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Effects of antecedent hydrologic conditions, time dependence, and climate cycles on the suspended sediment load of the Salinas River, California

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SUMMARY

Previous estimations of sediment flux for the Salinas River of central California were based on data collected in the 1970s and assumptions of time invariant suspended sediment–discharge behavior. The goals of this study were to estimate sediment flux from the Salinas River using data from 1967–2011 by incorporating time dependent behavior and reassess the role of El Niño Southern Oscillation patterns in inter-decadal sediment load. This study builds on previous findings that time-dependent suspended sediment behavior in this system is controlled in part by antecedent hydrologic conditions. The condition of temporal dependence was further tested herein through comparison of flux estimates obtained using time-dependent formulations and a multivariate approach incorporating hydrologic factors. Longer sampling records and incorporation of decadal scale behavior or antecedent hydrologic conditions resulted in average annual load estimates of 2.0–2.9 Mt/yr with 95% confidence intervals of ±25 to 202%, in comparison to earlier estimates of ~3.3 Mt/yr. Previous overestimation of sediment load is due largely to the extrapolation of suspended sediment behavior from a decade of high sediment concentrations to the entire record, and the use of log-linear regression techniques on a non-linear system. The use of LOESS methods lowered Q_{SS} estimates and decreased confidence interval size. The inclusion of time-stratified and antecedent flow indices further decreased Q_{SS} estimates, but increased confidence interval size. However, temporal dependence of the C_{SS}–Q relationship violates the assumptions of single base period regression, which suggests that time-stratified rating curves provide more realistic estimates of sediment flux means and uncertainty. The majority of suspended sediment was transported by flows of ~25–90 times mean discharge depending on transport constituent (fines or sand) and estimation method. Periods of differential suspended sediment behavior changed the relative importance of rare floods due to changes in the relationship of suspended sediment concentration vs. discharge. El Niño years dominated the sediment budget by producing on average ten times more sediment than non-El Niño years. Sediment load estimates provided further evidence that antecedent hydrologic conditions appear to have caused much of the temporal dependence of suspended sediment behavior.

1. Introduction

Most of the mass flux from terrestrial to oceanic spheres occurs as suspended river sediment, and most suspended sediment is transported by small (~10 to 10^4 km^2 catchment area), high relief rivers (Milliman and Syvitski, 1992). Such rivers are often prone to highly episodic sediment load behavior due to highly variable hydrologic regimes and nonlinear relationships between the supplies of sediment and water to the channel. These suspended sediment concentration (C_{SS})–discharge (Q) 'rating' relationships can also change over time due to changes in the conditions moderating sediment and/or water supply. Thus, accurate, multi-decadal estimates of suspended sediment flux from small rivers are complicated by highly variable behavior over time, the dynamics of which are often poorly described due to a lack of field data.

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It has long been recognized that suspended sediment behavior can be dependent on antecedent conditions across a broad domain of temporal scales. Hysteresis, or path dependence, is the most common event scale phenomenon in suspended sediment behavior, whereby different C_{SS}–Q relationships are observed for the rising and subsequent falling limbs of a given event hydrograph (Williams, 1989). Seasonal effects are also commonly considered, particularly in areas that experience cold winters with prolonged frozen conditions or areas with monsoonal precipitation regimes that may experience sediment exhaustion as the rainy season progresses (e.g. Walling, 1977). More recent studies have also incorporated temporal dependence in suspended sediment rating curves. Interannual to inter-decadal patterns of sediment behavior due to the effects of large flooding events (Kelsey, 1980; Klein and Anderson, 2012; Warrick et al., 2013), wildfire (Shakesby and Doerr, 2006; Warrick et al., 2012) urbanization (Warrick and Rubin, 2007) and combined land use changes (Pasternack et al., 2001) have all been shown to significantly affect decadal to inter-decadal scale suspended sediment flux.

Suspended sediment load is the product of C_{SS} and Q over time. Thus the concentration of any given transported constituent (e.g., any grain size fraction) together with the frequency distribution of discharge can be used to understand which flows are most significant for transporting that constituent. Effective discharge $Q(e)$, a concept coined by Wolman and Miller (1960), is the magnitude of discharge that produces the most of a given transported constituent over a given period. Effective discharge has been a measure of great interest in a wide range of environmental research including those concerned with fluvial geomorphic control (Andrews, 1980; Webb and Walling, 1982), terrestrial organic carbon flux to the oceans (Wheatcroft et al., 2010) and suspended sediment load behavior (Nash, 1994; Gao et al., 2007). Another useful method for examining discharge frequency control on water and water-transported constituents is the 'half-load discharge' ($Q_{1/2}$) (Vogel et al., 2003). Whereas $Q(e)$ is the estimation of the discharge class that transports the most of a given constituent, $Q_{1/2}$ is the discharge magnitude below which 50% of the constituent is transported over time.

Flow-frequency characterizations required for these analyses generally employ techniques that also assume stationarity in flow time series. However, it is now widely recognized that discharge magnitude/frequency behavior is also prone to non-stationarity, which can be the result of climatic cycles (Potter, 1958; Pelletier and Turcotte, 1997). On the west coast of the United States, El Niño Southern Oscillation (ENSO) cycles have been shown to cause interannual to decadal scale patterns in river discharge behavior due largely to steering of moisture convection from the tropical western Pacific. To account for the effect of climate cycles, peak annual discharge series subdivided by climatic states can be used to assess differences in peak discharge frequency between alternating climatic conditions, such as ENSO phases (Kahana et al., 2002).

The objectives of this study were to investigate the effects of antecedent hydrologic conditions and ENSO climate cycles on the estimation of suspended sediment load, Q_e, and $Q_{1/2}$ of the Salinas River in central California. Suspended load estimates from methods accounting for decadal scale suspended sediment behavior were also compared to those estimated without acknowledging temporal dependence. This work adds to a growing body of international research underscoring the importance of temporal dependence in suspended sediment behavior on multi-decadal sediment flux estimates, the diversity of mechanisms behind these dependencies, and serves as an example of small mountainous river behavior in a dry-summer subtropical climate.

2. Study site

The Salinas River drains a ~11,000 km^2 portion of the Central Coast Ranges of California from a maximum relief of ~1900 m with a mean discharge (Q_{mean}) calculated from the period of record (1930–2011) as 11.6 m^3/s. The regional climate is dry-summer subtropical, and most annual precipitation originates from winter storms, the largest of which are generally produced during strong El Niño years (Farnsworth and Milliman, 2003; Andrews et al., 2004). Three dams were emplaced on the mainstem and two major eastern tributaries previous to the initiation of suspended sediment sampling (Fig. 1). This study was based on data obtained from the two lowest USGS hydrologic gauging stations in this basin: Salinas River near Spreckels (gauge # 11152500) and Salinas River near Chualar (gauge # 11152300), hereafter referred to as S1 and S2, respectively (Fig. 1).

Three previous studies have estimated lower Salinas suspended sediment loads. Inman and Jenkins (1999) conducted a regional scale study on suspended sediment flux from central and southern California coastal rivers with a focus on episodic events and their relationship to regional climate cycles. They found that large events with recurrence intervals of 5–10 years dominated sediment transfer from the rivers in this region, including the Salinas, and that multi-decadal scale wet and dry cycles lead to concomitant increases and decreases in suspended sediment flux to the ocean, respectively. Their approach to calculating suspended sediment load utilized a rating curve constructed from data at S1 collected by the USGS from water years 1969–1979, which they applied to monthly averages of daily water discharge from 1944–1995, resulting in an estimated average annual suspended sediment load of 1.7 Mt/yr. Farnsworth and Milliman (2003) also examined the role of large discharge events in the estimation of total suspended sediment load at S1, and used the same set of S1 USGS data to compute a power law rating curve that was then applied to daily discharge data from 1930 to 2000 for an average annual suspended sediment discharge of 3.3 Mt/yr. Farnsworth and Warrick (2007) estimated lower Salinas fine sediment (clay and silt) load as part of a larger study on the flux of fine sediment to the California coast. The 1969–1979 S1 dataset was again employed, fitted in this case with a local regression (LOESS) rating technique, and then applied to the 1930–2004 discharge record for an average annual fine sediment discharge of 1.75 ± 0.9 Mt/yr.

3. Experimental overview

The experimental approach was to estimate independent loads for suspended fine- and sand-sized sediment, each through either (i) a single rating curve based on the entire temporal domain, (ii) separate rating curves for each respective period of persistent suspended sediment behavior, or (iii) a multiple linear regression rating curve incorporating indices describing antecedent hydrologic conditions previously found to influence suspended sediment behavior in the lower Salinas River (Gray et al., 2014a and b). The estimates involving antecedent hydrologic conditions were compared to decadal behavior-based estimates to further assess the role of antecedent conditions in decadal scale patterns. All estimates were then placed in the context of ENSO cycles and assessed using magnitude frequency analyses to examine the discharges responsible for moving most of the sediment through the lower Salinas.

4. Data

A brief summary of the data used for this study follows. For in depth reporting on available suspended sediment, water discharge and precipitation data see Gray et al. (2014a). The USGS collected