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

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ABSTRACT

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

1. Introduction

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

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

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

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

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

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

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

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

2. Regional setting

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

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

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

3. Materials and methods

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

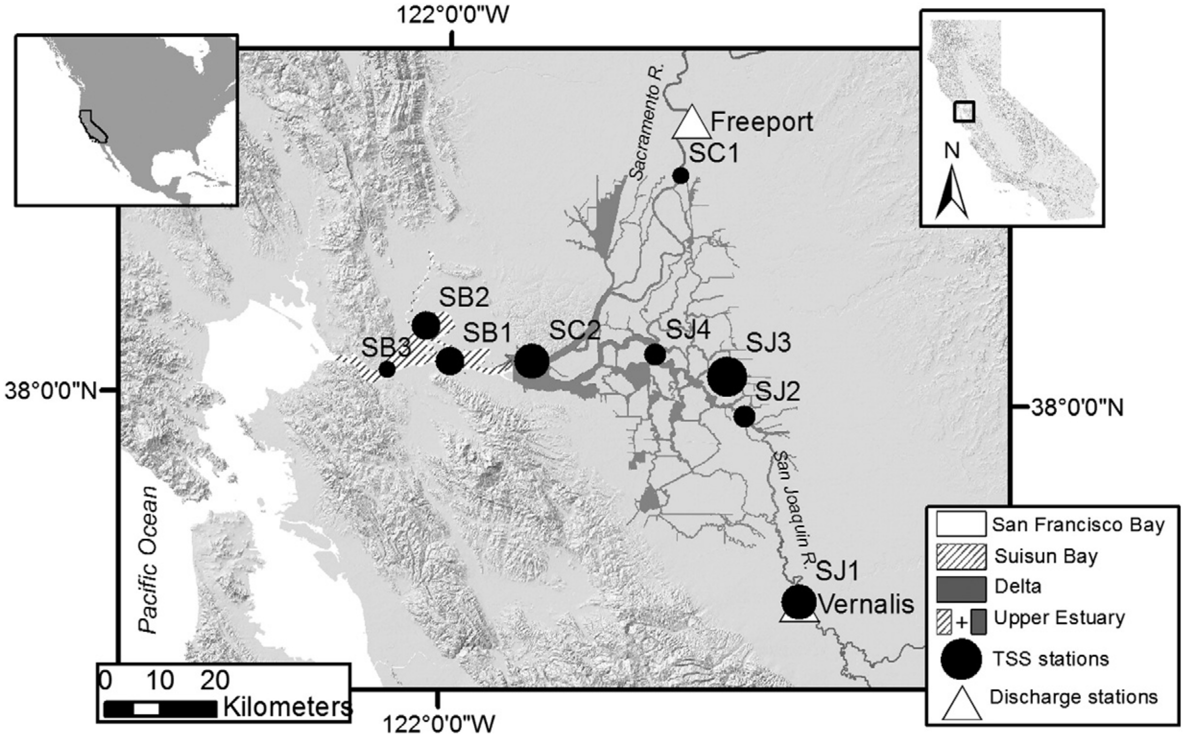

Fig. 1. TSS measurement stations are indicated by black circles. The size of the circles represents the relative magnitude of the declining trend for 1975–2010 (there was no significant trend in TSS at station SB3). For this study the upper San Francisco Estuary includes the Suisun Bay and the Sacramento–San Joaquin River Delta.

3.1. Total suspended solids concentration data

We used TSS concentration measurements collected once per month from ship cruises. The California Department of Water Resources (CA DWR) and the United States Bureau of Reclamation (USBR) collected water quality measurements during monthly cruises in the upper estuary from 1975 to 2010. Water samples for laboratory analysis of TSS were collected 1 below the water surface. The data and metadata on field and laboratory measurements and instrumentation are available on the CA DWR website and can be downloaded from http://www.water.ca.gov/bdma/meta/discrete.cfm. In the San Francisco Bay, TSS concentration is considered comparable to suspended sediment concentration (SSC) (Gray et al., 2000; Schoellhamer et al., 2007).

Of all the measurement stations, nine were missing just a few records (<9) for the period of record, 1975–2010. Thus, these were selected for the analysis (see Fig. 1 for the station locations). Fig. 3 shows the monthly TSS data for the period of record at the nine stations. As noted in previous studies (e.g. Cloern et al., 2002), the data show a general decline in TSS concentration in the upper estuary between 1975 and 2010 (Table 1).

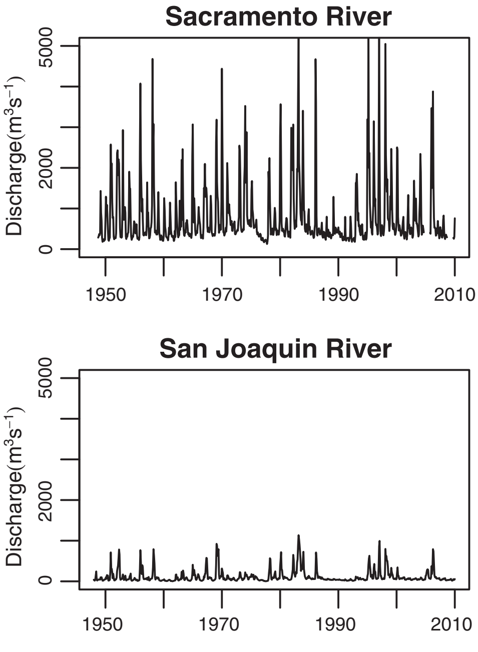

Fig. 2. Mean monthly discharge for the two major rivers entering the upper San Francisco Estuary, the Sacramento River (top) and the San Joaquin River (bottom).

3.2. Dating structural changes and performing trend analysis

We analyzed the TSS time series for structural changes using the R package *strucchange* (Inman and Jenkins, 1999). Supremum F-tests were used to test for structural change in the TSS record (Andrews, 1993; Bai and Perron, 2003; Zeileis and Kleiber, 2005). The probability of structural change was considered significant at $p < 0.05$. We selected a method for identifying the timing of the structural changes that did not require *a priori* identification of the amount or location of the step change, and was relatively insensitive to location within the time series. *Strucchange* provides a framework for determining structural changes by fitting piecewise linear models using a dynamic programming approach (Bai and Perron, 1998, 2003), which selects optimal breakpoints that result in a global minimization of the residual sum of squares (Gomez et al., 2004). The minimum adequate model that determines the optimal number of breakpoints is selected based on the lowest Bayesian information criterion (BIC), a measure of goodness of fit (similar to Akaike's information criterion) that includes a penalty for adding parameters (Winder et al., 2011). This modeling approach does not require an assumption of normality in the dependent variable, as it allows for different distributions of regressors across segments in

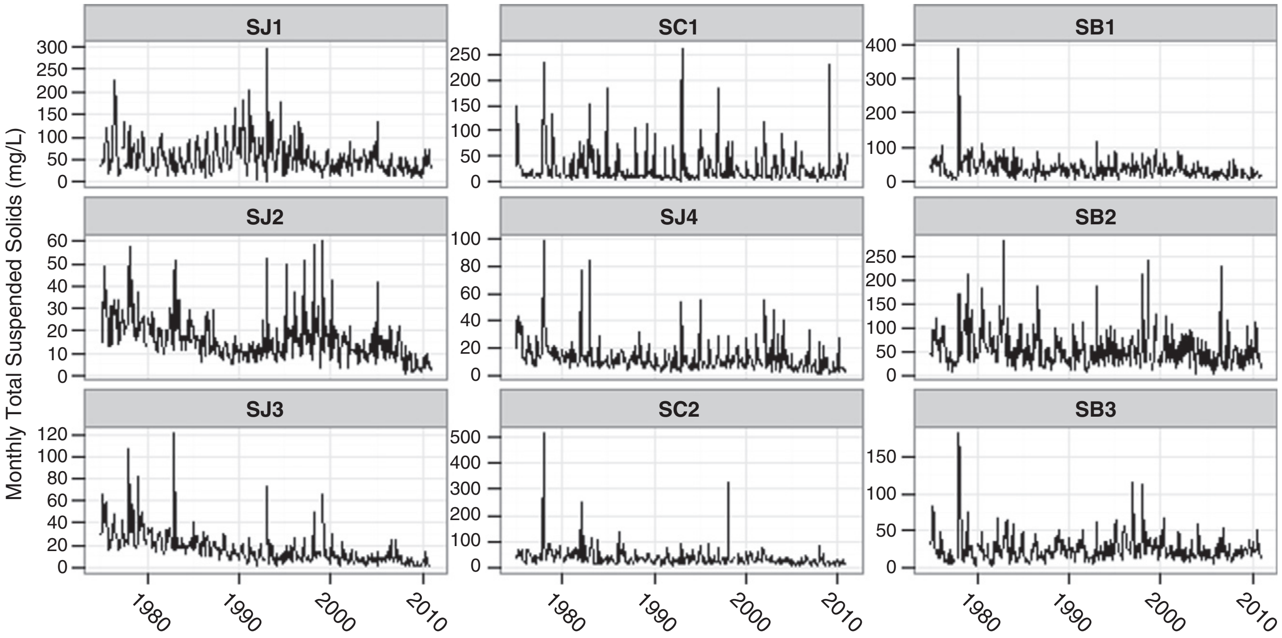

Fig. 3. TSS concentration measured monthly from 1975 to 2010 at nine locations throughout the upper estuary and Delta. Note the different scales for each measurement station.

the linear model, as well as general forms of serial correlation and heteroskedastic errors (Bai and Perron, 1998).

We identified breakpoints in the monthly time series of TSS for each measurement station. For each breakpoint, we calculated the 95% confidence interval (Zeileis and Kleiber, 2005). The breakpoint model assumes a complete and regular time series. Therefore, for the breakpoint analysis we interpolated missing data values using the cycle median implemented in the R package *wq* (Jassby and Cloern, 2011).

We then estimated both the overall trend for the period of record and the trends before and after each breakpoint in the time series. Once breakpoints in the record were identified, we applied a Seasonal Kendall test for trend (Helsel and Hirsch, 2002) on the segments identified by the breakpoints, and estimated the Theil–Sen slope (Helsel and Hirsch, 2002) for each segment in which a significant trend was identified. The Seasonal Kendall test for trend can accommodate missing values. Therefore, the trend analysis was conducted on the time series that was not interpolated. Trend analysis was conducted using the R packages *wq* (Jassby and Cloern, 2011) and *Kendall* (Andrews, 1993).

In order to provide regional estimates of TSS structure and trend, we calculated three regional means of TSS. The first was a region-wide aggregation of all the measurement stations. We considered this to be representative of the upper estuary. The second was a mean of the Suisun Bay (sites SB1, SB2, and SB3), and the third was just the Delta (sites SC1, SC2, SJ1, SJ2, SJ3, and SJ4).

3.3. Delta inflows and outflows

We used the same procedure for identifying structural changes and trend analysis for Delta inflows and outflows. Delta inflow was assumed to be represented by the two major tributaries, the Sacramento and San Joaquin rivers. Mean monthly discharge was downloaded from the USGS National Water Information System (http://waterdata.usgs.gov/nwis) for the same period of record as the TSS data. Sacramento River discharge was calculated as the sum of the discharge in the Sacramento River at Freeport (11447650) and the Yolo Bypass near Woodland (11453000), the latter a leveed floodplain constructed in the 1930s as a flood diversion for the Sacramento River upstream of Sacramento. San Joaquin River discharge was measured at Vernalis (11303500) (Fig. 1). The California water year (CAWY) is defined as October 1 through September 30. The year designation is the year which the period ends.

Table 1
Trends for the entire period of record (1975–2010) for TSS.

Station	DWR/USBR station ID	Location	Mean depth (m)	Latitude (°N)	Longitude (°W)	τ	p-Value[a] (τ)	Trend[a] (1975–2010)	Slope[b] (mg/L/yr)	Upper 95th CL of slope[c] (mg/L/yr)	Lower 95th CL of slope[c] (mg/L/yr)
Region-wide		All stations				−0.36	<0.01	Yes	−0.46	−0.36	−0.53
SC1	C3	Northern Delta Sacramento R.	2.62	38.37	121.52	−0.11	<0.01	Yes	−0.09	−0.02	−0.17
SC2	D4	Lower Sacramento R.	10.4	38.06	121.82	−0.30	<0.01	Yes	−0.63	−0.49	−0.77
SB1	D8	Suisun Bay	12.01	38.06	121.99	−0.22	<0.01	Yes	−0.54	−0.49	−0.72
SB2	D7	Suisun Bay	1.77	38.12	122.04	−0.14	<0.01	Yes	−0.53	−0.29	−0.79
SB3	D6	Suisun Bay	9.63	38.04	122.12	0.04	0.26	No	–	–	–
SJ1	C10	Southern Delta San Joaquin R.	3.43	37.68	121.27	−0.21	<0.01	Yes	−0.60	−0.40	−0.90
SJ2	P8	Southern Delta San Joaquin R.	11.06	37.98	121.38	−0.43	<0.01	Yes	−0.38	−0.33	−0.45
SJ3	MD10	Eastern Delta	5.61	38.04	121.42	−0.65	<0.01	Yes	−0.72	−0.66	−0.78
SJ4	D26	Lower San Joaquin R.	11.52	38.08	121.57	−0.35	<0.01	Yes	−0.24	−0.19	−0.28

[a] The probability of a trend within the period, as determined by Kendall's Seasonal test for trend (Helsel and Hirsch, 2002). Trends were considered significant at $\alpha = 0.05$.

[b] Sen's non-parametric method (Sen, 1968) was used to estimate the slope of existing trends within the period and presented as change per year in units (mg/L).

[c] CL = confidence limit. Large sample approximation equations from Helsel and Hirsch (2002) were used to calculate the upper and lower confidence limits of the Sen's slope estimates at 95%.

Although the largest contribution to Delta outflow is from the Sacramento River (~80%), outflow is also affected by water exports, agricultural extraction, and rainfall. The mass-balance model Dayflow provides an estimate of the daily average Delta outflow at the confluence of the Sacramento and San Joaquin Rivers. It does not account for tidal flows. Dayflow model outputs for the TSS period of record were downloaded from http://www.water.ca.gov/dayflow/. We used these data to calculate the mean monthly outflow from the Delta.

To identify extreme events in discharge and compare the two rivers, we calculated the standardized departure from the long-term mean. Similar in approach to the standardized precipitation index (SPI) (Helsel and Hirsch, 2002), we first determined the probability density function of the time series, then calculated the cumulative probability of a discharge observation, and finally applied the inverse normal function (using a Gaussian distribution) setting the mean = 0 and variance = 1 to the cumulative probability. This allowed us to compare extreme events in rivers with different magnitudes of flow (Fig. 2). The magnitude of the departure is a probabilistic measure of the severity of the discharge event. Greater values indicate flood events. To summarize the results we used the mean standardized departure of the winter wet season (January–March) and summer dry season (June–August).

4. Results

There was a significant stepdecrease in TSS after 1983 in the upper estuary (Fig. 4). Both region-wide and in the Suisun and Delta regions, there was significant structural change in the TSS record. Mean monthly TSS across all the stations (region-wide) exhibited two step decreases in 1983 (−29%) and 2004 (−30%). The Delta exhibited two step decreases in 1983 (−27%) and 1998 (−23%). The Suisun Bay had only one step decrease in 1983 (−31%). Seven of the nine TSS stations had significant structural change ($p < 0.05$) in the TSS record, and five of those seven shared a similar breakpoint corresponding to early–mid-1983 with step decreases of 31–48% after the 1983 breakpoint (Table 2). There was no significant structural change at station SC1 ($F = 6.43$, $p = 0.13$), the most upstream station on the Sacramento River, and SB3 ($F = 8.26$, $p = 0.06$), the most downstream stations in Suisun Bay.

Every station that had a significant structural change exhibited successive step decreases after each breakpoint, with the exception of the two most upstream stations on the San Joaquin River, SJ1 and SJ2 (Fig. 5). Stations SJ4, SC2, SB1, and SB2 in the central Delta and Suisun Bay all shared a coincident structural change around April 1983, which is typically the beginning of the dry season for the San Francisco Estuary. The TSS stations along the upper reaches of the San Joaquin River exhibited the most structural variability; stations SJ1, SJ2, and SJ3 have the greatest number of structural changes. However, contrary to the central Delta and Suisun Bay, the timing of the structural changes at these stations is not coincident between stations with the exception of a shared step change at stations SJ2 and SJ3 in the dry season of 2000.

Delta inflows are highly variable, yet there is no significant long-term trend in discharge from the Sacramento River (Kendall's Seasonal test, $\tau = 0.02$, $p = 0.66$), and only a small negative trend in discharge from the San Joaquin River ($\tau = -0.07$, $p = 0.04$, slope = −0.35%/year). There was no significant structural change in Sacramento River discharge ($F = 4.96$, $p = 0.25$), nor was there a significant trend or structural change in estimated Delta outflows ($F = 13.63$, $p = 0.06$; $\tau < -0.00$, $p = 0.95$). However, there was evidence of structural change in the San Joaquin River discharge record ($F = 19.81$, $p < 0.001$), with two breakpoints in CAWY 1981 and CAWY 1986 corresponding to the switch from a series of wet years to drought conditions beginning in CAWY 1987 (CA DWR, 2012). There was either a weak positive or no direct correlation between Delta inflow or outflow and TSS (Kendall's $\tau < 0.2$ for all sites).

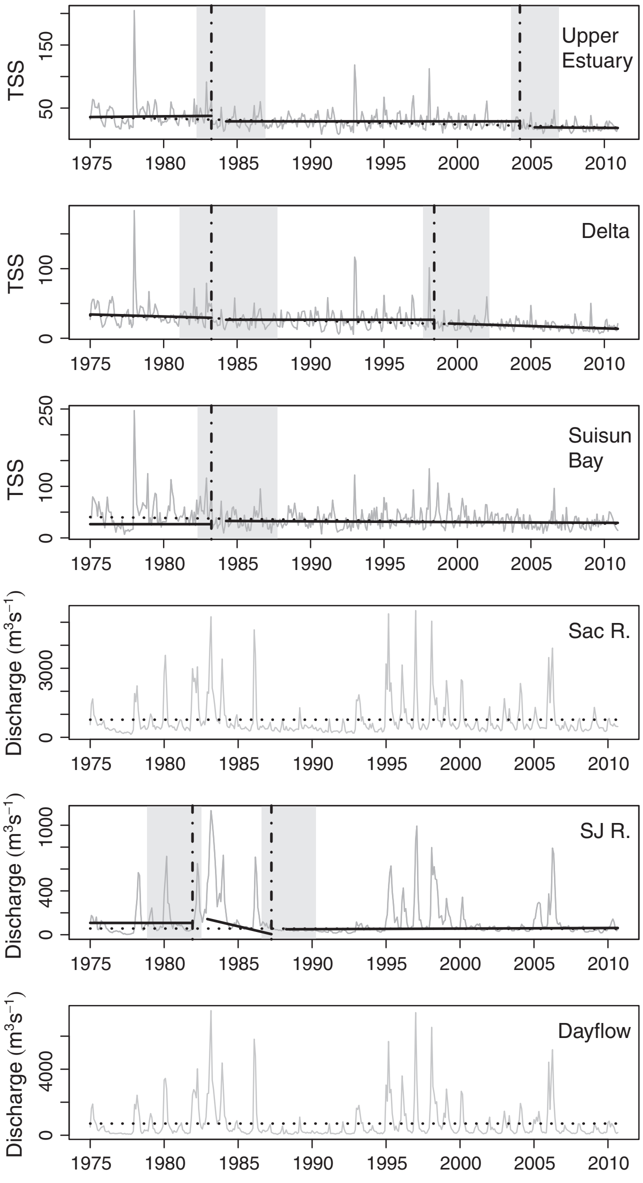

Fig. 4. Upper-estuary TSS, Delta TSS, Suisun Bay TSS, Sacramento River discharge, San Joaquin River discharge, and Delta outflows. Dates corresponding to a significant break point are indicated with a vertical dashed line. The 95% confidence interval around the break point is represented by the shaded gray area. The dotted lines indicate the overall trend for the period of record (1975–2010), and the solid lines indicate the trends for the periods separated by breakpoints. For periods with no significant trend, the trend is graphically represented by the mean.

Delta winter and summer outflows were the highest on record in 1983. The second highest winter and summer Delta outflows on record were in 1998. In both rivers, the most extreme flow events were concurrent with El-Niño events. The most extreme wet season events in both the Sacramento and San Joaquin rivers occurred in the winter of 1982 (Fig. 6), corresponding to high flows driven by El Niño precipitation events. The next most extreme event in the Sacramento River occurred in winter 1995, reflecting flooding in response to a series of storms that hit the basin that January (CA DWR, 2012). Another year of heavy precipitation during the 1997–1998 El Niño resulted in the next most extreme events on the Sacramento and San Joaquin rivers. Notably, the most extreme flows in summer were coupled with El-Niño related wet-season flows during both El Niño events. The most extreme summer events in both rivers were in 1983 and 1998, related to late winter season rains and reservoir discharges.

Table 2
Break dates and trends of TSS.

Station	No. breaks	Break date	95% CI of break date[a]	Change per period (%)	τ[b]	p-value[c] (τ)	Trend[c]	Slope[d] (mg/L/yr)	Upper 95th CL of slope[c]	Lower 95th CL of slope[c]
Upper Estuary	2	Apr. 1983	Feb. 1981 – Sep. 1987		-0.17	0.03	Yes	-0.98	1.38	-1.21
				-29.09%	-0.10	0.08	No	--	--	--
		Apr. 2004	Sep. 2003 – Nov. 2006	-30.46%	-0.39	<0.01	Yes	-0.68	0.95	-0.88
Delta	2	Apr. 1983	Feb. 1981 – Sep. 1987		-0.23	<0.01	Yes	-1.27	0.44	-1.88
		Jun. 1998	Sept. 1997 – Feb. 2002	-26.67%	-0.11	0.12	No	--	--	--
				-22.75%	-0.40	<0.01	Yes	-0.64	-0.39	-0.97
Suisun Bay	1	Apr. 1983	May 1982 – Sept. 1987		0.12	0.14	No	--	--	--
				-30.90%	-0.08	0.04	Yes	-0.18	0.04	-0.34
SC1	0	--	--	--	--	--	--	--	--	--
SC2	1	Apr. 1983	Oct. 1982 – Mar. 1988	-47.74%	0.05	0.53	No	--	--	--
					-0.20	<0.01	Yes	-0.42	-0.25	-0.59
SB1	2	Apr. 1983	Apr. 1982 – Sep. 1990		0.17	0.04	Yes	1.86	3.75	-0.78
				-30.95%						
		Jul. 2004	Jan. 2004 – Jun. 2006		0.07	0.15	No	--	--	--
				-39.37%						
					0.04	0.74	No	--	--	--
SB2	1	Apr. 1983	Sep. 1981 – Dec. 1986	-32.79%	0.10	0.24	No	--	--	--
					-0.03	0.45	No	--	--	--
SB3	0	--	--	--	--	--	--	--	--	--
SJ1	2	Mar. 1989	Sep. 1985 – Apr. 1990		-0.05	0.32	No	--	--	--
				+45.86%						
		Oct. 1994	Aug. 1994 – May 1996	-50.03%	0.08	0.53	No	--	--	--
					-0.22	<0.01	Yes	-1.00	0.89	-2.32
SJ2	3	Aug. 1983	Apr. 1983 – Jul. 1984		-0.27	<0.01	Yes	-1.00	-0.39	-1.68
				-44.53%	-0.22					
		Dec. 1994	Nov. 1991 – Sep. 1995	+50.77%	0.04	<0.01	Yes	-0.50	-0.12	-0.72
				-49.88%						
		Sep. 2000	Jun. 2000 – Feb. 2002		-0.40	0.76	No	--	--	--
						<0.01	Yes	-0.75	-0.51	-1.07
SJ3	3	Jul. 1980	May 1979 – Aug. 1982		-0.05	0.66	No	--	--	--
				-34.77%						
		Jul. 1987	Dec. 1986 – Jan. 1989		-0.13	0.21	No	--	--	--
				-46.02%						
		May 2000	Dec. 1999 – Dec. 2002		-0.10	0.12	No	--	--	--
				-47.26%						
					-0.25	<0.01	Yes	-0.40	-0.17	-0.62
SJ4	1	Mar. 1983	Aug. 1982 – Feb. 1986	-45.93%	-0.28	<0.01	Yes	-1.00	-0.03	-1.69
					-0.20	<0.01	Yes	-0.14	-0.07	-0.19

[a] CI = confidence interval. The CI of the breakpoint is calculated after Bai and Perron (2003), and integer-valued to correspond to the integer-valued break date (Zeileis and Kleiber, 2005).

[b] Kendall's tau, calculated from Kendall's seasonal test for trend (Helsel and Hirsch, 2002).

[c] The probability of a trend within the period, as determined by the Kendall's seasonal test for trend (Helsel and Hirsch, 2002). Trends were considered significant at $\alpha = 0.05$.

[d] Sen's non-parametric method was used to estimate the slope of existing trends within the period and presented as change per year in units (mg/L).

[e] CL = confidence limit. Large sample approximation equations from Helsel and Hirsch (2002) were used to calculate the upper and lower confidence limits of the Sen's slope estimates at 95%.

5. Discussion

5.1. Step decreases in TSS in the upper estuary

We observed step decreases in TSS of 29–41%, similar to the 36% decrease in mean suspended SSC observed in the San Francisco Bay by Schoellhamer (2011). At most stations, TSS concentrations did not increase subsequent to the step change despite subsequent increases in river discharge and Delta outflow (Fig. 5). Thus, the breakpoint in 1983 was likely a step decrease, and not just changing TSS responding to water year type.

The TSS measurement stations that shared a common break point at the end of the wet season of CAWY 1983 extend from Suisun Bay through the confluence of the Sacramento and San Joaquin rivers into the western Delta (SC2, SB1, SB3 and SJ4). The confidence interval around the 1983 breakpoint for the Delta and Suisun Bay is narrower in comparison with the overall regional estimate, indicating a greater likelihood of the breakpoint occurring as an abrupt event.

While Schoellhamer (2011) observed a step decrease in the Suisun Bay in 1998, we did not. This may be due to the different data sources used in the studies. Schoellhamer (2011) used SSC measurements from automated optical sensors aggregated to water year mean and monthly grab samples analyzed for suspended particulate matter from a different cruise-based monitoring program (http://sfbay.wr.usgs.gov/access/wqdata/). The step decrease observed in the Delta in 1998 is likely a result of the aggregation of TSS data, reflecting the varied responses of the San Joaquin River sites.

5.2. Sacramento River suspended sediment supply

The stations sharing the 1983 breakpoint are mainly influenced by the Sacramento River, the primary pathway of suspended sediment to the San Francisco Bay (Wright and Schoellhamer, 2005). Less than 20% of the sediment from the Sacramento River moves toward the San Joaquin River through the Delta (Wright and Schoellhamer, 2005), and the sediment supply is decreasing most strongly from the Sacramento River watershed (Canuel et al., 2009). However, the step decrease in TSS observed in the upper estuary is not due to a sudden decrease in river suspended sediment supply. We confirmed this by examining SSC in the Sacramento River, an indication of river suspended sediment supply.

Sacramento River SSC and TSS exhibit declining trends, but no step changes. The most upstream location on the Sacramento River, SC1, exhibits a declining trend in TSS for the period of record (1975–2010),

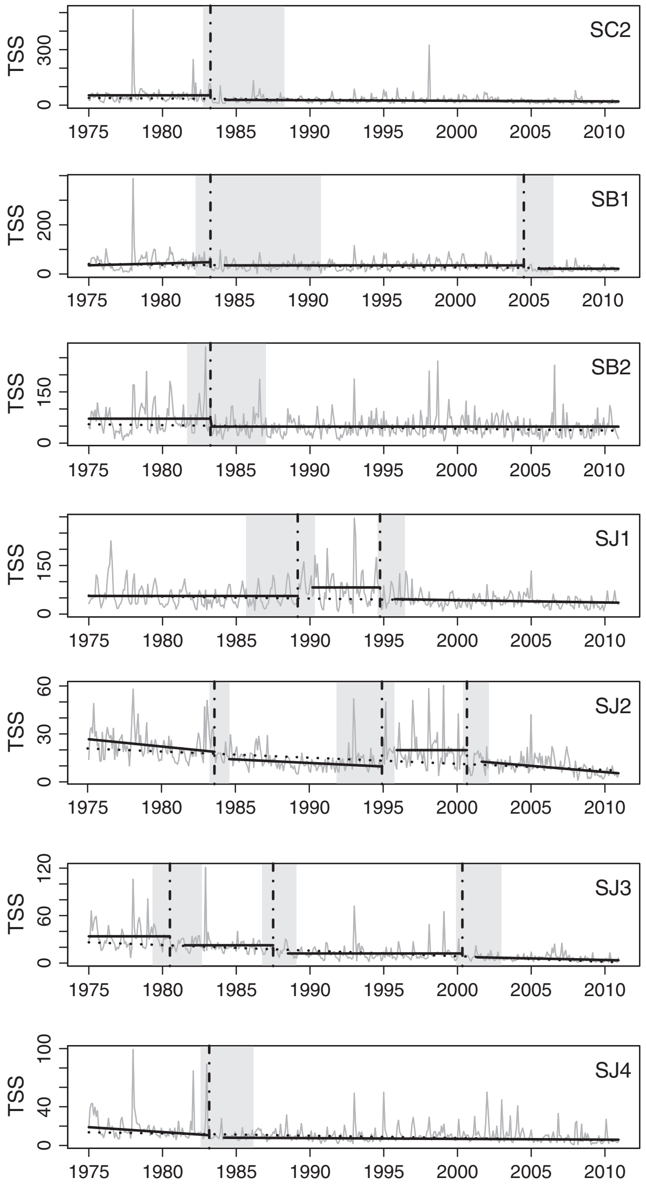

Fig. 5. TSS data at seven sampling stations where a significant breakpoint(s) was found. The date corresponding to a significant break point is indicated with a vertical dashed line. The confidence interval around the break point is represented by the shaded gray area. The dotted line indicates the overall trend for the period of record (1975–2010), and the solid lines indicate the trend for the periods separated by breakpoints. For periods with no significant trend, the trend is graphically represented by the mean. Five of the seven stations with significant structural change share a common break date corresponding to ~ April 1983 (typically the beginning of the "dry" season).

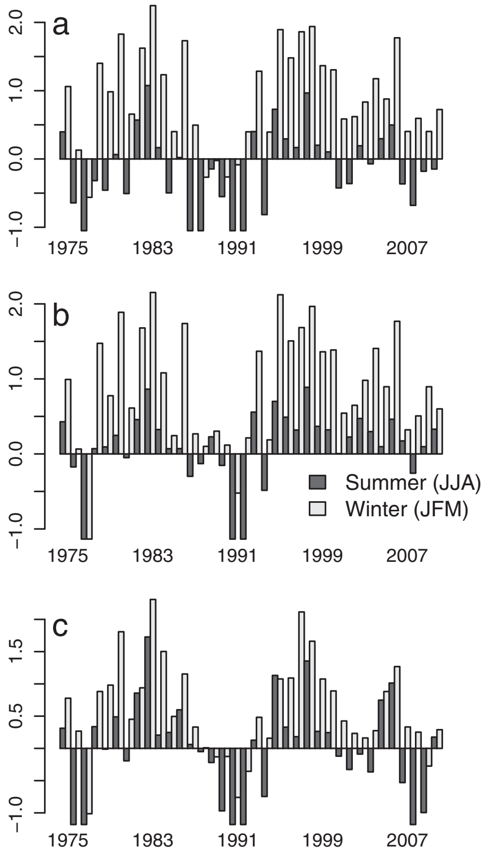

Fig. 6. The standardized departures from the long term monthly mean discharge of the Sacramento River (a), and San Joaquin River (b), and Delta outflows (c). Departures were binned into low-flow summer months (June, July and August), indicated in dark gray, and high flow winter months (January, February and March), indicated in light gray. Both summer and winter Delta outflows were highest in 1983.

but exhibited no significant structural change (F = 6.43, p = 0.13). We assessed SSC measured daily at Freeport (USGS site 11447650) sub-sampled to the monthly TSS sampling cruises and analyzed the data record for structural change. Similar to upstream Sacramento River TSS, SSC in the Sacramento River just upstream of the Delta exhibits a declining trend ($\tau = -0.17$, $p < 0.00$), and there is no significant structural change (F = 6.70, p = 0.12). Schoellhamer (2011) made a similar observation: the 1998 San Francisco Bay suspended sediment step decrease was also not due to a sudden decrease in river suspended sediment supply.

5.3. Evidence for an abrupt shift to sediment supply limitation

Dominated by the Sacramento River, the TSS signal in the upper estuary stations is most likely to be sensitive to the decline in sediment supply. Yet these stations exhibit a step decrease not observed upstream. This may be indicative of a sudden clearing event as proposed by Schoellhamer (2011). Schoellhamer's model shows there are two conditions required for a sudden clearing event in an estuary: the estuary must have an erodible sediment pool, and the threshold from sediment transport regulation to sediment supply regulation must be crossed. Over the past century and a half, the Delta and San Francisco Bay developed a large erodible sediment pool from anthropogenic disturbances in the watershed, including hydraulic mining, land clearing, and development (Gilbert, 1917; Wright and Schoellhamer, 2004). However, since that time, sediment supply to the upper estuary has been decreasing (Wright and Schoellhamer, 2004; McKee et al., 2006).

Examination of the trends in TSS before and after the 1983 breakpoint supports the sudden clearing event hypothesis. Prior to the 1983 breakpoint, TSS in the overall upper estuary was declining (−0.98 mg/L/yr), but the confidence limits of the slope indicate it was very weakly declining (−1.21 to 1.38 mg/L/yr). While TSS in the Delta was declining prior to 1983 (−1.27 mg/L/yr; −1.88 to 0.44 mg/L/yr), there was no trend in the downstream Sacramento River site (SC2) or in Suisun Bay. Therefore it is unlikely that the system was supply-limited at this time. The high winter and high summer flows in 1982 and 1983 may have reduced the erodible sediment pool from the Delta. However, the record prior to the first step change is limited.

The declining TSS trend after the first step decrease suggests supply limitation after the step change. After 1983, the Sacramento River-dominated stations (SC2 and Suisun Bay) had a significant declining trend in TSS (0.42 and 0.18 mg/L/yr, respectively) despite further occurrences of extreme events such as the high flows related to the

1997–1998 El Niño and high flows in 2006. If the erodible sediment pool were depleted or “flushed out” after the 1983 El Niño event, this coupled with declining river sediment supply may have led to the shift to supply limitation.

After 1983 there were several successive dry years (Fig. 6) during which time there was little trend in TSS in the Delta. This may indicate a transition to a more “clear” Delta with relative stability. The second step change observed in the Delta was likely a result of the large 1998 summer flows. After this step decrease, TSS exhibited a significant declining trend (0.64 mg/L/yr). The 1983 and 1998 step decreases in the Delta support the hypothesis by Schoellhamer et al. (2013–this issue) that further adjustment of the estuary and watershed to decreased sediment supply will be as steps that occur only during greater floods than previously experienced during the adjustment period.

5.4. El Niño-related “flushing” drives sudden clearing events

Episodic flood events have a strong influence on suspended sediment flux. In California, El Niño phases are often, but not necessarily, associated with high precipitation, increased stream and river discharge, and are more likely to result in flooding than are non-El Niño conditions (Andrews et al., 2004). During the 1982–1983 and 1997–1998 El Niño floods, major suspended sediment flux events were observed not just for the estuary (Kimmerer, 2002; Jassby et al., 2005; Ganju and Schoellhamer, 2006), but along the entire coast of California (Inman and Jenkins, 1999; Mertes and Warrick, 2001).

The concept of transport and supply regulation has been applied to riverine sediment transport, and the relative importance of flow versus sediment supply to regulating sediment transport varies in regulated river systems (Rubin and Topping, 2001). While there was no direct evidence for structural change in Sacramento River SSC, concentration was higher prior to 1983 (Wilcoxon rank sum test, $W = 21{,}110.5$, $p < 0.00$) though discharge was not ($W = 0.9$, $p = 0.98$). Before 1983 SSC was not significantly associated with discharge (Spearman's $\rho = -0.05$, $p = 0.92$), but after 1983 it was (Spearman's $\rho = 0.47$, $p = 0.01$) (Fig. 7). There are two causes for reduced sediment flux as visualized by sediment–discharge relationships: a reduction in sediment source or an increase in discharge (Warrick and Rubin, 2007). After 1983, the sediment flux per unit discharge in the Sacramento River decreased, but discharge over time did not. The change in the sediment–discharge relationship further suggests there was a shift from transport to supply regulation of sediments in the estuary sometime after 1983.

Tote et al. (2011) found a decrease in sediment export from a watershed in Peru after the 1982–1983 El Niño that lasted several years until eventually sediment equilibrium was re-established. It is questionable whether the San Francisco Estuary will return to such equilibrium. We hypothesize a series of sudden clearing events during which sediment-depleted waters successively “flush” the erodible sediment pool downstream. The modifications to the watershed restricted additional sediment sources, resulting in relatively “clear” water entering the Delta after 1983. Whereas river discharge and Delta outflow were very high during 1983 (annual mean discharge = 2022 m^3/s), SSC in the Sacramento River were not (annual mean concentration = 52 mg/L). This high flow of sediment-depleted water into the upper estuary may have had the effect of flushing the erodible sediment pool into the San Francisco Bay. The 1997–1998 El Niño and associated high discharge probably flushed sediment from the San Francisco Bay to the Pacific Ocean, depleting the estuary's erodible sediment pool enough to cross the threshold from transport to supply limitation mid-estuary by 1999. Schoellhamer's (2011) observation of the 1999 SSC step decrease may reflect this flushing event.

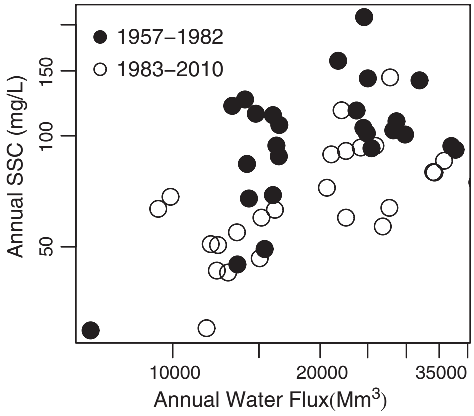

Fig. 7. Annual SSC and discharge measured at the Sacramento River at Freeport (USGS site 11447650). SSC was higher, but not significantly associated with discharge prior to 1983. After 1983 SSC was significantly associated with discharge.

5.5. Other impacts to the estuary

The extreme flows associated with the 1982–1983 El Niño have had other impacts on the upper estuary that support the association of the sudden clearing event with extreme flows. Delta smelt abundance abruptly declined around 1982 due to advection of larvae during the high flows that occurred in both the wet and dry seasons of CAWY 1983 (Kimmerer, 2002). Abundances have been persistently low since that time (Kimmerer, 2002). This has been attributed to the persistent drought of 1987–1992, coupled with multiple stressors from entrainment from water exports, contaminants, and competition from invasive alien species (Kimmerer, 2002; Nobriga et al., 2008). Increasing water clarity in the Delta has also been identified as a potential cause of the Delta smelt declines (Nobriga et al., 2005). It is possible that decreased turbidity in the upper estuary after 1983 contributed to the decline of the Delta smelt.

Additional evidence of changes in the upper estuary and Delta related to the TSS step change is provided by observed changes in macrophyte distribution. The sudden clearing after 1983 corresponds to the accelerated invasion of submerged macrophytes in the Delta between 1982 and 1999 (Nobriga et al., 2005; Brown and Michniuk, 2007; Hestir, 2010). Summer water clarity, measured by Secchi disk depth, has increased since 1970 (Jassby et al., 2002; Nobriga et al., 2008), with notable increases in the Delta where macrophytes are growing. The submerged macrophyte invasion of the Delta may explain why, despite being a net-depositional environment in 1999–2002 (Wright and Schoellhamer, 2005), TSS continued to decline. Sediment deposited in the Delta may be impounded in submerged macrophyte beds and vegetated wetlands (Wright and Schoellhamer, 2005; Hestir, 2010), thus not replenishing the erodible sediment pool.

6. Conclusions

Our results support the hypothesis that a step change in TSS and sedimentation occurred in the upper estuary similar to the clearing observed in the San Francisco Bay by Schoellhamer (2011). We investigated historic TSS observations in a highly modified estuary with a decreasing trend in SSC. We identified a step decrease in TSS in seven of the nine measurement stations. In the upper estuary TSS was 38% lower in 1984–2010 than in 1975–1983. This step decrease co-occurred with record high winter and summer season discharge events following El Niño-driven high precipitation. Despite another El Niño event in 1998–1999 with similarly extreme discharge events, a step increase in TSS did not occur. We conclude that high discharge during 1983 flushed the erodible sediment pool from the upper estuary, resulting in sediment depletion due to supply limitation.

This study shows the utility in examining both sediment flux trends and the structure of the trends to understand processes and infer transport or supply-limited sediment regimes. Extreme hydro-climate events in impounded watersheds that create high discharge events with sediment-depleted water may result in sediment depletion by flushing erodible sediment pools further downstream.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, http://dx.doi.org/10.1016/j.margeo.2013.05.008. These data include Google maps of the most important areas described in this article.

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