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Time Series Of Suspended-Solids Concentration, Salinity, Temperature, and Total.Mercury Concentration in San Francisco Bay During Water Year 1996

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Many physical processes affect how constituents within San Francisco Bay vary. Processes and their associated time scales include turbulence (seconds), semidiurnal and diurnal tides (hours), the spring-neap tidal cycle (days), freshwater flow (weeks), seasonal winds (months), ecological and climatic changes (years), and geologic changes (thousands of years). The effect and relative importance of physical processes on the Bay can be determined from continuous time series of suspended-solids concentration (SSC), salinity, and water temperature. SSC time series and Regional Monitoring Program (RMP) water-quality data can be used to calculate time series of some trace-element concentrations (Schoellhamer, 1997). The purpose of this chapter is to qualitatively describe time series of SSC, salinity, water temperature, and mercury during water year 1996 (October 1995 through September 1996). In addition, a calculated time series of mercury will be used to evaluate the accuracy of using instantaneous water samples to evaluate a 4-day average water-quality objective.

Salinity, temperature, and sediment are important components of the San Francisco Bay estuarine system. Salinity and temperature affect the hydrodynamics (Monismith *et al.*, 1996), geochemistry (Kuwabara *et al.*, 1989), and ecology (Cloern, 1984; Nichols *et al.*, 1986; Jassby *et al.*, 1995) of the Bay. Suspended sediments limit light availability in the Bay, which, in turn, limits primary production (Cloern, 1987; Cole and Cloern, 1987), and thus food for higher trophic levels. Sediments deposit in ports and shipping channels, which must be dredged to maintain navigation (U.S. Environmental Protection Agency, 1992). Potentially toxic substances, such as metals and pesticides, adsorb to sediment particles (Kuwabara *et al.*, 1989; Domagalski and Kuivila, 1993; Schoellhamer, 1997).

The transport and fate of suspended sediments are important factors in determining the transport and fate of constituents adsorbed on the sediments. For example, the concentration of suspended particulate chromium in the Bay appears to be controlled primarily by sediment resuspension (Abu-Saba and Flegal, 1995). Concentrations of dissolved trace elements are greater in South Bay than elsewhere in San Francisco Bay, and bottom sediments are believed to be a significant source (Flegal *et al.*, 1991). The sediments-on the Bay bottom provide the habitat for benthic communities that can ingest these substances and introduce them into the food web (Luoma *et al.*, 1985; Brown and Luoma, 1995). Bottom sediments also are a reservoir of nutrients that contribute to the maintenance of estuarine productivity (Hammond *et al.*, 1985).

Time Series Data

The US Geological Survey (USGS) operates several continuous salinity, temperature, and SSC monitoring sites in San Francisco Bay (Figure 45; Buchanan and Schoellhamer, 1996; Freeman *et al.*, 1997). At most sites, electrical conductance, temperature, and/or optical backscatterance (OBS) sensors are positioned at mid-depth and near the bottom. A measurement is taken every 15 minutes by a data recorder by averaging the output of each sensor for 1 minute. Electrical conductance and temperature are converted to salinity using the methods of Miller *et al.* (1988). The OBS sensors optically measure the amount of sus-

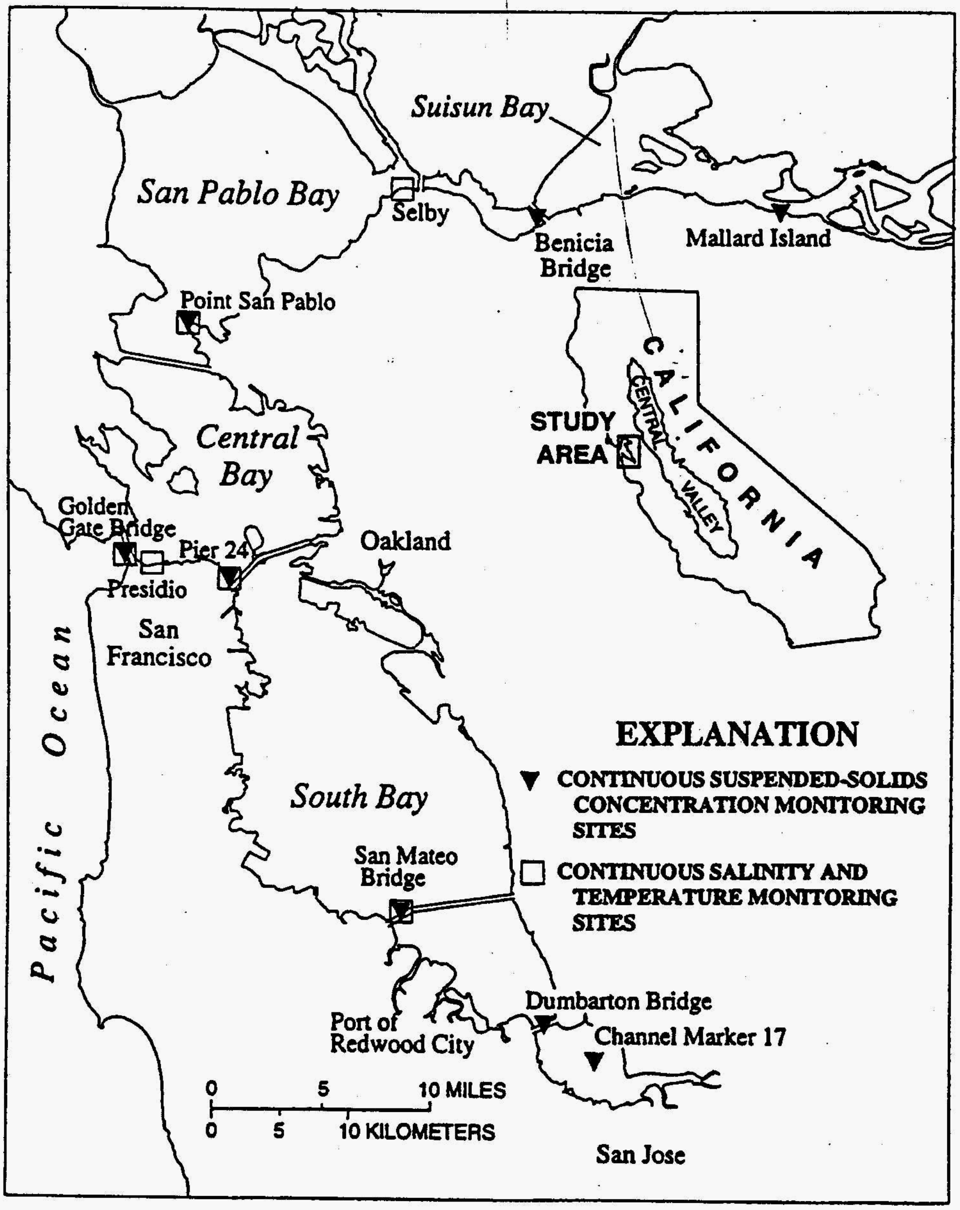

Figure 45. San Francisco Bay study area and USGS continuous monitoring sites.

pended material in the water, and the output of the sensors is converted to SSC with calibration curves developed from analysis of water samples. The sites are serviced every one to five weeks to clean the sensors, which are susceptible to biological fouling, and to collect water samples for sensor calibration. Biological growth fouls the sensors and invalidates sensor output. Equipment malfunctions also were responsible for some lost data.

This summary includes time series data on some processes that affect salinity and SSC. Estimates of discharge from the Sacramento-San Joaquin River Delta were obtained from the California Department of Water Resources (1986). Tidal currents are strongest during full and new moons, called spring tides, and weakest during half moons, called neap tides. The strength of the spring-neap cycle was quantified by calculating the low-pass root-mean-squared (RMS) water level by squaring water level measured at Point San Pablo, low-pass filtering, and taking the square root (Schoellhamer, 1996). Meteorological data, including insolation (solar energy) and wind speed and direction, were measured at the Port of Redwood City by Schemel (1995). Wind data were used to estimate the daily mean shear stress (force per unit area) on the water surface along the axis of South Bay from San Francisco toward San Jose (Pond and Pickard, 1983).

Salinity

Salinity decreased throughout the Bay during the winter wet season in 1996. The largest freshwater discharges from the Central Valley into San Francisco Bay for the water year occurred during the winter, and the lowest

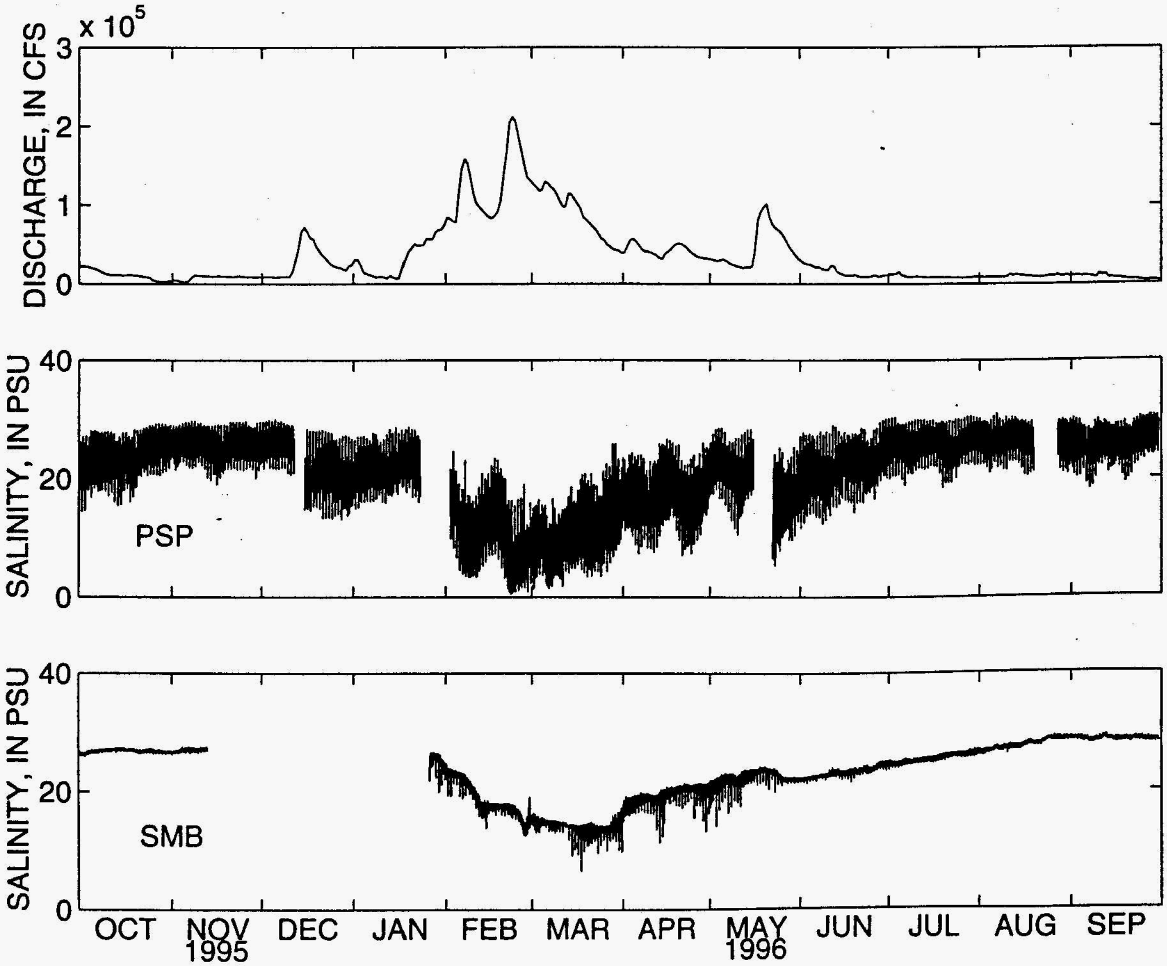

Figure 46. Time series of Delta discharge (California Department of Water Resources, 1986) and salinity at Point San Pablo (PSP) and the San Mateo Bridge (SMB), water year 1996.

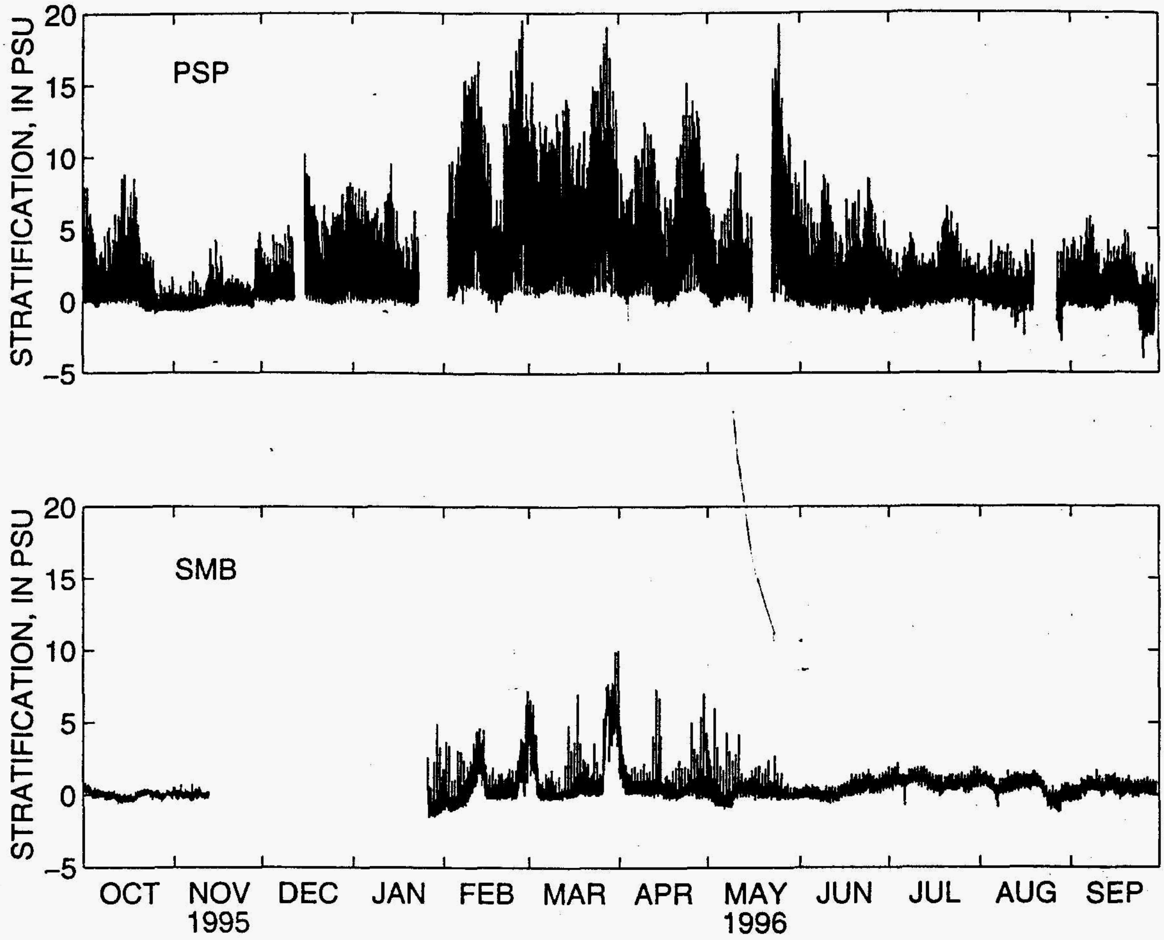

Figure 47. Time series of salinity stratification (bottom salinity minus mid-depth salinity) at Point San Pablo (PSP) and San Mateo Bridge (SMB), water year 1996.

salinity at mid-depth at Point San Pablo occurred at the end of February (Figure 46). In South Bay at the San Mateo Bridge, minimum salinities occurred during March. This delay in response in South Bay was because of the longer time required for mixing of oceanic water and freshwater in South Bay than in Central Bay. During summer and autumn, salinity was relatively high and gradually increased at both sites because freshwater discharge was relatively low.

Tidal variations of salinity, as indicated by the range of salinity on a given day, were much greater at Point San Pablo than at the San Mateo Bridge (Figure 46). Point San Pablo is closer to the Sacramento River, the primary source of freshwater to the Bay, and to the Pacific Ocean, the source of saltwater. Tidal currents also are greater at Point San Pablo than at the San Mateo Bridge. Thus, the change in salinity over a tidal cycle at Point San Pablo is greater than at the San Mateo Bridge.

The spring-neap cycle had a small, but noticeable, effect on salinity at Point San Pablo during the winter and spring. After the first discharge peak in mid-December, the envelope of tidal cycle salinity variations, which appears as a thick black band on Figure 46, oscillated with a 14-day period. Peaks in the envelope in late December, early January, and mid-January occurred during spring tides. Valleys in the envelope occurred during neap tides. Energetic spring tides pushed high salinity water farther up into the Estuary, and weak neap tides allowed low salinity water to move down into the Estuary. During late March, April, and early May, the salinity envelope increased and oscillated slightly with a period of 14 to 28 days that was similarly correlated with the spring-neap cycle.

Vertical salinity differences that stratify the water column result when denser, more saline water lies below lighter, fresher water. Stratification at Point San Pablo was greatest during the wet season when delta discharge was large (Figure 47). Throughout the water year, the greatest stratification occurred during neap tides, which were too weak to vertically mix the water column. Stratification was much smaller during spring tides, which vertically mixed the water column. Because South Bay had less freshwater inflow, there was less stratification than in other parts of San Francisco Bay. Stratification was observed at the San Mateo Bridge only during the neap tides of February, March, and April (Figure 47). The annual phytoplankton bloom in South Bay occurs during periods of salinity stratification (Cloern, 1984). In 1996, the phytoplankton bloom peaked during late March and early April after a period of significant stratification (B.E. Cole, U.S. Geological Survey, written commun., 1996).

Temperature

Time series of solar radiation (insolation) and water temperature had a strong seasonality. Maximum temperatures occurred during summer and minimum temperatures during winter at both Point San Pablo and the San Mateo Bridge (Figure 48). Because of the seasonal dependence of temperature on insola-

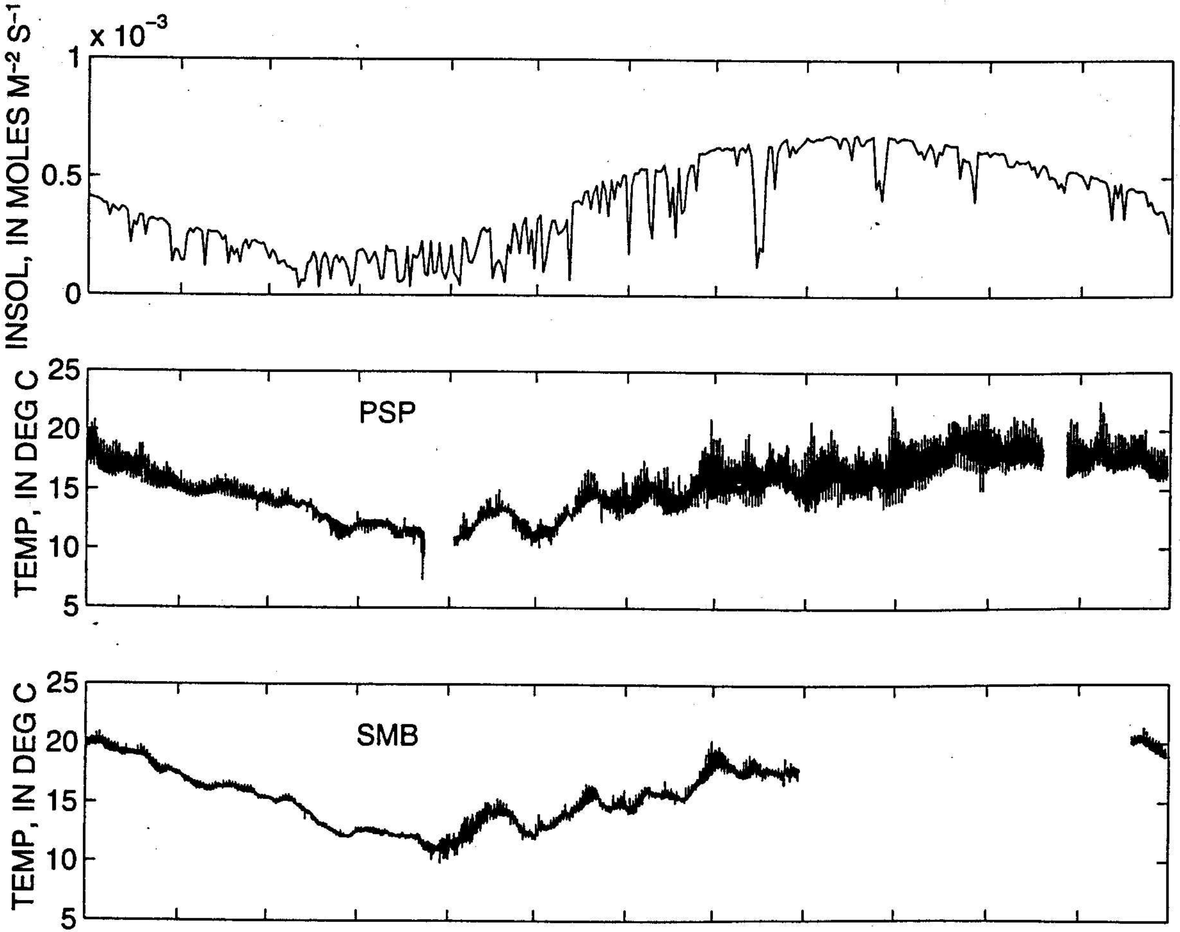

Figure 48. Time series of daily mean insolation at the Port of Redwood City (Schemel, 1995) and mid-depth water temperature at Point San Pablo (PSP) and the San Mateo Bridge (SMB), water year 1996.

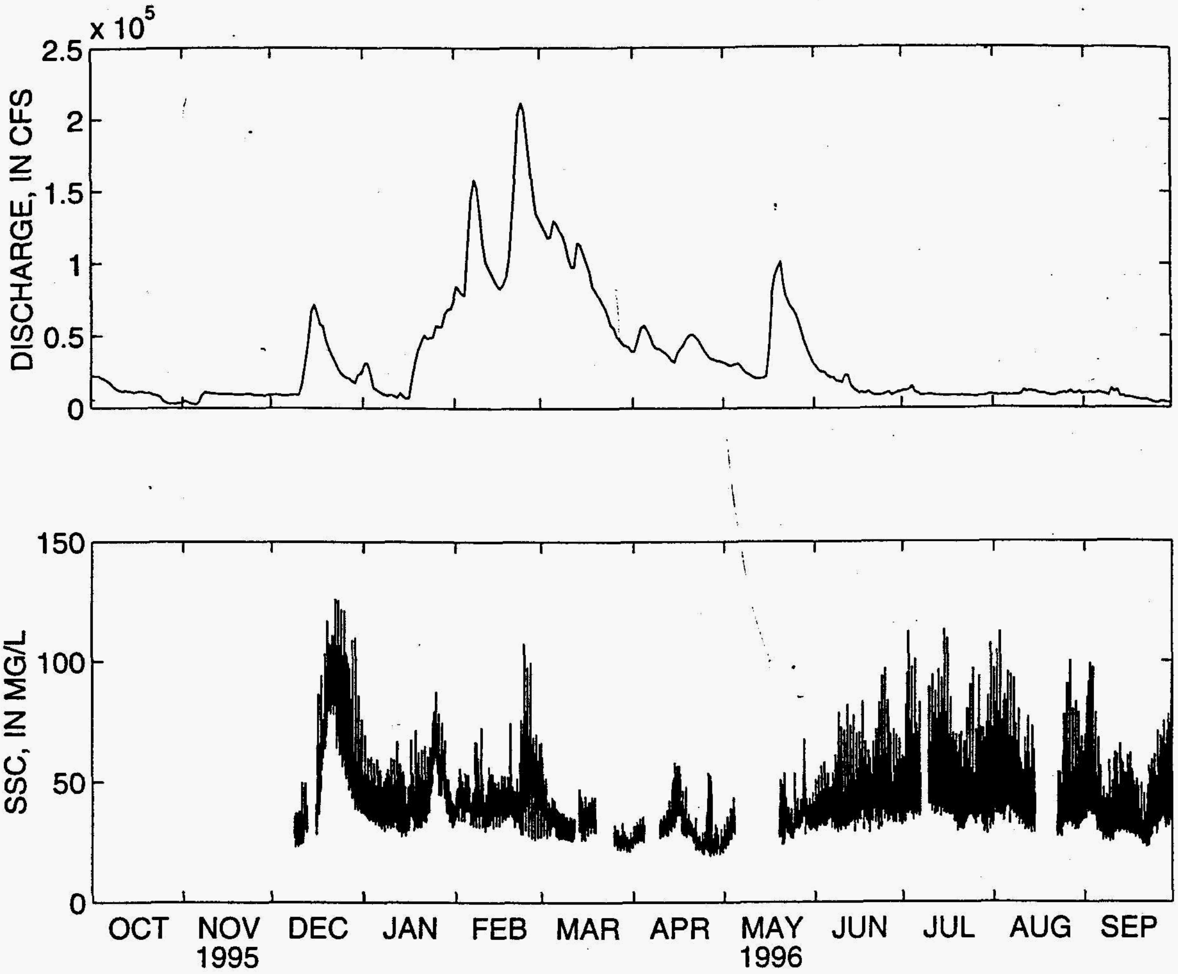

Figure 49. Time series of Delta discharge (California Department of Water Resources, 1986) and suspended-solids concentration (SSC) at Mallard Island, water year 1996.

tion, the general trend of water temperature at the two sites was very similar. The seasonal variation of water temperature lagged the seasonal variation of insolation by about 1 month. Tidal cycle variations in temperature were usually greatest at Point San Pablo because there is more exchange with the cooler Pacific Ocean. During winter, however, the differences in temperature over a tidal cycle at the two sites were small because water temperatures in the Bay and the ocean were more uniform. Instruments at both sites are located in deep channels adjacent to shallow waters, which are conducive to warming during the summer.

Suspended Solids Concentration

SSC in the northern part of San Francisco Bay varied in response to freshwater discharge from the Central Valley during water year 1996. In mid-December 1995, delta discharge peaked at 72,000 ft^3/s during the first large runoff event of the wet season (Figure 49). In response, SSC at Mallard Island, at the boundary between the Bay and the Delta, increased to more than 100 mg/L (Figure 49). This "first-flush" of the Central Valley watershed lasted about 2 weeks and produced the greatest SSC measured at Mallard Island during the water year. Larger peaks in Delta discharge that occurred after December produced smaller peaks in SSC, similar to the observations by Goodwin and Denton (1991). For example, the maximum daily mean discharge during the water year was 212,000 ft^3/s in late February, almost three times the December flow peak, but the response of SSC was much smaller.

During March and April 1996, discharge varied from 32,000 to 130,000 ft^3/s, and SSC at Mallard Island was relatively small. The variation in SSC as a result of tides also was small. SSC during late winter and early spring is often relatively small because of releases of reservoir water with low SSC and periods of relatively low wind (discussed later).

Delta discharge did not have as much effect on SSC farther seaward in the Bay, but the tidal variation of SSC, especially the spring-neap tidal cycle, was more important. Throughout the water year, SSC varied with the spring-neap cycle at Point San Pablo (Figure 50), with greater SSC during spring tides and smaller SSC during neap tides. Previous analyses indicate that about one-half the variance in SSC is caused by the spring-neap cycle and that SSC lags the spring-neap cycle by about 2 days (Schoellhamer, 1994; 1996). The first-flush in December and discharge peaks in February increased SSC at Point San Pablo, but this effect was less than that observed at Mallard Island.

Winds in the Bay Area are strongest during summer, and these winds generate waves on the Bay that resuspend bottom sediments in shallow water (Schoellhamer, 1996). Wind-wave resuspension in the shallow waters of Suisun Bay and subsequent transport increased SSC at Mallard Island during the summer (Figure 49). During water year 1996, the estimated daily mean wind shear along the axis of South Bay from San Francisco toward San Jose decreased from autumn to winter, was large during winter only during storms, increased during spring, and was sustained at a relatively large value through the summer (Figure 51). SSC at channel marker 17 in South Bay was relatively low during winter, increased during spring as the seabreeze increased, and diminished slowly

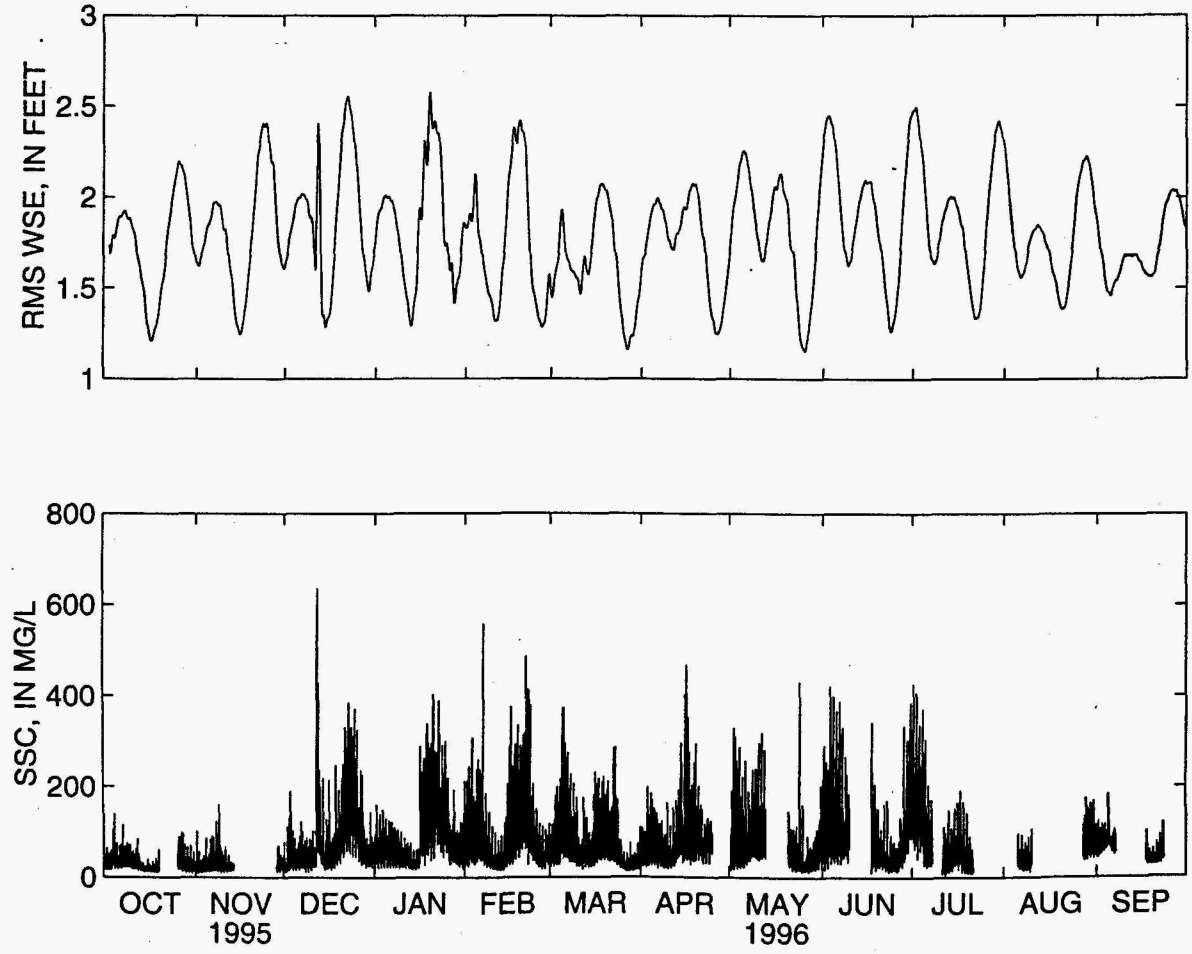

Figure 50. Root-mean-squared (RMS) water-surface elevation (WSE) and suspended-solids concentration (SSC) at Point San Pablo, water year 1996. Maxima in the RMS water-surface elevation indicate spring tides, and minima indicate weaker neap tides.

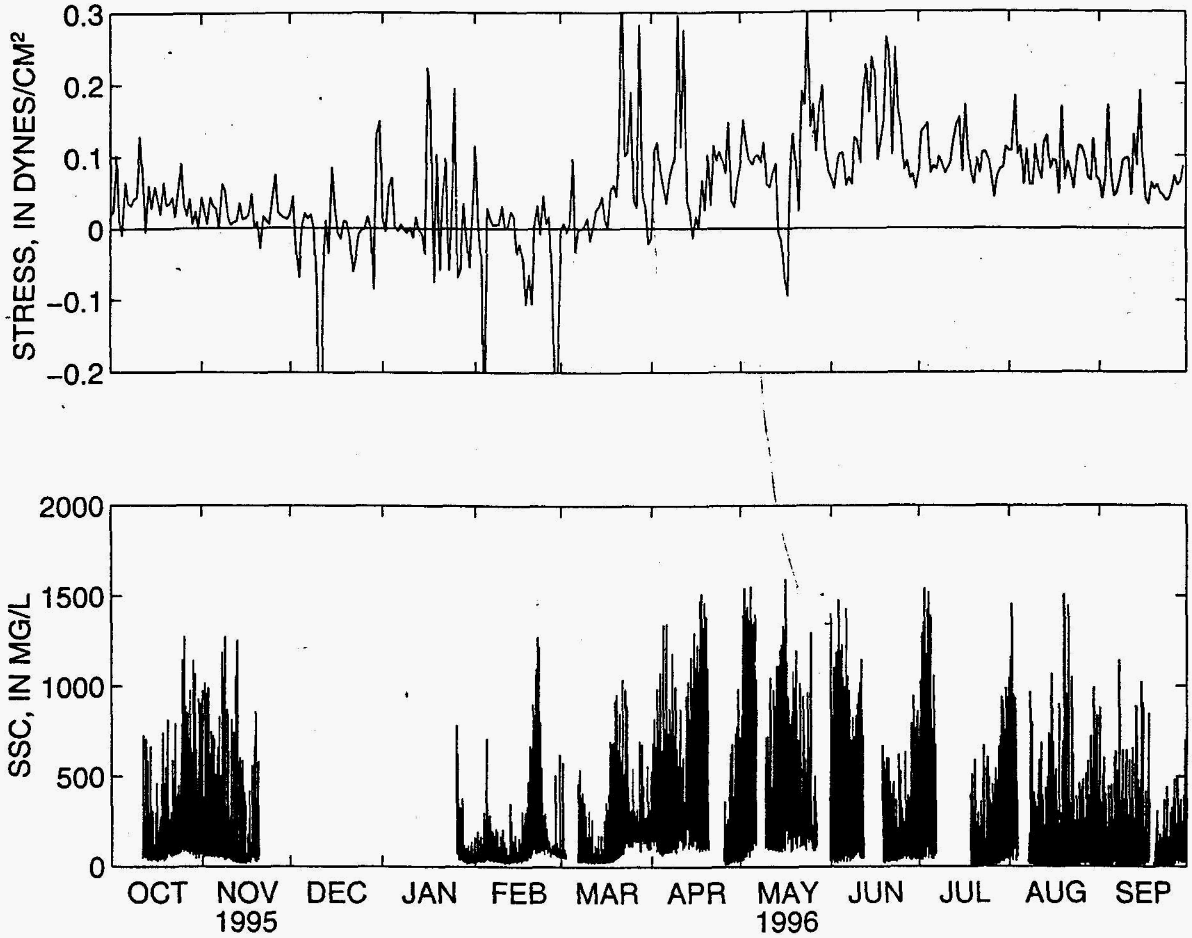

Figure 51. Estimated wind-shear stress along the landward axis of South Bay and suspended-solids concentration (SSC) at channel marker 17, water year 1996. Positive stress indicates wind blowing from San Francisco toward San Jose.

during the summer. The supply of finer, erodible sediment in shallow water is greatest during early spring and diminishes during the summer because wind-waves winnow fine sediment (Nichols and Thompson, 1985). Thus, SSC is greater in late spring and early summer compared to late summer, even though the wind-shear stress is about the same. The fortnightly spring-neap cycle also affects SSC at channel marker 17, with peaks in SSC corresponding to spring tides and valleys corresponding to neap tides. It is interesting to note that the variability in SSC at channel marker 17 is greater than at Point San Pablo (Figure 50) or at Mallard Island (Figure 49).

Strong southerly winds caused by winter storms increase SSC only for a length of time about equal to the duration of strong winds. On December 11 and 12, 1995, the strongest southerly winds of the water year blew in the Bay Area (Figure 51). The daily mean landward wind shear stress in South Bay was -0.54 dynes/cm^2 on December 11. Water levels measured at Point San Pablo were elevated 1 to 2 ft by the wind, which appears as a spike in the RMS water-surface elevation in Figure 50. SSC at Point San Pablo increased to over 600 mg/L early on December 12 and returned to prestorm levels of about 50 mg/L by mid-day on December 13 (Figure 50). Sediment resuspended by wind waves in San Pablo Bay and carried by tidal currents to Point San Pablo were the likely cause of the observed increase in SSC. Sediment resuspended by wind waves settled a few hours after the wind decreased. The fetch for southerly winds was smaller in Suisun Bay, and, therefore, SSC at Mallard Island increased only slightly to almost 50 mg/L (Figure 49).

Total Mercury Concentration

In the 1995 RMP annual report, RMP data from 1993 and 1994 were used to show that total concentrations of seven trace elements were well correlated with SSC (Schoellhamer, 1997). RMP mercury and SSC data from 1995 were added to the 1993 and 1994 data to update the relation between mercury and SSC shown in Figure 52. Some RMP sampling sites are located in tributary channels to the Bay. RMP data from tributaries sometimes had either low or high mercury compared to the predicted values based on SSC ('x' symbols in Figure 52). These data probably reflect the influent waters, not Bay waters and, therefore, were discarded (Schoellhamer, 1997). The slope is 0.32 ng/mg, the intercept is 2.8 ng/L, the squared correlation coefficient is 0.83, the significance level is less than 0.001, and the root-mean-squared error is 6.0 ng/L for 180 data points. These statistical properties are similar to those calculated using only the 1993 and 1994 data. These linear correlation results and SSC time series can be used to estimate time series of total mercury concentration. Example time series for SSC and mercury at mid-depth at Point San Pablo are shown in Figure 53.

The strong correlation between total mercury concentration and SSC indicates that the physical processes that affect SSC also affect total mercury concentration. These processes include semidiurnal and diurnal tides, the spring-neap tidal cycle, freshwater discharge, and seasonal winds. As with SSC, about one-half the variance of total mercury

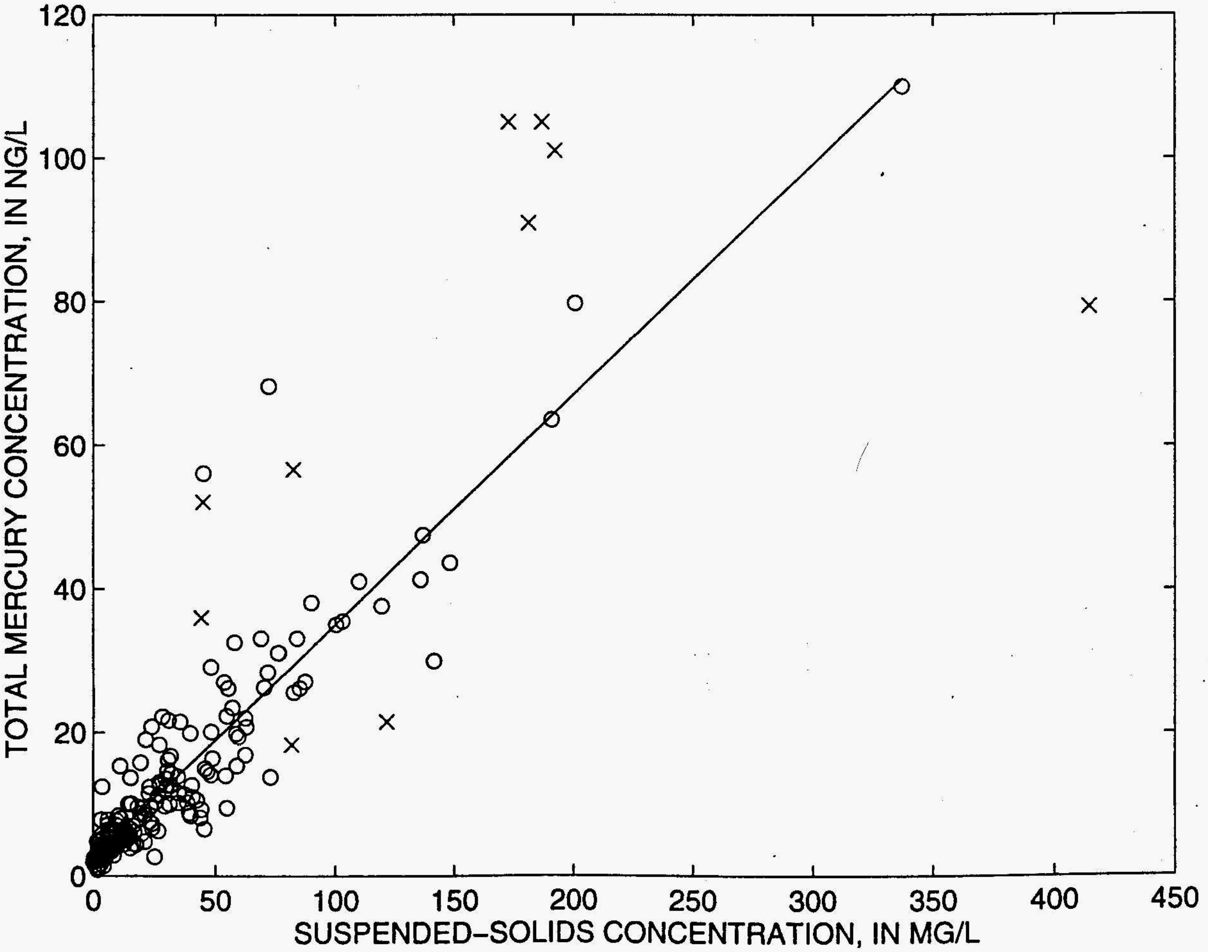

Figure 52. Correlation of suspended-solids concentration (SSC) and total mercury concentration. Outliers from samples taken from influent waters are indicated with an 'x'.

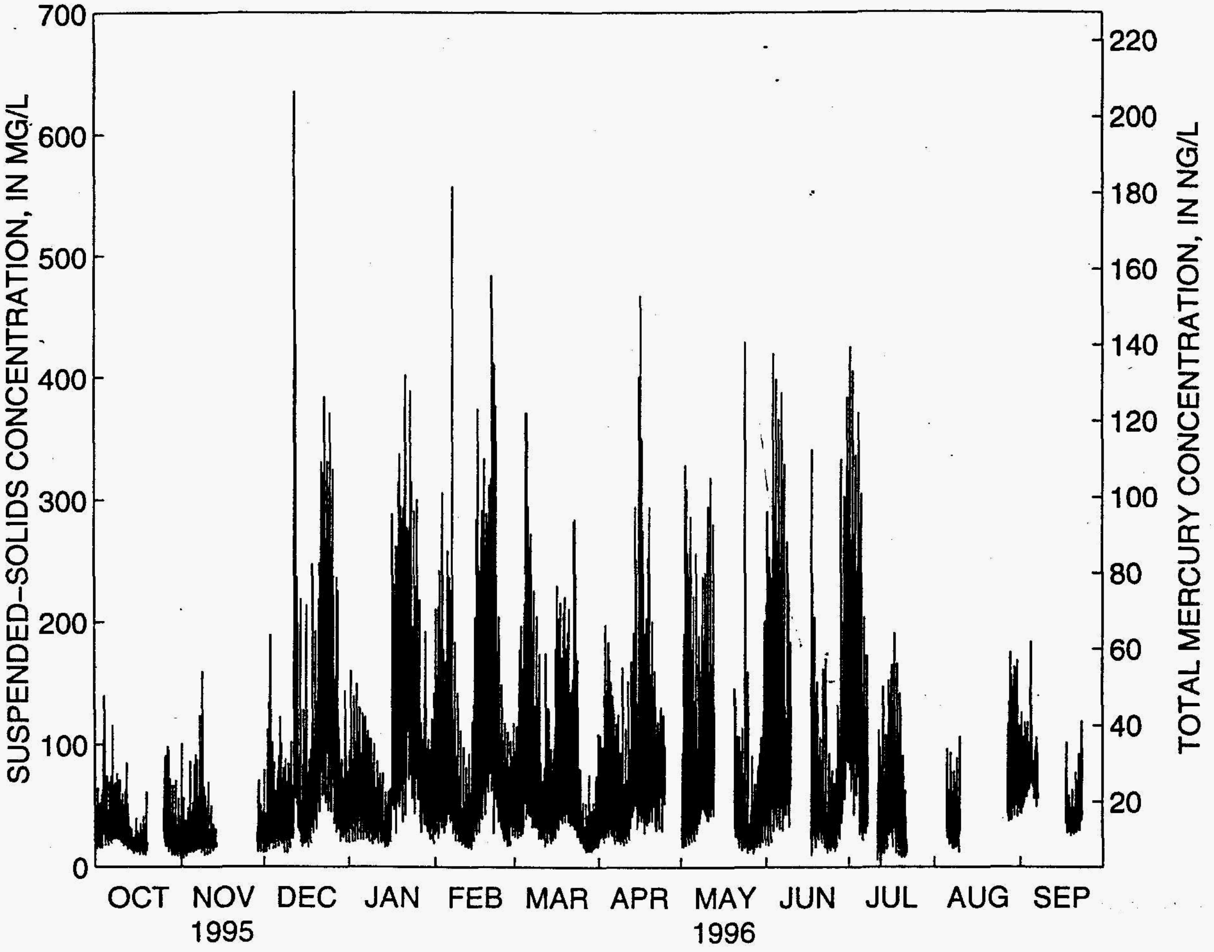

Figure 53. Time series of mid-depth suspended-solids concentration (SSC, measured) and total mercury concentration (calculated) at Point San Pablo, water year 1996.

concentration is the result of the spring-neap cycle.

The time series of total mercury concentration can be used to calculate the 4-day average concentration. The water quality objective currently in effect for mercury in the San Francisco Bay Estuary is a 4-day average total concentration of less than 25 ng/L (San Francisco Bay Regional Water Quality Control Board, 1995; Figure 15 of this chapter). This objective is based on laboratory experiments that expose organisms to constant contaminant levels, but the variability shown in Figure 53 reminds us that the Bay is a much more complex system. Discrete water samples provide an instantaneous value for total mercury concentration, not a 4-day average. The time series from a fixed point used here provides a Eulerian estimate of the 4-day average concentration. Individual parcels of water may experience a different 4-day average concentration because they are moving within the Estuary (a Lagrangian reference frame) and are not static at a fixed point. The 4-day centered running median of total mercury concentration at mid-depth at Point San Pablo is shown in Figure 54.

The 4-day averaging window removes the influence of diurnal and semidiurnal tides, primarily leaving a signal from the spring-neap cycle. Thus, for the present geochemical condition of the Estuary, the spring-neap cycle is the primary factor that determines whether the water-quality objective is satisfied at any given time.

The accuracy of using instantaneous water samples to evaluate a 4-day average water quality objective can be evaluated by comparing the time series averaged over 1 minute (Figure

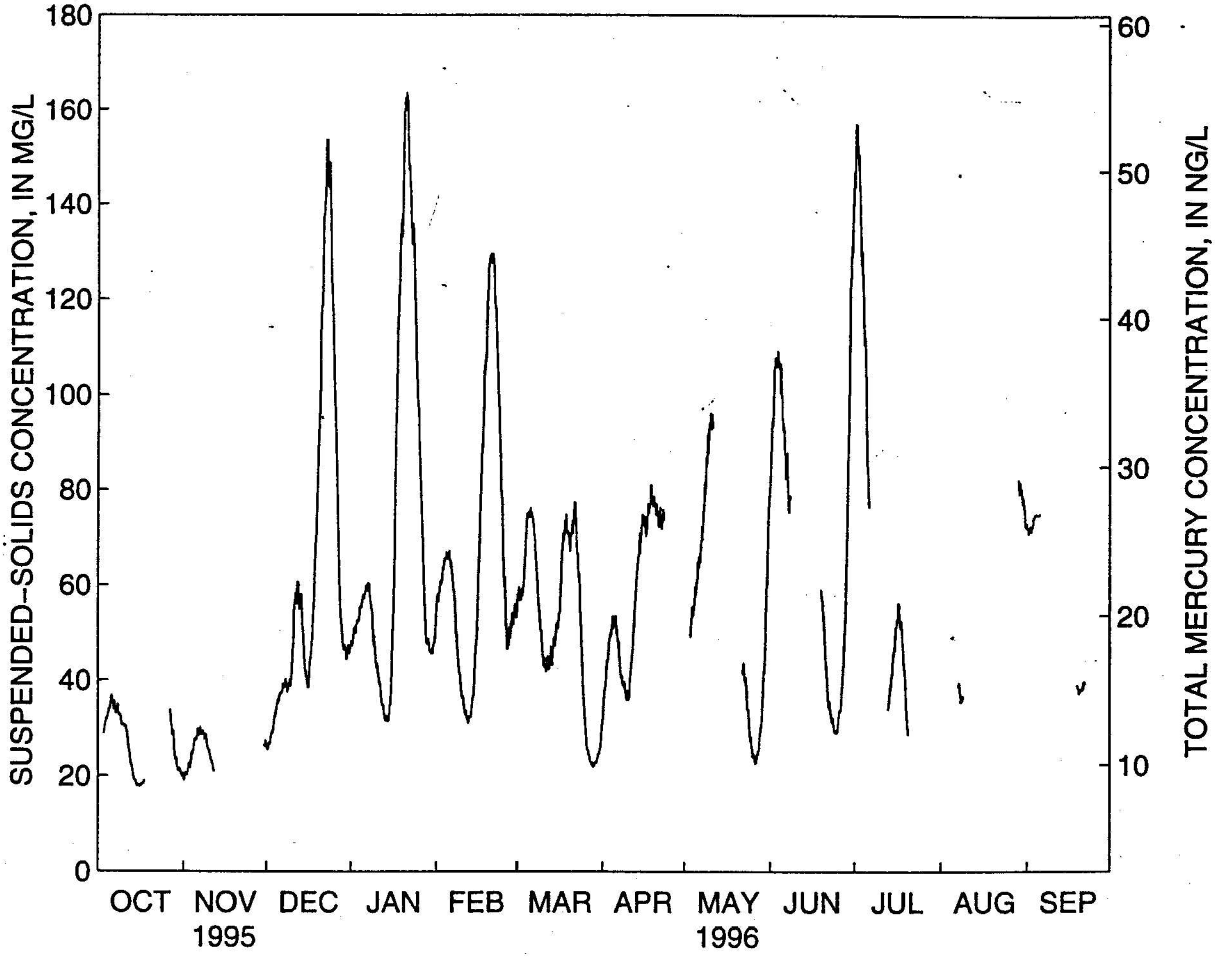

Figure 54. Four-day centered running median of suspended-solids concentration (SSC, measured) and total mercury concentration (calculated) at mid-depth at Point San Pablo, water year 1996. A median value was computed if more than 90 percent of the data within the 4-day averaging window were valid.

53) and averaged over 4 days (Figure 54). Instantaneous grab samples that are analyzed for total mercury concentration and 1-minute averaged OBS measurements that are converted to SSC and then to total mercury concentration are assumed to be equivalent for purposes of this analysis. The percent occurrence of the four possible combinations of the two averaging windows being less than or greater than the threshold concentration (25 ng/L) are presented in Table 6. Twenty percent of the time, a 1-minute average concentration gave an incorrect evaluation of the water-quality objective. When the 1-minute average was less than the threshold, 12 percent of the 4-day averages actually exceeded the threshold, and the water-quality objective was not satisfied. When the 1-minute average was greater than the threshold, 35 percent of the 4-day averages were actually less than the threshold, and the water quality objective was satisfied. Thus, the averaging periods for water quality objectives and sampling should be as similar as possible to evaluate water quality objectives accurately.

Conclusions

Time series data collected during water year 1996 reveal the influence of physical processes that are typically observed in San Francisco Bay. Freshwater discharge from the Central Valley during the winter and spring, seasonal wind, insolation, the spring-neap tidal cycle, and diurnal and semidiurnal tides affected salinity, temperature, suspended solids concentration, and total mercury concentration.

Table 6. Comparison of l-minute and 4-day average concentrations for evaluating a 4-day average water quality objective using calculated total mercury concentration time series at mid-depth at Point San Pablo, water year 1996.

Averaged concentration compared *to* threshold concentration		Percent occurrence for all data	Percent occurrence when l-minute	
1-minute average	4-day average		average is less than the threshold	average is greater than the threshold
Less	Less	58	88	—
Less	Greater	8	12	—
Greater	Less	12	—	35
Greater	Greater	22	—	65

Calculated time series of total mercury concentration, and other time series of trace element concentrations that are linearly correlated with SSC, can be used to evaluate water quality objectives that are based on averaging periods much longer than the time required **to** sample. Large differences between the averaging periods of water-quality objectives and sample collection can result in an inaccurate evaluation of water quality objectives from water samples (Table 6).

Acknowledgments

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