Time Series of Suspended-Solids Concentration, Salinity, Temperature, and Total Mercury Concentration in San Francisco Bay During Water Year 1998

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Contents

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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). Continuous time series of data on basic state variables of the bay, such as suspended-solids concentration (SSC), salinity, and water temperature, provide insight on the effect and relative importance of physical processes on the bay. SSC time series and Regional Monitoring Program (RMP) water-quality data can be used to calculate time series of some trace-element concentrations (Schoellhamer, 1997a, 1997b). The purpose of this chapter is to describe qualitatively time series of SSC, salinity, water temperature, and mercury during water year 1998 (October 1997 through September 1998).

Salinity, temperature, and sediment are important components of the San Francisco Bay estuarine system. Salinity and temperature affect the hydrodynamics (Monismith *et al.*, 1996; Schoellhamer and Burau, 1998), 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; Flegal *et al.*, 1996; Schoellhamer, 1997a, 1997b).

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 habitat for benthic communities that can ingest these substances and introduce them into the food web (Luoma *et al.*, 1985; Brown and Luoma, 1995, Luoma 1996). Bottom sediments also are a reservoir of nutrients that contribute to the maintenance of estuarine productivity (Hammond *et al.*, 1985).

Time Series Data

The U.S. Geological Survey (USGS) operates several salinity, temperature, and SSC monitoring sites in San Francisco Bay (fig. 1) (Buchanan 1999; Buchanan and Schoellhamer, 1999). At most sites, specific 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. Specific conductance was converted to salinity using the 1985 UNESCO standard (UNESCO, 1985) in the range of 2-42. Salinities below 2 were computed using the extension proposed by Hill *et al.* (1986). The OBS sensors optically measure the amount of suspended 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 1 to 5 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 and temporary shutdown of some sites due to seismic retrofit of bridges 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). Salinity data, calculated from the temperature record and the electric conductivity record, at Mallard Island and the reservoir release data were obtained from the Department of Water Resources "California Data Exchange Center" (http:// cdec.water.ca.gov). Chlorophyll *a* data were obtained from the water quality cruises by USGS RV Polaris through the Access USGS website at http:// sfbay.water.usgs.gov.

Salinity

Salinity decreased throughout the bay during the winter wet season. The largest freshwater discharges from the Central Valley into San Francisco Bay and the lowest near-surface salinity at Point San Pablo for the water year occurred during February (fig. 2). Near-surface salinity at Point San Pablo frequently approached zero during ebb tides in February. In South Bay at the San Mateo Bridge, minimum salinities occurred during February and 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 (fig. 2). 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.

Compared to mean monthly values for water years 1994-1997, which are shown as shaded lines in figure 2, freshwater discharge from the Central Valley was greater and salinity was less in February-September 1998.

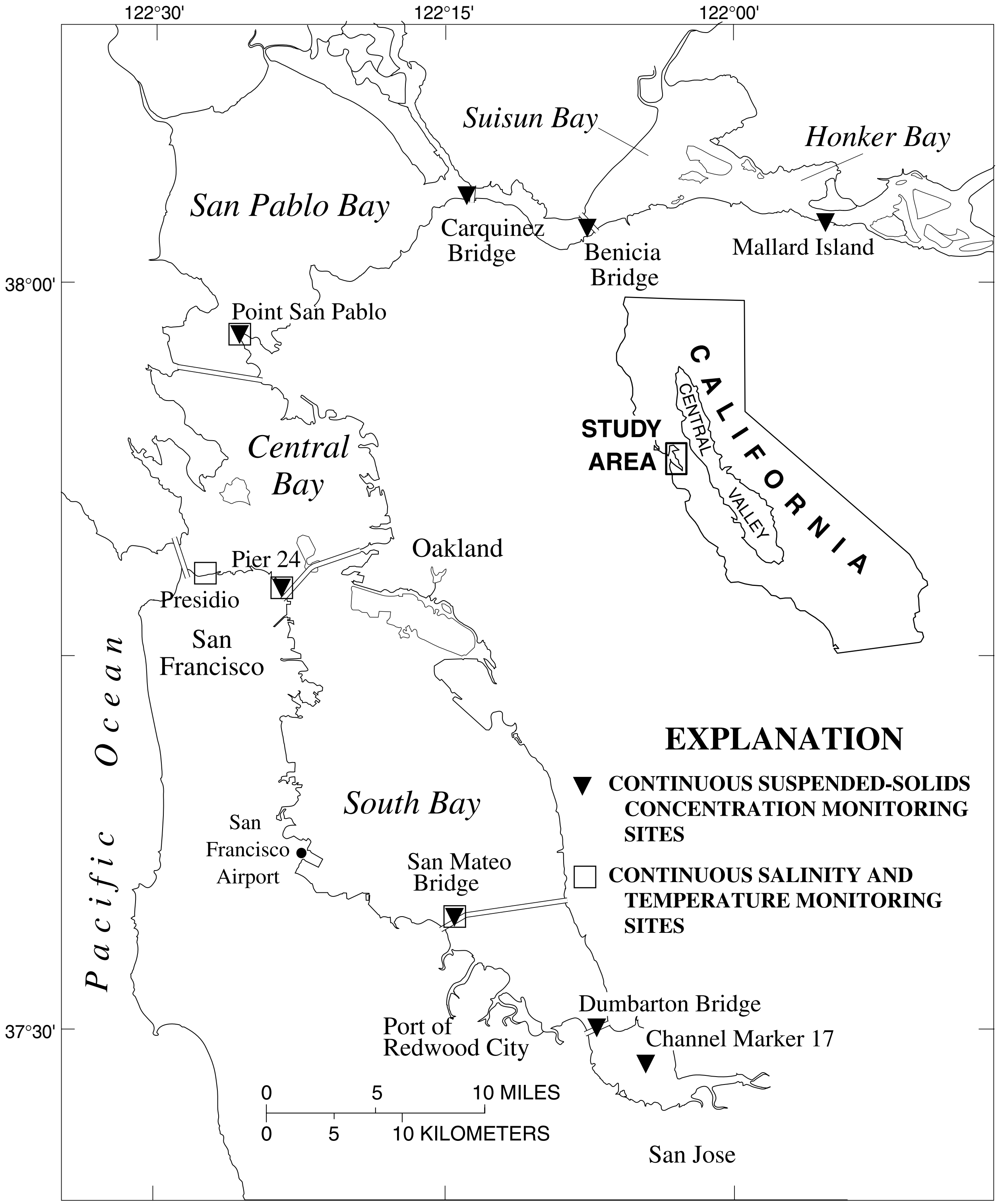

Figure 1. San Francisco Bay study area and USGS continuous monitoring sites.

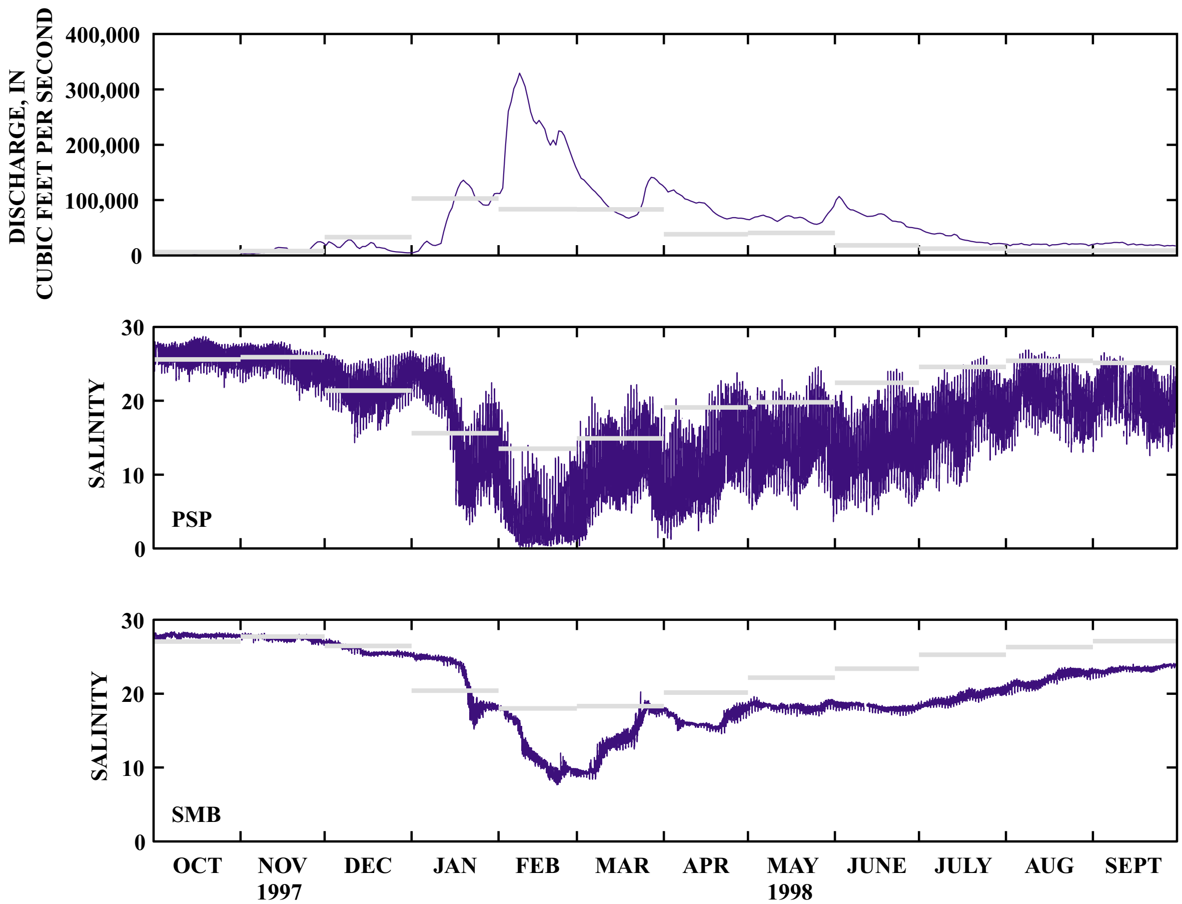

Figure 2. Time series of delta discharge (California Department of Water Resources, 1986) and near surface salinity at Point San Pablo (PSP) and the San Mateo Bridge (SMB), water year 1998. The shaded line indicates the mean monthly values for water years 1994-1997.

The spring-neap cycle had a small effect on salinity at Point San Pablo during the spring and summer. After the discharge peak in February, the envelope of tidal cycle salinity variations, which appears as a thick black band on figure 2, oscillated with a 14-day period. Peaks in the envelope occurred during spring tides and 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.

Vertical salinity differences that stratify the water column result when denser, more saline water lies below lighter, fresher water. At Point San Pablo, the water column was frequently stratified after January due to the relatively large freshwater discharge. Throughout the water year, the greatest stratification occurred during neap tides, which were too weak to vertically mix the water column. Stratification was 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 neap tides January-April (fig. 3). The annual phytoplankton bloom in South Bay occurs during periods of salinity stratification (Cloern, 1984). In 1998, the phytoplankton bloom began in early March during a period of significant stratification and peaked in mid-March (http:// sfbay.water.usgs.gov).

Temperature

Time series of 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 (fig. 4). Temperatures during water year 1998 were similar to the monthly mean temperatures during water years 1994-1997. 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 1998. In early December 1997, delta discharge peaked at 28,400 ft^3/s during the first large runoff event of the wet season (fig. 5). In response, SSC at Mallard Island, the boundary between the bay and the delta, increased to more than 100 mg/L (fig. 5). This “first-flush” of the Central Valley watershed lasted about 4 weeks. Maximum delta discharge and SSC for the water year coincided in February. During water year 1997 maximum delta discharge and SSC also coincided (Ruhl and

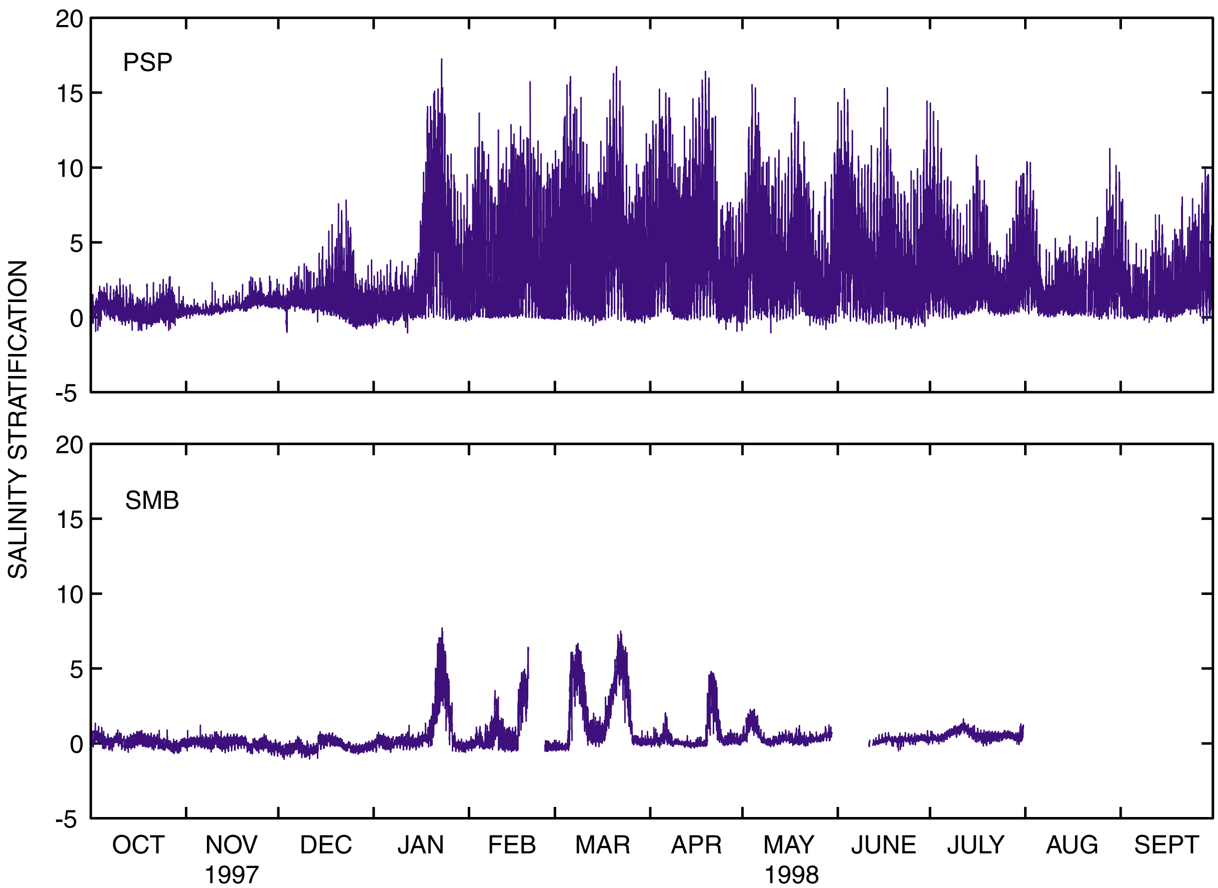

Figure 3. Time series of salinity stratification (bottom salinity minus near-surface salinity at Point San Pablo (PSP) and San Mateo Bridge (SMB), water year 1998.

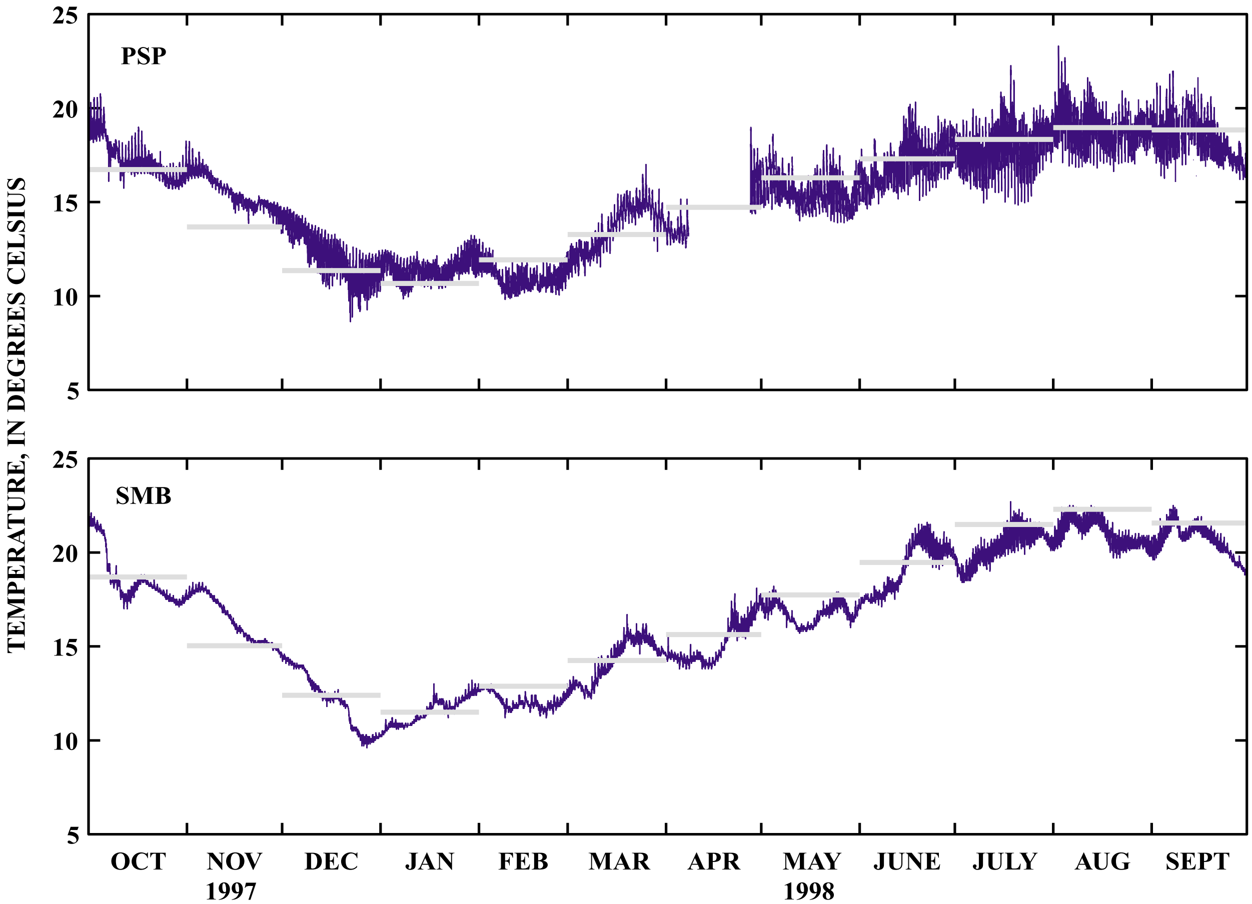

Figure 4. Time series of near-surface water temperature at Point San Pablo (PSP) and the San Mateo Bridge (SMB), water year 1998.

Schoellhamer, 1999) but during water year 1996 SSC was greatest during the first flush (Schoellhamer, 1997b). It is important to note that due to these "first flush" effects the highest concentrations of suspended sediments at Mallard Island do not always coincide with the peak delta discharge.

Delta discharge had a smaller effect on SSC farther seaward in the bay and the tidal variation of SSC, especially the spring-neap tidal cycle, was more important. At Point San Pablo, SSC was greatest during a spring tide in late February following high Delta discharge (fig. 6). In February and March, SSC was greater than the monthly means for water years 1994- 1997. Throughout the water year, SSC varied with the spring-neap cycle at Point San Pablo, 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, 1996).

From March through mid-July 1998 SSC was generally low at Mallard Island, with low tidal variations as well. Similar low SSC values during previous years have been attributed to spring-time reservoir flow when clear water released upstream keeps concentrations at Mallard Island low (Schoellhamer, 1997b). However, the reservoir release records from Oroville, Shasta, Folsom, Englebright, Don Pedro, Friant, New Exchequer, New Melones,

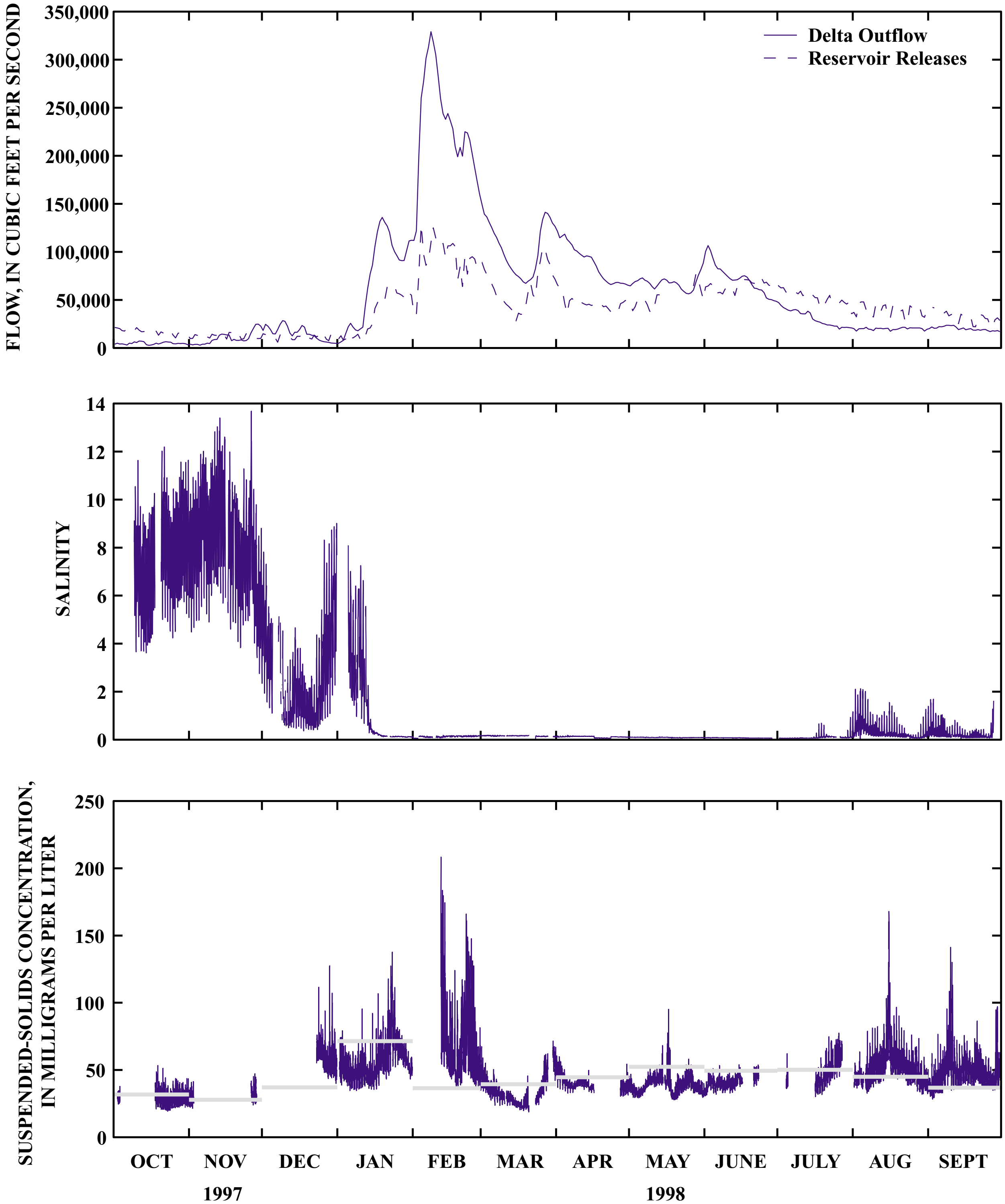

Figure 5. Time series of delta discharge (California Department of Water Resources, 1986) and releases from the major Sacramento and San Joaquin watershed reservoirs (California Department of Water Resources, http://cdec.water.ca.gov), near-surface salinity at Mallard Island (California Department of Water Resources, http://cdec.water.ca.gov), and suspended- solids concentration (SSC) at Mallard Island, water year 1998. The shaded line indicates the mean monthly values for water years 1994-1997.

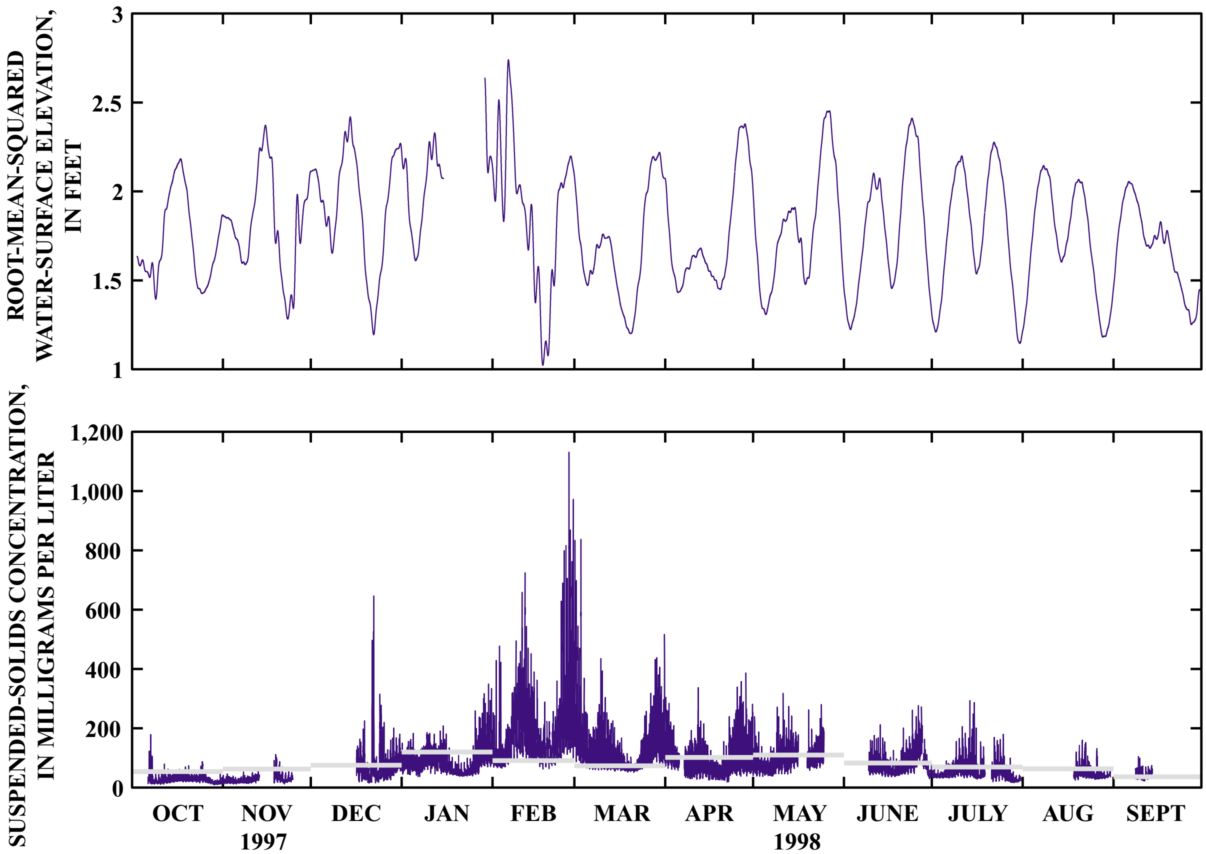

Figure 6. Time series of root-mean-squared (RMS) water-surface elevation (WSE) and mid- depth suspended-solids concentration (SSC) at Point San Pablo, water year 1998. Maxima in the RMS water-surface elevation indicate spring tides, and minima indicate weaker neap tides. The shaded line in figure 6b indicates the mean monthly values for water years 1994-1997.

and Comanche reservoirs (http://cdec.water.ca.gov) indicate that there is no major shift in reservoir operation that could account for low SSC at Mallard Island (fig. 5). During March and April, reservoir releases account for about one-half of Delta discharge. By July, reservoir release is greater than Delta discharge due to water diversions, but SSC and its tidal variability remain low. Therefore, reservoir releases appears to be an overly simplistic explanation. Other possible explanations are that bank storage, base flow, or water impounded on neighboring lands such as agricultural fields are contributing significant amounts of clear water to the riverine system which is not being captured through the reservoir release measurements alone.

In mid-July both the absolute concentration and the variability of suspended-solids measurements at Mallard Island begin to increase again. These changes are coincident with the return of salinity to the area (fig. 5). There is no definitive answer to explain this phenomenon. Some potential explanations are a sufficient decrease in delta outflow to allow transport of more turbid water in Suisun Bay to Mallard Island during flood tide, resuspension in the neighboring shallows of Honker Bay, or the onset of density current pulses (Tobin *et al.*, 1995).

In previous years, a seasonal SSC signal caused by greater wind and sediment resuspension during spring has been observed (Schoellhamer, 1996, 1997b; Ruhl and Schoellhamer 1999). Such a seasonal signal is not immediately apparent in these data, perhaps due to missing data or the large freshwater discharge. Wind speed during water year 1999 was similar to previous years (data not shown).

South Bay Phytoplankton Bloom and SSC

A predictable spring phytoplankton bloom occurs in SoutløSan Francisco Bay following periods of strong vertical salinity stratification in the water column (Cloern, 1996). Salinity stratification usually occurs during neap tides when vertical tidal mixing is weak. Stratification promotes phytoplankton blooms because the phytoplankton are effectively trapped near the surface where photosynthesis takes place and are separated from benthic grazers in the bed sediments (see Cloern, 1996).

During water year 1998 there were several periods of strong stratification in South Bay in January and February; however during the stratification events in March the chlorophyll *a* concentrations increase dramatically, indicating that biological primary production is increasing and the phytoplankton bloom is occurring (fig. 7). The data reported here for the San Mateo Bridge are the average of the data reported from two RV Polaris stations adjacent to the bridge (San Francisco Airport and Redwood Creek). The northern extent of the phytoplankton bloom is near the San Mateo Bridge and the chlorophyll *a* response seen at the Dumbarton Bridge is three to four times greater than that seen at the San Mateo Bridge during the bloom period (fig. 7).

The first spring tide following the peak of the phytoplankton bloom there is a dramatic increase in SSC, where, in some cases, the highest concentrations of the year are seen. The response at San Mateo Bridge shows a moderate increase in the SSC with peaks in late-March and early-April (fig. 7). The SSC at the Dumbarton Bridge, however, is almost twice as large following the spring phytoplankton bloom as at any other time of year (fig.7). The reason for this response in the SSC time series data is still unclear. One possible explanation is that the bloom biomass scavenges suspended-sediment particles. The biomass and scavenged particles deposit on the bed during a neap tide (~ March 20) and are resuspended during the spring tide at the end of March, greatly increasing SSC.

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, 1997a). In the 1996 RMP annual report, RMP mercury and SSC data from 1995 were added to the 1993 and 1994 data to update a linear regression equation between mercury and SSC (Schoellhamer, 1997b, figure 52).

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 8. 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-

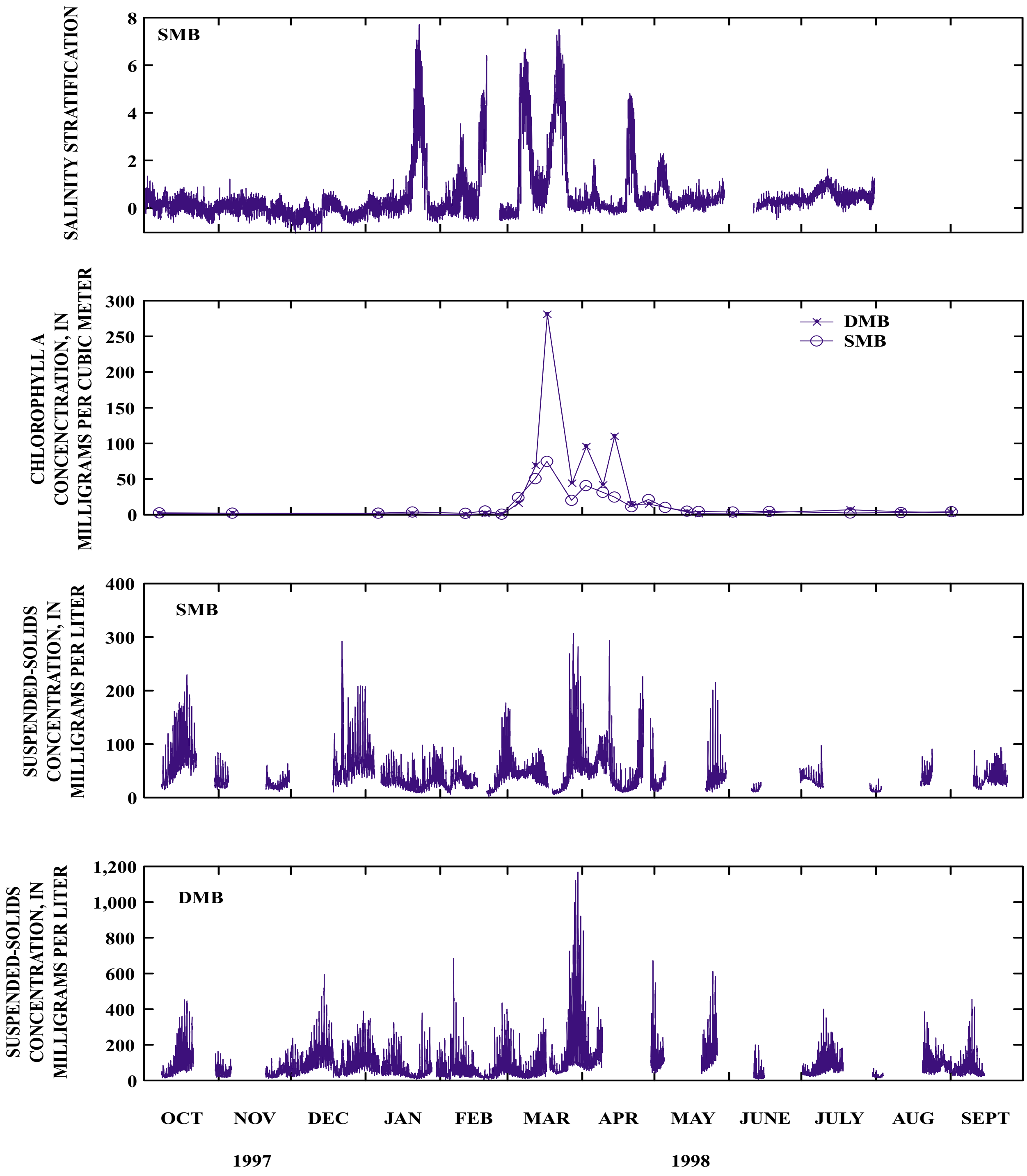

Figure 7. Time series of salinity stratification (bottom salinity minus near-surface salinity) at the San Mateo Bridge, chlorophyll concentration at the San Mateo Bridge (estimated by averaging the San Francisco Airport and Redwood Creek values reported by the RV Polaris) and the Dumbarton Bridge, mid-depth suspended-solids concentration (SSC) at the San Mateo Bridge (SMB), and mid-depth suspended-solids concentration (SSC) at the Dumbarton Bridge (DMB), water year 1998.

neap tidal cycle, freshwater discharge, and seasonal winds. As with SSC, about one-half the variance of total mercury 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). Discrete water samples provide an instantaneous value for total mercury concentration, not a 4-day average. Time series from a fixed point can provide 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 9.

The 4-day averaging window removes the influence of diurnal and semidiurnal tides, primarily leaving a signal from the spring-neap cycle and, for relatively wet water years such as 1998, a freshwater discharge signal. Thus, for the present geochemical condition of the estuary, the spring-neap cycle and freshwater discharge are the primary factors that determine whether the water-quality objective is satisfied at any given time.

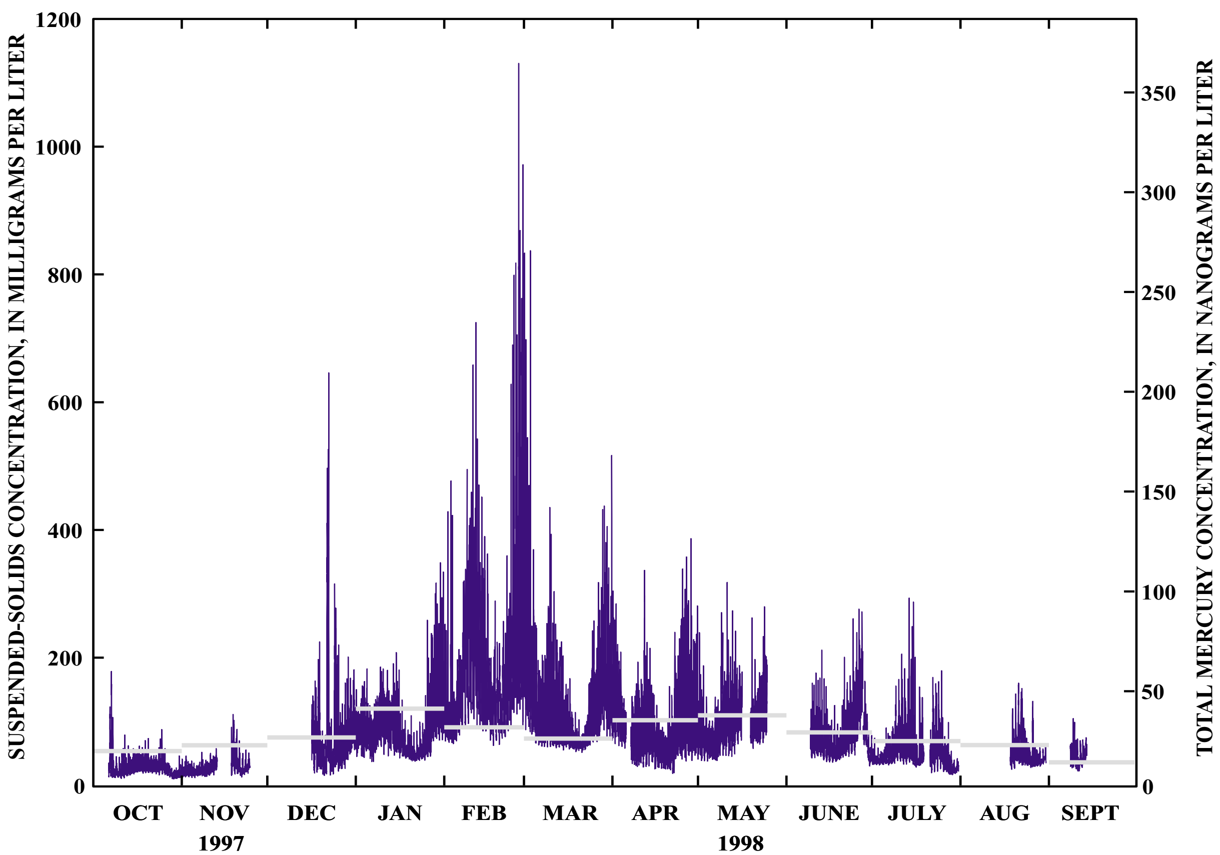

Figure 8. Time series of mid-depth suspended-solids concentration (SSC, measured) and total mercury concentration (calculated) at Point San Pablo, water year 1998.

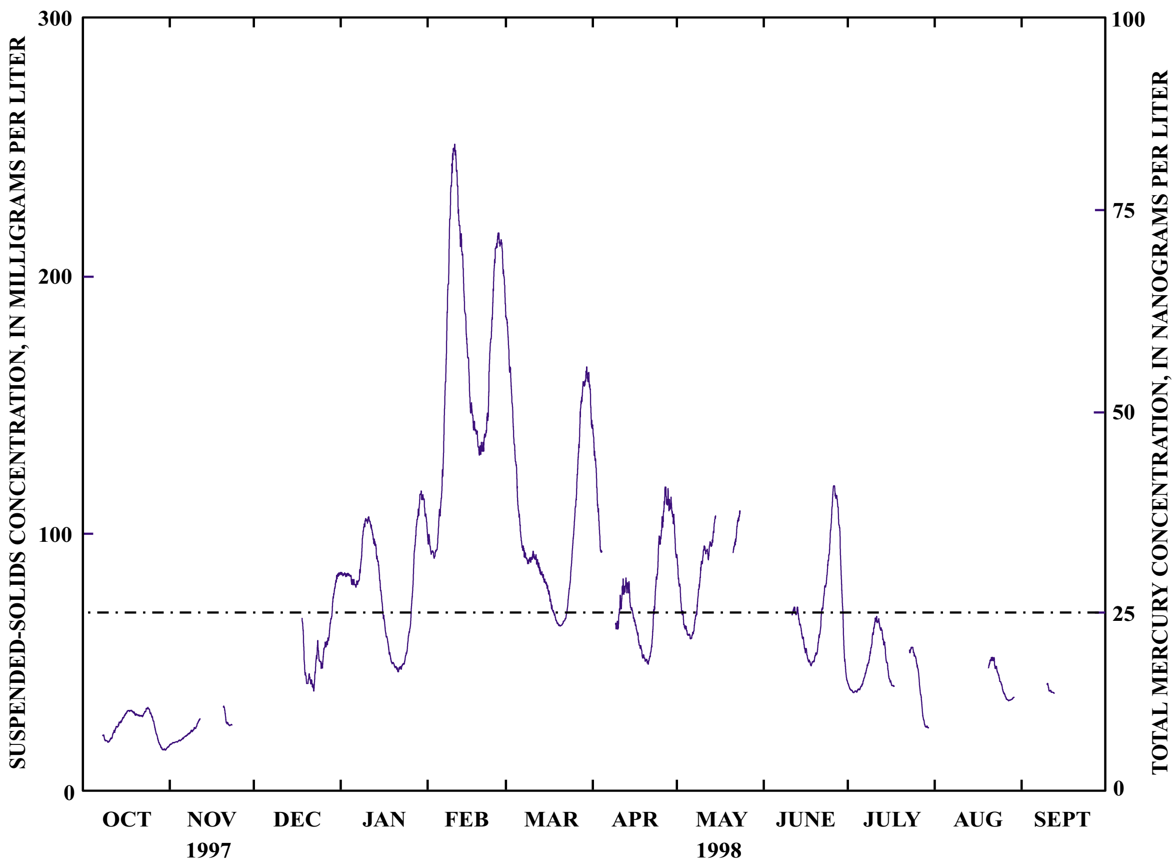

Figure 9. Four-day centered running median of suspended-solids concentration (SSC, measured) and total mercury concentration (calculated) at mid-depth at Point San Pablo, water year 1998. A median value was computed if more than 90 percent of the data within the 4-day averaging window were valid.

Conclusions

Time series data collected during water year 1998 reveal the influence of physical and biological processes that are typically observed in San Francisco Bay. Freshwater discharge from the Central Valley during the winter and spring, the spring-neap tidal cycle, annual primary production cycles, and diurnal and semidiurnal tides affected salinity, temperature, suspended- solids concentration, and total mercury concentration. 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.

Acknowledgments

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References

Abu-Saba, K.E., and Flegal, A.R., 1995, Chromium in San Francisco Bay: Superposition of geochemical processes causes complex spatial distributions of redox species: Marine Chemistry, v. 49, p. 189-199.

Brown, C.L., and Luoma, S.N., 1995, Use of the euryhaline bivalve Potamocorbula amurensis as a biosentinal species to assess trace metal contamination in San Francisco Bay: Marine Ecology Progress Series, v. 124, p. 129-142.

Buchanan, P.A., 1999, Specific conductance, water temperature, and water level data, San Francisco Bay, California, water year 1998: Interagency Ecological Program Newsletter, v. 12, no. 4, p. 46-51.

Buchanan, P.A., and Schoellhamer, D.H., 1999, Summary of suspended-solids concentration data, San Francisco Bay, California, water year 1997: U.S. Geological Survey Open-File Report 99-189, 52 p. URL http://ca.water.usgs.gov/rep/ofr99189/

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

Cloern, J.E., 1984, Temporal dynamics and ecological significance of salinity stratification in an estuary (South San Francisco Bay, U.S.A.): Oceanologica Acta, v. 7, no. 1, p. 137-141.

_______ 1987, Turbidity as a control on phytoplankton biomass and productivity in estuaries: Continental Shelf Research, v. 7, no. 11/12, p. 1367–1381.

_______ 1996, Phytoplankton bloom dynamics in coastal ecosystems: A review with some general lessons from sustained investigation of San Francisco Bay, California: Reviews of Geophysics, v. 34, no. 2, p. 127-168.

Cole, B.E., and Cloern, J.E., 1987, An empirical model for estimating phytoplankton productivity in estuaries: Marine Ecology Progress Series, v. 36, p. 299–305.

Domagalski, J.L., and Kuivila, K.M., 1993, Distributions of pesticides and organic contaminants between water and suspended sediment, San Francisco Bay, California: Estuaries, v. 16, no. 3A, p. 416–426.

Flegal, A.R., Rivera-Duarte, I., Ritson, P.I., Scelfo, G.M., Smith, G.J., Gordon, M.R., and Sanudo-Wilhelmy, S.A., 1996, Metal contamination in San Francisco Bay waters: Historic perturbations, contemporary concentrations, and future considerations: San Francisco Bay: The Ecosystem, Hollibaugh, J.T. ed., Pacific Division of the American Association for the Advancement of Science, San Francisco, p. 173-188.

Flegal, A.R., Smith, G.J., Gill, G.A., Sanudo-Wilhelmy, S., and Anderson, L.C.D., 1991, Dissolved trace element cycles in the San Francisco Bay Estuary: Marine Chemistry, v 36, p. 329-363.

Hammond, D.E., Fuller, C., Harmon, D., Hartman, B., Korosec, M., Miller, L.G., Rea, R., Warren, S., Berelson, W., and Hager, S.W., 1985, Benthic fluxes in San Francisco Bay: Hydrobiologia, v. 129, p. 69–90.

Hill *et al.*, 1986,

Jassby, A.D., Kimmerer, W.J., Monismith, S.G., Armor, C., Cloern, J.E., Powell, T.M., Schubel, J.R., and Vendlinski, T.J., 1995, Isohaline position as a habitat indicator for estuarine applications: Ecological Applications, v. 5, no. 1, p. 272-289.

Kuwabara, J.S., Chang, C.C.Y., Cloern, J.E., Fries, T.L., Davis, J.A., and Luoma, S.N., 1989, Trace metal associations in the water column of South San Francisco Bay, California: Estuarine, Coastal and Shelf Science, v. 28, p. 307–325.

Luoma, S.N., 1996, The developing framework of marine ecotoxicology: Pollutants as a variable in marineecosystems?: Journal of experimental marine biology and ecology, v. 200, p. 29-55.

Luoma, S.N., Cain, D., and Johansson, C., 1985, Temporal fluctuations of silver, copper, and zinc in the bivalve Macoma balthica at five stations in South San Francisco Bay: Hydrobiologia, v. 129, p. 109–120.

Monismith, S.G., Burau, J.R., and Stacey, M., 1996, Stratification dynamics and gravitational circulation in northern San Francisco Bay, in Holliibaugh, J.T., ed., San Francisco Bay: The Ecosystem: San Francisco, Pacific Division of the American Association for the Advancement of Science, p. 123-153.

Nichols, F.H., Cloern, J.E., Luoma, S.N., and Peterson, D.H., 1986, The modification of an estuary: Science, v. 231, p. 567-573.

Nichols, F. H., and Thompson, J. K., 1985, Time scales of change in the San Francisco Bay benthos: Hydrobiologia, v. 192, p. 121-138.

Ruhl, C.A., and Schoellhamer, D.H., 1999, Time series of suspended-solids concentration in Honker Bay during water year 1997: 1997 Annual Report of the Regional Monitoring Program for Trace Substances, p. 82-92, URL http://www.sfei.org/rmp/1997/c0304.htm

San Francisco Bay Regional Water Quality Control Board, 1995, 1995 basin plan: Oakland, California.

Schoellhamer, D.H., 1996, Factors affecting suspended-solids concentrations in South San Francisco Bay, California: Journal of Geophysical Research, v. 101, no. C5, p. 12087- 12095.

______ 1997a, Time series of trace element concentrations calculated from time series of suspended-solids concentrations and RMP water samples: 1995 Annual Report of the Regional Monitoring Program for Trace Substances, p. 53-55.

______ 1997b, Time series of SSC, salinity, temperature, and total mercury concentration in San Francisco Bay during water year 1996: 1996 Annual Report of the Regional Monitoring Program for Trace Substances, p. 65-77.

Schoellhamer, D.H., and Burau, J.R., 1998, Summary of findings about circulation and the estuarine turbidity maximum in Suisun Bay, California: U.S. Geological Survey Fact Sheet FS-047-98, 6 p. URL:http://sfbay.wr.usgs.gov/access/suisunbay/dschoell/

Tobin, A., Schoellhamer, D.H., and Burau, J.R., 1995, Suspended-solids flux in Suisun Bay, California *in* First International Conference of Water Resources Engineering, Sn Antonio, Texas, August 14-18, 1995, Proceedings: New York, American Society of Civil Engineers, p. 1511-1515.

UNESCO, 1985, The Internationalsystem of units (SI) in oceanography, UNESCO Technical Papers, No. 45

U.S. Environmental Protection Agency, 1992, State of the estuary: Dredging and waterway modification: U.S. Environmental Protection Agency San Francisco Estuary Project, chap. 8, p. 191–215.