Patterns of Water-Quality Variability in San Francisco Bay During the First Six Years of the RMP, 1993-1998

Prepared By
James E. Cloern, Brian E. Cole, Jody L. Edmunds,
Tara S. Schraga, and Andrew Arnsberg
U.S. Geological Survey MS496
345 Middlefield Road
Menlo Park, CA 94025

Prepared For
Regional Monitoring Program for Trace Substances
San Francisco Estuary Institute
1325 S. 46th Street
Richmond, CA 94804

Introduction

Since the inception of the Regional Monitoring Program (RMP), the U.S. Geological Survey (USGS) has contributed by measuring the spatial variability of basic water-quality constituents along the entire San Francisco Bay system. The San Francisco Bay Estuary is a large complex system of shallow basins and interconnecting channels that contain a mixture of freshwater and seawater. The USGS sampling program measures spatial variability in the vertical and longitudinal dimensions along a central transect from the lower South Bay to the Sacramento River (Figure 1). We know, from other measurement programs (Cloern and Nichols, 1985a; Powell *et al.*, 1989), that lateral (transverse) gradients of water quality can also develop between the deep channel domains and the shallow subtidal and intertidal habitats of South Bay, San Pablo Bay, and Suisun Bay. Although these transverse gradients are important features of water quality, the primary spatial component of variability is along the salinity gradient between the coastal Pacific Ocean and the rivers/streams that carry runoff and inputs from the Estuary's watersheds. The USGS element of the RMP was designed to document changes in water-quality indicators along this primary spatial gradient. Here we present and discuss the patterns of longitudinal variability along the river-ocean continuum, using results of surface water measurements. The full data set, including visual depictions of variability in the vertical dimension, are available at the USGS San Francisco Bay water-quality website (see below). In this review we focus on the key features of variability that occurred during the first six years of the RMP, as a foundation for understanding the patterns and mechanisms of variability in the other constituents measured within the RMP.

The USGS element of the RMP was designed to monitor fundamental water-quality constituents that are (a) basic descriptors of habitat and water chemistry, and (b) indicators of the processes that influence other components of water quality. The most basic indicator of water quality is salinity, which precisely measures the mixture between freshwater and seawater; salinity also influences chemical processes (sorption-desorption, flocculation) and physical processes (density stratification, vertical mixing) that directly influence the distribution and form of many trace substances. We measure the concentration of suspended solids (TSS) as a descriptor of the total concentration of particles suspended in the water. Many trace substances sorb to particle surfaces, so the total concentration or partitioning of those substances between the dissolved and particulate phases is largely determined by TSS concentration. A third basic descriptor of water quality is chlorophyll *a* concentration, measured as an indicator of the abundance of phytoplankton, the largest component of living biomass in San Francisco Bay. Primary production by phytoplankton is also the largest source of organic matter to some regions of San Francisco Bay (Jassby *et al.,* 1993), and the production of new phytoplankton biomass acts as a biological engine that transforms reactive elements from dissolved inorganic form into particulate organic form. These transformations strongly influence the cycling and biological availability of trace elements such as cadmium, nickel, zinc (Luoma *et al.,* 1998), and selenium. We measure dissolved oxygen concentration as a direct indicator of the rate of phytoplankton primary production and an indirect measure of the rate of phytoplankton-driven transformations of these trace-substances.

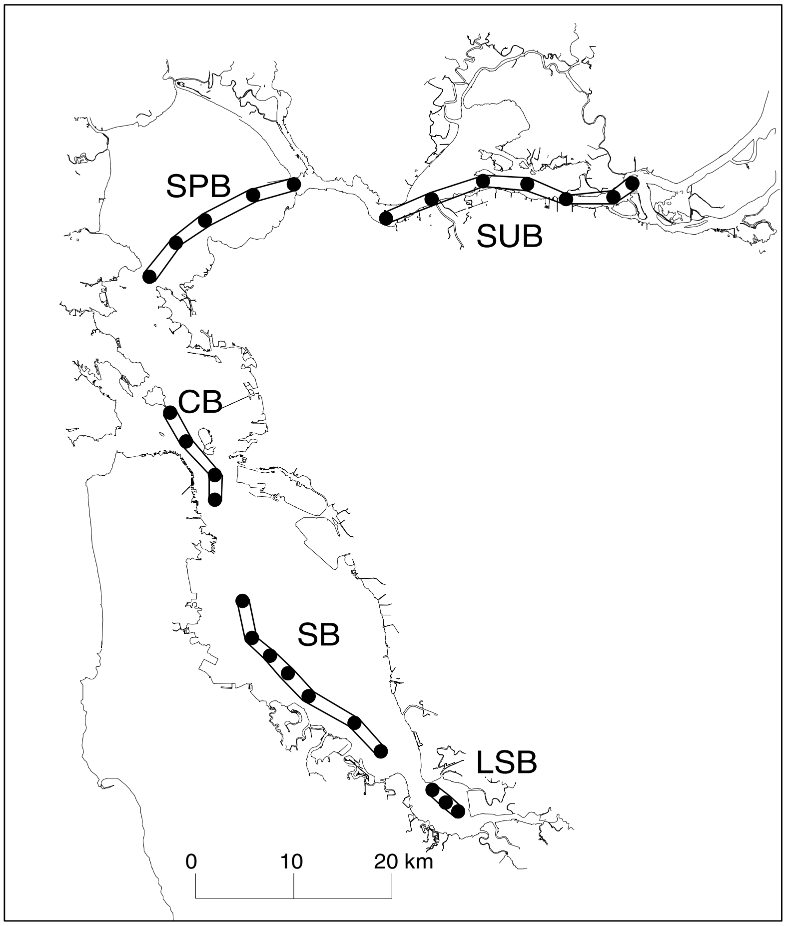

Figure 1. Map showing locations of USGS sampling stations along the axial transect of the San Francisco Bay-Delta, from the lower Sacramento River to the southern South Bay. Stations are grouped into the following domains: Lower South Bay (LSB), South Bay (SB), Central Bay (CB), San Pablo Bay (SPB), and Suisun Bay (SUB).

The Measurement Program

Design

This element of the RMP includes measurements at a series of fixed stations spaced every 3–6 km, from Rio Vista (lower Sacramento River, Figure 1), through Suisun Bay, Carquinez Strait, San Pablo Bay, the Central Bay, and South Bay to the mouth of Coyote Creek. Vertical profiles are taken at each station, so this measurement program provides two-dimensional (longitudinal-vertical) descriptions of spatial structure along the deep channel. Sampling along the 145-km transect requires 12–15 hours, so measurements are taken at varying phases of the semidiurnal tide cycle. Although it is logistically difficult to synchronize sampling to a fixed tidal phase, we minimized the effects of intratidal variability by sampling near the periods of monthly minimum tidal energy whenever possible. Therefore, this sampling program is biased toward neap-tide conditions, and it is confounded by intratidal variability during the course of sampling. Sampling was done once each month along the entire North Bay-South Bay transect. More frequent sampling was done in South Bay to follow the dynamic water-quality changes associated with the spring phytoplankton bloom (Cloern, 1996). Here, we present the results of sampling during the first six years of the RMP, comprising 70 dates of sampling along the entire North Bay-South Bay transect and 135 dates of sampling in South Bay.

Methods

Data for this RMP element were collected with an instrument package that includes sensors for measuring: sampling depth, conductivity, temperature, salinity (calculated from conductivity and temperature), TSS (optical backscatter sensor), chlorophyll *a* (fluorometer), and dissolved oxygen (oxygen electrode). The instrument package is lowered through the water column, making measurements about every 4 cm. Here, we report only the measurements made in the upper meter of the water column, calculated as the mean of all measurements made between 0.5 and 1.5 m. The complete data set, including measurements made at all depths, is available in data reports (Baylosis *et al.*, 1997, 1998; Caffrey *et al.*, 1994; Edmunds *et al.*, 1995, 1997) or over the internet at the USGS website that archives and displays results of the water-quality program: http://sfbay.wr.usgs.gov/access/wqdata/.

The conductivity and temperature sensors were calibrated by Sea-Bird Electronics prior to the first sampling in January of each year. The optical backscatter sensor, fluorometer, and oxygen electrodes were calibrated each sampling date with analyses of water samples. Surface samples were collected by pump, and bottom samples were collected with a Niskin bottle. Aliquots were analyzed for: TSS (gravimetric method of Hager, 1993); chlorophyll *a* (spectrophotometric method of Lorenzen, 1967, using the equations of Riemann, 1978); and dissolved oxygen (automated Winkler titration, following Granéli and Granéli, 1991). Values reported here are calculated quantities based on daily calibrations of the optical backscatter, fluorescence, and oxygen sensors from linear regressions of measured concentrations vs. voltage output of each instrument. We express dissolved oxygen (DO) as percent saturation, to eliminate the confounding effects of salinity and temperature on DO concentration. DO concentrations above 100% saturation indicate that the biological source of oxygen (phytoplankton photosynthesis) exceeds the losses of oxygen to the atmosphere and to respiration by the biota. Concentrations below 100% saturation indicate that the processes of biological and chemical oxygen consumption exceed the rate of primary production.

Results

Water-Quality Variability by Region in the San Francisco Bay System

As a pilot study in the first years of the RMP, we asked the question: Can water-quality transects along the Bay system be partitioned, or stratified, into a set of subregions (strata) that are relatively homogeneous? We used a tree-based regression approach to analyze nine transects of salinity, TSS, and chlorophyll *a* measured over a range of hydrologic conditions in 1994 and 1995. Results of this analysis (Jassby *et al.*, 1997) suggested that the transects into six spatial domains that have small within-domain variance relative to the variance along the entire transect. The boundaries between these domains correspond to physiographic features, such as the channel constrictions at the Dumbarton Bridge and Carquinez Strait. This result was consistent with the previous conclusions of Powell *et al.* (1986) that the spatial variability within San Francisco Bay is controlled by topography, presumably because topography strongly influences the circulation and transports along the Estuary. With this result as a guide, we pooled measurements from the individual sampling locations within each stratum, and calculated a mean salinity, TSS, chlorophyll *a*, and dissolved oxygen concentration within five subregions of the Bay on each sampling date from 1993 through 1998. The spatial grouping of sampling sites is shown in Figure 1, and we present here the results of mean measurements in the following regions: Lower South Bay (LSB, below the Dumbarton Bridge); South Bay (SB, between the Dumbarton Bridge and San Bruno Shoal); Central Bay (CB, between the San Bruno Shoal and Angel Island); San Pablo Bay (SPB, between Point San Pablo and Carquinez Strait); and Suisun Bay (SUB, between Martinez and Pittsburg).

Time series of the four water-quality indicators are shown for each region in Figures 2–6. The top panel of each figure shows the daily fluctuations of the Delta Outflow Index (DOI), calculated by the California Department of Water Resources as a measure of the net flow of water from the Delta into San Francisco Bay. The California Department of Water Resources classifies water years, and each year of RMP sampling except 1994 was classified as a wet year or year of above-normal inflow. A series of four consecutive wet years, from 1995–1998, has only happened once or twice previously in this century (Roos, 1998). Therefore, RMP results to date are strongly biased toward water-quality conditions characteristic of periods of high river discharge. The exception was 1994, a critical year of persistently low inflow. This six-year period was one of hydrologic extremes, and these extreme events can be used as natural experiments to learn how water quality in the Bay changes in response to seasonal and annual fluctuations of river discharge.

Each subregion of the Bay responded to changes in river flow. The responses to high flow were nearly-instantaneous in Suisun Bay (Figure 2) and San Pablo Bay (Figure 3). These responses included rapid dilution of surface salinity and large increases in TSS, especially during the first large pulse of river flow each year. The first flush of 1993 brought exceptionally high concentrations of suspended sediments into Suisun Bay (Figure 2), presumably because this runoff event ended five consecutive years of below-normal precipitation and runoff. Salinity in the other regions also changed in response to pulse inputs of freshwater through the Delta: note the mirror images of the DOI and surface salinity in the Central Bay (Figure 4) and the South Bay (Figure 5). Although there were also winter dilutions of salinity in the lower South Bay (Figure 6), we do not yet have a reliable technique to measure the relative importance of local inputs of fresh water from the South Bay watershed and the Delta-derived flows on the dilution of salinity in this southernmost region. The regions furthest from the Sacramento and San Joaquin rivers showed progressively weaker covariability between DOI (river flow) and TSS (turbidity), suggesting that Delta-derived inputs of sediments had less direct influence on suspended sediment concentrations in Central Bay and South Bay than in San Pablo and Suisun bays.

The five regions had very different mean concentrations of chlorophyll *a* and dissolved oxygen, with smallest concentrations in Suisun Bay, highest concentrations in the two South Bay regions, and intermediate concentrations in San Pablo and Central bays. The patterns of temporal variability were also different among the five regions, with low variability of chlorophyll *a* and DO in Suisun Bay (Figure 2) and progressively higher variability in San Pablo Bay (Figure 3), Central Bay (Figure 4), and then highest variability in the two South Bay regions (Figures 5 and 6). This pattern reflects the importance of phytoplankton blooms as features of water-quality variability in the regions seaward of Suisun Bay.

The mean spatial patterns of water-quality variability are illustrated in Figure 7, which shows the mean concentrations of salinity, TSS, chlorophyll a and DO in the surface waters of each region. This figure also shows the range of values measured in each region during the period January 1993 to December 1998. From this figure we can classify Suisun Bay as a freshwater-brackish domain with high mean TSS and persistently low phytoplankton biomass (chlorophyll *a*) and primary production (DO was persistently less than 100% saturation). San Pablo Bay is a more variable domain, with surface salinity that ranged from zero (i.e., freshwater) to 27 psu (near marine), and TSS that ranged from 4 to 132 mg/L. San Pablo Bay also had low mean phytoplankton biomass, but peak chlorophyll *a* concentration of 34.8 mg/m^3 that occurred during the exceptional spring phytoplankton bloom of 1998 (see below). The Central Bay had highest mean salinity, reflecting the strong marine influence on this region; but it also had events of low (5 psu) surface salinity that occurred during extreme events of high Delta outflow (see Figure 4). This region is the furthest from the riverine sources of sediments, so it had the smallest mean concentration of TSS. The Central Bay had low mean chlorophyll *a* concentration, indicating small mean phytoplankton biomass, but a range of DO that reached 127% saturation, indicating events of high primary production. These events were associated with the spring phytoplankton blooms, especially during the wet years 1995, 1997, and 1998 (Figure 4). The South Bay can be classified as a brackish-marine system with large fluctuations of salinity, relatively small TSS concentrations, high mean phytoplankton biomass, and episodes of very high primary production (evidenced by peak DO > 140% saturation). Surface salinity in the lower South Bay ranged from near zero to near-marine; this region had the highest concentrations of TSS and chlorophyll *a*, and extremely variable DO reflecting the highly variable primary productivity in this region. Note that the mean DO concentration in all regions was > 60% saturation; DO concentrations in near-bottom waters were generally similar. Therefore, San Francisco Bay does not have water-quality problems associated with hypoxia or anoxia.

Figure 7 illustrates the mean spatial patterns of water quality in San Francisco Bay, based on all the measurements made from 1993–1998. The ranges of values in Figure 7 show that there was large variability around each mean quantity. In the next sections we examine the patterns of temporal variability represented by these range bars, illustrating changes that occurred on three important time scales: interannual, seasonal, and episodic. The San Francisco Bay system is strongly influenced by fluctuations in river flow, and we use results from the USGS measurement program to demonstrate how the distributions of salinity, suspended sediments, chlorophyll *a*, and dissolved oxygen change in response to interannual, seasonal, and episodic changes in river flow. Many of these responses are general, and will be evident in the changing spatial distributions of other dissolved and particulate components of the Bay's water quality.

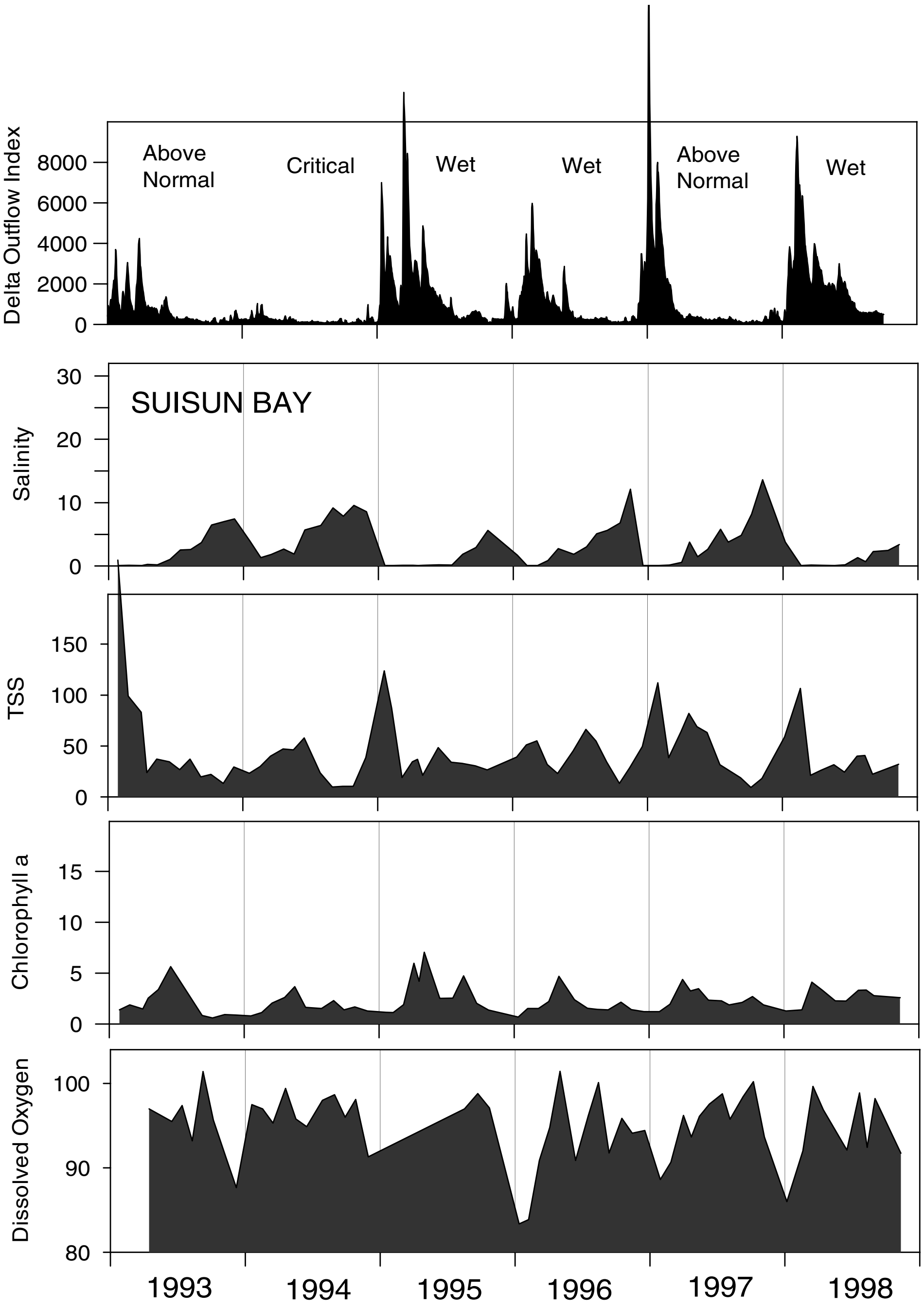

Figure 2. Upper panel shows the daily Delta Outflow Index (m^3/s, from the California Department of Water Resources) for water years 1993–1998, the first six years of the RMP. Lower panels show time series of surface salinity (psu), TSS (mg/L), chlorophyll a (mg/m^3), and dissolved oxygen (percent saturation) for Suisun Bay. Each observation is the mean of measurements made at the 7 sampling sites within the Suisun Bay region (Figure 1).

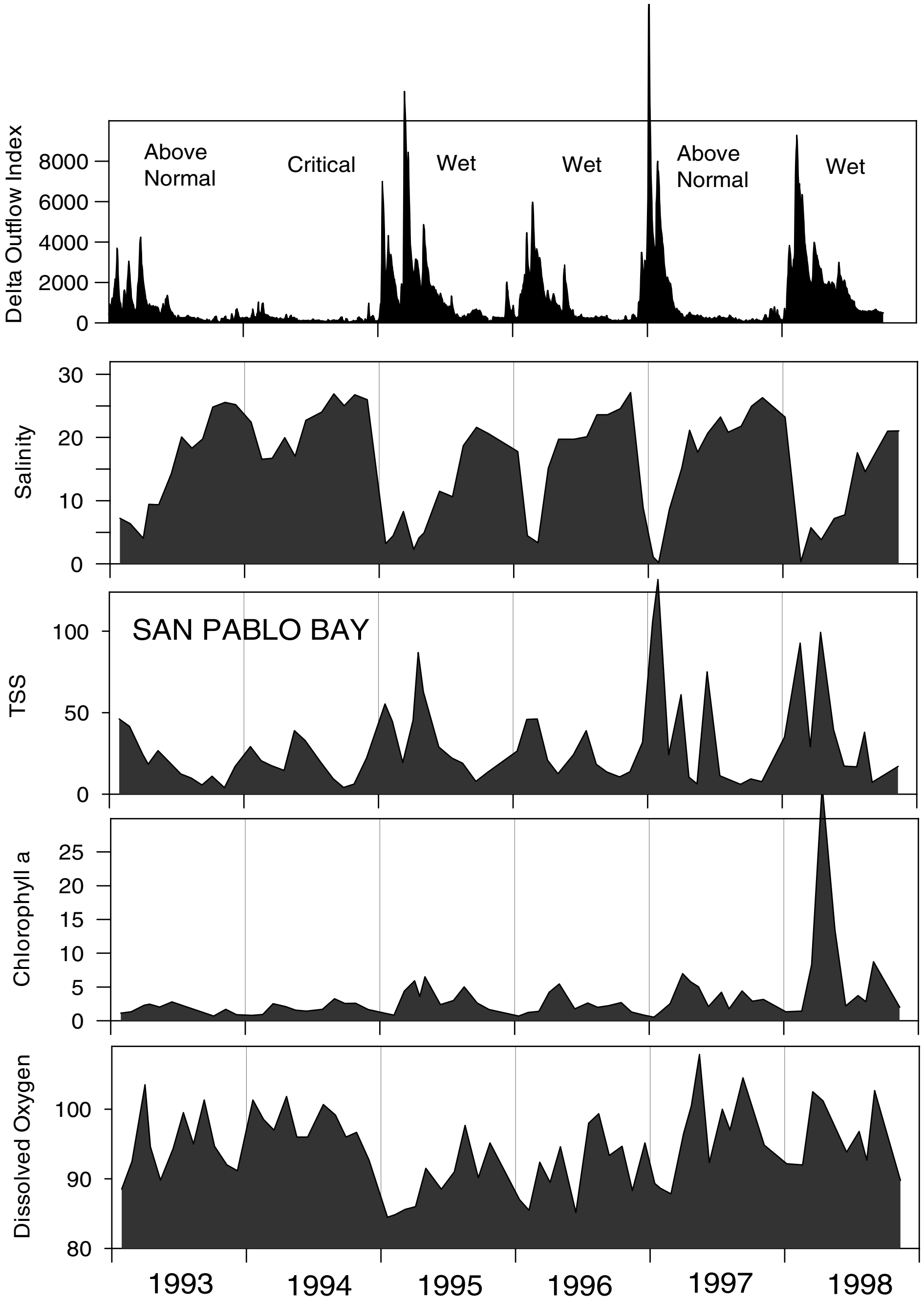

Figure 3. Upper panel shows the daily Delta Outflow Index (m^3/s, from the California Department of Water Resources) for water years 1993–1998, the first six years of the RMP. Lower panels show time series of surface salinity (psu), TSS (mg/L), chlorophyll a (mg/m^3), and dissolved oxygen (percent saturation) for San Pablo Bay. Each observation is the mean of measurements made at the 5 sampling sites within the San Pablo Bay region (Figure 1).

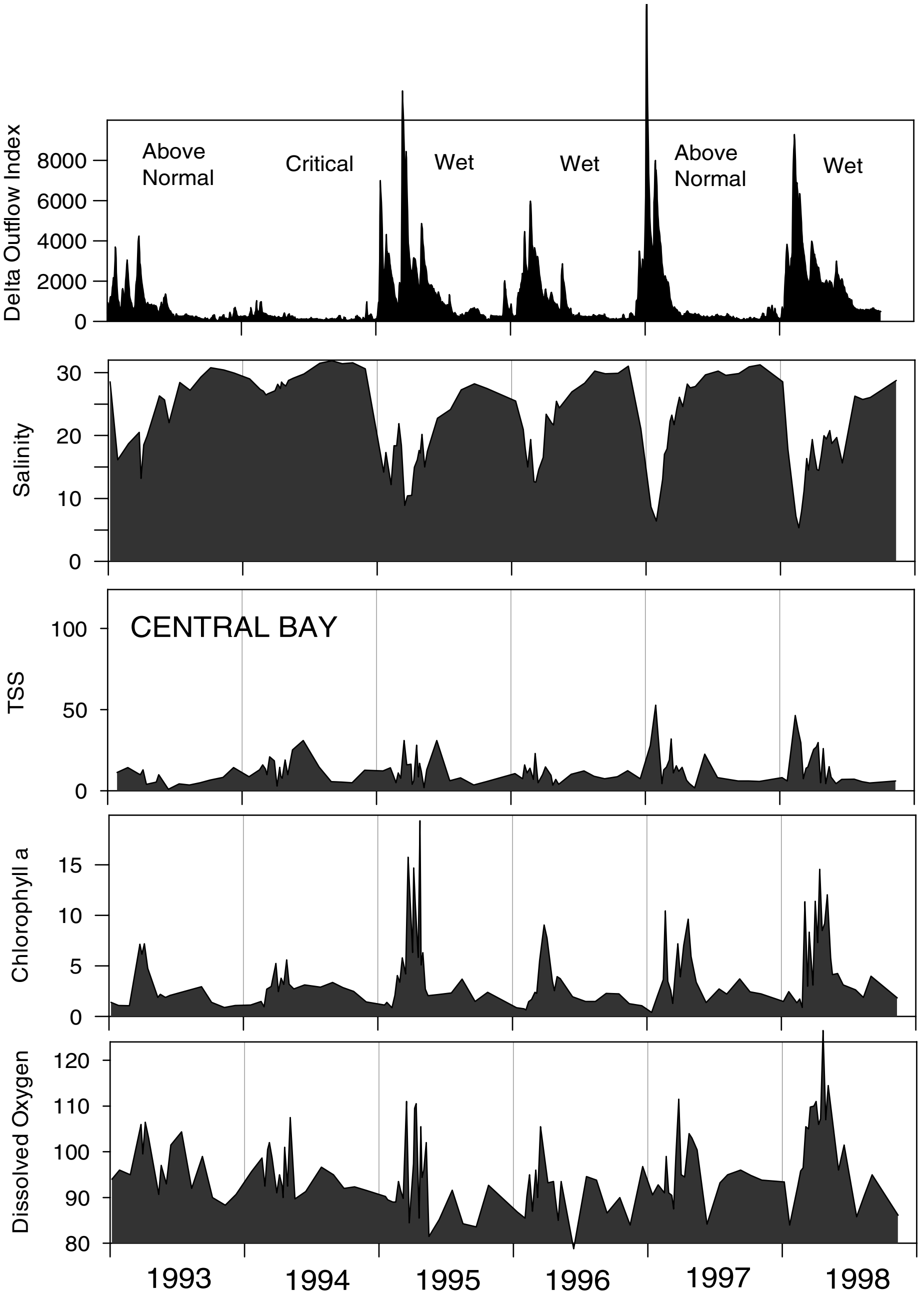

Figure 4. Upper panel shows the daily Delta Outflow Index (m^3/s, from the California Department of Water Resources) for water years 1993–1998, the first six years of the RMP. Lower panels show time series of surface salinity (psu), TSS (mg/L), chlorophyll a (mg/m^3), and dissolved oxygen (percent saturation) for Central Bay. Each observation is the mean of measurements made at the 4 sampling sites within the Central San Francisco Bay region (Figure 1).

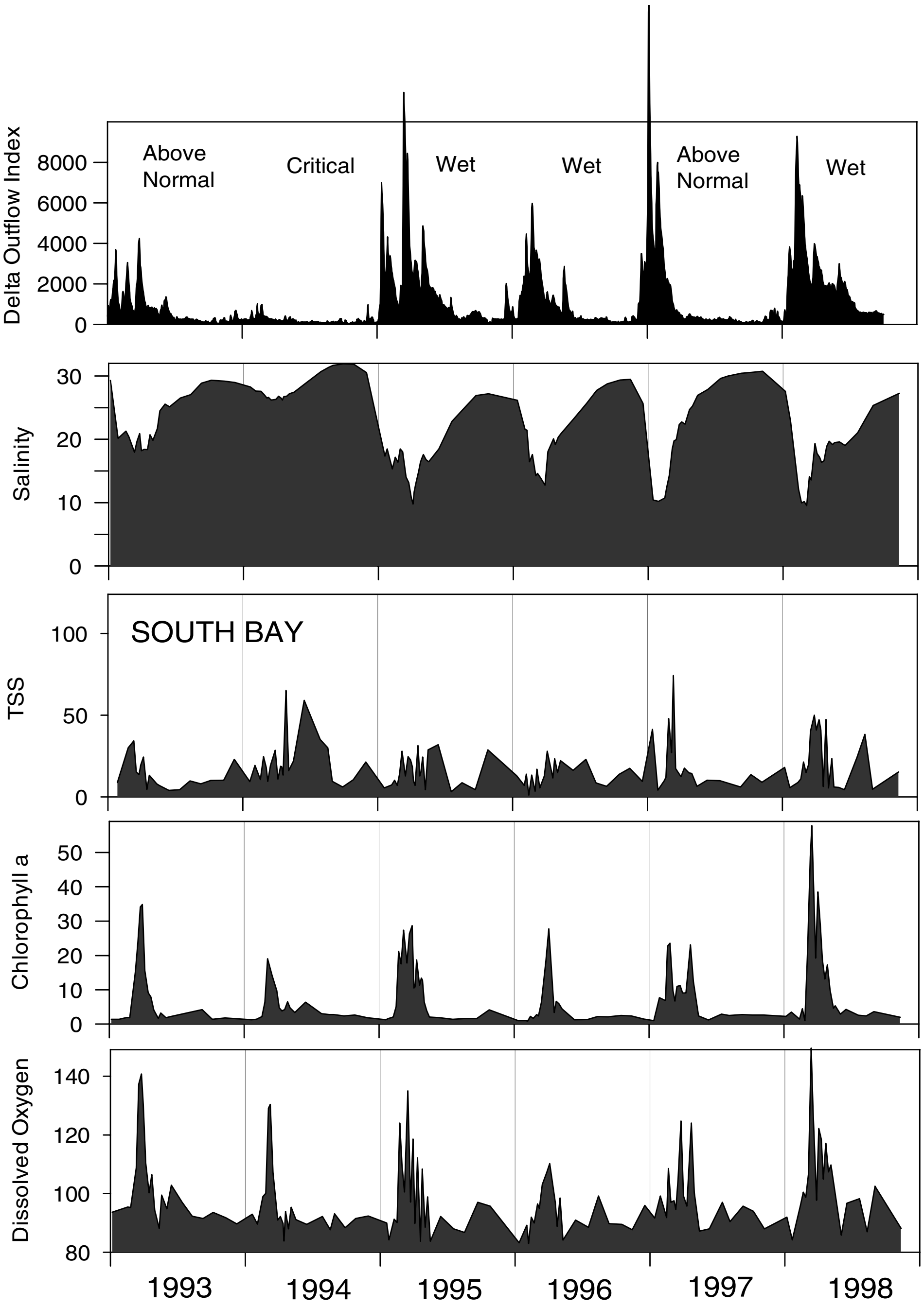

Figure 5. Upper panel shows the daily Delta Outflow Index (m^3/s, from the California Department of Water Resources) for water years 1993–1998, the first six years of the RMP. Lower panels show time series of surface salinity (psu), TSS (mg/L), chlorophyll a (mg/m^3), and dissolved oxygen (percent saturation) for South Bay. Each observation is the mean of measurements made at the 7 sampling sites within the South San Francisco Bay region (Figure 1).

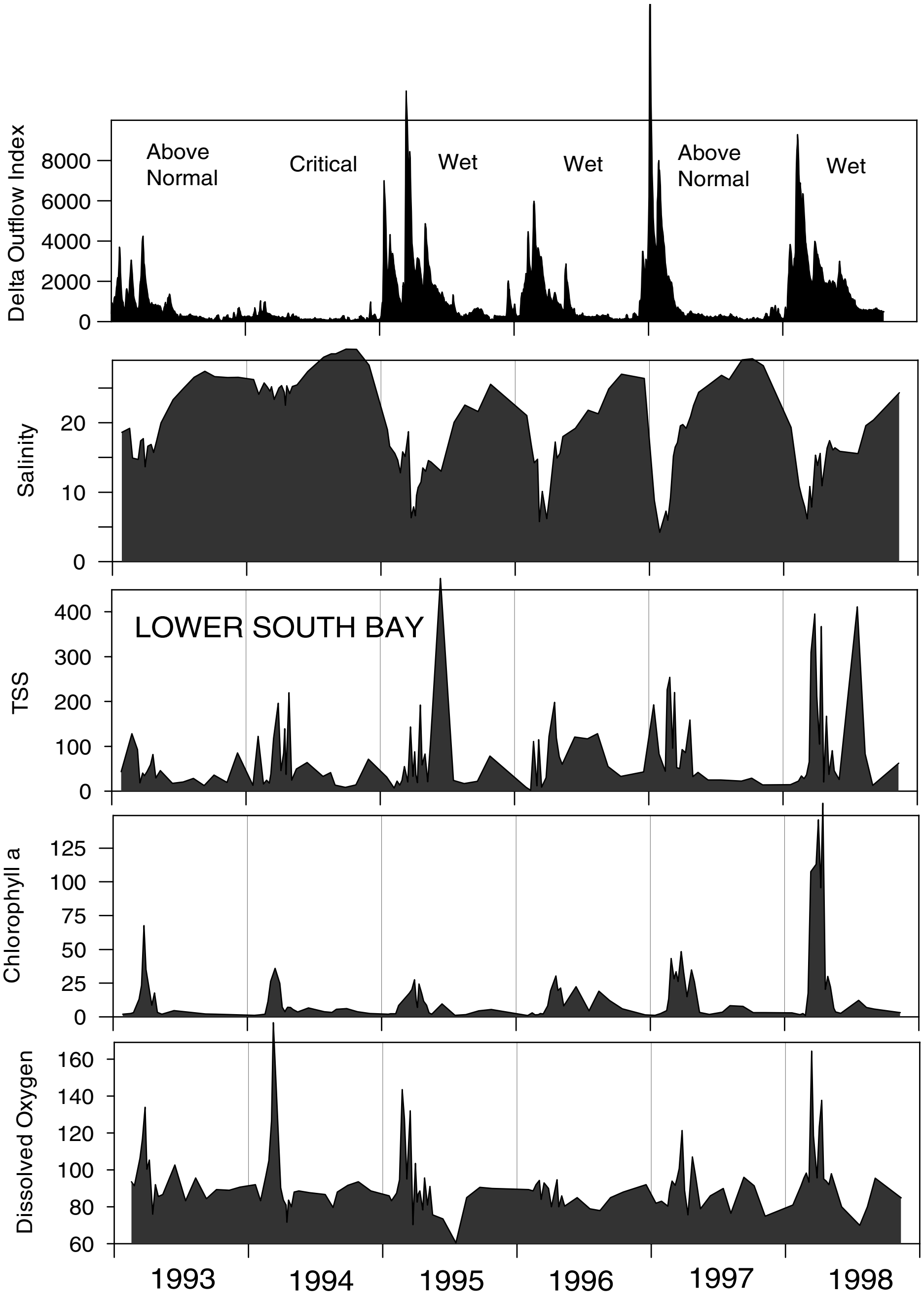

Figure 6. Upper panel shows the daily Delta Outflow Index (m^3/s, from the California Department of Water Resources) for water years 1993–1998, the first six years of the RMP. Lower panels show time series of surface salinity (psu), TSS (mg/L), chlorophyll a (mg/m^3), and dissolved oxygen (percent saturation) for Lower South Bay. Each observation is the mean of measurements made at the 3 sampling sites within the Lower South San Francisco Bay region (Figure 1).

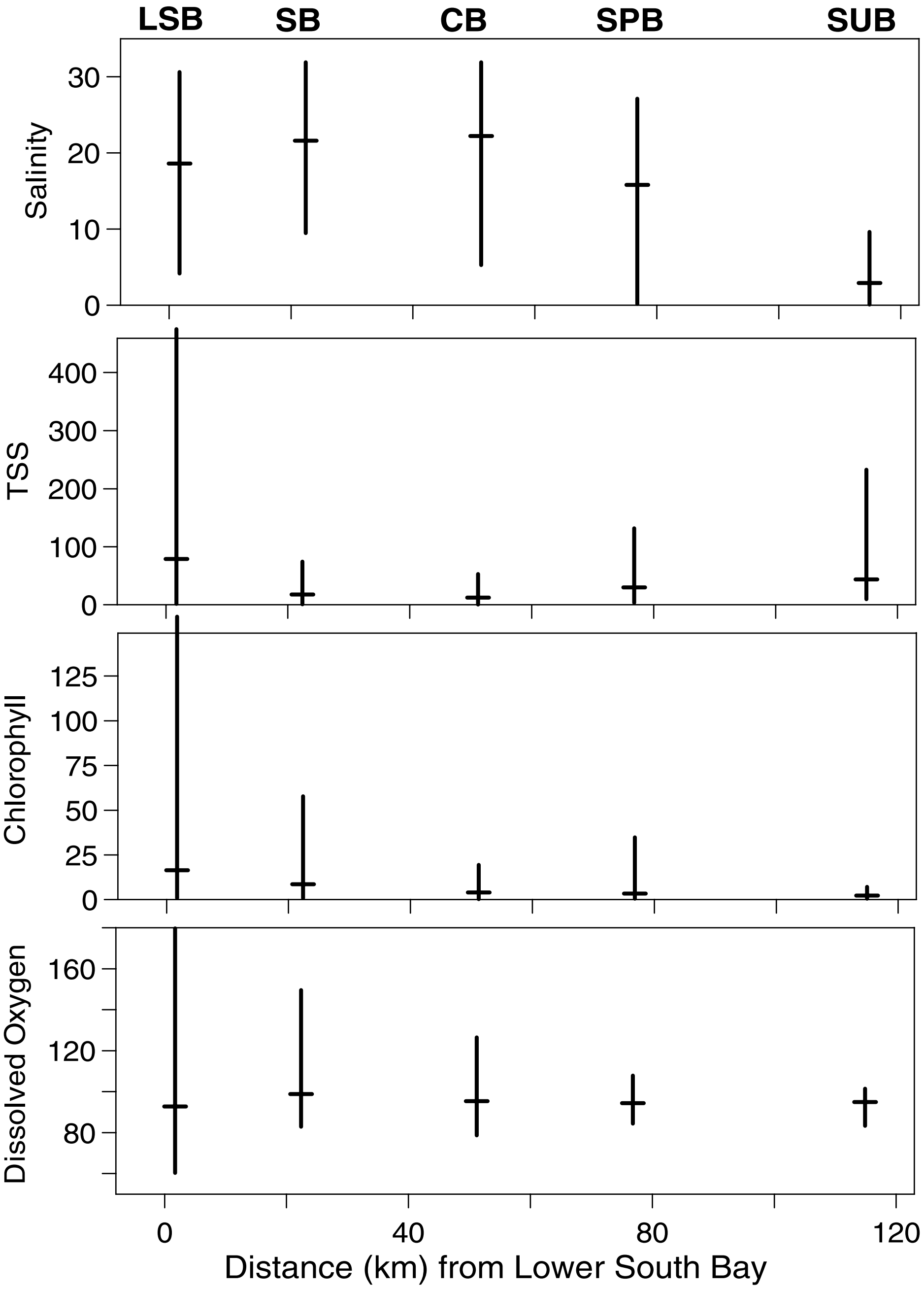

Figure 7. Mean spatial patterns of surface salinity, suspended solids (TSS), chlorophyll a, and dissolved oxygen in the five regions of San Francisco Bay: Lower South Bay (LSB), South Bay (SB), Central Bay (CB), San Pablo Bay (SPB), and Suisun Bay (SUB). Each horizontal bar shows the grand mean of all measurements made within each region during the period January 1993 through December 1998. Vertical bars show the range of measurements made within each region and for each water-quality constituent.

Interannual Variability in Water Quality: Contrast Between 1994 and 1998 as an Example

As an example of how water quality can change from year to year, we compare (Figure 8) spatial distributions of the four constituents during the April samplings of 1994 (a critically dry year) and 1998 (an exceptionally wet year). In April 1994, the Estuary was marine in character with surface salinity >25 psu throughout all of South Bay, Central Bay, and into San Pablo Bay. There was a near-linear longitudinal gradient of surface salinity between the Central Bay and Suisun Bay. However, during the April 1998 sampling this longitudinal salinity gradient was displaced about 40 km seaward, and surface salinity in the Central Bay and South Bay was only 10–16 psu. The displacement of the horizontal salinity gradient and dilution of surface salinities were responses to the exceptionally heavy precipitation and runoff during the 1997–1998 El Niño, when the Delta Outflow Index peaked above 9,000 m^3/s. This compares with 1994, when the DOI was persistently below 1,000 m^3/s.

River flow is a source of sediments, and years of high flow are years of high TSS concentration. This response is evident in Figure 8, showing that TSS concentrations were higher in San Francisco Bay during April 1998 than April 1994. A clearly-defined surface turbidity (TSS) maximum developed in San Pablo Bay during April 1998, while a smaller turbidity maximum developed upstream, in Suisun Bay, during April 1994. Large inputs of sediments to South Bay were evident from the very high TSS concentrations measured in lower South Bay during April 1998. At that time, TSS concentration exceeded 400 mg/L, among the highest surface TSS concentrations measured during the six-year period.

The 1998 wet El Niño was also a year of exceptional phytoplankton blooms; during April 1998 we measured a large chlorophyll *a* maximum (peak 34.8 mg/m^3) in San Pablo Bay and even higher chlorophyll *a* concentrations (> 150 mg/m^3) in lower South Bay (Figure 8). Chlorophyll *a* concentrations were uniformly low during April 1994. The April 1998 bloom in San Pablo Bay was the only large phytoplankton bloom observed there since 1993 (Figure 3), and it was reminiscent of the spring blooms that occurred routinely in San Pablo Bay before the arrival of the Asiatic clam *Potamocorbula amurensis* (Cloern *et al.*, 1985b). The chlorophyll *a* maximum in lower South Bay was also unusual, with chlorophyll *a* concentrations above 100 mg/m^3 during most of the month. The chlorophyll *a* maximum in San Pablo Bay did not coincide with elevated DO concentrations, and this suggests that the localized chlorophyll *a* maximum there (which paralleled the TSS maximum) developed through transport processes, such as estuarine gravitational circulation, that cause localized accumulations of suspended particles. However, the events of elevated chlorophyll *a* concentration in South Bay were periods of elevated DO, suggesting that the South Bay blooms were events of very high phytoplankton primary production (Figures 5 and 6).

The contrast of results from April 1994 and April 1998 shows that wet years are characterized by: diluted salinities throughout the Estuary, high TSS concentration and intense turbidity maxima that can develop as far seaward as San Pablo Bay, very high primary production and accumulation of exceptionally high phytoplankton biomass. All of these changes should be reflected in the form and spatial distribution of the trace substances measured in other elements of the RMP.

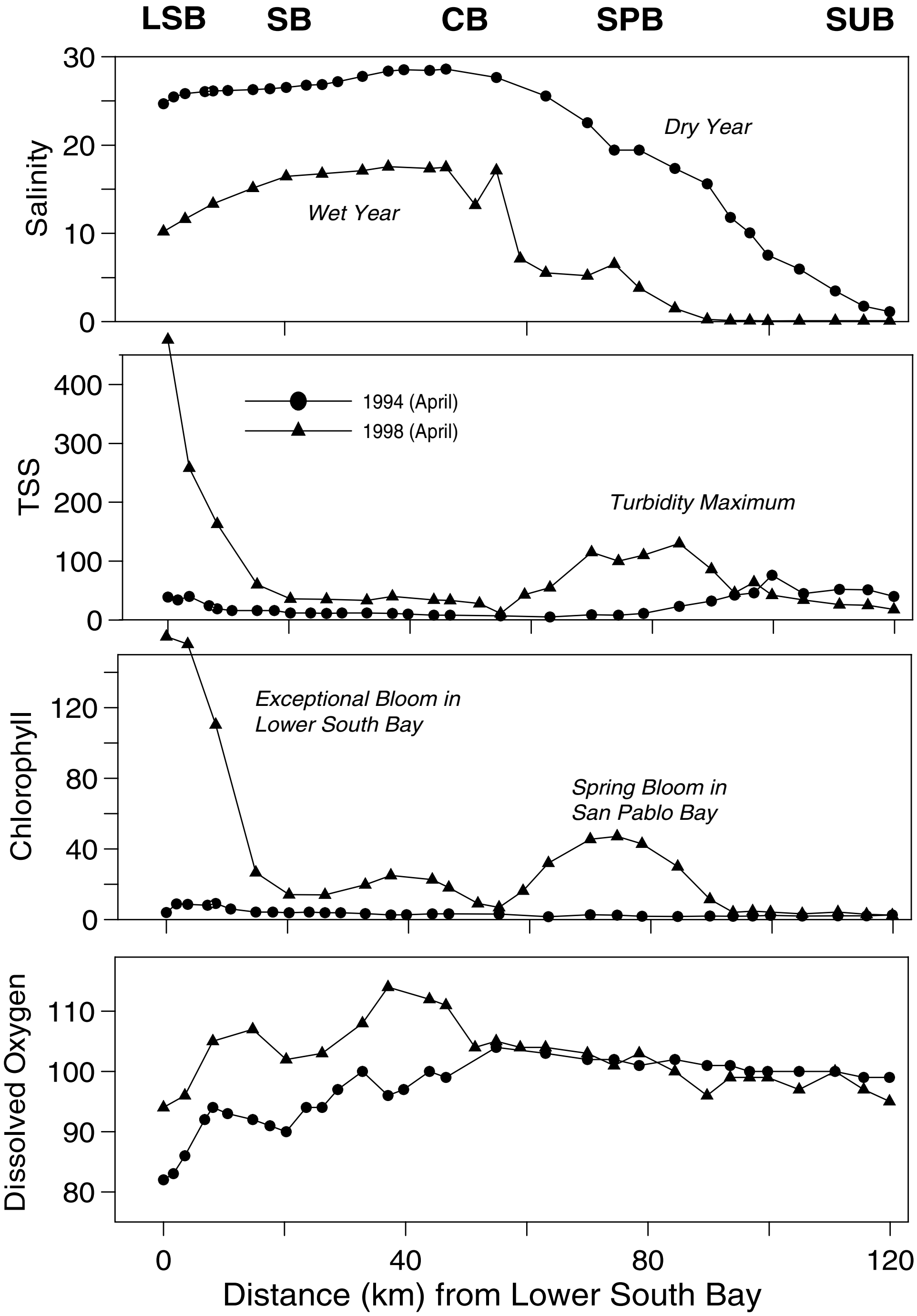

Figure 8. Interannual variability of water-quality indicators along the San Francisco Bay estuary, comparing results from spring (April) sampling during a critical dry year (1994) and a wet year (1998). Individual points show the mean salinity, TSS, chlorophyll a, and DO concentrations in the near-surface waters at each sampling station along the estuarine gradient, from the extreme lower South Bay to the lower Sacramento River.

Seasonal Variability in Water Quality: the 1996 Example

A second component of temporal variability in San Francisco Bay is associated with the large seasonal changes in river flow, especially those changes during the transition from the wet winter-spring to the dry summer-autumn. This scale of variability has been explicitly included in the RMP design, which has included sampling for trace substances during the wet season and dry season of each year since 1993. As an example of this component of variability, we compare (Figure 9) spatial distributions of the four constituents during the period of high river flow and biological activity (April) and the period of low river flow and biological activity (October), for the year 1996. The seasonal changes in water quality patterns between April and October of 1996 were surprisingly similar to the changing patterns between a wet (1998) and dry (1994) year, reflecting the overriding influence of river flow on the water quality of San Francisco Bay. Measurements during October 1996 are representative of low-flow conditions: near-marine salinity in South Bay, Central Bay, and San Pablo Bay, with salinity intrusion upstream into Suisun Bay (Figure 9); generally low TSS concentrations throughout the Estuary, reflecting the small riverine inputs of sediments; low chlorophyll *a* concentration and undersaturated DO, showing persistent low phytoplankton biomass and primary production.

During April 1996 the salinity distribution was very different, with large horizontal salinity gradients in both South Bay and the northern Estuary (Figure 9). This distribution, with a pronounced salinity maximum in Central Bay, is characteristic of wet seasons when the salinity of South Bay is diluted by locally-derived runoff and the salinity of the northern reach is diluted by Delta outflow. The separate influence of inputs from the South Bay watershed and Delta is also evident in the TSS distributions, which showed highest concentrations of suspended sediments in lower South Bay, minimum suspended sediments in Central Bay, and a surface turbidity maximum in the northern reach between San Pablo Bay and Suisun Bay (Figure 9). A large phytoplankton bloom developed in South Bay during April 1996, with chlorophyll *a* concentrations above 20 mg/m^3 and supersaturated dissolved oxygen.

This contrast of estuarine condition between April and October of 1996 illustrates some general features of seasonal water-quality variability in San Francisco Bay, including: the spring season of intense phytoplankton primary production (and associated biogeochemical transformations of trace substances); changes in the chemistry of South Bay caused by inputs of freshwater from the local watershed; and formation of turbidity maxima in the northern Estuary. All of these features disappear, or become damped, during the dry season when watershed inputs are greatly reduced.

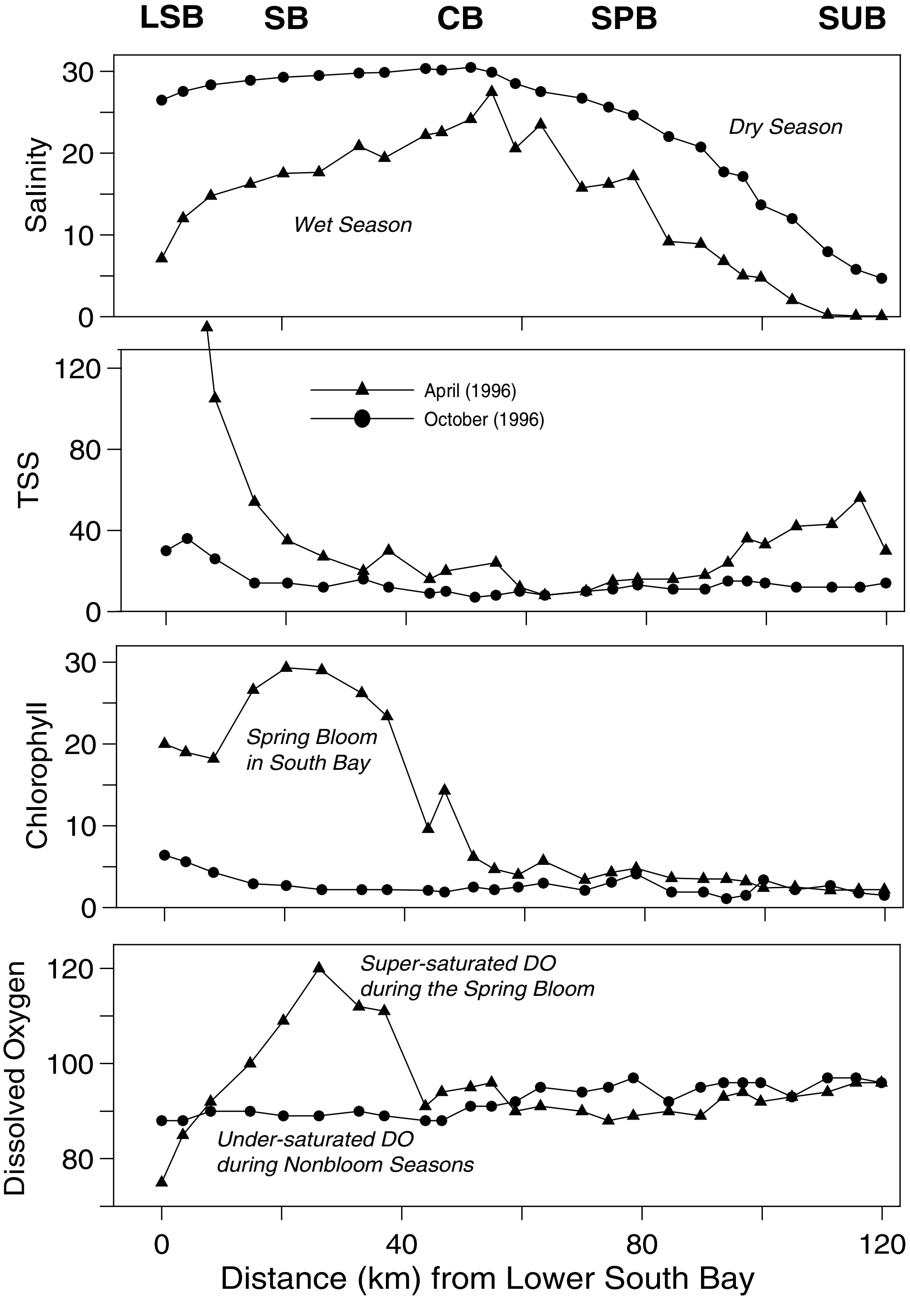

Figure 9. Seasonal variability of water-quality indicators along the San Francisco Bay Estuary, comparing results from spring (April) and autumn (October) sampling during 1996. Individual points show the mean salinity, TSS, chlorophyll a, and DO concentrations in the near-surface waters at each sampling station along the estuarine gradient, from the extreme lower South Bay to the lower Sacramento River.

Event-Scale Changes in Water Quality: Floods During The 1998 El Niño as an Example

The seasonal transition from the dry to wet condition does not necessarily happen gradually. Large flood events can cause rapid changes in the water quality of San Francisco Bay. During the past six years we have followed the rapid response to flood events of 1995, 1996, and the exceptional flood event of January 1997 (Cloern *et al.*, 1999). The 1998 El Niño provided another opportunity to document responses to hydrologic events, and we use the first large floods of 1998 to illustrate the magnitude of water-quality changes that can occur at the time scale of days to weeks. In Figure 10 we compare the spatial distributions of the four water-quality indicators from measurements made in January and February 1998. Between these two samplings, the Delta Outflow Index increased from only 134 m^3/s on January 1 to a peak of 9,294m^3/s on February 8. Sustained high DOI in early 1998 was a result of a series of El Niño-driven storms that produced twice the normal precipitation in January and three times the normal precipitation in February (Roos, 1998).

The distribution of salinity changed remarkably between January and February 1998, with rapid dilution of surface salinity and large-scale displacement (~50 km) of the salinity gradient along the northern reach (Figure 10). In response to this large flood event, surface salinity in South Bay and Central Bay dropped from 28–30 psu (only ~ 17 % freshwater) to about 10 psu (~ 70 % freshwater). Salinity changes in the bottom waters of the Estuary were less pronounced, but this event caused rapid and baywide dilution of salinity, indicating a rapid flushing event. The shape of the salinity distribution in South Bay (without a local salinity minimum in the lower South Bay) suggests that this particular event was driven by the large pulse input of Delta-derived flows rather than flows from the South Bay watershed. The distributions of TSS were consistent with this interpretation: TSS concentrations were high along the entire northern estuary, as far seaward as the Central Bay (Figure 10). However there was not clear evidence of Delta-derived inputs of sediments into the South Bay.

The spring phytoplankton blooms typically occur in South Bay during March and/or April, and these biological events can be triggered by inputs of freshwater that establish vertical salinity stratification (Koseff *et al.*, 1993; Cloern, 1996). Soon after the flood events of early 1998, we measured increases of both chlorophyll *a* and DO in South Bay (Figure 10), suggesting an anomalously early start to the season of bloom development. Supersaturation of DO confirmed that the period of high primary production began in February of 1998, and this early start to the bloom cycles may have been responsible, in part, for the exceptionally high phytoplankton biomass that accumulated later in the spring (see Figure 8).Our measurements during the 1998 wet El Niño year provide clear examples of how extreme climatic conditions can radically alter the water quality of San Francisco Bay.

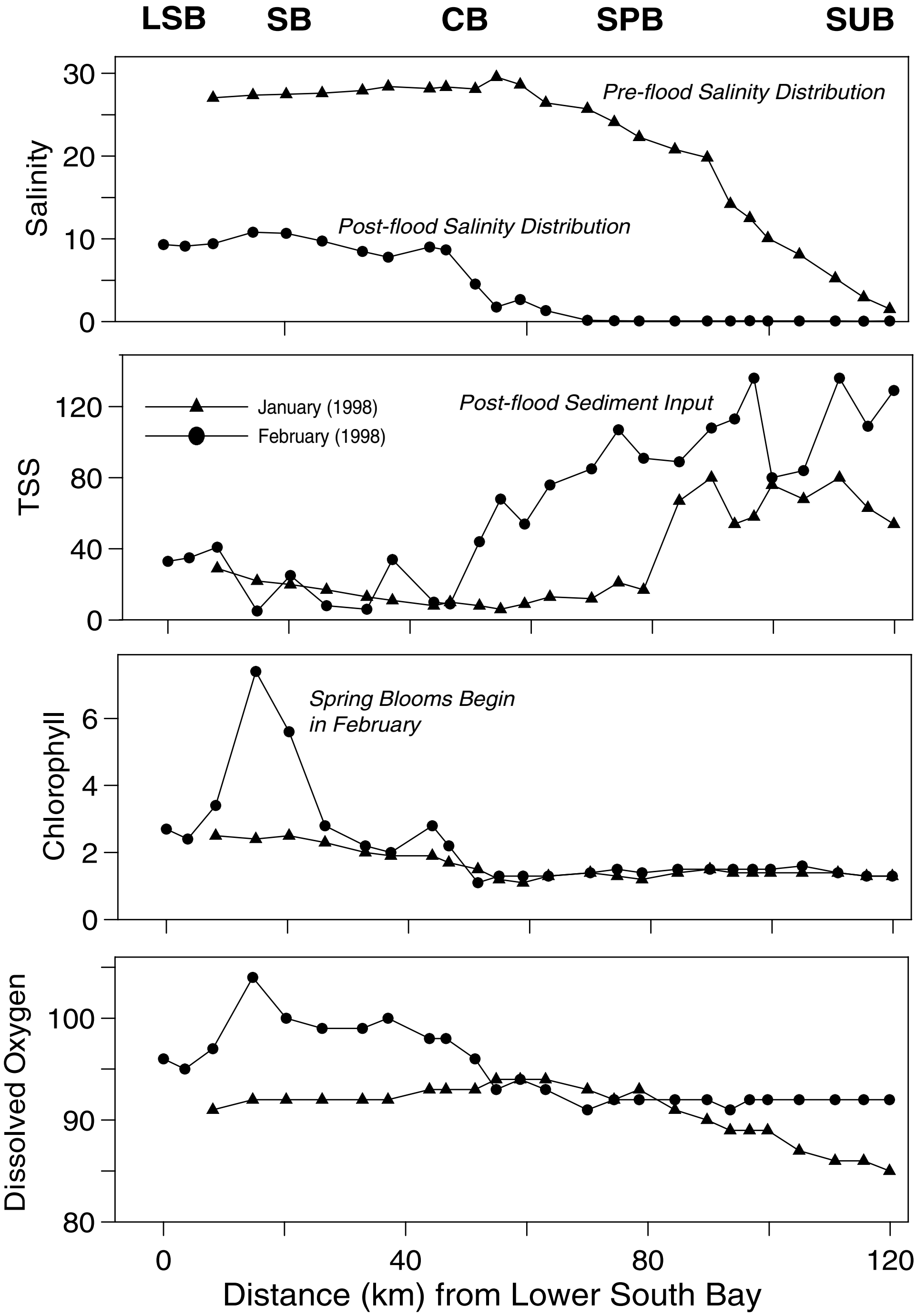

Figure 10. Event-scale variability of water-quality indicators along the San Francisco Bay Estuary, comparing results before (January) and after (February) a series of large flood events in 1998. Individual points show the mean salinity, TSS, chlorophyll a, and DO concentrations in the near-surface waters at each sampling station along the estuarine gradient, from the extreme lower South Bay to the lower Sacramento River.

Summary

One objective of the RMP is to identify trends of changing water quality as steps are progressively taken to reduce inputs of trace contaminants that threaten living resources or impair ecosystem functions. The detection of trends is a challenging problem in estuaries that are influenced by inputs from the coastal ocean, atmosphere, multiple watersheds, historic sources of contamination in sediments, and point sources. The specific goal of the USGS program is to follow, at monthly event scales, the changing distributions of four basic indicators of water quality. Results from the first six years of the RMP are used here to identify the mean spatial patterns along the Estuary, and to show the deviations around the mean patterns caused by interannual, seasonal, and episodic changes in the climate system. These primary patterns of spatial and temporal variability provide a foundation for interpreting and understanding the patterns of variability in the other constituents measured within the RMP.

Acknowledgments

This program of water-quality measurement in San Francisco Bay is a partnership supported by the U.S. Geological Survey (Water Resources Division National Research Program, Toxic Substances Hydrology Program) and the Regional Monitoring Program for Trace Substances. We thank the coordinators of these programs and the members of the San Francisco Estuary Institute and the San Francisco Regional Water Quality Control Board for their continuing support of this partnership.

References

Baylosis, J.I., J.L. Edmunds, B.E. Cole, and J.E. Cloern. 1997. Studies of the San Francisco Bay, California, Estuarine Ecosystem. Pilot Regional Monitoring Program Results, 1996. U.S. Geological Survey Open-File Report 97-598, 218 p.

Baylosis, J.I., B.E. Cole, and J.E. Cloern. 1998. Studies of the San Francisco Bay, California, Estuarine Ecosystem. Regional Monitoring Program Results, 1997. U.S. Geological Survey Open-File Report 98-168, 194 p.

Caffrey, J.M., B.E. Cole, J.E. Cloern, J.R. Rudek, A.C. Tyler, and A.D. Jassby. 1994. Studies of the plankton and its environment in the San Francisco Bay Estuary, California. Regional Monitoring Results, 1993. U.S. Geological Survey Open-File Report 94-82, 411 p.

Cloern, J.E., and F.H. Nichols, 1985a. Time scales and mechanisms of estuarine variability—a synthesis from studies of San Francisco Bay. Hydrobiologia 129:229-237.

Cloern, J.E., and F.H. Nichols, eds., 1985b. Temporal dynamics of an estuary—San Francisco Bay: Developments in Hydrobiology No. 30, Kluwer Academic Publishers, Dordrecht, 237 pages.

Cloern, J.E. 1996. Phytoplankton bloom dynamics in coastal ecosystems: A review with some general lessons from sustained investigation of San Francisco Bay, California. Reviews of Geophysics 34:127–168.

Cloern, J.E., B.E. Cole, J.L. Edmunds, and J.I. Baylosis. 1999. Water-quality variability in San Francisco Bay: general patterns of change during 1997. *In* 1997 Annual Report: San Francisco Estuary Regional Monitoring Program for Trace Substances. San Francisco Estuary Institute, Richmond, CA. pp. 67-81.

Edmunds, J.L., B.E. Cole, J.E. Cloern, J.M. Caffrey, and A.D. Jassby. 1995. Studies of the San Francisco Bay, California, Estuarine Ecosystem. Pilot Regional Monitoring Program Results, 1994. U.S. Geological Survey Open-File Report 95-378, 436 p.

Edmunds, J.L., B.E. Cole, J.E. Cloern, and R.G. Dufford. 1997. Studies of the San Francisco Bay, California, Estuarine Ecosystem. Pilot Regional Monitoring Program Results, 1995. U.S. Geological Survey Open-File Report 97-15, 380 p.

Granéli, W., and E. Granéli. 1991. Automated potentiometric determination of dissolved oxygen. Marine Biology 108:341–348.

Hager, S.W. 1993. Dissolved nutrient and suspended particulate matter data for the San Francisco Bay Estuary, California. October 1988 through September 1991. U.S. Geological Survey, Open-File Report 93-57.

Jassby, A.D., J.E. Cloern, and T.M. Powell. 1993. Organic carbon sources and sinks in San Francisco Bay: variability induced by river flow. Marine Ecology Progress Series 95:39–54.

Jassby, A.D., B.E. Cole, and J.E. Cloern. 1997. The design of sampling transects for characterizing water quality in estuaries. Estuarine, Coastal and Shelf Science 45:285–302.

Koseff, J.R., J.K. Holen, S.G. Monismith, and J.E. Cloern. 1993. Effects of vertical mixing and benthic grazing on phytoplankton populations in shallow, turbid estuaries. Journal of Marine Research 51:843–868.

Lorenzen, C.J. 1967. Determination of chlorophyll and phaeopigments: spectrophotometric equations. Limnology and Oceanography 12:343–346.

Luoma, S.N., A. van Geen, B.-G. Lee, and J.E. Cloern. 1998. Metal uptake by phytoplankton during a bloom in South San Francisco Bay: Implications for metal cycling in estuaries. Limnology and Oceanography 43:1007–1016.

Powell, T.M., J.E. Cloern, and R.A. Walters. 1986. Phytoplankton spatial distribution in South San Francisco Bay—mesoscale and small-scale variability. *In* D.A. Wolfe, ed., Estuarine Variability. Academic Press, NY., pp. 369–383.

Powell, T.M, J.E. Cloern, and L.M. Huzzey. 1989. Spatial and temporal variability in South San Francisco Bay. I. Horizontal distributions of salinity, suspended sediments, and phytoplankton biomass and productivity. Estuarine, Coastal and Shelf Science 28:583–597.

Riemann, B. 1978. Carotenoid interference in spectrophotometric determination of chlorophyll degradation products from natural populations of phytoplankton. Limnology and Oceanography 23:1059–1066.

Roos, M. 1998. Water year 1997–98. Newsletter, Interagency Ecological Program for the Sacramento-San Joaquin Estuary 11:11–14.