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ARTICLE 1

Spatial and Temporal Variability of Suspended-sediment Concentration in A Shallow Estuarine Environment

Catherine A. Ruhl and David H. Schoellhamer

ARTICLE 2

Trends in the Sediment Yield of the Sacramento River, California, 1957 – 2001

Scott A. Wright and David H. Schoellhamer

ARTICLE 3

Biology and Population Dynamics of Sacramento Splittail (*Pogonichthys macrolepidotus*) in the San Francisco Estuary: A Review

Peter B. Moyle, Randall D. Baxter, Ted Sommer, Ted C. Foin, and Scott A. Matern

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Spatial and Temporal Variability of Suspended-sediment Concentration in a Shallow Estuarine Environment

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ABSTRACT

Shallow subembayments respond differently than deep channels to physical forces acting in estuaries. The U.S. Geological Survey measured suspended-sediment concentrations at five locations in Honker Bay, a shallow subembayment of San Francisco Bay, and the adjacent channel to investigate the spatial and temporal differences between deep and shallow estuarine environments. During the first freshwater pulse of the wet season, the channel tended to transport suspended sediments through the system, whereas the shallow area acted as off-channel storage where deposition would likely occur. Following the freshwater pulse, suspended-sediment concentrations were greater in Honker Bay than in the adjacent deep channel, due to the larger supply of erodible sediment on the bed. However, the tidal variability of suspended-sediment concentrations in both Honker Bay and in the adjacent channel was greater after the freshwater pulse than before. During wind events, suspended-sediment concentrations in the channel were not affected; however, wind played a crucial role in the resuspension of sediments in the shallows. Despite wind-wave sediment resuspension in Honker Bay, tidally averaged suspended-sediment flux was controlled by the flood-dominated currents.

KEYWORDS

Suspended sediment, spatial variability, temporal variability, wind waves, freshwater pulse, San Francisco Bay.

SUGGESTED CITATION

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INTRODUCTION

Estuaries commonly include deeper channels and shallower shoals or subembayments. Most sediment transport studies of estuaries have focused on the deeper channels because these serve as the primary conduit of sediment between the watershed and ocean (see review by Uncles 2002). Sediment transport in shoals and subembayments, however, will differ from that in deeper channels because of greater wind wave resuspension, proximity to shore and tributaries, and greater relative benthic filtering of the shallower water column. If the tidal and tidally-averaged exchange between deeper channels and neighboring shoals is sufficiently large, variability in one can not be explained without considering variability in the other. Wind wave resuspension in shallower water can be transported to the neighboring deep channel and increase suspended-sediment concentrations (SSC) during ebb tide and less turbid water from the deep channel can move onto adjacent shoals during flood tide (Jing and Ridd 1996; de Jonge and van Beusekom 1995; Schoellhamer 1996). In the Tay Estuary, sediment transport from shallow waters during ebb tide creates turbidity maxima in the deeper channel (Weir and McManus 1987). Transport from shallow water can also change the composition of suspended sediment in a deep channel; Edelvang and Austen (1997) observed fecal pellets from shoals in the adjacent deep channel at the end of ebb tide. In these cases, the deeper channel and shoal are communicating with one another. In this paper, we compare SSC measurements in a deeper channel and adjacent subembayment that demonstrate much less communication, suggesting a somewhat independent subembayment.

San Francisco Bay includes extensive shallow areas, with approximately one-half of its surface area being less than 2 m deep (Conomos and others 1985). However, the deep channels along the spine of the bay are sampled most regularly for physical, chemical, and biological parameters (Buchanan and Ruhl 2000; Edmunds and others 1997; Webster and others 1998). To investigate the spatial and temporal variability of SSC in shallow-water areas and deep-water channels, Honker Bay, a shallow subembayment of San Francisco Bay, and the adjacent channel were studied (Figure 1). Shallow estuarine environments such as Suisun Bay are ecologically significant because a large fraction of the biota depends on these areas for shelter and nourishment (Cloern and others 1985; Caffrey and others 1998). Suspended sediments are an important component of the estuarine environment harboring a nutrient supply, impacting light penetration through the water column, and adsorbing potential contaminants (Cloern 1987; Domagalski and Kuivila 1993).

In this paper, we present observed spatial and seasonal patterns of SSC variability that indicate that shallow estuarine environments respond differently to physical forces than neighboring deep channel environments. Honker Bay is somewhat independent of the adjacent channel and tends to act as a temporary off-channel storage zone for sediments washed down during early winter storms, whereas the channels along the spine of San Francisco Bay tend to transport the sediments farther down-estuary. Another difference between these two environments is the effect of wind waves on SSC; wind waves successfully resuspend sediments in shallow areas but have little effect on SSC in the deep channels (de Jonge and van Beusekom 1995).

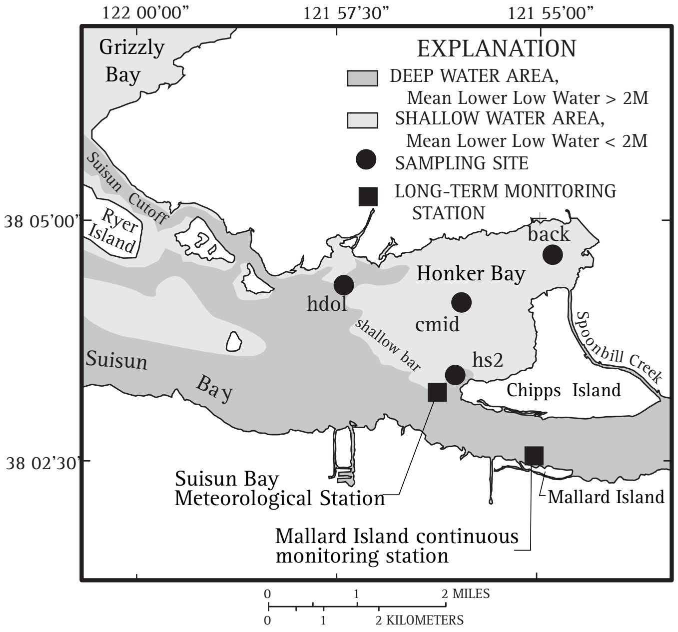

Figure 1. Location of study area and sampling sites

SITE DESCRIPTION AND DATA COLLECTION

Honker Bay is located at the eastern side of San Francisco Bay covering approximately 10 km^2, most of which is less than 2 m in depth. Suspended sediments throughout San Francisco Bay are comprised predominantly of silts and clays. Two major features of Honker Bay are a bar at the mouth of the bay, and Spoonbill Creek, which connects the head of the bay to Suisun Bay east of Mallard Island (Figure 1). Very little exchange occurs across the shallow bar at the mouth of Honker Bay, and the dominant tidal currents run parallel to the bar. Additionally, the orientation of Honker Bay is such that the currents are strongly flood-dominant (Lacy 2000). Tidally averaged flow through Spoonbill Creek is typically northward; however, southward flows through Spoonbill Creek can occur due to wind setup and a water level differential between the head of Honker Bay and the eastern side of Suisun Bay (Warner and others 1997).

Freshwater discharge and wind are two seasonal forcing mechanisms affecting SSC in San Francisco Bay. Most precipitation occurs from December to April, causing short duration peaks in freshwater flow and increases in SSC. Baseline freshwater discharge into the bay is greatest during the spring months, as a result of runoff from snowmelt. About 90% of the discharge into the bay is from the Sacramento-San Joaquin River Delta, which drains the Central Valley of California (Smith 1987). The peak discharge of approximately 14,800 m^3 s^{-1} during water year 1997 was extremely high and has been exceeded 0.01% of the time in the record collected since water year 1956 (CDWR 1986). Winds typically blow as an afternoon onshore breeze and generally begin to increase during the spring months and remain elevated through the summer months.

Data presented in this paper were collected from four sampling sites located in Honker Bay during two 3-month deployments and from one long-term monitoring station located in the adjacent channel (Figure 1). The objective of the first deployment, from December 1996 through March 1997, was to observe the first winter freshwater pulse pushing salinity out of Honker Bay and delivering the first flush of sediment from the Central Valley watershed to the San Francisco Bay. The objective of the second deployment, from April through August 1997, was to monitor the changes in SSC during low flows and increased wind. Not all of the data collected are presented in this paper, due to biological fouling, equipment failure, and other problems that invalidated the data.

Sites *back* and *cmid* were located in the shallowest interior parts of Honker Bay with sensors collecting data approximately 0.5 m from the bed. Sites *hdol* and *hs2* were located on the boundary of Honker Bay with water depths of approximately 4 m and 7 m, respectively; the sensors collected data at approximately 3 m and 0.5 m from the bed, respectively. The long-term monitoring station at Mallard Island is located on the south side of the Suisun Bay channel at a depth of approximately 13.5 m. The sensor is attached to a float and measures SSC 1 m below the water surface. A second sensor collects SSC data approximately 1.5 m above the bottom; however due to instrument problems and fouling, there are significant periods of missing data during the study and the data will not be presented. Concentrations measured at the lower sensor are higher than those measured by the upper sensor; however, the patterns and responses to the physical forces discussed here are consistent between the two sensors.

Each shallow-water deployment package included a velocity meter and a conductivity-temperature-depth (CTD) probe with an additional channel programmed to collect SSC data. Each parameter was collected at ten-minute intervals. SSC was determined with optical backscatterance sensors that measure the amount of suspended material in the water, the output of which was converted to SSC using calibration curves developed from the analysis of water samples. In addition, CTD probes were programmed to collect wave data at two-hour intervals at sites *cmid* and *back*. Sensors at each of the sampling locations were serviced every three to five weeks to retrieve data, to clean the sensors to minimize biological fouling, and to collect water samples for sensor calibration.

RESULTS AND DISCUSSION

Seasonal Variability

During both deployments, the shallow-water and deep-channel sites showed similar temporal SSC trends (Figure 2). In December, SSC was low throughout Honker Bay and Suisun Bay. In early January, following the extreme first flush winter storm event, SSC increased dramatically at every site. Data collected during the second deployment show consistently higher tidal variability as compared to the pre-flood conditions and similar temporal patterns associated with the spring neap cycle among the study sites; however, the amount of tidal variability at the shallow sites was approximately two times greater than at the channel station. The tidal variability of SSC in the shallow areas was on the order of 20 to 50 mg L^{-1} before the freshwater pulse arrived whereas the tidal variability increased to 200 to 300 mg L^{-1} during the second deployment. In comparison, the tidal variability of SSC at Mallard Island was approximately 10 to 20 mg L^{-1} before the freshwater pulse arrived and the tidal variability increased to 100 mg L^{-1} during the second deployment.

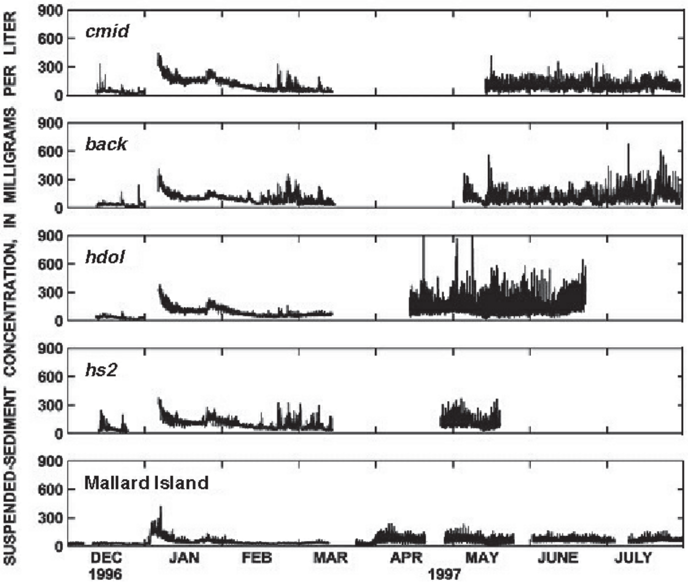

Figure 2. Suspended-sediment concentration time series at sampling sites: *cmid*, *back*, *hdol*, *hs2*, and long-term monitoring station, Mallard Island. Due to instrument fouling or failure, not all of the sites have data sets covering the entire deployment period. There is a one-month break from mid-March to mid-April between the two shallow water deployment periods.

A similar comparison of the mean SSC during the second deployment and mean SSC before the freshwater pulse shows increases at all of the study locations (Table 1). However, the mean SSC increased approximately three to five times between December and the spring months in Honker Bay, whereas mean SSC at Mallard Island only doubled over the same period.

Table 1. Mean suspended-sediment concentrations at sampling sites in December 1996 and spring 1997

Sampling Site	***Pre-Freshwater Pulse: Dec. 1996 (mg L^{-1})***	***Second Deployment: Spring 1997 (April-July) (mg L^{-1})***
back	35	112
cmid	37	102
hdol	32	151
hs2	44	114
Mallard Island	27	65

Although we did not see a reduction in SSC at the end of the second deployment compared to levels measured prior to the high freshwater flow event, it has been seen elsewhere in San Francisco Bay that the finer, more erodible sediments are winnowed from the bed throughout the windy season and SSC tends to decrease by fall (Krone 1979; Nichols and Thompson 1985; Schoellhamer 2002). Our data set is, perhaps, too short to see this phenomenon during 1997; however, if the levels seen in late 1996, prior to the freshwater pulse, are typical late-fall concentrations in Honker Bay, it is reasonable to assume that sediments must be either winnowed from the bed or consolidated into a less erodible matrix to account for relatively low concentrations late in the year.

Winter Freshwater Pulse

The immediate effect of freshwater pulses in both the deep channel and the shallow water areas was an abrupt increase in SSC as sediment from the Central Valley watershed was flushed into San Francisco Bay. The first freshwater pulse of water year 1997 occurred on January 4, 1997, peaking at approximately 14,800 m^3 s^{-1}, and a second pulse occurred several weeks later on January 27, 1997, peaking at approximately 7,760 m^3 s^{-1} (CDWR 1986). Six days of SSC data (January 1–6) were lost at all of the shallow water sites in Honker Bay due to equipment malfunction; however, the Mallard Island SSC monitoring station was operational during this period (Figure 3). Comparison of Mallard Island data to site *cmid* data shows a marked difference between these two locations after the influx of sediment from the two 1997 freshwater pulses. Both sites had a baseline SSC of 25 to 50 mg L^{-1} before the first freshwater pulse. Mallard Island approached baseline concentrations one to two weeks after each freshwater pulse, whereas site *cmid* reached higher concentrations than Mallard Island and did not approach baseline concentrations until nearly one month after the second freshwater pulse.

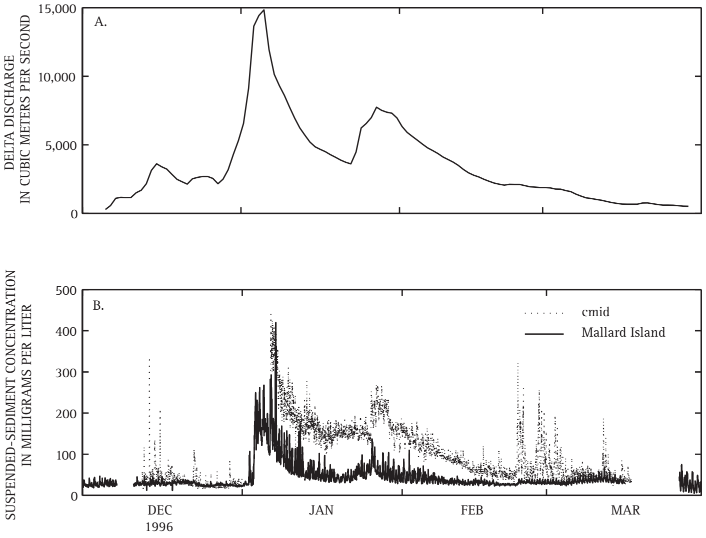

Figure 3. (A) Delta discharge and (B) suspended-sediment concentrations at sampling site *cmid* and long-term monitoring station Mallard Island during the first deployment

SSC was greater in Honker Bay than at Mallard Island during January and February (Figure 3) because of the relatively large supply of erodible sediment on the bottom of Honker Bay. During freshwater pulses, relatively large quantities of suspended sediment pass Mallard Island. Some of this sediment enters Honker Bay. Tidal velocities are on the order of 100 cm s^{-1} at Mallard Island and only on the order of 20 cm s^{-1} in Honker Bay. Thus, sediment is more likely to deposit in Honker Bay than at Mallard Island or in the other deep channels. The newly deposited sediments then undergo cycles of resuspension by tidal currents and deposition. Tidal currents control deposition and resuspension during the winter months because wind speed is relatively low and wind-wave resuspension usually is minor. After the freshwater pulse, the primary source of suspended sediment at Mallard Island remains the decreasing riverine input, but in Honker Bay, the source of suspended sediment shifts from riverine input to tidal resuspension. By the end of February, SSC in Honker Bay has decreased to the levels at Mallard Island because of bed sediment consolidation and partial tidal-current winnowing of the sediment supplied by the freshwater pulse.

SSC time-series data in Honker Bay have broadened peaks and lag behind SSC time-series data at the Mallard Island monitoring station after each freshwater pulse, indicating that the residence time of flood-derived sediments in Honker Bay is longer than in the adjacent channel. Shallow water provides temporary off-channel storage for sediment on the bay floor, which is slowly depleted through repeated cycles of resuspension, transport, and deposition.

Spring Winds

Sediment resuspension by wind waves in shallow water is an important factor controlling SSC during the spring and summer months when wind velocity increases (Krone 1979; de Jonge and van Beusekom 1995; Schoellhamer 1996, 1997a). Wind blowing over shallow water generates waves that create a shear stress on the bay floor. Wind speed and direction were measured by the U.S. Geological Survey at a continuously operated meteorological station near Honker Bay (Figure 1). Linear wave theory and spectral analysis of wave data were used to calculate bottom orbital velocity (Schoellhamer 1995). Bed shear stress is approximately proportional to the square of the bottom orbital velocity and increases as the water depth decreases (Dean and Dalrymple 1984). Relatively large winds and the associated bed shear stress are maintained throughout the second deployment (data not shown here).

Wind waves have a significantly greater effect on SSC in shallow areas than in deep channels. Suspended-sediment data from *cmid* in Honker Bay, and Mallard Island in the channel, as well as wind speed were filtered using a Butterworth filter to remove frequencies less than 30 hours (Figure 4). The peaks and valleys seen in the *cmid* data are consistently reflected in the wind time-series data, indicating that wind-wave resuspension controls SSC in Honker Bay. There is no apparent correlation between the filtered SSC at Mallard Island and the filtered wind data, indicating that the SSC in the deeper channel at Mallard Island was not affected by local wind-wave resuspension or by advection of more turbid water from Honker Bay.

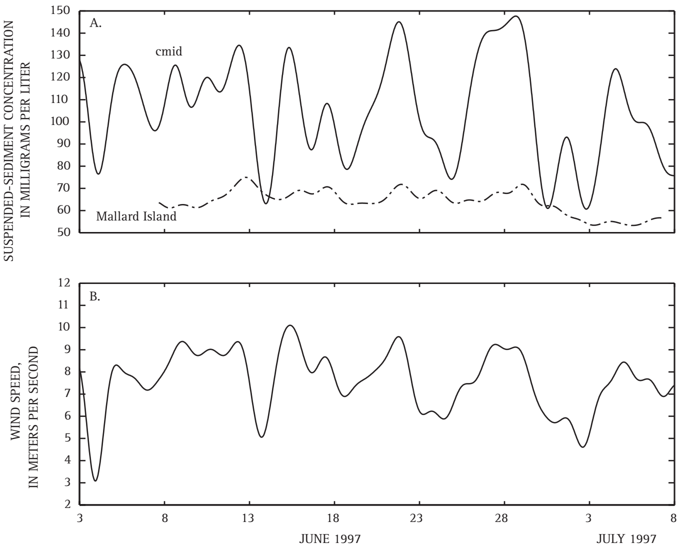

Figure 4 (A) Tidally averaged suspended-sediment concentration time-series data at sampling site *cmid* and long-term monitoring station Mallard Island. (B) Filtered wind-speed data from the Suisun Bay meteorological station.

Lacy (2000) found that wind has very little impact on the residual velocities throughout most of Honker Bay. One exception to this finding is at the head of Honker Bay, near site *back* and Spoonbill Creek where westerly winds drive water through Spoonbill Creek due to water level differences between Honker Bay and Suisun Bay across Spoonbill Creek. Warner and others (1997) found that sediment also moves through Spoonbill Creek during these westerly wind events.

Suspended-sediment Flux

To understand the mechanisms moving sediments through and within Honker Bay, the tidally averaged suspended-sediment flux (SSF) was calculated at each station. Tidally averaged SSF (a) is equal to the sum of advective (b), dispersive (c), and Stokes' drift (d) components

$$\underset{(a)}{\overline{uhc}} = \underset{(b)}{\overline{u}\,\overline{h}\,\overline{c}} + \underset{(c)}{u'\overline{h}c'} + \underset{(d)}{u'h'\overline{c}} \qquad (1)$$

where u is velocity, h is water depth, c is SSC, a prime symbol (') indicates tidal deviation, and an overbar (¯) indicates a tidal averaging such that $x=\overline{x}+x'$. During the low flow conditions, SSF was overwhelmingly dominated by the advective component and sediment tended to move in the flood-tide direction (Figure 5). The advective portion of SSF accounted for nearly 70% and approached 80% to 90% of the total SSF during certain periods. Suspended sediments in Honker Bay tend to travel parallel to the mouth of the bay and ultimately exit in the southwest near station *hs2*. Very little sediment is transported toward the head of Honker Bay near site *back*. Note that due to equipment problems, concurrent time series of SSF at each of the stations in Figure 5 were not available, but similar low-flow hydrologic conditions were used to develop this conceptual model. This finding is complemented by Lacy's (2000) results showing that advection drives salt flux through Honker Bay and, due to the orientation of the subembayment, ebb tides are relatively small and the flood tide dominates.

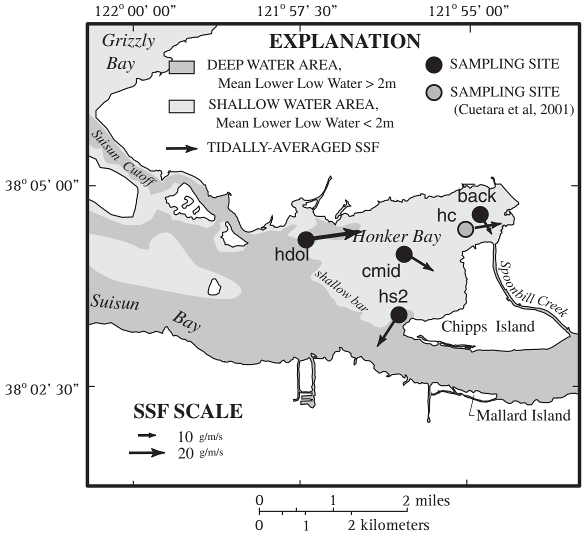

Figure 5. Mean tidally averaged suspended-sediment flux during low flow conditions as measured in Honker Bay. The size of the arrows is proportional to the magnitude flux and the direction of the arrows indicates the average direction of the flux.

While wind increases SSC, the response of tidally-averaged SSF to wind varies spatially in Honker Bay. At site *cmid*, wind and tidally-averaged SSF are poorly correlated ($r^2 = 0.03$). Similarly, Lacy (2000) found that wind has very little effect on tidally averaged velocities throughout most of Honker Bay. In a previous study (Cuetara and others 2001), currents at site *hc* (Figure 5) were flood-dominant (toward the east and back of Honker Bay) and the primary component of SSF was the advective flux (Warner and others 1997). Unlike site *cmid*, however, SSF at *hc* increased during strong westerly winds. As SSF toward the east increased at *hc*, SSF toward the south increased in Spoonbill Creek due to wind set-up in the back of Honker Bay. The effect of Spoonbill Creek on Honker Bay is limited to the region near the Creek (at site *hc*, not site *cmid*).

Sediment transport in Honker Bay responds differently to wind than the shallow waters of South San Francisco Bay, where a persistent sea breeze induces tidally averaged currents and SSF (Lacy and others 1996). The sea breeze shifted the direction of SSF 90 degrees and increased the magnitude of SSF by a factor of four. Unlike Honker Bay, South Bay has a deep longitudinal channel (depth approximately 10 m) aligned with the tidal currents and wind. Surface flows and advective flux are in the direction of the wind, resulting in wind set-up, which then produces return flows in the opposite direction in the channel at depth (Walters 1982). The absence of a deep channel in Honker Bay restricts return flows and diminishes the importance of wind-induced advective flux. Instead of a deep channel, Spoonbill Creek essentially acts as a pathway for relieving wind setup at the head of Honker Bay, but with less impact on subembayment SSF.

CONCLUSIONS

SSC plays an important role in the ecology of San Francisco Bay and understanding its dynamics and variability will lead to further understanding of other components of the estuarine environment. For example, Schoellhamer (1997b) shows that SSC is well correlated to a number of trace metals. Water-quality objectives for trace metals are based on a four-day average, so whether and where an objective is met can be determined by subtidal processes such as SSC response to freshwater pulses and spring winds.

Suspended-sediment concentrations respond differently in shallow water areas than in deep channels to seasonal forces, such as freshwater discharge and wind. During freshwater pulses, particularly during the first freshwater pulse of the season, SSC increases in shallow water areas and deep channels. Shallow subembayments provide temporary off-channel storage for newly arrived sediments and their associated trace elements. Subsequent resuspension of unconsolidated bed sediment by tidal currents in shallow water cause SSC to take longer to return to baseline concentrations than in the deeper channels. Winds tend to increase in the spring thereby, increasing wind-wave resuspension of bed sediments in shallow areas; however, winds have minimal impact on SSC in the channels. Despite wind-wave sediment resuspension in Honker Bay, tidally averaged suspended-sediment flux was controlled by the flood-dominated currents.

The results of this work highlight the importance of sample collection timing. When designing a sampling protocol for parameters that may be associated with SSC, the temporal and spatial patterns of variability must be considered. If these processes are not well understood, it could lead to spurious interpretation of sample results.

ACKNOWLEDGEMENTS

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REFERENCES

Buchanan PA, Ruhl CA. 2000. Summary of suspended-solids concentration data, San Francisco Bay, California, water year 1998: U.S. Geological Survey Open-File Report 00-88. 41 p.

Caffrey JM, Grenz C, Cloern JE. 1998. Changes in production and respiration during a spring phytoplankton bloom in San Francisco Bay, California, USA: implications for net ecosystem metabolism. Marine Ecology Progress Series 172:1–12.

[CDWR] California Department of Water Resources. 1986. DAYFLOW program documentation and DAYFLOW data summary user's guide.

Cloern JE. 1987. Turbidity as a control on phytoplankton biomass and productivity in estuaries. Continental Shelf Research 7(11/12):1367-1381.

Cloern JE, Cole BE, Wong RLJ, Alpine AE. 1985. Temporal dynamics of estuarine phytoplankton: a case study of San Francisco Bay. Hydrobiologia 129:153–176.

Conomos TJ, Smith RE, Gartner JW. 1985. Environmental setting of San Francisco Bay. Hydrobiologia 129:1-12.

Cuetara JI, Burau JR, Schoellhamer DH. 2001. Hydrodynamic and suspended-solids concentration measurements in Suisun Bay, California, 1995. U.S. Geological Water-Resources Investigations Report 01-4086. 221 p. Available at: http://water.usgs.gov/pubs/wri/wri014086/

Dean RC, Dalrymple RA. 1984. Water wave mechanics for engineers and scientists. Englewood Cliffs (NJ): Prentice-Hall, Inc. 350 p.

Domagalski JL, Kuivila KM. 1993. Distributions of pesticides and organic contaminants between water and suspended sediment, San Francisco Bay, California. Estuaries 16(3A):416-426.

Edelvang K, Austen I. 1997. The temporal variation of flocs and fecal pellets in a tidal channel: Estuarine, Coastal and Shelf Science 44:361-367.

Edmunds JL, Cole BE, Cloern JE, Dufford RG. 1997. Studies of San Francisco Bay, California, estuarine ecosystem-pilot regional monitoring program results, 1995. U.S. Geological Survey Open-File Report 97-15. 380 p.

Jing L, Ridd PV. 1996. Wave-current bottom shear stresses and sediment resuspension in Cleveland Bay, Australia. Coastal Engineering 29:169-186.

de Jonge VN, van Beusekom JEE. 1995. Wind- and tide-induced resuspension of sediment and microphytobenthos from tidal flats in the Ems Estuary. Limnology and Oceanography 40(4):766-778.

Krone RB. 1979. Sedimentation in the San Francisco Bay system. In: Conomos TJ, editor. San Francisco Bay: the urbanized estuary. San Francisco (CA): AAAS, Pacific Division. p 347-385.

Lacy JR. 2000. Circulation and transport in a semi-enclosed estuarine subembayment [Ph.D. dissertation]. Available from: Department of Civil and Environmental Engineering, Stanford University. 226 p.

Lacy JR, Schoellhamer DH, Burau JR. 1996. Suspended-solids flux at a shallow-water site in South San Francisco Bay, California. In: Proceedings of the North American Water and Environment Congress, 24-28 June 1996, Anaheim, California.

Nichols FH, Thompson JK. 1985. Time scales of change in the San Francisco Bay benthos. Hydrobiologia 192:121-138.

Schoellhamer DH. 1995. Sediment resuspension mechanisms in Old Tampa Bay, Florida. Estuarine, Coastal and Shelf Science 40:603-620.

Schoellhamer DH. 1996. Factors affecting suspended-solids concentration in South San Francisco Bay, California. Journal of Geophysical Research 101(C5):12087-12095.

Schoellhamer DH. 1997a. Time series of SSC, salinity, temperature, and total mercury concentration in San Francisco Bay during water year 1996. In: 1996 Annual Report: San Francisco Estuary Regional Monitoring Program for Trace Substances. Richmond (CA): San Francisco Estuary Institute. p 65-77.

Schoellhamer DH. 1997b. Time series of trace element concentrations calculated from time series of suspended-solids concentrations and RMP water samples. In: 1995 Annual Report: San Francisco Estuary Regional Monitoring Program for Trace Substances. Richmond (CA): San Francisco Estuary Institute. p 53-55.

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

Smith LH. 1987. A review of circulation and mixing studies of San Francisco Bay, California: U.S. Geological Survey Circular 1015. 38 p.

Uncles RJ. 2002. Estuarine physical processes research: some recent studies and progress: Estuarine, Coastal and Shelf Science 55:829-856.

Walters RA. 1982. Low-frequency variations in sea level and currents in South San Francisco Bay. Journal of Physical Oceanography 12:658-668.

Warner JC, Schoellhamer DH, Burau JR. 1997. A sediment transport pathway in the back of a nearly semi-enclosed subembayment of San Francisco Bay, California. In: Proceedings of the XXVII International Association of Hydraulic Research Congress, 10-15 August 1997, San Francisco, California, vol. 2. p 1096-1101.

Webster MD, Friebel MF, Freeman LA. 1998. Water resources data, California, water year 1997. U.S. Geological Survey Water-Data Report CA-97-2, vol. 2. 322 p.

Weir DJ, McManus J. 1987. The role of wind in generating turbidity maxima in the Tay Estuary. Continental Shelf Research 7(11/12):1315-1318.