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Suspended sediment behavior in a coastal dry-summer subtropical catchment: Effects of hydrologic preconditions

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ABSTRACT

Variation in fluvial suspended sediment–discharge behavior is generally thought to be the product of changes in processes governing the delivery of sediment and water to the channel. The objective of this study was to infer sediment supply dynamics from the response of suspended sediment behavior to antecedent hydrologic factors. The Salinas River (California) is seasonally active, moderately sized, and potentially susceptible to lasting impacts of hydrologic event history because of aridity, high discharge variability, and in-channel terminating flows. Forty-five years of suspended sediment data from the lower Salinas and 80 years of hydrologic data were used to construct hydrologic descriptors of basin preconditioning and to test the effects of these preconditions on suspended sediment behavior. Hydrologic precondition factors — including change in mean daily discharge and increasing elapsed time since the last moderate discharge event (~10–20 times mean discharge (Q_{mean})) — were found to have significant positive effects on discharge-corrected, fine suspended-sediment concentrations. Conversely, increased elapsed time since the last low discharge event (~0.1–0.4 times Q_{mean}), and the sum of low flow conditions over interannual time scales were found to cause significant negative trends in fine suspended sediment concentration residuals. Suspended sand concentrations are suppressed by increased elapsed time after threshold discharges of ~0.1–2 and 5–100 times Q_{mean}, and increased low to no flow days over time scales from 1 to 2000 days. Current and previous year water yield and precipitation magnitudes correlate positively with sand concentration. Addition of fine sediment from lower Salinas hillslope or channel sources on the rising limb of the hydrograph is the major mechanism behind an overall positive hysteretic pattern, which was forensically supported by the annual occurrence of in-channel suspended sediment deposition by early season, channel terminating flows and by the flushing function of moderate hydrologic events found in this study. The importance of hillslope and/or channel fine sediment contributions proximal to the lower Salinas are further highlighted by the lack of control exerted by upper subbasin water provenance on fine suspended sediment concentration, while sand behavior is differentiated by upper basin water provenance. Investigation of suspension of bed-sized sediment showed that the channel bed could exert significant effects on fine and sand-sized suspended sediment dynamics, but this mediation for fine sediment was most likely small in terms of decadal-scale sediment budgets. The magnitude of the effects of hydrologic variables on sediment dynamics remains uncertain, but the factors identified here may play a significant role in water quality, if not long-term sediment flux to the ocean.

1. Introduction

Rivers of small to moderate size (~10^1–10^4 km^2) draining active margins are recognized as transporting the majority of terrestrial sediment to the oceans (Milliman and Syvitski, 1992). Sediment yields from their basins are often highly episodic, caused by rare high discharge floods (Gonzalez-Hidalgo et al., 2010; Wheatcroft et al., 2010). Small rivers in dry-summer subtropical regions, such as coastal California, are particularly prone to episodic hydrologic event control on sediment discharge, as most precipitation occurs during a short winter season that occasionally produces intense storm events (Inman and Jenkins, 1999; Farnsworth and Milliman, 2003; Warrick and Mertes, 2009).

Sediment dynamics in systems with high discharge variability are further impacted by the deposition and/or reorganization of sediment in the channel by flow recession and ephemeral flows that terminate in the channel (López-Tarazón et al., 2011) as well as sediment supply augmentation or suppression associated with large precipitation/hydrologic events and prolonged periods of no precipitation (Lana-

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Renault et al., 2007). Basin preconditioning — the sequence and temporal proximity of events that impact hillslope and channel sediment supply — and the long-term implications of these events as well as slower, extensive alteration of the land surface and vegetation also play significant roles in altering fluvial sediment production, particularly in episodic systems (Lenzi and Marchi, 2000; Pasternack et al., 2001; Chakrapani, 2005; Gao and Josefson, 2012; Warrick et al., 2013).

Sediment transported in suspension accounts for the majority of particulate matter conveyed by rivers (Meade et al., 1990). Because of the difficulty in collecting suspended sediment data, suspended sediment transport for most rivers has been estimated through rating curves that relate suspended sediment concentration (C_{SS}) to water discharge (Q), as the latter is more easily measured and often available in longer time series (Horowitz, 2003). Early investigations into antecedent hydrologic effects on suspended sediment flux were primarily focused either on the association of regional scale patterns in suspended load resulting from long-term precipitation and discharge characteristics (i.e., Langbein and Schumm, 1958) or watershed scale studies of the 'lag effect' during individual hydrologic events, which results from slower moving sediment pulses relative to the transmission of peak water discharge at the event scale (Heidel, 1956; Carson et al., 1973; Shi et al., 1985). Identification of the principal factors affecting suspended sediment behavior has been an active field of study since suspended sediment–discharge rating relationships were found to lack predictive power in smaller catchments (Walling, 1977; Syvitski et al., 2000; Warrick and Rubin, 2007; Sadeghi et al., 2008).

As the amount of suspended sediment moved by a river is generally limited by sediment supply rather than the transport capacity of channelized flow, the residual variability of C_{SS} beyond that explained by Q in a given watershed is usually the result of factors that affect erosional processes, the delivery of eroded sediment to the channel, or the trapping efficiency of the channelized system (de Vente et al., 2007). Sediment and water supply to the channel are controlled by the same major factors, namely precipitation distribution and intensity, basin structure (relief, substrate composition), and basin preconditions (moisture levels, vegetation states, disturbance states) (Wischmeier and Smith, 1978; Syvitski et al., 2000; Lana-Renault et al., 2007; Mano et al., 2009). Increased shear stress during floods can erode channel margins, scour away stabilizing structures such as vegetation, and activate landslide snouts adjacent to the channel in upper basin areas, all of which can lead to increased channel bank and hillslope sediment delivery (Kelsey, 1980; Benda and Dunne, 1997; Poesen and Hooke, 1997; Korup, 2012). Conversely, large events can flush the channel system of fine sediment stores deposited by recessional or ephemeral flows and can exhaust intermediate storage of hillslope sediment supplies, which can lead to depressed sediment yields from subsequent discharges (Droppo and Stone, 1994; Walling et al., 1998; Brasington and Richards, 2000; Hudson, 2003; Constantine et al., 2005; Batalla and Vericat, 2009). Thus, the C_{SS}–Q rating curve is an exercise in the use of discharge as a proxy for the master variables controlling sediment delivery to the stream of channelized flow, even though it will not capture the dynamics of these landscape and channel processes.

The overall goal of this study was to test the hypothesis that antecedent hydrologic conditions significantly control suspended sediment behavior. The specific objectives were to (i) develop variables representing basin preconditions from hydrologic and precipitation time series data and (ii) determine if variability in suspended sediment behavior could be explained using the precondition variables. As the Salinas River flows only intermittently during the year, it was posited that in-channel deposition of sediment from incipient flows, and the eventual reworking of this sediment, would have a significant effect on suspended sediment dynamics. The results of hydrologic precondition analysis were explored to infer the sediment supply processes at play. The most significant aspect of this work is that it provides an approach for incorporating event to interannual scale hydrologic precondition characterization into the process of deciphering sediment supply dynamics at the basin scale.

2. Study region characteristics

The ~11,000-km^2 Salinas River watershed drains a portion of the Central Coast Ranges of California, USA, flowing from the SE to NW along the Rinconada fault zone between the Sierra de Salinas and Santa Lucia Mountains to the SW and the Diablo and Gabilan Ranges to the NE (Rosenberg and Joseph, 2009) (Fig. 1). Maximum relief is ~1900 m; average watershed bounding ridge heights are 750 m to the NE and 1200 m in the SW, with ridge crest height generally decreasing toward the mouth of the Salinas (Neagley et al., 1990). Mountainous highlands are mostly composed of Mesozoic-aged sedimentary and metasedimentary rock with some igneous intrusions, while the northern extent of the mainstem valley floor is Tertiary and younger alluvial fill (Nutter, 1901). Land cover in the Salinas watershed largely follows local relief, with steep forested terrain giving way downslope to chaparral/scrub in the wetter western hills and grassland in the drier eastern hills (Farnsworth and Milliman, 2003). Valley bottoms were mostly converted to irrigated agriculture with a small proportion of urbanization (Thompson and Reynolds, 2002).

Climate along California's central coast is dry-summer subtropical with most precipitation delivered by a few winter storms. The largest storms are produced during strong El Niño years (Farnsworth and Milliman, 2003; Andrews et al., 2004). Convection of western tropical moisture through westerly storm tracks generally leads to S–SW impingement of storms (Andrews et al., 2004). Because of the SE to NW orientation of the basin and its small size, such storms can simultaneously deliver precipitation to the entire watershed to produce the largest floods on record. Orographically forced precipitation in the SW mountain ranges coupled with the preponderance of smaller storms and prevailing storm tracks leads to average annual precipitation rates that are much higher (~1000 mm/y) than in the NE region (~300 mm/y) (Farnsworth and Milliman, 2003).

Average annual suspended sediment load was previously calculated as 1.7–3.3 Mt using monthly and daily Q with log-linear rating curves (Inman and Jenkins, 1999; Farnsworth and Milliman, 2003). Ongoing work in this system by the authors has found that suspended sediment load estimated from daily discharge data using a combination of sand and fine suspended sediment rating curves for temporal domains of distinct suspended sediment behavior resulted in an average annual load of ~2.2 Mt.

The Salinas is a losing stream with naturally transient flow and no surface water passing through the lower reaches for much of the summer. The aquifers in the alluvial valley are overdrafted for agriculture, causing saltwater intrusion. Three major dams emplaced from 1941 to 1965 on the San Antonio and Nacimiento tributaries, as well as the upper most reaches of the Salinas, moderate flow from a total of ~2100 km^2 of the Salinas watershed, primarily for groundwater recharge purposes (Fig. 1). Average sediment trapping efficiency for dams in the central California coastal region have been estimated as ~84% by Willis and Griggs (2003) with the simple Brune (1953) method. Estimations of trapping efficiency by the authors based on the methods of Brown (1943) and the improved Brune method from Heinemann (1981, 1984) place the Salinas basin reservoirs in the range of 94–99% for bulk sediment and ~90% or greater for fine sediment (clay and silt) trapping efficiency.

United States Geological Survey (USGS) daily average Q gaging stations on the mainstem and on the Arroyo Seco tributary date to 1901 (A3, Arroyo Seco near Greenfield) and 1931 (S1, Salinas River near Spreckels), respectively (Table 1; Fig. 1). The confluence of the Arroyo Seco and the Salinas is located 1.36 and 1.74 river kilometers below the nearest upstream gages on the Salinas (S3, Salinas River near Soledad) and the Arroyo Seco (A1, Arroyo Seco below Reliz Creek near Soledad), respectively. Below the Arroyo Seco/Salinas confluence is referred to as the 'lower Salinas' in this study, which bears two mainstem gages 28.41 km (S2, Salinas River near Chualar) and 51.92 km (S1, Salinas River near Spreckels) downstream, respectively,