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Adjustment of the San Francisco estuary and watershed to decreasing sediment supply in the 20th century

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A B S T R A C T

The general progression of human land use is an initial disturbance (e.g., deforestation, mining, agricultural expansion, overgrazing, and urbanization) that creates a sediment pulse to an estuary followed by dams that reduce sediment supply. We present a conceptual model of the effects of increasing followed by decreasing sediment supply that includes four sequential regimes, which propagate downstream: a stationary natural regime, transient increasing sediment supply, transient decreasing sediment supply, and a stationary altered regime. The model features characteristic lines that separate the four regimes. Previous studies of the San Francisco Estuary and watershed are synthesized in the context of this conceptual model. Hydraulic mining for gold in the watershed increased sediment supply to the estuary in the late 1800s. Adjustment to decreasing sediment supply began in the watershed and upper estuary around 1900 and in the lower estuary in the 1950s. Large freshwater flow in the late 1990s caused a step adjustment throughout the estuary and watershed. It is likely that the estuary and watershed are still capable of adjusting but further adjustment will be as steps that occur only during greater floods than previously experienced during the adjustment period. Humans are actively managing the system to try to prevent greater floods. If this hypothesis of step changes occurring for larger flows is true, then the return interval of step changes will increase or, if humans successfully control floods in perpetuity, there will be no more step changes.

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1. Introduction

The watershed of the San Francisco Estuary (Fig. 1) has experienced tremendous anthropogenic disturbances to sedimentation processes. Hydraulic mining for gold from 1852 to 1884 washed sediment into Sacramento Valley rivers and much of this sediment pulse deposited in the rivers, their floodplains, and the estuary (Gilbert, 1917).

Since hydraulic mining was severely curtailed in 1884, several factors have decreased sediment supply from the San Francisco watershed to the estuary. The hydraulic mining sediment pulse has diminished asymptotically and much of it now resides behind dams, on levee-protected flood plains, and in the estuary (James, 1999). During the 1900s, many dams that trap sediment were constructed in the watershed (Wright and Schoellhamer, 2004). Until recently, the largest source of watershed sediment was the Sacramento River, for which 87–99% of the total load is suspended load (Porterfield, 1980; Wright and Schoellhamer, 2004). With decreased sediment supply from the Sacramento River, McKee et al. (2013–this issue) found that local tributaries that drain directly to San Francisco Bay now supply more sediment than the Sacramento River. More than one half of the banks of the lower Sacramento River were riprapped during the latter half of the twentieth century to protect them from erosion and thus decreased sediment transport in the river (USFWS, 2000). Flood control bypasses built in the Sacramento River floodplain during the early 20th century trap sediment and reduce downstream sediment supply (Singer et al., 2008). In addition, local tributaries that drain directly to San Francisco Bay experienced a similar pattern of increased sediment supply as population grew in the mid 1900s (Schoellhamer, 2011) and subsequent decreased supply (McKee et al., 2013–this issue).

The combined effects of hydraulic mining and subsequent development are that the San Francisco Estuary and watershed (SFEW) experienced a period of increasing sediment supply beginning in 1852 and decreasing sediment supply by the late 1900s. The SFEW has followed the general progression of human land use in coastal watersheds of initial disturbance (deforestation, mining, agricultural expansion, overgrazing, and urbanization) that creates a sediment pulse to an estuary followed by dams that reduce sediment supply (Wolman, 1967; Pasternack et al., 2001; Syvitski et al., 2005; Hu et al., 2009; Ruiz-Fernandez et al., 2009; Warrick and Farnsworth, 2009). This sequence of changing sediment supply can affect sedimentation, geomorphology, and ecology (Williams and Wolman, 1984; Petts and Gurnell, 2005).

In this paper, we present conceptual models and a synthesis of other studies to address two questions regarding how the SFEW has adjusted to decreasing sediment supply:

1) When did the SFEW begin adjusting to decreasing sediment supply?
2) Has the SFEW completed adjusting to decreasing sediment supply?

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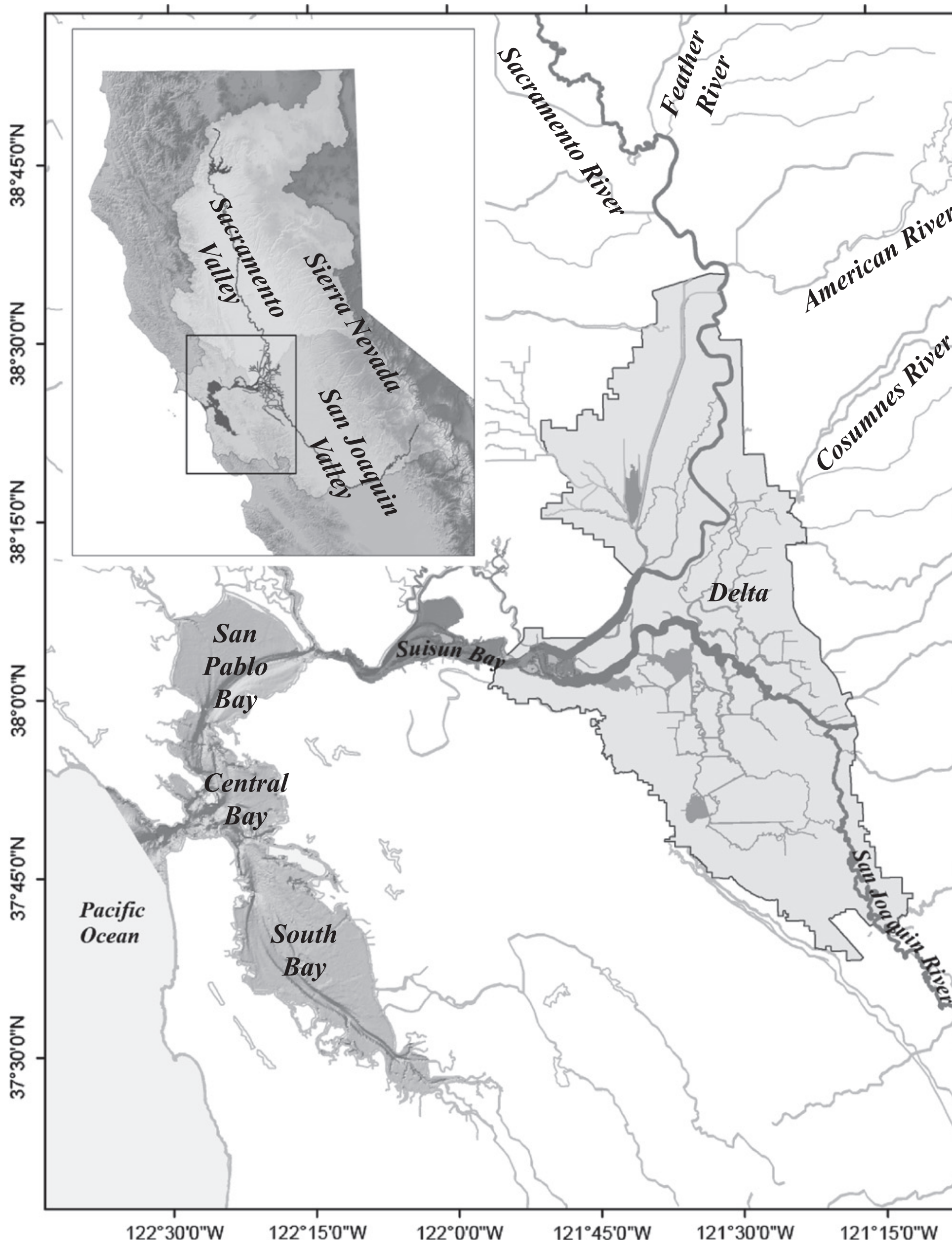

Fig. 1. San Francisco Estuary and watershed. The Estuary includes the Sacramento–San Joaquin River Delta and San Francisco Bay which has subembayments of Suisun, San Pablo, Central, and South Bays.

The emphasis of this paper is the period of decreasing sediment supply but the scope includes the preceding period of increasing supply in order to address these questions.

2. Conceptual model of sediment supply reduction and its downstream propagation

Our conceptual model builds on that presented by Petts and Gurnell (2005) for the response of a riparian system to the addition of a dam (Fig. 2). We define a longitudinal coordinate x with origin at the point of the disturbance for which the domain extends downstream into an estuary. Prior to anthropogenic reduction of sediment supply in the watershed at time t_0, the watershed and the estuary it drains into are assumed to be in a natural regime N (Fig. 3). System variables V that depend on sediment supply, such as river bed elevation, sediment discharge, geomorphic features, riparian vegetation composition and abundance, turbidity, fish abundance, and estuarine phytoplankton are assumed to be stationary and vary at different time scales. In this paper the system variables we are most concerned with are suspended-sediment concentration and discharge.

We assume that sediment supply is reduced at a specific time and place. The location of a dam was the point at which Petts and Gurnell (2005) assumed sediment supply would be reduced in a river when the dam's gates were closed. In SFEW dams and other factors reduced sediment supply. Reservoir capacity in California grew steadily and more than doubled from about 1950 to 1975 (Ganju et al., 2008). Bank protection was installed over decades along the Sacramento River to stabilize levees (USFWS, 2000), thus preventing meandering and reducing sediment supply (Florsheim et al., 2008). Sediment is also permanently lost where a floodplain is allowed to be inundated, often for flood control, but the river banks are protected, which prevents river meandering and remobilization of sediment deposited on the floodplain (Singer et al., 2008). Thus, sediment supply reduction events were temporally and spatially distributed within the watershed