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

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ABSTRACT

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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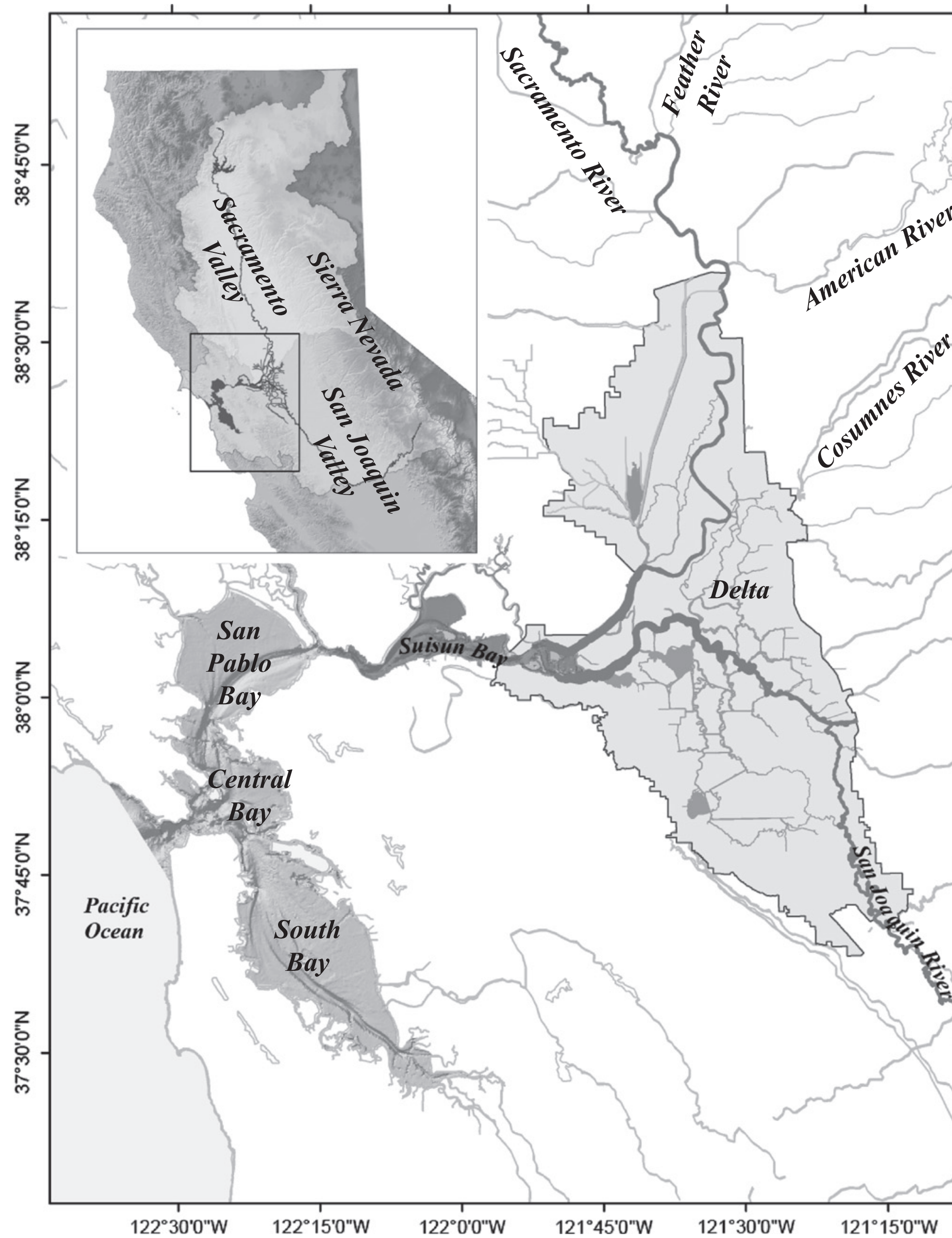

Fig. 1. San Francisco Estuary and watershed. The Estuary includes the Sacramento–San Joaquin River Delta and San Francisco Bay which has subembayments of Suisun, San Pablo, Central, and South Bays.

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

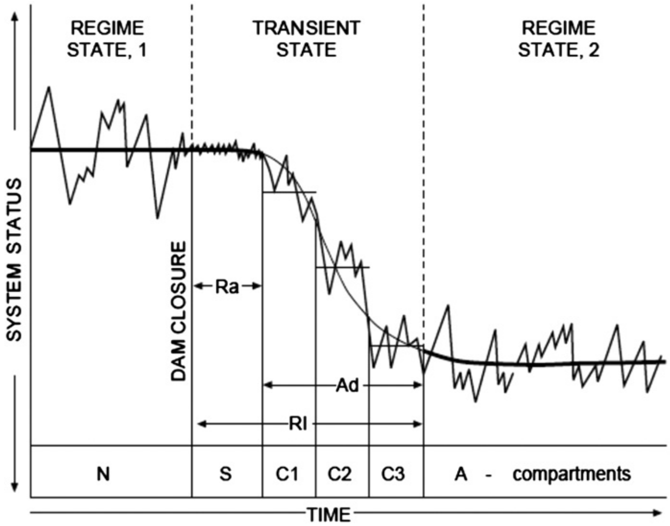

Fig. 2. The hypothetical trajectory of fluvial metamorphosis following dam closure (from Petts and Gurnell, 2005). Change from the natural regime state (N) to the adjusted regime state (A) passes through the relaxation period (Rl) comprising a reaction phase (Ra) and an adjustment phase (Ad). The relaxation period comprises a sequence of transient states. These include an accommodation state (S), in which regulated flows are accommodated within the inherited channel form, and changed channel states (here C1–3) adjust to the regulated flow and changing sediment loads as the adjustment process conveys sediments through the downstream sequence of regulated reaches.

as multiple dams were built, river banks were protected, and floodplain were transformed to a managed flood bypasses. We conceptually combine upstream changes and assume that at a downstream location there is a specific time where sediment supply is reduced.

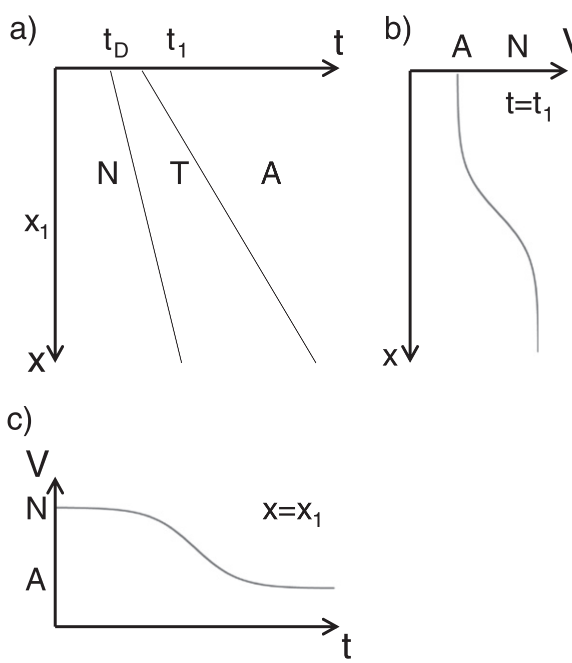

Fig. 3. Conceptual model of sediment supply reduction and downstream propagation. a) Longitudinal and temporal (x,t) space containing characteristic lines that define the boundaries between natural (N), transient (T), and adjusted (A) regimes. Sediment supply reduction occurs at time t_D at $x = 0$. The longitudinal coordinate x extends from the point of supply reduction downstream into the estuary. b) Longitudinal variation of a system variable (V) at a particular time t_1. The variable is equal to its altered value in the upstream reach, its natural value in the downstream reach, and is a transient intermediate value in between. c) Temporal variation of a system variable at a particular point x_1, similar to Fig. 2. The variable is equal to its natural value initially, its altered value at the end of the period, and is a transient intermediate value in between.

After reduction in sediment supply, the system enters a transient state (T) where it adjusts from the natural regime to an adjusted regime (A). Adjustment balances channel form and physical processes after a disturbance. Petts and Gurnell (2005) state 'This approach has its roots in regime-type analysis of stable canal design, which suggests that the dimensions of width, depth and gradient adjust to carry a given supply of water loaded with a given silt charge. Thus, any change in discharge and/or sediment load below a dam would disturb the existing quasi-equilibrium (or 'regime') state and cause an adjustment of the channel form.' The initial reaction phase (Ra) is likely to be reduced variability in system variables because flow variability is typically reduced downstream from a dam (Fig. 2). Immediately downstream from a disturbance such as a dam, this phase may have an insignificant duration. For example, sediment discharge may immediately reduce to zero. Downstream from a disturbance, this phase may have a duration of decades (Williams and Wolman, 1984). Petts and Gurnell (2005) called this an accommodation state where regulated flow from a dam was accommodated within the existing channel.

Adjustment of system variables to reduced sediment supply propagates downstream from the disturbance (Fig. 3a). The variables may change as a step function or continuously. A system variable is typically most perturbed at the disturbance and the perturbation decreases in the downstream direction (Fig. 3b). For example, suspended-sediment discharge immediately downstream from a dam that is a perfect sediment trap will be zero and erosion after that point will increase sediment discharge until the natural state is reestablished downstream. Over time, bed armoring reduces the rate of sediment erosion and the river reach experiencing clear flows expands downstream and the river reach experiencing erosion shifts downstream. The propagation of the disturbance continues into the estuary and ultimately the ocean. At a particular point, the value of a system variable is initially its natural value and changes until it attains its altered value (Fig. 3c), which may be greater than or less than its natural value.

At the conclusion of the transient regime, the system becomes stationary in an adjusted regime. Processes that take place at longer time scales such as climate change and tectonics are not considered in this model, so the natural and adjusted regimes are assumed to be stationary.

This conceptual model is analogous to the method of characteristics used to calculate the propagation of flood waves in open channel flow (Henderson, 1966). The principles of conservation of mass and momentum are used to calculate characteristic lines in longitudinal and temporal (x,t) space that represent the location of a flood wave. Movement along a characteristic line represents motion of a wave. The slope of a characteristic line is the speed of propagation. We define the transition from the natural to transient regime to be the NT characteristic and the transition from the transient to adjusted regime to be the TA characteristic. Thus, the transitions from natural to transient to adjusted regimes are conceptualized as waves propagating downstream.

3. Conceptual model of downstream propagation of increased sediment supply and a subsequent decrease

In the SFEW, the natural regime was followed by a large increase in sediment supply from hydraulic mining in the late 1800s which caused adjustment of the downstream rivers and estuary. Subsequently the rivers and estuary were adjusting to decreasing sediment supply due to reservoir construction, floodplain management, and cessation of hydraulic mining. In this section a transient regime of increasing sediment supply is added to the conceptual model to enable application to the SFEW.

The resulting conceptual model includes the following four regimes in chronological order: stationary natural regime (N), transient response to increasing sediment supply (I), transient response to decreasing sediment supply (D), and stationary adjusted regime (A) (Fig. 4). We assume that the abrupt halt of hydraulic mining precludes a stationary sediment supply regime between regimes I and D. Three characteristic lines result: NI is the beginning of the sediment pulse, ID is the peak of the sediment

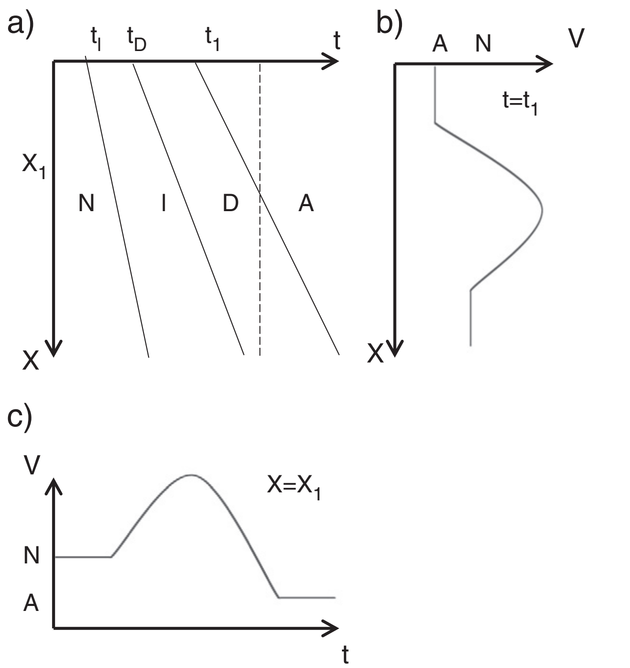

Fig. 4. Conceptual model of downstream propagation of increased sediment supply and a subsequent decrease. a) Longitudinal and temporal space containing characteristic lines that define the boundaries between stationary natural (N), transient increasing supply (I), transient decreasing supply (D), and adjusted (A) regimes. At $x = 0$, sediment supply increases at time t_I and sediment supply reduction occurs at time t_D. The longitudinal coordinate x extends from the point of supply change downstream into the estuary. In the case where the entire system suddenly transitions from the transient decreasing supply to altered regime, the DA characteristic is the vertical dashed line. This may be the case for the San Francisco Estuary and its watershed. b) Longitudinal variation of a system variable (V) at a particular time t_1. The variable is equal to its altered value in the upstream reach, its natural value in the downstream reach, and is a transient intermediate value in between. c) Temporal variation of V at a particular point x_1. The variable is equal to its natural value initially, its altered value at the end of the period, and is a transient intermediate value in between.

pulse, and DA is the end of adjustment to the alterations of sediment supply. The peak of the pulse (ID) is defined as the transition from adjusting to increasing supply to adjusting to decreasing supply. Otherwise, the assumptions made in the development of the prior model are applicable here.

4. Synthesis of relevant studies

Numerous sedimentation studies have been conducted in the San Francisco Estuary and watershed (Barnard et al., 2013–this issue). In this section, we synthesize studies related to our hypotheses from the headwaters of the watershed to the San Francisco Bay. For this purpose, clear signals of increasing or decreasing sediment supply are desired so only studies of depositional and erosional environments such as river channels and estuarine open water are included. Studies on historical vertical accretion in marshes are excluded because they rely on core data that only reflect net deposition. Such deposition may be variable through time due to factors such as marsh elevation, inundation regime, topography, and plant community composition and, therefore, may not provide a clear signal of changes in the sediment supply of the watershed. The results are summarized in the longitudinal and temporal (x, t) space that is the foundation of our conceptual model (Fig. 4).

Little is known or documented about sedimentation in the SFEW prior to hydraulic mining. Given the lack of data, Gilbert (1917) made a speculative estimate that the pre-hydraulic mining supply of sediment from the watershed to the estuary was 1.5 Mm^3/yr. Given that human disturbances were certainly much smaller before hydraulic mining than after, we assume that the SFEW was in a natural regime prior to hydraulic mining.

In the upstream portion of the SFEW, rivers in the Sierra Nevada aggraded during hydraulic mining and subsequently degraded. Tremendous amounts of sediment were deposited from 1858 to 1884 concurrent with hydraulic mining (Gilbert, 1917). James (1999) analyzed stream gage records to show degradation in the Bear River from 1905 to 1927. He also found degradation from 1985 to 1996 in the upper Bear River watershed.

Although hydraulic mining was the primary disturbance, other mining activities and land use practices caused aggradation in lower Sacramento Valley rivers. Deposition on the lower Cosumnes River floodplain increased from 3 mm/yr before 1849 to 25 mm/yr 1849–1920 after which levees separated the floodplain and river (Florsheim and Mount, 2003).

Hydraulic mining sediment began to aggrade rivers in the lower Sacramento Valley during floods in 1861–1862 (Gilbert, 1917; James et al., 2009) and the rivers were generally degrading during the 20th century. River channel cross section data indicate that the Sacramento River below the American River aggraded 3.1 m from 1855 to 1890 then degraded 2.4 m by 1914 (Gilbert, 1917). Degradation continued until 1930 when the bed apparently returned to its pre-hydraulic mining elevation (Meade, 1982; James, 1997). The Lower Feather River degraded from 1909 to 1970 and the rate of degradation increased in the late 1960s after construction of Oroville dam upstream (Porterfield et al., 1978). The Lower American River degraded at the H Street bridge from 1924 to 1982 and at the Hazel Avenue bridge from 1940 to 1995 (James, 1997). Large flows in water year 1997 degraded the channel which was stable from 1997 to 2005 (Fairman, 2007).

Sediment supply from the Sacramento Valley to the estuary increased during hydraulic mining, peaked between 1858 and 1914, and has decreased since (Schoellhamer, 2011). Sediment supply from the Sacramento River, the largest sediment source for the estuary, decreased by about one-half from 1957 to 2001 despite no overall time trend in annual flow or flow variability during this period (Wright and Schoellhamer, 2004). Three large reservoirs in the watershed have accumulated a mass of sediment of the same order of magnitude as the decrease in suspended-sediment yield during 1957–2001, indicating that much of this supply reduction is due to trapping behind dams. Oroville Dam began regulating flow on the Feather River in 1967 and suspended-sediment transport curves prior to 1967 and for 1968–1975 show that 9 and 43 km downstream from the dam suspended-sediment concentration decreased but 79 km downstream there was no change (Porterfield et al., 1978).

Total suspended-solid (TSS) concentration in the Sacramento–San Joaquin River Delta decreased from 1975 to 1995 (Jassby et al., 2002). Hestir et al. (2013–this issue) identify step decreases in Delta TSS of 27% in 1983 and 23% in 1998. These step decreases co-occurred with record high wet and dry season discharge following El Niño-driven high precipitation. From 1998 to 2010, Delta TSS had a significantly decreasing trend of −0.64 mg/L/yr. Total water discharge of the Sacramento Valley and mean SSC in the Sacramento River upstream from the Delta did not have significant trends during the 2000s, suggesting that neither flow nor river supply are responsible for the TSS decrease in the Delta.

Suspended sediment also decreased in San Francisco Bay, the seaward portion of the estuary, in the late 1900s. In Suisun Bay, Hestir et al. (2013–this issue) observed a 31% step decrease in 1983 and a significant decreasing trend of −0.18 mg/L/yr 1983–2010. In 1999 there was a 36% step decrease in suspended-sediment concentration in San Francisco Bay (Schoellhamer, 2011). The hypothesized cause for this step decrease is that the threshold from transport- to supply-regulation of sediment transport was crossed as the erodible sediment pool created by hydraulic mining was depleted.

Bed sediment volume changes in 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. Overall, San Francisco Bay had net deposition from the mid 1800s to the mid 1900s and net erosion during the latter half of the 1900s (Schoellhamer, 2011). Suisun Bay is the subembayment of San Francisco Bay closest to the hydraulic mining source and it was depositional in the latter half of the 1800s and erosional during the 1900s (Cappiella et al., 1999). San Pablo Bay is the next subembayment downstream and it was depositional until the mid 1900s then experienced a small amount of erosion from 1951 to 1983 (Jaffe et al., 1998). Central Bay, the most seaward subembayment, eroded in the latter half of the 1800s, was depositional in the first half of the 1900s, and eroded from the mid to late 1900s (Fregoso et al., 2008). In addition, Dallas and Barnard (2011) found that the volume of an ebb-tidal delta seaward of Central Bay changed in a similar pattern to Central Bay.

To graphically summarize these studies from the 1850 to 2010 period, the trend of each study is plotted in longitudinal and temporal (x,t) space (Fig. 5) similar to our conceptual models (Figs. 3 and 4). Geographic categories are used on the longitudinal axis in downstream order. The Sierras category includes the upper watershed upstream from dams, which generally are located at the base of the Sierras. The Rivers category includes the Sacramento Valley floor downstream from dams. All but one major tributary in the Sacramento Valley (Cosumnes River) is regulated by a dam. Dam construction in the 20th century is assumed to have halted sediment transport from the Sierras to the rivers. The Delta is the landward end of the estuary and the San Francisco Bay subembayments on the flowpath from the Delta to the Pacific Ocean are Suisun Bay, San Pablo Bay, and Central Bay. The Central Bay category includes the ebb-tidal delta seaward of Central Bay. Fig. 5 does not convey the magnitudes of the trends, which we expect would vary locally but generally decrease downstream further away from the disturbances.

This graphic summary allows us to propose straight characteristic lines consistent with our conceptual model (Fig. 5). Where studies of bed and suspension trends overlap they generally corroborate each other so we neglect the potential timing differences in adjustment of bed and suspension variables when drawing characteristic lines. The NI characteristic line represents the progression of the leading edge of the hydraulic mining sediment pulse. The ID characteristic line represents the peak of the pulse and the conversion from increasing to decreasing sediment supply. A nearly vertical characteristic line that follows the observed step changes in the late 1900s is shown. If the step changes signify that a stationary adjusted regime was reached at the end of the 20th century, this line would be a DA characteristic. Possible completion of adjustment to reduced sediment supply is discussed in Section 6.2.

5. Quantitative conceptual model of San Francisco Estuary and Watershed

Fig. 5 provides a qualitative summary of the downstream progression of the hydraulic mining sediment pulse and adjustment to the pulse. Straight characteristic lines are visually approximated. In this section a more objective calculation of the characteristic lines is presented. The studies on the Sierras will not be considered because construction of dams in the 20th century is assumed to have halted sediment transport from the Sierras to the Valley rivers.

For the other geographic regions (Rivers, Delta, Suisun Bay, San Pablo Bay, Central Bay), a time series of a weighted sedimentation index S(t) is calculated. For the duration of each study i presented in Fig. 5, a sedimentation index s_i is assigned a value corresponding to the observed trend and regime. A value of $s_i = 0.5$ corresponds to the natural regime before hydraulic mining, 1.5 to the transient regime of increasing sediment supply, 2.5 to the transient regime of decreasing sediment supply, and 3.5 to after a step change that may indicate the start of a stationary adjusted regime. Thus, the NI characteristic has an index value of 1, the ID characteristic has an index value of 2, and the possible DA characteristic (PDA) has an index value of 3 (Table 1). A time series is constructed for each region by calculating a weighted sedimentation index

$$S(t) = \frac{\sum_{i=1}^{n} w_i(t) s_i}{\sum_{i=1}^{n} w_i(t)} \quad (1)$$

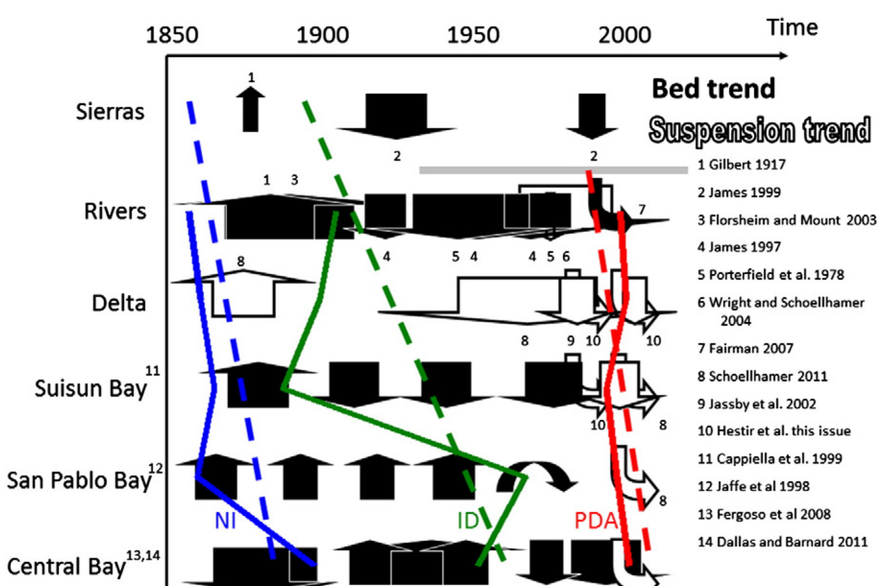

Fig. 5. Temporal and longitudinal summary of studies related to the hydraulic mining sediment pulse and subsequent adjustment and characteristic lines. Up and down arrows indicate increasing and decreasing trends, not magnitudes. Other arrows indicate peaks and step changes. Solid arrows are for bed elevation data, empty arrows for water column data (suspended sediment concentration or discharge). The width of the arrows indicates the time period over which the observation was made. The gray horizontal line between Sierras and Rivers in the 20th century indicates our assumption that dam construction halted sediment transport from the Sierras to the rivers. Straight dashed lines approximate the NI (blue), ID (green), and possible DA characteristic (PDA, red) if a stationary adjusted regime was reached at the end of the 20th century, similar to the conceptual model in Fig. 4. Solid lines are the same characteristic lines from the quantitative conceptual model.

Table 1
Sedimentation index s for regimes and characteristic lines at the boundaries of the regimes (Fig. 4). Time progresses from the top to the bottom of the table.

Regime	Characteristic	Sedimentation index s
Stationary natural (N)		0.5
	NI	1
Transient increasing supply (I)		1.5
	ID	2
Transient decreasing supply (D)		2.5
	DA	3
Stationary adjusted (A)		3.5

in which n is the number of studies for the region and the weight $w_i(t)$ is equal to one for the study period and zero before or after the study. Thus, for a given year, S(t) is the mean value of sedimentation index for all the active studies during that year in a specific region. Linear interpolation was used to determine S(t) for regions and years with no active studies. For studies showing a step adjustment to decreased supply, we assign $s = 3.0$ to the year prior to the step and $s = 3.5$ to the next year to replicate the step change. A pre-hydraulic mining stationary natural regime ($s = 0.5$) was assumed through 1861 (Gilbert, 1917; James et al., 2009).

An example time series of weighted sedimentation index for a region with four hypothetical studies is shown in Fig. 6. The first study is the assumed pre-hydraulic mining natural regime from 1850 to 1861. That is followed chronologically by studies showing increased supply from 1870 to 1910, decreased supply from 1900 to 1950, and a step adjustment in 2000. The time of passage of the NI characteristic ($S(t) = 1$) is found by linear interpolation from the end of the first study to beginning of the second study. From 1900 to 1910, one study shows increasing supply ($s = 1.5$) and another shows decreasing supply ($s = 2.5$) so S(t) is the mean (2.0) and the ID characteristic is assumed to pass in 1905, the midpoint of $S(t) = 2.0$. The PDA characteristic passes at the base of the step change in 1999 where $S(t) = 3$.

The quantitative conceptual model results are presented as crooked characteristic lines in Fig. 5. The NI characteristic ($s = 1$) is well-constrained from the rivers to San Pablo Bay because of the assumption of a stationary natural regime in the 1850s. In the late 1800s and early 1900s the geography of the Delta was greatly altered by land reclamation so we were unable to locate undisturbed bed elevation data for channels. This causes a large information gap where the ID characteristic ($S(t) = 2$) is poorly defined.

6. Discussion

Many studies of the SFEW describe the pulse of sediment created by hydraulic mining in the late 1800s and the subsequent decrease in sediment supply caused by cessation of hydraulic mining and water resources development. The sedimentation index method synthesizes previous studies in the SFEW by objectively calculating characteristic lines that describe the propagation of the arrival of the hydraulic mining sediment pulse, peak sediment supply transition, and possible arrival of a stationary adjusted regime (Fig. 5).

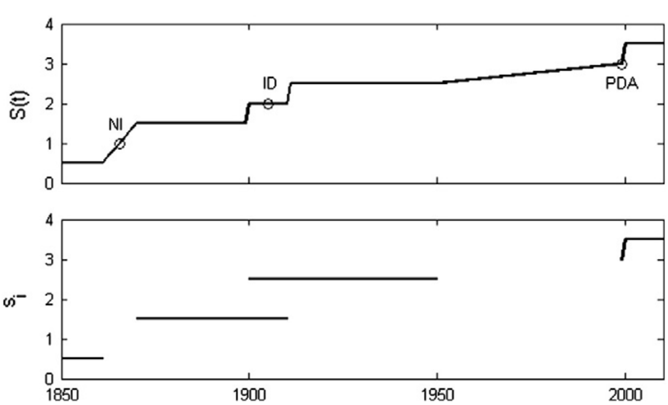

Fig. 6. Example of a time series of weighted sedimentation index S(t) and sedimentation index s_i for a region with four hypothetical studies. Open circles in the S(t) plot indicate where the NI ($S(t) = 1$), ID ($S(t) = 2$), and PDA ($S(t) = 3$) characteristics pass through the region.

There are several sources of uncertainty in the quantitative conceptual model including insufficient study density, insufficient study resolution in time and space, study results that span several decades, unquantified uncertainty of some individual studies, and the coarsely categorized longitudinal scale. Such uncertainties are difficult to quantify but could potentially add up to a period of roughly one decade. Sediment supply reductions in SFEW were spatially and temporally distributed in the watershed so the assumption that supply reduction was a singular event in space and time introduces more uncertainty in the rivers than downstream in the estuary. When sediment supply is declining we use only one region (rivers) in the watershed and further discretization would require that the longitudinal distribution of supply reduction be defined.

6.1. Downstream propagation of adjustment

Spatial and temporal interpolation of sparse study results illustrates general trends but not the complex nonlinear progression of adjustment. This analysis uses very broad geographic categories and depicts linear downstream propagation. On smaller spatial scales, propagation may be nonlinear as different reaches adjust quicker than others. The slope reversals of the quantitative conceptual model characteristic lines may result from uncertainties or from nonlinear adjustment.

In the rivers of the Sacramento Valley, the sediment pulse was asymmetric with the aggrading limb being much shorter than the degrading limb (James, 1999) and the quantitative conceptual model (Fig. 5) further supports this finding. The duration of the transient increasing supply regime (I) is the distance between the NI and ID characteristics and the duration of the transient decreasing supply regime (D) is at least the distance between the ID and PDA characteristics. In the rivers, the I regime duration was 49 years while the D regime duration was or is at least 95 years.

The upper estuary (Delta and Suisun Bay) had similar durations of the I (23–40 years) and D regimes (at least 102–108 years). Suisun Bay is the most landward subembayment of San Francisco Bay. It directly receives sediment discharged from the Delta, and thus responds to changes in sediment supply more like the channelized rivers and Delta than San Pablo and Central Bays. Some disturbances that reduce sediment supply such as dam construction and levee protection took place over several decades during the 20th century and this distribution in time may contribute to the asymmetry.

In the lower estuary (San Pablo and Central Bays), however, the increasing supply regime lasted 2–3 times longer (54–109 years) and the decreasing supply regime has lasted 30–50 years (Fig. 5). Two factors that may account for the longer I regime duration in the lower estuary compared to the rivers and upper estuary are different sediment storage volumes and sediment sources.

Sediment storage volume is much greater in San Francisco Bay than in the rivers and Delta. In rivers, excess sediment from the pulse was stored in channels and floodplains that transport sediment seasonally during high flows. In the Bay, pulse sediment was stored on the bed for decades because suspension was transport regulated and the supply of sediment was greater than the removal until about 1960 (Schoellhamer, 2011). Gilbert (1917) estimated that as of 1914, 48% of hydraulic mining debris was stored in the Bay, 22% in piedmont deposits, 12% in Valley floodplains and Delta tidal marshes, 11% in the Sierra Nevada, 4% in the channels of valley rivers, and 2% in the Pacific Ocean. The relatively large storage volume in the Bay may have slowed the pulse, which arrived in Suisun Bay in the late 1800s and did not arrive in Central Bay until the early 1900s (Fig. 5).

Another factor that may account for the longer duration of the I regime in the lower estuary is that San Francisco Bay had an additional source of sediment in the early and mid 1900s from urban and agricultural land use changes. Bay sediment volume change data indicate that from the late 1800s to early 1900s there was no change in sediment volume but there was an increase from the early to mid 1900s (Schoellhamer, 2011). This second pulse of sediment was about 60% of the hydraulic mining sediment pulse that deposited in the Bay in the late 1800s. Schoellhamer (2011) found that freshwater flow was an unlikely explanatory variable for the changes in sediment volume and suggested that urbanization adjacent to the bay or agriculturalization in the Sacramento and San Joaquin Valleys could have created a second pulse of sediment. Fig. 5 shows that the rivers, Delta, and Suisun Bay were in a decreasing sediment supply regime in the early 1900s and thus these Valleys are an unlikely source of the second sediment pulse. 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.

While sediment storage and additional sources may slow downstream propagation in estuaries, greater sediment mobility in the estuary may have the opposite effect and act to hasten adjustment compared to rivers. River sediment is mobilized primarily by large episodic seasonal flows (Wright and Schoellhamer, 2004). In contrast, estuarine sediment is constantly mobilized by tides and wind waves (Schoellhamer, 2011) so adjustment occurs continuously rather than episodically as in rivers.

6.2. Completion of adjustment to decreasing sediment supply as a series of flood-induced steps

Each geographic area has had at least one study in the late 1900s that shows a step adjustment to decreased sediment supply associated with large floods. El Nino conditions in 1983 and in the late 1990s created the largest flows observed in the Sacramento Valley during the adjustment period and were the likely drivers of these step adjustments (Hestir et al., 2013–this issue; Schoellhamer, 2011). Flood peaks in rivers were at channel capacity and in 1998 relatively large flows that persisted into the dry season greatly increased seaward sediment transport in the estuary (Ganju and Schoellhamer, 2006). In addition, McKee et al. (2013–this issue) found that sediment supply from local tributaries that drain directly to San Francisco Bay experienced a step decrease around 1999.

We hypothesize that SFEW has not achieved a stationary adjusted regime and is still capable of adjusting but the adjustment has become a series of steps that occur only during greater floods. Smaller floods with a magnitude that has occurred during the adjustment period are capable of mobilizing only relatively small amounts of sediment. Larger flows that have not previously occurred during the adjustment period remain capable of transporting relatively large quantities of sediment and causing a step change in system variables. These large flows cause simultaneous adjustment throughout the watershed and estuary which creates vertical characteristic lines in our conceptual model (Fig. 5).

Human efforts to reduce flood flows in the Sacramento Valley currently suppress the large flows that are capable of causing adjustment. The large flows in the late 1900s were at the upper limit of what the Sacramento Valley flood control system is designed to allow. Thus, humans are actively managing the system to try to prevent larger flows. If flood control is successful in perpetuity, there would be no more adjustment and a stationary adjusted regime would be attained. Porter et al. (2011), however, found that a flood with a 500 year or greater return period would overwhelm the Sacramento Valley flood control system. If flood control is not successful, there will be future adjustments. In this case, the return interval of adjustment floods is likely to increase as larger and larger flows would be needed to cause adjustment.

Increasing return interval of adjustment floods can also be explained by considering exceedances of geomorphic thresholds with intervening periods of equilibrium (Bull, 1991). The flood magnitude required to cause adjustment is a geomorphic threshold. After the threshold is surpassed and a subsequent response time, a period of equilibrium exists until the next flood that exceeds the geomorphic threshold. The geomorphic threshold increases after each adjustment. Thus the period of equilibrium and return interval generally increase with time.

6.3. Ecosystem adjustments

When the return interval of adjustment floods becomes greater than ecological response times, ecological variables will adjust to the prevalent environmental conditions as if a stationary adjusted regime exists. For example, consider the simple case of a tidal marsh in an estuary with a prevalent condition of 1) an inadequate sediment supply rate to maintain elevation relative to rising sea level and 2) episodic floods that deposit much greater quantities of sediment. The marsh survives as long as the return interval of these nourishing floods is less than the time for marsh drowning under prevalent conditions. If the nourishing floods are too infrequent, the marsh will drown between them. In the San Francisco Estuary, large flows in the late 1900s decreased subsequent suspended-sediment concentrations and some aspects of the ecosystem have adjusted to clearer waters.

In 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 when SSC decreased (Schoellhamer, 2011), 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.

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; Mac Nally et al., 2010. 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.

Coverage of invasive submerged aquatic vegetation (SAV) has expanded in the Delta during the latter half of the 20th century. Brazilian waterweed (*Egeria densa*) is the dominant submerged aquatic plant species in the Delta and comprises 85% of the SAV community biomass (Hestir et al., unpublished data). Decreasing turbidity and increasing water column light are likely explanatory factors for this invasion. *E. densa* expanded in the Delta from the 1960s to late 1990s and reached nuisance levels in the 1990s (Jassby and Cloern, 2000). *E. densa* is an unusual plant in that it functions as an ecosystem engineer, changing the basic properties and functions of an ecosystem (Jones et al., 1994a,b). With respect to sedimentation processes, *E. densa* is capable of increasing sedimentation rates in channels and reducing turbidity and flow velocity in the water column (Champion and Tanner, 2000; Wilcox et al., 1999). These changes in the physical environment are particularly pronounced when *E. densa* grows to the top of the water column during the height of the growing season (mid-summer to fall).

6.4. Decreasing trend of suspended sediment after a step decrease

Suspended sediment has trended downward following step decreases in the Delta in 1998 and Suisun Bay in 1983 (Hestir et al., 2013–this issue). Two factors, SAV and suspended-sediment regulation, may account for the decreasing trend after a step decrease. These factors may prevent establishment of a stationary altered regime or of prevalent conditions that appear stationary between adjustment floods.

SAV may be an example of an ecosystem factor that can begin to control prevalent sedimentation conditions as the return interval of adjustment floods increases. Delta TSS experienced a step decrease in 1983, no trend 1983–1998, a step decrease in 1998, and a significant decreasing trend 1998–2010 (Hestir et al., 2013–this issue). The 2000s TSS decrease may be caused by SAV trapping sediment and acting as an internal sediment sink independent of the watershed factors decreasing sediment supply. This may indicate that forcing mechanisms other than the hydraulic mining sediment pulse and subsequent adjustment to decreased supply are beginning to control sedimentation in the SFEW and can be expected to increase in importance in the future.

Another possible factor that could cause a decreasing trend of suspended sediment following a step decrease is that the step decrease shifted the system from transport to supply regulation (Hestir et al., 2013–this issue; Schoellhamer, 2011). Under transport regulation which may have been present before the observed step decreases, degradation by prevalent conditions that would have decreased the size of the erodible sediment pool would not affect the quantity of suspended sediment because of the excess supply of sediment. As the erodible sediment pool decreases and the system shifts from transport to supply regulation, degradation by prevalent conditions would decrease the erodible sediment pool that in turn would decrease suspended sediment.

7. Conclusions

When did SFEW begin adjusting to decreasing sediment supply?

After hydraulic mining in the late 1800s increased sediment supply, adjustment to decreasing sediment supply began in the rivers, Delta, and Suisun Bay around 1900 and further downstream in San Pablo and Central Bays around the1950s. Two possible explanations for this apparent slowing of the beginning of adjustment are that greater sediment storage in the Bay compared to the rivers and Delta and land use change provided sediment to the Bay that increased the duration of the transient increasing supply regime.

Has SFEW completed adjusting to decreasing sediment supply?

Several sedimentation and ecological studies indicate that there was a step adjustment in the late 1990s associated with larger freshwater flows. It is likely that SFEW is still capable of adjusting but adjustment has become a series of steps that occur only during greater floods than previously experienced during the adjustment period. These large flows cause simultaneous adjustment throughout the watershed and estuary (Fig. 5, PDA characteristic) and are at the upper limit of what the Sacramento Valley flood control system is designed to allow. Thus, humans are actively managing the system to try to prevent future flows that may cause flooding and perhaps another step change in sedimentation. 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 as described in our conceptual model. Decreasing trends of suspended sediment after step decreases may be caused by SAV or transition from transport to supply regulation, preventing establishment of a post hydraulic mining stationary adjusted regime or of prevalent conditions that appear stationary between adjustment floods.

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