Estuaries and Coasts
DOI 10.1007/s12237-011-9382-x

Sudden Clearing of Estuarine Waters upon Crossing the Threshold from Transport to Supply Regulation of Sediment Transport as an Erodible Sediment Pool is Depleted: San Francisco Bay, 1999

David H. Schoellhamer

Received: 21 June 2010 / Revised: 23 December 2010 / Accepted: 28 January 2011

Abstract The quantity of suspended sediment in an estuary is regulated either by transport, where energy or time needed to suspend sediment is limiting, or by supply, where the quantity of erodible sediment is limiting. This paper presents a hypothesis that suspended-sediment concentration (SSC) in estuaries can suddenly decrease when the threshold from transport to supply regulation is crossed as an erodible sediment pool is depleted. This study was motivated by a statistically significant 36% step decrease in SSC in San Francisco Bay from water years 1991–1998 to 1999–2007. A quantitative conceptual model of an estuary with an erodible sediment pool and transport or supply regulation of sediment transport is developed. Model results confirm that, if the regulation threshold was crossed in 1999, SSC would decrease rapidly after water year 1999 as observed. Estuaries with a similar history of a depositional sediment pulse followed by erosion may experience sudden clearing.

Keywords Estuary · Sediment · Turbidity · Estuarine sediment transport · Suspended sediment · Sediment supply · Geomorphology · San Francisco Bay · Bed sediment · Bottom sediment · Sedimentation · Deposition · Aggradation · Degradation · Erosion · Resuspension · Erodible sediment pool · Sudden clearing · Suspended-sediment concentration

D. H. Schoellhamer (✉)
US Geological Survey,
6000 J Street, Placer Hall,
Sacramento, CA 95819, USA
e-mail: dschoell@usgs.gov

Introduction

Suspended-sediment concentration (SSC) in an estuary is commonly determined by a periodic cycle of erosion and deposition (for examples see Grabemann et al. 1997; Schoellhamer 2002; Tattersall et al. 2003; Wolanski et al. 1995). Slack tides, neap tides, and periodic stratification enable deposition on the bed, and tidal currents, spring tides, and wind waves apply shear force to the bed that resuspends sediment. At any moment, the amount of sediment that estuarine waters can suspend is regulated either by the available hydrodynamic energy (transport regulation) or by the mass of erodible sediment in the estuary (supply regulation). In addition, estuaries can be transport-regulated if the quantity of suspended sediment is limited by the duration of resuspension. For example, the duration of tidal resuspension may be limited by the time between slack tides, and the duration of wind-wave resuspension may be limited by the duration of storms, diurnal wind, or shallow depths that allow surface waves to apply sufficient shear to the bed. The concept of transport and supply regulation has been applied to riverine sediment transport (Rubin and Topping 2001).

A simple conceptual model of estuarine sedimentation is that an estuary contains an erodible sediment pool, some or all of which is suspended or resting on the bed at any given time (Fig. 1a). If all of the erodible sediment is suspended, then sediment transport is supply-regulated. If some of the erodible sediment is always on the bed, then sediment transport is transport-regulated. Outflow to the ocean and permanent deposition such as in a wetland reduce the erodible sediment pool. Supply from the watershed or ocean increases the erodible sediment pool. An estuary is in dynamic equilibrium when the erodible bed sediment

Published online: 19 February 2011

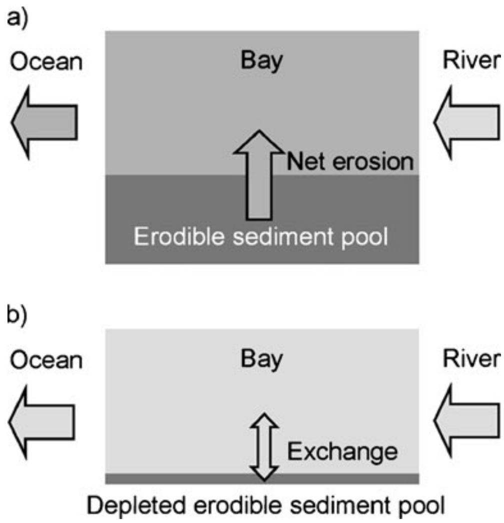

Fig. 1 Conceptual model of an erodible sediment pool (**a**) that becomes depleted, reducing SSC (**b**)

mass is constant. A time scale of perhaps decades must be considered for dynamic equilibrium because of seasonal and annual variations in watershed hydrology and oceanography.

The purpose of this paper is to demonstrate that SSC in an estuary can suddenly decrease when an erodible sediment pool becomes depleted, and this may explain a decrease in SSC in San Francisco Bay beginning in 1999. First, the motivation for this work, a decrease in SSC in San Francisco Bay beginning in 1999, is presented. Analysis of bathymetric change data supports the hypothesis that the bay contained an erodible pool of sediment that was depleted in the late 1990s. A simple quantitative conceptual model is then developed to test the plausibility of the hypothesis that depletion of an erodible sediment pool causes a step decrease in SSC. Homogeneity within the estuary is assumed as this paper focuses on the net functionality of the estuary as a component in the watershed/estuary/ocean system.

San Francisco Bay Sedimentation

San Francisco Bay is composed of four subembayments, Suisun, San Pablo, Central, and South Bays, connected to the Pacific Ocean through the Golden Gate (Fig. 2). The bottom sediments in South Bay and in the shallow water areas (less than 3–4 m) of Central, San Pablo, and Suisun Bays are composed mostly of silts and clays. Silts and sands are present in the deeper parts of Central, San Pablo, and Suisun Bays and in Carquinez Strait (Conomos and Peterson 1977). The average depth of the Bay is 2 m at mean lower low water. Tides are mixed with a range of 1 to 3 m. About 90% of freshwater inflow to the Bay comes from the Central Valley of California and flows through the Sacramento-San Joaquin River Delta to Suisun Bay. South Bay receives much less freshwater flow than Suisun Bay. Tributaries from much smaller local watersheds provide the rest of the freshwater inflow. About 89% of SSC variability is associated with semidiurnal, fortnightly, monthly, and semiannual tidal cycles, seasonal wind, and river supply (Schoellhamer 2002). Winds and wind wave resuspension are greatest in spring and summer. There are two distinct hydrologic seasons: a wet season from late autumn to early spring with the remainder of the year being dry. Sediment from the watershed is delivered during the wet season (McKee et al. 2006). Thus, the water year (WY), which begins on October 1 and ends on September 30, is a convenient period to average water quality data such as SSC because it begins in the dry season, includes a single wet season, and ends in the dry season.

Watershed sediment supply to the bay from the Central Valley has been severely disturbed by humans since the late 1800s (Fig. 3). Hydraulic mining for gold in the late 1800s washed sediment into Central Valley rivers and the bay (Gilbert 1917). During the 1900s, many dams that trap sediment were constructed in the watershed (Wright and Schoellhamer 2004). The largest source of watershed sediment is the Sacramento River, for which 87–99% of the total load is suspended load (Porterfield 1980; Schoellhamer et al. 2005; Wright and Schoellhamer 2004). More than one half the banks of the lower Sacramento River were riprapped during the later half of the twentieth century, protecting them from erosion and decreasing sediment transport in the river (USFWS 2000). Flood control bypasses built in the Sacramento River floodplain during the early twentieth century trap sediment and reduce downstream sediment supply (Singer et al. 2008). Diminishment of the hydraulic mining sediment pulse, sediment trapping behind dams and in flood control bypasses, and bank protection all contribute to decreased sediment supply from the Central Valley to the bay. Suspended sediment supply from the Sacramento River gradually decreased by one half from 1957 to 2001 (Wright and Schoellhamer 2004). Total suspended-solid concentration in the Sacramento-San Joaquin River Delta decreased from 1975 to 1995 (Jassby et al. 2002). Canuel et al. (2009) found that sediment and carbon accumulation rates in the Sacramento-San Joaquin River Delta were 4–8 times greater before 1972 than after. At the end of the 1900s, sediment supply from the Central Valley was about equal to that from other more local bay tributaries (Schoellhamer et al. 2005).

The hydraulic mining sediment pulse deposited in Suisun, San Pablo, and Central Bay in the 1800s (Cappiella et al. 1999; Fregoso et al. 2008; Jaffe et al. 1998). In the 1900s, these subembayments became erosional.

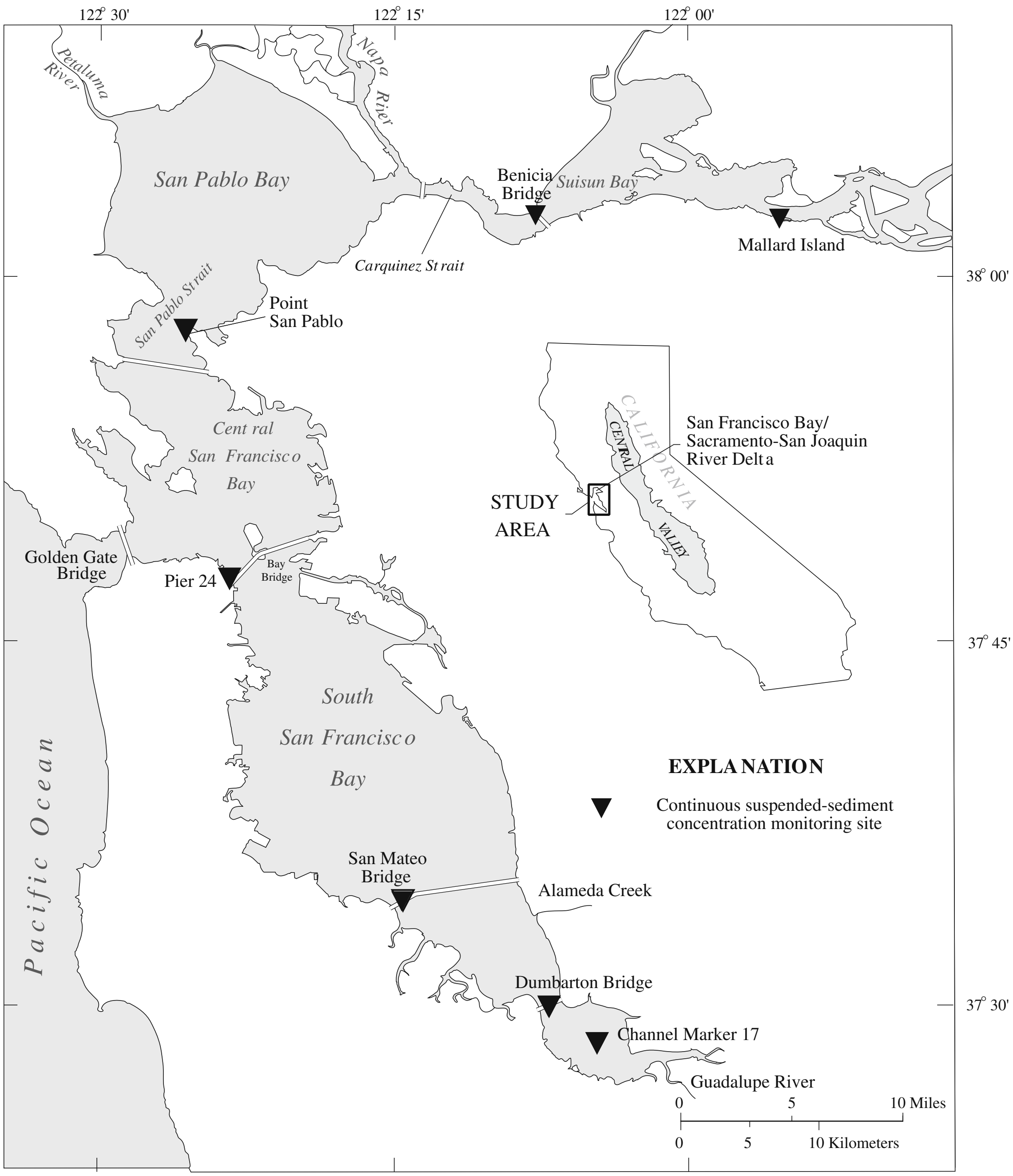

Fig. 2 San Francisco Bay study area

San Francisco Bay Suspended-Sediment Concentration Step Decrease

The US Geological Survey has used automated optical sensors to measure SSC every 15 min at several stations in San Francisco Bay beginning in December 1991 (Fig. 2, Buchanan and Lionberger 2009; Schoellhamer et al. 2007). Sensors from several manufacturers have been deployed. An optical sensor transmits a pulse of light that scatters off of suspended particles and is measured by the sensor. Every 3–4 weeks, the sensors are cleaned, data are downloaded, and calibration samples are collected. About one half of the data are invalid due to biofouling of the optical sensor, but the quantity of valid data in more recent years is approaching three quarters because self-cleaning sensors have improved.

An example time series of SSC data from mid-depth at Point San Pablo shows a decrease in SSC in the late 1990s (Fig. 4). This time series is shown because it is relatively lengthy and complete. Much of the tidal variability of the

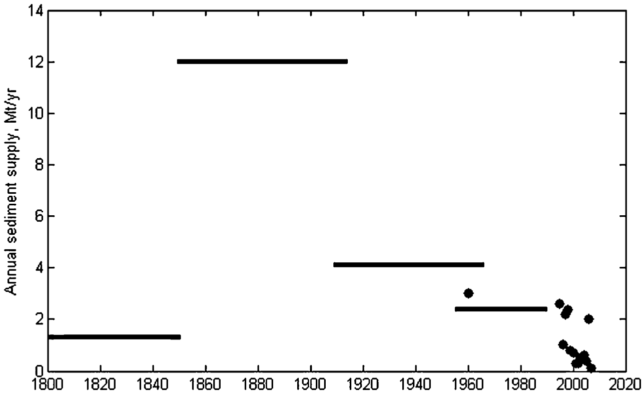

Fig. 3 Estimated annual sediment supply from the Central Valley to San Francisco Bay. Estimates from Gilbert (1917), Krone (1979), Porterfield (1980), Ogden Beeman and Associates (1992), McKee et al. (2006), and David et al. (2009). *Bars* indicate estimates over entire period, and *points* indicate yearly estimates. A bulk density of 850 kg/m^3 was assumed (Porterfield 1980)

data is compressed into what appears as a solid band of data. The band is generally thickest in the spring and early summer when wind waves resuspend sediment deposited during the previous winter wet season. The band is thinnest in autumn when wind decreases and before the wet season delivers new sediment from the watershed. Maximum values of SSC were observed during floods in early 1997 and 1998.

SSC at most sites from the early 1990s to WY 1998 was almost double that from WYs 1999 to 2007 (Table 1). Mean SSC after September 30, 1997 was 36% less than before. The step change in the water year mean SSCs from WY 1998 to 1999 was significant (one-sided rank-sum test $p<0.01$) at all sites except San Mateo Bridge. Water year mean SSC was analyzed rather than monthly mean SSC to avoid problems with variation of the timing of seasonal inflow, turbidity maxima, and seasonal wind from year to year and by increased susceptibility of missing data biasing monthly means.

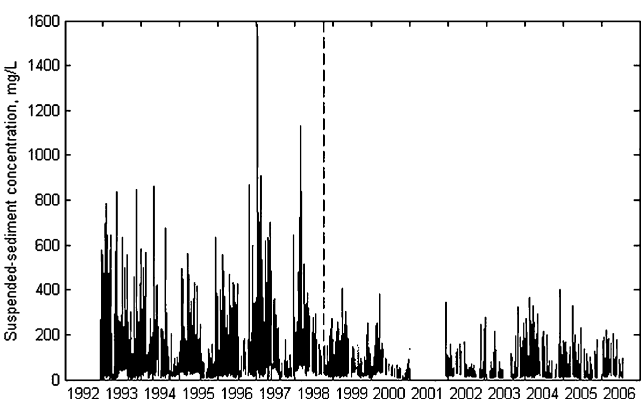

Fig. 4 Suspended-sediment concentration, mid-depth, Point San Pablo. The *vertical dashed line* indicates when the step decrease occurred

Table 1 Mean and median near-surface or mid-depth suspended-sediment concentrations (mg/L) during dry WY 1994, before the step decrease, after the step decrease, and during wet WY 2006

Site	Water year	Mean	Median	% valid
Mallard Island	1994–1998	45	39	67
	1999–2007	33	30	80
	2006	27	24	87
Benicia	1996–1998	73	65	69
	2002–2007	42	33	65
	2006	52	45	58
Point San Pablo	1994	99	79	66
	1992–1998	83	62	73
	1999–2006	39	31	51
	2006	37	31	38
Pier 24	1994	43	38	35
	1992–1998	33	29	43
	1999–2002	24	22	43
San Mateo Bridge	1994	63	52	36
	1992–1998	51	40	37
	1999–2005	46	39	33
Dumbarton Bridge	1994	97	86	38
	1992–1998	102	81	41
	1999–2007	62	48	48
	2006	41	28	83
Channel Marker 17	1994	166	135	66
	1991–1998	144	101	56
	1999–2005	84	56	50

The SSC time series are derived by editing data from optical instruments and are subject to some interpretation, but the step change also appears in the water samples collected to calibrate the sensors. At Point San Pablo, 248 water samples were collected at mid-depth from WY 1993 to 2006, and SSC had a statistically significant step decrease (rank-sum test $p=3.4\times10^{-10}$) from WYs 1993–1998 to WYs 1999–2006. The same laboratory method was used for all samples (Buchanan and Lionberger 2009).

Data from monthly water quality cruises by the US Geological Survey provide some confirmation of a step decrease despite a significantly smaller sampling frequency. At specified stations along the axis of the bay from South Bay to the Delta, vertical profiles of basic water quality properties are measured (http://sfbay.wr.usgs.gov/access/wqdata/). Suspended particulate matter (SPM) is measured, for which the laboratory analysis is identical to SSC measured by the continuous monitoring program (Gray et al. 2000). SPM in Suisun Bay and San Pablo Bays 1 m below the water surface had a significant step decrease (one-sided rank-sum test p=0.00) from WYs 1975–1998 (median 34 mg/L) to WYs 1999–2008 (median 23 mg/L). SPM in South Bay south of the Dumbarton Bridge also had a significant step decrease (one-sided rank-sum test $p=6.2\times10^{-5}$) from a median of 36 to 27 mg/L. Central Bay and South Bay north of the Dumbarton Bridge did not have a significant decrease. Cloern et al. (2007) found that SPM from 1978 to 2005 in South Bay had an increasing trend that was not statistically significant. Their results differ from the analysis presented here because they tested for a trend rather than a step decrease, used a slightly smaller data set, and combined all South Bay data.

The step decrease in SSC does not appear to be due to a sudden decrease in sediment supply from rivers. In general, most measured years before the step decrease had large sediment loads, and all but 1 year after the decrease had small sediment loads (Fig. 5). The exceptions, however, indicate that SSC in a given year cannot be explained by river supply during that year. Before the step decrease, WY 1994 was a dry year (7,419 Mm^3 of runoff from the Central Valley), but mean SSC was relatively large (95 mg/L, Table 1). Freshwater inflow is used here as a surrogate for sediment supply (Fig. 5) because no sediment supply data are available for WY 1994. After the step decrease, WY 2006 was a wet year (50,020 Mm^3), yet mean SSC was only 39 mg/L (Table 1). If river sediment supply in a given water year is the only source of suspended sediment, then SSC would vary with river sediment supply. WYs 1994 and 2006 indicate that river supply does not directly determine SSC.

A hypothesis to explain these data is that the bay contained an erodible pool of sediment that was depleted in the late 1990s (Fig. 1b). Prior to the step decrease, bay SSC would remain high in water years with little watershed sediment supply because the erodible sediment pool supplied suspended sediment and SSC was transport-regulated. Bathymetric surveys (Cappiella et al. 1999; Fregoso et al. 2008; Foxgrover et al. 2004; Jaffe et al. 1998) and sediment budgets prior to 1999 (Ogden Beeman and Associates 1992; Schoellhamer et al. 2005) show that the bay was eroding. WY 1998 was a wet year for which high flow persisted well into summer, probably flushing sediment from the bay to the Pacific Ocean. Despite a large sediment supply, sediment export from Suisun Bay was 8–9 times greater than sediment supply (Ganju and Schoellhamer 2006). After the step decrease in WY 1999, bay SSC is lower because the erodible pool decreased enough that sediment transport crossed the threshold from transport to supply regulation. Suspended and bed sediment exchange through erosion and deposition, but the erodible sediment pool is smaller. Not even wet years (e.g., 2006) supply enough sediment to restore the pool and transport regulation of suspended sediment, so SSC remains low. The transport capacity of bay waters exceeds the river supply and the depleted erodible pool, so sediment transport is now supply-regulated.

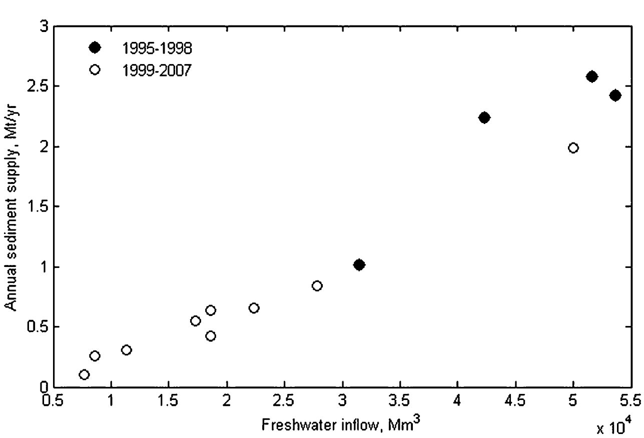

Fig. 5 Sediment supply from the Central Valley to San Francisco Bay, water years 1995–2007 (McKee et al. 2006; David et al. 2009)

San Francisco Bay Erodible Sediment Pool

Analysis of historical changes in bed sediment volume supports the hypothesis that the bay contained an erodible pool of sediment that was depleted in the late 1990s. Bed sediment volume changes in the four subembayments of San Francisco Bay from the mid 1800s to late 1900s were calculated by comparing successive bathymetric surveys by Cappiella et al. (1999), Fregoso et al. (2008), Foxgrover et al. (2004), and Jaffe et al. (1998). The analyses used nearly identical methods and corrected for tidal epoch, sea level, dredging, borrow pits, and subsidence. Readers should refer to these reports for details. Systematic errors within a subembayment are less than 10 cm and typically range from one to several centimeters (Fregoso et al. 2008). In the best case, these errors would be random between subembayments, and they would cancel. In the worst case, these subembayment errors would be additive, and the maximum error for baywide sediment volume change would be 12–120 Mm^3 (3–30% of the maximum bay volume change). Surveys were conducted at different times in different subembayments, and not all surveys covered an entire subembayment. From 1855 to 1990, the entire bay was surveyed five times, and for each survey, 11 to 14 years passed from surveying the first to last subembayment. Thus, the change in bed sediment volume from the first survey period (1855–1867) can be calculated for the four subsequent periods. Bed sediment volume change for incomplete surveys was estimated by multiplying the measured volume change by the ratio of total to measured surface area.

Supply of hydraulic mining sediment increased bed sediment volume by at least 260 Mm^3 in the late 1800s

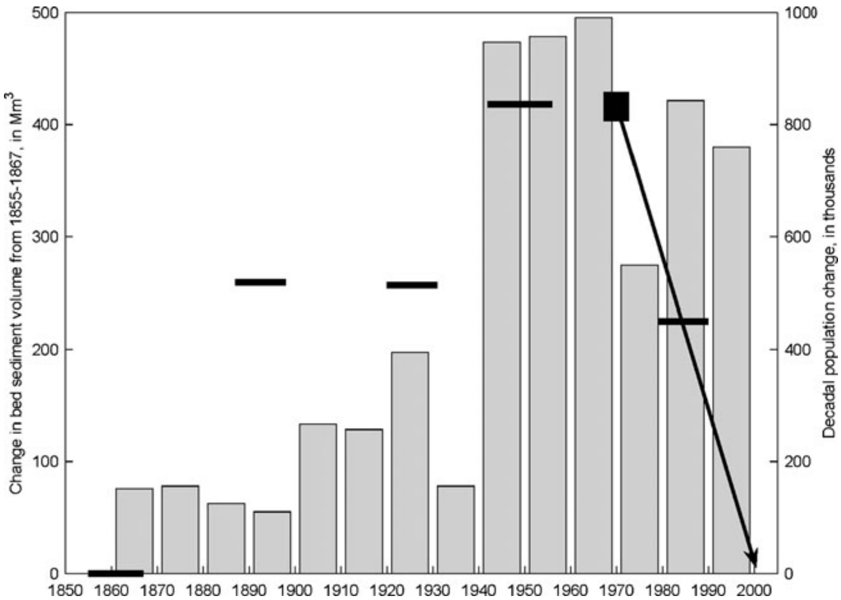

Fig. 6 San Francisco Bay sediment volume change from the 1855 to 1867 surveys (*lines*) and decadal population change (*bars*). Each subembayment was surveyed during the period shown by *each line*. Population is within the nine counties bordering San Francisco Bay (Bay Area Census 2009). Bathymetry data are from Cappiella et al. (1999), Fregoso et al. (2008), Foxgrover et al. (2004), and Jaffe et al. (1998). Assuming that the bed sediment volume in 1970 was equal to the mid-1900s value (*square*, see text for explanation), a *line that passes through the midpoint of the late 1990s bed sediment volume measurement period* indicates that bed sediment volume would equal the 1855–1867 value in 2001

(Fig. 6), almost entirely in Suisun and San Pablo Bay. There was little change in total bed sediment volume in the early 1900s as hydraulic mining sediment continued to enter the bay at what was probably a smaller rate (Fig. 3) and the pulse of hydraulic mining sediment moved into the intertidal zone or Pacific Ocean.

From the early to mid-1900s, bay sediment volume increased by 160 Mm^3. This second pulse of sediment was about 60% of the hydraulic mining sediment pulse and may have been caused by urbanization or increased agricultural land use. Unfortunately, there are no sediment load measurements in rivers supplying sediment to the bay during this time, so ascription of this sediment pulse is somewhat speculative. The probability that a given extremely large freshwater inflow, which are responsible for most sediment supply from the Central Valley to the bay (McKee et al. 2006), would be exceeded increased from the 1861 to 1984 (Fig. 7). Thus, freshwater inflow is an unlikely explanatory variable for the variation in bay sediment volume or the mid-1900s sediment pulse. Population of the nine county San Francisco Bay Area increased by almost one million people per decade from 1940 to 1970 (Fig. 6) as the population increased from 1.7 to 4.6 million people (Bay Area Census 2009). To accommodate this growth, land use shifted from agricultural to suburban. Population in the 18 counties of the Central Valley increased from 1.1 to 2.8 million people from 1940 to 1970 (California Department of Finance 2009). Erosion controls for land being graded for construction increased during the 1970s (Tran et al. 1999); thus, urbanization may have produced a greater yield of sediment prior to the 1970s than after. In addition, the portion of the Central Valley used for irrigated agriculture was constant from 1922 to 1940 then approximately doubled from 1940 to 1970 to 15,000 km^2 (Nady and Larragueta 1983) and has been about 16,000 km^2 since 1980 (California Department

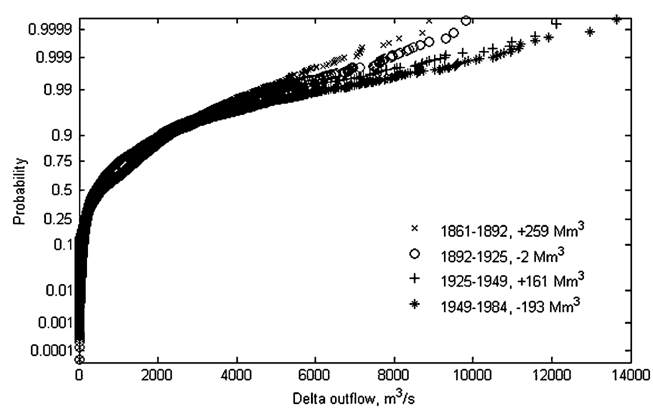

Fig. 7 Probability of flow exceedance for Delta outflow for the periods between the midpoints of San Francisco Bay bathymetric surveys. Daily flow data are from Ganju et al. (2008). Bay sediment volume change is given in the legend. The probability that a given extremely large freshwater inflow will be exceeded has increased with time. Changes in freshwater inflow cannot explain the variation in bay sediment volume

of Finance 2009). Conversion to agriculture and urban land use and overgrazing can increase sediment loads (Pasternack et al. 2001; Ruiz-Fernandez et al. 2009; Warrick and Farnsworth 2009; Wolman 1967) and thus may have supplied this second pulse of sediment. Sediment load measurements began in water year 1957, probably too late to detect the rising limb of such a pulse. Sediment yield from the Sacramento River decreased by about one half from WY 1957 to 2001 (Wright and Schoellhamer 2004). In addition, the Guadalupe River in South San Francisco Bay has a smaller (414 km^2) and more urban watershed than the Sacramento River (60,900 km^2), and provides evidence of an urbanization sediment pulse in the mid-1900s. Suspended sediment yield from the Guadalupe River watershed during WYs 1958–1962 was a factor of 4 to 8 greater than during WYs 2003–2005 (Schoellhamer et al. 2008).

San Francisco Bay was eroding in the late 1900s as bed sediment volume decreased (Fig. 6). As discussed previously, diminishment of the hydraulic mining and urbanization sediment pulses, sediment trapping behind dams and in flood bypasses, and bank protection all contribute to decreased sediment supply to the bay. Erosion by tides and wind waves exceed sediment supply, causing net erosion.

Prior to 1855, the San Francisco Bay and its watershed were relatively undisturbed and probably were in dynamic equilibrium with a small erodible sediment pool. In the late 1900s, however, anthropogenic sediment pulses from the late 1800s and mid-1900s were eroding and leaving the bay. Therefore, the bed sediment volume change from the 1855 to 1867 surveys can be assumed to approximate the erodible sediment pool (Fig. 6).

Changes in the erodible sediment pool caused by changes in hydrodynamic forcing, specifically decreased tidal prism due to construction fill and levees, are assumed to be negligible. Approximately 95% of tidal marsh in San Francisco Bay and the Delta was leveed or filled from 1850 to the late twentieth century, and the tidally affected surface area decreased by about two thirds (Atwater et al. 1979). Tidal marsh elevations are mostly near mean-higher-high water, however, so the fraction of lost tidal prism volume would be much smaller than the fraction of lost surface area and the decrease in tidal marsh would decrease tidal currents only during the highest of tides.

For a mean bay volume of 8,446 Mm^3 (USGS 2009) and assuming the mean bay SSC equaled the mean SSC up to 1998 in Table 1 (75 mg/L) and a bed density of 850 kg/m^3 (Porterfield 1980), the erodible sediment pool in the mid-1900s (420 Mm^3) was about 560 times greater than the mean suspended sediment mass. Thus, the pool would have largely resided on the bed rather than in suspension, and sediment transport would have been transport-regulated.

The size of the erodible sediment pool in the mid-1900s was about 60 times greater than the mean annual sediment supply from 1909 to 1966 (6.6 Mm^3/year, Porterfield 1980). Thus, in a dry year with little watershed sediment supply, the erodible sediment pool was large enough to supply sediment to bay waters and maintain SSC without being depleted.

Linear extrapolation of the late 1900s erosion rate indicates that the bed sediment volume would return to 1855–1867 levels around 2001. If the sediment pulse observed in the mid-1900s was caused by urbanization, it likely would have continued until at least 1970 because of population growth and minimal, if any, erosion controls on suburban development. If the sediment pulse was caused by agriculturalization, it likely would have decreased around 1970 when expansion of irrigated agriculture markedly slowed. Assuming that the bed sediment volume in 1970 was equal to the mid-1900s value, a line that passes through the midpoint of the late 1990s bed sediment volume measurement period indicates that bed sediment volume would equal the 1855–1867 value in 2001 (Fig. 6). With the assumption that the bed sediment volume change equals the erodible sediment pool, the erodible sediment pool would become depleted around 2001. This rough estimate is essentially identical to when the step decrease in SSC was observed beginning in WY 1999 and thus supports the hypothesis that the SSC decrease was caused by depletion of the erodible sediment pool. A more refined model is developed in the next section.

Quantitative Conceptual Model of an Erodible Sediment Pool

In this section, a simple numerical model of a depleting erodible sediment pool is derived and applied. The model quantifies the concepts of sediment supply, storage, and outflow in an estuary under transport and supply regulation. The model is intended to test the plausibility of the hypothesis that SSC would undergo a step decrease as an erodible sediment pool is depleted and transport-regulated sediment transport becomes supply-regulated. The model is also intended to simulate the general behavior of an erodible sediment pool. Details on bathymetry, tides, winds, and other factors that affect estuarine sediment transport are not included. This is an exploratory model designed to explain sudden clearing by simulating only the essential processes, rather than a simulation model designed to reproduce the estuary as completely as possible (Murray 2003).

Assume that the estuarine waters can be represented as a well-mixed volume with suspended sediment mass $S(t)$ that varies with time t. The maximum value of $S(t)$ due to transport regulation of suspended sediment is S_{max}. An erodible sediment mass $M(t)$ resides in suspension and on the bed. When suspended sediment is supply-regulated, $S(t)$

is proportional to $M(t)$. Thus, $S(t)$ equals the minimum of S_{max} and $c_sM(t)$ where c_s is a dimensionless suspension coefficient. River supply of sediment is $R(t)$ with units of mass per unit time. Outflow of sediment to the ocean $O(t)$ is proportional to $S(t)$ such that $O(t)=c_oS(t)$ where c_o is an outflow coefficient with units of time^{-1}. By conservation of mass (inflow−outflow=change in storage),

$$R(t) - O(t) = dM(t)/dt \tag{1}$$

Transport Regulation

For the case of transport regulation, suspended sediment mass $S(t)=S_{max}$ is a constant. Then,

$$R(t) - c_oS_{max} = dM(t)/dt \tag{2}$$

For exponentially decreasing river supply $R(t) = R(0)e^{-\alpha t}$, the solution to Eq. 2 is

$$M(t) = M_T(0) + \frac{1}{\alpha}(1 - e^{-\alpha t})R(0) - c_oS_{max}t \tag{3}$$

where $M_T(0)$ is the initial erodible sediment mass for transport regulation. For constant $R(t)=R_o$,

$$M(t) = (R_o - c_oS_{max})t + M_T(0) \tag{4}$$

Supply Regulation

For the case of supply regulation, $S(t)=c_sM(t)$. Then,

$$R(t) - c_oc_sM(t) = dM(t)/dt \tag{5}$$

For declining $M(t)$, when transport regulation ends and supply regulation begins, time t is reset to zero for convenience. The initial condition for supply regulation is that the erodible sediment mass is $M_S(0)$. At the threshold where regulation changes from transport to supply, $c_sM_S(0)=S_{max}$. For exponentially decreasing $R(t)$, the solution to Eq. 5 is

$$M(t) = \left(M_S(0) - \frac{R(0)}{c_oc_s - \alpha}\right)e^{-c_oc_st} + \frac{R(0)}{c_oc_s - \alpha}e^{-\alpha t} \tag{6}$$

For constant R, the solution to Eq. 5 is

$$M(t) = \left(M_S(0) - \frac{R}{c_oc_s}\right)e^{-c_oc_st} + \frac{R}{c_oc_s} \tag{7}$$

and the suspended mass is $S(t)=c_sM(t)$, so

$$S(t) = \left(c_sM_S(0) - \frac{R}{c_o}\right)e^{-c_oc_st} + \frac{R}{c_o} \tag{8}$$

At infinite time constant inflow R equals outflow c_oS_∞ or $S_\infty = R/c_o$ and $M_\infty = R/(c_oc_s)$.

The time scale over which suspended mass decreases in a supply-regulated estuary with a diminishing erodible sediment pool and constant sediment supply is quantified as follows. As suspended mass declines from the threshold between transport and supply regulation to a supply-regulated equilibrium, the midpoint of $S(t) = (S_{max} + S_\infty)/2$ occurs at $t_{1/2}$. Equation 8 then gives

$$\frac{1}{2}(S_{max} + S_\infty) = (S_{max} - S_\infty)e^{-c_oc_st_{1/2}} + S_\infty \tag{9}$$

Solving for $t_{1/2}$ gives

$$t_{1/2} = \frac{\ln(2)}{c_oc_s} \tag{10}$$

$t_{1/2}$ is a parameter indicating the time scale over which suspended mass decreases in a supply-regulated estuary with a diminishing erodible sediment pool and constant sediment supply. The product c_oc_s is the rate at which sediment mass leaves a supply-regulated estuary, so as the outflow increases, $t_{1/2}$ decreases (Fig. 8).

Application to San Francisco Bay

Application of the quantitative conceptual model to San Francisco Bay demonstrates that depletion of an erodible sediment pool in 1999 would cause a sudden decrease in SSC. The initial erodible mass is calculated from the bed volume from the 1942 to 1956 surveys when the bed volume was 418 Mm^3 greater than in 1855–1867. San Francisco Bay bed dry density varies from about 500 to 1,300 kg/m^3 (Caffrey 1995; Sternberg et al. 1986). Assuming a value of 850 kg/m^3 (Porterfield 1980) and that the change in bed sediment volume from the 1855 to 1867

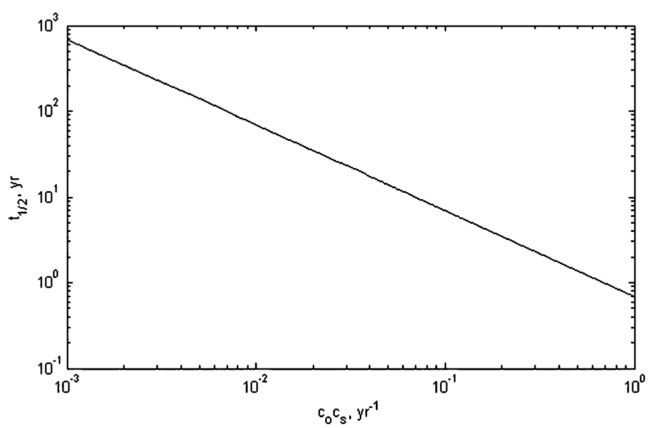

Fig. 8 $t_{1/2}$ as a function of c_oc_s. As suspended mass declines from the threshold between transport and supply regulation to a supply-regulated equilibrium, the midpoint of suspended mass between the two states occurs at $t_{1/2}$

Table 2 Initial year, initial river sediment supply $R(0)$, suspension coefficient c_s, outflow coefficient c_o, and resulting mean suspended mass 1999–2007 for simulations of an erodible sediment pool in San Francisco Bay

Initial year	$R(0)$, Mt/year	c_o, year^{-1}	c_s	1999–2007 mean suspended mass (Mt)
1949	2.57	10.5	0.00529	0.53
1960	2.23	13.4	0.00668	0.48
1970	1.96	20.2	0.01875	0.26

The best estimate of mean suspended mass for WYs 1999–2007 is 0.40 Mt (Table 1)

surveys equals the erodible sediment pool, the erodible sediment pool was 355 Mt in 1949. Schoellhamer et al. (2005) estimated that the mean river sediment supply to San Francisco Bay was 1.91 Mt/year from 1955 to 1990. Hestir et al. (submitted) applied the Seasonal Kendall test to flow-adjusted SSC (Schertz et al. 1991) in the Sacramento River at Freeport and the San Joaquin River at Vernalis and found that each decreased 1.31%/year. These rivers drain the Central Valley of California and account for the majority of sediment entering San Francisco Bay (Schoellhamer et al. 2005). Suspended sediment discharge was not measured on any other tributaries to San Francisco Bay from 1974 to 1999. Suspended sediment discharge in the Guadalupe River decreased by a factor of 4–8 from 1957–1962 to 2003–2008 (Schoellhamer et al. 2008). The change in suspended sediment discharge in Alameda Creek from circa 1960 to the 2000s is ambiguous because water discharge increased but sediment yield decreased. Thus, river sediment supply is assumed to decrease at 1.31%/year (α= 0.0131 year^{-1}). At this decay rate, river supply would have been 2.57 Mt/year in 1949 ($R(0)$). Maximum suspended mass is assumed to equal the mean of SSC measured through WY 1998, 75 mg/L (Table 1), multiplied by the mean bay volume (8,446 Mm^3, USGS 2009), which is 0.63 Mt. The outflow coefficient c_o is determined by forcing the erodible sediment mass M to equal the remaining mass for the 1979–1990 surveys, 289 Mt in 1985.

As the erodible sediment pool decreases, the time when the threshold between transport and supply regulation of suspended sediment is reached t_T is given by $S_{max}=c_sM(t_T)$. Substitute this expression into Eq. 3, assuming t_T corresponds to the beginning of the observed SSC step decrease in WY 1999, and given α, c_o, $R(0)$, $M(t_T)$, and S_{max}, Eq. 3 can be solved for

$$c_s = S_{max}/\left(M(t_T) + \frac{1}{\alpha}\left(1 - e^{-\alpha t_T}\right)R(0) - c_o S_{max} t_T\right) \qquad (11)$$

These initial values and coefficients are used to solve Eq. 1 with a 1-year time step and the second order Runge–Kutta method. This approach calculates c_o such that the erodible sediment mass is correct in the 1980s and calculates c_s such that the threshold from transport to supply regulation is crossed in 1999. The initial time to start the simulation is uncertain so initial times of 1949 (midpoint of mid-1900s surveys), 1960 (intermediate point), and 1970 (end of large urbanization period, Fig. 6) are used. For these three initial times, $R(0)$, c_s, and c_o are given in Table 2.

As the start time of the simulation gets later, the exponential decrease in suspended mass after the threshold from transport to supply regulation is passed becomes steeper and more step like (Fig. 9). Assuming the mean SSC from WY 1999 onward (48 mg/L, Table 1) applied to the entire bay volume, the mean suspended mass was 0.40 Mt. The simulation started in 1960 overpredicts this value, and the simulation started in 1970 underpredicts it (Table 2). The model is sensitive to the chosen start time because, for the same initial erodible sediment pool mass, outflow to the ocean must increase as the start time becomes later. After the threshold is crossed, a later start time causes greater outflow (c_o) and a more rapid decrease in suspended mass. Deposition rates upstream from San Francisco Bay in the Sacramento-San Joaquin River Delta were 4–8 times greater from 1944 to 1972 than from 1972

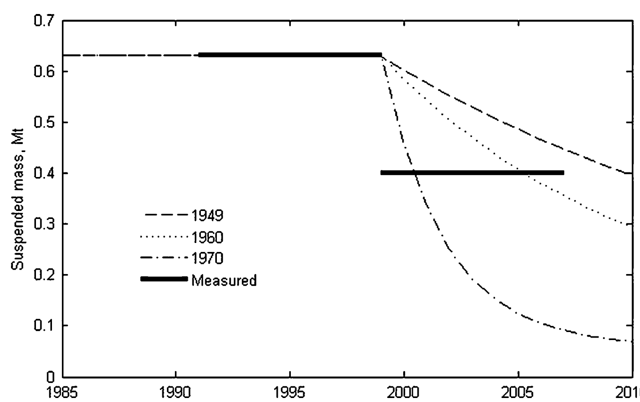

Fig. 9 Simulated and measured suspended sediment mass. Simulations specified (1) transport regulation before 1999 and supply regulation after 1999, (2) suspended mass before 1999 equals measured suspended mass (0.63 Mt), (3) initial erodible sediment mass equals the 1942–1956 estimate (355 Mt), and (4) erodible sediment mass in 1985 equals the 1979–1990 estimate (289 Mt). Dates refer to the starting time of the simulation when the initial sediment pool began to erode. The results support the hypothesis that crossing the threshold from transport to supply regulation of suspended sediment can cause the observed step decrease in suspended-sediment mass

to 2005 (Canuel et al. 2009), indicating that a downstream shift from deposition to erosion in the 1960–1970 period is reasonable.

The model is constructed to have a constant suspended mass until the threshold is reached at a specified time. These simulations demonstrate that given realistic rates of erosion, suspended mass, and river supply, if the threshold was crossed in 1999 as hypothesized, the result would be a rapid decrease in suspended mass.

If a constant river supply were used rather than an exponentially decreasing supply (not shown), then the time the threshold is crossed changes, but the suspended mass subsequently decreases rapidly in either case.

The assumption that the initial mass of the erodible sediment pool was equal to the change in sediment volume since the 1855–1867 surveys ignores the erodible sediment pool that would have existed before hydraulic mining. Prior to 1849, river supply to the bay was assumed to equal 2 million cubic yards per year (Gilbert 1917). A bulk density of 850 kg/m^3 (Porterfield 1980) was used to estimate river supply R= 1.3 Mt/year. For the simulation started in 1960, the size of the pre-1855 equilibrium erodible sediment pool $M_\infty = R/(c_o c_s)$ is estimated to have been 14.5 Mt. This is only 4% of the increase in bay sediment volume from the mid-1800s to mid-1900s (355 Mt). Thus, the pre-1855 erodible sediment pool was probably much smaller than the subsequent sediment pulses and is unlikely to significantly alter these results.

To test the model, the hydraulic mining sediment pulse was hindcast with the coefficients derived for the 1949, 1960, and 1970 start times of the erosion simulations. This however is not a true validation because deposition calculated from bathymetry data was used to estimate river supply from 1849 to 1914 (Gilbert 1917), and these are the only data available to compare with the model. The three sets of coefficients in Table 2 and R=1.3 Mt/year were used, and the model was run from 1700 to 1849 and established a steady state. Then, river supply from the Central Valley was increased to 18.4 million cubic yards per year for 1849–1914 (Gilbert 1917) or 12 Mt/year. This is the sum of depositional volume and outflow estimated by Gilbert (1917). The coefficients for the 1960 erosion simulation start date best match the 1880s and 1920s estimates of the erodible sediment pool from bathymetric change data (Fig. 10). Gilbert (1917) used the 1880s bathymetry data to estimate sediment supply to the bay, so that value does not offer a true validation. Deposition of the hydraulic mining pulse is too large for the 1949 coefficients and too small for the 1970 coefficients. The 1940s increase in the erodible sediment pool is not simulated because there is no corresponding quantified increase in sediment supply. Porterfield (1980) used suspended-sediment discharge measurements from the late 1950s and early 1960s to develop rating curves that were

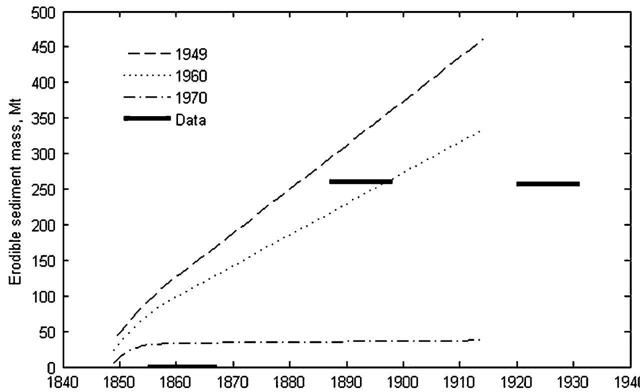

Fig. 10 Simulated and estimated mass in the erodible sediment pool during the hydraulic mining sediment pulse 1849–1914, San Francisco Bay. Simulations are for three different pairs of suspension and outflow coefficients determined by starting simulations of erosion at three different start times (1949, 1960, and 1970, Table 2). Sediment volume change from the 1855 to 1867 surveys is assumed to approximate the erodible sediment pool. A bulk density of 850 kg/m^3 is also assumed (Porterfield 1980). Each subembayment was surveyed during the period shown by *each thick line*. Bathymetry data are from Cappiella et al. (1999), Fregoso et al. (2008), Foxgrover et al. (2004), and Jaffe et al. (1998)

extrapolated back to 1909. Thus, there are no measurements of the second sediment pulse hypothesized to have occurred prior to the 1950s. In this simulation of the entire hydraulic mining sediment pulse, the threshold from transport to supply regulation of suspended sediment occurs in the early 1950s, and SSC decreases rapidly (not shown). Similar to the comparison with 1999–2007 suspended mass, simulation of the hydraulic mining pulse shows that the model produces reasonable results with the exception of the unquantified sediment pulse in the mid-1900s, that the coefficients for the 1960 erosion simulation start time are best, that coefficients for an erosion simulation that starts between 1960 and 1970 would be optimal, and that SSC declines rapidly once the threshold from transport to supply regulation of suspended sediment is crossed.

Discussion

The general progression of human land use has been characterized by disruptions (deforestation, mining, agricultural expansion, overgrazing, and urbanization) that create a sediment pulse to an estuary followed by dams that reduce sediment supply (Fig. 3, Hu et al. 2009; Pasternack et al. 2001; Ruiz-Fernandez et al. 2009; Syvitski et al. 2005; Warrick and Farnsworth 2009; Wolman 1967). In San Francisco Bay, hydraulic mining increased sediment discharge by a factor of 9 from the mid to late 1800s (Fig. 3, Gilbert 1917). Sedimentation rates increased 2–10-fold in other California estuaries in the nineteenth and twentieth centuries (Warrick and Farnsworth 2009). These increases are typical of the 5–10-fold increase found in lake and marine sediment records downstream from disturbed watersheds (Dearing and Jones 2003). Sediment discharge from the primary sediment source to San Francisco Bay, the Sacramento River, decreased about 50% from 1957 to 2001 (Wright and Schoellhamer 2004). This magnitude of decrease is not uncommon; river sediment discharge to the coastal zone has decreased 45% in Southern California due to trapping behind dams (Warrick and Farnsworth 2009), 50–70% from the Mississippi River (Kesel 2003), 75% from the Trinity River in Texas (Ravens et al. 2009), and globally riverine sediment discharge to oceans has decreased 10±2% (Syvitski et al. 2005). Reforestation and dams have reduced the sediment discharge in the Changjiang (Yangtze River) 68% from the 1950s to 2000s, and the decrease is expected to reach 82% (Hu et al. 2009). Thus, the sequence of predevelopment equilibrium, a sediment pulse that creates an erodible sediment pool, and reduced sediment supply in San Francisco Bay is similar to that of other estuaries.

Conditions Required for Sudden Clearing

The quantitative conceptual model demonstrates that, when transport-regulated suspension becomes supply-regulated as an erodible sediment pool is depleted, suspended mass can rapidly decrease. An erodible sediment pool and crossing the regulation threshold are both necessary to have a rapid decrease in suspended mass.

Without an erodible sediment pool, annual suspended mass would be dependent on river supply and would not suddenly decrease, unless the river supply suddenly decreased. The river supply to San Francisco Bay varies annually and decreased 1.3%/year during the later half of the twentieth century (Hestir et al. submitted), which does not account for the sudden 36% decrease in suspended mass in 1999.

If sediment transport remained transport-regulated and the transport capacity does not suddenly change, then SSC would not change. Tides and seasonal winds are primarily responsible for sediment suspension in San Francisco Bay, and they are consistent from year to year, so transport capacity is likely to be constant (Schoellhamer 2002). If sediment transport were actually supply-regulated, SSC would have sharply declined from the 1950s to 1980s when the bay eroded. Data are not available for the earlier part of this period, but from 1969 to 1980, there was no significant trend ($p>0.15$) in discrete monthly SPM 2 m below the water surface at nine US Geological Survey sampling stations with enough data for analysis by the Seasonal Kendall trend test (Schertz et al. 1991). Thus, it is unlikely that there was a large decline in suspended sediment from the 1950s to 1980s and that sediment transport was supply-regulated.

For an estuary with an erodible sediment pool, decreasing river sediment supply hastens crossing the threshold from transport to supply regulation and the severity of the subsequent decrease in SSC, but decreasing river supply was not solely responsible for the SSC decrease. For San Francisco Bay, the simulation beginning in 1960 with constant sediment supply crossed the regulation threshold in 2002 (3 years later than observed) and increased the predicted 2010 suspended mass 34%. If an estuary is in equilibrium or is depositional, decreased river supply may make the estuary erosional, and if it is transport-regulated, set up the conditions required for eventual sudden clearing.

Erodible Sediment Pool

An erodible sediment pool in an estuary can be created or enlarged by a pulse of sediment from the watershed. A large flood can deliver a sediment pulse. For example, tropical storm Agnes produced 1 week of sediment discharge from the Susquehanna River to Chesapeake Bay equal to 30–50 normal years of sediment supply (Schubel 1974). Anthropogenic disturbance within the watershed can increase the quantity of erodible sediment, enabling normal runoff to deliver a pulse. Hydraulic mining increased the supply of sediment to San Francisco Bay by a factor of about 9 over several decades (Gilbert 1917). Deforestation and conversion to agricultural and urban land use are a more common anthropogenic mechanism for increasing sediment yield of a watershed (Pasternack et al. 2001; Ruiz-Fernandez et al. 2009; Wolman 1967). In general, sediment supplied from watersheds in the tropics and Indonesia in particular has increased due to deforestation (Syvitski et al. 2005).

This study applies the concept of an erodible sediment pool to an entire estuary. This is an extension of the erodible sediment pool concept used to explain tidal and fortnightly variability of SSC in some narrow estuaries and tidal rivers (Ganju et al. 2004; Grabemann and Krause 1994; Grabemann et al. 1997; Tattersall et al. 2003). At this smaller spatial scale, flood and ebb tidal currents alternately resuspend and transport the erodible sediment pool, which deposits during slack tide. The result is a tidally oscillating sediment mass that can create an estuarine turbidity maximum. The size of the oscillating sediment mass is greatest on spring tides and smallest on neap tides. The application of the erodible sediment pool concept to an entire estuary in this study differs from these previous applications in terms of spatial variability, temporal variability, and size of the erodible sediment pool

Application of the concept to an entire estuary considers neither spatial variability in erosion, deposition, or SSC nor proximity to river inputs and the ocean. The objective of this study, however, is to understand the net functionality of the estuary as a component in the watershed/estuary/ocean system, for which the erodible sediment pool concept is applicable.

Annual to interannual time scales rather than tidal and fortnightly time scales are considered in this study. Temporal variability due to tides, wind, and river flow are not considered. At annual and interannual time scales, these forcings suspend sediment, some of which is transported from the estuary to the ocean. The quantitative conceptual model simulates this process.

At the tidal time scale, an erodible sediment pool is the quantity of sediment suspended by a particular tide. In both the Weser Estuary and Petaluma River, the size of the pool is less than the annual river supply, 4% and 82%, respectively (Ganju et al. 2004; Grabemann and Krause 1994). At the interannual time scale of this study, an erodible sediment pool is the difference between the existing sediment mass and the sediment mass of the estuary at equilibrium (no net deposition or erosion). To supply sediment during low-supply years, the pool must be larger than the average annual sediment supply. Thus, an erodible sediment pool at the interannual time scale is larger than at the tidal time scale.

Transport and Supply Regulation of Suspended Mass

As an estuarine sediment pool erodes, crossing the threshold from transport to supply regulation of suspended sediment mass can trigger a rapid decrease in SSC. In the quantitative conceptual model, the entire estuary is assumed to be either transport- or supply-regulated, and seasonal and tidal variations in regulation are neglected. In reality, some parts of an estuary may be transport-regulated while others are supply-regulated. Regulation may also vary seasonally and fortnightly. For example, in San Francisco Bay and other estuaries, there is a seasonal cycle of sediment inflow during the wet season and winnowing and redistribution of sediment by tides and waves during the dry season (Deloffre et al. 2005; Krone 1979; Lesourd et al. 2003; Ryu 2003). Thus, suspended mass may be transport-regulated after delivery of sediment from the watershed and supply-regulated at the end of the dry season. In addition, SSC in San Francisco Bay and other estuaries varies with the spring/neap tidal cycle (Brennan et al. 2002; Grabemann et al. 1997; Schoellhamer 2002; Wolanski et al. 1995), and the depth of bed sediment reworking decreases during neap tides (Brennan et al. 2002; Deloffre et al. 2005). Thus, suspended mass may be transport-regulated during neap tides and supply-regulated during spring tides. Identification and quantification of transport and supply regulation in estuaries need further research.

Ramifications of Decreased SSC

A less turbid estuary has ramifications for dredging, wetland restoration, water quality, and the ecosystem.

Smaller SSC reduces deposition, which in turn reduces maintenance dredging volumes and increases the life expectancy of dredged-material disposal sites in an estuary. In San Francisco Bay, ocean disposal is now about equal to the average supply of sediment from the Central Valley (Schoellhamer et al. 2005). Bay disposal sites may be able to accommodate more material, reducing the need for costly ocean disposal.

Wetland restoration typically involves opening a diked area to tidal action, allowing sediment to deposit until the bed elevation is high enough for plant colonization. The rate of deposition is proportional to SSC (Krone and Hu 2001). The time required to create a wetland increases as SSC decreases. If the rate of deposition is less than the rate of sea level rise, a vegetated wetland will never form. Thus, decreased SSC affects restoration of subsided land to tidal marsh by (1) increasing the time needed to restore tidal marsh vegetation and (2) increasing the possibility that natural sedimentation cannot restore tidal marsh as sea level rises.

Many contaminants are associated with sediment (David et al. 2009; Luengen and Flegal 2009; Schoellhamer et al. 2007; Turner and Millward 2002). Smaller SSC decreases the water column concentration of sediment-associated contaminants. Water quality standards written in terms of total (dissolved and sediment-associated) concentration are more likely to be achieved because SSC is smaller. Suspended sediment moving into, within, and out of estuaries provides a pathway for the transport of sediment-associated contaminants (Bergamaschi et al. 2001; David et al. 2009; Le Roux et al. 2001; Turner and Millward 2000). Decreased SSC decreases the pelagic flux of contaminants within an estuary and from an estuary to the ocean.

In some estuaries including San Francisco Bay, suspended sediment limits light in the water column which limits phytoplankton growth (Cloern 1987). Thus, a decrease in SSC would increase phytoplankton. In San Francisco Bay beginning in 1999, chlorophyll concentrations increased, and autumn blooms occurred for the first time since at least 1978 (Cloern et al. 2007). Both SSC and chlorophyll indicate that the bay crossed a threshold and fundamentally changed in 1999. San Francisco Bay has been transformed from a low-productivity estuary to one having primary production typical of temperate-latitude estuaries. Cloern et al. (2007) also state that a shift in currents in the Pacific Ocean, improved wastewater treatment, reduced sediment inputs, and introductions of new species may be responsible for the chlorophyll increase. Larger phytoplankton blooms may also affect contaminant fate. Blooms dilute methyl mercury concentrations in phytoplankton cells, but decay of phytoplankton after a bloom increases dissolved methyl mercury (Luengen and Flegal 2009). Thus, the net effect of increased phytoplankton blooms on methyl mercury uptake into the food web is uncertain.

Reduced SSC may be one of several factors contributing to a collapse of several San Francisco Bay estuary fish species that occurred around 2000 (Sommer et al. 2007). Abundance of some fish species increases in more turbid waters (Feyrer et al. 2007). The population collapse has had the most serious consequences for Delta smelt which require turbid water for successful feeding and predator avoidance. The relation between decreased SSC and fish decline, however, is not well established, and the concurrence of less SSC, more phytoplankton, and fewer fish merits additional study.

Conclusions

Anthropogenic disturbances in a watershed, such as mining, deforestation, and urbanization, can create a pulse of sediment that deposits in an estuary, creating an erodible sediment pool. As the erodible pool is depleted, regulation of suspended sediment can cross the threshold from transport regulation to supply regulation. A quantitative conceptual model demonstrates that upon crossing this threshold, suspended sediment mass in the estuary can decrease rapidly, suddenly clearing the estuarine waters. In San Francisco Bay, this sequence of events appears to explain a 36% step decrease in SSC beginning in WY 1999. Changes in the San Francisco Bay ecosystem in the 2000s have been symptomatic of this sudden clearing. A decreasing watershed sediment supply averaging 1.3%/year contributes to decreased SSC but cannot account for the step decrease in SSC. Human development of watersheds follows a similar pattern: disturbance creates a pulse of sediment followed by decreased sediment supply, often due to trapping behind dams. Thus, many estuaries may be susceptible to sudden clearing.

Acknowledgments I would like to thank those that have helped collect, process, and publish the continuous SSC data: Rick Adorador, Greg Brewster, Paul Buchanan, Laurie Campbell, Mike Farber, Amber Forest, Neil Ganju, Tom Hankins, Megan Lionberger, Allan Mlodnosky, Tara Morgan, Heather Ramil, Cathy Ruhl, Rob Sheipline, Brad Sullivan, and Jessica Wood. Bruce Jaffe, Neil Ganju, John Oram, and two anonymous reviewers provided helpful comments on earlier versions of this article. This work was supported by the US Army Corps of Engineers, San Francisco District, as part of the Regional Monitoring Program for Water Quality in the San Francisco Estuary.

References

Atwater, B.F., S.G. Conard, J.N. Dowden, C.W. Hedel, R.L. MacDonald, and W. Savage. 1979. History, landforms, and vegetation of the estuary's tidal marshes. In *San Francisco Bay, the urbanized estuary, 347–385*, ed. T.J. Conomos. San Francisco: Pacific Division of the American Association for the Advancement of Science http://www.estuaryarchive.org/archive/conomos_1979/.

Bay Area Census, 2009, http://www.bayareacensus.ca.gov/historical/copop18602000.htm. Accessed 16 June 2010.

Bergamaschi, B.A., K.M. Kuivila, and M.S. Fram. 2001. Pesticides associated with suspended sediments entering San Francisco Bay following the first major storm of WY 1996. *Estuaries* 24: 368–380.

Brennan, M.L., D.H. Schoellhamer, J.R. Burau, and S.G. Monismith. 2002. Tidal asymmetry and variability of bed shear stress and sediment bed flux at a site in San Francisco Bay, USA. In *Fine sediment dynamics in the marine environment*, eds. J.C. Winterwerp, and C. Kranenburg, 93–108. Elsevier Science B.V.

Buchanan, P.A., and M.A. Lionberger. 2009. *Summary of suspended-sediment concentration data, San Francisco Bay, California, Water Year 2006*. US Geological Survey Data Series Report 362, 35 http://pubs.usgs.gov/ds/362/

Caffrey, J.M. 1995. Spatial and seasonal patterns in sediment nitrogen remineralization and ammonium concentrations in San Francisco Bay, California. *Estuaries* 18: 219–233.

California Department of Finance. 2009. California Statistical Abstracts, http://www.dof.ca.gov/HTML/FS_DATA/STAT-ABS/Statistical_Abstract.php. Accessed 16 June 2010.

Canuel, E.A., E.J. Lerberg, R.M. Dickhut, S.A. Kuehl, T.S. Bianchi, and S.G. Wakeham. 2009. Changes in sediment and organic carbon accumulation in a highly-disturbed ecosystem: The Sacramento-San Joaquin River Delta (California, USA). *Marine Pollution Bulletin* 59: 154–163.

Cappiella, K., C. Malzone, R. Smith, and B. Jaffe. 1999. Sedimentation and bathymetry changes in Suisun Bay, 1867–1990. US Geological Survey Open-File Report 99–563. http://pubs.er.usgs.gov/usgspubs/ofr/ofr99563

Cloern, J.E. 1987. Turbidity as a control on phytoplankton biomass and productivity in estuaries. *Continental Shelf Research* 7: 1367–1381.

Cloern, J.E., A.D. Jassby, J.K. Thompson, and K.A. Heib. 2007. A cold phase of the East Pacific triggers new phytoplankton blooms in San Francisco Bay. *Proceedings of the National Academy of Science* 104: 18561–18565.

Conomos, T.J., and D.H. Peterson. 1977. Suspended-particle transport and circulation in San Francisco Bay, an overview. Estuarine Processes, 2:82–97. New York, Academic Press.

David, N., L.J. McKee, F.J. Black, A.R. Flegal, C.H. Conaway, D.H. Schoellhamer, and N.K. Ganju. 2009. Mercury concentrations and loads in a large river system tributary to San Francisco Bay, California, USA. *Environmental Toxicology and Chemistry* 28: 2091–2100.

Dearing, J.A., and R.T. Jones. 2003. Coupling temporal and spatial dimensions of global sediment flux through lake and marine sediment records. *Global and Planetary Change* 39: 147–168.

Deloffre, J., R. Lafite, P. Lesueur, S. Lesourd, R. Verney, and L. Guezennec. 2005. Sedimentary processes on an intertidal mudflat in the upper macrotidal Seine estuary, France. *Estuarine, Coastal and Shelf Science* 64: 710–720.

Feyrer, F., M.L. Nobriga, and T.R. Sommer. 2007. Multidecadal trends for three declining fish species: habitat patterns, and mechanisms in the San Francisco Estuary, California, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 64: 723–734.

Foxgrover, A.C., S.A. Higgins, M.K. Ingraca, B.E. Jaffe, and R.E. Smith. 2004. Deposition, erosion, and bathymetric change in South San Francisco Bay: 1858–1983. US Geological Survey Open-File Report 2004-1192, 25 p. http://pubs.er.usgs.gov/usgspubs/ofr/ofr20041192

Fregoso, T.A., A.C. Foxgrover, and B.E. Jaffe. 2008. Sediment deposition, erosion, and bathymetric change in central San Francisco Bay: 1855–1979. US Geological Survey Open-File Report 2008-1312, 41 p. http://pubs.usgs.gov/of/2008/1312/

Ganju, N.K., and D.H. Schoellhamer. 2006. Annual sediment flux estimates in a tidal strait using surrogate measurements. *Estuarine, Coastal and Shelf Science* 69: 165–178.

Ganju, N.K., D.H. Schoellhamer, J.C. Warner, M.F. Barad, and S.G. Schladow. 2004. Tidal oscillation of sediment between a river and a bay: A conceptual model. *Estuarine, Coastal and Shelf Science* 60: 81–90.

Ganju, N.K., N. Knowles, and D.H. Schoellhamer. 2008. Temporal downscaling of decadal sediment load estimates to a daily interval for use in hindcast simulations. *Journal of Hydrology* 349: 512–523.

Gilbert, G.K. 1917. *Hydraulic mining debris in the Sierra Nevada*. US Geological Survey Professional Paper 105.

Grabemann, I., and G. Krause. 1994. Suspended matter fluxes in the turbidity maximum of the Weser Estuary. In *Changes in fluxes in estuaries*, ed. K.R. Dyer and R.J. Orth, 23–28. Denmark: Olsen & Olsen.

Grabemann, I., R.J. Uncles, G. Krause, and J.A. Stephens. 1997. Behaviour of turbidity maxima in the Tamar (U.K.) and Weser (F.R.G.) estuaries. *Estuarine, Coastal and Shelf Science* 45: 235–246.

Gray, J.R., G.D. Glysson, L.M. Turcios, and G.E. Schwarz. 2000. *Comparability of suspended-sediment concentration and total suspended-solids data*. US Geological Survey Water-Resources Investigations Report 00-4191.

Hu, B., Z. Yang, H. Wang, X. Sun, N. Bi, and G. Li. 2009. Sedimentation in the Three Gorges Dam and the future trend of Changjiang (Yangtze River) sediment flux to the sea. *Hydrology and Earth System Sciences* 13: 2253–2264.

Jaffe, B.E., R.E. Smith, and L.Z. Torresan. 1998. *Sedimentation and bathymetric change in San Pablo Bay, 1856–1983*. US Geological Survey Open-File Report 98-759. http://pubs.er.usgs.gov/usgspubs/ofr/ofr98759.

Jassby, A.D., J.E. Cloern, and B.E. Cole. 2002. Annual primary production: Patterns and mechanisms of change in a nutrient-rich tidal ecosystem. *Limnology and Oceanography* 47: 698–712.

Kesel, R.H. 2003. Human modifications to the sediment regime of the Lower Mississippi river flood plain. *Geomorphology* 56: 325–334.

Krone, R.B., 1979. Sedimentation in the San Francisco Bay system. In *San Francisco Bay, the Urbanized Estuary*, ed. T.J. Conomos, 85–96. San Francisco, California: Pacific Division of the American Association for the Advancement of Science. http://www.estuaryarchive.org/archive/conomos_1979/.

Krone, R.B., and G. Hu. 2001. Restoration of subsided sites and calculation of historic marsh elevations. *Journal of Coastal Research* 27: 162–169.

Le Roux, S.M., A. Turner, G.E. Millward, L. Ebdon, and P. Apprion. 2001. Partitioning of mercury onto suspended sediments in estuaries. *Journal of Environmental Monitoring* 3: 37–42.

Lesourd, S., P. Lesueur, J.C. Brun-Cottan, S. Garnaud, and N. Pupinet. 2003. Seasonal variations in the characteristics of superficial sediments in a macrotidal estuary (the Seine inlet, France). *Estuarine, Coastal and Shelf Science* 58: 3–16.

Luengen, A.R., and A.R. Flegal. 2009. Role of phytoplankton in mercury cycling in the San Francisco Bay estuary. *Limnology and Oceanography* 54: 23–40.

McKee, L.J., N.K. Ganju, and D.H. Schoellhamer. 2006. Estimates of suspended sediment flux entering San Francisco Bay from the Sacramento and San Joaquin Delta, San Francisco Bay, California. *Journal of Hydrology* 323: 335–352.

Murray, A.B. 2003. Contrasting the goals, strategies, and predictions associated with simplified numerical models and detailed simulations. In *Prediction in Geomorphology*, 151–165. American Geophysical Union Geophysical Monograph 135.

Nady, P., and L.L. Larragueta. 1983. *Development of irrigation in the Central Valley of California*. US Geological Survey Hydrologic Atlas 649.

Ogden Beeman & Associates, Inc. 1992. Sediment budget study for San Francisco Bay. Report prepared for the San Francisco District, US Army Corps of Engineers.

Pasternack, G.B., G.S. Brush, and W.B. Hilgartner. 2001. Impact of historic land-use change on sediment delivery to a Chesapeake Bay subestuarine delta. *Earth Surface Processes and Landforms* 26: 409–427.

Porterfield, G. 1980. *Sediment transport of streams tributary to San Francisco, San Pablo, and Suisun Bays, California, 1909–1966*. US Geological Survey Water-Resources Investigations Report 80–64, 91.

Ravens, T.M., R.C. Thomas, K.A. Roberts, and P.H. Santshi. 2009. Causes of salt marsh erosion in Galveston Bay, Texas. *Journal of Coastal Research* 25: 265–272.

Rubin, D.M., and D.J. Topping. 2001. Quantifying the relative importance of flow regulation and grain-size regulation of suspended-sediment transport α, and tracking changes in bed-sediment grain size β. *Water Resources Research* 37: 133–146.

Ruiz-Fernandez, A.C., C. Hillaire-Marcel, A. de Vernal, M.L. Machain-Castillo, L. Vasquez, B. Ghaleb, J.A. Aspiazo-Fabian, and F. Paez-Osuman. 2009. Changes of coastal sedimentation in the Gulf of Tehuantepec, South Pacific Mexico, over the last 100 years from short-lived radionuclide measurements. *Estuarine, Coastal and Shelf Science* 82: 525–536.

Ryu, S.O. 2003. Seasonal variation of sedimentary processes in a semi-enclosed bay: Hampyong Bay, Korea. *Estuarine, Coastal and Shelf Science* 56: 481–492.

Schertz, T.L., R.B. Alexander, and D.J. Ohe. 1991. *The computer program estimate_trend (ESTREND), a system for the detection of trends in water-quality data*. US Geological Survey Water Resources Investigations Report 91-4040. http://pubs.usgs.gov/wri/wri91-4040/

Schoellhamer, D.H. 2002. Variability of suspended-sediment concentration at tidal to annual time scales in San Francisco Bay, USA. *Continental Shelf Research* 22: 1857–1866.

Schoellhamer, D.H., M.A. Lionberger, B.E. Jaffe, N.K. Ganju, S.A. Wright, and G.G. Shellenbarger. 2005. *Bay sediment budgets: Sediment accounting 101*. In *The pulse of the estuary: Monitoring and managing water quality in the San Francisco Estuary*, 58–63. Oakland: San Francisco Estuary Institute. http://www.sfei.org/rmp/pulse/2005/RMP05_PulseoftheEstuary.pdf.

Schoellhamer, D.H., T.E. Mumley, and J.E. Leatherbarrow. 2007. Suspended sediment and sediment-associated contaminants in San Francisco Bay. *Environmental Research* 105: 119–131.

Schoellhamer, D.H., J.L. Orlando, S.A. Wright, and L.A. Freeman. 2008. Sediment supply and demand. In *South Bay Salt Pond Restoration Project 2006 Science Symposium Presentation Synopses*, 20–22. http://www.southbayrestoration.org/science/2006symposium/2006%20Science%20Symposium%20Synopses%20Final.pdf

Schubel, J.R. 1974. Effect of tropical storm Agnes on the suspended solids of the Northern Chesapeake Bay. In *Suspended solids in water*, ed. R.J. Gibbs, 4:113–132. Plenum Marine Science.

Singer, M.B., R. Aalto, and L.A. James. 2008. Status of the lower Sacramento Valley flood-control system within the context of its natural geomorphic setting. *Natural Hazards Review* 9: 104–115.

Sommer, T., C. Armor, R. Baxter, R. Breuer, L. Brown, M. Chotkowski, S. Culberson, F. Feyrer, M. Gingras, B. Herbold, W. Kimmerer, A. Mueller-Solger, M. Nobriga, and K. Souza. 2007. The collapse of pelagic fishes in the upper San Francisco estuary. *Fisheries* 32: 270–277.

Sternberg, R.W., D.A. Cacchione, D.E. Drake, and K. Kranck. 1986. Suspended sediment transport in an estuarine tidal channel within San Francisco Bay, California. *Marine Geology* 71: 237–258.

Syvitski, J.P.M., C.J. Vorosmarty, A.J. Kettner, and P. Green. 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* 308: 376–380.

Tattersall, G.R., A.J. Elliot, and N.M. Lynn. 2003. Suspended sediment concentrations in the Tamar estuary. *Estuarine, Coastal and Shelf Science* 57: 679–688.

Tran, H.N., L. Chuang, and C.L. Guss. 1999. Natural resources conservation laws. In *Erosion and sediment control laws, Ch. 3*. Natural Resources Conservation Service. http://www.nrcs.usda.gov/technical/references/pdf/NRCLawsch3.pdf

Turner, A., and G.E. Millward. 2000. Particle dynamics and trace metal reactivity in estuarine plumes. *Estuarine, Coastal and Shelf Science* 50: 761–774.

Turner, A., and G.E. Millward. 2002. Suspended particles: their role in estuarine biogeochemical cycles. *Estuarine, Coastal and Shelf Science* 55: 857–883.

USFWS. 2000. Impacts of Riprapping to Ecosystem Functioning, Lower Sacramento River, California. http://www.fws.gov/sacramento/hc/reports/sac_river_riprap.pdf. Accessed 16 June 2010.

USGS. 2009. San Francisco Bay bathymetry. http://sfbay.wr.usgs.gov/sediment/sfbay/geostat.html. Accessed 16 June 2010.

Warrick, J.A., and K.L. Farnsworth. 2009. Sources of sediment to the coastal waters of the Southern California Bight. In *Earth science in the urban ocean: The Southern California Borderland*, eds. H. J. Lee and W.R. Normark, Special paper 454, 39–52. The Geological Society of America.

Wolanski, E., B. King, and D. Galloway. 1995. Dynamics of the turbidity maximum in the Fly River estuary, Papua New Guinea. *Estuarine, Coastal and Shelf Science* 40: 321–337.

Wolman, M.G. 1967. A cycle of sedimentation and erosion in urban river channels. *Geografiska Annaler A, Physical Geography* 49: 385–395.

Wright, S.A., and D.H. Schoellhamer. 2004. Trends in the sediment yield of the Sacramento River, California, 1957–2001. *San Francisco Estuary and Watershed Science* 2. http://repositories.cdlib.org/jmie/sfews/vol2/iss2/art2.