Salinity and Temperature in South San Francisco Bay, California, at Dumbarton Bridge: Measurements from the 1995-1998 Water Years and Comparisons with Results from the 1990-1993 Water Years

By Laurence E. Schemel

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U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

U.S. Geological Survey
Water Resources Division
345 Middlefield Road, MS439
Menlo Park, California 94025

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CONVERSION FACTORS

Metric units are used in this report. For readers who prefer inch-pound units, the conversion factors for the terms used in this report are listed below.

Multiply	BY	To obtain
m^3/s (cubic meters per second)	35.31	cubic feet per second
cm (centimeters)	0.3937	inch
m (meter)	3.281	foot
m^2	10.76	square feet

Temperature is given in degrees Celsius (°C) and can be converted to degrees Fahrenheit (°F) using the following:

$$(^{\circ}F) = 1.80\ (^{\circ}C) + 32$$

Salinity is given in units of the Practical Salinity Scale. This is roughly equivalent to parts-per-thousand units used in previous scales for values greater than about 3 psu.

SALINITY AND TEMPERATURE IN SOUTH SAN FRANCISCO BAY, CALIFORNIA, AT DUMBARTON BRIDGE: MEASUREMENTS FROM THE 1995-1998 WATER YEARS AND COMPARISONS WITH RESULTS FROM THE 1990-1993 WATER YEARS.

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ABSTRACT

Salinity and temperature of near surface waters were measured during the 1995-1998 water years (WY) at Dumbarton Bridge in South San Francisco Bay. This report presents the methods, describes the results, and provides numerical values for the measurements in ASCII text files on the enclosed IBM formatted disk. The four years of this study were unusual in that they were the first extended period of greater-than-normal rainfall and river inflow to San Francisco Bay since the early 1980's. Results from 1995WY-1998WY provide detailed information on the influences of freshwater inflows (from the Sacramento-San Joaquin Delta and from local streams) and climate- and weather-related events and processes on salinity and temperature at the study site. Earlier records from this site were collected over the 1990-1993 water years, the first three years of which had lower-than-normal rainfalls and freshwater inflows. Comparisons of the 1995WY-1998WY record with measurements from 1990WY-1992WY showed generally higher salinity and less variability in salinity during the dry years. Details show a rapid response to local freshwater inflows and the influence of the general freshening of the bay by Delta outflow during the wet winters. Records from both wet and dry years show that salinity and temperature respond to weather events and climate variations over time scales of days to months.

INTRODUCTION

During the summer of 1989, the U.S. Geological Survey (USGS) in cooperation with the California State Department of Water Resources (CDWR) established a monitoring and research site in southern San Francisco Bay (South Bay) on the east span of the old Dumbarton Bridge (fig. 1). Physical and chemical properties of the water column were measured during the 1990-1993 and 1995-1998 water years[1] (WY; 1995WY = October 1994 through September 1995). During 1990WY-1993WY, salinity, temperature, and water level were measured at 15-minute intervals by electronic sensors located approximately 2m off the bottom. Results were reported by Schemel (1995a). During 1995WY-1998WY, salinity and temperature were measured at 15-minute intervals by electronic sensors that floated 1m below the surface of the water. This report presents the methods, describes the results, and provides numerical values for the measurements collected over these four water years. General hydrographic characteristics of South Bay also are summarized. The 1995-1998 water years were unusual in that all four years had higher than normal rainfall. As a consequence, stream and river discharges (flows) to the bay were greater than normal and very different compared to 1990WY-1993WY. Aspects of bay-system hydrology, including general climatology and variability in seasonal and annual patterns over 1990WY-1998WY, also are described.

Objectives of the 1990WY-1993WY and 1995WY-1998WY studies were to observe changes in salinity and temperature and tides (measured by water level or calculated) and to relate them to other variables, particularly those associated with biogeochemical processes, interannual and seasonal climate variations, and weather-related events (winds, rainfall, and runoff to the bay; for examples see Schemel and Hager, 1996). In addition, these studies contribute basic data for other on-going ecosystem and hydrodynamic research conducted by USGS, CDWR, other federal and state agencies, and universities.

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[1] Several short records of salinity, temperature, and water level were collected for special studies and to develop new instrumental techniques during the 1994 water year. These records are unpublished, but data are available from the author.

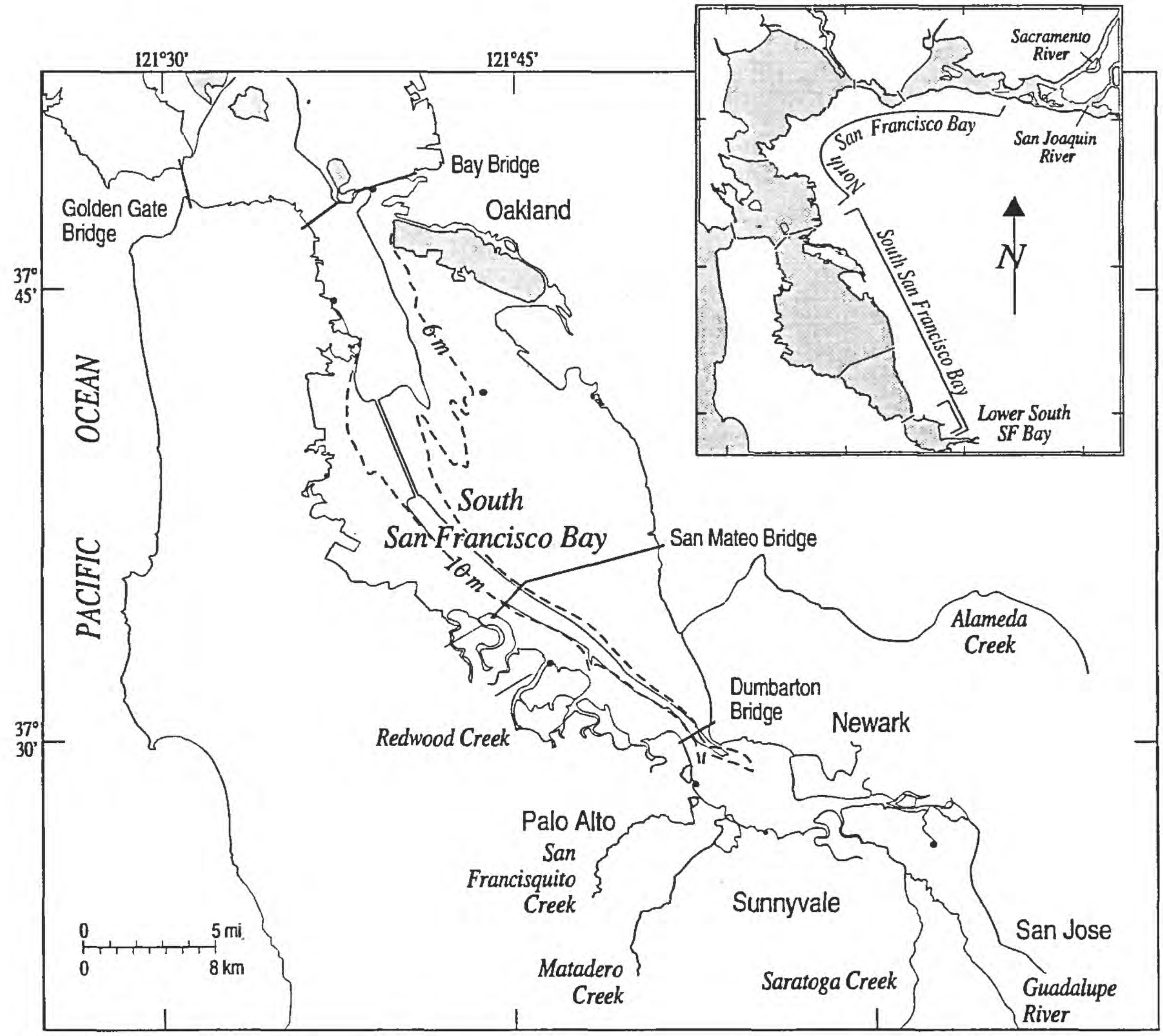

Fig. 1. Map showing San Francisco Bay and locations in South San Francisco Bay.

Hydrologic Characteristics of the 1990-1998 Water Years

The 1995-1998 water years were the first extended period of greater-than-normal rainfall to the San Francisco Bay drainage since the early 1980's. Figure 2 shows the long-term (149-year) record of total annual[2] rainfall for San Francisco (downtown at Mission Dolores). Rainfall was below normal (long-term average of 55.3cm) for 1987WY-1992WY and 1994WY. Rainfall totals for 1993WY and 1995-1998WY were above normal. The total for 1998WY was the second highest on record, exceeded only by 1862WY, the year with the most extensive flooding on record (for a description of this flood see Peterson and others, 1985). During 1995WY-1998WY, high rainfall produced runoff that flooded local watersheds as well as extensive areas of the Sacramento River and San Joaquin River drainages. Locally, the highest flows on record were measured for San Francisquito Creek in February 1998 and for the Guadalupe River in March 1995. Record flows in many rivers in northern and central California resulted in extensive flooding in January 1997, particularly in the Sacramento River valley.

Monthly measurements of rainfall from the San Francisco International Airport (SFO in fig. 1; fig. 3) show that rainfall during most months of 1995WY-1998WY was above normal, with the exception of the unusually dry spring in 1997WY. In contrast, rainfall during most of the winter and spring months of 1990WY-1992WY were below normal (fig. 3). This illustrates an important difference between conditions during our previous set of measurements (1990WY-1993WY) and those for the results presented in this report. Rainfall and runoff (streamflow) dilute bay waters (lower salinity), and can change water temperature. In addition, storm fronts often produce lower air temperatures and can cool bay waters.

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[2] Annual totals for rainfall are usually calculated for July through June. Totals shown in fig. 2 were calculated for the water year, October through September. Monthly rainfall totals that were used to compute these values are available at URL: http://ggweather.com/sf/monthly.html.

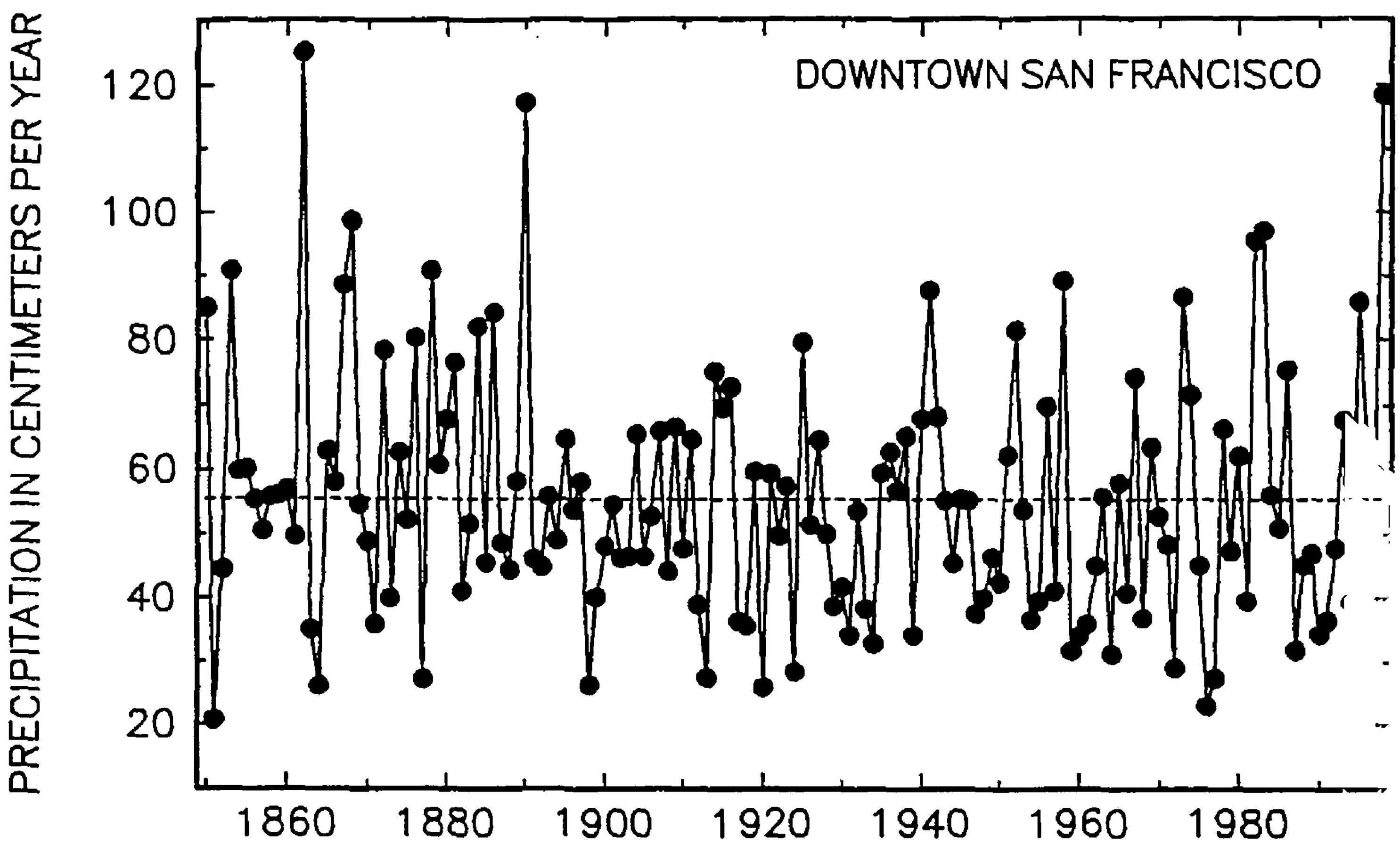

Fig. 2. Graph showing total annual precipitation in downtown San Francisco at Mission Dolores for the 1850-1998 water years.

Also shown in fig. 3, the normal monthly total rainfall varies greatly during each year, and rainfall is largely limited to late fall through early spring. As a consequence, evaporation from South Bay, which is greatest in summer, typically exceeds precipitation many months of the year (see Hager and Schemel, 1996). Years with relatively dry springs, such at 1997WY, result in longer periods when effects of evaporation can intensify. Direct effects of evaporation on concentrations of dissolved substances are most apparent in the reach landward of the San Mateo Bridge (landward reach) because of shallow water depths and large intertidal areas (Fig. 1; Schemel and Hager 1996).

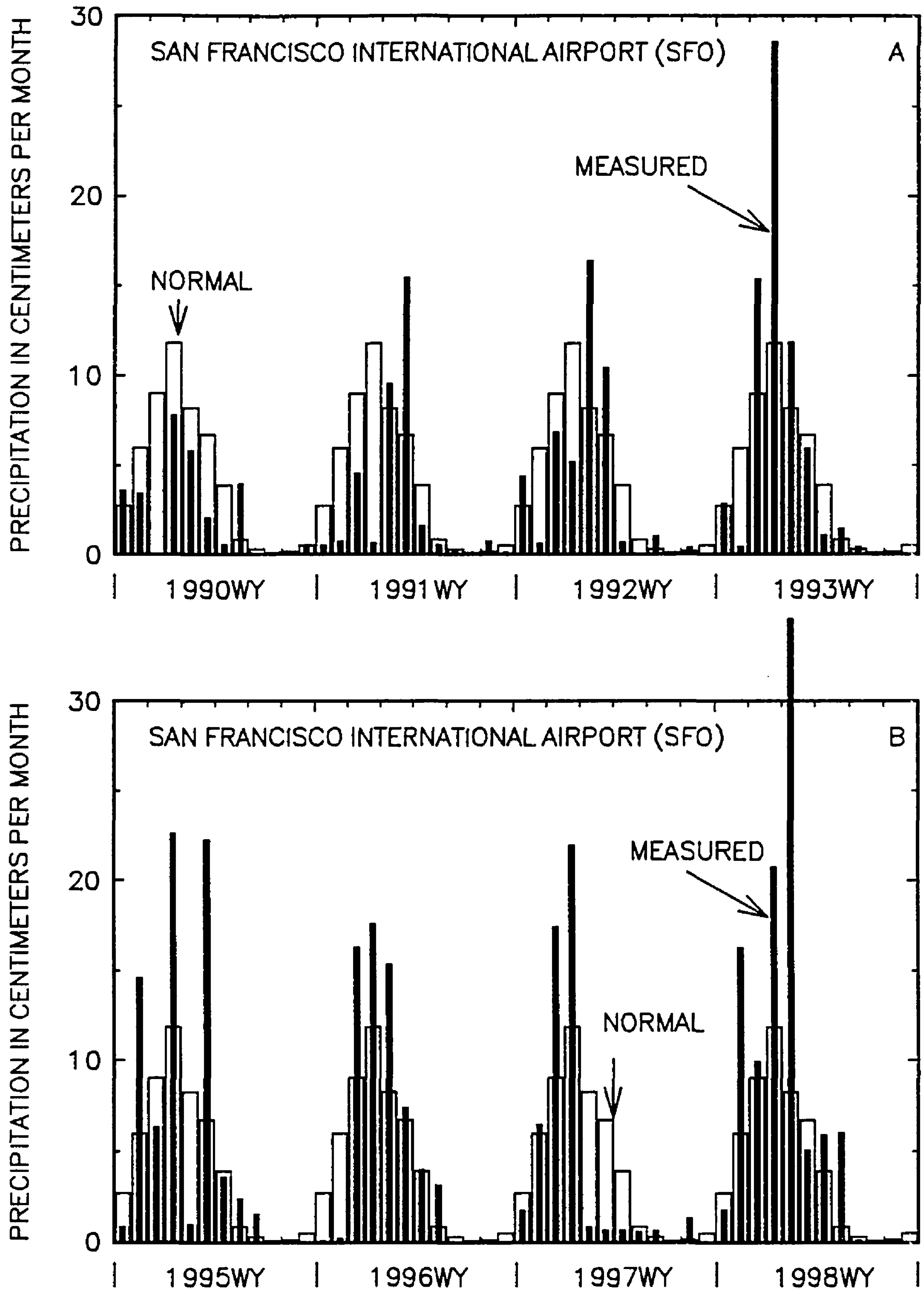

Fig. 3. Monthly values for precipitation at San Francisco International Airport (SFO) for water years 1990-1993 (A) and 1995-1998 (B).

Large variability in the amount of precipitation in northern California over 1990WY-1997WY is reflected in the flow of Delta outflow to northern San Francisco Bay (North Bay; fig. 4), and in runoff from local streams into the landward reach of South Bay (fig. 5). The level of Delta outflow directly affects salinity and a suite of other water-column variables in North Bay, which in turn influence conditions in South Bay. Daily values for Delta outflow shown in fig. 4 were computed by CDWR using the DAYFLOW97 program. Published values for Delta outflow and local stream flows were not available for 1998WY at the time this report was prepared.[3] Delta outflow values based on DAYFLOW extend back to 1956, but estimates have been made for years since 1922. This provides a 76-year, long-term record for comparisons.

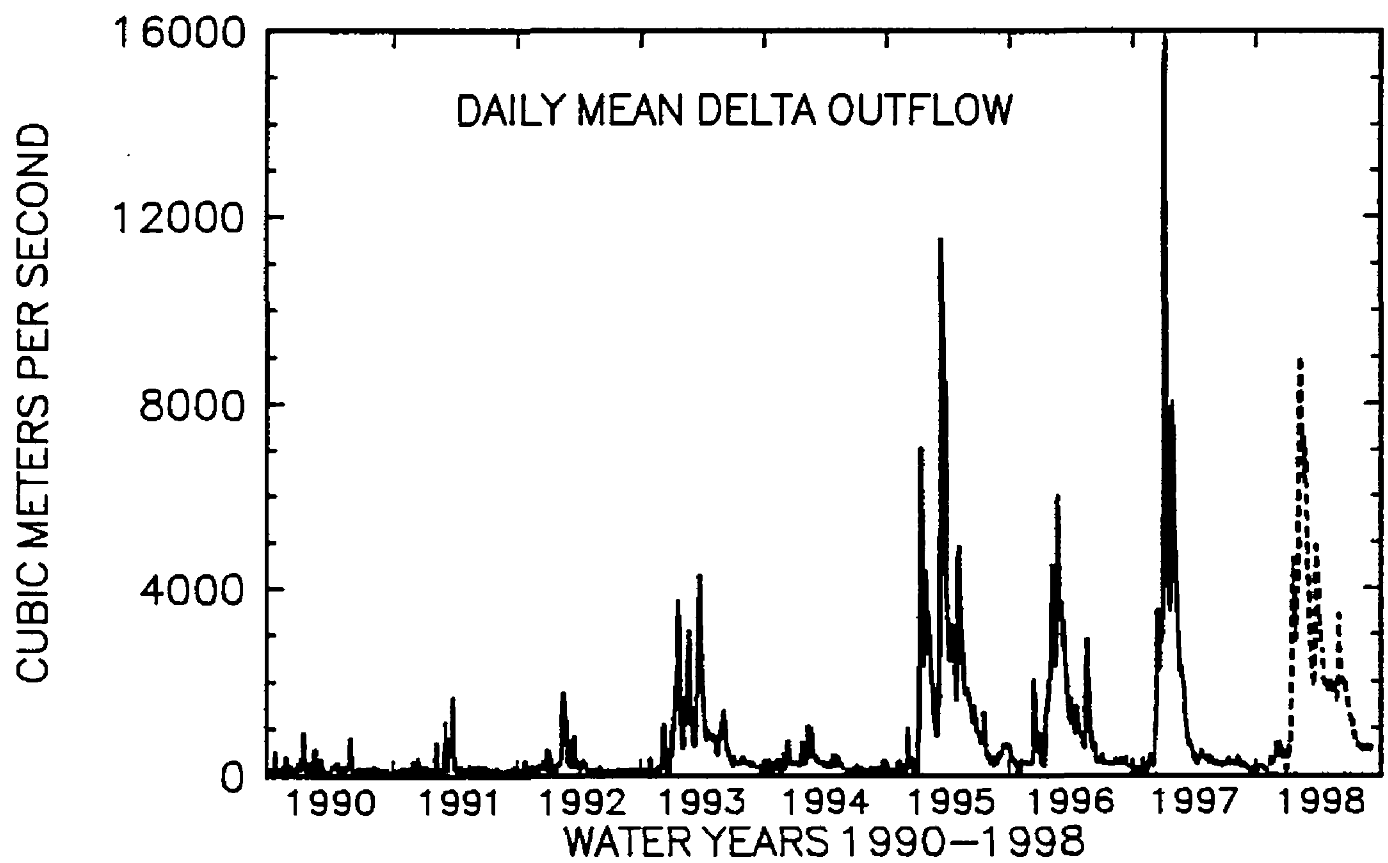

Fig. 4. Daily mean outflow from the San Francisco Bay delta for water years 1990-1998. Data for 1998 are estimates (see text).

[3] Delta Outflow Index (DOI), an estimate based on provisional values for flows, is used in place of Delta outflow for the 1998 water year in the presentation of results from this study.

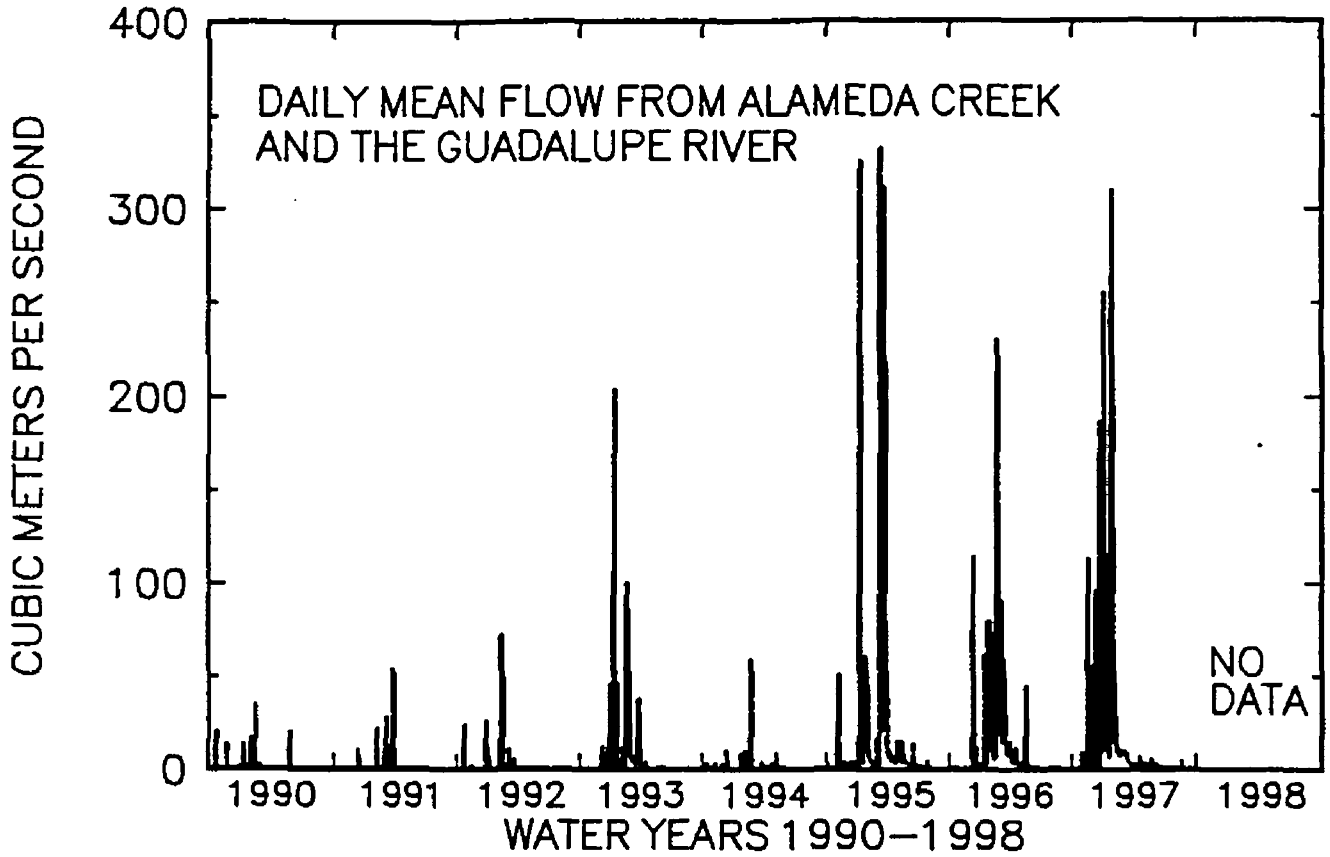

Fig. 5. Total daily mean flow from Alameda Creek and the Guadalupe River to South San Francisco Bay for the 1990-1997 water years. Data are from USGS annual reports for 1990-1997. Data for 1998 were not available when this report was written.

Annual and winter totals for Delta outflow over 1990WY-1992WY and 1994WY were among the (nine) lowest on record. Delta outflow for 1993WY corresponded to the annual median value for the 76-year record, and ranked above the median value for winter flow. In contrast, annual and winter totals for the 1997 water year were the second highest on record (1983 was the highest). Values for 1995WY and 1996WY ranked 5th and 47th in winter flow and 6th and 13th in annual flow, respectively. Estimates based on Delta Outflow Index indicate that 1998WY should rank higher than 1997 for winter flow and rank within the top four years for annual flow.

Delta outflow is the product of regional weather conditions over a very large area of northern California, including the western slope of the Sierra Nevada mountain range. Local streamflow to South Bay, however, is controlled largely by local weather, and it is limited by small drainage basins. Consequently, runoff from local streams to South Bay is much lower than Delta outflow to North Bay. The actual amount of runoff to South Bay from streams and urban drains is unknown because few of these discharges are gaged near the bay (See Hager and Schemel, 1996). In most cases, discharge from local streams is significant only during and immediately following major storms (fig. 5). Because inflow from local streams is largely limited to late fall, winter, and early spring, municipal waste facilities discharge most of the freshwater to South Bay most of the year (see below).

Hydrographic Characteristics of South Bay

Hydrographic characteristics of South Bay have been summarized by Conomos and others (1979) and more recently by Hager and Schemel (1996). Some important features are reviewed here.

South Bay is a tributary estuary of North Bay (fig. 1), the estuary of the Sacramento-San Joaquin River system. South Bay is often described as a lagoon-like system, because its drainage basin is small and direct runoff to the bay is small relative to the total volume of the bay. Salinity and other water-column variables in South Bay are affected by changes in water quality conditions in the main estuary, North Bay. Much of the hydrodynamic research on South Bay (for example see Walters and others, 1985) has focused on the complex interactions between North Bay and the reach seaward of San Mateo Bridge (seaward reach). However, relatively little information has been available to evaluate responses of the landward reach of South Bay to a variety of climate- and weather-related factors, including inflow from local streams.

Table 1. Hydrographic and geographic characteristics of South San Francisco Bay (South Bay). Values are based on relations between tidal height and sectional volumes and areas presented by Selleck and others (1966). HHW = Higher High Water; LLW = Lower Low Water

Section	Area ($10^8 m^2$)			Volume ($10^9 m^3$)		
	Mean LLW	Mean	Mean HHW	Mean LLW	Mean	Mean HHW
Bay Bridge to San Mateo Bridge	3.5	3.7	3.8	1.8	2.1	2.4
San Mateo Bridge to Dumbarton Bridge	0.68	0.88	0.10	0.26	0.34	0.42
South of Dumbarton Bridge	0.19	0.34	0.46	0.058	0.086	0.12

Note: The mixed tide produces two low tides and two high tides (usually of unequal heights, e.g,Lower High Water, LHW, and Higher High Water, HHW, each lunar day (24.8h).

Hydrographic characteristics (sectional water volumes and areas; table 1) vary greatly between the landward and seaward reaches of South Bay. The term, landward reach, refers to all of the bay landward of San Mateo Bridge, including Lower South Bay. Landward and seaward reaches as defined here do, in fact, show different circulation characteristics (Powell and others 1986).

Approximately 83 percent of the mean-tide volume of South Bay is contained in the seaward reach, which also contains 75 percent of the surface area at mean tide level. South Bay narrows considerably landward of San Mateo Bridge to a strait at Dumbarton Bridge. The small basin landward of Dumbarton Bridge, Lower South Bay, is about 20 percent of the total volume of the landward reach at mean tide level.

In addition to the smaller volume and area, other important features distinguish the landward reach from the seaward reach. Water depth at mean tide in the landward reach averages 3.5m, compared to about 6m in the seaward reach. The average water depth in Lower South Bay is only 2.6m at mean tide, and there are large changes in surface area, volume, and depth over the tidal range (table 1.). About 85 percent of the South Bay watershed drains into the landward reach (USGS 1962; U.S. Environmental Protection Agency, USEPA, 1992). Therefore, effects of inflow from local streams are potentially greatest in the landward reach. The direct influence of mixing with North Bay waters is greatest in the seaward reach. However, most of South Bay can be affected by conditions in North Bay when Delta outflows are high (McCulloch and others, 1970; Imberger and others, 1977).

About half the total municipal waste flow to South Bay discharges into the small basin of Lower South Bay (USEPA, 1991; Fig. 6). Most of the remaining waste enters South Bay in the seaward reach near the Bay Bridge, where it is rapidly dispersed into a large volume of water. Dumbarton Bridge is an important location to characterize variability in water-column properties because municipal waste entering Lower South Bay must travel through Dumbarton Strait to leave the estuary. Municipal waste discharge to Lower South Bay contributes to strong longitudinal gradients in salinity and in concentrations of waste-derived solutes in the landward reach (Conomos and others, 1979). Consequently, the movement of water by tides alone contributes to large, short-term variations in water-column properties at Dumbarton Bridge (see Schemel, 1995a).

Diurnal range of the tide increases landward in South Bay, increasing from about 1.7m at Golden Gate to 2.6m at Dumbarton Bridge (Selleck and others, 1966). This increase in tidal range combined with shallow water depths in the landward reach results in tidal prisms (the volume of water that is moved by the tide) that are large compared to the volumes of water at mean tide level. This is greatest in Lower South Bay, where the volume at mean lower low water is less than half the volume at mean higher high water. In addition, the area covered by water in Lower South Bay at mean lower low water is less than half the surface area at mean higher high water, indicating that over half of Lower South Bay consists of shallow mud flats that are exposed at low tides.

The tidal prism of Lower South Bay is equivalent to about 24 percent of the volume of the basin bounded by the San Mateo and Dumbarton Bridges at mean lower low water.

Currents generated by the tides not only move water masses, but also mix the water column, particularly during periods of strong tides. In addition to two high tides and two low tides each lunar day (24.8 hr), there are diurnal differences between the two high and the two low waters and the corresponding current speeds. The tides and the tidal currents also vary on about a two-week period, with two periods of stronger (spring) tides and two periods of weaker (neap) tides per month. Likewise, semi-annual cycles with two periods of weak tides near the equinoxes and periods of strong tides near the solstices are apparent in the tidal record. Thus, longitudinal transport and mixing due to tides varies on time scales from hours to months.

Weather and climate variables are also important to transport and mixing in South Bay. Winds can be effective in mixing the water column in South Bay and in generating currents that move water masses (Walters and others, 1985; Huzzey and others, 1990; Schemel and Hager, 1996; Cheng and others, 1998). Depending on wind speed and direction and the bathymetry of South Bay, wind can produce net currents that enhance or oppose residual circulation driven by tides or other processes. An annual pattern in wind speeds in South Bay is apparent, with generally stronger daily mean wind speeds in late spring through summer (Conomos and others, 1985; Schemel, 1995b). These seasonal winds are typically from the west or north-west, and vary in speed over the day. Wind speeds are low at night, then increase during daylight hours to maximum values in the late afternoon. During winter and spring, storm fronts and other weather-related phenomena produce strong winds that usually last for a few days. During storms, winds will often increase in speed from the south, then blow from the north after passage of the front. Strong winds from the north are particularly effective in moving surface waters landward in South Bay (Walters, 1982). Strong winds, in general, are effective in mixing the water column in most areas of South Bay.

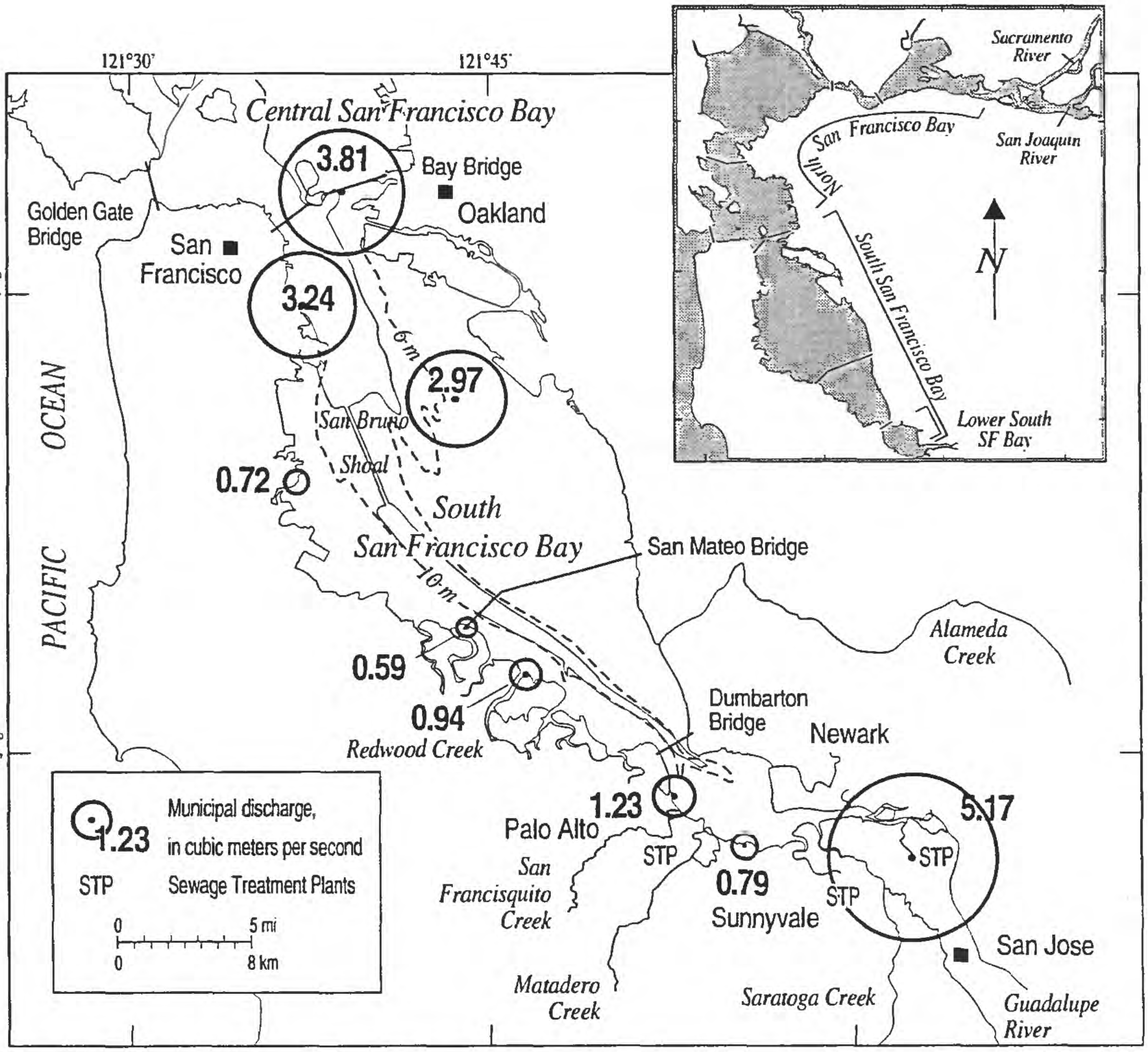

Fig. 6. Locations and mean discharges for municipal waste treatment plants in South San Francisco Bay.

Acknowledgments

This study would not have been possible were it not for dedicated volunteers. In particular, I would like to thank Norton Bell for writing the computer programs that controlled the bouy systems, and for writing other programs that calculated the final values for salinity and temperature from the bouy data and predicted tidal heights. I gratefully acknowledge support from the California Department of Water Resources and specifically thank Randy Brown for his encouragement. The U.S. Fish and Wildlife Service maintained the pier facilities. Helpful reviews of this manuscript by M.H. Cox and R.J. Avanzino are appreciated, as well as other contributions by my colleagues at the U.S. Geological Survey.

METHODS

After construction of the new Dumbarton Bridge, which parallels the old bridge approximately 50m seaward, the center section of the old Dumbarton Bridge was demolished and the remaining eastern causeway was converted to a public fishing pier. The California State Department of Water Resources built a small structure near the west end of the fishing pier during summer 1989 to house instruments for monitoring water-column properties. Water depth at mean tide level was approximately 6m. The U.S. Geological Survey installed sensors near the bottom of the water column to measure salinity, temperature, and water level. Data were collected with these sensors during the 1990-1993 water years. Methods for this study were described by Schemel (1995a). Beginning in November 1995 and continuing through the 1998 water year, salinity and temperature were monitored with a sensor system that floated 1m below the surface of the water. Details of the instruments and methods used in this study are described below.

Two instrument wells were cut into the floor of the structure, and each well was equipped with a hand winch, stainless steel cable, and a 50 kg cement weight. The instrument package was attached to a bouy assembly on one of the stainless steel cables. The bouy assembly consisted of a plastic float with a plastic-lined stainless steel tube passed through its center hole and extending below the float. Two brackets on the tube held the instrument packages at a depth 1m below the surface of the water.

Each instrument package was constructed of a PVC plastic housing attached to a stainless-steel end cap, where an electrodeless conductivity sensor and linearized thermistor elements were mounted. Electronic circuitry for the sensors, a battery pack, and a controller-logger were contained in the plastic housing. Sensors and related electronic circuits for the measurements were similar to those described by Dedini and Schemel (1980). All field measurements were made at 15-minute intervals. The controller-logger (Tattletale 4A, Onset Computer, Inc.) recorded date, time, voltages proportional to specific conductance and temperature, and reference voltages from the electronics in battery-backed-up solid state memory (RAM). The controller-logger also controlled the measurement circuitry, switched power to the sensors, and averaged the signals before storing the values.

Two instrument packages were used in this study (identified here as BYC and BYD). An instrument package was deployed for about two weeks, then replaced with the other instrument package. Instrument packages were returned to the laboratory to download the data file, recharge the batteries, and clean the sensors. Upon deployment and retrieval of an instrument package, sensors were held about 10cm below the water surface and a bucket sample was collected near the sensors. The bucket sample provided salinity and temperature values for comparison with values measured by the instrument package. These values provided quality assurance, but were not used to adjust or correct values from the instruments.

The instrument packages were calibrated annually in the laboratory for temperature (5 to 25 Celsius, °C) and specific conductance (equivalent to a salinity range of 2 to 33 practical scale units, psu; Lewis 1980). Calibration data were collected at 2-degree and 3-psu intervals, and values stored by the logger were fitted to linear functions for temperature and specific conductance. Recorded values for field measurements were converted to values for temperature and salinity using programs that utilized the linear functions from the laboratory calibrations and equations consistent with the Practical Salinity Scale of 1978 (Lewis, 1980). Coefficients for the linear functions showed little change over the four-year term of the study. Maximum differences in computed values due to changes in the coefficients over the entire four years were equivalent to 0.25 psu and 0.18 degrees celsius. Estimated precisions for the field measurements were 0.1 psu and 0.2 degrees Celsius.

Salinity values for samples collected for quality assurance and calibration were determined in the laboratory. The conductivity ratio of each sample was measured on a Guildline Autosal salinometer that was calibrated with a secondary standard of Pacific Ocean seawater. Salinity and conductivity ratio values for the secondary standard were established by comparison with standard seawater (IAPSO Standard Seawater Service). The estimated accuracy of salinity measurements for quality assurance and calibration samples was approximately 0.01 psu. To assure the accuracy of salinity measurements in the laboratory, 10 to 15 percent of the samples from each analytical run were re-analyzed during the following run. As expected, most values were slightly higher for the second analysis due to evaporation; these differences rarely exceeded 0.02 psu. In addition to showing a high degree of reproducibility in the measurement of salinity, these results are some assurance that the laboratory measurements were consistent from one analytical run to the next.

RESULTS

Results from this study are contained in four files on the IBM-formatted disk provided with this report. These self-expanding files produce free-format, comma delimited, ASCII text files. Data columns are identified in table 2.

Table 2. Column identification for comma-delimited, ASCII files containing 15-minute-interval measurements.

File Names:	DMBWYXX.EXE	XX = 95, 96, 97 or 98 Water Year
Data Columns	C1 Calendar Year	
	C2 Day of Calendar Year with Decimal Time	
	C3 Pacific Std. Time HRMN (HR = hour; MN = minute)	
	C4 Salinity in psu	
	C5 Temperature in degrees Celsius	
	C6 Day of Water Year with Decimal Time	

"M" values identify cells where data were deleted.

Both of the instrument packages, BYC and BYD, performed well over the study, as evidenced by small changes in the calibration coefficients (see Methods) and good agreement with field sample values (see below). Data editing was limited to removal of short sections at the ends of some salinity records because of biological fouling of the sensor. Effects of fouling were often apparent in comparisons of final instrument values and bucket sample values, particularly during spring and summer. Figure 7 shows box plots of the differences between deployment (initial, I) and retrieval (final, F) instrument and field sample values for each instrument. Median (and mean) values of the differences for both bouys were within 0.1 degrees and 0.04 psu for the initial (I) comparisons upon deployment. Median and mean values for both bouys also were within 0.1 degrees for the final comparison (F) upon retrieval, but values were higher for salinity because of fouling, which lowered the instrument values. Some outliers were attributable to water column stratification, which made it difficult to sample the same water measured by the sensor package.

Time scales of variability in salinity and temperature at Dumbarton Bridge were described in the report for water years 1990-1993 (Schemel, 1995a). The general relations between short-term variations in salinity and temperature (on the order of a few days or less) and tides, winds, and freshwater inflows that were shown in that study also apply to the data set presented here. The following presentation of results for 1995WY-1998WY emphasizes variations on the order of a few days to annual cycles. Daily mean values for salinity and temperature are shown in the figures in order to illustrate these time scales more clearly.

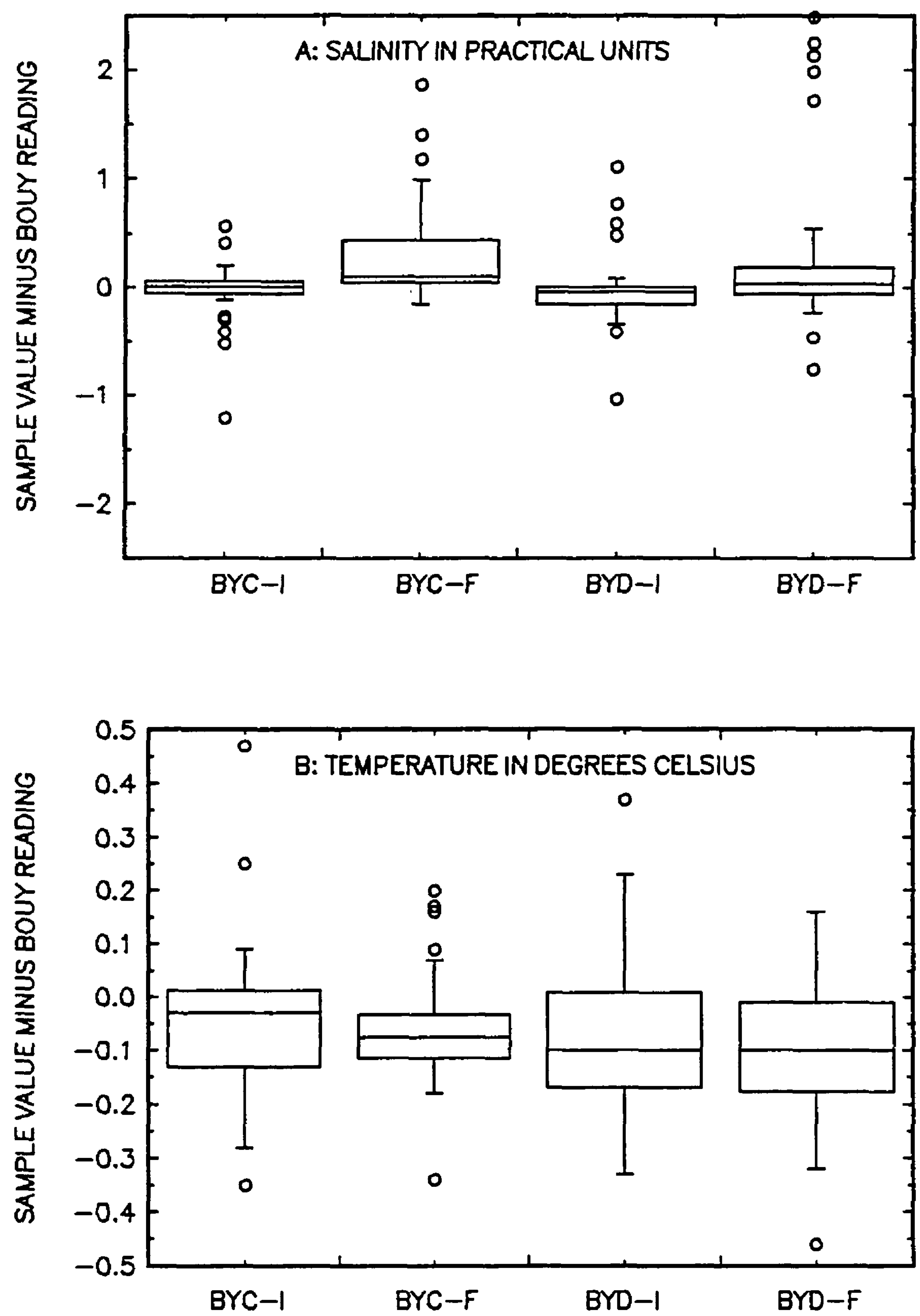

Fig. 7. Differences between recorded values from BYC and BYD and samples collected during deployment (initial, I) and retrieval (final, F). Boxes enclose 50 percent of the values with the median value near the center. The whiskers extending vertically from the boxes are equal to 1.5 times the quartile ranges from the median. Values that lie outside the ranges of the whiskers are shown individually.

Salinity

Daily mean salinity at Dumbarton Bridge over the four water years is shown in fig. 8 (with flow from local streams on the inverted right axis). Highest values for salinity were observed in late summer or early fall, which roughly correspond to beginnings or ends of water years. Highest salinity in the record was early in 1995WY, which followed a water year that was among the driest on record. The lowest late-summer salinity was at the end of 1998WY, which was among the wettest on record.

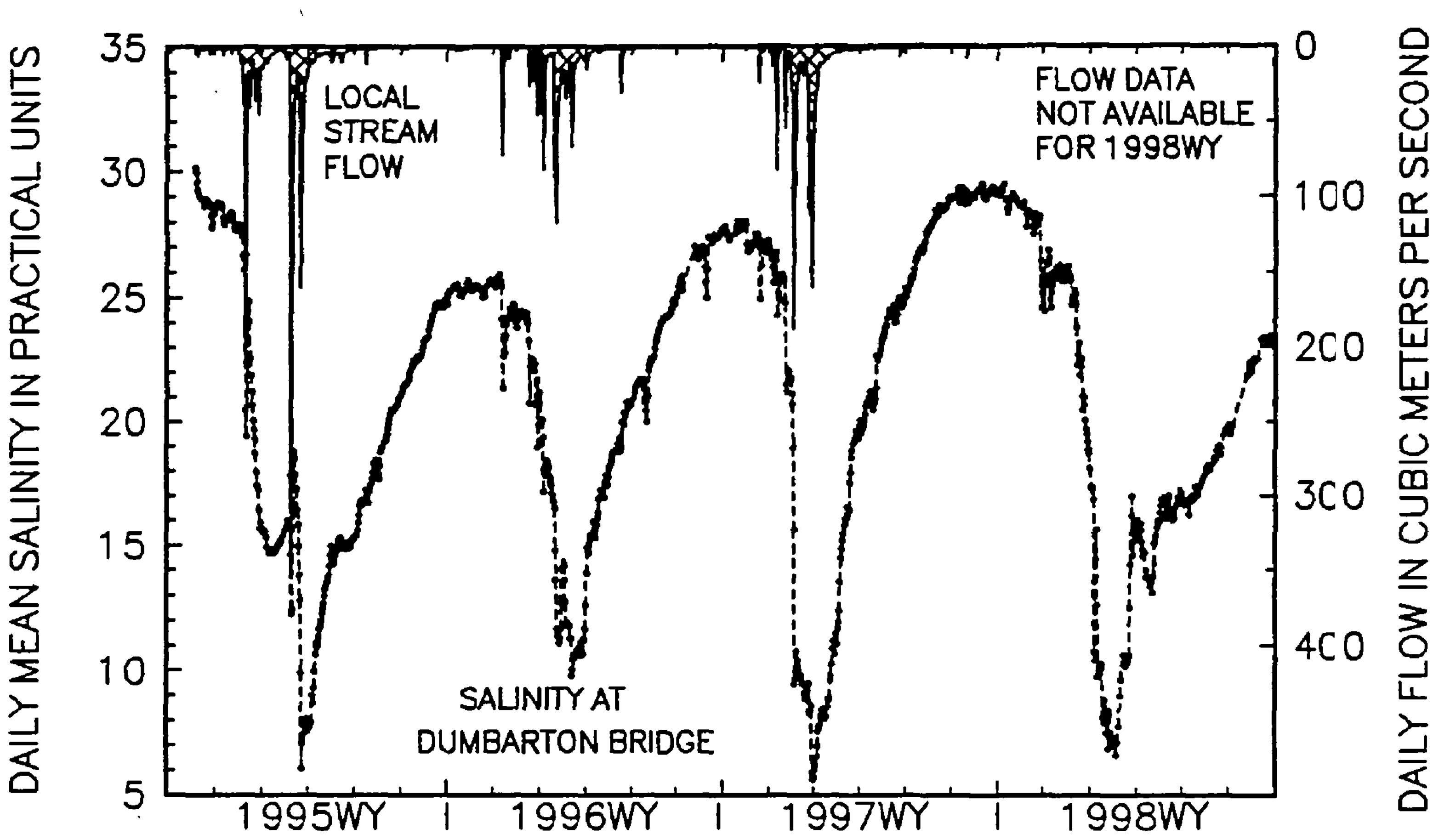

Fig. 8. Daily mean salinity at Dumbarton Bridge and daily mean flow from local streams for water years 1995-1998.

Lowest annual values for salinity were observed during winter of each year. Lowest values typically corresponded with short periods of high discharge from local streams, indicating the influence of major storm systems. Local streams can be effective in lowering salinity in South Bay near Dumbarton Bridge, but the persistence of low salinity is related to the general freshening of the bay caused by Delta outflow (see details below). Nevertheless, the lowest salinity values in South Bay are usually found landward of Dumbarton Bridge due to local stream flow, municipal waste discharge, or a combination of both.

Both 1995WY and 1996WY showed gradual salinity increases during spring, whereas a more-rapid increase was observed in 1997WY. This can be explained by the unusually dry spring during 1997WY, which reduced local stream inflows and Delta outflows to below-normal levels. In contrast, rainfall and Delta outflow were unusually high in spring 1998WY, and salinity remained low into early summer.

Salinity over the mostly dry 1990WY-1993WY showed similar seasonal variability (fig. 9), but some attributes of the record are distinctly different from those over 1995WY-1998WY (fig. 8). Highest salinity values over 1990WY-1992WY were consistently greater than 30psu, whereas those near the ends of 1995WY through 1998WY were lower than 30psu. Rainfall during 1993WY was near normal, and salinity at the end of the record (mid-summer) indicates that late summer measurements might have been lower than 30psu. Lowest salinity values over 1990WY-1992WY were greater than 20psu, whereas those for 1995WY-1998WY were less than 10psu.

The large quantity of freshwater that enters the bay system from the Delta during winter usually affects the entire bay (see Introduction). Seawater from the Pacific Ocean and freshwater from the Delta are transported into or exchange with South Bay waters near Bay Bridge. Winters 1993WY and 1995WY-1998WY had high levels of Delta outflow that coincided with periods of low salinity near Bay Bridge during each winter (fig. 10). During dry years, 1990WY-1992WY and 1994WY, salinity was lowest during winter, but values remained much greater than those during the years with high Delta outflows. Regulation of salinity at Bay Bridge by Delta outflow controls the flushing of salt from South Bay during winter and the transport of salt into South Bay during spring and summer. Consequently, salinity at Dumbarton Bridge even during summer can be limited by the salinity at Bay Bridge. This can be seen during late summer 1995WY and 1998WY, when salinity was low at Bay Bridge compared to other summers and low summer values were also observed at Dumbarton Bridge (fig. 8). A similar but less intense effect can be seen in late summer 1993WY (figs. 9 and 10).

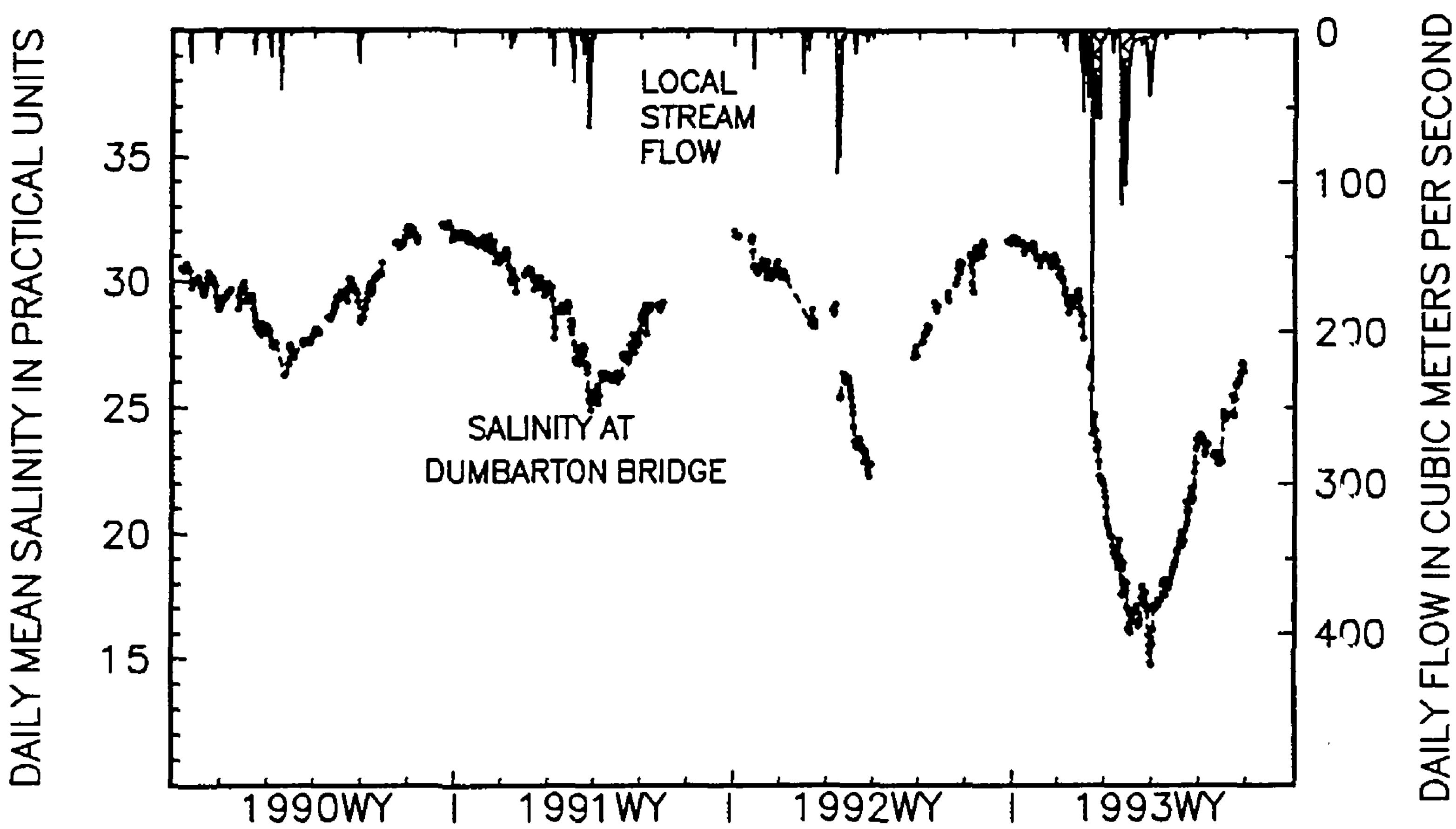

Fig. 9. Daily mean salinity at Dumbarton Bridge and daily mean flow from local streams for water years 1990-1993.

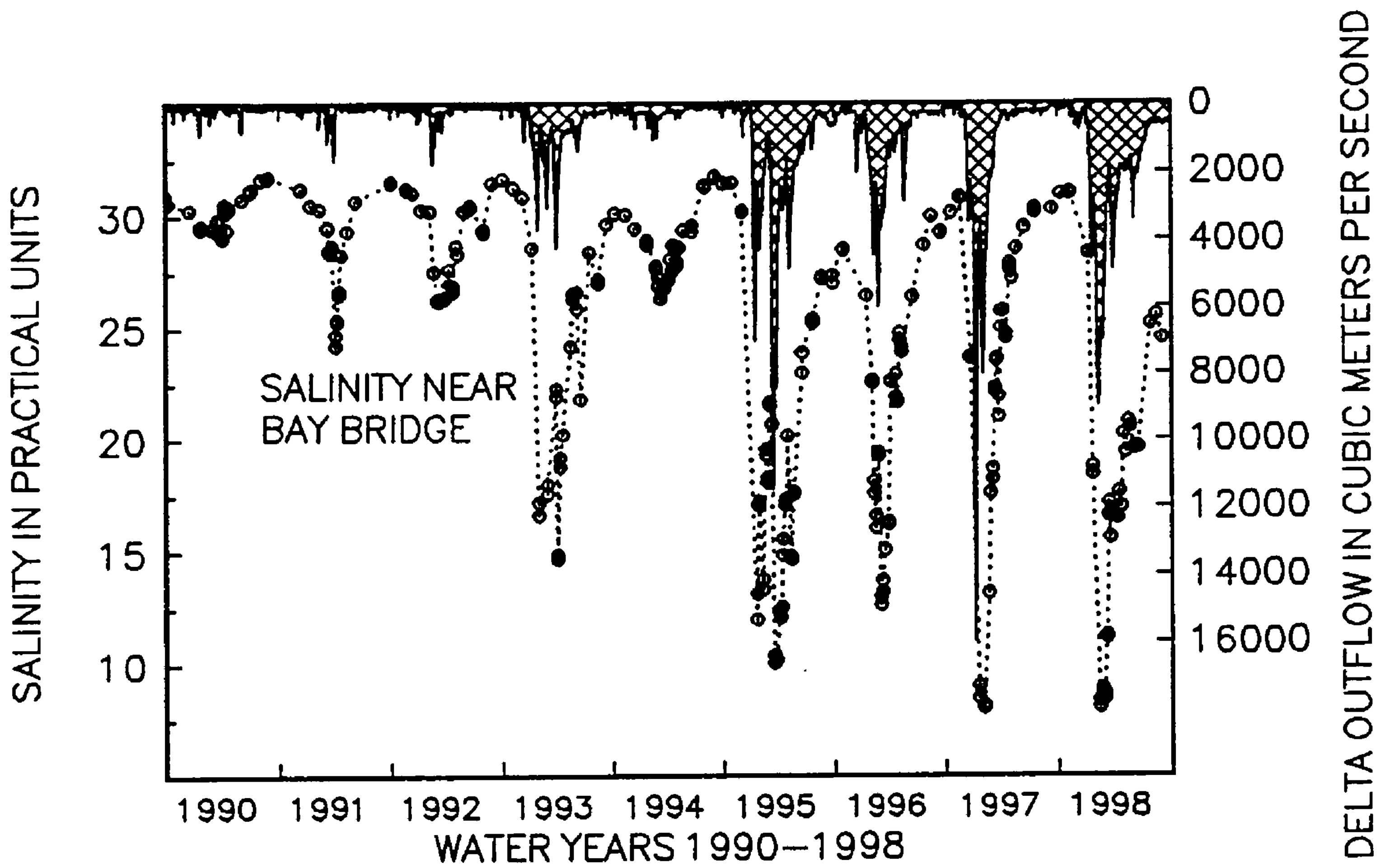

Fig. 10. Salinity near Bay Bridge and daily mean Delta outflow for water years 1990-1998. Salinity data for Bay Bridge are available from:
URL http://sfbay.wr.usgs.gov/access/wqdata/index.html.

Large changes in Delta outflow during most winters can rapidly influence salinity over most of South Bay. In the example from 1997WY shown in fig. 11, salinity was nearly the same bay-wide at the beginning of the record. As Delta outflow decreased, salinity at Bay Bridge and San Mateo Bridge increased, but salinity at Dumbarton Bridge continued to decrease. By the time Delta outflow was beginning to increase in mid-record, the longitudinal salinity gradient between Bay Bridge and Dumbarton Bridge was nearly 10 psu and values were mid-range at San Mateo Bridge. Salinity at Bay Bridge decreased rapidly with the increase in Delta outflow and this was followed by a decrease in salinity at San Mateo Bridge to values that were not as low as those at Bay Bridge. Salinity also decreased at Dumbarton Bridge, but values were lower that those at the other two bridges. Over the last two weeks of the record Delta outflow decreased and salinity at all three bridges increased. Salinity at the end of the record was highest at Bay Bridge, lowest at Dumbarton Bridge, and an intermediate value at San Mateo Bridge. This example shows the influence of local streamflow in maintaining lowest salinity at Dumbarton Bridge even during periods of high Delta outflow, and illustrates the potentially large influence of Delta outflow on salinity bay-wide during winter. An additional factor that increases the influence of local streamflow at Dumbarton Bridge is that the effect of inflow on salinity is fast relative to the transport of water down the bay from the seaward reach. Winds, however, have been shown to have considerable influence on landward transport processes (see Introduction).

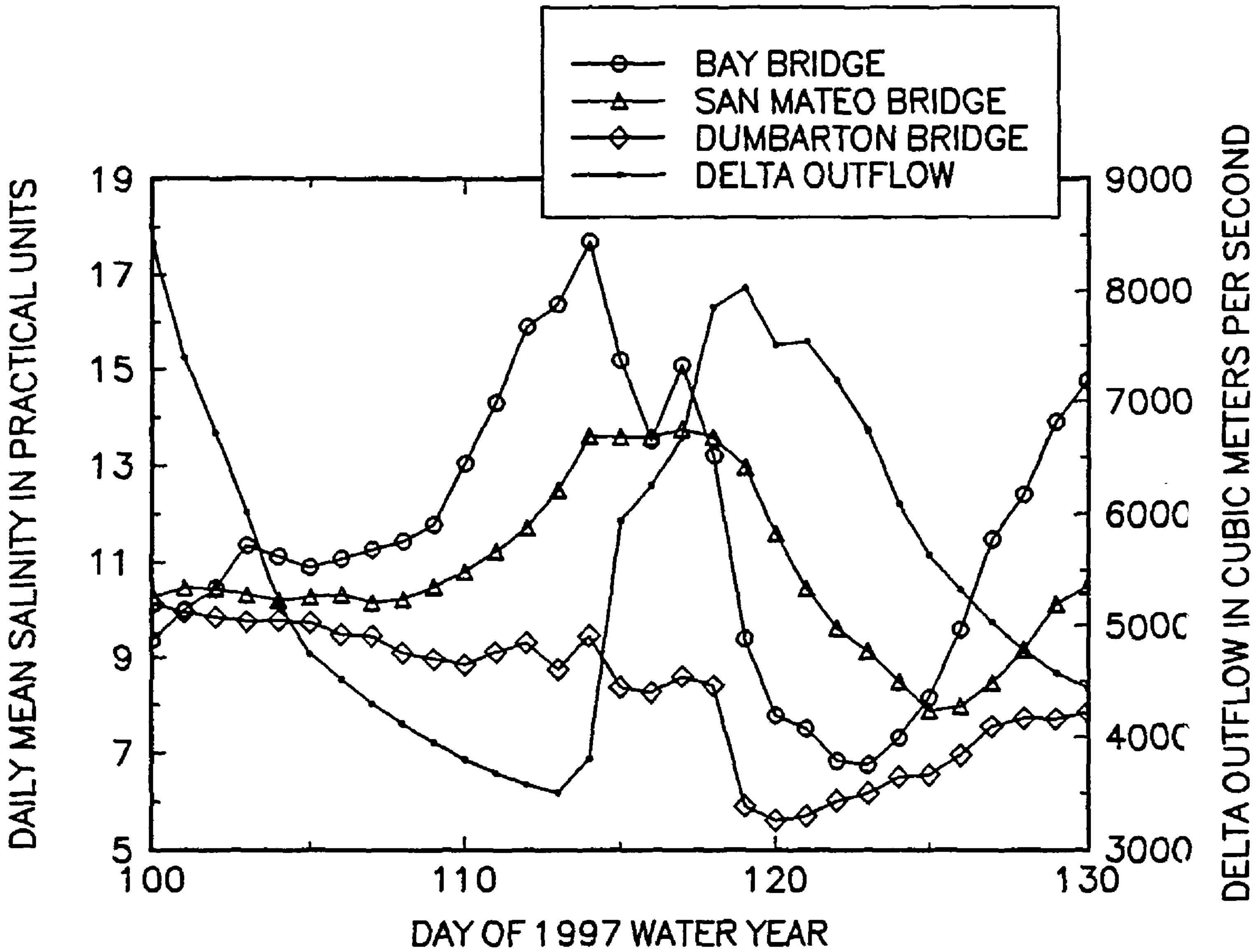

Fig. 11. Delta outflow and salinity at Bay Bridge, San Mateo Bridge, and Dumbarton Bridge during winter 1997.

Temperature

Seasonal-scale variability in water temperature at Dumbarton Bridge followed the annual solar cycle (fig. 12). Lowest temperatures were observed in late fall and early winter, within a few weeks of the winter solstice. Highest temperatures, however were often several weeks later than the summer solstice. Annual range in temperature was about 15 degrees Celsius. Although there was considerable short-term variability in the record, this was considerably less than that shown by air temperature at Redwood Creek (fig. 13; Schemel, 1998). Minimum air temperatures, however, were lower than minimum water temperatures at Dumbarton Bridge. Rapid increases in water temperature were often related to large increases in air temperature, particularly during early summer. Some rapid decreases in water temperature during fall and early winter appeared to be associated with storm events and inflows of freshwater. A more detailed comparison of solar irradiance, air temperature, and water temperature is shown with the results for 1993WY in Schemel (1995a).

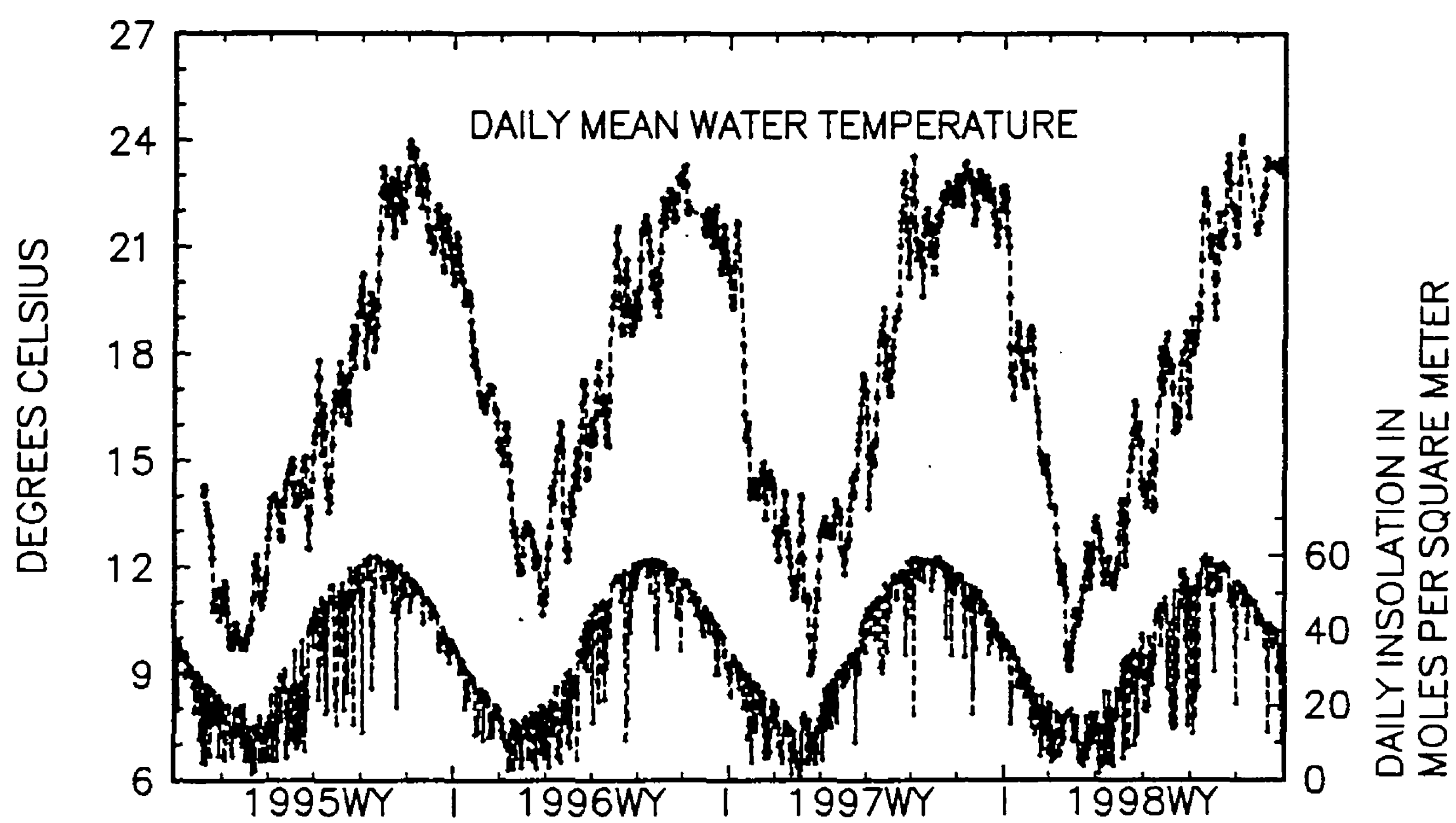

Fig. 12. Daily mean water temperature at Dumbarton Bridge and daily insolation at Redwood Creek for water years 1995-1998.

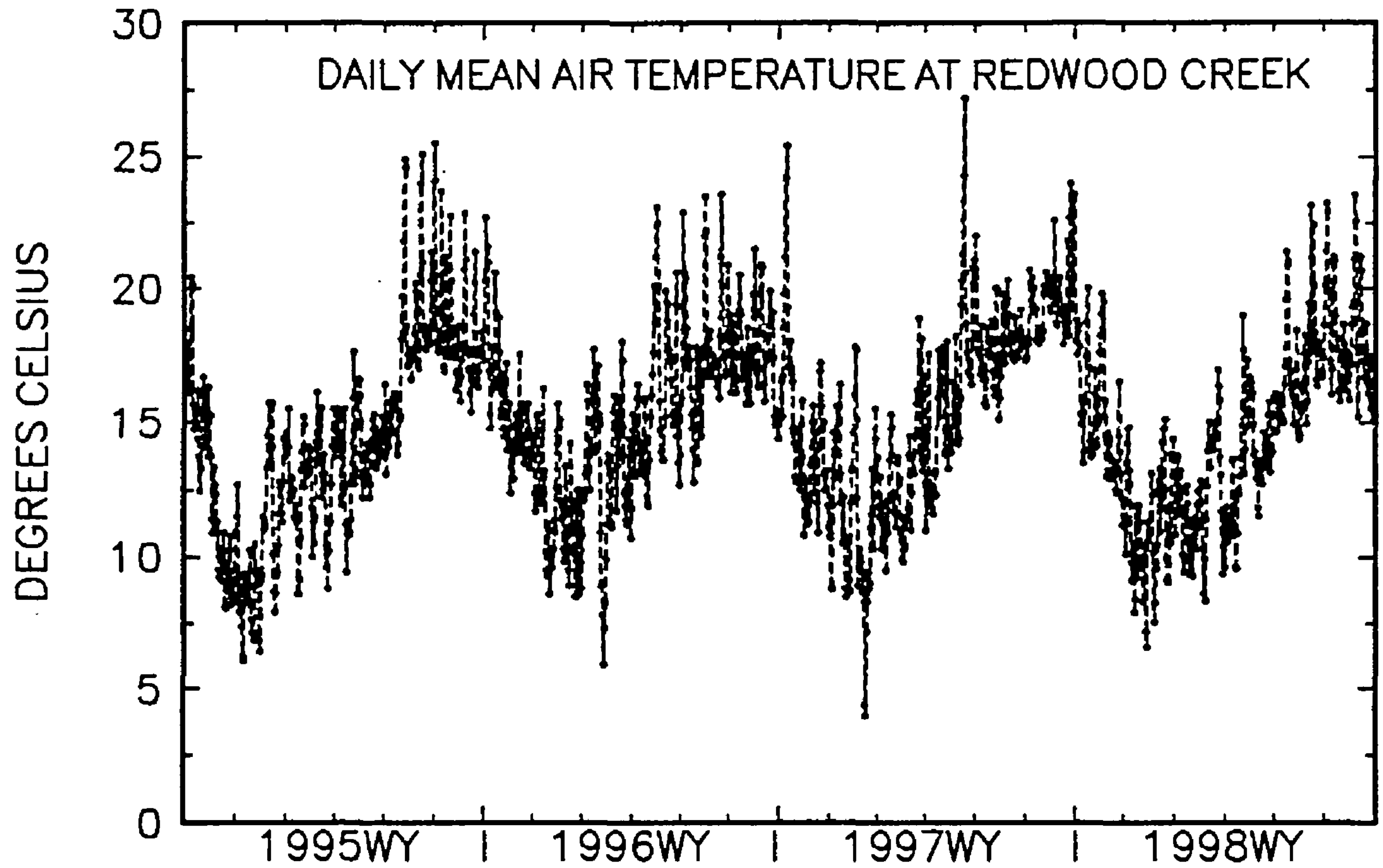

Fig. 13. Daily mean air temperature at Redwood Creek for water years 1995-1998.

Differences in temperature variability among the annual records for 1995WY-1998WY at Dumbarton Bridge are shown in fig. 14. In general, the largest differences were observed among the records during spring and fall. Some of these differences were consistent with weather patterns for the years. For example, high temperatures in May 1997 and over November-December 1996 corresponded with the unusually dry weather. Lowest temperatures during February 1998 corresponded with the highest rainfall over the 1995WY-1998WY record. Differences among the years were least during July-August, when water temperatures reached annual maxima.

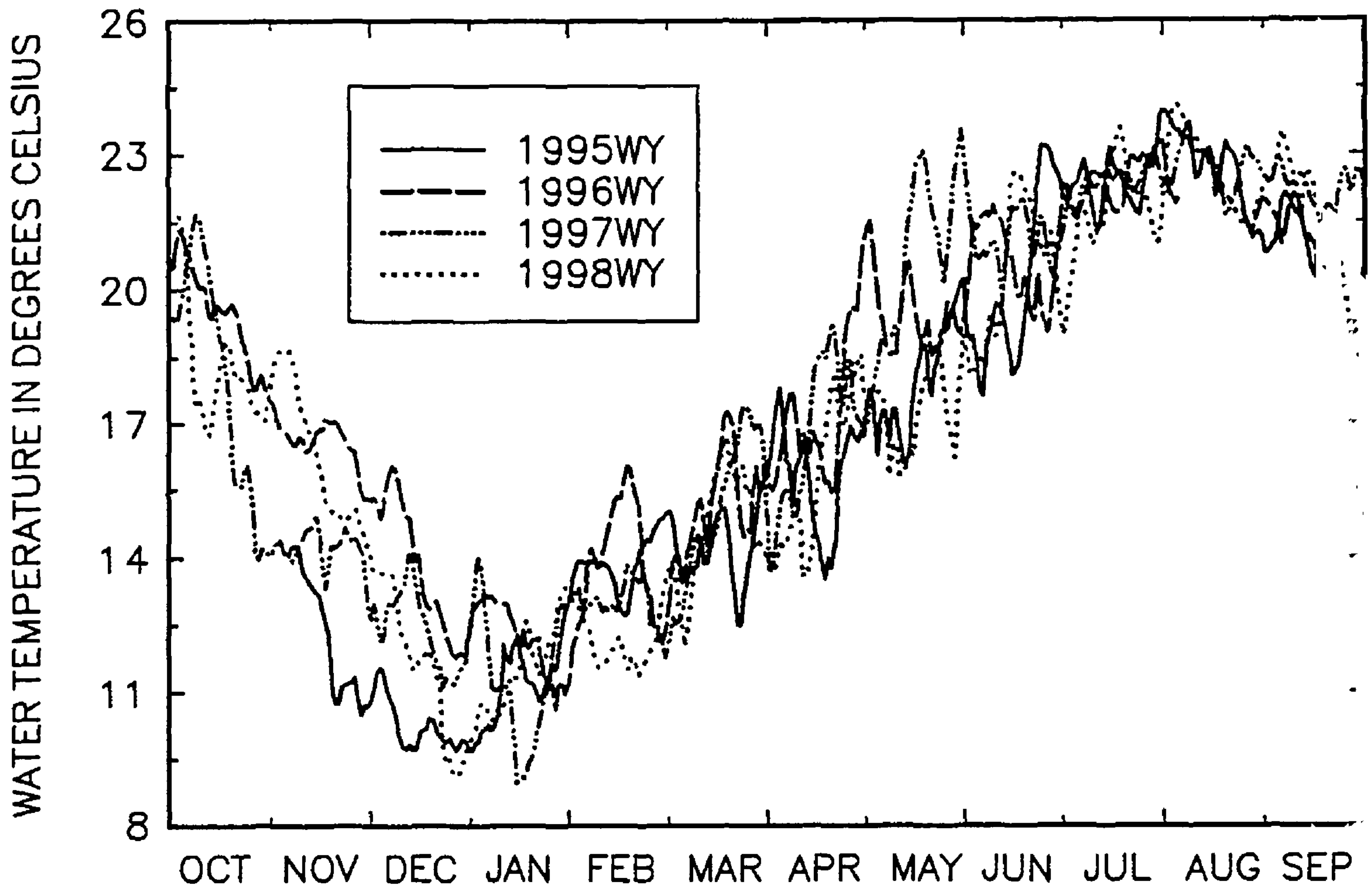

Fig. 14. Daily mean water temperatures for water years 1995-1998.

SUMMARY

Salinity and temperature of near surface waters were measured during the 1995-1998 water years at Dumbarton Bridge in South San Francisco Bay. This report presents the methods, describes the results, and provides numerical values for the measurements in ASCII text files on the enclosed IBM formatted disk. The four years of this study were unusual in that they were the first extended period of greater-than-normal rainfall and river inflow to San Francisco Bay since the early 1980's. Results from 1995WY-1998WY provide detailed information on the influences of freshwater inflows (from the Sacramento-San Joaquin Delta and from local streams) and climate- and weather-related events and processes on salinity and temperature at the study site. Earlier records from this site were collected over the 1990-1993 water years, the first three years of which had lower than normal rainfalls and freshwater inflows. Comparisons with results from 1995WY-1998WY record with the records from 1990WY-1992WY showed generally higher salinity and less variability in salinity during the dry years. Both sets of records show that salinity and temperature respond to weather events and climate variations over time scales of days to months.

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