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A step decrease in sediment concentration in a highly modified tidal river delta following the 1983 El Niño floods

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ABSTRACT

Anthropogenic activities in watersheds can have profound effects on sediment transport through river systems to estuaries. Disturbance in a watershed combined with alterations to the hydro-climatologic regime may result in changes to the sediment flux, and exacerbate the impacts of extreme events (such as large-magnitude floods) on sediment transport. In the San Francisco Estuary, suspended sediment has been declining over the past 30 years as a result of declining sediment supply, contributing to dramatic changes in the ecology and geomorphology of the estuary. However, the decline has not been gradual. Recent observations of an abrupt decrease in suspended sediments in the San Francisco Bay have been explained by a model that suggests that the step change has occurred due to exceedance of a sediment regulation threshold that triggered the change from a sediment transport regime to a supply-limited system. We investigated structural changes in the historical record of total suspended solids (TSS) concentration measured in the upper estuary to verify the model predictions. TSS in the upper estuary exhibited an abrupt step decrease in 1983 corresponding to the record-high winter and summer flows from the 1982 to 1983 El Niño event. After this step change, TSS concentrations had a significant declining trend despite subsequent near-record high flows. The abrupt change in TSS followed by the declining trend provides evidence for the hypothesis of sediment supply limitation in the San Francisco Estuary.

1. Introduction

Estuaries play an important role in the transport of sediment from watersheds to marine environments. In particular, fine (suspended) sediment that is delivered by rivers is often temporarily stored in estuaries (Ogston et al., 2008), where it plays a key role in sustaining aquatic ecosystems and facilitating biogeochemical cycling. The amount of sediment that is delivered to and stored in estuaries is influenced by sediment load in the watershed, river discharge, tidal processes, and wind wave resuspension. However, human activities in watersheds have led to significant changes in sediment delivery, and consequently, degradation of estuarine physical environments (Hopkinson and Vallino, 1995; Billen et al., 2001). Further, perturbations to estuarine inputs caused by extreme events (e.g. episodic floods, drought, hurricanes) may exacerbate anthropogenic degradation in estuaries, resulting in long-term effects to ecological functioning (Paerl et al., 2006).

Anthropogenic alterations to fine sediment transport to the world's estuaries often follow a pattern of initial disturbance in the watershed that increases sediment inputs followed by a decrease in sediment as time progresses (Syvitski and Kettner, 2011). Over time, estuaries may be depleted of fine sediment downstream of highly modified watersheds as land use conversion is slowed, land conservation programs are implemented, sediment is impounded behind dams, bank erosion is limited, and erosion below dams moves into equilibrium. This pattern has been observed in many systems across the globe, most notably in the Nile River Delta in Egypt (Daniel Jean, 1996), the Changjiang (Yangtze River) in China (Hu et al., 2009; Yang et al., 2011), and the Mississippi River Delta (Kesel, 1988) and Chesapeake Bay (Pasternack et al., 2001) in the USA.

The San Francisco Estuary is a highly modified system with a sediment flux pattern typical of anthropogenic disturbance (Schoellhamer, 2011). Deforestation, mining, agricultural development, and urban expansion induced a sediment pulse to the estuary, which was followed by a reduction in sediment flux as humans increasingly managed water resources in the watershed. Hydraulic mining for gold throughout many of the Sacramento River's watersheds in the 1800s resulted in nearly an order of magnitude increase in sediment discharge to the estuary (Gilbert, 1917). This was coupled with disturbances in both the Sacramento River and San Joaquin River watersheds (which did not undergo hydraulic mining) that increased sediment inputs such as land clearing, and heavy agricultural and urban development (Wright and Schoellhamer, 2004).

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Land reclamation, flood control, storage and diversion projects dominated the first half of the 20th century, and by 1968 nearly every tributary to the San Francisco Estuary had been diverted or dammed (Winder et al., 2011), trapping sediment and reducing supply to the estuary (Wright and Schoellhamer, 2004). Flood bypasses constructed during the same era along the estuary's main tributary and source of sediment, the Sacramento River, followed by riprap construction on the lower river in the latter part of the century further diverted sediments and reduced bank erosion (Florsheim et al., 2008; Singer et al., 2008). From 1957 to 2001 the sediment load from the Sacramento River decreased nearly 50% (Wright and Schoellhamer, 2004). Total suspended solids (TSS) and turbidity in the upper estuary (Cloern et al., 2002, 2011) followed similar declining patterns in the latter part of the 20th century.

While numerous studies have identified monotonic trends of declining sediment in the San Francisco Estuary, recent work by Schoellhamer (2011) identified an abrupt change in suspended sediment concentrations in the San Francisco Bay that could not be attributed to a sudden decrease in sediment supply from rivers. The study observed a 36% step decrease in suspended-sediment concentration (SSC) between 1991–1998 and 1999–2007. Schoellhamer (2011) attributed this step decrease to a crossing of a sediment regulation threshold. The study proposed a quantitative conceptual model of the San Francisco Bay's sediment transport: There is an erodible sediment pool in the bay, created by the historic disturbance in the watershed, which can be replenished by river supply and depleted by outflow to the ocean and by wetland deposition. The model assumes that sediment transport in the bay is supply-regulated if all of the erodible sediment is suspended, transport-regulated if some remains on the bed, and in dynamic equilibrium when the mass of erodible bed sediment is constant (typically measured at decadal scales). Schoellhamer (2011) suggested that the abrupt step change in SSC in the bay was due to depletion of the erodible sediment pool. The system became supply-limited and the decreasing sediment supply hastened the crossing of the threshold from transport-regulated to supply-limitation. With a decreasing or potentially depleted sediment supply from the watershed, the new supply-regulated estuary may remain in a long term low suspended-sediment concentration state.

Schoellhamer (2011) applied the erodible sediment pool concept to the entire estuary, although it is likely there is spatial variability within the estuary. For example, Jassby et al. (2005) observed a similar step decrease in TSS concentrations in the upper estuary in 1983, describing the event as a "sediment washout" from the high flows during the 1982–1983 El Niño from which there was no recovery up to 1995, the limit of their data record. In a model-based cluster analysis of TSS stations, Jassby et al. (2005) found that the Suisun Bay and western river delta accounted for more than 30% of the variability in upper estuary TSS from 1975 to 1995 and contained the prominent signal of the observed El Niño sediment washout.

Further, the current sediment depletion model does not account for the timing or role of extreme events in the depletion of the erodible sediment pool. However, episodic flood events are critical to sediment transport processes (Milliman and Meade, 1983). Climatic fluctuations such as the El Niño/Southern Oscillation can be strongly coupled to river discharge and variations in sediment flux (Gomez et al., 2004; Syvitski and Kettner, 2011). The step decrease observed in the San Francisco Bay in 1999 was coincident with high river discharge resulting from extreme precipitation events during the 1997–1998 El Niño (although this was not explicitly noted by Schoellhamer (2011)). During the 1982–1983 and 1997–1998 El Niño-driven floods in California, major suspended sediment flux events were observed along the entire coast of California (Inman and Jenkins, 1999; Mertes and Warrick, 2001).

Based on the spatial and temporal variability in TSS trends, it is possible that the erodible sediment pool was transported in discontinuous pulses down the estuary, shifting from transport to supply regulation in stages. The objective of this study was to determine whether there is spatial variation in the step changes in suspended sediment, and whether the upper estuary (comprised of the Suisun Bay and upstream tidal river delta) follows the predictions of the erodible sediment pool depletion model. We tested whether a step change occurred by analyzing the historic record of total suspended solid observations from 1975 to 2010 in the upper San Francisco Estuary to identify change points in the time series.

2. Regional setting

The San Francisco Estuary is the largest estuary in Western North America. The estuary is tectonically formed by an extensive fault system, and forms the largest drainage in California, covering 40% of the state (Fig. 1). It is a relatively shallow estuary; most of the bay has an average depth of 5m (Barnard and Kvitek, 2010). Estuarine salinity is controlled by freshwater inflow primarily from the Sacramento and San Joaquin River drainage (Conomos et al., 1985; Ingram et al., 1996), though the Sacramento River is the primary source of inflow and sediment to the estuary (Wright and Schoellhamer, 2005). The upper estuary is partially mixed, and the southern San Francisco Bay is a shallow tidal lagoon (Kimmerer et al., 2009). Freshwater inflows to the upper estuary are dominated by strong seasonal variability driven by California's Mediterranean climate and interannual variability driven by El Niño-Southern Oscillation and Pacific Decadal Oscillation climate cycles (Fig. 2; Jassby and Cloern, 2000). Freshwater inflows peak in winter and spring due to winter rainfall and spring snowmelt runoff from the Sierra Nevada Mountains (Conomos, 1979a). The estuary is subject to alternating drought–flood cycles, reflecting the variable precipitation of California, which have been exacerbated by the hydrologic alterations resulting from the reclamation activities that finished in the 1960s (Malamud-Roam et al., 2007; Winder et al., 2011).

The upper estuary comprises the Suisun Bay, the most landward subembayment of the San Francisco Bay, and the "Delta," which is formed by the confluence of the Sacramento and San Joaquin Rivers (Jassby, 2008). The Delta comprises a reticulated network of levee-bound tidal channels and lakes that surround "islands" of reclaimed marsh land now used primarily for agriculture. Upstream dam releases from the Sacramento River and its tributaries during the low-flow summer period maintain the Delta as a freshwater tidal system (Conomos et al., 1985).

The San Francisco Estuary is highly urbanized with a long history of anthropogenic disturbance and watershed modification (Conomos, 1979b; Nichols et al., 1986), and is now considered to be in a state of ecological crisis due to numerous threats to its environmental sustainability (Lund et al., 2007, 2010). The declining sediment in the San Francisco Estuary has been cited as a potential cause of many observed ecological changes. Although the estuary has historically a light-limited low-productivity system (Cloern, 1987; Cloern et al., 2002), phytoplankton production has increased as water clarity has increased, resulting in a productivity level more typical of other temperate-latitude estuaries (Cloern et al., 2007; Schoellhamer, 2011). Further, declining turbidity in the upper estuary has been cited as a cause of declining fish abundances (Jaffe et al., 2007; Thomson et al., 2010), and may have contributed to the spread of invasive aquatic macrophytes in the Delta (Hestir, 2010).

3. Materials and methods

We performed statistical analyses on historic water quality measurements sampled at monthly intervals in the upper estuary. To identify any significant step changes in the time series, we used a change-point regression analysis of the monthly observations. We then estimated the trend in water quality condition before and after any identified break points. All analyses were performed using the R statistical software (R. Development Core Team, 2011).