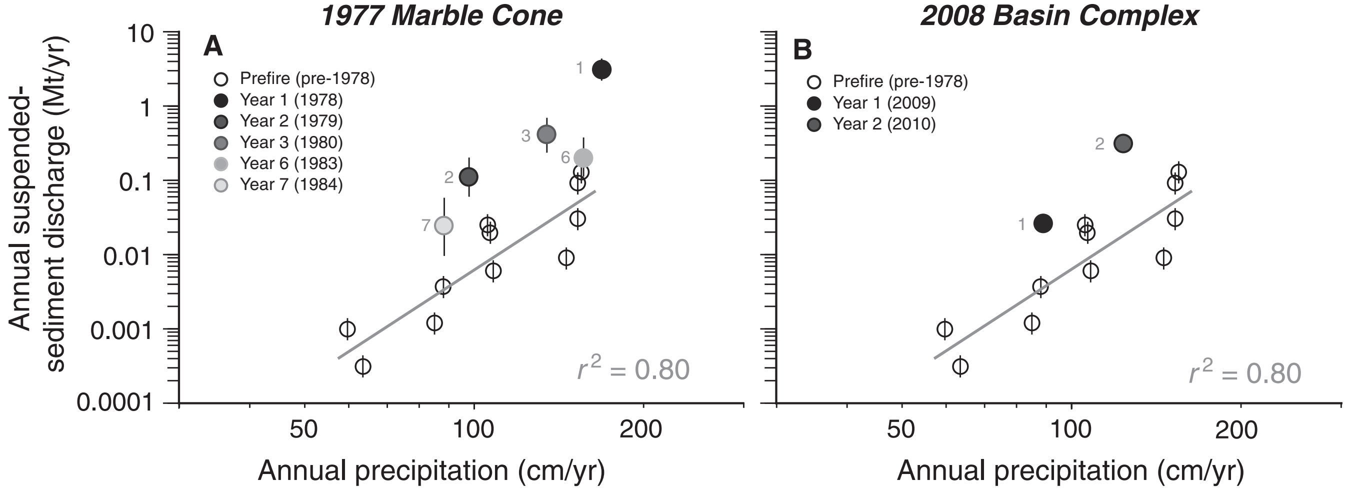


Figure 8. The relation between suspended-sediment discharge from the Arroyo Seco watershed (USGS 11151870) and precipitation at Big Sur (BGS) highlighting the 1977 and 2008 wildfires (A and B, respectively). Power-law regression lines and correlation coefficients are shown only for prefire data. Vertical lines are 95% confidence intervals of the sediment discharge estimates.

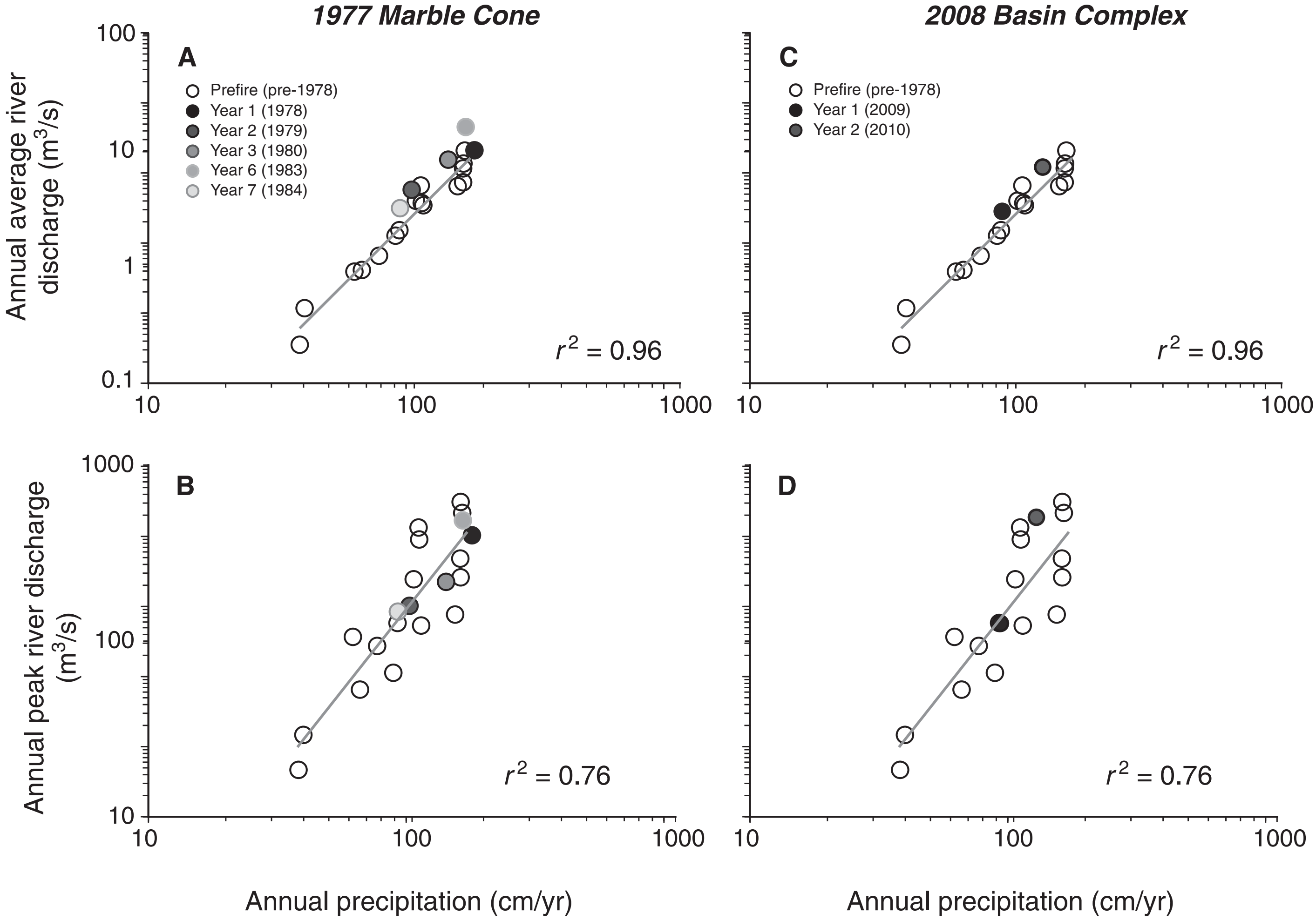


Figure 9. The relation between precipitation at Big Sur (BGS) and the annual average and annual peak discharges from the Arroyo Seco watershed (USGS 11151870) highlighting the 1977 (A, B) and the 2008 (C, D) wildfires. Power-law regression lines and correlation coefficients are shown only for prewildfire (pre-1978) data.

San Lorenzo Rivers) to the burned Arroyo Seco watershed, however, reveals higher annual average discharge in the burned watershed but no difference in peak discharge. For example, Arroyo Seco discharge is compared to the San Lorenzo River in Figure 10. During the first four years after the 1977 fire, mean annual discharge in the burned watersheds was 87% higher (Fig. 10A). These differences are significant using an unpaired Student *t*-test ($p < 0.001$). Annual peak discharge did not show significant deviations from the historical patterns (Fig. 10B).

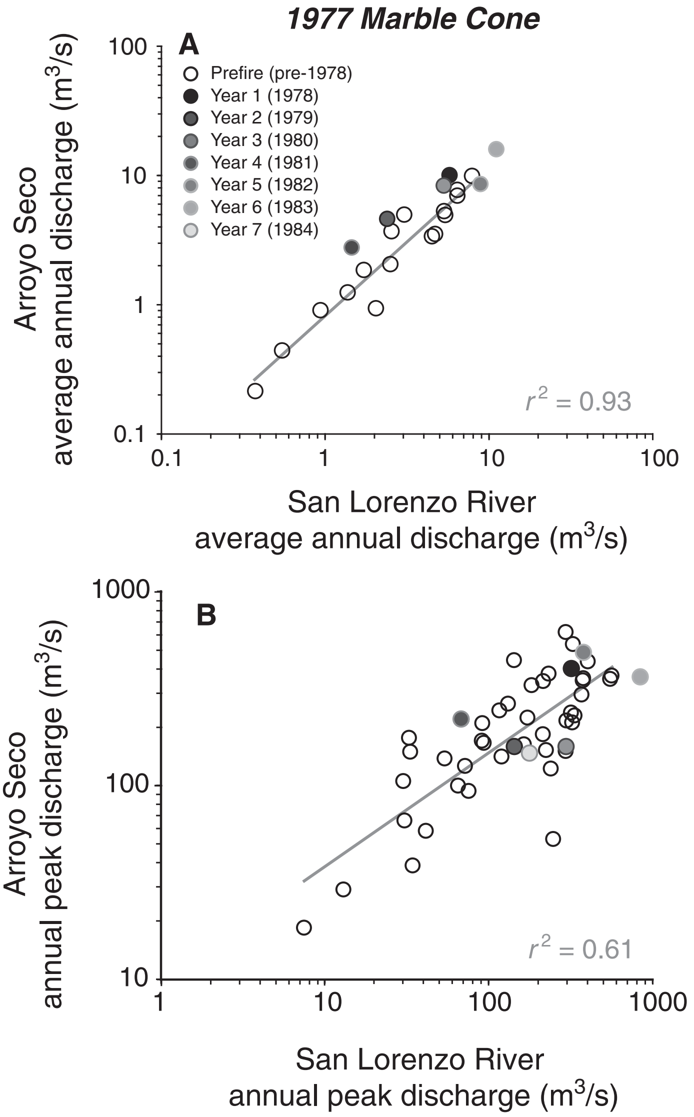


Figure 10. Comparison of the annual average and annual peak discharges in the Arroyo Seco (USGS 11151870) with the San Lorenzo River (USGS 11160500) before and after the 1977 Marble Cone wildfire. Postwildfire water years are highlighted with filled symbols. Power-law regression lines and correlation coefficients are shown only for prewildfire (pre-1978) data.

Integration of Sediment Yield Results

In Figure 11, we compile all of the relative changes in suspended-sediment discharge reported herein. These data come from three sources: changes in the discharge-concentration relationship (Figs. 5 and 6), changes in the discharge–sediment discharge relationship (Fig. 7), and changes in the rainfall–sediment discharge relationship (Fig. 8). All of the values in Figure 11 are taken from the ratio between measured values and expected values from regressions through the prefire data (Table 3).

There are discrepancies, however, in these metrics (Figs. 11B and 11E). Specifically, the discharge-based metrics for sediment discharge ($f[Q]$, blue symbols) are consistently lower than the precipitation-based metric ($f[P]$, red symbols; Figs. 11B and 11E). This should be expected, as noted in the previous section, because discharge will not be an independent variable when it increases after a fire. Thus, we used Equations 1 and 2 to correct the relative increases in suspended-sediment concentrations and sediment discharge with respect to flow using r_w derived from comparisons of mean annual discharge with precipitation (Figs. 9A and 9C).

After these corrections, the three estimates of the relative change in sediment yield are much more consistent (Figs. 11C and 11F). Increases in sediment yield were observed to last for several years after the fires (Figs. 11C and 11F). The 1977 wildfire caused an initial increase in sediment yield that was 35 times greater than expected without fire, and sediment yield decreased somewhat steadily with time (Fig. 11C). Unfortunately, data could not be generated for 1981 and 1982 because there were no precipitation data collected on which to base a correction. Although the observations of sediment yield during water year 1983 were consistent with continued decay, water year 1984, which was the seventh year following the fire, revealed increases in all sediment yield metrics (Fig. 11C). It is not evident from these data whether these elevated sediment yields were related to the 1977 wildfire or not, so we consider both possibilities in the discussion. In contrast, sediment yield during the first year following the 2008 fire was 5 times greater than expected during unburned conditions, and this increased to 9 times during year 2 (Fig. 11F).

Observations from the Salinas Watershed

Sediment and water discharge increased substantially in the Arroyo Seco watershed following wildfire. Because the sediment yield effect was pronounced, we looked downstream to data from the Salinas River gauge (site 2; Fig. 2) to evaluate whether wildfire influenced sediment concentrations and fluxes from this larger coastal watershed. Unfortunately, we were only able to evaluate the effects of the 1977 Marble Cone wildfire because of the limited data collection at this site.

During the 1977 Marble Cone wildfire, ~400 km^2 of the Salinas watershed were burned. Therefore, we made the following first-order approximations for the Salinas River: (1) the burned area had a sediment yield response similar to the Arroyo Seco (i.e., ~35-fold increase in sediment yield), and (2) the remaining unburned watershed had a relatively constant sediment yield. Only ~9000 km^2, or 81%, of the Salinas River watershed are undammed and actively contributing suspended sediment to the river (Willis and Griggs, 2003), so a total of 4.4% of the undammed Salinas River watershed burned in 1977. A 35-fold increase in sediment yield from this burned area without a change in the sediment yield of the remaining watershed would result in a 2.5-fold increase in the total sediment flux.

Consistent with this hypothetical effect on sediment yield, suspended-sediment concentrations from USGS sampling of the Salinas River were significantly higher than normal during the first two years after the 1977 fire (Fig. 12). For example, the five highest (and 10 of the top 14) suspended-sediment concentrations measured in the river were obtained during these two postfire years. Although these postfire samples were taken at higher discharge rates than the prefire samples (4 of the top 5 sampled discharge rates occurred postfire), we note that postfire suspended-sediment concentrations from the lowest discharge rates deviate to a greater extent from prefire concentrations (Fig. 12). This nonparallel shift is different from the parallel shift observed in the Arroyo Seco (cf. Fig. 5).

Statistical analyses of the Salinas River data can be made with a comparison between the prefire and postfire concentrations for the most heavily sampled discharge range of the postfire record (40–300 m^3/s; Fig. 12) using an unpaired Student *t*-test. The mean suspended-sediment concentrations with this discharge range (2420 and 8240 mg/L, respectively) are significantly different at $p < 0.001$ (both linear and logarithmically transformed), even though the mean discharge rates of these samples (122 and 116 m^3/s, respectively) are not significantly different ($p = 0.83$). Thus, even though there is substantial scatter in the prefire samples, the postfire samples were more likely to have elevated concentrations of suspended sediment, and the mean rate of this increase was ~3-fold.

Suspended-sediment discharge from the Salinas River during the first year after the 1977 fire was substantially greater than any other year in the record (Fig. 13). Over 15 Mt of suspended sediment were discharged during water year 1978, which is almost 10 times the next greatest rate of 1.6 Mt during 1973 (Fig. 13). Unfortunately, the sediment discharge record does not include other water years with high discharge (e.g., water years 1969, 1980, or 1983), for which a better comparison could be made. Thus, during the two years after the 1977 fire, the Salinas River discharged suspended sediment at higher concentrations and at higher rates than was expected from historical records. The

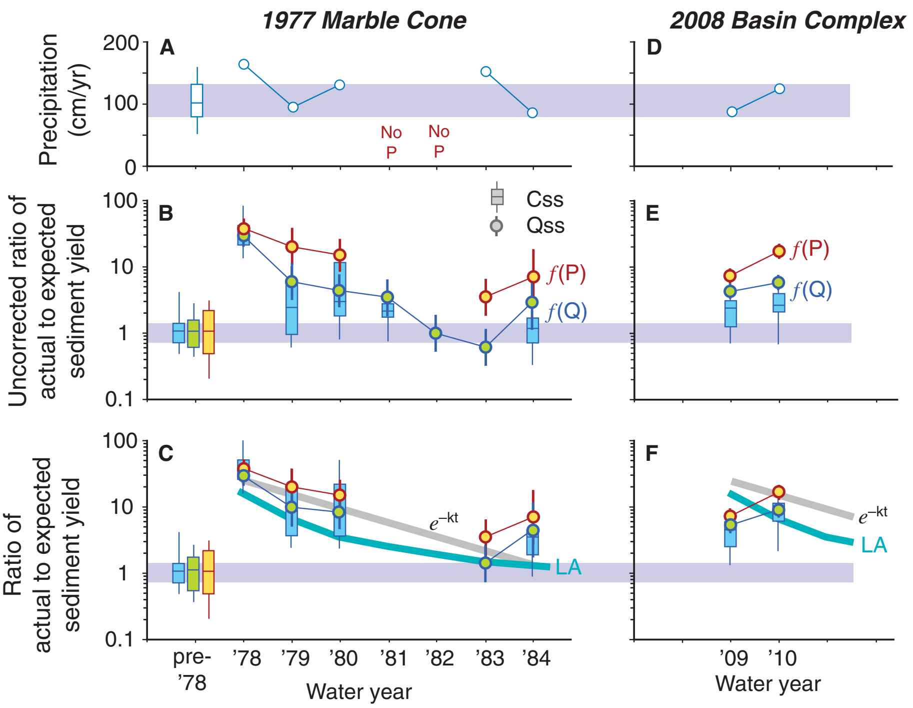


Figure 11. The effect of time after the Marble Cone (A–C) and Basin Complex (D–F) wildfires on the Arroyo Seco suspended-sediment discharge (Qss) and concentrations (Css) relative to the prefire (pre-1978) conditions. The relative changes shown in B and E are the ratio between measured values and expected values from prefire regressions shown in Figures 5, 7, and 8. These prefire regressions are either with respect to precipitation "*f*(P)" or discharge "*f*(Q)." The values in B and E have been corrected for the effects of discharge in C and F using Equations 1 and 2. A least-squares fit exponential function through the corrected data was found to have a 1.4 yr half-life ($k = 0.51$) and is shown with a gray line in C and F. The LACFCD (1959) vegetation-based decay function is also shown with a light-blue line and denoted with "LA" in C and E. Annual precipitation in A is shown for Big Sur (BGS); "No P" denotes years with incomplete precipitation records; and incomplete records during 1981 and 1982 account for the missing data in C. Box plots show the following percentiles: 5% and 95% (whiskers), 25% and 75% (box), and 50% (line). Whiskers on the symbols represent 95% confidence intervals.

TABLE 3. POWER-LAW REGRESSION EQUATIONS FOR THE LEAST-SQUARES FITS SHOWN IN FIGURES OF THIS PAPER

Figure numbers	Equation*	Description	r^2
5A, 5C, 6A, and 6C	$C_{fs} = 0.850Q_{inst}^{1.24}$	Arroyo Seco annual prefire (pre-1978)	0.69
5A, 5C, 6A, and 6C	$C_{fs} = 34.7Q_{inst}^{1.16}$	Arroyo Seco annual postfire (1978)	0.76
5B and 6B	$C_{cs} = 0.00923Q_{inst}^{2.25}$	Arroyo Seco annual prefire (pre-1978)	0.75
5B and 6B	$C_{cs} = 0.600Q_{inst}^{2.10}$	Arroyo Seco annual postfire (1978)	0.90
5C and 6C	$C_{fs} = 0.438Q_{inst}^{1.58}$	Arroyo Seco annual postfire (2009)	0.55
7	$Q_{s\text{-}an} = 0.000581Q_{an}^{2.29}$	Arroyo Seco annual prefire (pre-1978)	0.88
8	$Q_{s\text{-}an} = 7.52e^{-13}P_{an}^{4.96}$	Arroyo Seco annual prefire (pre-1978)	0.80
9A and 9C	$Q_{an} = 0.0000819P_{an}^{2.27}$	Arroyo Seco annual prefire (pre-1978)	0.96
9B and 9D	$Q_{peak} = 0.0266P_{an}^{1.90}$	Arroyo Seco annual prefire (pre-1978)	0.76
10A	$Q_{an1} = 0.815Q_{an2}^{1.15}$	Arroyo Seco annual prefire (pre-1978)	0.93
10B	$Q_{peak1} = 10.6Q_{peak2}^{0.575}$	Arroyo Seco annual prefire (pre-1978)	0.61
12	$C_{fs} = 2504Q_{inst}^{0.226}$	Salinas River prefire (pre-1978)	0.27
12	$C_{fs} = 107Q_{inst}^{0.594}$	Salinas River postfire (1978–1979)	0.51
13	$Q_{s\text{-}an} = 0.00732Q_{an}^{1.77}$	Salinas River annual prefire (pre-1978)	0.97
14B	$R = 0.0101P_{an} - 0.464$	Arroyo Seco postfire (all)	0.78
14C	$R = 0.000405P_{an}^{1.72}$	Arroyo Seco postfire (all)	0.37

*Variables include: C_{fs}—concentration of fine suspended sediment (mg/L); C_{cs}—concentration of coarse suspended sediment (mg/L); P_{an}—annual precipitation (cm/yr); R—ratio of expected to measured sediment yield increase; Q_{an}—average annual river discharge (m^3/s); Q_{an1} and Q_{an2}—average annual river discharge of the *y*-axis and *x*-axis variables (m^3/s), respectively; Q_{inst}—instantaneous river discharge (m^3/s); Q_{peak}—annual peak river discharge (m^3/s); Q_{peak1} and Q_{peak2}—annual peak river discharge of the *y*-axis and *x*-axis variables (m^3/s), respectively; $Q_{s\text{-}an}$—annual suspended sediment discharge (Mt/yr).

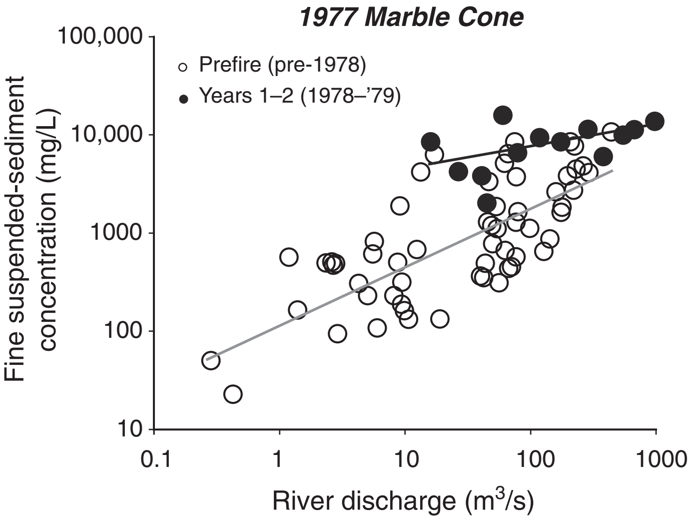


Figure 12. The relation between river discharge and fine (less than 0.063 mm) suspended-sediment concentration for the Salinas River at Spreckels (USGS 11152500) before and after the 1977 Marble Cone wildfire. Samples are shown only from "stormflow" sampling, which is defined by sampling within 4 d of rainfall and a peak in river discharge. Other samples obtained during base-flow conditions are not shown. Power-law regressions are shown with lines.

magnitude of these increases (roughly 3-fold) was consistent with the Arroyo Seco results, using a simple sediment yield mass balance.

SYNTHESIS

Sediment Yield in the Arroyo Seco Following Wildfires

The Arroyo Seco watershed responded to the 1977 and 2008 wildfires in fundamentally different ways. For example, first-year sediment yields following these wildfires varied by over 100-fold (11,000 vs. 90 t/km^2/yr), even though the wildfire burn severity and extent were roughly equivalent. The exceptional sediment yields in the Arroyo Seco following the 1977 Marble Cone fire were similar to sediment yields from other watersheds burned by this fire. For example, Hecht (1981) noted that the Padres Reservoir within the upper Carmel River watershed experienced unprecedented sedimentation during the 1977–1978 winter. Assuming a 1600 kg/m^3 bulk density for sediment in the reservoir, Hecht's (1981) results suggested an upper Carmel River sediment yield of 6800 t/km^2/yr during the 1977–1978 winter, or 62% of the measured suspended-sediment yield of the Arroyo Seco.

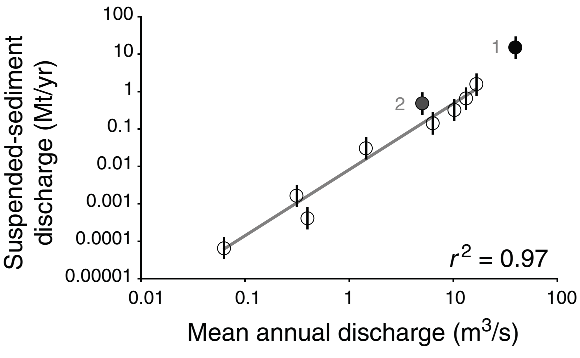
The observations of Griffin (1978) suggest that the landscape responded to the 1977 fire and 1977–1978 precipitation with extensive soil loss, rilling, gullying, and mass movements. In contrast to these observations, we only observed the production and erosion of dry ravel talus during the 2008–2009 winter, and unpublished isotopic characterization of the 2009 Arroyo Seco suspended sediment suggests it was dominated by surface soil materials (0–1 cm soil depth; J. Hatten, 2011, personal commun.). Combined, this provides evidence that the differences in sediment yield between 1978 and 2009 were related to precipitation-enhanced hillslope erosion processes, such as rilling and mass movements (cf. Fig. 1C).

Although the Arroyo Seco exhibited 100-fold differences in the sediment yield during the first postfire years, both years showed significant increases in sediment yield relative to expected values for unburned conditions (Fig. 11). Considering that (1) the time interval between preceding wildfires was roughly equivalent (30–50 yr and 31 yr, respectively), (2) both fires burned with moderate to high intensities, and (3) there was no evidence for exhaustion of soil within the watershed (BAER, 2008), the fundamental differences between these postfire years were the total amount and intensity of rainfall. Next, we evaluate whether rainfall contributed significantly to sediment production rates.

Statistical models for postwildfire sediment yield suggest large initial increases and exponential (or near-exponential) decay in sediment yield with time (e.g., LACFCD, 1959; Wells, 1981; Swanson, 1981; Cerdà, 1998; Lavé and Burbank, 2004). In Figures 11C and 11F, we show the exponential-like decay model developed by LACFCD (1959), for which the vegetation-related response of postfire erosion includes a first-year 15.3-fold increase in yield and a nonlinear decay (line denoted "LA"). This model was recently evaluated and supported by the analyses of sediment yield in the San Gabriel Mountains of southern California by Lavé and Burbank (2004). We also show a least-squares fit exponential function through the first six postfire years, which was found to have a half-life of 1.4 yr (line denoted "e^{-kt}"; Figs. 11C and 11F). When the 1984 water year is included in the regression, an exponential decay with a half-life of 2.0 yr is computed.

While neither one of these postfire decay functions adequately describes the time-varying change in sediment yield (Figs. 11C and 11F), they are found to be useful, especially when combined with rainfall. For example, the residuals about both decay functions, expressed as ratios of the actual to modeled sediment yield, were significantly correlated with annual rainfall (Fig. 14). The majority (78%) of variance in the exponential decay residuals (half-life = 1.4 yr) could be explained by annual precipitation (Fig. 14B). The LACFCD

Figure 13. A comparison of annual river discharge and annual suspended-sediment discharge for the Salinas River at Spreckels (USGS 11152500) for the available data (1970–1979). Annual values for water year 1978 are denoted with "1," and 1979 values are denoted with "2." The power-law regression for the prefire record is shown (solid line, r^2 = 0.97). Whiskers on the symbols represent 95% confidence intervals.



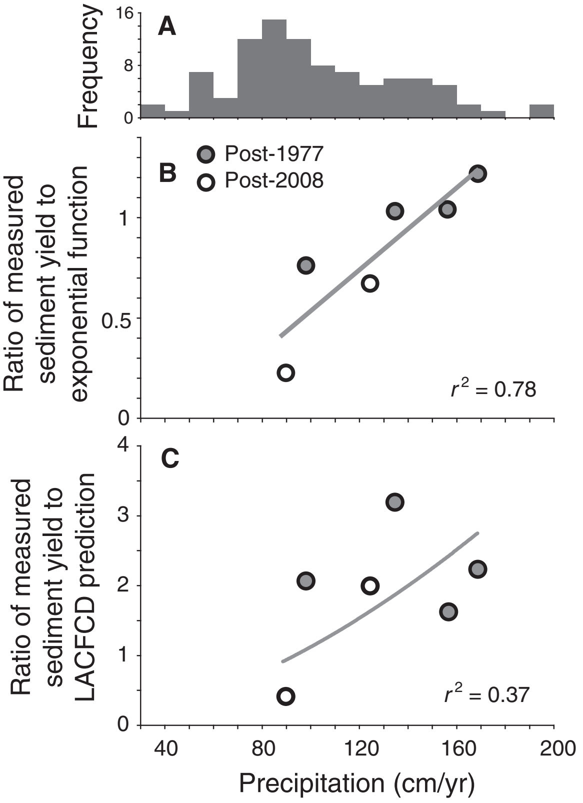


Figure 14. (A) Annual precipitation histogram from BGS for 1915–2010 (shown for comparison). (B–C) The relation between annual precipitation (at BGS) and the ratio between measured and predicted postfire suspended-sediment yields. Predictions utilize the relationships from (B) least-squares fit of an exponential function through the first 6 yr after the fire, and (C) the LACFCD (1959) functions that account for the effects of vegetation growth following wildfire.

model, in contrast, generally underpredicted the Arroyo Seco sediment yield (most residuals are greater than unity; Fig. 14C), and rainfall could explain only 37% of the variance in these residuals. The combination of the exponential model and the linear residual model shown in Figure 14B can explain 90% of the variance in sediment yield after both wildfires ($p < 0.05$), and this outperforms the LACFCD and its residual model, which can explain only 80% of the sediment yield variance. Combined, these results suggest that there is a strong influence of both wildfire and rainfall on sediment yield of this watershed.

Because the 1978 water year had an unusually large sediment yield, it also is valuable to assess the approximate recurrence interval of this event. Although there continues to be debate about the natural recurrence intervals and sizes of wildfire (e.g., Griffin, 1978; Keeley and Zedler, 2009), coastal shrublands of California likely burn every 50–100 yr without the added pressures of human-sourced ignitions (Syphard et al., 2007), and large fires such as the two recorded here are not unusual (Keeley and Zedler, 2009). The 1978 precipitation had an ~25 yr recurrence interval based on the 1915–2010 records, which suggests that the combination of wildfire and flood for 1977–1978 had a recurrence interval over 1000 yr (computed range ~1250–2500 yr).

Monte Carlo Simulation

Our results suggest that the effects of wildfire on watershed-scale sediment yields can be exceptional and persist for several years after the burn. However, the 15 yr of suspended-sediment sampling in the Arroyo Seco does not provide an assessment of the century- to millennial-scale effects of wildfire on sediment yield. Here, we evaluate these effects using Monte Carlo simulations, a technique that is ideally suited to evaluate long-term sediment yields in settings such as California's chaparral ecosystem (Rice, 1982). The purpose of this exercise is to evaluate the ways in which wildfires influence sediment yields over intervals of time that are both greater than sampling records and more relevant to geologic records.

Because we do not have adequate information to develop a process-based model (e.g., Gabet and Dunne, 2003), we simulated the suspended-sediment yield of the Arroyo Seco using a simple wildfire- and precipitation-based model such as suggested by Rice (1982) and Swanson (1981). Annual sediment discharge from the watershed (Q_{s-an}) was predicted from:

$$Q_{s-an} = mP_{an}^{n}\ F(t)E, \tag{3}$$

where P_{an} is annual precipitation, m and n are coefficients from the least-squares regression through prefire data shown in Figure 8A and listed in Table 3, $F(t)$ is the fire factor during the tth year following a wildfire, and E is an error term to incorporate the appropriate level of uncertainty in the model. Thus, annual rainfall formed the basis for suspended-sediment discharge, and wildfire acted as a stochastic perturbation to sediment discharge.

For each year, a random annual precipitation was generated from the rainfall probability distribution of the 1915–2010 record at Big Sur. Because there was substantial variance in the fundamental precipitation-sediment discharge relationship defined by m and n (Fig. 8A), annual offsets (E) were generated with a unique random number and a normally distributed variance density function fit to the residuals between the log-transformed sediment yield values and the best-fit power-law regression shown in Figure 8A. The standard deviation of this density function was 0.376.

Wildfire was added using a burn model that allows only for the possibility of complete burning of the watershed. Although this model could be easily modified to include partial burning of the watershed (e.g., Gabet and Dunne, 2003), we used the more simple model because: (1) recent assessments suggest that large fires (~100 km^2) are historically dominant in California shrublands (Keeley and Zedler, 2009), and (2) using an incomplete (or "patchy") burn model with an equivalent average fire recurrence has the same long-term effects on total sediment yield (although different annual yields) as those shown here. The annual probability for fire was based on a fuel model that assumed no wildfire during the first 5 yr following the previous fire, and a linearly increasing fire probability with time afterward. This linear increase is similar to the measurements of annual burn probability in central California by Moritz (2003).

During the years after a wildfire, the increase in watershed sediment yield was defined by the fire factor (F):

$$\begin{aligned} F(t) &= 1 \qquad (t \geq 8) \\ &= \left[Ce^{-kt}\right] \quad (t < 8) \end{aligned}, \tag{4}$$

where t is the year number following a wildfire (first year = 1), C is a factor that includes the magnitude of the postfire sediment yield response and the precipitation enhancement of this response, and k is the rate of exponential decay, which is equivalent to –0.5062 for the 1.4 yr half-life. The values of C are defined by the best-fit exponential decay function (Fig. 11C) and the linear function between sediment yield residuals and precipitation shown in Figure 14B:

$$C = 46.5\left(0.0101P_{an} - 0.4957\right). \tag{5}$$

A model run consisted of 10,000 simulated years. An example of the annual exceedance probability function of sediment yield with and without wildfires having 100 yr average recurrence intervals is shown in Figure 15. These results show that for the vast majority of the annual records, the sediment yield with and without wildfire differed by negligible amounts. For example, 95% of the records differed by 20% or less (Fig. 15). Sediment yield deviated strongly for the years with the largest sediment discharge, and wildfire caused sediment yield to be up to 13 times higher than expected to occur when wildfire effects were excluded (Fig. 15). The infrequent years with massive sediment discharge were similar in scale (~10,000 t/km^2/yr) to the first year after the 1977 Marble Cone wildfire, and these years of combined fire and flood produced the largest-magnitude sediment discharge.

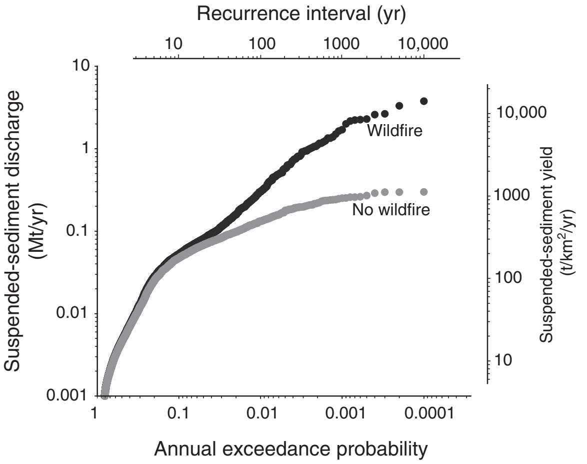


Figure 15. The effect of wildfire on the sediment yield of the Arroyo Seco watershed from two separate 10,000 year Monte Carlo simulations. Simulations use either a precipitation-influenced sediment yield response to wildfire ("wildfire") or no wildfire effects on sediment yield ("no wildfire") as noted in the text. Average wildfire recurrence interval for the data presented was 100 yr.

A simple Monte Carlo model, such as the one described here, contains several degrees of freedom to explore. Here, we investigated the effect of wildfire recurrence on the sediment yield using multiple 10,000 yr simulations with varying probabilities for wildfire. The probability for wildfire was adjusted so that the average wildfire recurrence interval varied between 20 and 700 yr. Consistent with the conceptual models of Swanson (1981), wildfire recurrence interval had a first-order and inverse effect on the long-term sediment yields (Fig. 16). For the Arroyo Seco this model predicted that wildfire recurrence intervals of ~60 yr would double sediment yield (Fig. 16). Although this model predicted that sediment yield would increase monotonically with decreasing recurrence intervals of wildfire, we acknowledge that there will be a point where sediment yields could not continue to increase because soil erosion would exceed soil production. This limitation to sediment yield is shown with dashed lines and shading in Figure 16.

Lavé and Burbank (2004) suggested that a simple model to assess the long-term effects of wildfire on sediment yield would have the form:

$$R = \frac{\left(\zeta_f / Q_{ss} \right)}{T_f} = \frac{S_f}{T_f}, \qquad (6)$$

where R is the relative increase in sediment yield (dimensionless), ζ_f is the average multiple-year mass sediment flux increase from the watershed caused by a wildfire (t), Q_{ss} is the average annual sediment discharge of the watershed (t/yr), S_f is the average increase of sediment discharge following wildfire expressed in the equivalent time at a steady Q_{ss} to accumulate ζ_f (yr), and T_f is the wildfire recurrence interval (yr).

Although Lavé and Burbank (2004) did not test this simple model with simulations, here we find an excellent fit for Equation 6 with S_f solved to be 61 yr by minimizing the root mean square error between predicted and Monte Carlo values (gray line, Fig. 16). This suggests that the average wildfire in the Arroyo Seco will generate 61 yr of sediment discharge during the first seven postfire winter seasons (after 7 yr, the wildfire effect has completely decayed). We note that this value is roughly three times that suggested for the San Gabriel Mountains of southern California by Lavé and Burbank (2004); the difference may be accounted for by geological, vegetation, or hydrologic differences in the settings or to the imperfect sediment trapping efficiency of the debris basins used in the Lavé and Burbank (2004) study.

DISCUSSION

The sediment yield of a watershed will influence downstream fluvial and coastal landforms and habitats, flooding hazards, geochemical cycling, reservoir sedimentation, debris basin maintenance, and sedimentation rates and patterns in the geologic record. Inventories of sediment flux from active margins (Milliman and Syvitski, 1992; Syvitski et al., 2005) and the North American west coast in particular (Brownlie and Taylor, 1981; Inman and Jenkins, 1999; Willis and Griggs, 2003; Farnsworth and Warrick, 2008) have never directly assessed or purposely evaluated the effects of wildfires. Exceptions include Lavé and Burbank (2004), who reported debris basin and reservoir-based sediment yields for the tributaries of the San Gabriel Mountains, California, and Warrick and Rubin (2007), who reported that wildfires significantly influenced suspended-sediment and water discharge rates of the Santa Ana River (4406 km^2) of southern California. Still, little has been done to incorporate these wildfire results into regional sediment yield analyses.

Although regional sediment flux assessments have not specifically addressed wildfires, there have been a number of large wildfires that have coincided with these data collection efforts. For example, the USGS data from the Salinas River (Figs. 12 and 13) clearly show how an upland

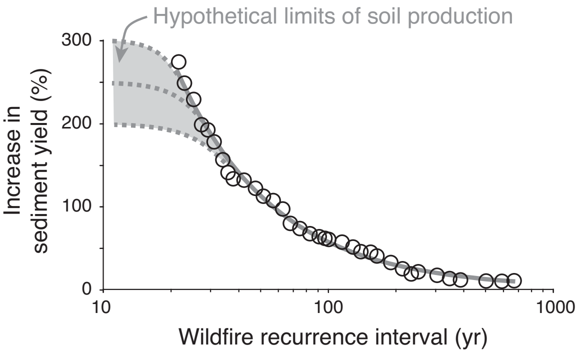


Figure 16. The effect of wildfire recurrence interval on sediment yield of the Arroyo Seco watershed. Each result was calculated by the percent difference between two 10,000 yr Monte Carlo simulations of the sediment yield of the Arroyo Seco: one with and one without the effects of wildfire. The gray line is derived from Equation 6. The dashed lines and shading show the hypothetical effect of limits to the rate of soil production on sediment yield.

wildfire influenced suspended-sediment concentrations from this 11,000 km^2 watershed. Previous assessments of the Salinas River have not included wildfire as a perturbation to sediment yield (Inman and Jenkins, 1999; Willis and Griggs, 2003; Farnsworth and Milliman, 2003; Farnsworth and Warrick, 2008), even though the USGS data utilized for these assessments had substantial wildfire effects for 2 of the 10 yr sampled and for 16 of the 106 (15%) suspended-sediment samples (Fig. 12).

We assume that there are additional rivers like the Salinas that have had large wildfires during years of suspended-sediment data collection, and other rivers that have not. For the rivers that have had no wildfires during suspended-sediment data collection, the sediment yields are likely underestimated by traditional rating curve techniques. For steep, coastal watersheds of California with similar chaparral vegetation, actual yields may be twice those estimated without wildfire (Fig. 16).

Thus, the results presented here suggest that river sediment discharge from wildfire-prone landscapes such as coastal California should be carefully reexamined. Future work is needed to evaluate the sample intervals that contained wildfires, how these wildfires influenced sediment yields, and whether models such as those shown here are more broadly applicable to other watersheds. Furthermore, lumping all suspended-sediment samples together for the purpose of "rating curve" calculations of fluxes may miss important time-dependent patterns—from wildfires or other events—in the sediment transport processes.

Wildfire effects on watershed sediment yields can rival those of human impacts, such as urbanization (Trimble, 1997; Warrick and Rubin, 2007), land-cover degradation from grazing (Cole and Liu, 1994; Pinter and Vestal, 2005), and land-cover conversion (Pasternack et al., 2001; Gabet and Dunne, 2002, 2003). Because humans continue to actively influence and change fire frequencies, fire extent, burn severity, land cover, watershed connectivity, and local and regional climate (McKenzie et al., 2004; Fried et al., 2004; Syphard et al., 2007), it is important for future inventories of sediment yield from this and similar regions to include comprehensive assessments of both natural and human-induced variations.

CONCLUSIONS

Here, we provided observations of the suspended-sediment concentration and yield of a steep coastal California watershed following two wildfires. Sediment yield increased after both fires, although the scale of this effect was moderated by the amount of rainfall. Water discharge rates were also found to increase following wildfire. Although discharge increases were substantially less than increases in sediment yield, water discharge rates did have significant effects on the discharge-related relationships of suspended-sediment concentrations and yield (i.e., the "rating curves"). These results are generally consistent with plot-scale and landscape studies (e.g., Inbar et al., 1998; Doerr et al., 2000; Lavé and Burbank, 2004; Moody et al., 2005, 2008; Shakesby and Doerr, 2006; Malmon et al., 2007), although they expand upon these results by including detailed measurements of postfire suspended-sediment fluxes at larger spatial scales.

Wildfire followed by heavy precipitation was shown to produce annual watershed sediment yields that were an order of magnitude greater than expected without wildfire. This combination of fire and flood was shown to occur at recurrence intervals of greater than 1000 yr, and sediment discharge from these infrequent events is likely important to landform evolution, geomorphology, and rates and styles of sedimentation within the geologic record.

These results suggest that wildfire can play an important forcing role in sediment yields from small watersheds (100–10,000 km^2). Unfortunately, most assessments of sediment yields of coastal California watersheds have not evaluated the ways in which wildfires influenced the reported results (Brownlie and Taylor, 1981; Inman and Jenkins, 1999; Farnsworth and Warrick, 2007). The results of this study suggest that many of these sediment yield assessments should be reexamined. Without including the effects of wildfire, sediment yields from steep, fire-prone watersheds will be substantially underestimated.

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