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Suspended sediment and sediment-associated contaminants in San Francisco Bay

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Abstract

Water-quality managers desire information on the temporal and spatial variability of contaminant concentrations and the magnitudes of watershed and bed-sediment loads in San Francisco Bay. To help provide this information, the Regional Monitoring Program for Trace Substances in the San Francisco Estuary (RMP) takes advantage of the association of many contaminants with sediment particles by continuously measuring suspended-sediment concentration (SSC), which is an accurate, less costly, and more easily measured surrogate for several trace metals and organic contaminants. Continuous time series of SSC are collected at several sites in the Bay. Although semidiurnal and diurnal tidal fluctuations are present, most of the variability of SSC occurs at fortnightly, monthly, and semiannual tidal time scales. A seasonal cycle of sediment inflow, wind-wave resuspension, and winnowing of fine sediment also is observed. SSC and, thus, sediment-associated contaminants tend to be greater in shallower water, at the landward ends of the Bay, and in several localized estuarine turbidity maxima. Although understanding of sediment transport has improved in the first 10 years of the RMP, determining a simple mass budget of sediment or associated contaminants is confounded by uncertainties regarding sediment flux at boundaries, change in bed-sediment storage, and appropriate modeling techniques. Nevertheless, management of sediment-associated contaminants has improved greatly. Better understanding of sediment and sediment-associated contaminants in the Bay is of great interest to evaluate the value of control actions taken and the need for additional controls.

Keywords: Sediment; Suspended sediment; Contaminants; San Francisco Bay; Estuaries

1. Introduction

Water-quality managers of San Francisco Bay are confronted by many fundamental questions that are being addressed by the Regional Monitoring Program for Trace Substances (RMP). These questions include:

- *Are water-quality objectives being attained*? Water-quality objectives are maximum desirable levels of contaminants in fish, sediment, and water. Contaminants in water and sediment enter the food web at lower trophic levels and propagate to higher trophic levels, such as fish (Stewart et al., 2004). Tides cause water in the Bay to oscillate between the Pacific Ocean and landward boundaries of the Bay. Contaminant concentration at any point in the Bay is expected to vary in time (temporally) with the tides and other temporally varying forcing factors such as wind and freshwater runoff.
- *Why are some parts of the Bay more contaminated than others*? Contaminant concentrations in the Bay vary spatially due to proximity to sources and spatial variability in the physical processes that suspend or remove contaminants from the water column (Brown et al., 2003; Linville et al., 2002; Squire et al., 2002).
- *What is the contaminant load from the watershed*? Magnitude of contaminant load and control of watershed

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sources vary by type and location (Bergamaschi et al., 2001; Davis et al., 2000; Leatherbarrow et al., 2005; McKee et al., 2004). The potential to control sources and the resulting load reduction benefit also vary by contaminant type and source location. The costs to implement controls obviously are of concern, and managers seek assurances that control actions will be effective in reducing Bay contaminant concentrations.

- *What is the contaminant load from Bay sediments*? There is a large reservoir of contaminants in Bay sediments associated with historical discharges from the watershed (Hornberger et al., 1999; Venkatesan et al., 1999). In some areas, contaminated bed sediments are being buried by cleaner sediments; in other areas, contaminated sediments or clean sediments overlying contaminated sediments are eroding. Loading from eroding contaminated sediments may out-weigh or mask loading from watershed sources (Conaway et al., 2003).
- *What is the capacity of the Bay to assimilate watershed and in-Bay sources of contaminants and attain water-quality objectives*? Section 303(d) of the Federal Clean Water Act requires States to establish a total maximum daily load (TMDL) of a contaminant that is allowed to be discharged to a water body when a contaminant water-quality objective is not met. Development of a TMDL requires quantitative knowledge of the mass budget of a contaminant, its sources and sinks, and the resulting levels in fish, sediment, and water. Allocation and implementation of the TMDL requires understanding of the relative importance and controllability of sources and the ability to evaluate the effect of management actions and controls on contaminant levels in the Bay.

Some contaminants associate with sediment and, thus, their fate in the environment is determined by the fate of sediment. Several trace metals and hydrophobic organic chemicals of environmental concern primarily are associated with particulate organic matter and sediments in aquatic systems largely due to processes of adsorption onto mineral surfaces, absorption into organic matter, ion-exchange, and salting-out effects in estuarine environments (Turner and Millward, 2002). Accordingly, suspended sediment moving into, within, and out of estuaries, provides a pathway for the transport of sediment-associated contaminants (Bergamaschi et al., 2001; Le Roux et al., 2001; Turner et al., 1999; Turner and Millward, 2000). Over time, deposition of contaminated suspended sediment on the bottom creates reservoirs of contaminants in many estuaries (Ridgeway and Shimmield, 2002; Taylor et al., 2004), including San Francisco Bay (Hornberger et al., 1999; Venkatesan et al., 1999). Subsequent erosion of bottom sediment can remobilize previously buried contaminants (Arzayus et al., 2002; Hornberger et al., 1999; Lee and Cundy, 2001), which potentially contributes to contamination of the overlying water column (Turner and Millward, 2002; Conaway et al., 2003). This is of particular concern for many legacy contaminants (e.g., the pesticide, DDT) that no longer are supplied to an estuary in large quantities, compared to historic inputs, but continue to persist because the bottom sediment acts as a source, as in the case of San Francisco Bay (this issue).

Sediment dynamics in San Francisco Bay are important in determining the transport and fate of hydrophobic organic contaminants (Bergamaschi et al., 2001; Venkatesan et al., 1999; Ross and Oros, 2004; Oros et al., 2005), mercury (Conaway et al., 2003; Choe et al., 2003), and other trace metals (Sanudo-Wilhelmy et al., 1996; Schoellhamer 1997; Hornberger et al., 1999). For sediment-associated contaminants, the contaminant mass budget and contaminant transport and fate are strongly linked to the Bay sediment budget. Monitoring and modeling of sediment transport in the system are critical for TMDL development and implementation.

Because of the close linkage between sediment and contaminant transport, the RMP includes a sediment transport component. Measuring contaminant concentrations at sufficient resolution to define temporal and spatial variability in an estuary, to estimate loads, and to develop contaminant mass budgets is costly and difficult. The RMP uses suspended-sediment concentration (SSC) as a less costly and more easily measured surrogate for sediment-associated contaminants. The objective of this paper is to summarize findings on the temporal and spatial variability of SSC and sediment-associated contaminants and to discuss management of sediment-associated contaminants in San Francisco Bay.

2. SSC as a surrogate for contaminant concentration

From 1993 to 2001, the RMP collected seasonal surface water samples from 26 stations to characterize spatial and temporal distributions of contaminants in the Bay. Sediment-associated contaminants monitored by the RMP include trace metals and various types of organic chemicals: polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and pesticides. Additional measures of water quality included conventional parameters, such as total suspended solids (TSS) and dissolved organic carbon (DOC), which influence transport patterns of associated contaminants in particulate and dissolved forms, respectively (Conaway et al., 2003; Kuwabara et al., 1989). Suspended sediment in San Francisco Bay primarily is fine sediment less than 63 μm in diameter, therefore, TSS and SSC virtually are the same (Gray et al., 2000) and this paper refers to TSS as SSC. SSC includes organic and inorganic matter.

RMP water samples were collected for analyses of unfiltered and filtered trace metals and water-quality parameters (e.g., SSC) using a peristaltic pumping system and trace-metal clean techniques, according to procedures described in Flegal et al. (1991). Filtered water samples were passed through polypropylene 0.45-μm nominal pore size filter cartridges. Water samples also were collected for analyses of particulate and dissolved concentrations of organic contaminants in a manner similar to that for trace metals, only using a polyurethane foam plug sampler from 1993 to 1996, as described in Jarman et al. (1997), and an Axys Infiltrex sampler[1] (Axys Environmental Systems, Ltd., Sidney, B.C.) from 1997 to 2001 (SFEI, 2003). Water pumped through both samplers was passed through a glass fiber filter with 1.0-μm nominal pore size to obtain the particulate fraction and then through either polyurethane foam plugs mounted in series in the foam plug sampler (Jarman et al., 1997) or two parallel Teflon® columns filled with XAD-2 resin in the Axys Infiltrex sampler to obtain the dissolved fraction (SFEI, 2003).

Analytical methods are described in previous RMP-related studies of mercury (Conaway et al., 2003), trace metals (e.g., Squire et al., 2002), and organic contaminants (e.g., Ross and Oros, 2004). Mercury samples were analyzed using cold vapor atomic fluorescence by University of Maryland, Chesapeake Biological Laboratory following methods of Gill and Fitzgerald (1985) and Bloom and Fitzgerald (1988), as described in Conaway et al. (2003). Other trace metals and SSC were analyzed by University of California, Santa Cruz, WIGS Laboratory. Trace metal samples were prepared according to methods in Bruland et al. (1985) and analyzed using graphite furnace atomic spectroscopy or inductively coupled plasma mass spectrometry over the course of RMP monitoring (Squire et al., 2002). SSC (or TSS) was measured using Standard Method 2540-D in APHA et al. (1992). Organic contaminant analyses were performed by University of Utah, Energy and Geosciences Institute (SFEI, 2003). Extracts of particulate and dissolved fractions were separated using Florisil® columns to isolate fractions containing PCBs and organochlorine pesticides that were then analyzed on a gas chromatograph with electron-capture detectors (Jarman et al., 1997).

In this study, simple linear regression was used to evaluate the influence of SSC on concentrations of monitored contaminants in Lower South San Francisco Bay (Lower South Bay). Lower South Bay, defined as the region south of the Dumbarton Bridge, was selected for regression analyses due to high levels of contamination, relative to other Bay regions (Ross and Oros, 2004) and the fact that USGS has collected a suitable continuous record of SSC for the duration of RMP monitoring. RMP stations designated as Lower South Bay include Coyote Creek (BA10) and South Bay (BA20) (Fig. 1). Samples were collected for trace metal analyses from both stations, while samples for organic contaminant analyses were collected only from BA10.

RMP contaminant data evaluated in this study include total and particulate concentrations of trace metals and organic contaminants. Particulate concentrations of trace metals were calculated by subtracting dissolved concentrations, operationally defined as the sample fraction filtered through a 0.45-μm filter, from concentrations in unfiltered samples (total). It is important to note that an equal-size filter is used to obtain SSC measurements. Total concentrations of organic contaminants were derived by summing concentrations measured in the particulate and dissolved fractions.

Analysis of RMP data indicates that SSC has a significant influence on total and particulate concentrations of several trace metals, individual PCB compounds, and the DDT metabolite, *p,p′*-DDE (Table 1). Based on coefficients of determination (R^2) from linear regression, SSC explained approximately 54–79% of the variance in trace metal concentrations ($p<0.0001$) and 44–52% of the variance in organic contaminant concentrations ($p \leqslant 0.004$). Values of R^2 are slightly greater for particulate contaminant concentrations than for total contaminant concentration, which includes dissolved concentration. A specific example is shown in Fig. 2 for SSC and total mercury concentration. Overall, the results indicate that SSC is an appropriate surrogate for concentrations of sediment-associated contaminants in this region of the Bay.

3. Temporal variability

3.1. Continuous SSC time series

In order to address water-quality management questions, the SSC monitoring network was designed to capture the spatial and temporal variability of SSC. During the early and mid-1990s, stations were established in the deep (about 7–15 m) channels of each major subembayment of San Francisco Bay, often at salinity monitoring stations (Mallard Island, Benicia, Point San Pablo, Golden Gate Bridge, Pier 24, San Mateo Bridge, Dumbarton Bridge, and Channel Marker 17; Fig. 1). Other stations subsequently were added to improve spatial coverage, and some stations were discontinued if they became too difficult to service or if the data they provided no longer were determined to be useful (Buchanan and Ganju, 2005).

Optical sensors (manufactured by BTG, Downing and Associates, Hydrolab, and YSI) are used to measure SSC (Buchanan and Ganju, 2005). The sensors emit a pulse of light that scatters off of suspended particles. A receiver either 90° or 180° from the transmitter, depending on sensor design, converts the scattered light to an output signal. Near-bottom and mid-depth optical sensors are used to measure SSC at the deep channel stations. An electronic data logger (Campbell Scientific) controls data acquisition. A measurement averaged over 1 min is recorded every 15 min to resolve temporal variability caused by the semidiurnal (twice daily) tides.

Calibration is needed to determine the relation between sensor output and SSC. This relation varies according to the size and optical properties of the suspended sediment; therefore, the sensors must be calibrated for each site using

[1]Any use of trade, product, or firm names in this article is for descriptive purposes only and does not imply endorsement by the US Government.

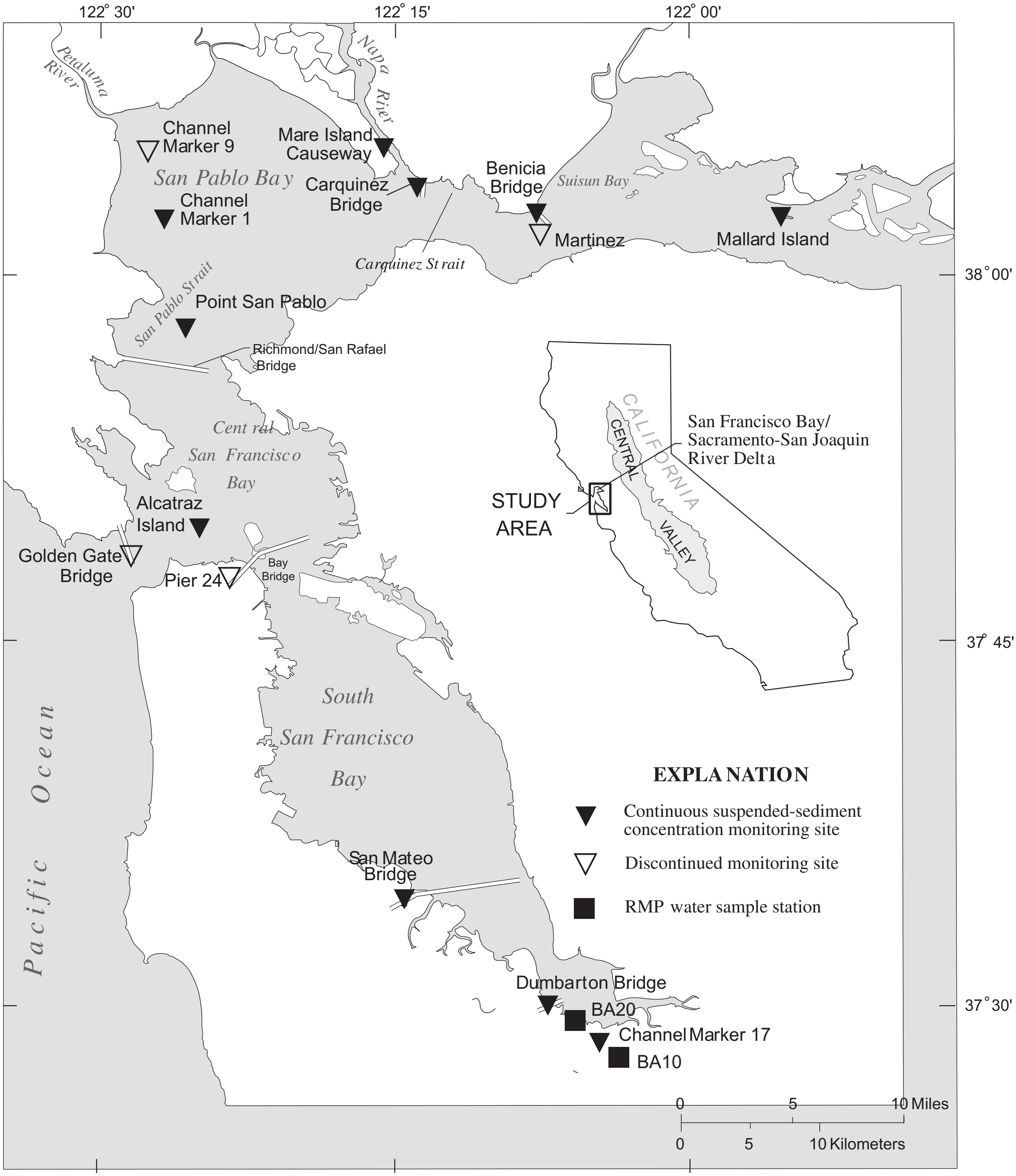

Fig. 1. RMP water sampling stations in Lower South San Francisco Bay and continuous suspended-sediment concentration monitoring sites in San Francisco Bay.

suspended material from the field (Levesque and Schoellhamer, 1995). Water samples are collected before and after sensor cleaning during site visits every 1–5 weeks (usually 3 weeks) (Buchanan and Ganju, 2005). The water samples are analyzed to determine SSC, which ranges from nearly zero to more than 1000 mg/L. Suspended particles

Table 1
Linear regression of SSC and contaminants (total and particulate) in Lower South Bay

	Total				Particulate			
	Slope	Intercept	R^2	p	Slope	Intercept	R^2	p
Trace metals								
Mercury	0.00035	0.0045	0.61	<0.0001	0.00036	0.0017	0.64	<0.0001
Copper	0.0361	3.60	0.54	<0.0001	0.0347	0.74	0.61	<0.0001
Nickel	0.0876	4.49	0.66	<0.0001	0.0853	1.34	0.69	<0.0001
Lead	0.0287	0.315	0.77	<0.0001	0.0275	0.279	0.79	<0.0001
Zinc	0.136	3.99	0.67	<0.0001	0.123	2.25	0.71	<0.0001
PCBs								
PCB 118	1.91	37.1	0.51	0.001	1.92	25.2	0.52	0.001
PCB 153	3.93	39.9	0.46	0.003	3.87	25.6	0.46	0.003
Pesticides								
p,p′-DDE	7.58	174	0.45	0.004	7.18	140	0.44	0.004

RMP data were collected from 1993 to 2001 in Lower South Bay stations, Coyote Creek (BA10) and South Bay (BA20). Particulate trace metal concentrations represent the difference between unfiltered (total) and filtered (dissolved) concentrations. Units of slope are µg/mg for trace metals and pg/mg for PCBs and pesticides. Units of intercept are µg/L for trace metals and pg/L for PCBs and pesticides.

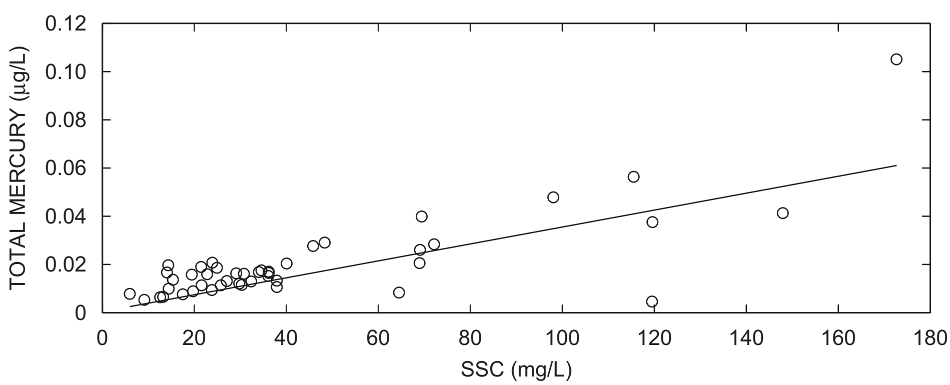

Fig. 2. Relation between total mercury concentration and suspended-sediment concentration, Lower South San Francisco Bay, 1993–2001. Statistics for the linear regression line shown are given in Table 1.

primarily are fine sediments (Krank and Milligan, 1992; Ganju et al., 2007), therefore, particle size variability and flocculation does not affect calibration of the sensors and sensor output is proportional to SSC (Buchanan and Ganju, 2005). The output from the optical sensors is converted to SSC using the robust, nonparametric, repeated median method (Siegel, 1982; Buchanan and Ganju, 2005).

The greatest problem in using optical sensors in San Francisco Bay is biofouling that invalidates about one-half of the data (Buchanan and Ganju, 2005). Biofouling begins to affect sensor output from a couple days to several weeks after cleaning, depending on the level of biological activity in the Bay. Generally, biofouling is greatest during spring and summer and at stations in saltier water. Frequent cleaning is required to prevent biofouling from invalidating optical sensor data but, due to the difficulty in servicing some of the monitoring stations, they are cleaned every 1–5 weeks (usually 3 weeks). Self-cleaning sensors have proven to reduce data loss in relatively freshwater and only recently (2003) has their design improved to be effective in saltwater.

Continuous SSC data collected at mid-depth at Channel Marker 17 in Lower South Bay during 1993–2001 is shown in Fig. 3. We present this time series because RMP data show that Lower South Bay has higher concentrations of sediment-associated contaminants compared to other subembayments (e.g., Ross and Oros, 2004) and other time series have long (months) data gaps when instruments could not be deployed due to site construction. Of the data that could have been collected every 15 min, 58% were useable. Statistical properties of these data are shown in Fig. 4. The linear relation given in Table 1 and shown in Fig. 2 is used to convert the time series of SSC to a time series of total mercury concentration, presented as a secondary vertical axis on Fig. 3.

3.2. Factors affecting SSC

In San Francisco Bay, an annual cycle of deposition and resuspension begins with a large influx of sediment during

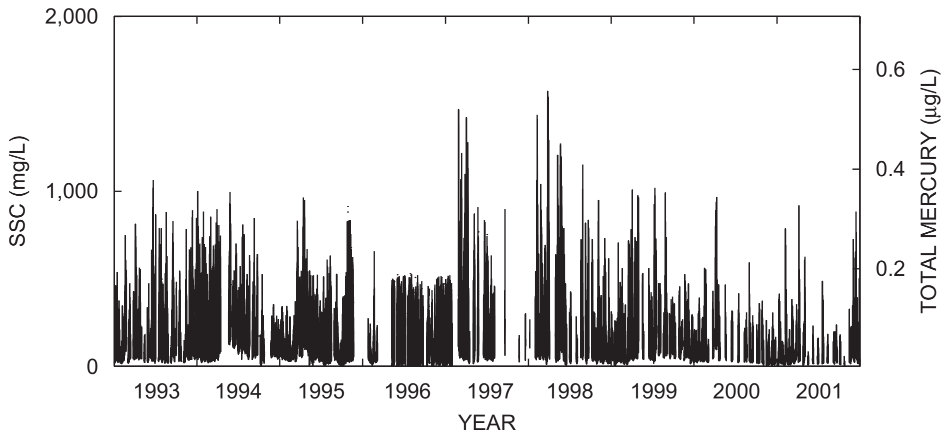

Fig. 3. Time series of suspended-sediment concentration and total mercury, channel marker 17, Lower South San Francisco Bay, 1993–2001.

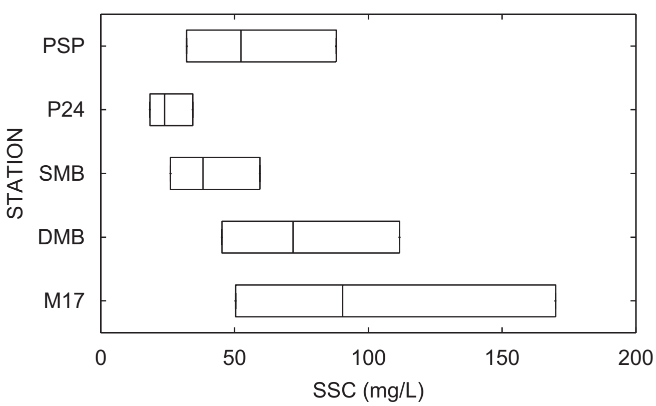

Fig. 4. Box plots of mid-depth suspended-sediment concentration data, San Francisco Bay, 1993–2001. The left edge of each box indicates the lower quartile, the middle line indicates the median, and the right edge indicates the upper quartile. Stations on the vertical axis are arranged from north to south (Fig. 1). Point San Pablo (PSP) is at the boundary between Central and San Pablo Bays, San Francisco Pier 24 (P24) is in Central Bay and is closest to the Pacific Ocean, San Mateo Bridge (SMB), Dumbarton Bridge (DMB), and Channel Marker 17 (M17) are in South Bay.

large freshwater flows in winter (Conomos and Peterson, 1977; Goodwin and Denton, 1991; McKee et al., 2006). The first freshwater pulse in winter delivers a relatively large amount of sediment compared to subsequent pulses (Goodwin and Denton, 1991). For example, data from Ruhl and Schoellhamer (2004) show that the first pulse in winter 1997 was about a factor of four greater than the second pulse. Typically, discharge from the Delta contains over 60% of the fluvial sediments that enter the Bay (McKee et al., 2006), though this percentage varies from year to year. Much of this new sediment deposits in shallow water subembayments, especially in north San Francisco Bay seaward from the Delta (Krone, 1979; Ruhl and Schoellhamer, 2004). A stronger seabreeze during spring and summer causes wind-wave resuspension of bottom sediment in these shallow waters and increases SSC (Ruhl et al., 2001; Ruhl and Schoellhamer, 2004; Schoellhamer, 1996, 2002; Warner et al., 2004). The ability of wind to increase SSC is greatest early in the spring, when unconsolidated fine sediments can be resuspended easily. As the fine sediments are winnowed from the bed, however, the remaining sediments progressively become less erodible (Krone, 1979; Nichols and Thompson, 1985). The result is that tidally averaged SSC is greatest in spring and least in fall (Schoellhamer, 1996, 2002; Ruhl and Schoellhamer, 2004).

SSC variability and suspended-sediment transport in South San Francisco Bay (Fig. 3) are caused by a combination of tidal advection (transport of sediment by tides), seasonal winds, tidal energy associated with the spring–neap tidal cycle, and phytoplankton blooms. Ruhl et al. (2001) observed a filament of turbid water in the South Bay channel emanating from shallow water during ebb tide. Tidal advection is greatest during spring tides when the tidal excursion (distance a parcel of water moves during a tide) is sufficiently large to transport high SSC water to the main channel from shallow water (less than about 2 m deep at mean lower low water) (Schoellhamer, 1996). During neap tides, advection is smaller, and the tidal excursion is not large enough to transport high SSC water to the main channel from shallow water. SSC in the channel is well correlated with the seasonal variation in wind-shear stress due to advective transport of sediment resuspended by wind waves in shallow water. Advective transport has a greater influence on SSC than does local resuspension in the channel.

In addition to seasonally varying SSC, seasonal variations of wind shear in South Bay vary the spatial pattern of tidally averaged transport of suspended sediment (Schoellhamer, 1996). During the spring and summer, an afternoon northwesterly seabreeze blows from the Golden Gate towards Lower South Bay. This seabreeze generates waves that increase SSC and establish a landward tidally averaged flux of suspended sediment in shallow water and a seaward flux of suspended sediment in the main channel (Lacy et al., 1996; Walters et al., 1985). With the seabreeze, tidally averaged sediment flux at a shallow water site (Fig. 1) was landward (southeasterly) in March 1994 while without the seabreeze sediment flux was one-quarter the magnitude and directed toward the shoreline (northeasterly) in December 1993 (Lacy et al., 1996). Suspended sediment in shallow water is transported to the main channel, primarily during spring tides when tidal excursions are greatest (Schoellhamer, 1996). Settling traps some suspended sediment in the main channel; therefore, there is a net export of sediment from South Bay during the summer. During winter, winds and SSC are smaller, and the wind-driven and baroclinic circulation are variable, so there is no clear pattern of tidally averaged transport of suspended sediment.

The fortnightly spring–neap cycle accounts for one-half of the variance of SSC in South Bay (Schoellhamer, 1996). Tidal currents during spring tides are stronger than those during neap tides. The relatively short duration of slack water limits the duration of deposition of suspended sediment and consolidation of newly deposited bed sediment during the tidal cycle. During spring tide and the approach to spring tide, suspended sediment accumulates in the water column and during neap tide and the approach to neap tide, suspended sediment deposits on the bed. SSC lags the spring–neap cycle by about 2 days. Perturbations in SSC caused by wind and local runoff from winter storms usually are negligible, compared to SSC variations caused by the spring–neap cycle (Schoellhamer, 1996 Figs. 4 and 5). SSC in San Pablo Bay is similarly dependent on the spring–neap cycle and monthly and semiannual tidal cycles (Schoellhamer, 2002).

In addition to physical processes, an annual phytoplankton bloom affects SSC in South San Francisco Bay. A predictable spring phytoplankton bloom occurs following periods of strong vertical salinity stratification in the water column (Cloern, 1996). The annual maximum of SSC typically is during the spring tide following the end of the spring phytoplankton bloom (Ruhl and Schoellhamer, 2001). One possible explanation of the SSC maxima is that the bloom biomass scavenges suspended-sediment particles. The biomass and scavenged particles deposit on the bed during a neap tide and are resuspended during the subsequent spring tide, greatly increasing SSC. Another possible explanation is that the phytoplankton bloom and die-off increase the abundance of macrobenthic species that destabilize the bed, making the bed more erodible and increasing SSC (de Deckere et al., 2000).

3.3. Water-quality objective attainment

Continuous SSC data help evaluate the attainment of water-quality objectives. For example, the San Francisco Bay Regional Water Quality Control Board (1986) has set a threshold water-quality objective for total mercury concentration of 25 ng/L averaged over any 4-day period. A time series of the estimated mercury concentration can be used to evaluate how often that objective was met between 1993 and 2001. Fig. 5 shows the 4-day-averaged suspended sediment and estimated total mercury concentrations at channel marker 17 during 1993–2001. A centered mean was calculated if at least one-half of the data during the 4-day window were valid. The 4-day averaging window removes the influence of diurnal and semidiurnal tides, primarily leaving a seasonal wind signal, fortnightly spring–neap tidal signal, lunar monthly tidal signal, and a solstice/equinox semiannual tidal signal. The horizontal line on Fig. 5 represents the 25 ng/L threshold concentration—any data above the line exceeded the water-quality objective. The objective was exceeded about 84.5% of the time. Neap tides typically are the only time when the objective was met at channel marker 17. An 84.5% exceedance rate is a relatively large value for San Francisco Bay because SSC is relatively large at channel marker 17 (Fig. 4). A similar analysis at Point San Pablo during 1993–2000 found that the total mercury water-quality objective was exceeded about 25% of the time (Schoellhamer et al., 2003). Note that, because SSC increases with water depth, satisfaction of the water-quality objective is dependent on position in the water

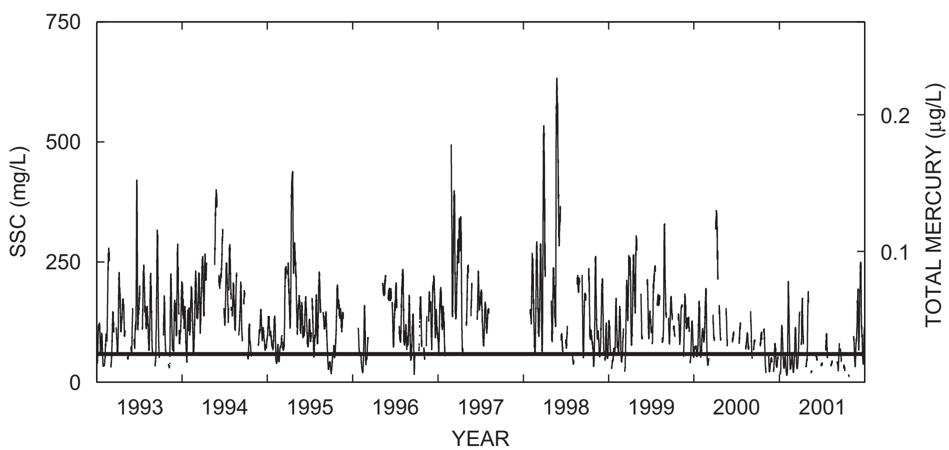

Fig. 5. Four-day averaged suspended sediment and estimated total mercury concentrations at mid-depth at channel marker 17, Lower South San Francisco Bay. The horizontal line is the threshold water-quality objective for total mercury concentration of 25 ng/L averaged over any 4-day period.

column. In addition, revision of this objective is being considered.

4. Spatial patterns and variability

Continuous time-series data at a point provide detailed temporal, but not spatial, resolution. In this section, data and analysis from monitoring stations besides Channel Marker 17, temporary instrument deployments, remote sensing, and synoptic surveys will be presented to describe spatial patterns and variability of SSC and sediment-associated contaminants.

SSC generally increases as water depth decreases. Shallower waters tend to have smaller tidal currents (Walters et al., 1985) but the orbital motion of surface wind waves reaches the bed, increasing shear stress on the bed and sediment resuspension. SSC is greater in shallow water and subembayments than in adjacent deeper channels in South Bay (Lacy et al., 1996; Powell et al., 1989; Schoellhamer, 1996), San Pablo Bay (Ruhl et al., 2001), Grizzly Bay (Warner et al., 2004), and Honker Bay (Ruhl and Schoellhamer, 2004).

Another axis of variation is from the relatively clear Pacific Ocean to the turbid heads of the estuary in South and Suisun Bays. SSC is smallest in Central Bay adjacent to the Pacific Ocean and greatest in South and Suisun Bays furthest from the Ocean (Fig. 4). During large inflows from the Delta, turbid waters can extend from Suisun Bay into northern South Bay (Carlson and McCulloch, 1974) and into the Pacific Ocean (Ruhl et al., 2001). During low inflow, three factors contribute to a seaward gradient of decreasing SSC. First, the Pacific Ocean is an effective sink for suspended sediment. Second, Central Bay has the smallest fraction of shallow water (32% shallower than 5 m, USGS, 2005) of any subembayment, which makes wind-wave resuspension relatively less important than tidal resuspension. Finally, the Pacific Ocean supplies sand to the bottom of Central Bay (Rubin and McCulloch, 1979), which is less erodible than the fine sediments deposited in shallow water at the heads of the Bay (Conomos and Peterson, 1977).

The spatial distribution of SSC includes localized maxima of SSC, called estuarine turbidity maxima (ETM). Three ETM are caused by gravitational circulation. An ETM in the low salinity zone where gravitational circulation terminates is sometimes found during low freshwater inflows in the southern deep channel of Suisun Bay (Schoellhamer, 2001). An ETM is at Benicia where a sill (moving landward, a sudden decrease in water depth, or "step up") limits gravitational circulation, accumulating suspended sediment, especially during spring (Jay and Musiak 1994; Schoellhamer, 2001). Another sill at the mouth of Grizzly Bay creates an ETM in the Reserve Fleet Channel in northern Suisun Bay (Schoellhamer, 2001). Two ETM are caused by tidal trapping of sediment. In northern San Pablo Bay, the Petaluma River and Sonoma Creek each contain a mass of sediment that tidally oscillates between the tidal river channels and northern San Pablo Bay (Ganju et al., 2004). When the sediment mass is suspended, SSC is commonly 1000–2000 mg/L, the greatest regularly measured SSC in San Francisco Bay (Buchanan and Ganju, 2005; Ganju et al., 2004). The RMP Petaluma River site has anomalously high values of sediment-associated contaminants because of the relatively large SSC (Schoellhamer et al., 2003).

In addition to spatial variability of SSC, rates of net deposition or erosion of bottom sediment vary by subembayment. During the second half of the 20th century, net erosion occurred in Suisun Bay (1.2 cm/year, Cappiella et al., 1999), San Pablo Bay (0.09 cm/year, Jaffe et al., 1998) and South Bay north of Dumbarton Bridge (0.5 cm/year, Foxgrover et al., 2004). Lower South Bay was depositional (1.3 cm/year, Foxgrover et al., 2004). These values are for the entire subembayment—each of these subembayments contained smaller areas of net erosion and net deposition.

Applying a finer spatial resolution, physical processes cause exceptionally large deposition at specific locations. For example, an attempt to cut an 11-m-deep approach basin for a wharf at Benicia resulted in the formation of a 5-m-deep deposit in 3 months (Krone, 1979), probably because of sediment accumulation in the Benicia ETM. In Mare Island Strait, the phasing of the currents with Carquinez Strait creates a tidally averaged salinity minimum in Mare Island Strait and baroclinic convergence of sediment in this salinity minimum, resulting in relatively large sediment deposition rates (Warner et al., 2002).

Contamination in benthic communities can reflect patterns of convergent transport, sediment accumulation, and sediment deposition. For example, in October 1995, selenium bioaccumulation in clams in Mare Island Strait was greatest at the tidally averaged salinity minimum and smaller landward and seaward (Linville et al., 2002). The source of selenium primarily was refineries located in Carquinez Strait and Suisun Bay, so convergent transport, rather than a local source, must have been responsible for the clam selenium maximum in Mare Island Strait.

5. Advances in understanding during the past 10 years and critical uncertainties remaining

In this section, we briefly review the past 10 years during which the RMP has quantified the relation between suspended sediment and contaminants associated with suspended sediment and determined how suspended sediment, and thus associated contaminants, vary temporally and spatially (e.g., Schoellhamer, 1997). Based on this association between contaminants and suspended sediment, SSC has proven to be an accurate surrogate for many contaminants of concern in San Francisco Bay (Table 1). Accordingly, physical processes that determine SSC also largely determine concentrations of associated contaminants (Schoellhamer et al., 2003; Leatherbarrow et al., 2005). The RMP also has estimated the primary watershed sediment load to the Bay and developed sediment budgets and a simple numerical model to help determine TMDL allocations.

SSC and sediment-associated contaminants vary at several different time scales. Alternating tidal currents alter SSC by resuspending, advecting, and depositing sediment. In addition to these semidiurnal and diurnal cycles, tidal currents and SSC vary with fortnightly, monthly, and semiannual cycles. The majority of the variation of SSC and, therefore, sediment-associated contaminants, is at time scales longer than the semidiurnal and diurnal tides. An annual cycle of sediment supply from runoff, wind-wave resuspension, and winnowing of fines from bottom sediment also affects SSC. Several years of continuous SSC time series were needed to quantify variability from tidal to annual time scales (Schoellhamer, 1996, 2002).

Spatial variability of SSC directly affects spatial variability of sediment-associated contaminants. Natural physical processes, such as tides, wind waves, ETM, and mixing with clear ocean water explain some of the spatial variability of SSC and associated contaminant concentrations. For example, Lower South Bay and the Petaluma River have relatively large SSC and, therefore, relatively large concentrations of sediment-associated contaminants, while Central Bay has relatively small SSC and small concentrations of sediment-associated contaminants (Schoellhamer et al., 2003).

Continuous SSC monitoring data collected at landward boundaries of the Bay have been used to help estimate sediment and contaminant loads from the watershed. McKee et al. (2006) used continuous SSC data and a freshwater flow estimate to estimate sediment flux at Mallard Island where waters from the Sacramento River and Central Valley flow into the Bay. Based on methodology described in McKee et al. (2006), Leatherbarrow et al. (2005) were able to use linear relationships between SSC and contaminants collected at Mallard Island and the continuous SSC record as a surrogate for estimating annual loads of mercury and organic contaminants to the Bay during 1995–2003.

Our improved understanding of sediment transport allowed us to develop a simple numerical model that contains the most important physical processes and can simulate sedimentation over decades (Lionberger et al., 2006). The model is tidally averaged for simplicity and efficiency. Mixing with clear ocean water, inflow of fluvial sediment, wind-wave resuspension, and fortnightly, monthly, and semiannual tidal cycles of deposition and resuspension are simulated. The model is calibrated to measured bathymetric changes and has been used to help develop sediment budgets (Schoellhamer et al., 2005). Efforts are under way to use the model to simulate PCBs and other sediment-associated contaminants and to help develop TMDLs for the estuary. Preliminary results indicate key uncertainties that need to be addressed to improve model accuracy and reliability.

5.1. Remaining uncertainties

Management efforts aimed at improving water quality and reducing long-term adverse impacts of contamination in the Bay contend with considerable uncertainties in understanding the transport and fate of sediment and associated contaminants. Recently, mass budget models for sediment and contaminants in the estuary have been developed to answer management questions about loads, sources, and sinks and to assist in the development of TMDLs (Lionberger et al., 2006; Davis, 2004). In this section, we will consider the uncertainties encountered in developing a mass budget for sediment. These uncertainties would be a subset of the uncertainties encountered for developing a budget for sediment-associated contaminants. Reducing these uncertainties would improve the accuracy and robustness of TMDLs.

The simplest sediment or associated contaminant budget that conserves mass that can be developed for an estuary is *inflow-outflow = change in storage.* In order to develop this simple budget, watershed inflow, bed-sediment dynamics, and boundary fluxes must be known. The complexities of sediment and contaminant dynamics in the Bay, however, make it difficult to accurately estimate parameters that describe these processes.

Uncertainties in our knowledge of contemporary sediment yields to the Bay are reflected in the fact that the last comprehensive study of sediment supply from the local Bay tributaries used data from the late 1950s (Porterfield, 1980). The local tributary gages used for that study had all been discontinued by 1973 and some began to be resumed in 2000. During the 30–40-year hiatus, the local Bay watersheds became much more urbanized, so the historical records may not reflect present conditions. For example, for a given water discharge, sediment load in the Guadalupe River decreased by a factor of 4–8 from 1958–1962 to 2003–2005 (Schoellhamer et al., 2006). In addition, measurements generally are taken just above the extent of the tides so the tidal portion of tributaries is ungaged.

The lack of data on sediment loads leads to uncertainties in our ability to estimate contaminant loads from the local Bay tributaries. Thus, current estimates of contaminant loads to the Bay are based on the use of a simple model (rational method) (Davis et al., 2000; Kinnetic Laboratories and EOA Inc., 2002) and monitoring studies of contaminant loads entering the Bay from the Sacramento–San Joaquin River Delta (Leatherbarrow et al., 2005) and the Guadalupe River (McKee et al., 2004). These studies note key uncertainties and limitations that prevent accurate extrapolation of existing data to quantify the total contaminant loads entering the Bay from the surrounding watersheds.

Within the Bay, bed sediments act as a reservoir of sediment and associated contaminants so uncertainties regarding the dynamics of bottom sediments, including vertical mixing, consolidation, erosion, and burial, apply to the long-term fate of sediment-associated contaminants. As noted by Davis (2004), the greatest uncertainty in predicting the long-term fate of persistent contaminants in the Bay is the extent to which bottom sediment actively mixes and interacts with the overlying water column. Bottom sediment dynamics vary seasonally and appear to be affected by biota that confound this challenge. A sediment coring study has been planned to better understand bed-sediment dynamics and contaminant loads.

In order to develop mass budget models for the entire Bay or a subembayment, the quantity of sediment passing through cross sections of the estuary is needed, especially at the estuarine boundaries. McKee et al. (2006) estimate sediment flux at Mallard Island, the landward boundary of the estuary that has the largest sediment input. Within the estuary, Ganju and Schoellhamer (2006) estimate sediment flux at Benicia. Suisun Bay lies between Mallard Island and Benicia and Ganju and Schoellhamer (2006) used both sediment flux estimates to develop sediment budgets for Suisun Bay. Comparable measurements at the Golden Gate Pacific Ocean boundary have not been collected due to difficulties caused by the wide and deep cross section, currents in excess of 2 m/s, complex flow patterns, large waves, vessel traffic, and fog.

Several problems confound application of numerical models to help develop mass budgets, develop TMDLs, and predict removal rates and residence times of legacy contaminants. Desirable model characteristics of accurately representing physical processes, detailed spatial and temporal resolution, spatial domain of an entire estuary, simulation duration of years or decades, and model efficiency are in conflict. Thus, a model must compromise some of these desirable characteristics but the costs and benefits are unknown. Calibration and validation data that increase confidence in relevant model results such as change in bed-sediment storage or sediment outflow to the Pacific Ocean are needed. Simulation techniques are needed for periods with little or no boundary condition data, such as a hindcast that begins before introduction of a contaminant to the environment or a forecast of legacy contaminant removal.

6. Management: then (1993) and now (2006)

The complexity of management questions posed to the RMP has increased and sediment has remained a key issue for managing the water quality of the Bay. At the onset of the RMP in 1993, the primary regulatory concern was attainment of water-quality objectives for metals in the Bay (arsenic, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, and zinc) (San Francisco Estuary Project, 1993). Applicable water-quality objectives were expressed as the 4-day average concentration of the total (particle bound and dissolved) metal (San Francisco Bay Regional Water Quality Control Board, 1986). Sources of interest included municipal and industrial wastewater, urban runoff, and influx from the Delta. Municipal and industrial wastewater discharges had realized large reductions of pollutant loadings through source control and treatment. Metals in these discharges primarily were in dissolved form due to effective solids removal of treatment processes. On the other hand, loadings from urban runoff were a growing concern, and metals in urban runoff primarily were particle bound. It also was assumed that there was a large reservoir of pollutants in Bay sediments, but the role of resuspension of sediments and sediment transport to and throughout the Bay was poorly understood (San Francisco Estuary Project, 1991).

Several regulatory and management actions occurred during the subsequent years. In 1998, the State of California (State) reviewed and updated the list of impaired waters required by the federal Clean Water Act §303(d) (State Water Resource Control Board, 1999). Relying primarily on RMP data, previous listings of Bay segments as impaired by metals were revised to specify copper, mercury, nickel, and selenium. In addition, as part of the 1998 §303(d) list update, the State listed all segments of the Bay as impaired by PCBs due to threats to human and wildlife consumers of Bay fish with elevated levels of PCBs.

In 2002, the State established a site-specific water-quality objective for copper applicable to Lower South San Francisco Bay (San Francisco Bay Regional Water Quality Control Board, 2002). Of particular relevance is that the objective was established for the dissolved form of copper rather than for the total amount of copper in Bay waters. A similar effort applicable to the rest of the Bay is underway. However, even though this regulatory action recognizes the dissolved fraction of the metal as the toxic, bioavailable form, the relevance of the reservoir of copper in Bay sediments and sediment transport remains a concern.

In the late 1990s, Clean Water Act §303(d) requirements to establish TMDLs for pollutants causing impairment of waters emerged as a primary regulatory driving force for action. The aforementioned effort to establish site-specific water-quality objectives for copper began as a TMDL project. Other TMDL projects by the State include mercury and PCBs with the goal of reducing levels of these pollutants in fish such that they do not harm human or wildlife consumers (San Francisco Bay Regional Water Quality Control Board, 2005). Both of these projects are being constructed on recognition that these pollutants are associated strongly with particles, that there is a large legacy reservoir of them in sediments in the Bay, and that elevated levels in fish are due to the benthos food web of the Bay (Davis et al., 2006; Tetra Tech Inc., 2006). A complication with the projects is the presence of highly elevated levels of these pollutants in sediments in localized areas of the Bay. The role of these sediment hot spots as a source of pollutants to organisms in the Bay and the transport of sediment and pollutant bound sediment to and from these areas is not well understood. These issues underscore the importance of improved understanding of sediment-bound pollutant fate and transport.

One of the more noteworthy areas of management actions concerns the evolving progress on controlling pollutants in urban runoff discharges to the Bay. Urban runoff is considered a large source of several pollutants of concern in the Bay—most notably copper, mercury, PCBs, and polycyclic aromatic hydrocarbons. All of these pollutants strongly are associated with suspended sediment in urban runoff (Davis et al., 2001). Efforts to establish TMDLs for mercury and PCBs have been based on current understanding of sediment and sediment-bound pollutants in the Bay, and proposed TMDLs call for considerable reductions in urban runoff loads (San Francisco Bay Regional Water Quality Control Board, 2004a, b). Consequently, improved understanding of sediment-bound pollutant fate and transport is of great interest in demonstrating the value of control actions taken and the need for additional controls.

7. Summary

The RMP uses SSC as a less costly and more easily measured surrogate for sediment-associated contaminants in San Francisco Bay. Continuous measurements of SSC help answer some of the fundamental questions confronting water-quality managers:

- *Are water-quality objectives being attained*? Time series of SSC can be converted to time series of sediment-associated contaminants to measure temporal variability of contaminants and objective compliance at tidal to annual time scales.
- *Why are some parts of the Bay more contaminated than others*? Physical processes vary within the Bay and cause spatial variability of SSC and sediment-associated contaminants. The network of continuous SSC monitoring stations helps identify these processes.
- *What is the contaminant load from the watershed*? Continuous measurements of SSC can be combined with estimates or measurements of freshwater flow to estimate the load of sediment and sediment-associated contaminants to the Bay from its watersheds.
- *What is the contaminant load from Bay sediments*? Analysis of continuous time series of SSC indicate the physical processes that control deposition and erosion in the Bay.
- *What is the capacity of the Bay to assimilate watershed and in-Bay sources of contaminants and attain water-quality objectives*? Understanding temporal variability, spatial variability, and sediment loads to the Bay allow development of sediment budgets, sediment-associated contaminant budgets, and simple numerical models that quantify sources and sinks. These tools aid development of a TMDL allocation for a sediment-associated contaminant and allow estimation of the time required for the Bay to attain a water-quality objective for a given watershed-load reduction.

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