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Comparison of the Basin-scale Effect of Dredging Operations and Natural Estuarine Processes on Suspended Sediment Concentration

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ABSTRACT: Suspended sediment concentration (SSC) data from San Pablo Bay, California, were analyzed to compare the basin-scale effect of dredging and disposal of dredged material (dredging operations) and natural estuarine processes. The analysis used twelve 3-wk to 5-wk periods of mid-depth and near-bottom SSC data collected at Point San Pablo every 15 min from 1993–1998. Point San Pablo is within a tidal excursion of a dredged-material disposal site. The SSC data were compared to dredging volume, Julian day, and hydrodynamic and meteorological variables that could affect SSC. Kendall's τ, Spearman's ρ, and weighted (by the fraction of valid data in each period) Spearman's ρ_w correlation coefficients of the variables indicated which variables were significantly correlated with SSC. Wind-wave resuspension had the greatest effect on SSC. Median water-surface elevation was the primary factor affecting mid-depth SSC. Greater depths inhibit wind-wave resuspension of bottom sediment and indicate greater influence of less turbid water from down estuary. Seasonal variability in the supply of erodible sediment is the primary factor affecting near-bottom SSC. Natural physical processes in San Pablo Bay are more areally extensive, of equal or longer duration, and as frequent as dredging operations (when occurring), and they affect SSC at the tidal time scale. Natural processes control SSC at Point San Pablo even when dredging operations are occurring.

Introduction

Dredging and disposal of dredged material (dredging operations) commonly are required to maintain navigation of ports and waterways in estuaries. Turbidity and suspended sediment concentration (SSC) can be much greater in the immediate vicinity of dredging operations than ambient conditions (Goodwin and Michaelis 1984). At the larger basin length scale (kilometers), increased turbidity can be particularly relevant to the ecology of estuaries in which primary production, seagrass photosynthesis, or fish predation is limited by turbidity in the water column (Cloern 1987; Dennison 1987; Benfield and Minello 1996). Estuaries can be dynamic environments in which natural physical processes such as tidal currents, wind-waves, and gravitational circulation resuspend and transport sediment. The purpose of this paper is to analyze SSC data from San Pablo Bay, California, and to compare the basin-scale effect of dredging operations and natural estuarine processes.

San Pablo Bay, a subembayment of San Francisco Bay, is an example of a dynamic estuary with a ship channel that requires maintenance dredging (Fig. 1). The semidiurnal tidal range is about 2 m in San Pablo Bay and varies with the fortnightly spring/neap cycle. Typical tidal currents range from 20 cm s^{-1} in shallow water (less than 2 m) to more than 100 cm s^{-1} in the deep (11–22 m) Pinole Shoal Ship Channel near the southern shore (Cheng and Gartner 1984). Gravitational circulation has been observed in the Pinole Shoal Ship Channel (Burau et al. 1993). Winds typically are strongest during the summer when an afternoon sea breeze blows from Central Bay through San Pablo Strait into San Pablo Bay. Most precipitation occurs from late autumn to early spring. About 90% of the freshwater discharge to San Francisco Bay is from the Sacramento-San Joaquin River Delta, which drains the Central Valley of California (Conomos and Peterson 1977).

Discharge from the Delta contains 83–86% of the fluvial sediments that enter San Francisco Bay (Porterfield 1980). Bottom sediments in San Pablo Bay are composed mostly of silts and clays in shallow water and silts and sands in deeper water (Conomos and Peterson 1977). An annual cycle of deposition and resuspension begins with large influx of sediment during winter, primarily from the Central Valley (Goodwin and Denton 1991; Oltmann et al. 1999). Much of this new sediment is deposited in San Pablo and Suisun Bays. Stronger westerly winds during spring and summer cause wind-wave resuspension of bottom sediment in these shallow waters and increase SSC (Ruhl et al. 2001). The ability of wind to increase SSC is greatest early in the spring, when unconsolidated fine sediments

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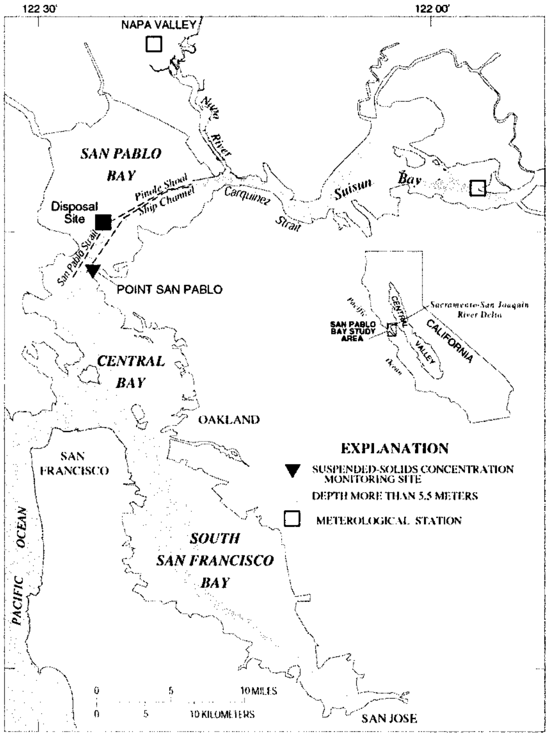

Fig. 1. Study area, San Pablo Bay, California.

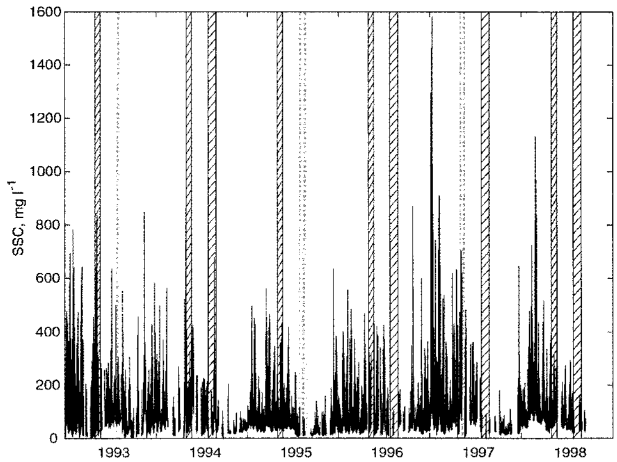

Fig. 2. Time series of mid-depth suspended sediment concentration (SSC) at Point San Pablo, California, January 1993 to September 1998. Shading indicates the three data periods when the Pinole Shoal Ship Channel was dredged and material was disposed at the San Pablo Bay disposal site. Cross-hatching indicates the nine data periods when no dredging operations were occurring.

easily can be resuspended. As the fine sediments are winnowed from the bed, the remaining sediments become progressively coarser and less erodible (Conomos and Peterson 1977; Krone 1979; Nichols and Thompson 1985; Ruhl and Schoellhamer 1999).

Maintenance dredging of the Pinole Shoal Ship Channel in San Pablo Bay was conducted in late July and August 1993 and 1995 and May 1997. Material dredged from Pinole Shoal Ship Channel is disposed at a site in San Pablo Bay that primarily is used for disposal of material from that channel (Fig. 1).

Methods

The U.S. Geological Survey (USGS) operates several SSC monitoring stations in San Francisco Bay (Buchanan and Ruhl 2000). Since 1993, the USGS has operated an SSC monitoring station at Point San Pablo, at the boundary between San Pablo and Central Bays, and about 4.9 km south of the San Pablo Bay disposal site. Water from the disposal site and the shallower depths of San Pablo Bay passes Point San Pablo during ebb tide because the tidal excursion in San Pablo Strait is 10–20 km and Point San Pablo is down (ebb) current. The Point San Pablo station is the closest station to a dredged material disposal site and has one of the longer and more complete SSC data sets, so data from it will be used to compare the effect of dredging operations and natural estuarine processes on SSC.

At Point San Pablo, optical backscatter sensors are deployed at mid-depth and near the bottom, and measurements are automatically collected every 15 min (Buchanan and Ruhl 2000). Mean lower low water depth at this site is 8 m. Water samples are collected periodically and analyzed for SSC and the results of these analyses are used to calibrate the sensors. Continuously deployed optical sensors are susceptible to biological fouling, which can invalidate data for 2–3 wk, depending on the fouling rate and instrument servicing schedule. Mid-depth data collected from January 1993 to September 1998 are shown in Fig. 2.

For the purposes of this article, SSC at Point San Pablo will be assumed to be representative of the basin-scale effect of dredging operations and natural processes. This assumption is reasonable because observations at Point San Pablo will be averaged over many tidal cycles and the tidal excursion is 10–20 km, which is similar to the horizontal scale of Central and San Pablo Bays.

Twelve periods of data were selected for analysis (Table 1 and Fig. 2). Data were chosen from non-dredging years to provide a comparison with years when dredging operations occurred. Data from 6 yr were used (1993–1998), 3 yr with dredging operations and 3 yr without. Two time periods, spring and summer, from each of the 6 yr were analyzed to make a total of 12 periods. The dates for analysis were the dates of dredging operations in spring

TABLE 1. Data periods selected for analysis of suspended sediment concentration at Point San Pablo, California.

Initial Date	Final Date	Dredging Volume (m^3)	Fraction of Valid Data	
			Mid-depth	Near-bottom
May 1, 1993	May 22, 1993	0	0.68	0.65
July 25, 1993	August 7, 1993	90,000	0.98	0.98
May 1, 1994	May 22, 1994	0	0.99	0.83
July 26, 1994	August 27, 1994	0	0.62	0.86
May 1, 1995	May 22, 1995	0	0.96	0.66
July 26, 1995	August 27, 1995	286,000	0.42	0.46
May 1, 1996	May 22, 1996	0	0.64	0.55
July 26, 1996	August 27, 1996	0	0.17	0.39
May 1, 1997	May 22, 1997	196,000	0.55	0.19
July 26, 1997	August 27, 1997	0	0.25	0.53
May 1, 1998	May 22, 1998	0	0.87	0.94
July 26, 1998	August 27, 1998	0	0.45	0.59

1997 (May 1–22) and summer 1995 (July 26–August 27). One exception was that the dates of dredging operations in 1993 (July 25–August 7) were used for the summer 1993 period. Dates from dredging years were used in non-dredging years to attempt to reduce the effect of any seasonal process that could mask the effect of dredging operations.

Statistical properties for SSC and various parameters were calculated for each of the 12 time periods. An advantage of grouping the data into 3-wk to 5-wk periods is the elimination of variability caused by semidiurnal tides and reduction of the effect of the fortnightly spring/neap cycle, increasing the likelihood that a response to dredging operations can be detected. Grouping the data into a small number of time periods increases the difficulty of achieving a prescribed level of significance with statistical tests.

Twelve quantities were calculated for each of the 12 periods (separate values were calculated based upon mid-depth and near-bottom SSC time series) as follows. Median SSC at Point San Pablo was calculated from valid data during each period. Fouling of the optical sensors invalidated some of the data. The amount of valid data ranged from 17–99% with a mean and median of 63% (Table 1). Volume of sediment dredged from Pinole Shoal Ship Channel and disposed in San Pablo Bay during each period was obtained from U.S. Army Corps of Engineers (1993–1998; Table 1). The median Julian day when SSC values are available during each period was calculated to help identify seasonal variations. Temporal variability of the erodibility of bottom sediment was qualitatively determined by the correlation, or lack thereof, of SSC with Julian day. Mean Delta discharge (California Department of Water Resources 1986) from December to March prior to each period was obtained from daily mean Delta discharge calculated by the California Department of Water Resources (CDWR) DAYFLOW program (CDWR 1986). This value is intended to indicate the supply of sediment from the Central Valley to the Bay. The median Delta discharge (CDWR 1986) was calculated during each period. The median water surface elevation at Point San Pablo when SSC values are available during each period (Buchanan 1999) was obtained from surface elevation data collected every 15 min. The standard deviation of water surface elevation at Point San Pablo when SSC values are available was also calculated. This value indicates the magnitude of tidal fluctuations. Larger values indicate spring tides and smaller values indicate neap tides. SSC in San Pablo Bay varies with the spring/neap cycle (Ruhl et al. 2001). Median salinity at Point San Pablo at the same elevation as the SSC time series when SSC values are available during each period (Buchanan 1999) was obtained from salinity data collected every 15 min. The standard deviation of salinity at Point San Pablo at the same elevation as the SSC time series when SSC values are available during each period were calculated. The strength of gravitational circulation increases as the longitudinal salinity gradient increases (Hansen and Rattray 1965; Burau et al. 1998); this variable will increase as the gradient increases. Median difference between mid-depth and near-bottom salinity at Point San Pablo when SSC values are available during each period were determined. Greater salinity stratification decreases vertical mixing of the water column (Walters et al. 1985). Median wind speed in the southern Napa Valley (Fig. 1; California Irrigation and Management Information System 1999) was obtained for times with valid SSC data. Wind direction is not considered but there is a predominant sea breeze through San Pablo Strait toward the Napa Valley and Carquinez Strait during the spring and summer. May 1994 wind data are not available, so the mean wind speed for the five other periods in May was used. The median barometric pressure at the

TABLE 2. Kendall's τ, Spearman's ρ, and weighted Spearman's ρ_w correlation coefficients of processes that have the potential to affect suspended sediment concentration at Point San Pablo, California. The correlations are significant at $\rho = 0.01$ level if $|\tau| = 0.585$ or if $|\rho|$ or $|\rho_w| = 0.727$ and at $p = 0.05$ level if $|\tau| = 0.448$ or if $|\rho|$ or $|\rho_w| = 0.580$ (for 12 data points). $*p < 0.05$; $**p < 0.01$.

Process	Mid-depth			Near-bottom		
	τ	ρ	ρ_w	τ	ρ	ρ_w
Dredging volume	−0.061	0.156	0.218	−0.273	−0.340	−0.465
Median Julian day	−0.424	−0.643*	−0.526	−0.545*	−0.734**	−0.742**
Prior winter delta discharge	−0.242	−0.283	−0.280	−0.121	−0.184	−0.089
Median delta discharge	0.121	0.182	−0.064	0.394	0.497	0.477
Median water-surface elevation	−0.606**	−0.797**	−0.706*	−0.409	−0.613*	−0.581*
Standard deviation of water-surface elevation	0.470*	0.578	0.403	0.273	0.336	0.214
Median salinity	0.121	0.154	0.351	−0.258	−0.319	−0.339
Standard deviation of salinity	0.000	0.014	−0.223	0.364	0.455	0.450
Median salinity stratification	0.045	0.021	−0.159	0.424	0.538	0.599*
Median wind speed	0.000	−0.035	0.012	−0.348	−0.501	−0.554
Median barometric pressure	0.348	0.462	0.250	0.379	0.592*	0.649*

USGS Suisun Bay meteorological station when SSC values are available during each period was calculated. Barometric pressure was not measured at the station in 1993. The mean barometric pressure for the five other periods in May was used for May 1993 and mean of the other five periods during July–August was used for July–August 1993. Barometric pressure alters the water-surface elevation.

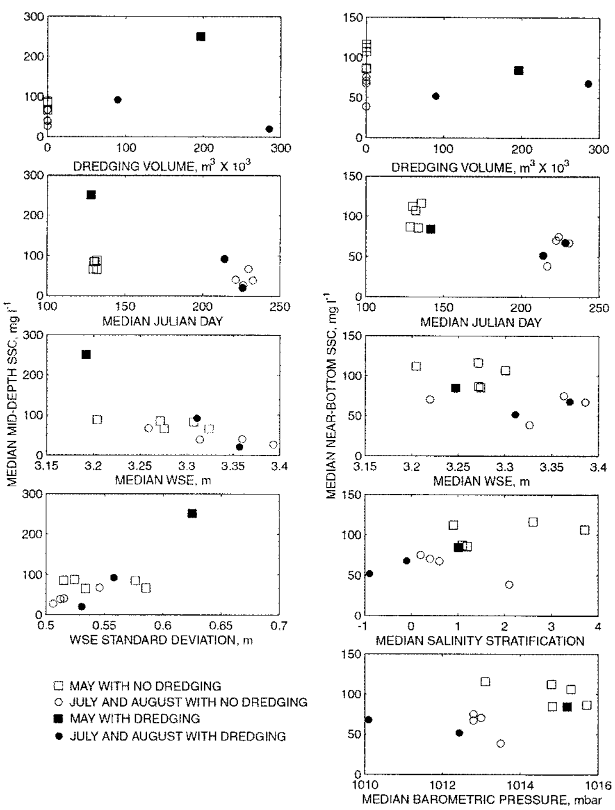

Fig. 3. Comparison of mid-depth and near-bottom suspended sediment concentration (SSC) with dredging volume and significantly correlated natural processes, Point San Pablo, California.

Kendall's τ, Spearman's ρ, and weighted Spearman's ρ_w correlation coefficients were computed for median SSC and the other variables listed above (Conover 1980; Helsel and Hirsch 1992). These non-parametric rank correlation coefficients are used because they determine whether the data have a monotonic trend. Pearson's correlation coefficient (r) was not used because it determines whether data have a linear trend, assumes a bivariate normal distribution, and is more susceptible to outliers. The fraction of valid data in each data period was used to weight ρ_w so that the relative effect of periods with less data was diminished and the effect of periods with more data was enhanced. Removing the estimated values for wind speed and barometric pressure from the analysis did not significantly alter the results.

Results

Correlation coefficients for mid-depth and near-bottom SSC and the quantities given in the methods section of this paper are given in Table 2. Plots of SSC versus dredging volume and quantities significantly correlated with SSC are given in Fig. 3.

Dredging Operations and SSC

Dredging volume and SSC at Point San Pablo were not significantly correlated at either mid-depth or near-bottom (Fig. 3 and Table 2). SSC at mid-depth was greatest in May 1997 when dredging operations were occurring, but water-surface elevation was small, erodible sediment supply was large, and tidal energy was large during this time and were much better correlated with SSC. While dredging operations may affect SSC at the dredging site and at the disposal site, there is no identifiable effect at Point San Pablo.

Processes that Affect SSC

Processes other than dredging operations were significantly correlated with SSC. Some variables that were significantly correlated with SSC co-varied with one another. Mid-depth SSC was correlated with median water-surface elevation ($\tau = -0.606$ p = 0.007, $\rho = -0.797$ p = 0.004, and $\rho_w = -0.706$ p = 0.014), so that the greater the water-surface elevation the less the SSC. Mid-depth SSC is correlated best with median water-surface elevation, which varied by 0.2 m. There are several possible explanations for this correlation. Greater water-surface elevation reduces the shear stress from wind waves on the Bay bottom, which in turn reduces resuspension and SSC. Wind speed is not correlated with SSC ($\tau = 0.000$ $p > 0.2$, $\rho = -0.035$ $p > 0.2$, and $\rho_w = -0.012$ $p > 0.2$), so for this analysis water-surface elevation seems to be the primary factor controlling wind-wave resuspension. Another possible physical explanation is that relatively greater water-surface elevation in San Pablo Bay could be caused by less turbid water from Central Bay moving into San Pablo Bay. Central Bay is less turbid because its greater depths limit wind-wave resuspension and it is closer to the Pacific Ocean. Cross correlation of water-surface elevation with the standard deviation of water-surface elevation (spring/neap cycle) and Julian day (erodible sediment supply) also are possible contributors to the correlation of water-surface elevation and SSC.

The correlation of mid-depth SSC with the standard deviation of water-surface elevation ($\tau = 0.470$ p = 0.039, $\rho = 0.578$ p = 0.051, and $\rho_w = -0.403$ p = 0.196) indicates the influence of the spring/neap tidal cycle with greater SSC on spring tides and less SSC on neap tides. Greater SSC during spring tides could be caused by either greater resuspension of bottom sediment by greater tidal currents or increased tidal excursion that is large enough to transport turbid water from the shallows of San Pablo Bay to Point San Pablo during ebb tides (Ruhl et al. 2001). The standard deviation of the water surface is correlated significantly with median water-surface elevation ($\tau = -0.500$, p = 0.028 and $\rho = -0.648$, p = 0.028), so the water-surface elevation is greater during neap tides than spring tides. The correlation between SSC and standard deviation of water-surface elevation could be a result of their correlation with median water-surface elevation.

Mid-depth SSC is also correlated with median Julian day ($\tau = -0.424$ p = 0.064, $\rho = -0.643$ p = 0.029, and $\rho_w = -0.526$ p = 0.082), so that SSC is greater in May than in August (Fig. 3). This seasonal variability probably is a result of the seasonal variability in the supply of erodible sediment discussed previously. Median water-surface elevation is somewhat correlated with the Julian day ($\tau = 0.455$ p = 0.047, $\rho = 0.559$ p = 0.062, and $\rho_w = 0.468$ p = 0.129). The SSC and Julian day correlation could be a result of their correlation with water-surface elevation.

Near-bottom SSC was correlated with median Julian day ($\tau = -0.545$ p = 0.016, $\rho = -0.734$ p = 0.009, and $\rho_w = -0.742$ p = 0.009), as a result of the seasonal variability in the supply of erodible sediment. Mid-depth SSC is correlated best with median water-surface elevation. Near-bottom SSC was also correlated with median water-surface elevation ($\tau = -0.409$ p = 0.074, $\rho = -0.613$ p = 0.039, and $\rho_w = -0.581$ p = 0.050). Decreased wind-wave resuspension or an influx of less turbid Central Bay water may cause this correlation. Median water-surface elevation usually is greater in August than in May (Fig. 3) and is correlated significantly with Julian day ($\tau = 0.530$ p = 0.019, $\rho = 0.673$ p = 0.020, and $\rho_w = 0.587$ p = 0.048). SSC is greater in May than in August. The SSC and median water-surface elevation correlation may be a result of their correlation with Julian day and reflects seasonal variability. Salinity stratification is also correlated with near-bottom SSC ($\tau = 0.424$ p = 0.064, $\rho = 0.538$ p = 0.075, and $\rho_w = 0.599$ p = 0.044) because stratification reduces vertical mixing. Resuspended sediment is more likely to remain near the bottom when salinity stratification is greater, increasing near-bottom SSC. If salinity stratification were great enough to reduce bottom shear stress and resuspension, then SSC would decrease. Salinity stratification tends to be greater in May than August (Fig. 3) so the SSC and stratification correlation may be a result of their correlation with Julian day.

Median barometric pressure ($\tau = 0.379$ p = 0.099, $\rho = 0.592$ p = 0.046, and $\rho_w = 0.649$ p = 0.027) is also correlated with near-bottom SSC. Julian day is correlated significantly with SSC and barometric pressure ($\tau = -0.652$ p = 0.004, $\rho = -0.820$ $p < 0.002$, and $\rho_w = -0.805$ p = 0.003), so the correlation of SSC and barometric pressure most likely is a result of their correlation to Julian day.

Discussion

Relative Importance of Anthropogenic Perturbations and Natural Processes

Resuspension of bottom sediment is commonly the most important source of suspended sediment in an estuary. Over a period of time that includes many resuspension events, the time-averaged resuspension rate R (mass per unit time) can be expressed as the product

$$R = EAfT \quad (1)$$

in which E is the resuspension (or erosion) rate during an event (mass per unit area per unit time), A is the area of the sediment bed being resuspended, f is the frequency of the resuspension event, and T is the duration of the resuspension event. In this simplified model, resuspension rate, areal extent of resuspension, frequency, and duration control the relative effect of a perturbation or process on resuspension and SSC. These controlling factors are relevant to San Pablo Bay, other estuaries, and the continental shelf.

Relative magnitudes of resuspension rate help determine the relative effect of a perturbation or process on SSC in an estuary. Tidal currents and wind waves resuspend bottom sediment on the tidal time scale in San Pablo Bay and mask turbid plumes created by dredging operations. In the less energetic Hillsborough Bay, Florida, natural processes cause little resuspension on the tidal time scale. Trawlers, on the other hand, can generate plumes of resuspended sediment several times that of the ambient SSC. A plume of resuspended sediment created by a trawler persisted for at least 8 h as tidal currents transported the plume in Hillsborough Bay (Schoellhamer 1996a). Sediment resuspension by trawling can be a primary source of suspended sediment over the outer shelf of the Middle Atlantic Bight where storm-related bottom stresses generally are weak (Churchill 1989).

The relative importance of a perturbation or process on SSC will increase with the areal extent of sediment resuspension. Dredging operations have only two potential point sources for suspended sediment: the dredge and the disposal site. Natural resuspension typically covers the entire basin because the bed is an omnipresent potential source of suspended sediment. On a basin scale in a dynamic estuary, natural resuspension processes will tend to be more important than dredging operations, as is the case in San Pablo Bay. When an anthropogenic perturbation resuspends bottom sediment in most of a basin then the anthropogenic perturbation is more likely to be important at the scale of the basin. Examples include vessel-generated long waves that propagate over much of Hillsborough Bay (Schoellhamer 1996a), clam dredging in Chesapeake Bay (Ruffin 1998), and trawling in the Gulf of Maine (Pilskaln et al. 1998).

The product of frequency and duration determine the fraction of time a process will affect SSC. As the frequency of dredging operations or other anthropogenic perturbations increases relative to the frequency of natural processes, the importance of the anthropogenic perturbations will increase. When dredging operations are taking place in San Pablo Bay, the frequencies of dredging plumes, spring tidal currents, and wind-wave resuspension are similar. In estuaries that have less frequent natural resuspension, however, dredging operations and other anthropogenic perturbations may be more important than natural processes acting on the entire basin. In Hillsborough Bay, the primary natural resuspension process is wind waves generated by winter and tropical storms that occur only a few times a year. The frequency of resuspension by vessel-generated long waves is 0.7–1.0 d^{-1}. Because of this greater frequency, the annual mass of sediment resuspended by vessel-generated long waves is about one order of magnitude greater than the annual mass of sediment resuspended by wind waves generated by storms (Schoellhamer 1996a). Churchill et al. (1994) found that resuspension by trawling occurred more frequently than storm-generated resuspension on the continental shelf of the Atlantic Ocean east of the Delmarva Peninsula. Pilskaln et al. (1998) found that sediment and benthic worms in sediment traps in the Gulf of Maine increased as the frequency of bottom trawling increased.

The duration of a resuspension event can vary from seconds to days and can determine the relative importance of the process or perturbation. Spring or neap tides in San Pablo Bay are several days in duration and affect SSC for several days. About one-half of the variance of SSC in South San Francisco Bay is associated with the spring/neap tidal cycle (Schoellhamer 1996b). Some anthropogenic perturbations that place sediment in suspension, such as dumping of dredged material at a disposal site, vessel-generated long waves, or resuspension under a moving vessel, often last only seconds or minutes. Even though perturbations may suspend a large quantity of sediment, the generated turbulence lasts only seconds or minutes, and deposition occurs after the turbulence has dissipated (Schoellhamer 1993, 1996a; Ruffin 1998).

Resuspension rate, areal extent, frequency, and duration determine the relative basin-scale effect of anthropogenic perturbations and natural processes on SSC. Natural physical processes in San Pablo Bay are more areally extensive, of equal or longer duration, as frequent as dredging operations (when occurring), and affect SSC at the tidal time scale. Therefore, natural processes control SSC at Point San Pablo, even during dredging operations.

Erodibility of Bottom Sediment

At a dredged material disposal site in Chesapeake Bay, erodibility of bottom sediment and the time since the last disposal had an inverse relation (Sanford 1994). Dredge material disposal may increase the erodibility of bottom sediment at the San Pablo Bay disposal site but no basin-scale increase in erodibility was observed in San Pablo Bay. Erodibility of bottom sediment in San Pablo Bay varies seasonally with runoff and wind-wave resuspension. Trawling and vessel-generated long waves can disturb bottom sediment and increase basin-scale erodibility (Churchill et al. 1994; Schoellhamer 1996a).

Conclusions

Natural physical processes, not maintenance dredging of the Pinole Shoal Ship Channel and disposal in San Pablo Bay, account for the variability of SSC at Point San Pablo. Wind-wave resuspension had the greatest effect on SSC. Median water-surface elevation is the primary factor affecting mid-depth SSC. Greater depths inhibit wind-wave resuspension of bottom sediment and indicate greater influence of less turbid water from down estuary. Seasonal variability in the supply of erodible sediment is the primary factor affecting near-bottom SSC. These factors were determined with 3-wk to 5-wk periods of data, which eliminates the significance of semidiurnal tides and reduces the significance of the fortnightly spring/neap cycle. Natural physical processes in San Pablo Bay are more areally extensive, of equal or longer duration, as frequent as dredging operations (when occurring), and affect SSC at the tidal time scale. Therefore, natural processes control SSC at Point San Pablo, even during dredging operations.

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