APPENDIX 6

SALINITY AND TEMPERATURE VARIATIONS IN SAN FRANCISCO BAY

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ACKNOWLEDGEMENTS

Many people have contributed in a significant way to this work. The original idea for the study was Randy Brown's, and the early data processing for the Presidio and Alameda stations was performed by Shiela Green under Randy's direction. The balance of the data was obtained through the assistance of Ed Winkler, Ed Huntley, and Kamyar Guivetchi of the DWR and of Sheryl Baughman, Ralph Finch, and Harold Meyer of the USBR. Many of the concepts and approaches used in this work were developed through discussions with all of the above-named folks as well as Jim Arthur and Doug Ball of the USBR; Larry Schemel, Fred Nichols, and Ralph Cheng of the USGS; and B.J. Miller and Peter Russell, local Bay-area consultants. The computer graphics and data processing were mostly done by Alison Britton, and Peter Russell performed the statistical analyses.

ACRONYMS AND DEFINITIONS

California Undercurrent: This current flows northward at depth along the California coast and is sometimes called the California Countercurrent. It is characterized by high temperature and salinity.

California Current: This current flows southward along the California coast and comprises cold, low-salinity subarctic waters. It is the continuation of the Aleutian Current of the North Pacific, and this name is applied to the southward flow between lat. 48^{0} and 23^{0} N.

Chlorinity: This is the weight of chloride, bromide, and iodide, all reported as chloride, per unit weight of sample (g/kg or ppt). Formerly, chlorinity was used as a measure of salinity since it is easy to measure and chloride is the major ion in sea water. Chlorinity can be converted to salinity using Knudsen's relationship (APHA 1985).

Davidson Current: This current flows northward along the California coast and comprises warm, high-salinity tropic and subtropic waters. This current develops after the fall upwelling ceases and is the surface expression of the California Undercurrent. It moves along the coast to at least 48^{0} N from November to January.

DPW: California Department of Public Works, the predecessor to DWR.

DWR: California Department of Water Resources.

EC: Electrical conductivity. This is a measure of the salinity of a water sample. The electrical conductivity at a site can be converted to either salinity or chlorinity using regression relationships reported by the DWR (Guivetchi 1986).

Kurtosis: This is a measure of the relative peakedness or flatness of a distribution. A normal distribution (the classical bell-shaped curve) has a kurtosis of zero.

LOWESS: Locally weighted regression scatter plot smoothing. This is a statistical procedure to smooth data so that long-term trends can be identified.

NOS: National Ocean Service, formerly the U.S. Coast and Geodetic Survey. This is a branch of the National Oceanic and Atmospheric Administration.

ppt: Parts per thousand. This is a concentration unit commonly used to report salinity. It is equal to 1000 parts per million.

Salinity: This is the total solids in water after all carbonates have been converted to oxides, all bromide and iodide have been replaced by chloride, and all organic matter has been oxidized. It is numerically smaller than the total dissolved solids and usually is reported as g/kg or ppt.

Skewdness: This is a measure of how much a data set differs from the normal distribution. It takes on a value of zero when the distribution is a completely symmetric, bell-shaped, normal curve.

STORET: The U.S. EPA computerized data base for water quality data.

TAF: Thousands of acre feet.

Tidal-Maximum Salinity: Salinity varies with the tidal phase. Maximum salinities typically occur on the ebb tide, within 1.5 to 2 hours of higher-high tide. Five of the salinity data sets analyzed here (Collinsville, Antioch, Port Chicago, Martinez, Point Orient) are reported as tidal-maximum values.

USBR: U.S. Bureau of Reclamation.

SALINITY AND TEMPERATURE VARIATIONS IN SAN FRANCISCO BAY

We have analyzed data from seven sites in the San Francisco estuary that span the period 1920 to 1985. Our goal was to determine whether salinity and temperature were changing in the Bay, the rate at which they were changing, and the causes of any noted changes. This is the first time we are aware of that these data sets have been analyzed. The details of our analyses are presented in Attachments A and B. This report summarizes our results.

CONCLUSIONS

Salinity and water temperature in the Bay are highly variable. Changes in these two parameters due to upstream flood control/water development are very small compared to changes due to natural variability. Our analyses of historical salinity and temperature data indicate that there has been no significant increase in these parameters since the 1920's anywhere in the Bay except at the Presidio.

At the Presidio, salinity has increased over the past half century at a rate of about 0.1 percent per year or 34 parts-per-million per year (ppm/yr.) Our analyses suggest that this increase has been caused by changes in off-shore oceanic conditions rather than changes in Delta outflow. Since ocean water has 300 times more salt in it than Delta outflow, minor changes in conditions in the ocean can have a major effect on salinity at the Presidio and other locations in the Bay.

Oceanographic research indicates that the high-salinity, northward flowing counter-current in off-shore waters has strengthened, transporting higher salinity water off the California coast. We estimate that this may have increased salinity at the Presidio by as much as 24 ppm/yr. The sea level is also rising at the Golden Gate at a rate of about 0.0005 feet/year (ft/yr). This has increased the volume of ocean water that enters the Bay. We estimate that this may have increased salinity at the Presidio by at least 10 ppm/yr. Corresponding changes at other stations in the Bay due to the oceanic factors would be smaller.

METHODS

The Data

Seven stations with long-term, daily records were selected to examine the historical salinity trends in San Francisco Bay (Figure 1). These stations are:

1) Antioch near the mouth of the San Joaquin River,

2) Collinsville near the mouth of the Sacramento River,

3) Port Chicago in Suisun Bay,

4) Martinez in Carquinez Strait,

5) Point Orient near the entrance to San Pablo Bay,

6) Alameda on the northeast shore of the South Bay, and

7) Presidio at the south side of the Golden Gate.

All measurements at these seven sites were of surface salinities, which are typically within 10 percent of the average salinity in the entire vertical cross-section (DPW 1931, p. 180; DWR 1962, p. 53).

The location, period of record, and type of data available for each site are summarized in Table 1. The first five of these stations were operated by the California Department of Water Resources (DWR) and the U.S. Bureau of

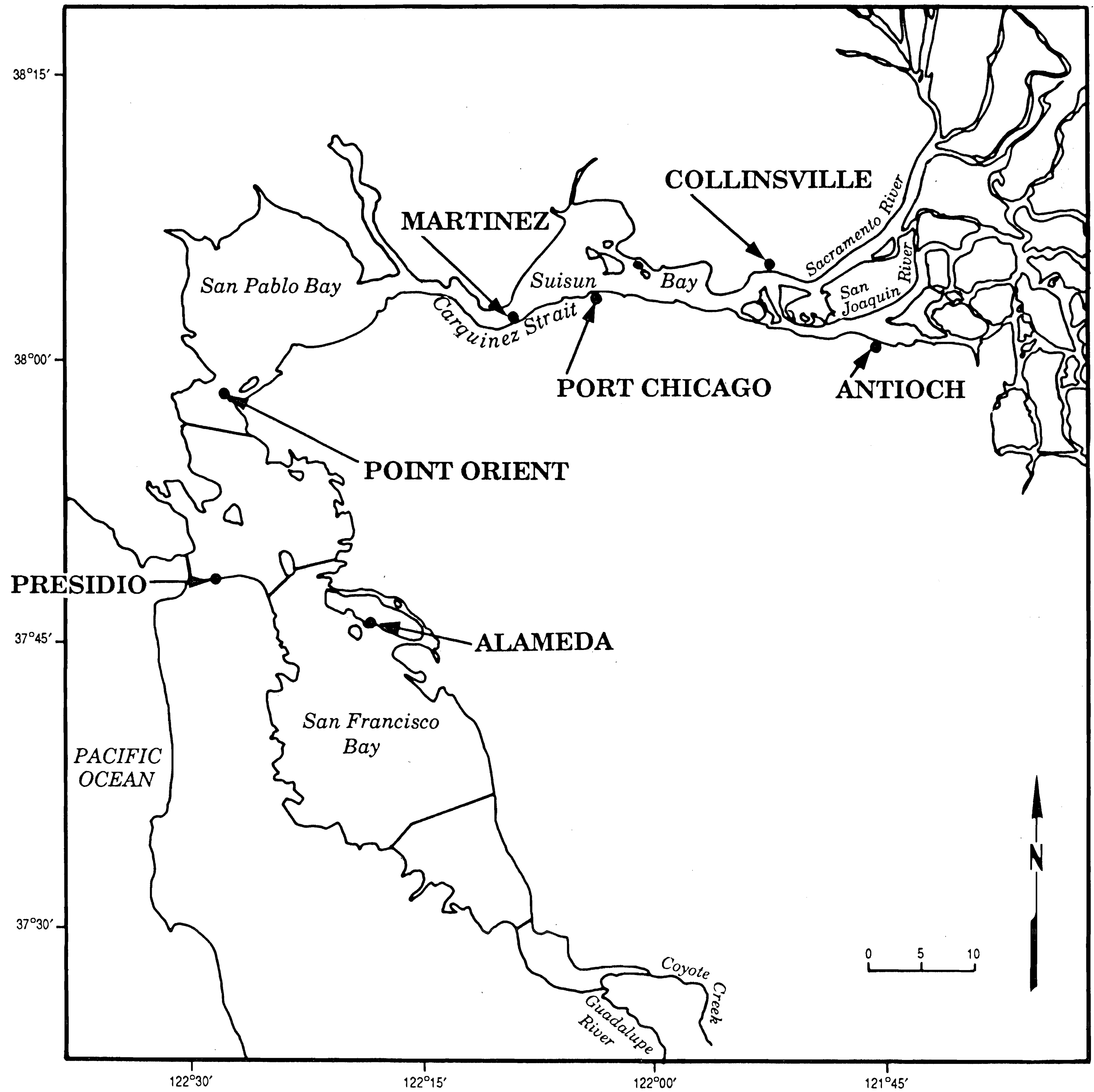


FIGURE 1. Map Showing the Location of the Seven Salinity Stations Studied in this Work.

TABLE 1

DESCRIPTIVE INFORMATION ON THE SEVEN SALINITY STATIONS ANALYZED IN THIS STUDY

Station	Distance From Golden Gate (mi)	Type of Data Available	Period of Record	Responsible Agency/ Data Source
Antioch	54.9	4-day grab chlorinity[1]	6/20 - 12/70	DWR/Storet
		Daily average electrical conductivity	11/64 - 12/85	USBR/Storet
Collinsville	50.8	4-day grab chlorinity[1]	6/20 - 3/71	DWR/Storet
		Daily average electrical conductivity	10/67 - 12/85	USBR/Storet
Port Chicago	41.0	4-day grab chlorinity[1]	1/47 - 6/71	DWR/Storet
		Daily average electrical conductivity	10/67 - 12/85	USBR/Storet
Martinez	32.7	4-day grab chlorinity[1]	1/46 - 3/71	DWR/Storet
		Daily average electrical conductivity	1/65 - 12/85	USBR/Storet
Point Orient	12.3	4-day grab chlorinity[1]	1/27 - 8/57	DWR/Storet
Alameda	10.2	Daily grab salinity, air and water temperature, sea level	3/39 - 12/85	NOS/NOS
Presidio	0	Daily grab salinity, air and water temperature, sea level	1/39 - 12/85	NOS/NOS

[1] All samples taken at the time of maximum tidal salinity within 1.5 to 2 hours of higher-high tide.

Reclamation (USBR) and the last two by the National Ocean Service (NOS). Air and water temperatures and water levels were also reported for two of these stations (Presidio and Alameda) and were used to help assess variability and trends. Additional information on each of these sites, including location, data sources, sampling methods, chemical analysis methods, and data reduction procedures are described in Attachment A.

Data Analysis

Daily data from each of these seven sites were checked and validated. The daily temperature data at Alameda and Presidio were adjusted to remove the influence of sampling time, which changed several times over the 46-year record (Attachment B, Step 1). Monthly averages were then computed from the daily data and used in all analyses to eliminate time biases due to missing values.

We used three types of analyses to evaluate the data. Patterns in the data were identified by plotting the historical data against time (time series). Trends in the data were investigated using a moving-average procedure and a regression model. Simple regression analyses were also used to identify possible causes for observed trends.

All analyses were conducted using the parameter (i.e., chlorinity, salinity) of the original data base. The results were converted to salinity for presentation using Knudsen's (1901) relationship. The data for the five DWR/USBR stations (Antioch, Collinsville, Port Chicago, Martinez, Point Orient) were analyzed as monthly average tidal-maximum chlorinity. The data for the two NOS stations (Alameda, Presidio) were analyzed as monthly average salinity and are not corrected for tidal variations. Since sampling was random with respect to the tidal cycle, these are approximately mean tidal cycle salinities.

RESULTS

Salinity

Salinity in San Francisco Bay is determined by conditions at its two boundaries, the Golden Gate and the western Delta. Oceanic conditions play an important role in the salinity regime of the Central and South Bay while Delta outflow is more important in the North Bay and western Delta. Other studies on salinity in the Bay (e.g., Rumboltz 1979; DPW 1931; DWR 1962) have focused on the role of Delta outflow, excluding the equally important role of oceanic conditions. One of our goals in this work is to put oceanic factors into perspective.

The salinity at any point in the Bay is determined by the relative proportions of ocean water and fresh water present in the Bay. Since the majority of the water in the Bay at any given time is ocean water, the Bay is a predominantly estuarine environment. For example, the total volume of new water entering the Bay during an average tidal cycle of 12.6 hours, is as follows:

Source of Water	Volume of New Water[1]	Percent of Total New Water
Delta Outflow	32,000 acre-feet	12%
New Ocean Water	235,000 acre-feet	88%

[1] Ocean water was calculated from DWR Exhibit DWR-41 using a mean tidal range of 4.1 ft and a tidal exhange ratio of 0.24. Delta outflow is the 28-yr average for 1985 (22,662 TAF) divided by the number of flood tides per year (709).

These quantities of water bring the following amounts of salt into the Bay:

Source of Salt	Quantity[1] of Salt	Percent of Total
Delta Outflow	22,000 tons	0.2%
New Ocean Water	10,500,000 tons	99.8%

[1] Calculated by multiplying the water volumes given immediately above by an outflow salinity of 500 ppm and an ocean salinity of 33,000 ppm.

These volumes and salt loadings would result in an average Bay-wide salinity concentration of about 30 parts per thousand (ppt) if the Bay were well-mixed. However, it isn't. The actual salinity concentration never reaches steady state and constantly varies due to changes in Delta outflow. Since oceanic conditions are comparatively uniform while Delta ouflow is highly variable, Delta outflow controls variability while oceanic inputs control the magnitude of salinity. Thus, salinity is much higher and less variable in the Central and South Bay than in the North Bay and western Delta.

Variability

The historical salinity data for each of the seven stations is compared in Figure 2. Delta outflow is also included for comparative purposes. The nearly straight line through each data set is a long-term average and will be discussed in the section on Time Trends. This figure shows that the principal characteristic of salinity at these sites is its variability. This is demonstrated by the large amount of scatter in the data. The natural variability in the system greatly exceeds the very small long-term changes shown by the trend curve.

This variability generally decreases with increasing distance from the Delta. Salinity is most variable at sites close to the Delta (Antioch, Collinsville, Port Chicago, Martinez) due to the influence of Delta outflow. In this area, salinity concentrations typically vary from less than 50 ppm to over 10,000 ppm or by a factor of 200. Salinity is least variable in the Central and South Bay due to the moderating influence of oceanic conditions, where concentrations vary from 5,000 to over 30,000 ppm or by a factor of six.

This can be more clearly seen when the coefficient of variation for each station is examined. This parameter is the ratio of the standard deviation to the average expressed as a percent. The larger the coefficient of variation, the more scatter or

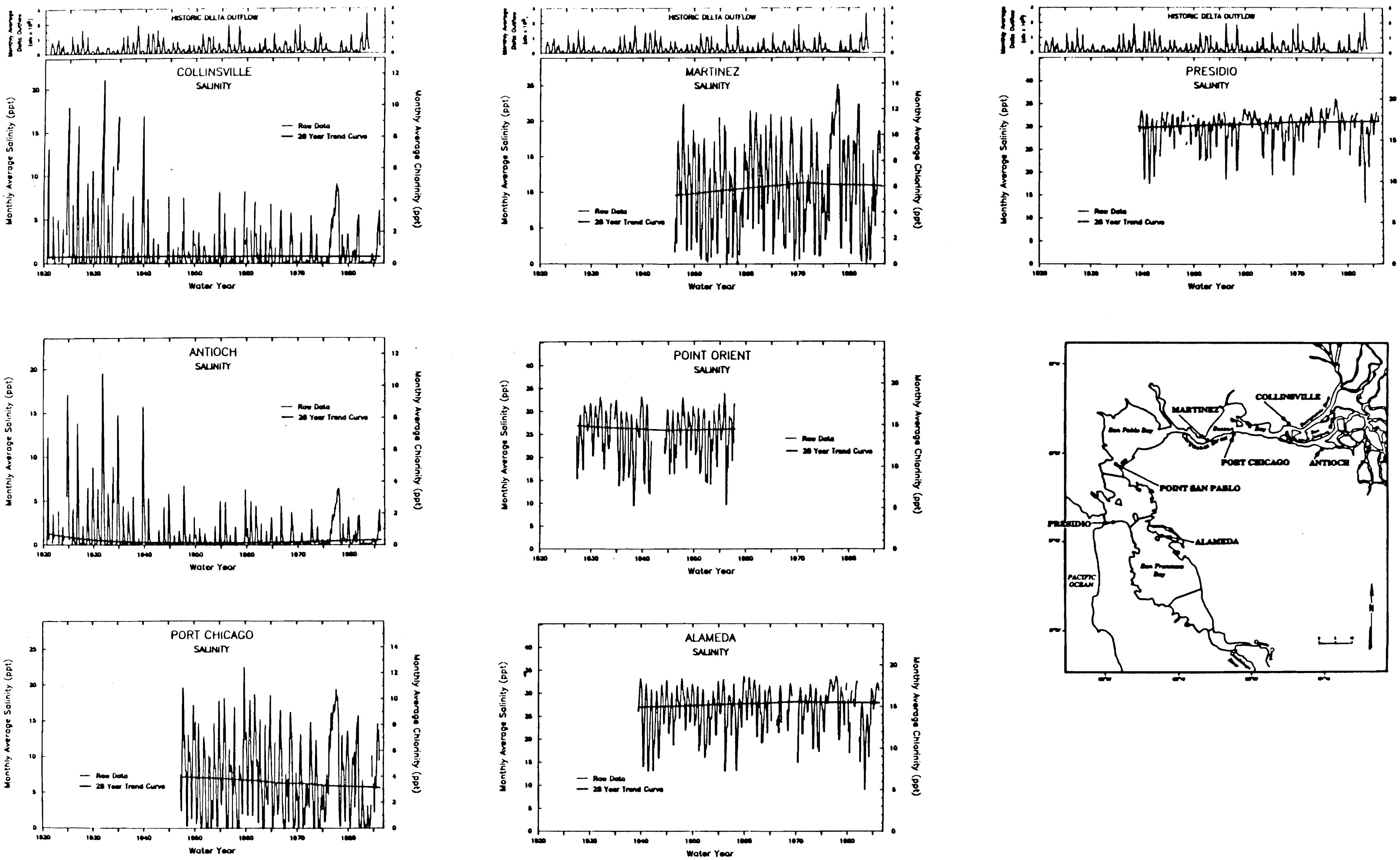


FIGURE 2. Historical Salinity Data at Seven Sites.

variability there is in the data. If the seven stations are ranked according to distance from the Golden Gate, it is readily seen that variability decreases dramatically as one approaches the Golden Gate, or:

Station	Average Salinity (ppm)	Coefficient of Variation (%)
Antioch	1,400	187%
Collinsville	1,850	169%
Port Chicago	7,200	75%
Martinez	10,700	57%
Point Orient	25,200	21%
Alameda	26,750	18%
Presidio	29,900	11%

Annual Patterns

Figure 2 indicates that salinity in the Bay varies in a consistent annual pattern. These annual patterns are summarized in Figure 3 for a station in the western Delta (Collinsville) and the Central Bay (Point Orient). On an annual basis, salinity is cyclical, reaching its minimum during the winter-spring high runoff period and its maximum during the dry summer-fall period. The annual patterns are similar at all sites in the Bay, differing primarily in the magnitude and timing of maxima and minima.

Effect of Water Projects

The impact of flood control/water development on salinity in the Bay can be determined by comparing the pre-1942 and post-1942 curves in Figure 3. The year 1942 was selected as the transition for evaluating impacts of water projects because the filling of Shasta, the first major component of the CVP, commenced in January 1942. The average Four River Index for the post-Shasta period is about 20 percent greater than for the pre-Shasta period. Figure 3, nevertheless, demonstrates that

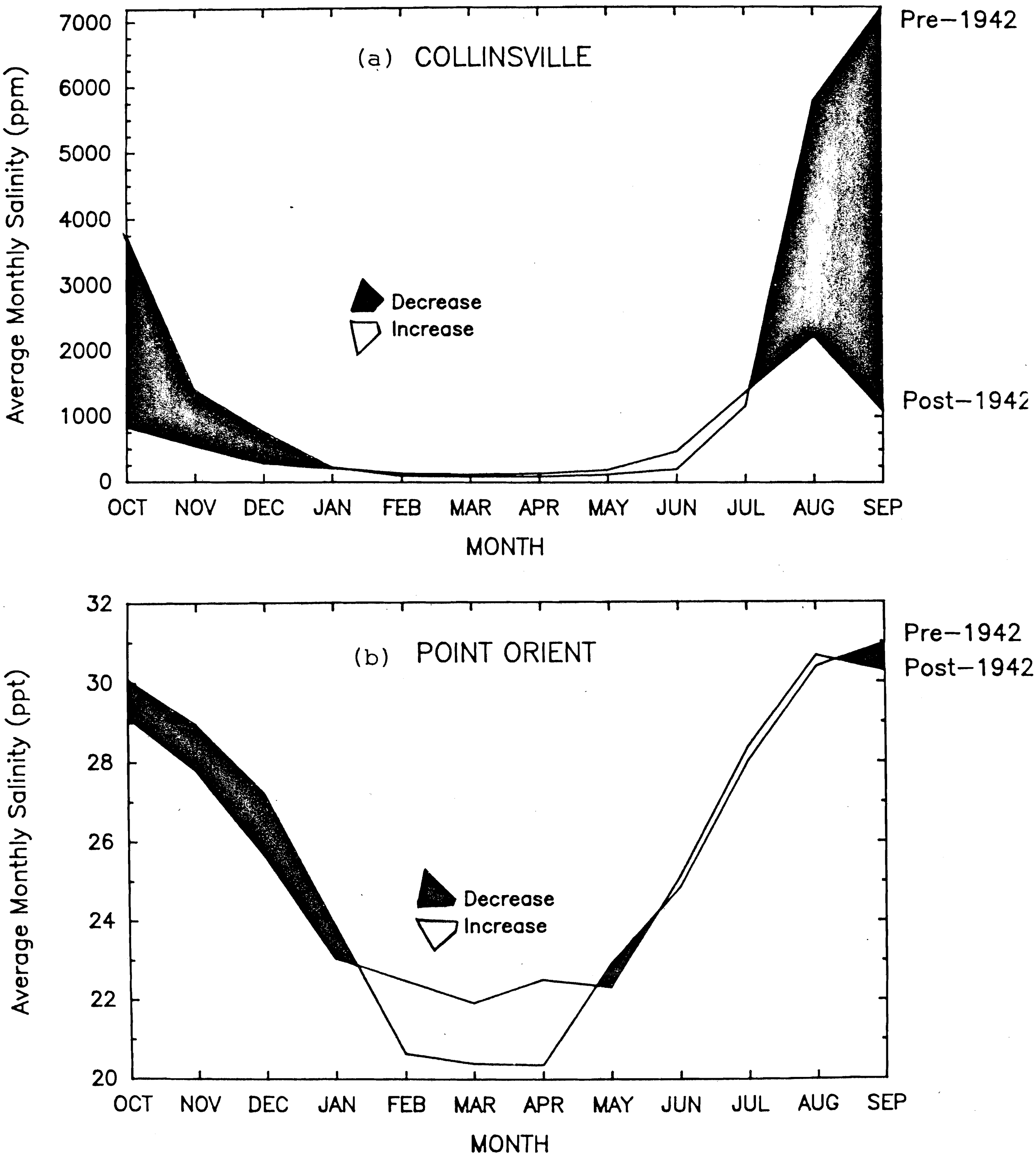


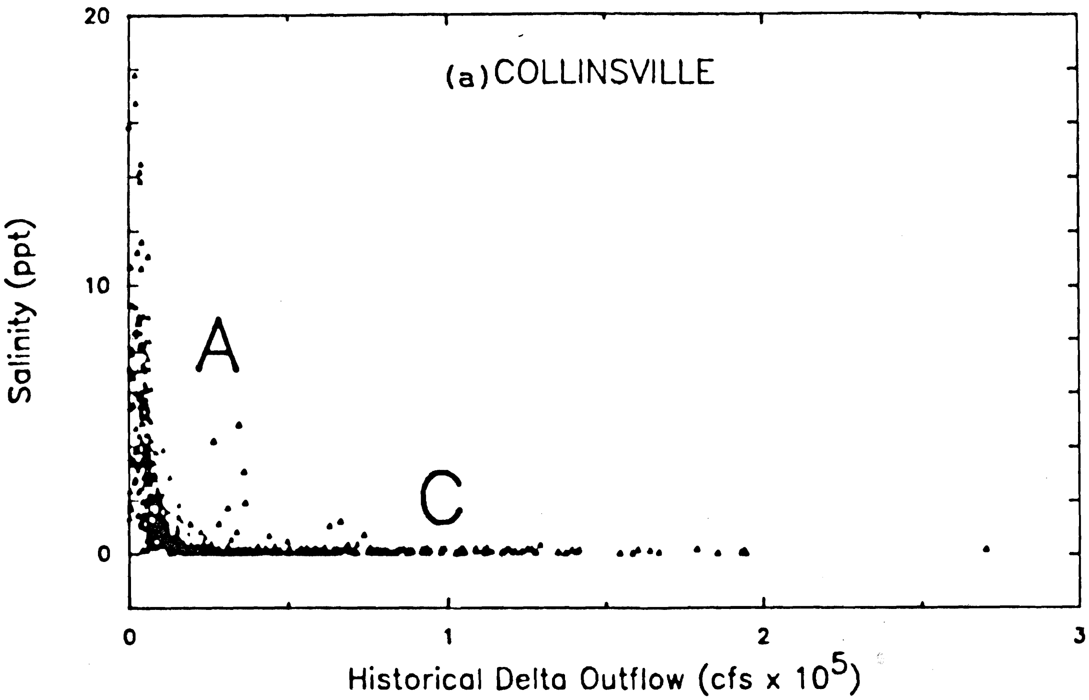
FIGURE 3. Average Monthly Salinity Prior to Shasta (Pre-1942) and After Shasta (Post-1942).

upstream development has significantly decreased summer and fall salinities in the western Delta, while only slightly increasing winter and spring salinities (Figure 3a). Salinity has decreased during the months of August to December, on the average, by 500 to nearly 4,000 ppm, while during February to July, salinities have only slightly increased. Similar trends are also evident in the Central and South Bay. Point Orient was selected to represent these trends because its pre-and post-Shasta records are about the same length. This figure shows that salinity has increased during March, April, July, and August and decreased at all other times.

One reason that salinity has not increased in proportion to diversions is because the hydrologic system is highly nonlinear. This means that a reduction in flow does not necessarily cause an increase in salinity. This is demonstrated graphically by Figure 4, which shows the relationship between flow and salinity at several of the stations studied here. Conceptually, during high flows, the embayments fill with fresh water, and increases in flow beyond the amount required to hold back advancing ocean waters has little effect on salinity. This fact is used to advantage in operation of upstream reservoirs. Very small releases of water during the dry summer months when salt water is present in the western Delta cause large reductions in salinity. In contrast, storage of water during high flow periods has little or no effect on salinity in the North Bay.

Time Trends

We explored changes in salinity over time using two simple statistical procedures — a smoothing procedure and a linear regression model. The smoothing analysis was used to identify long-term time trends while the regression model was used to estimate the rate of change in salinity. The trends that we identify using these techniques are due to the cumulative effect of all upstream development, including water diversions, flood control, reclamation of marshes and swamplands,



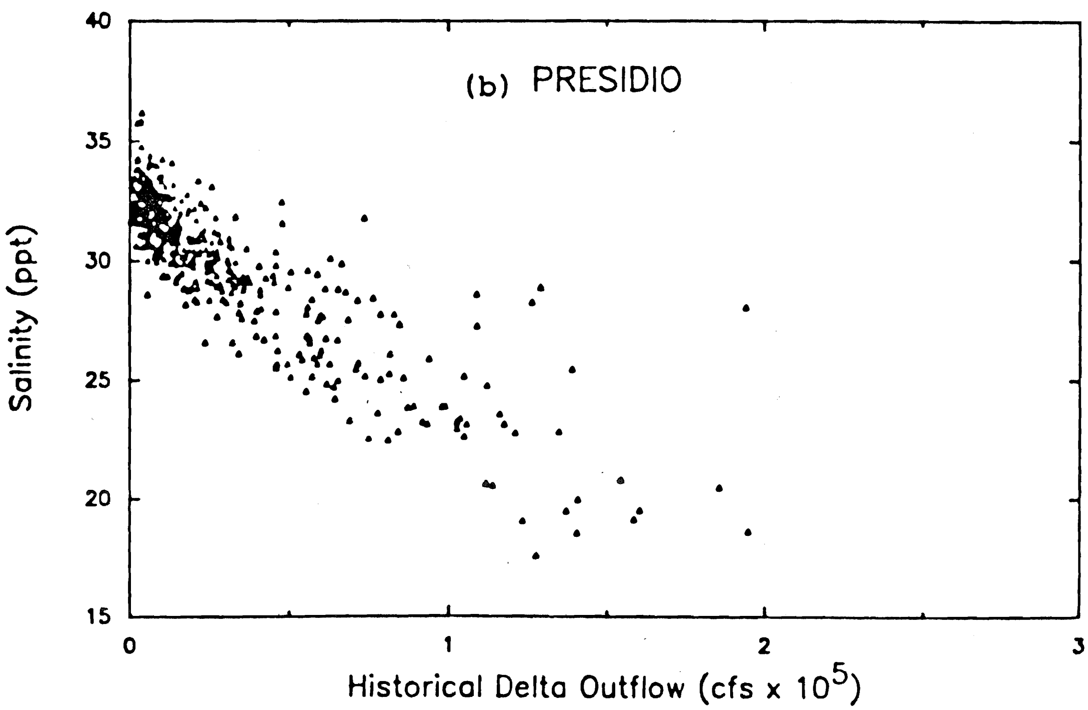


FIGURE 4. The Relationship Between Delta Outflow and Salinity at Collinsville and Presidio.

deforestation, effluent discharges (e.g., agricultural drainage), dredging for navigation, etc.

Smoothing

Smoothing is a technique to enhance the underlying trend of interest while diminishing short-term cyclical trends. Methods for smoothing data can be as simple as a moving average or as complicated as stochastic time series methods. We used a procedure called LOWESS, or locally weighted regression scatter plot smoothing. This technique is discussed further in Attachment B, Step (6).

The data were smoothed using LOWESS to approximate a 5-year and a 28-year moving average. The 5-year salinity trend curves for each station are compared with the Delta outflow trend curve in Figure 5. This figure shows that 5-year trends are highly correlated with Delta outflow and that all stations behave in a similar fashion. This means that the separate embayments comprising the estuary behave in a highly dependent, integrated manner, rather than as separate units. The 1976-77 drought is clearly evident at all stations except the Presidio, where the drought had a much reduced influence due to the moderating influence of oceanic conditions. This figure also shows that salinity is not increasing or decreasing with time.

The 28-year trend curves are presented in Figure 6. Figure 6 shows that there have been minor long-term changes in salinity. At some stations, salinity has decreased while at others, slight increases are evident. Additional analyses presented in the next section, indicate that these changes are much smaller than the natural variability in the system and therefore are not statistically significant, except at Presidio.

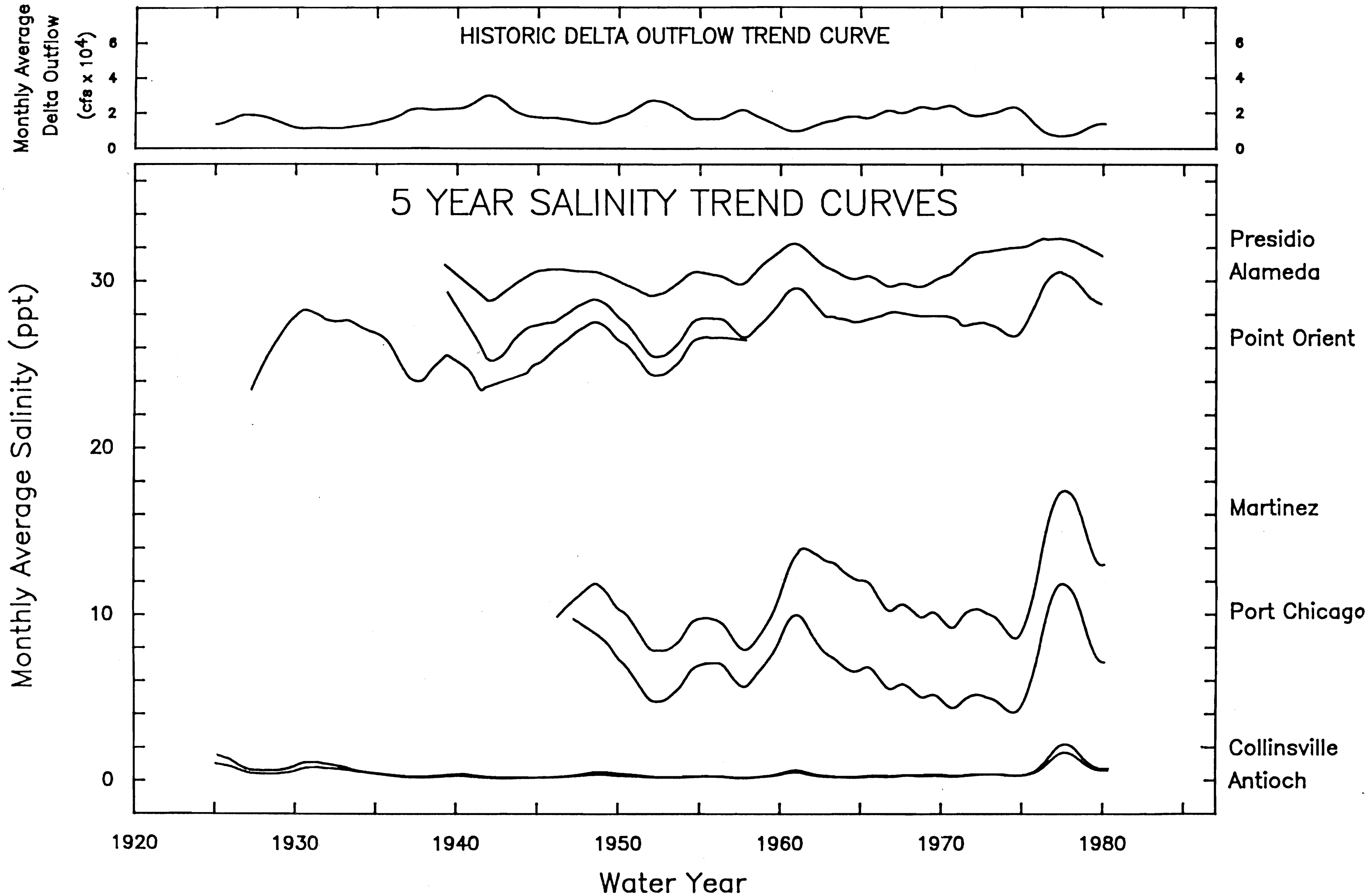


FIGURE 5. Five-Year Trend Curves for Historic Delta Outflow and Salinity.

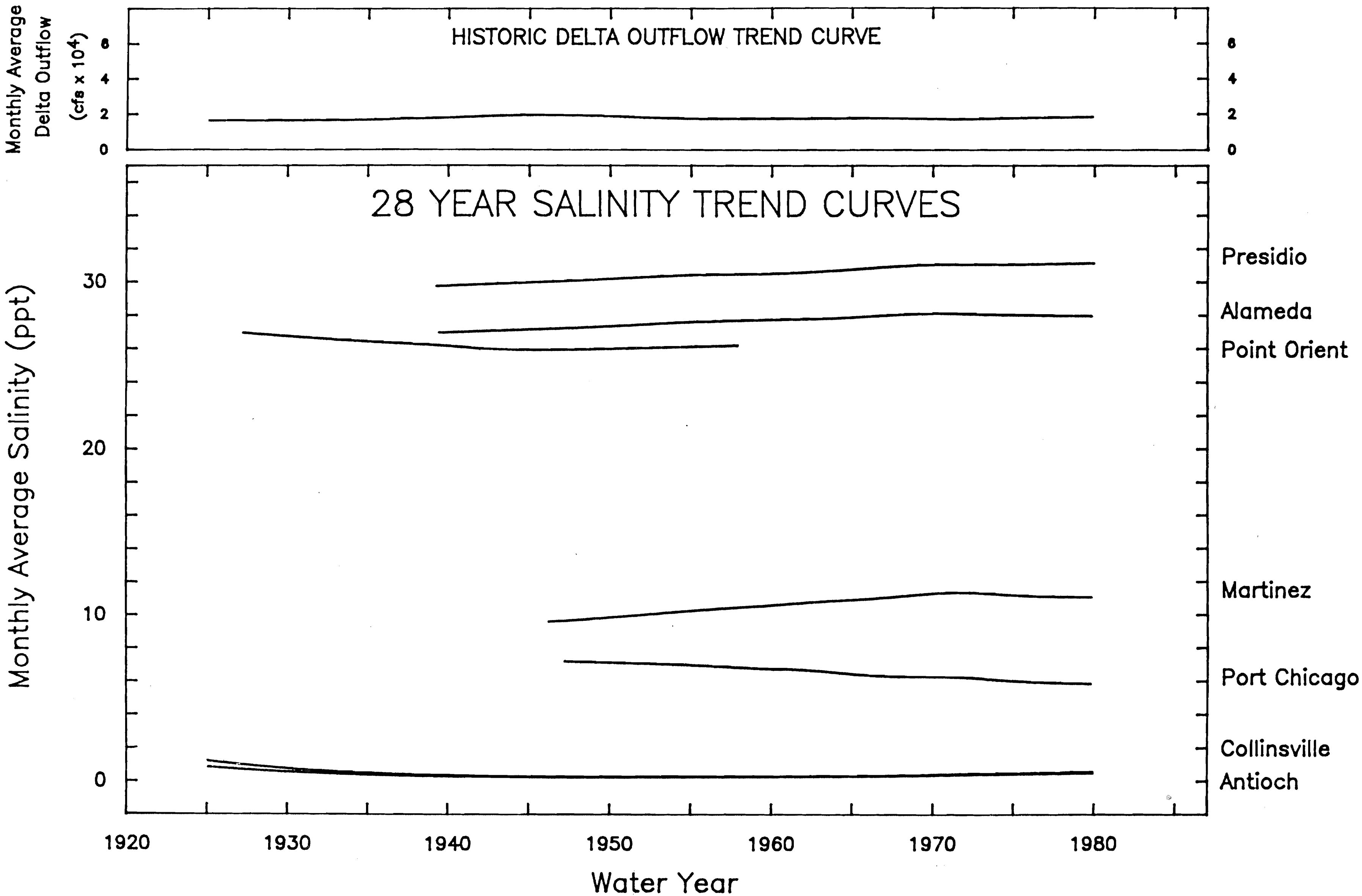


FIGURE 6. Twenty-Eight-Year Trend Curves for Historic Delta Outflow and Salinity.

Regression Model

We next used a linear least-squares regression procedure (Nie et al. 1975) to determine if any of the changes in the trend curves (Figures 5 and 6) were statistically significant. The procedure used in this analysis is described in Attachment B, Step (5). This analysis revealed that there was no statistically significant change in salinity at any of the stations except the Presidio. This is partially because the natural variability is much larger than the small changes shown by the trend analysis.

The significance of time trends was assessed with the coefficient of determination (R^2) and the probability statistic (P). The coefficients of determination (R^2) ranged from a low of 0.000 at Antioch to a high of 0.007 at Martinez. This means that almost none of the variability at any of these stations is explained by time. Time was not a significant covariant at any of these sites ($P=0.081$ to 0.908), except the Presidio ($P = 0.00003$). This means that the slight changes apparent in the trend curves (Figures 5 and 6) are due to chance everywhere but at the Presidio. At Presidio, time was a highly significant covariant. Calculations with the resulting regression model indicate that salinity has increased at a rate of 34 parts per million per year (ppm/yr) or about 0.1 percent per year over the period of record at this station.

Temperature

Water temperature is important in many organism's life cycles and is known to influence their occurrence, distribution, and behavior (Gunter 1957). Temperature can control the timing of spawning runs, the distribution of fish in the Bay, and the composition and distribution of plankton, fish, and other marine organisms in off-shore oceanic water (e.g., Chelton et al. 1982; Radovich 1960). Temperature is an important indicator of climatic and oceanic change, and can influence Bay water quality, as discussed in the last section of this report.

We studied air and water temperature at two sites in the Bay -- the Presidio and Alameda. The Presidio was selected because it is indicative of conditions at the entrance to the Bay. We were primarily interested in determining if any significant changes had occurred near the Golden Gate that could explain changes in abundances of fish in the Bay. Alameda was selected as a control to help isolate changes due to oceanic factors from those due to Delta outflow.

Variability

The historical air and water temperature data at Presidio and Alameda are compared in Figure 7. The nearly straight line through each data set is a long-term average trend curve that is discussed in the section, Time Trends. The data plotted in this figure were adjusted to remove the variability due to sampling time, which changed several times over the period of record (Attachment B, Step 1). This figure shows that temperature, like salinity, is highly variable. We performed a Pearson correlation analysis on these data. Air and water temperature at each station were highly correlated (R^2 = 0.79 - 0.85). The correlation between Delta outflow and both air and water temperature was not as significant. We obtained the following coefficients of determination (R^2) in this analysis:

	Coefficient of Determination (Delta Outflow)
Alameda Air	0.37
Alameda Water	0.44
Presidio Air	0.29
Presidio Water	0.39

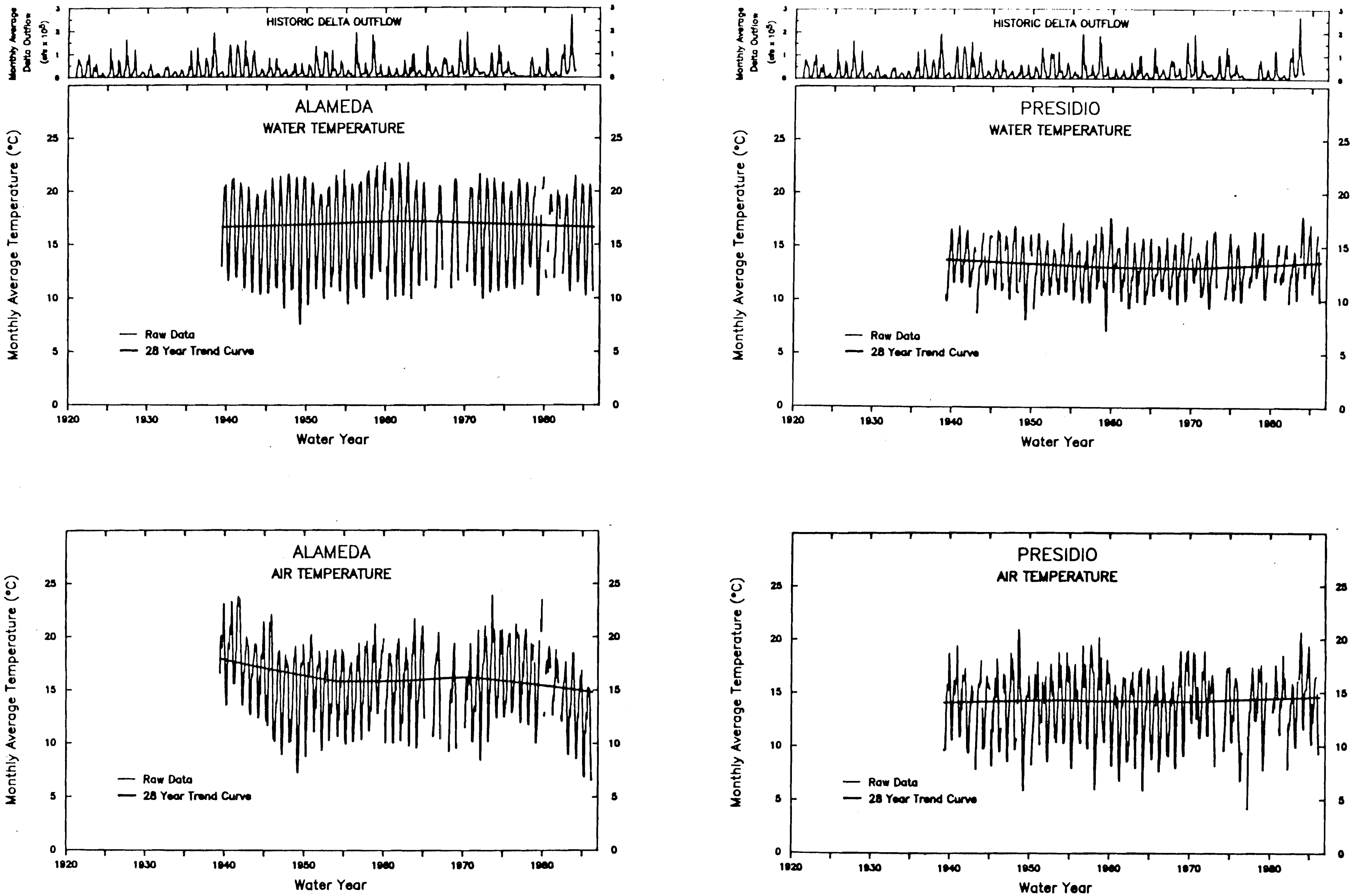


FIGURE 7. Historical Air and Water Temperature Data at Alameda and Presidio.

These analyses suggest that Delta outflow is not the principal factor that controls temperature in the Bay although it can account for 39 to 44 percent of its variability, Climate and oceanic conditions are probably more important at these stations. This is consistent with analyses presented by others (Reid et al 1958; Roden 1960). Since the correlations between both air and water temperature and Delta outflow are about the same, climate is probably the dominant variable influencing both Delta outflow and water temperature.

The Presidio water temperature data (Figure 7) shows a change due to a well-known shift in oceanic conditions. In February 1960, the average monthly water temperature plunged to the lowest value of record, 7.2 ^{o}C and in six months, soared to the highest value of record, 17.9 ^{o}C. Similar changes have been reported in ocean water along the California Coast and have been attributed to the major El Nino event of that year (Huang 1972; Reid 1960; Namias 1972; Chelton et al. 1982, etc.). Since this change does not correspond to a change in either Delta outflow, air temperature at Presidio, nor in air or water temperature at Alameda, it is concluded that it too was triggered by off-shore oceanic events.

Time Trends

Changes in temperature at Alameda and Presidio were investigated using the same two procedures previously described for salinity analyses, smoothing and linear regression. The 5-year and 28-year temperature trend curves are compared with Delta outflow trend curves in Figures 8 and 9.

The 28-year trend curve for Presidio shows a gradual decrease in water temperature through about 1960, followed by a gradual increase. The year 1960, which is the transition point, coincides with the temperature shift discussed above (Figure 7). Similar trends have been reported for ocean waters along the California coast, and they have been attributed to a shift in the relative strength of off-shore currents. No

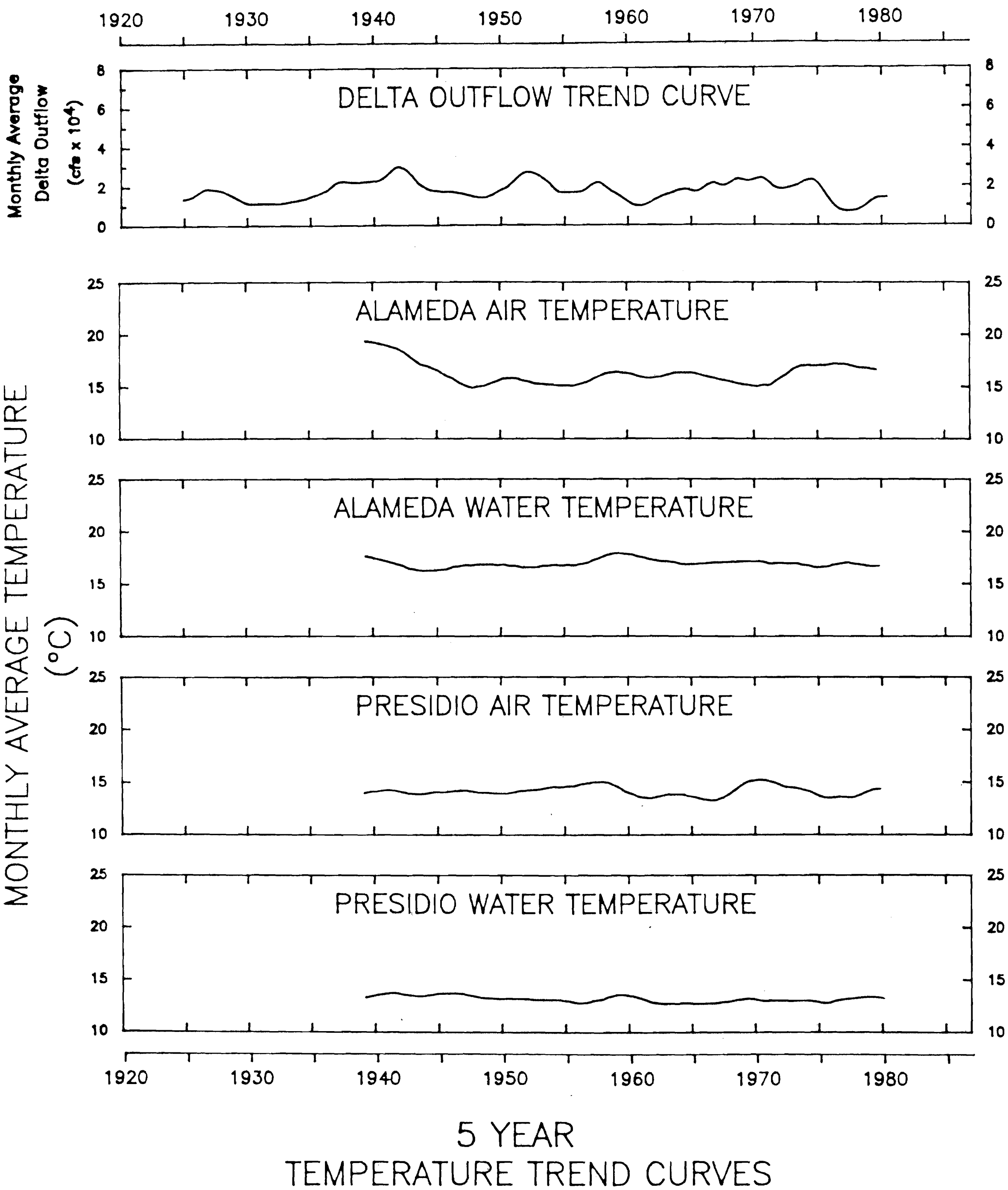


FIGURE 8. Five-Year Trend Curves for Historic Delta Outflow and Temperature.

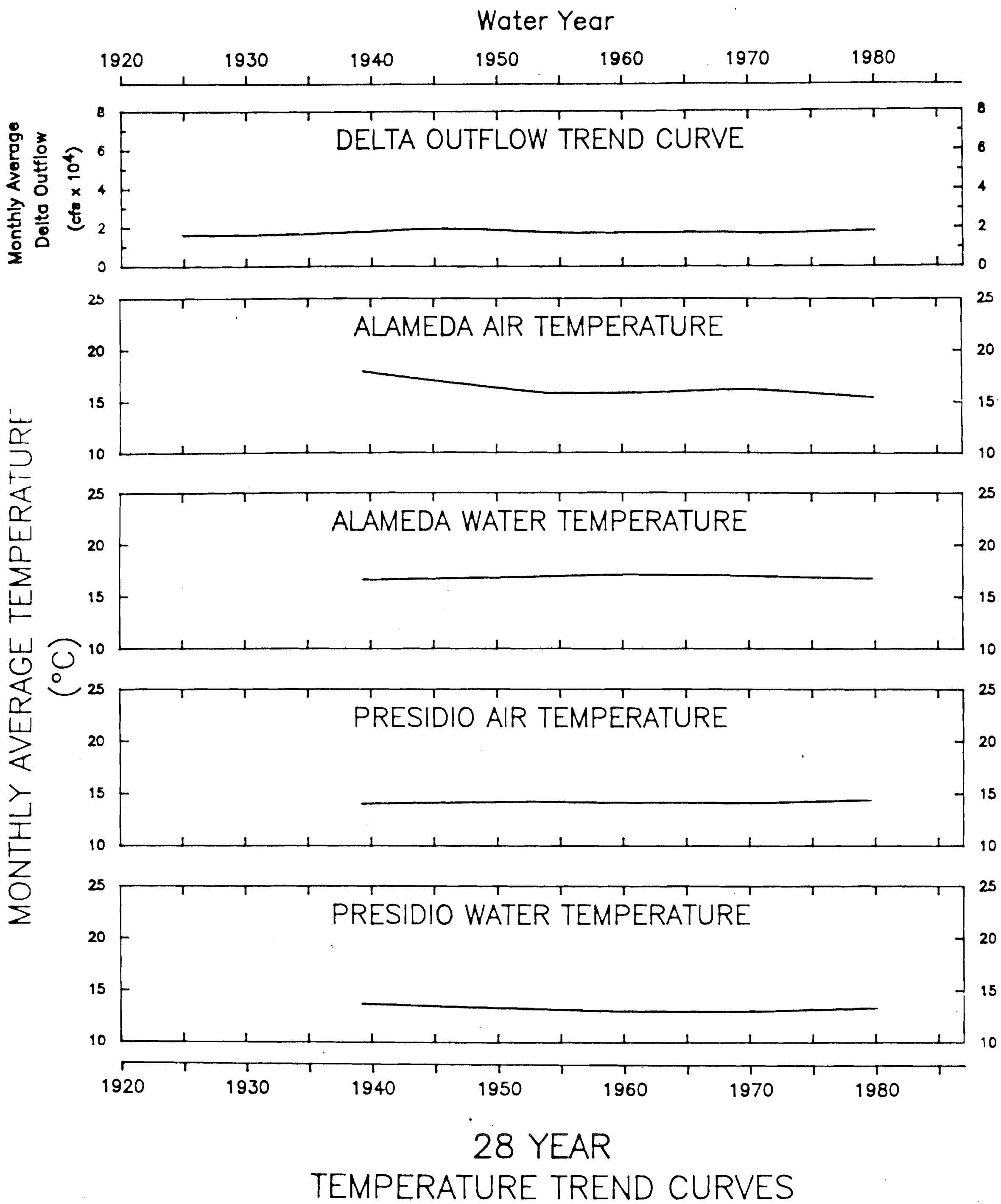


FIGURE 9. Twenty-Eight-Year Trend Curves for Historic Delta Outflow and Temperature.

corresponding change in air temperature or Delta outflow are apparent, suggesting climate is not the driving force of these shifts in water temperature.

Others believe that the Presidio water temperature shift reflects a major change in oceanic climate (Marine Research Committee 1960; Chelton et al. 1982). This shift is important because it has changed the abundance and distribution of marine and pelagic organisms normally present in off-shore waters (Sette 1962). This could also affect the abundance of marine fish in the Bay. The shift coincides with the decline in Dungeness crab fishery landings in central California and has been proposed as a possible contributing factor (Wild et al. 1983). Other changes in species distribution due to this event have also been described, including the appearance of tropical fish off the California coast (Radovitch 1960, 1961) and an increase in phytoplankton abundance (Chelton et al. 1982).

These types of changes in off-shore oceanic waters are common and are highly correlated with variations in sea level (Chelton et al. 1982). The 1957-60 events, however, are more frequently cited because they were the first to be comprehensively studied. Since these shifts can influence water quality and the ecosystem in the Bay, we believe that it is important to monitor these events. In many cases, these changes may be far more significant in affecting species distribution in the Bay than Delta outflow. This is further explored in the last section, Physical Concepts.

PHYSICAL CONCEPTS

In this section, we provide a conceptual framework for understanding the salinity and temperature trends presented previously. Our analyses indicate that salinity is increasing faster at the mouth of the estuary (34 ppm/yr), which is farthest removed from the source of freshwater, than at the upstream end where no change is evident. If freshwater inflow were the only factor affecting salinity in the Bay, the rate at which salinity increases due to withdrawals of freshwater should decrease with increasing distance from the source of freshwater. In other words, the largest increases in salinity should occur at Antioch and Collinsville at the upstream end of the estuary and the smallest at Presidio at the mouth of the estuary. We found the reverse.

Water temperature at the Presidio bottoms out in 1960 and has been increasing steadily ever since. The identical trend has been observed in off-shore waters (Wild et al. 1983; Huang 1972; Reid 1960) but is absent at other points in the Bay.

Both of these results at the Presidio suggest that salinity and temperature at this station is more strongly influenced by oceanic conditions than by upstream conditions. Such changes at the Presidio will eventually affect water quality throughout the Bay. Thus, we analyzed sea level and oceanic salinity in an attempt to explain our results and place oceanic influences in perspective.

These analyses, presented below, suggest that the increase in salinity and temperature at Presidio is due to a shift in off-shore oceanic conditions. The sea level is rising at a rate of 0.005 ft/yr at the Presidio. The salinity and temperature of off-shore oceanic water may also be increasing due to a change in the strength of longshore currents. These two changes can account for most of the 34 ppm/yr increase in salinity at Presidio that we calculated from historic data.

Salinity and temperature in the Bay are controlled by conditions at the Golden Gate and the western Delta. Since about 90 percent of the water and over 99 percent of the salts in the Bay originate in the ocean, it seems obvious that changes in off-shore oceanic conditions can have significant effects on Bay salinity. Simply stated, the Golden Gate is the source of salts in the Bay while Delta outflow perturbs the salt input. This section will focus on salinity. However, the same concepts also apply to water temperature.

The principal oceanic factors that could cause salinity at the Presidio to increase are an increase in sea level and an increase in the salinity of ocean water that enters the Bay through the Golden Gate. We explored both of these factors by reviewing the oceanographic literature for evidence of changes in sea level and oceanic salinity.

Sea Level

The amount of ocean water that enters the Bay during each tidal cycle depends upon the surface area of the Bay and the height of the ocean (i.e., sea level) at the Golden Gate. These two factors influence the size of the tidal prism, which is the volume of water that enters the Bay during a tidal cycle. This volume has been determined for San Francisco Bay (DPW 1931; DWR 1962). If the volume of ocean water entering the Bay increases, salinity will increase if all else remains constant.

The sea level at Presidio has been rising at an average rate of 0.004 ft/yr (1.2 mm/yr) since 1855, when the NOS tidal gaging station was established there (Hicks et al. 1983; Smith 1980; Saur 1972). This rate slightly increased to 0.005 ft/yr (1.5 mm/yr) in the post-1940 period (Hicks et al. 1983). The record (Figure 10) shows periods of rise, periods of fall, and periods when sea level has not changed appreciably relative to the land. However, the most impressive feature of the record is the rising trend after the late 1800s. We estimate that this rise (0.005 ft/yr) could have increased the volume of new ocean water entering the Bay by at least 45,000 acre feet/day over the 46-year record, increasing the salinity at Presidio by about 10 ppm/yr or 30 percent of the noted 34 ppm/yr change.

This rise is projected to continue and to greatly accelerate if polar ice caps melt (Williams 1985; Broecker 1975). The increase in sea level at Presidio is part of a

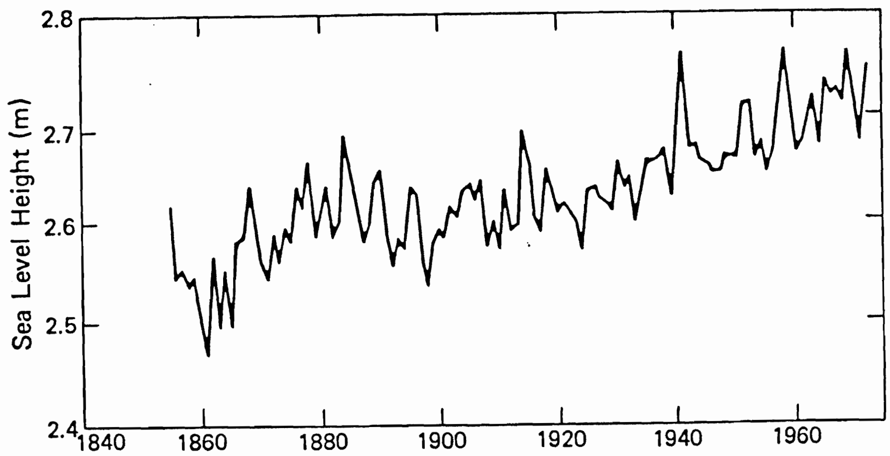


FIGURE 10. Yearly Means of Sea Level at Presidio for the Period 1855-1978 (Smith 1981).

secular trend, and similar or greater increases have been reported throughout the north Pacific and particularly south along the California coast (Saur 1972; Chelton and Davis 1982; Hicks et al. 1983; Harris 1981).

Ocean Salinity

Off-shore ocean water contains over 300 times more salt than Delta outflow. Additionally, the volume of new ocean water that moves into the Bay during a tidal cycle is seven times greater than average Delta outflow. Therefore, changes in the salinity of ocean water can significantly alter Bay salinity levels, particularly in the Central and South bay.

The salinity of new ocean water that enters the Bay during each flood tide depends principally on the movement of off-shore currents. The California Current System is operative in waters off the Golden Gate (Hickey 1979; Sverdrup et al. 1942; Fairbridge 1966). This system consists of two current systems with different physical properties. The California Current flows southward and moves cold, low-salinity (32.8-33.0 ppt) subartic waters into the region off the Golden Gate (Saur 1980). The California Undercurrent and the Davidson Current flow northward and move warm, high salinity (33.9-34.6 ppt) tropic and subtropic waters off the Golden Gate (Wooster and Jones 1970). The Davidson Current, which is a surface expression of the California Undercurrent (Hickey 1979), is only present from November through February.

There are two processes by which water in the California Current System can increase in salinity: by upwelling of cold, high salinity water from the ocean bottom due to local wind stress or by an increase in the strength of the northward moving, high-salinity countercurrents. These processes are demonstrated by Figure 11, which shows the mean longshore salinity distribution of the California Current. This figure shows that salinity increases with depth, which is why upwelling increases

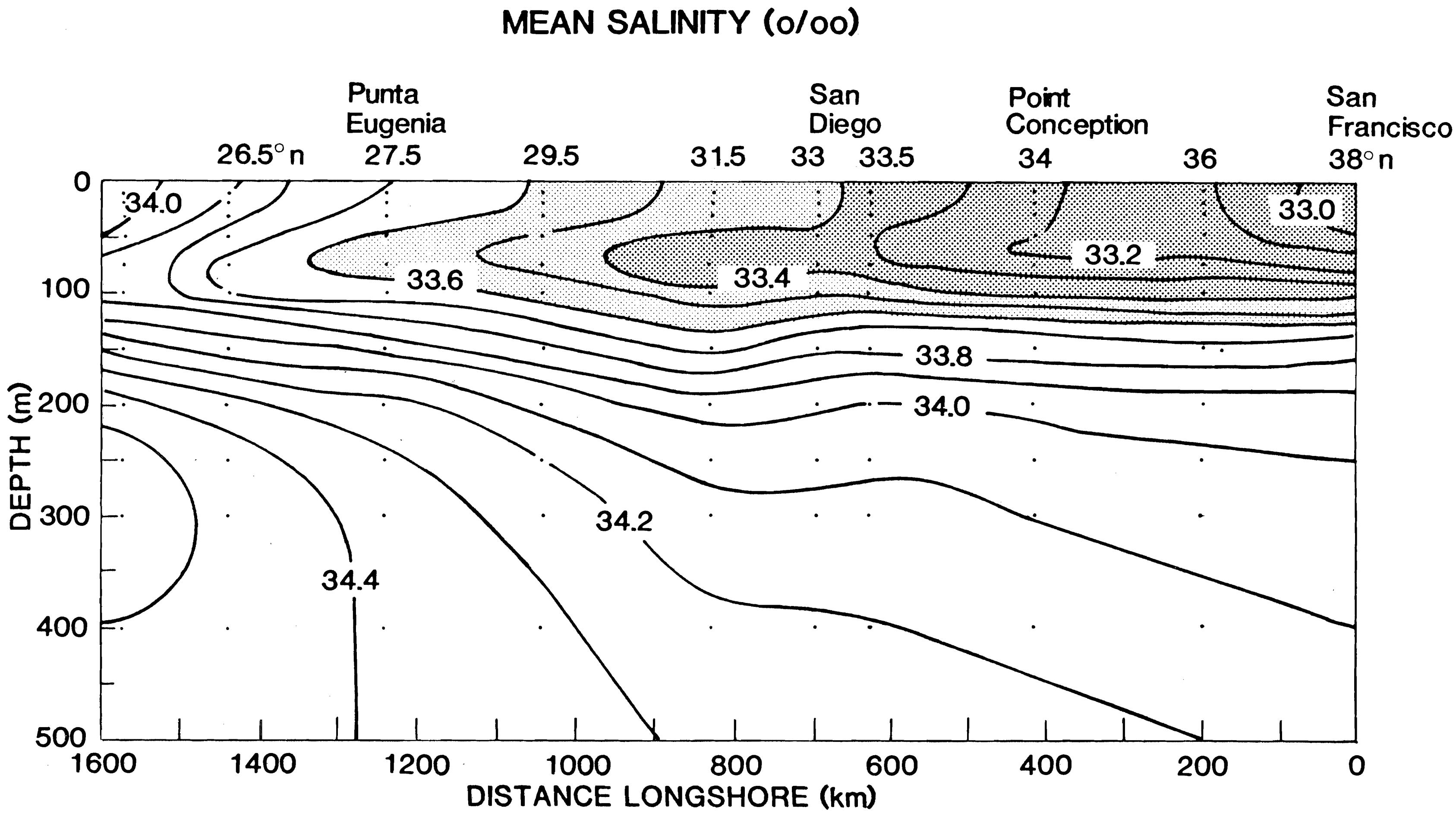


FIGURE 11. The Mean Longshore Salinity Distribution Off the California Coast (Chelton 1981).

surface salinity. It also shows the tongue of low-salinity water extending from high to low latitudes that is carried into the Bay area by the California Current.

The effect of upwelling on salinity off the California coast has not been studied directly. However, wind velocity along the California coast, in Suisun Bay, and the Delta have increased dramatically since 1975 (Lehman 1987), which would increase upwelling and hence ocean salinity. Nevertheless, upwelling is probably not the dominant factor responsible for the increase in Presidio salinity because it would be accompanied by a decrease in water temperature, and a rise in water temperature has been observed (Figure 7).

On the other hand, there is evidence that the strength of the northward-flowing, high-salinity countercurrents have increased (Huang 1972) and that salinity has increased in off-shore waters. A strong relationship exists between sea level and current strength (Chelton et al. 1982; Chelton and Davis 1982; Saur 1972; Namais and Huang 1972). High sea level corresponds to stronger than normal northward flow and low sea level to above normal southward flow. Since it has been amply demonstrated that sea level at the Presidio and elsewhere along the California coast has consistently increased since the late 1800's, is likely that the strength of the northward-flowing, high-salinity countercurrents has also increased.

Huang (1972) concluded that the southward flowing California Current weakened during the decade after 1957 relative to the prior decade and that the northward flowing countercurrents increased. These changes resulted in the advection of more warm, high-salinity water into the California Current region. He reported that the salinity off San Diego increased by 0.13 ppt in the decade from 1948-57 to 1958-69 or at a rate of about 10 ppm/yr. Similar results have also been reported for ocean waters off the Golden Gate (Reid 1960).

Shifts in these off-shore currents could account for part of the observed changes in salinity at Presidio. We estimate that an increase in ocean salinity from 32.5 ppt, which is characteristic of the California current (Saur 1980) to about 33.5 ppt, which is characteristic of the countercurrent (Wooster and Jares 1970) could increase the salinity at Presidio by about 24 ppm/yr. We believe trends in off-shore oceanic data should be studied to identify possible influences on the Bay and to confirm these analyses.

These results highlight the importance of considering the influence of off-shore oceanic conditions in the Bay. Analyses of actual, historical data indicate that upstream modifications have not resulted in a statistically significant increase in salinity anywhere in the Bay, while shifts in oceanic currents have produced a significant and measurable increase in salinity at the Presidio. Since the Golden Gate is the entrance to the Bay, conditions there are important in determining Bay water quality. A permanent salinity and temperature monitoring station should be established at the Presidio so that changes at this important boundary due to shifts in oceanic conditions can be detected and distinguished from other factors.

ATTACHMENT A

SALINITY AND TEMPERATURE SAMPLING, ANALYSIS, AND DATA REDUCTION PROCEDURES

A.1 INTRODUCTION

Seven stations with long-term, daily records were selected to examine historic salinity and temperature trends in San Francisco Bay. These stations are:

1) Antioch near the mouth of the San Joaquin River,

2) Collinsville near the mouth of the Sacramento River,

3) Port Chicago in Suisun Bay,

4) Martinez in Carquinez Straits,

5) Point Orient near the entrance to San Pablo Bay,

6) Alameda on the northeast shore of the South Bay, and

7) Presidio at the south side of the Golden Gate.

Daily salinity and temperature data from these seven stations were used to calculate monthly averages. This attachment discusses the sources of the raw data, period of record, sampling methods used to collect the data, methods of chemical analysis, and data reduction. Statistical analyses are discussed in Attachment B.

Two major sources of long-term salinity and temperature data were used in this work: (1) California Department of Water Resources (DWR) and U.S. Bureau of Reclamation (USBR) salinity data at five stations in the Delta and San Francisco Bay and (2) National Ocean Service (NOS) salinity and temperature data at

Presidio and Alameda. Since identical sampling, analysis, and data reduction procedures were used for each station in these two broad groups, the following sections first discuss the generic procedures that apply to all stations in the class, followed by station-specific details where appropriate.

A.2 DWR/USBR SALINITY DATA

The Department of Water Resources (DWR) has maintained a salinity monitoring network in the Delta and San Francisco Bay since 1920. Grab-samples were collected every four days, usually 1.5 to 2 hours after higher-high tide and analyzed for chlorinity at up to 40 stations. In the 1970's, this program was phased out and replaced by continuous electrical conductivity monitors operated by the USBR and DWR.

Five of these stations were selected for analysis in this work (Table 1): (1) Antioch, (2) Collinsville, (3) Port Chicago, (4) Martinez, and (5) Point Orient. Stations were selected to geographically cover the North Bay, from the river mouths to the entrance of the South Bay (Figure 1). The stations with the longest continuous record were selected from each region (Sacramento River, San Joaquin River, Suisun Bay, Carquinez Straits, and San Pablo Bay).

This section broadly describes this salinity monitoring network, including its history, sampling and analytical methods, and data sources. The data reduction procedures used in this study are also described, including methods used to mate the later continuous electrical conductivity data with the earlier four-day grab chlorinity data, to convert chlorinity and electrical conductivity to salinity, and to validate the data.

History

Salinity intrusion into the Delta has been the subject of more or less extended investigations since 1916 (DWR 1930, 1931). In 1921, the State Water Commission, predecessor to the Division of Water Rights, established a number of salinity observation stations in the Delta, Suisun Bay, and Carquinez Straits. In 1924, the program was shifted to the California Department of Public Works (predecessor to the Department of Water Resources), Office of the Sacramento-San Joaquin Water Supervisor. At this time, the program was expanded to include 32 stations. Data have been collected from this network of stations, with some annual additions and deletions, more or less continuously since 1924 except during the period 1941-43 when miscellaneous field studies were conducted.

Since 1944, the network has been maintained under a cooperative agreement with the USBR, who used the data in determining releases from Central Valley Project (CVP) reservoirs. The number of stations in the grab-sampling network has been gradually decreased, and the program was terminated in 1972. The USBR established continuous electrical conductivity recorders at some stations in the network starting in 1954 in connection with operation of the Contra Costa Canal and Delta-Mendota Canal. These have been maintained through the present, and four sets of data from this network are analyzed here (Antioch, Collinsville, Port Chicago, Martinez). Data from some of these monitors are published in the Bureau's monthly operating reports, but the bulk of it remains unpublished in hardcopy and available only from Storet, which is the U.S. EPA's computerized water quality data base.

Sampling Methods — 4-Day Grab Samples

Four-day grab samples were collected at the five DWR/USBR stations from 1920 through 1971. This section describes the grab-sampling methods. Samples of water were collected by local observers on specified days from 1.5 to 2 hours after the predicted time for higher-high tide. From 1920 until 1925, samples were taken at 2-day intervals at many stations (e.g., Antioch, Collinsville). Beginning in 1926, all observers were instructed to take samples on the 2nd, 6th, 10th, 14th, 18th, 22nd, 26th, and 30th of each month (DPW 1930, p. 405).

The program was designed to determine the maximum salinity conditions for a specified day. Therefore, samples were taken at a particular time with reference to the tide. An early investigation of the relation between tidal stage and salinity indicated that the maximum salinity occurred at approximately two hours after higher-high tide. Thus, samples taken from 1920 through 1925 were taken 2 hours after higher-high tide. Later investigations seemed to show, however, that 1.5 hours would, on the whole, more correctly represent this interval (DPW 1930, p. 406). Thus, from 1926 through the end of the program, all samples were taken 1.5 hours after higher-high tide under normal circumstances.

In the earlier work, it was left to the observer to determine the time of high tide at his particular station and then to allow the proper time interval to pass before taking the sample. Later, the average time for travel of the high tide from the Golden Gate to each station was determined, and the observer was instructed to add this time interval, plus 1.5 - 2 hours to the time for high tide as given in the tide tables for Golden Gate. Starting about 1926, each observer was furnished with a schedule showing the exact time at which samples were to be taken, based on tide tables. The times for sampling after both the higher-high and low-high tides were also given in the schedule.

The observers were instructed to sample only after the higher-high tide when possible. If not possible, or impracticable, the observer was instructed to sample after the low-high tide. Salinity records analyzed here indicated that 62 to 96 percent of the samples were taken within 1.5 to 2 hours of the higher-high tide, most of the others at 1.5 to 2 hours of low-high tide, and a few were made at other times. This occurs because approximately 20 percent of the higher-high tides during the course of a year occur at night. Since salinity observation stations are maintained by volunteer personnel, it is more convenient to sample during the day during slack water than at night. Only measurements taken at higher-high tide were used in this study.

The samples were collected from immediately below the water surface using a weighted bottle. The bottle was thoroughly rinsed with water from the site immediately prior to sampling. Water from the sampling bottle was poured into a two-ounce mailing bottle, and a pre-affixed label was filled in with the date, station name, sampling time, and tide stage. The bottle was then mailed to the testing laboratory of the State Division of Highways at Sacramento (DWR 1931, p. 248).

Sampling Methods — Electrical Conductivity

Beginning in 1964-1967, continuous electrical conductivity recorders were installed at four U.S. Bureau of Reclamation stations (Table 1). The DWR installed a continuous electrical conductivity recorder at Point Orient in 1983 (DWR Nov. 1986). Since very little data are presently available from this monitor, no continuous electrical conductivity data for Point Orient was included in this study. This section describes the methods used by the USBR to continuously record conductivity.

The four USBR conductivity monitors are located in tubs in instrument sheds at the end of 100+ foot long piers at each site. A stationary, submersible pump located 6 to 8 feet below the higher-high tide water surface, continuously pumps water into a tub equipped with an overflow standpipe. Since the Martinez pier is float mounted, all measurements are made at a constant distance below the surface. All other sites are located on fixed piers, and sampling depth varies with the tides.

Chemical Analysis Methods

The 4-day grab samples are analyzed for chlorinity. Chlorinity was selected as an indicator of salinity because it is the major constituent of sea water and because it can be measured easily. The argentometric method (APHA 1985), which was formerly called the Mohr method, was used to determine chlorinity. In this method, the sample is titrated with a standard solution of silver nitrate using potassium chromate as the indicator. The specific procedures used in the salinity investigation are presented in Bulletin 27 (DPW 1931, pp. 263-266).

The USBR continuous monitors record specific conductance (i.e., electrical conductivity). Martinez and Port Chicago are equipped with Westronic meters, which continuously record on strip charts. The area under the curve is planimetered, and the salinity computed by applying a factor. Collinsville and Antioch are equipped with Foxborough instruments, which telemeter hourly data back to the Central Valley Operations Office, where they are transferred to Storet. The monitors are calibrated about once a week and cleaned as needed.

Data Sources

The four-day chlorinity grab sample data from these stations have been regularly reported in the annual bulletins of the Department of Water Resources and its predecessors. The bulletin series in which these data are published and its format have changed several times over the 50-year history of the program, resulting in a rather complex paper trail.

Chlorinity data for the period 1920 to 1931 are published in Appendix C of DPW Bulletin 27 (DPW 1931). The record for 1932 through 1955 is reported in the Sacramento-San Joaquin Water Supervisor's Report series for that period (DPW/DWR 1932-1957). The record for 1956 through 1960 is published in the

Surface Water Flow series (DWR 1959-1961), and the record for 1962 is published in the Quality of Surface Waters in California series (DWR 1965). The final portion of the record, from 1963 through 1971, is published in the Hydrologic Data series, Volume III (DWR 1965-1972). Most of these data have also been archived on Storet as a result of the D 1485 Delta Hearings. We used the Storet data set in this work, which excludes some of the earlier records for unknown reasons.

Continuous electrical conductivity data at these stations are collected by the U.S. Bureau of Reclamation. The 1-hour data are used to compute daily averages and daily minima and maxima, which are entered into Storet. These data are not published in paper copy, and the raw 1-hour data are not archived. We used the Storet daily average data in this work.

Data Reduction

In general, the data were used as received from Storet, under the presumption that effective error checking had already been applied. We screened the Storet data for obvious errors and compared randomly selected records with published copy (DPW/DWR 1931-1972) where available, to verify that we were working with the correct data sets.

The 4-day chlorinity grab sample data were provided with a five digit tidal code that indicates when the sample was taken with reference to tidal minima and maxima. We eliminated all grab samples not taken within 2 hours of the higher-high tide to provide a tidally uniform data set. These data were eliminated because there is no reliable method to convert samples taken at one point in the tidal cycle to tidal maximum values without more information than we had. The remaining data is referred to as tidal-maximum, 4-day chlorinity because it is approximately equal to the maximum chlorinity over the tidal cycle. These values are approximately equal to the maximum monthly salinity in an entire vertical cross section of channel (DPW 1931; DWR 1962, p. 53).

The daily chlorinity and conductivity data were also screened for obvious errors. The USBR conductivity data included daily averages, maxima, and minima. We compared the daily average with the daily maximum and minimum and eliminated any daily average that was less than the minimum or greater than the maximum. This removed less than 1 percent percent of the daily values from the data base.

A.3 NATIONAL OCEAN SERVICE DATA

The National Ocean Service (formerly U.S. Coast and Geodetic Survey) has monitored air and water temperature, water density, and tidal height at a number of points in San Francisco Bay. Alameda and Presidio have the longest and most complete records, and they are among the best records of their kind available anywhere in the world.

Station Location and Period of Record

Presidio

The NOS tidal station at Fort Point in the Presidio is located at the end of a pier on the south shore of the Golden Gate. The record at this station starts in May 1855 and is the longest salinity record we are aware of anywhere in the United States. The present-day station is located at latitude 37^{o} 48.4′ N, longitude 122^{o} 27.9′ W. The station was previously located at other sites.

Measurements at the Presidio started in May 1855 and ran continuously through May 1877. The earlier temperature data has been previously reported and analyzed (Davidson 1885; Roden 1966). Sampling was re-initiated on November 7, 1921 and conducted approximately continuously through the present. The salinity and water temperature data for the period 1968 to 1977 were previously summarized (Conomos 1979). The period of record from January 1939 through December 1985 was analyzed in this work.

Alameda

This station is located at the end of a pier at the Alameda Naval Air Station at latitude 37° 46.5′ N, longitude 122° 17.9′ W. Measurements started on March 9, 1939, and have been made approximately continuously since that time. The available record through the end of 1985 was analyzed in this study. The salinity and water temperature data for the period 1968 to 1977 were previously summarized (Conomos 1979).

Sampling Methods

A typical data sheet for these stations is shown in Table A-1. The air and water temperature, water density, barometric pressure (Presidio only), and time of observation have been recorded approximately daily by an observer. Many of the data sheets also include reduced density at 15° C and later sheets include calculated salinities. These calculated values were determined using standard hydrographic tables (Knudsen 1901), and many errors were noted. Thus, the calculated values were not used in this study, and salinity was computed from the temperature and density measurements using Millero's equations (Millero et al. 1976). The raw data are archived by the National Oceanic and Atmospheric Administration (NOAA), National Ocean Service, Tidal Datum Section, Rockville, Maryland.

Daily observations at these stations have not been made on a fixed schedule and appear to have been taken at the beginning or at the end of a work shift or during lunch. Random checks using tide tables indicate that sampling was independent of

TABLE A-1

TYPICAL RAW DATA SHEET FOR PRESIDIO

Form 457
DEPARTMENT OF COMMERCE
U. S. COAST AND GEODETIC SURVEY

DENSITY AND TEMPERATURE

Lat.
Long.

Station Fort Point

Month March Year 1944 Observer

Warmest Sea Water (Degrees. Date.) *Heaviest Sea Water (Density. Date.)

Coldest Sea Water *Lightest Sea Water

	DAY OF MONTH	TIME OF OBSERVATION	TEMPERATURE			HYDROMETER NO.	DENSITY		REMARKS
			OUTDOOR AIR	SEA WATER	WATER IN JAR		OBSERVED READING	*REDUCED VALUE	Barometer
		h. m.	°	°	°			15° C.	
March	1	0803	49°	11.	11	H1002	1.0 235	1.0	29.95
"	2	0817	48°	11	11	H1002	1.0 238	1.0	29.88
"	3	0826	50°	11.1	11.1	H1002	1.0 231	1.0	30.01
"	4	0810	52°	11	11	H1002	1.0 223	1.0	29.94
"	5	0840	52°	10.9	11	T1000	1.0 208	1.0	30.24
"	6	0823	49°	11	11.1	T1000	1.0 188	1.0	30.29
"	7	0728	52°	11.1	11.3	T1000	1.0 175	1.0	30.35
"	8	0817	56°	11.5	12	T1000	1.0 179	1.0	30.35
"	9	0818	53°	11.4	11.9	T1000	1.0 188	1.0	30.29
"	10	0826	53°	11.2	11.2	H1002	1.0 208	1.0	30.15
"	11	0841	55°	11.7	12.4	H1002	1.0 226	1.0	30.03
"	12	1235	58°	11.6	11.9	H1002	1.0 224	1.0	30.01
"	13	0818	51°	11.4	11.5	H1002	1.0 222	1.0	29.93
"	14	0825	47°	11.3	11.5	H1002	1.0 221	1.0	30.06
"	15	0747	49°	11	11	H1002	1.0 225	1.0	30.19
"	16	0820	56°	11.2	11.3	H1002	1.0 227	1.0	30.14
"	17	0750	50°	11.2	11.3	H1002	1.0 23	1.0	29.99
"	18	0813	62°	11.2	11.7	H1002	1.0 23	1.0	29.95
"	19	0719	49°	11.3	11.3	H1002	1.0 23	1.0	30.12
"	20	0815	52°	11.3	11.3	H1002	1.0 23	1.0	30.30
"	21	0755	54°	11.5	11.7	H1002	1.0 218	1.0	30.24
"	22	0800	59°	11.5	11.6	H1002	1.0 216	1.0	30.35
"	23	0838	60°	11.7	12	H1002	1.0 214	1.0	30.41
"	24	0820	58°	12	12.3	H1002	1.0 214	1.0	30.19
"	25	0826	54°	11.9	12.2	H1002	1.0 215	1.0	30.02
"	26	No	opportunity.				1.0	1.0	
"	27	0930	58°	12.2	12.4	H1002	1.0 218	1.0	30125
"	28	0935	63°	12	12.2	H1002	1.0 218	1.0	30.32
"	29	0730	50°	11.1	11.5	H1002	1.0 239	1.0	30.28
"	30	0945	64°	11.7	12	H1002	1.0 24	1.0	30.20
"	31	0810	60°	11.5	11.7	H1002	1.0 24	1.0	30.01
	Sum								
	Mean								

* Not to be filled out by observer.

11—4518 (OVER) Density reduced by

tidal phase. At Presidio, prior to 1971 the majority of the samples were taken between 7:00 AM and 9:00 AM; between 1971 and 1982, the measurements were made between noon and 5:00 PM; and from 1983 through 1985, measurements were made between about 5:00 PM and midnight. At Alameda, prior to 1980, the majority of the samples were taken between noon and 5:00 PM. Starting in June 1980, the sampling time was shifted to 6:30 AM on weekdays and to late morning on weekends.

Since both air and water temperatures vary diurnally, this shift in sampling time biases the temperature data. Air temperatures taken in the early morning can be as much as 10 to 20^{o} F lower than those taken at midday. This explains the dramatic decrease in air temperature noted at Alameda. Therefore, we used a simple statistical procedure to remove the variability due to sampling time from the data set prior to working with it. This procedure is described in Appendix B, Step (1).

The sampling sites are located at the ends of piers that are equipped with shelters where the sampling and analysis equipment is stored. A sample of water is first collected by dropping a bucket on a line into the water to a point 1 to 2 feet below the surface. The bucket remains in the water for one full minute to allow it to adjust to the water temperature before it is withdrawn. The bucket sample, which is placed in the shade at the sampling site, is analyzed at the site for temperature and density as described in the next section.

Analysis Methods

The water temperature is measured by inserting a bulb thermometer into the water in the bucket immediately after it is withdrawn from the water. Water from the bucket is then decanted into a hydrometer jar, and its density is measured using the hydrometric method as described in Standard Methods (APHA 1985). Air temperature is measured with a thermometer that is hung in the shade at the beginning of the sampling trip and read at the very end.

Data Reduction

The raw data sheets (Table A-1) were purchased from NOAA and computerized by the DWR and by the author. The time of observation, air temperature, water temperature, jar temperature, and observed density were keyed into an ASCII file and screened for outliers using computer programs. The temperature data were variously reported in degrees Centrigrade and Farenheit, and we converted all measurements to ^{o}C. The following quality control checks were made: (1) temperature data were screened for values falling outside of the range of 1 to 40^{o} C; outliers were checked against raw data sheets; (2) each individual value was compared with its nearest neighbor, and those with deviations greater than 20 percent were checked; and (3) all marginal notes on the data sheets were checked to assure they were properly accounted for during data entry.

The jar temperature and observed density were used to compute daily salinity in parts per thousand (ppt) using the Millero equations for seawater (Millero et al. 1976). The Millero equations were selected instead of standard hydrographic tables (Knudsen 1901) to facilitate computations and because they were based upon a wider range of seawater samples.

ATTACHMENT B

STATISTICAL ANALYSES

This section provides detailed descriptions of the statistical analyses performed on the salinity and temperature data. These discrete operations are as follows:

1) time of day adjustment for the temperature measurements taken at Alameda and Presidio;

2) calculation of monthly averages from daily values;

3) conversion of salinity data at Antioch, Collinsville, Port Chicago, and Martinez [which were variously reported as chlorinity and conductivity],to a consistent chemical and tidal basis;

4) transformation of monthly averages to give approximately normal distributions;

5) fitting transformed monthly average data sets to a regression model.

6) smoothing of the adjusted, transformed monthly averages followed by inverse transformation of the smoothed values.

Each of these operations is discussed in turn. Some of the procedures discussed below involve regression models. All regressions were performed using the standard least-squares criterion. The time variable discussed in all of the steps is expressed as serial monthly time where t = 1 is October 1899, t = 2 is November 1899, t = 472 is January 1939, and so on.

Statistical calculations were performed using Systat Version 3.0. Additional data manipulation was accomplished using dBASE III (Developer's Release). The hardware was an IBM-compatible AT clone with an 80286 Processor. Graphs were produced using Sigma Plot (Jandell Scientific, Sausalito, CA) and a Roland 880 Plotter.

B.1 TIME OF DAY ADJUSTMENT FOR TEMPERATURE MEASUREMENTS

The daily air and water temperature measurements at Alameda and Presidio were not taken at fixed times of day throughout the periods of record. Rather, measurement times appear to coincide with work-shift transitions and changed periodically. Since air and water temperature vary diurnally, it is necessary to correct the daily measurements for the influence of sampling time before calculating the monthly averages.

We eliminated the bias due to sampling time using the Multivariate General Linear Hypothesis (MGLH) module of Systat. First, the daily data were categorized into eight 3-hour periods (i.e., midnight to 3 AM, 3 AM to 6 AM, 6 AM to 9 AM, etc.). Next, the raw daily temperature data were fitted to a regression model consisting of a constant and the time of day category (an integer from 1 to 8). The MGLH module outputs a residual value for each case, which is the difference between the model estimate for that case and its raw value. The adjusted daily temperature data were then calculated as the residuals plus the constant from the regression equation. Monthly average air and water temperature data for Alameda and Presidio were calculated from these adjusted daily data. These values are referred to as "time-adjusted" monthly average temperatures.

B.2 COMPUTATION OF MONTHLY AVERAGES

Monthly average values were used in all statistical analyses described in Steps (4) - (6). The validated (Appendix A) observed daily values were averaged for all salinity data. Time-transformed (Step 1) temperature data were averaged. Monthly averaging was used to uniformly weight the best available estimate of the prevailing conditions for each month. This was found to be necessary because patterns of missing data varied with time, tending to be more common in earlier years. The salinity data at four of these stations were initially reported as chlorinity and later as conductivity. These data sets were next converted to chlorinity, as described in Step (3).

At Presidio and Alameda, the monthly averages typically included 20 to 30 daily values. At the other five stations, the monthly averages prior to the mid-1970s typically are based on six to eight grab samples while those after the mid-1960s are based on 28 to 31 days of data.

B.3 CONVERSION OF DWR/USBR DATA TO CONSISTENT SALINITY UNITS

At Antioch, Collinsville, Port Chicago, Martinez and Point Orient, the early part of the record is recorded as tidal-maximum, 4-day chlorinity and the balance as daily average electrical conductivity. Thus, it was necessary to convert the data into consistent units over the entire period. This was done by developing a regression relationship between average monthly electrical conductivity and monthly average, tidal-maximum chlorinity. We chose to convert conductivity to chlorinity because the majority of the data had been reported as chlorinity. This choice minimizes uncertainty introduced by unit conversions.

All of the stations except Point Orient had a 4 to 6 year period when both 4-day chlorinity grab samples and continuous electrical conductivity (EC) data were simultaneously collected. The overlapping period of record for all stations was pooled, and regression techniques were used to find the best-fit linear equation, using chlorinity (Cl) as the dependent variable. The period of record for each station used in the pooled regression analyses and the number of values used in the regression are as follows:

	Overlap Period	No of Values Pooled Regression
Antioch	11/64 - 12/70	74
Collinsville	10/67 - 12/69	25
Port Chicago	10/67 - 6/71	57
Martinez	1/65 - 3/71	72

The resulting regression equation, which had an R^2 of 0.95, is as follows:

$$\text{Monthly average tidal-maximum Cl} = 0.4519 \times (\text{monthly average EC}) \quad \text{(A-1)}$$

In using this equation, chlorinity must be expressed in parts per million and electrical conductivity in micromhos/cm. We did not use DWR's salinity unit conversion equations (Guivetchi 1986) because they were developed using grab sample data that were not tidally adjusted.

Equation (A-1) was used to convert the monthly average electrical conductivity at Antioch, Collinsville, Port Chicago, and Martinez into monthly tidal-maximum chlorinity. Electrical conductivity data were not available for other stations. For the overlap period when both chlorinity and conductivity were available, the monthly averages were computed as the mean of both data sets after proper conversion.

Since the majority of the records at all of these stations were originally reported as chlorinity, all statistical analyses were conducted in chlorinity and subsequently converted into salinity for presentation. In all cases, we have converted chlorinity into salinity (i.e., in all graphs in this report) using Knudsen's (1901) relationship,

$$\text{Salinity} = 0.03 + 1.805 \times (\text{Chlorinity}) \quad \text{(A-2)}$$

Both salinity and chlorinity must be expressed in ppt in this equation.

B.4 Transformation of Monthly Average Data Sets

The tests for statistical significance used here assume that the data are normally distributed. We tested each monthly average data set (salinity, temperature, Delta outflow) to determine if it was normally distributed. We found that all data sets except Martinez salinity and Presidio temperature deviated significantly from the normal, bell-shaped curve. While modest violations of this assumption do not appreciably affect the test results, it is advisable to transform the data to approximate the normal distribution prior to performing regression procedures. Thus, we transformed all data sets.

We first computed skewness and kurtosis for the monthly average data sets. The time-adjusted temperature (Step 1) was used as the temperature data set. These computations were done using the STAT module of Systat. Skewness measures deviations from symmetry. It is zero when the distribution is a completely symmetric curve. A positive value indicates that the observed values are clustered more to the left of the mean and a negative value indicates clustering to the right. Kurtosis is a measure of the relative peakedness or flatness of the distribution. A normal distribution has zero kurtosis. A positive kurtosis means the distribution is more peaked (narrow) and a negative value that it is flatter than the normal distribution. The results of these computations are summarized in the top half of Table B-1, together with the mean, minimum, maximum, and standard deviation. The statistical significance of the skewness and kurtosis values summarized in Table B-1 can be determined by comparing them with significance levels (Pearson and Hartley 1956).

We then tested [by trial and error] various transforms, including the natural log and numerous power transforms (e.g., x^2, x^{-3}). In every case, a power transform yielded

TABLE B-1

STANDARD STATISTICS ON UNADJUSTED (RAW) AND TRANSFORMED MONTHLY AVERAGE DATA

			Chlorinity (ppm)					Salinity (ppt)		Air Temperature (°C)[b]		Water Temperature (°C)[b]	
	Unimpaired Flow (cfs)	Historical Flow (cfs)	Collinsville	Antioch	Port Chicago	Martinez	Pt. Orient	Alameda	Presidio	Alameda	Presidio	Alameda	Presidio
Unadjusted Data													
Mean	39,378	30,913	1,007	767	3,987	5,922	13,967	26.75	29.88	15.9	14.0	16.5	13.2
Minimum	2,472	65	6.0	10	20.2	33	5,300	9.16	13.43	6.6	4.2	7.6	7.2
Maximum	258,426	270,412	11,650	10,825	12,447	13,944	18,838	33.72	36.16	23.9	20.9	22.7	17.9
Standard Deviation	40,521	36,041	1,710	1,435	2,999	3,380	2,876	4.68	3.31	3.30	2.9	3.5	1.94
Skewness	1.62	2.16	2.9	3.5	0.41	0.067	-0.728	-0.86	-1.47	-0.23	-0.40	0.25	-0.013
Kurtosis	2.99	5.75	10.0	15.5	-0.89	-0.92	-0.182	0.26	2.46	-0.41	-0.34	-1.21	-0.662
Sample Size	756	743	725	744	462	456	332	515	505	515	519	515	519
Transformed Data													
Exponent (n)[a]	-0.0085	0.098	-0.037	-0.15	0.68	0.94	2.91	3.58	5.83	1.45	1.82	2.06	1.04
Standard Deviation	0.009	0.302	0.057	0.106	152.6	1,903	0.634×10^{12}	7.27×10^{4}	2.12×10^{8}	16.4	49.2	139.4	2.24
Skewness	0.000	-0.000	0.001	0.006	0.005	0.002	-0.001	-0.001	-0.001	-0.002	-0.001	0.000	-0.001
Kurtosis	-1.23	-0.24	-1.14	-0.955	-1.09	-0.93	-0.94	-0.98	-0.023	-0.474	-0.533	-1.304	-0.668

[a] A power transform (y^n) yielded the more normal distribution for all stations. This is the exponent (n) used in the power transform.

[b] Adjusted to remove variability due to sampling time, as described in Appendix B, Step (1).

a more normal data set than a log transform. Since symmetry is more important in the assumption of normality than is kurtosis, transforms were selected such that skewness equaled zero (+/- 0.01). The resulting kurtosis was generally +/- 1.3 or less (Table B-1). All of the transformed data sets were normal at the 1 percent significance level with respect to skewness. The data sets were then transformed using a power function, and the transformed data sets were used in all subsequent statistical manipulations.

B.5 REGRESSION OF TRANSFORMED MONTHLY AVERAGES

The adjusted data sets were used in a multivariate linear regression model to estimate the rate of change of salinity and temperature with time. The reader is referred to standard statistics texts for a description of multivariate linear regression techniques (Snedecor and Cochran 1967; Nie et al. 1975).

The transformed monthly average data sets for each station were individually fitted to a model of the form:

$$y^n = a + cT \qquad \text{(B-1)}$$

where:

- y = dependent variable, which is either untransformed monthly average salinity or untransformed and time-adjusted monthly average temperature.
- n = exponent of power function used to transform each data set to a normal distribution. The exponents for each dependent variable are listed in Table B-1.
- a = the regression constant, which is the intercept of the best fit line.
- c = regression coefficient for time.
- T = serial time in months.

This equation is used to calculate the time rate of change in salinity or temperature for the entire period of record when time (T) is found to be a significant covariate.

Significance as used here means that the time trend represented by the term cT is real rather than due only to chance in sampling from the population. We used as our criterion of significance a probability of 0.05 or the 5 percent significance level. This means that results are considered statistically significant if they are more extreme than what would occur 95 percent of the time if only chance variation were responsible.

Equation (B-1) was used to calculate the time rate of change of salinity or temperature for the entire period of record. The average monthly rate of change (i.e., the average slope of the curve defined by Equation B-1) can be calculated from

$$\Delta y/\Delta T = [y(T_1) - y(T_o)]/(T_1 - T_o) \qquad \text{(B-2)}$$

$\Delta y/\Delta T$	=	average rate of change of salinity or temperature in units/mo or °C/mo.
T_o	=	serial time at beginning of the record
T_1	=	serial time at end of the record
T_1-T_o	=	number of months of record

The instantaneous rate of change in y (i.e., the rate of change at any specified time) in units (ppm or °C) per month can be determined by taking the derivative of Equation (B-2) or

$$dy/dT = (c/n)\,(a + cT)^{(1/n)-1} \qquad \text{(B-3)}$$

B.6 SMOOTHING OF TRANSFORMED MONTHLY AVERAGE DATA

Smoothing is a way of increasing the signal-to-noise ratio of data. It enhances the underlying signal of interest while diminishing short-term cyclical trends. Methods for smoothing data can be as simple as a moving average or as complicated as stochastic time series methods. We selected a procedure called lowess, which stands for locally weighted regression scatter plot smoothing. We selected this procedure because it is robust (not distorted by a small fraction of outliers, which is a prevalent problem in our data sets) and locally weighted (the closest points are weighted more heavily). The reader is referred to Chambers et al. (1983) or Cleveland (1979) for a mathematical description of lowess.

The adjusted, transformed monthly averages from Step (4) were subjected to lowess. This procedure is similar to calculating moving averages in that it eliminates the short-term variability in the data, allowing the longer term trends to be observed more easily. This smoothing procedure calculates an initial smoothed value for each input datum by computing a regression estimate for the datum's x-axis location. This regression estimate includes a specified number of nearest neighboring data points, each weighted by their proximity to the x-axis location of the datum. Next, the smoothed values are recalculated in a robustness step that introduces a weighting factor to diminish the influence of neighboring data points that differ greatly from their regression estimates. The smoothing is completed by performing the robustness step again, this time revising the first robustness weighting factor to reflect the amount by which the original data points differ from the estimates of the first robustness step. In the Systat Series module's implementation of lowess, the user can specify how many nearest neighboring data points to consider in the regressions for each datum. The fewer the number of nearest neighbors specified, the less the degree of smoothing. Conversely, the more nearest neighbors considered, the greater the smoothing and the more long-term trends are displayed. Since Point Orient's data set contains the fewest number of monthly averages (332), this number was selected as the number of nearest neighbors to be used by lowess. In this way, the degree of smoothing from one data set to another is kept constant, while maximizing the smoothing of shorter term trends.

The effect of the number of nearest neighbors included in lowess on the resulting smoothed curve is demonstrated by Figure B-1, which plots smoothed data for historic Delta outflow for three cases (number of nearest neighbors equal to 60, 180,

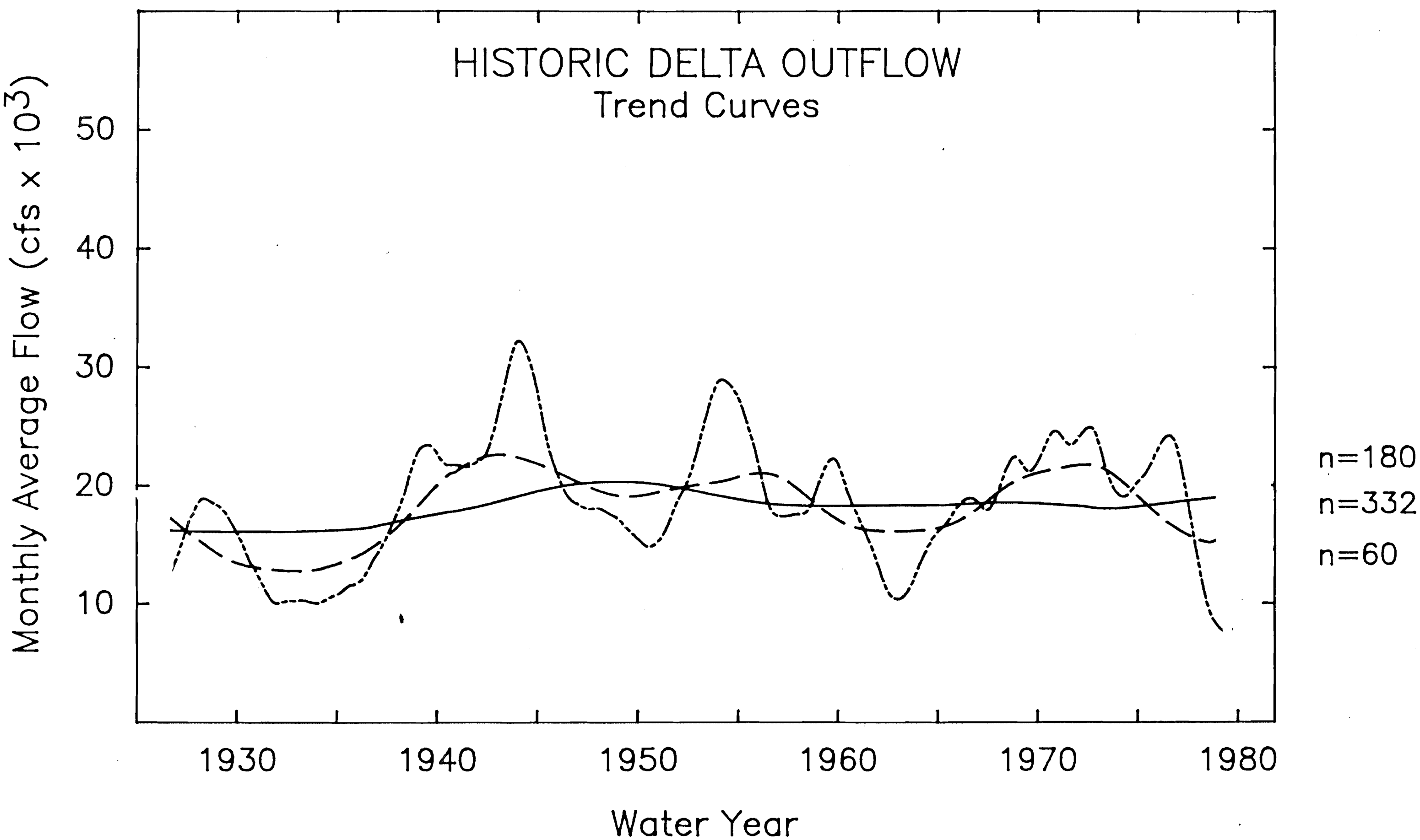


FIGURE B-1 Three Smoothed Curves for Historic Delta Outflow. In the first case, n = 60 which is equivalent to about a 5 year moving average. In the second case, n = 180, which is equivalent to about a 15-year moving average. In the third case, n = 332, which is equivalent to about a 28-year moving average.

and 332). In this figure, the smoothest curve is the result of including 332 nearest neighbors. This case approximately corresponds to a 28-year moving average, except in these data sets 332 adjacent data points span more than 28 years due to months in which missing data prevent monthly averages from being calculated. The waviest curve is the result of including only 60 nearest neighbors. This curve roughly corresponds to a 5 year moving average.The intermediately wavy curve on the figure results from including 180 nearest neighbors, or slightly more than 15 years due to missing values.

ATTACHMENT C

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