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TECHNICAL COMMUNICATIONS

Continuous Salinity and Temperature Data from San Francisco Estuary, 1982–2002: Trends and the Salinity–Freshwater Inflow Relationship

Gregory G. Shellenbarger and David H. Schoellhamer

U.S. Geological Survey
California Water Science Center
Placer Hall, 6000 J Street
Sacramento, CA 95819, U.S.A.
gshellen@usgs.gov

ABSTRACT

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The U.S. Geological Survey and other federal and state agencies have been collecting continuous temperature and salinity data, two critical estuarine habitat variables, throughout San Francisco estuary for over two decades. Although this dynamic, highly variable system has been well studied, many questions remain relating to the effects of freshwater inflow and other physical and biological linkages. This study examines up to 20 years of publically available, continuous temperature and salinity data from 10 different San Francisco Bay stations to identify trends in temperature and salinity and quantify the salinity–freshwater inflow relationship. Several trends in the salinity and temperature records were identified, although the high degree of daily and interannual variability confounds the analysis. In addition, freshwater inflow to the estuary has a range of effects on salinity from -0.0020 to -0.0096 $(m^3\ s^{-1})^{-1}$ discharge, depending on location in the estuary and the timescale of analyzed data. Finally, we documented that changes in freshwater inflow to the estuary that are within the range of typical management actions can affect bay-wide salinities by 0.6–1.4. This study reinforces the idea that multidecadal records are needed to identify trends from decadal changes in water management and climate and, therefore, are extremely valuable.

ADDITIONAL INDEX WORDS: *Physical forcing, estuarine variability, management, U.S.A., California.*

INTRODUCTION

Salinity and temperature are two key estuarine habitat variables that can affect physical processes in an estuary and the distribution of organisms around the estuary. For more than two decades, there has been a detailed effort to collect continuous data on these two variables at locations throughout San Francisco estuary (SFE). A variety of state and federal organizations has led this large-scale monitoring effort, including California Department of Water Resources, U.S. Bureau of Reclamation, and U.S. Geological Survey.

The dominant processes that control the distribution of salt and temperature throughout SFE result from the interaction of the freshwater inflow at the head with the coastal ocean water at the mouth of the estuary. Fresh water enters the estuary through the Sacramento–San Joaquin River delta (referred to as the delta). The amount of freshwater inflow can have a dramatic effect on salinities that, in turn, can have ecological effects on the overall production of phytoplankton, zooplankton, and higher trophic-level organisms (Jassby *et al.,* 1995; Roman *et al.,* 2005). In fact, it is likely that SFE exhibits one of the strongest responses between flow and organisms of any large estuary (Kimmerer, 2004). San Francisco estuary is a particularly dynamic estuarine environment that experiences naturally large seasonal and annual variability in salinity, temperature, precipitation, and freshwater inflow to the bay (Peterson *et al.,* 1996). Although many questions remain about the physical and biological controls and linkages in SFE, the region is well studied and numerous papers detail what is known about the system (*e.g.,* Kimmerer, 2004; Monismith *et al.,* 2002; Nichols *et al.,* 1986; Walters, Cheng, and Conomos, 1985).

California has a heavily managed water system that uses a series of upstream dams throughout the state to capture peak flows and snowmelt runoff early in the year and release the water during low precipitation periods. This type of river management has been shown to redistribute the seasonality of discharge without affecting the total annual freshwater flow

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(accounting for diversions from the system, Knowles, 2000; Meier and Kauker, 2003). However, water is diverted from the system for urban, industrial, and agricultural uses, thereby leaving roughly 60% of the unimpaired freshwater flow entering SFE (Alber, 2002; Kimmerer, 2004). In the past, these diversions have been implicated in affecting the salinity distribution and contributing to the decline of some populations in the bay and led to an ecosystem standard for the location of salinity of 2 isohaline (referred to as X_2) in the 1990s (Jassby *et al.,* 1995) that is managed by controlling reservoir releases and diversions.

This article represents an initial analysis of an extensive, publically available dataset that includes up to 20 years of continuous salinity and temperature data collected throughout San Francisco estuary. The analyses presented here are intended to address three main goals: (1) present an exploratory statistical evaluation of the dataset, (2) analyze for significant trends in salinity and temperature over the time period of the dataset, and (3) investigate aspects of the freshwater flow and salinity relationship within SFE, particularly with regard to different timescales.

METHODS

Study Area

The watershed area for San Francisco estuary (SFE) represents about 40% of the area of California, including the seasonally high precipitation regions of the Sierra Nevada Mountains. Predominant freshwater inflows to the bay come from the Sacramento and San Joaquin Rivers, with additional freshwater inputs from local tributaries and wastewater treatment plants. High annual and interannual variability in freshwater inflow results from the region's Mediterranean climate (wet winters and dry summers), normal decadal climate variability, and, to a lesser degree, the effects associated with El Niño–Southern Oscillation (ENSO). Additional details about SFE, including descriptions of the subbasins within the bay, are provided in Conomos, Smith, and Gartner (1985), Monismith *et al.* (2002), and Smith and Hollibaugh (2006).

Salinity and Temperature Data

Ten temperature and specific conductance monitoring stations located throughout SFE were used for this study (Figure 1; Table 1): Mallard Island (MAL), Benicia Bridge (BEN), Carquinez Bridge (CAR), Wickland Oil Pier (WIC), Channel Marker 9 (CM9), Point San Pablo (PSP), Presidio (PRE), Pier 24 (P24), San Mateo Bridge (SMB), and Dumbarton Bridge (DUM). These stations are part of the monitoring network overseen by the U.S. Geological Survey (USGS) and the California State Department of Water Resources (CDWR; MAL and WIC). Most stations are located near the deep channel that follows the axis through SFE, and these stations typically have two sets of sensors—one located near surface or middepth and one near the bottom of the water column (referred to as "upper" and "lower," respectively). Four of the ten stations have only one set of sensors because they are located away from the channel in shallower water. The two sites located in South San Francisco Bay, SMB and DUM, are somewhat disconnected from effects of inflow through the delta except during periods of high flow (Williams, 1989). However, South San Francisco Bay comprises 36% of the area of SFE, and the extensive shallow water areas may be more responsive to other forcing factors such as air temperature. Trend results are for each site individually, so the inclusion of these sites does not alter the results for other bay stations. Data from all sites are typically collected at 15-minute intervals and edited prior to publication. Gaps in the data typically occur from biofouling of the sensors, instrument malfunction, or funding issues. The servicing and calibration checks of the sensors occur on roughly a 3-week schedule, and the details of the methods are documented in Wagner *et al.* (2000). Measured specific conductance values are converted to salinity using algorithms developed for the 1978 United Nations Educational, Scientific, and Cultural Organization standard by Fofonoff and Millard (1983) with low-salinity corrections developed by Hill, Dauphinee, and Woods (1986). Salinity values are presented using the unitless Practical Salinity Scale. An example of one of the temperature and salinity time series is data from P24_upper shown in Figures 2A and 2B.

Inflow Data and Other Potential Forcing Factors

Q_{OUT} is a daily estimate of the amount of fresh water that enters the northern reach of SFE at Mallard Island. $Q_{EXPORTS}$ is a daily estimate of the amount of fresh water removed from the delta by numerous means, most notably the California State and Federal Central Valley Water Projects (SWP and CVP, respectively). Q_{OUT} and $Q_{EXPORTS}$ values were obtained from the DAYFLOW program operated by the California Department of Water Resources (CDWR, 1986) available through the Interagency Ecological Program website (http://www.iep.ca.gov). The equation defining Q_{OUT} is

$$Q_{OUT} = Q_{TOT} + Q_{PREC} - Q_{GCD} - Q_{EXPORTS} - Q_{MISDV} \tag{1}$$

where Q_{TOT} is the total inflow to the delta, Q_{PREC} is an estimate of precipitation in the delta, Q_{GCD} estimates the gross local consumptive use of water in the delta, and Q_{MISDV} is an estimate of water on flooded islands and stored in the delta. $Q_{EXPORTS}$ represents the removal of fresh water by several water projects, most importantly the SWP and the CVP. The SWP pumps water from the Clifton Court Forebay—not directly from the Delta—and this value contributes to $Q_{EXPORTS}$. Separate ungauged inlet gates control flow from the Delta into the forebay. Management actions drive the opening of the inlet gates to the Clifton Court Forebay for the SWP. The use of the forebay as a water holding basin prior to pumping somewhat decorrelates the effects of pumping from removal of water from the Delta. However, the forebay has limited volume capacity and realistically only lags the correlation between water withdrawal and pumping by no more than 3 days based on simple volume calculations. The 20-year record of daily Q_{OUT} and $Q_{EXPORTS}$ is shown in Figures 2C and 2D. In this paper, management actions are defined as the export of water from the delta and associated releases of water

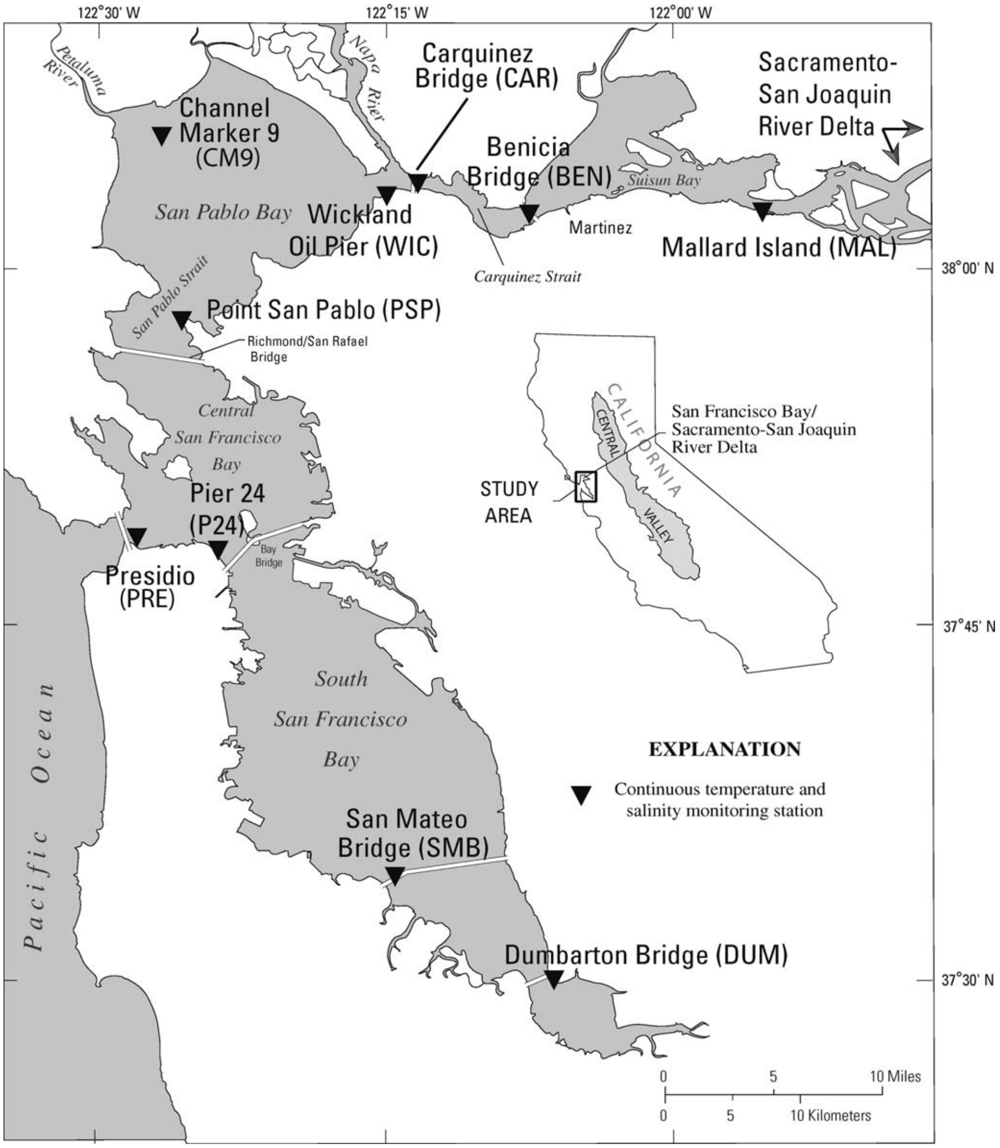

Figure 1. Map of the study region with the specific data collections sites identified.

from upstream reservoirs; upstream water diversions and other reservoir releases (*e.g.,* for flood control or fish migration) are not considered.

Hourly air pressure, ocean temperature, and wind data were collected from the National Data Buoy Center (http://www.ndbc.noaa.gov/rmd.shtml, Figures 2E and 2F). Station 46026, located 18 nautical miles west of San Francisco, was selected because the offshore buoy is in an area that is better representative of the larger regional scale wind and atmospheric conditions that affect the bay. The westerly component of the wind was calculated from the velocity and directional data because this is the direction that wind enters the estuary through the Golden Gate. Hourly air temperature data were collected in San Jose (Station 69) as part of the CDWR's California Irrigation Management Information System.

Trend Analysis

Analysis for monotonic trends in the temperature and salinity data was conducted using the EStimate TREND package (ESTREND, Schertz, Alexander, and Ohe, 1991) for S-Plus (TIBCO Spotfire S+ v8.1) developed by the U.S. Geological Survey. ESTREND performs the nonparametric seasonal Kendall test (Helsel and Hirsch, 1992) and has an option for correcting the constituent of interest by changes in another variable (called "flow" in ESTREND). Daily averaged bay water temperatures and salinities were selected as constituents for trend analysis, and "flow" corrections separately used Q_{OUT}, air temperature, and air pressure records. ESTREND seasons were defined as 12 per year (*i.e.,* monthly). Trends were significant if the probability of Type 1 error was

Table 1. *Overview of records used for all data sites. The "Type" column refers to the type of data collected: C = conductivity and T = temperature. "Frequency" refers to the sampling frequency, and "Depths" refer to the number of sensors or the location of the sensor in the water column. Data records may not be continuous between the start and end times.*

Site	Lat. (N)	Long. (W)	Type	Freq. (min)	Depths	Start	End	Source
MAL	38°02′34″	121°55′09″	*C*	15	1 (low)	1 Aug 92	31 Dec 02	http://iep.water.ca.gov/cgi-bin/dss/dss1.pl?station=RSAC075
MAL	38°02′34″	121°55′09″	*T*	60	1 (up)	1 Jan 84	30 Sep 02	http://iep.water.ca.gov/cgi-bin/dss/dss1.pl?station=RSAC075
BEN	38°02′42″	122°07′32″	*C,T*	15	2	1 Oct 95	30 Sep 02	http://sfbay.wr.usgs.gov/sediment/cont_monitoring/
CAR	38°03′68″	122°13′53″	*C,T*	15	2	1 Oct 98	30 Sep 02	http://sfbay.wr.usgs.gov/sediment/cont_monitoring/
WIC	38°03′30″	122°14′24″	*C,T*	15	2	1 Oct 86	31 Jan 98	http://iep.water.ca.gov/cgi-bin/dss/dss1.pl?station=RSAC045
CM9	38°05′19″	122°26′29″	*C,T*	15	1 (mid)	1 Oct 98	30 Sep 02	http://sfbay.wr.usgs.gov/sediment/cont_monitoring/
PSP	37°57′53″	122°25′42″	*C,T*	15	2	1 Oct 89	30 Sep 02	http://sfbay.wr.usgs.gov/sediment/cont_monitoring/
PRE	37°48′24″	122°27′54″	*C,T*	15	1 (mid)	1 Oct 90	30 Sep 02	http://sfbay.wr.usgs.gov/sediment/cont_monitoring/
P24	37°47′27″	122°23′05″	*C,T*	15	2	1 Dec 82	30 Sep 02	http://sfbay.wr.usgs.gov/sediment/cont_monitoring/ and http://iep.water.ca.gov/cgi-bin/dss/dss1.pl?station=SHWSF009
SMB	37°35′04″	122°14′59″	*C,T*	15	2	1 Oct 89	30 Sep 02	http://sfbay.wr.usgs.gov/sediment/cont_monitoring/
DUM	37°30′24″	122°06′59″	*C,T*	15	1 (low)	1 Oct 89	30 Sep 02	http://water.usgs.gov/pubs/wri/wri034005/
Flow	38°03′19″	121°54′39″	Inflow, Q_{OUT}	1440		1 Dec 82	30 Sep 02	http://iep.water.ca.gov/dayflow/output/index.html
Flow	38°03′19″	121°54′39″	Exports, Q_{EXPORTS}	1440		1 Dec 82	30 Sep 02	http://iep.water.ca.gov/dayflow/output/index.html
Buoy	37°45′32″	122°50′00″	Wind speed, V	60		1 Dec 82	30 Sep 02	http://www.ndbc.noaa.gov/station_page.php?station=46026
Buoy	37°45′32″	122°50′00″	Air pressure, P	60		1 Dec 82	30 Sep 02	http://www.ndbc.noaa.gov/station_page.php?station=46026
Buoy	37°45′32″	122°50′00″	Water temperature, T	60		1 Dec 82	30 Sep 02	http://www.ndbc.noaa.gov/station_page.php?station=46026
Land	37°19′33″	121°57′00″	Air temperature, T	60		8 Jun 87	22 Nov 02	http://wwwcimis.water.ca.gov/cimis/frontStationDetailData.do?stationId=69

less than 5% ($p < 0.05$). At least 50% of the data in a given year and a minimum of 5 years of data were required for the test. These requirements mean that the ESTREND analysis could not necessarily be applied for the entire period of the records listed in Table 1.

Lagged Correlations

To explore the effects of forcing on the temperature and salinity data, daily averaged temperature and salinity data were lag-correlated with each forcing mechanism (*i.e.,* Q_{OUT}, Q_{EXPORTS}, atmospheric pressure, and wind speed)—with the temperature and salinity lagged behind the forcing data. Lagging data behind Q_{OUT} is particularly important because the salinity at a given location is partly controlled by antecedent inflows from the delta (Denton, 1993a, 1993b). Lag times up to 1 year were permitted, but lag times on the order of a season or a year were typically not considered in this analysis. Lags of less than 60 days with the strongest correlations coefficients are reported. The lag times computed here are based on daily averaged data and Q_{OUT} on a single day for each location. This likely produces correlation coefficients that are not as strong as those that are computed from a more complex consideration of antecedent flow, such as the "G-model" (Denton, 1993a). The salinity-Q_{OUT} correlation for MAL is not discussed, because the salinity at MAL is often zero. During these periods, an increase in Q_{OUT} cannot change the salinity, thereby leading to a weak correlation between these two variables (Wong, 1995).

Natural Experiment

There are three important timescales of variability in the tidally averaged salinity time series: the shortest is daily, and next is the event/pulse, and the longest is the annual timescale. The daily timescale includes variability related to daily freshwater inflow or the strength of the tides. The event/pulse timescale describes the period it takes for an abrupt change in flow to propagate its effect throughout the estuary. In the northern reaches of SFE (*e.g.,* Carquinez Strait), this timescale is on the order of days to weeks for an effect to propagate down estuary (Monismith *et al.,* 2002). These flow changes are typically one order of magnitude above daily median flows and can generate salinity effects in the range of 5 for Carquinez Strait. This timescale would be relevant for many of the management decisions that could affect Q_{OUT}. The longer timescale is the annual scale. This timescale is dominated by the annual amount of precipitation and other seasonal climatic conditions. Flow variability on the annual scale can be two orders of magnitude above annual-median flows, although this typically occurs only in the wettest years. A large change in flow on the annual timescale can lead to salinity variability of about 25 in Carquinez Strait.

One method of exploring the effects that changing Q_{OUT} has on bay salinities is to analyze the Q_{OUT} record for abrupt changes in flow and track the associated salinity response. The upper salinity sensor at the Wickland Oil Pier site (WIC_upper) was selected for this analysis. The upper salinity sensor is more responsive to less dense, freshwater

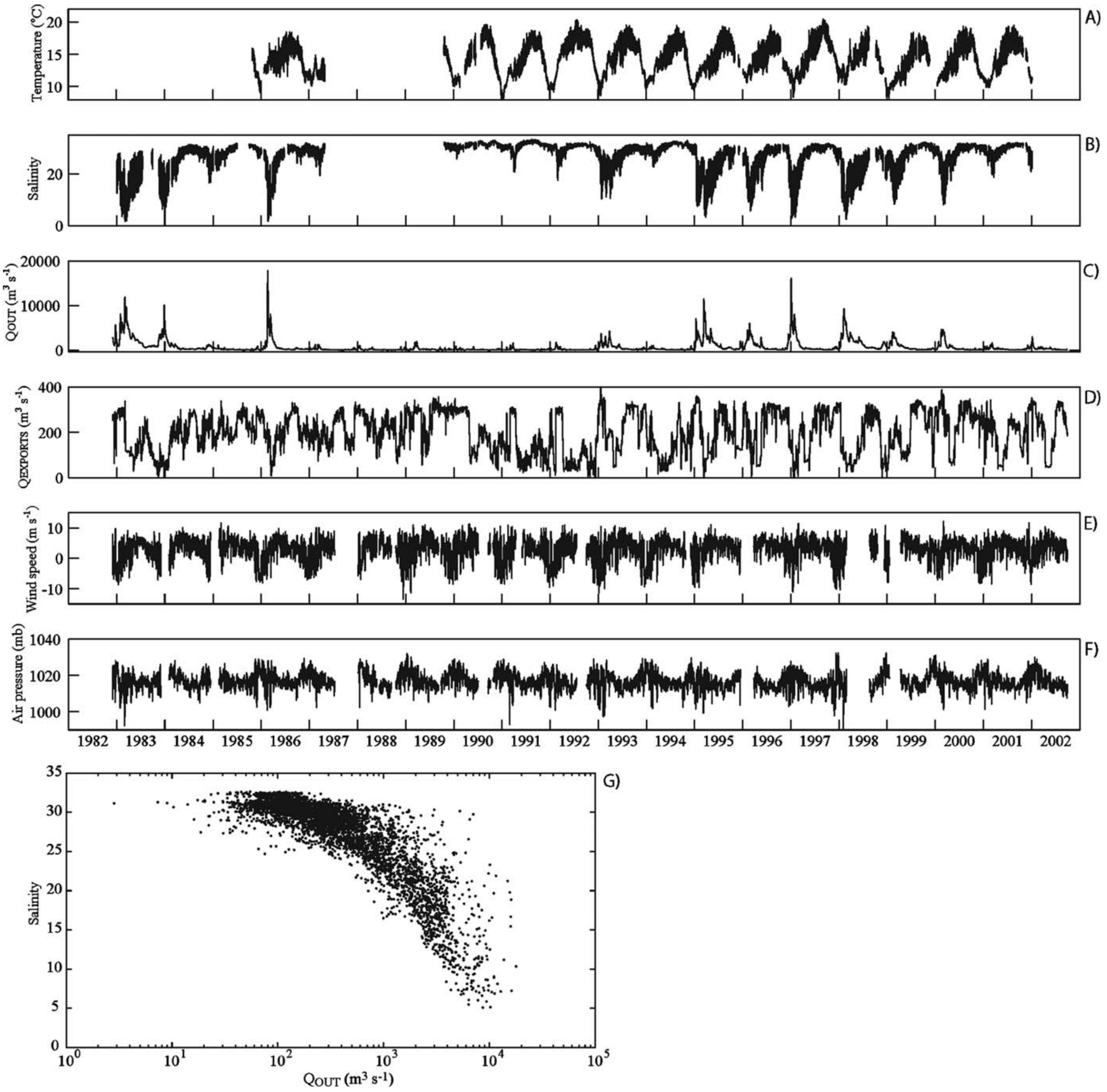

Figure 2. Sample of (A) temperature and (B) salinity time series from P24_upper, and the time series of four forcing mechanisms: (C) Q_{OUT}, (D) Q_{EXPORTS}, (E) wind speed (westerly), and (F) air pressure for the 20-year period. Plot (G) depicts the salinity–flow relationship for daily averaged salinities at P24_upper.

flows than the near-bottom sensor, and the upper sensor typically remains shallower than stratification effects that can isolate the bottom sensor from surface waters. The Wickland site is most suited for this analysis because it is the closest site to the delta (site of dominant freshwater input) with a long period of record. The Benicia and Carquinez sites are indeed closer to the Delta, but both have relatively short records of usable data. The Mallard Island site is not appropriate because the salinity is zero much of the time. During these times, an increase in Q_{OUT} will not result in a salinity change at Mallard Island.

The Q_{OUT} record was visually scanned for abrupt increases in flow during periods of otherwise relatively constant low flow. When an increase in flow was noted, the local minimum and maximum flows of the increasing hydrograph were recorded (Figure 3A). For the subsequent decreasing flow,

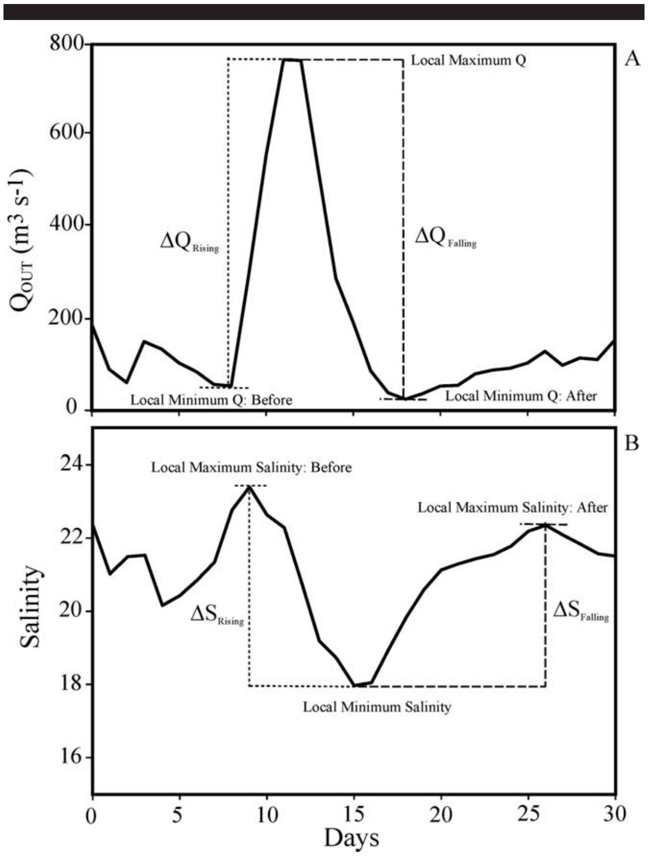

Figure 3. Diagram of one event from the Natural Experiment at the Wickland Oil Pier. (A) An abrupt increase and subsequent decrease in Q during a period of low flow, (B) the corresponding decrease and subsequent increase in salinity that results from the change in Q. The subscripts "Rising" and "Falling" refer to the hydrograph.

the local minimum flow of the decreasing hydrograph immediately following the local maximum flow was recorded. The change in flow between the local minima and maximum (for both the rising and falling hydrograph) was computed. The corresponding local maximum, minimum, and next local maximum salinities at WIC_upper that result from the changing flow were selected and differenced (Figure 3B). This results in two sets of numbers, a change in flow rate and a resulting change in salinity for each of the rising and the falling periods selected in the hydrographs. Thirteen separate change in flow and salinity events were used for this analysis. Regressions were performed on the data separately for the rising and falling hydrographs. In addition, a regression analysis was performed for the annual averaged Q_{OUT} and annual averaged salinity at 11 of the stations during their periods of record to understand better the spatial variability of this relationship throughout SFE.

RESULTS

Summary statistics for each sensor location are listed in Table 2. Presidio exhibited the highest median and mean salinity and the lowest median and mean temperature of all the sites. The standard deviations of the temperature and salinity data were also very low. This results from the close proximity of this site to the relatively cold, salty water of the Pacific Ocean. The lowest salinity site was MAL, the closest site to the main freshwater input to SFE. Benicia Bridge_upper had the highest median temperature (based on a short dataset), while DUM had the highest mean temperature.

Trends

Several significant trends were identified, as detailed in Table 3. Uncorrected records (uncorrected for a flow variable) of salinity for MAL and WIC_lower showed a positive and negative trend, respectively, for the two sites during the periods of record (Table 3A). The temperature at DUM also showed a decreasing trend. Strong trends toward increasing salinity at MAL were identified using air pressure, air temperature, and Q_{OUT} as correction variables (Table 3B). A trend of decreasing salinity was found at PSP_lower when corrected for Q_{OUT}. DUM still had a decreasing water temperature trend when corrected for air temperature trends, although the trend was weaker than

Table 2. *The summary statistics of salinity and temperature data for all sites over the entire periods of record are listed below.*

	Salinity			Temperature (°C)		
Site	Median	Mean	Standard deviation	Median	Mean	Standard deviation
MAL	1.38	2.71	3.03	17.3	16.4	4.43
BEN_upper	10.5	9.25	6.89	18.2	17.0	3.58
BEN_lower	14.3	13.3	5.81	17.3	16.4	3.63
CAR_upper	17.4	16.4	5.64	15.6	15.3	3.83
CAR_lower	19.5	18.5	5.03	15.8	15.6	3.46
WIC_upper	18.7	16.9	6.35	16.5	15.7	3.97
WIC_lower	19.8	18.5	5.43	16.2	16.6	3.82
CM9	20.4	18.7	5.72	16.9	16.1	4.42
PSP_upper	25.6	23.4	6.76	15.3	15.0	3.20
PSP_lower	25.9	24.2	5.71	14.9	14.7	2.98
PRE	30.7	29.3	3.94	13.5	13.6	1.97
P24_upper	29.2	27.2	5.16	14.0	14.1	2.35
P24_lower	29.4	28.0	4.00	13.8	13.7	2.29
SMB_upper	27.2	25.8	5.28	16.2	16.1	3.91
SMB_lower	27.4	26.3	4.57	16.4	16.2	3.88
DUM	25.3	24.1	5.71	17.0	17.1	4.27

Table 3. *The significant results of the trend analysis using ESTREND (see text for a description). The "Trend" column is the trend slope in constituent units over the period of record. Trend % is the trend slope divided by the mean constituent value times 100. Table 3A shows significant trends (*$p < 0.05$*) for the constituents of interest, while Table 3B shows significant trends in constituents after being corrected for changes in a particular "flow" variable. Flow in this case does not refer to river inflow (Q); rather this is the ESTREND naming convention for the correction variable.*

Constituent	"Flow" variable	Station	Trend	Trend %	p	Years
A. Constituent trend						
Air temperature		—	−0.15	−0.96	0.037	1988–2002
Air temperature		—	—	—	—	1988–98
Salinity		MAL	0.32	19	3.2×10^{-5}	1996–2002
Salinity		WIC_lower	−0.71	−3.9	0.048	1988–97
Temperature		DUM	−0.14	−0.82	0.0060	1990–2002
B. "Flow"-corrected trend						
Salinity	Air pressure	MAL	0.32	19	0.012	1996–2002
Salinity	Air temperature	MAL	0.50	29	0.0007	1996–2002
Salinity	Q_{OUT}	MAL	0.62	36	0.0003	1996–2002
Salinity	Q_{OUT}	PSP_lower	−0.16	−0.65	0.0099	1990–2002
Temperature	Air temperature	DUM	−0.098	−0.57	0.010	1990–2002
Temperature	Air temperature	WIC_lower	0.19	1.2	0.030	1988–98
Temperature	Q_{OUT}	MAL	0.12	0.65	0.049	1985–2001
Temperature	Q_{OUT}	WIC_lower	0.26	1.6	0.025	1988–98
Temperature	Q_{OUT}	WIC_upper	0.19	1.1	0.039	1988–98

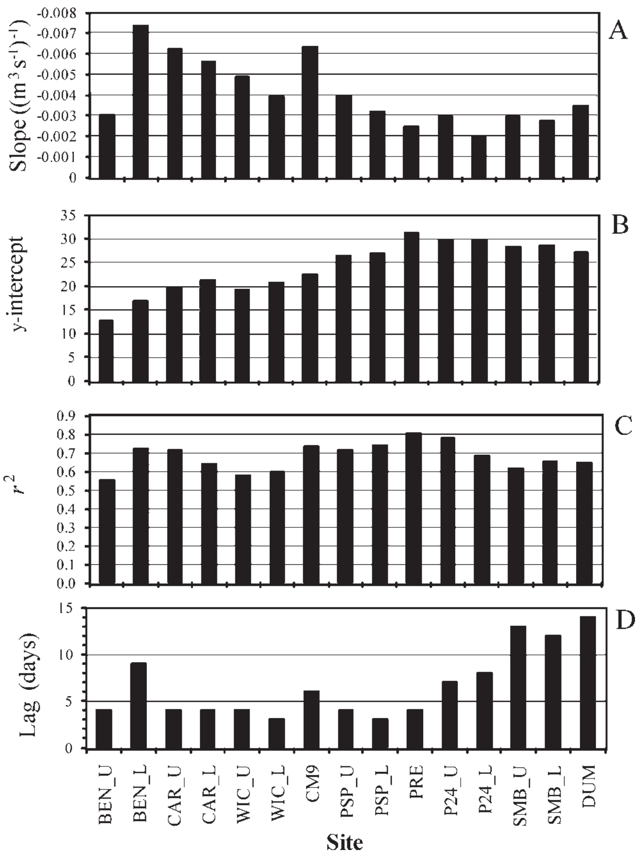

Figure 4. (A) The slopes of the linear fits from daily averaged salinity *vs.* Q_{OUT} for the lagged daily correlations at each site. (B) The *y*-intercept for the above-mentioned linear fits. (C) The coefficient of determination for each fit. (D) The lag in days for the maximum negative correlations. MAL results are not displayed here, because the salinity at this site is often zero, which leads to a weak relationship between salinity and Q_{OUT}.

the uncorrected trend. Wickland Oil Pier_lower, WIC_upper, and MAL had increasing water temperature trends when the correction variable was Q_{OUT} (MAL, WIC_lower, WIC_upper) or air temperature (WIC_lower). A decreasing trend in air temperature was found for the period 1988–2002, but no trend was found for the shorter period 1988–98.

Lagged Correlations

The salinity data were most strongly correlated with Q_{OUT}, with correlation coefficients at all sites < -0.70 (Figure 4, MAL not included in analysis). Correlation coefficients for Q_{EXPORTS}, pressure, and wind were weaker and fell between 0.50 and −0.50. The number of days lagged for the strongest negative correlations with Q_{OUT} were less than 15 days for all sites, and the lag tended to increase with distance from the delta. The number of days lagged for the correlations between salinity *vs.* Q_{EXPORTS}, pressure, or wind was much larger and tended to occur on expected seasonal, half-year, and yearly timescales (results not shown).

The strongest correlations (positive and negative) between temperature and the four forcing mechanisms tended to occur at the North Bay sites (not shown). None of the correlation coefficients exceeded ±0.65. Some of the strongest negative correlations with lags less than ~90 days occurred with air pressure and water temperature at all sites, where lags were less than 26 days (except at BEN). Wind was relatively well correlated ($r = 0.35$ to 0.54) with water temperature at BEN, CAR, WIC, and CM9 with lags from 19 to 44 days. In general, the correlation coefficients decrease with distance from the delta. Because we expect seasonal and annual correlations (positive and negative) between temperature (and salinity) and the forcing mechanisms (*i.e.,* we expect the forcing conditions to change on these timescales and for data to be positively correlated on annual timescales), results with lags greater than

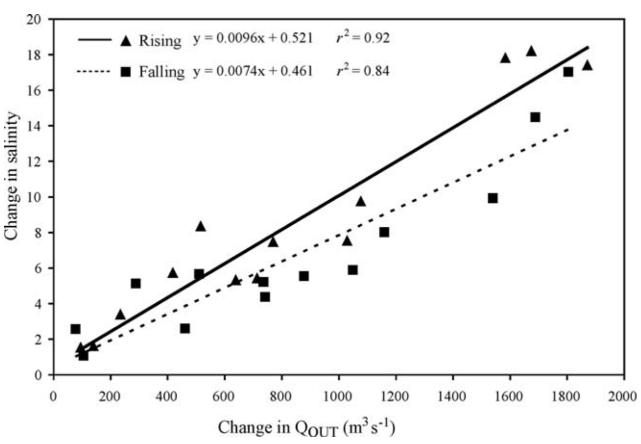

Figure 5. Natural experiment results from Wickland Oil Pier (upper) salinity data and $Q_{\rm OUT}$ on the event/pulse timescale. Thirteen separate events were analyzed. The absolute value of salinity and $Q_{\rm OUT}$ change is used. The actual relationship is that an increase in $Q_{\rm OUT}$ results in a decrease in salinity.

60 days are deemed less interesting to this study and will not be explored further.

Natural Experiment

The regressions of the salinity response at WIC_upper to changing $Q_{\rm OUT}$ for the 13 pulse events analyzed exhibit slightly different slopes for the rising and falling hydrographs (Figure 5). The slope of the regression of the data from the rising hydrograph (-0.0096 (m^3 s^{-1}) $^{-1}$, n = 13, r^2 = 0.92) is steeper than the falling hydrograph (-0.0074 (m^3 s^{-1}) $^{-1}$, n = 13, r^2 = 0.84).

These results compare well with the magnitude of the slope of the regression for the annual averaged salinity *vs.* $Q_{\rm OUT}$ from the WIC_upper sensor (-0.0069 (m^3 s^{-1}) $^{-1}$, n = 11, r^2 = 0.78; Figure 6). In addition, the 11 other locations detailed in Figure 7 show a similar or even smaller slope in the regression between annual average salinity and annual $Q_{\rm OUT}$ reflecting increased effects of tidal mixing or reduced influence by $Q_{\rm OUT}$ at these stations. Coefficients of determination for the relationship of annual averaged salinity *vs.* $Q_{\rm OUT}$ are high and all over 0.7, with the exception of MAL (where, if the salinity is already zero, it cannot respond to increases in $Q_{\rm OUT}$). As expected, all sites generally displayed a strong relationship between average salinity and $Q_{\rm OUT}$.

DISCUSSION

Temporal Trends

The identification of only a few significant trends in these data is not surprising given the high degree of physical variability in the system and relatively short length of the records. Two sites showed decreasing salinity trends: WIC_lower and PSP_lower (when $Q_{\rm OUT}$ is used as the correcting flow variable). Interestingly, both sensors are lower in the water column in San Pablo Bay. Decreasing salinity can result from a decreasing fraction of seawater, which can result from decreasing seawater intrusion into the bay or increasing freshwater inflow. However, given that the PSP_lower trend has been corrected with the freshwater inflow variable, the trend toward decreasing salinity in San Pablo Bay appears to be decoupled from the freshwater inflow (*i.e.,* $Q_{\rm OUT}$). Although MAL displays a strong increase in salinity, this likely results from a bias created from a relatively short period of record (1996–2002) that begins with several very wet years (1997 and 1998). Later years have less precipitation and a concurrent increase in salinity at this station.

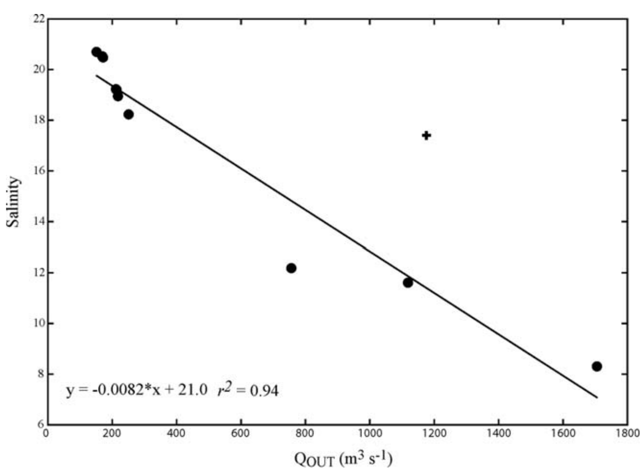

Figure 6. Average annual salinity at the upper sensor at Wickland Oil Pier *vs.* average annual $Q_{\rm OUT}$ for the same years. The linear regression was fit to data from 1987–96 (closed circles). The year 1997 (+) had more than 50% of the data available for the year, but this site was missing most of the wet-season data for the year. This biased the salinity–flow relationship, so this point was not used for the regression.

A decreasing trend in air temperature was identified for the period 1988–2003 (-0.01°C y^{-1}). Interestingly, a similar decreasing trend was seen in the water temperature data for DUM (-0.01°C y^{-1}). The DUM site is adjacent to extensive shallow water and mudflat habitats. This region of the bay has a higher surface area to volume ratio than much of the rest of SFE, and the water temperature in the region would be expected to respond relatively quickly to changes in air temperature. That the strength of the trend is so similar between DUM and the air temperature is somewhat surprising, particularly given that DUM water temperatures still exhibit a decreasing trend when air temperature is used as the correction variable. However, most of the significant water temperature trends are positive, with WIC_lower (when corrected by air temperature) and MAL, WIC_lower, and WIC_upper (when corrected for $Q_{\rm OUT}$) exhibiting a 0.01–0.02°C y^{-1} increase.

The natural variability of this estuary is large enough generally to confound trend analysis of these data up to 20 years in length. Seasonal and annual variability in the datasets dominate the overall variability of the temperature and salinity signals, although tidal variability can easily be half of the annual variability (data not shown). The power of a trend analysis comes from having long, continuous records from a number of the same sites over long periods. The variability in

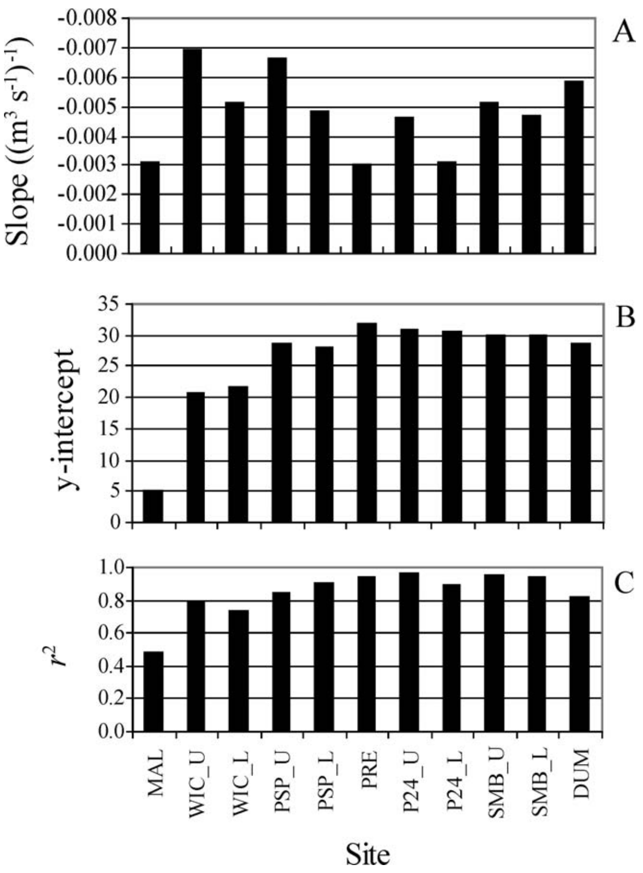

Figure 7. The results of the annual averaged relationship between salinity and Q_{OUT} at sites that had more than 5 years of data. (A) The slopes of the linear fits from plots of salinity *vs.* Q_{OUT} for each site. (B) The *y*-intercept for the above-mentioned linear fits. (C) The coefficient of determination for each linear fit.

this estuarine system is naturally high because of the combination of mixed semidiurnal tides and the influence and variability of freshwater inflow on the data. In addition, this system is subjected to decadal climate variability and, to a lesser degree, periodic ENSO conditions. These conditions can dramatically influence temperature and precipitation (freshwater inflow) on a decadal timescale. To be able to distinguish true longer term climatic trends through time, a data set needs to cover a number of these cycles to gain sufficient statistical power. Even with up to 17 years of data from MAL, long-term trends are difficult to determine in this region. The trend line derived from a short data record can become sensitive to the beginning or ending conditions that existed. If, for example, the data collection began in a wet year and ended in a dry year, a trend toward increasing salinities is likely to be assumed, even though this may not be representative of true trends over a longer period. In addition, the high degree of variability in Q_{OUT} (daily records over the entire period range from a minimum of about -35 m^3 s^{-1} to a maximum of about 18,000 m^3 s^{-1}) can mean that it is extremely difficult to identify statistically significant trends.

Salinity–Freshwater Inflow Relationship

It must be noted that the salinity–freshwater flow (*S*-*Q*) relationship is generally sigmoidal (see Figure 2G), with a linear region around intermediate salinities and flow (Wong, 1995) and sloping tails at high-salinity/low-flow and low-salinity/high-flow conditions. This analysis uses only linear regressions to fit *S*-*Q* data. However, these fits use data in the linear region of the relationship, where Q_{OUT} is between 100 and 2000 m^3 s^{-1} (Figures 4–7). The daily averaged data used for the lagged correlations cover a larger range of *S*-*Q* conditions and may be more appropriately modeled with a sigmoidal function. However, the slopes and *y*-intercepts for the lagged correlations are similar to those calculated by the other methods (Table 4), and using linear regressions for these fits make them easier to compare between methods. So, although the mechanisms of the *S*-*Q* relationship are more complex than a linear model would suggest, the results we found are fairly linear and consistent between methods.

Analysis of lagged correlations of daily averaged data, correlations of annual averaged data, and the natural experiment all indicate that a 1 m^3 s^{-1} change in Q_{OUT} changes salinity between -0.0020 to -0.0096 for San Francisco estuary (Table 4). Overall, there is good agreement of the inflow effect between the three different methods and timescales of analysis, with a difference in effect on salinity of only a factor of five baywide. In general, the effect of Q_{OUT} on salinity appears to be the least at MAL, the most landward site where the salinity is frequently zero, and the greatest at WIC_upper, near the middle of the estuary. At WIC, the salinity–freshwater flow relationship is consistent over the three timescales studied (*i.e.,* daily, event/pulse, and annual), with a range of less than a factor of two (Table 4).

The slope of the relationship between Q_{OUT} and salinity for the lagged correlations ranges from -0.0013 to -0.0074 (m^3 s^{-1})$^{-1}$ throughout the bay (Figure 4; Table 4), with a slope at WIC upper of -0.0049 (m^3 s^{-1})$^{-1}$. All sites, except for MAL, had a maximum (negative) salinity response correlation to Q_{OUT} when lagged less than 15 days. This timescale agrees with a 7–11 day response time calculated by Monismith *et al.* (2002) for the North Bay, and the 14 day (summer) and 3–14 day (winter) residence time estimated by Walters, Cheng, and Conomos (1985) for South Bay.

The range of slopes for correlations between the annual averaged Q_{OUT} *vs.* salinity is -0.0030 to -0.0069 (m^3 s^{-1})$^{-1}$, with a slope at WIC_upper of -0.0069 (m^3 s^{-1})$^{-1}$ (Figures 6 and 7; Table 4). These agree very well with the slopes of the daily averaged salinity and Q_{OUT} correlations. The annual averaged results are similar to, but lower than, an estimate from modeled results reported in MacCready (2004) of -0.011 (m^3 s^{-1})$^{-1}$ for San Francisco Bay. The estimates derived from MacCready's results use his figures 8 and 9 and assume $x = -40.5$ km (WIC) and coastal ocean salinity $s_0 = 32$ (Monismith *et al.,* 2002). Not surprisingly, annual averaged salinities at all of the upper sensors throughout the bay are more responsive to changing inflow than the salinities at the corresponding lower sensors (Figure 7A) because upper sensors are closer to and more directly affected by the buoyant freshwater inflow.

Table 4. *Details of salinity effects when Q_{OUT} changes by 1 $m^3\ s^{-1}$ using different methods and timescales. Values at WIC_upper are shown for all methods. The terms "rising" and "falling" refer to the hydrograph. Specific station values included in the bay-wide range can be found in Figure 4 (daily averaged lagged correlations) and Figure 7 (annual averaged correlations).*

Method	Bay-wide range [$(m^3\ s^{-1})^{-1}$]	Value at WIC_upper [$(m^3\ s^{-1})^{-1}$]
Daily averaged lagged correlations	−0.0020 to −0.0074	−0.0049
Annual averaged correlations	−0.0030 to −0.0069	−0.0069
Natural experiment (WIC_upper)—rising		−0.0096
Natural experiment (WIC_upper)—falling		−0.0074

The results of the natural experiment also show a similar relationship between Q_{OUT} and salinity. During the rising hydrographic, the relationship was $-0.0096\ (m^3\ s^{-1})^{-1}$, while the relationship was $-0.0074\ (m^3\ s^{-1})^{-1}$ during the subsequent falling hydrograph (Table 4). The slopes of the regressions between the rising and falling hydrographs differ because the increase in Q_{OUT} and decrease in salinity occurs over about 10 days, whereas the subsequent decrease in Q_{OUT} and increase in salinity occurs over roughly 20 days for the events examined. The salinity change on the rising hydrograph results mainly from the tidally averaged flows from the fresh water advecting salt seaward, while the rebound of salinity during the falling hydrograph results mainly from tidal dispersion and exchange flows. The latter processes occur at slower timescales resulting in the noted time difference of change for the rising and falling hydrographs. This leads to a decreased regression slope for the falling compared with the rising hydrograph (Figure 5). This hysteresis results from the changed salinity field in the bay (Peterson *et al.,* 1996). The timescale of the change essentially agrees with Monismith *et al.* (2002), who suggest that 2 weeks is the characteristic timescale for adjustment of the salinity field in the northern reaches of SFE.

Kimmerer (2004) found that, on a monthly timescale, there is no inverse relationship between Q_{OUT} and Q_{EXPORTS} for low Q_{OUT}, and he therefore concluded that water exported from the delta is not water that would otherwise flow into the bay. The rationale is that, on a monthly timescale, water removed for export is balanced by water released from upstream reservoirs in an effort to maintain Q_{OUT} above a certain level (particularly during low-flow periods). Q_{OUT} can be thought of as the sum of undiverted outflow Q_{U}, Q_{EXPORT}, and the change in reservoir storage $\Delta STOR$. The volume of water flowing into the bay during time T is

$$\int^{T} Q_{\mathrm{OUT}}dt = \int^{T} Q_{U}dt - \int^{T} Q_{\mathrm{EXPORT}}dt - \Delta STOR \qquad (2)$$

During periods of low undiverted flow, reservoirs release water (negative $\Delta STOR$) to allow water exports, while keeping outflow to the bay at a level that provides the desired salinity field (maintain X_2 location). This reservoir management accounts for the lack of an inverse relation between Q_{EXPORTS} and salinity in our data and the apparent absence of a time when Q_{OUT} was low and exports increased with a corresponding decrease in Q_{OUT} and increase in salinity. During periods of high undiverted flow, reservoirs store water (positive $\Delta STOR$).

On longer annual and interannual timescales (increasing T), the outflow, undiverted flow, and export terms in Equation 2 increase and the reservoir storage term becomes relatively small. The maximum magnitude of $\Delta STOR$ is the capacity of reservoirs in the watershed, about 1 year of undiverted flow (Knowles, 2002). Thus, at interannual timescales, reservoir capacity becomes less important to the water balance in Equation 2, water exports decrease the volume of water entering the bay, and bay salinities subsequently increase. Our analyses found that a 1 $m^3\ s^{-1}$ change in the average annual Q_{OUT} (T = 1 year) alters bay-wide salinities 0.0030 to 0.0069. Thus, the diversion of the annual mean Q_{EXPORTS} of 198 $m^3\ s^{-1}$ corresponds to bay-wide salinity increases of 0.6 to 1.4. This generally agrees with the conclusion of Knowles (2002) that management effects have increased northern bay salinities by about 1–2.

A small change in salinity can affect SFE habitats and ecology. Altering the freshwater inflow and the salinity gradient in the estuary can affect the locations of estuarine turbidity maxima, which have implications for the locations of higher concentrations of phytoplankton as a food resource for higher trophic levels (Jassby *et al.,* 1995). In addition, increasing salinities in certain areas of SFE could decrease stratification in the water column, thereby decreasing phytoplankton bloom potential in this light-limited estuary (Williams, 1989). Altering the salinity field can also change the location of the low-salinity zone (where salinity is 0.5–6), which is the location of the maxima for several zooplankton species that are important fish prey (Kimmerer *et al.,* 1998). Given the shape of San Francisco estuary, a small change in the upstream–downstream location of the low-salinity zone can have a tremendous effect on the area of the bay experiencing a specific salinity. This can affect benthic ecosystems in particular (Jassby *et al.,* 1995; Williams, 1989). Finally, since some of the planktonic food resources in the estuary, such as the copepods *Eurytemora* and *Acartia* or the rotifer *Synchaeta,* have salinity ranges that vary by only 2–6 units (Kimmerer, 2002), an altered salinity field will affect the location that these prey items occur. This in turn can affect the availability of prey to higher trophic-level predators such as fish.

CONCLUSIONS

Climate and water management changes occur on a decadal timescale. This study reinforces that multidecadal records are critical for identifying salinity and temperature trends in the environment. Three main conclusions can be drawn from this work in San Francisco estuary. First, in spite of the high degree of natural variability in the estuary, several trends in temperature and salinity could be identified. The strongest trends are for increasing salinity at MAL, which may be biased by the period of record, and increasing temperature at WIC. Second, freshwater inflow to the estuary has a range of effects on salinity from -0.0020 to -0.0096 $(\mathrm{m}^3\ \mathrm{s}^{-1})^{-1}$, depending on location in the estuary and the timescale of data analyzed. Spatially, the effect varies by a factor of four, with the strongest relationship occurring near the middle of the estuary. The effect at WIC, when analyzing daily, event/pulse, and annual timescales, varies only by a factor of about two. Third, we quantified that even small changes in freshwater inflow, changes that are within the average range of management actions, can alter the salinity in the estuary by 0.6 to 1.4.

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