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Water, salt, and nutrient exchanges in San Francisco Bay

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Abstract

We constructed water, salt, and nutrient budgets for San Francisco Bay and used them to analyze the net biogeochemical performance of the bay. The bay was subdivided into three sectors, North, Central, and South Bay, with the Central Bay serving as a proxy for the oceanic end member. Separate budgets were constructed for the wet (October–March) and dry (April–October) seasons of each year for 6 yr (1990–1995). This period of record contained 2 yr of above normal runoff (1993, 1995) and 4 yr of below average runoff. Effluent from sewage treatment plants accounts for approximately 50% of the nutrient loading to the bay in winter and 80% of the summer loading. Both arms of the bay were apparently net heterotrophic during the winter, with this signal being strongest during the wet winters of 1993 and 1995. We conclude that overall the bay is slightly net autotrophic (production of new organic matter in the bay by plant growth exceeds respiratory demands); however, this varies seasonally (strongest in summer) and is complicated by the possibility of significant abiotic P adsorption in the North Bay.

San Francisco Bay (38°49.2′N, 122°28.8′W) is one of the largest embayments on the Pacific coast of the Americas. With a human population of approximately seven million living around its perimeter, San Francisco Bay has been referred to as the urbanized estuary (Conomos 1979). Human activity around the bay, as well as agricultural activity in California's Central Valley, has affected bay water quality and resulted in profound modifications of land and freshwater use. Much of the region is arid, but substantial precipitation in the Sierra Nevada mountain range in eastern California is tapped for human use. Water flow to the bay is thus modified by regulation for flood control and by diversions for consumptive use (Arthur et al. 1996). While freshwater flow to the bay generally reflects interannual variations in precipitation within the watershed, the details of the annual hydrograph strongly reflect human control.

The bay may be thought of as three hydrographically distinct basins (Conomos et al. 1985): North Bay, Central Bay, and South Bay (Fig. 1). North San Francisco Bay is a classical river-dominated, macrotidal estuary receiving flow from the Sacramento and San Joaquin Rivers and from several smaller rivers via a complex network of distributaries (the delta) that discharge into the subembayment of Suisun Bay. These rivers drain an area of approximately 150,000 km^2, about 40% of the area of California. South San Francisco Bay and the Central Bay have very small catchment basins. The South Bay is a macrotidal marine embayment receiving little natural freshwater discharge. Effluent from sewage treatment plants (hereafter STP effluent or effluent) is the dominant freshwater input (Conomos et al. 1985; Hager and Schemel 1996), and the South Bay can become slightly hypersaline (relative to the Central Bay) during the summer. These hydrologically distinct arms each exchange water with Central San Francisco Bay, which in turn exchanges water with the coastal Pacific Ocean via the Golden Gate (Walters et al. 1985; Largier 1996; Uncles and Peterson 1996).

North and South San Francisco Bays, although hydrologically distinct, are both strongly influenced by human perturbation. The San Francisco metropolitan area surrounds the bay and influences it in many ways. Moreover, agricultural activities and water diversion from North San Francisco Bay represent a further human perturbation associated with land and water use in the catchment. Our analysis is concerned with water and nutrient dynamics of the San Francisco Bay ecosystem, so we will focus our attention on aspects of environmental modification most directly related to these aspects of the system.

A major perturbation to the bay at present is regulation of river water flow. Historically the North Bay has also been modified extensively by deposition of large amounts of sediment and mercury resulting from gold mining in the mid-19th century. Water quality of North San Francisco Bay is strongly influenced by river discharge, although we will demonstrate possible additional influences within the North Bay itself. By contrast, STP effluent dramatically alters water quality of the South Bay.

Materials and methods

Conceptual design—The purpose of this analysis is to assess water and nutrient inputs to the bay and the exchanges

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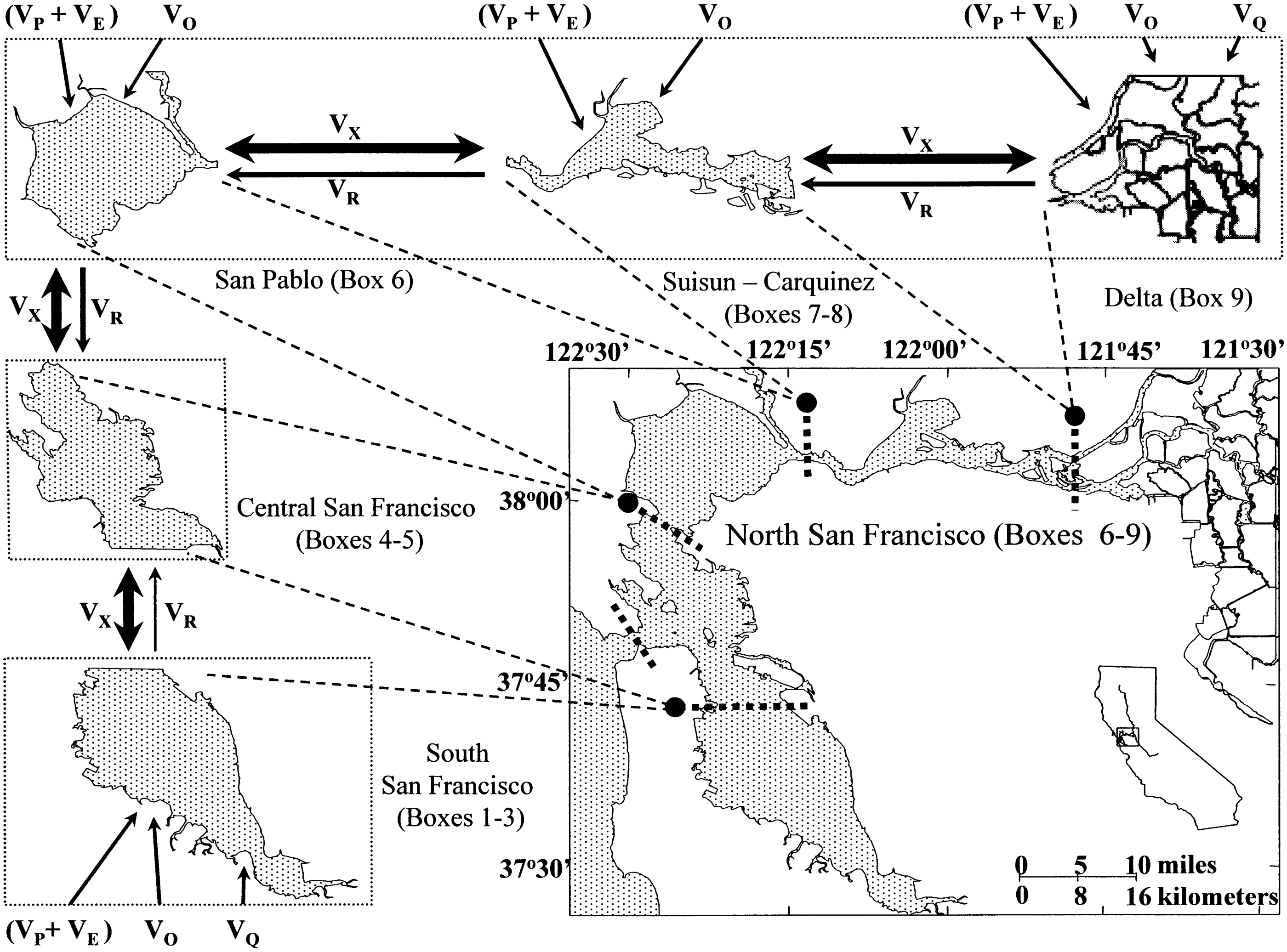

Fig. 1. Idealized plumbing diagram used in developing the water, salt, and nutrient budgets for San Francisco Bay. Variables (in units of $m^3 d^{-1}$) are V_Q, river flow; V_P, precipitation; V_E, evaporation; V_O, other flows into the system; V_X, mixing exchange; and V_R, residual flow. The final analysis treated sectors 1–3 (South San Francisco Bay) as one box and sectors 6–9 (North San Francisco Bay) as a second box. Sectors 4–5 (Central San Francisco Bay) serve as the oceanic end member. The Central Bay connects to the Pacific Ocean at the Golden Gate (38°49.2′N, 122°28.8′W).

of these materials between North and South San Francisco Bay and the Central Bay. Specifically, we establish water budgets to estimate the flow of water through the system. Salt budgets provide estimates of mixing. These budgets can be considered conservative, that is, water and salt do not accumulate in the system, so over time (at steady state) water and salt inputs must equal outputs.

Dissolved nutrients (nitrogen and phosphorus) are added along with the water and salt. Because of limited data on organic nutrients, only inorganic nutrients are considered in our analysis. Unlike water and salt, dissolved nutrients may either be taken up or released as a result of biological and geochemical processes within the system. Budgets of these materials are termed nonconservative with respect to both water and salt because processes other than water flow and mixing take up and release dissolved inorganic N and P. These processes include the biotic reactions of primary production, respiration, nitrogen fixation, and denitrification; and abiotic reactions such as sorption or desorption from sediment and coprecipitation.

The budgetary procedure we use has been formalized into a standard protocol for an international research program called the Land Ocean Interactions in the Coastal Zone (LOICZ) that is available on the LOICZ web site. The formal analytical protocol is well described in publications by Gordon et al. (1996), Smith and Hollibaugh (1997), and Smith et al. (1991) and is summarized briefly below to clarify our treatment of the San Francisco Bay data.

Figure 1 presents the plumbing diagram that was used to assess water, salt, and nutrient budgets in San Francisco Bay. The two arms of the bay are treated independently in the analysis. The budget was initially developed with North San Francisco Bay treated as three sectors in series (Delta, Suisun Bay/Carquinez Strait, and San Pablo Bay). Because water exchange time in the Delta and the Suisun/Carquinez sectors is short, their budgets proved to be unreliable. Nevertheless, as discussed by Webster et al. (1999), the overall analysis of a system this complex is more accurate if the system is segmented. The segmentation provides a box model approximation of the longitudinal gradients in water properties, and estimates of salt exchange according to equations presented below are more accurate than they would be with larger boxes. A similar approach was taken by Peterson et al. (1996) and Uncles and Peterson (1996). Consequently, we have performed the analyses for the three sectors and then combined the data into estimates for the entire North Bay. The Central Bay is treated as the oceanic end member for both North and South Bays. While it would be desirable to budget the Central Bay as well as the North and South Bays, the analytical protocol employed here requires water composition data on the oceanic side of each budgeted box. Because the coastal ocean outside the Golden Gate is hydrographically complex (Largier 1996) and is not sampled routinely, it was only feasible to use the Central Bay as the oceanic end member for this analysis.

Seasonal and interannual variability in rainfall and runoff are high, and both water exchange and delivery of nutrients and other materials are influenced by this variability. Water composition is strongly responsive to flow, with clear seasonal and interannual differences (e.g., Peterson et al. 1985; Hager and Schemel 1996; Schemel and Hager 1996). In order to capture these time scales of variability in our analysis of the system, we used hydrological and climatological data for water years (1 October–30 September) 1989–1990 to 1995–1996 (hereafter referred to by the second calendar year, i.e., water year 1989–1990 is referred to as 1990). We constructed budgets for summer (April–October, dry season) and winter (October–April, wet season). This period includes 4 yr with below normal runoff (dry, 1990–1992; 1994) and 2 yr with above normal runoff (wet, 1993, 1995). The water quality data for Central San Francisco Bay needed to establish the oceanic end member were not available for summer 1990, so that period is missing from our analysis.

Both North and South San Francisco Bay stratify periodically, particularly in response to gravitational circulation during periods of neap tides and high flows (Conomos et al. 1985; Walters et al. 1985; Peterson et al. 1996; Monismith et al. 1996). While this stratification is pulsed (i.e., ephemeral), the budgetary analysis might be considerably strengthened if the data were available to calculate the effects of stratification on the budgets (Webster et al. 1999). Unfortunately, the development of a two-layer nutrient budget model for this system is not feasible because of data limitations, though Uncles and Peterson (1996) were able to apply a two-layer analysis to salt distributions. Because the stratification is ephemeral we assume that this is not a major limitation of the analysis. The budgets developed here are therefore based on linked one-dimensional sectors, or boxes, along the bay.

The fluxes considered in the model are shown in Fig. 1. As shown in the figure, the water budget terms V_Q, V_P, V_E, and V_O represent river flow, precipitation, evaporation, and any other flows into the system, respectively. These water fluxes are related by

$$\frac{dV_{\text{syst}}}{dt} = V_Q + V_P + V_E + V_O + V_R \tag{1}$$

The contribution of groundwater to V_O can be assumed to be minor relative to the other freshwater sources in San Francisco Bay, and the major flow associated with V_O in this system is likely to be STP effluent. By convention, flow *into* the system is positive, so V_E (which represents removal of water) is subtracted. This is a steady-state model, so we assume that the volume of the system remains constant over the budgeting period.

The term V_R represents the residual flow, the amount of water flow to or from a box that must occur to balance the budget. Neglecting the smaller terms in the equation, $V_R = -V_Q$ in river-dominated North San Francisco Bay because of the excess water delivered by the river. By contrast, the other terms become important in South San Francisco Bay. During the summer (dry season), V_E can exceed the other terms. V_R then becomes positive (i.e., residual flow into the South Bay) in order to compensate for evaporative water loss.

If dV_{syst}/dt is assumed to be 0, Eq. 1 can be solved with V_R as the unknown, retaining all of the other terms:

$$V_R = -V_Q - V_P - V_E - V_O \tag{2}$$

An analogous equation can be written to describe the salt balance by multiplying water fluxes by their appropriate salinity (Eq. 3).

$$\frac{d(V_{\text{syst}}S_{\text{syst}})}{dt} = V_R S_R + V_X(S_{\text{ocn}} - S_{\text{syst}}) \tag{3}$$

The equation is simplified by dropping out terms likely to be insignificant in the salt budget: river water, precipitation, evaporation, groundwater (usually), and other can all be assumed to have negligible salinity. The salinity of the residual flow is assumed to be that at the boundary between the box of interest and the adjacent source box (usually the oceanic end member). This salinity is estimated as the average of those two boxes, i.e., $S_R = (S_{\text{syst}} + S_{\text{ocn}})/2$.

The salt budget has one term (V_X) that does not appear in the water budget because mixing occurs between the system and the ocean.

$$V_X = -\frac{V_R S_R}{(S_{\text{ocn}} - S_{\text{syst}})} \tag{4}$$

Note that the term $(S_{\text{ocn}} - S_{\text{syst}})$ is the box model equivalent of the horizontal salinity gradient. As long as there is a measurable salinity difference between the system of interest and the adjacent box(es), the box model equations can be solved for water exchange between many water bodies and the adjacent ocean. If the salinity difference between the boxes is not significantly different from 0, the equation cannot be used to solve for residual fluxes and nonconservative behavior.

One potential complication in applying this model to San Pablo and South San Francisco Bays is the harvest and removal of salt by seawater evaporation to dryness. As a result, salinity is not strictly conservative, relative to water, in this system. However, this term is negligible compared with the conservative mixing of salt and has not been budgeted explicitly. With the assumptions and simplifications given above, V_R, V_X, and τ [$\tau = V_{\text{syst}} \cdot (V_X + |V_R|)^{-1}$ is the water exchange time, sometimes called residence time, although this term has been used for a variety of differing calculations] have been calculated.

Once Eqs. 2 and 4 have been used to quantify advection and mixing, an equation analogous to Eq. 3 can be written to describe the nonconservative behavior of any other material (Y). Our analysis of nonconservative fluxes is limited to dissolved materials because budgets of particulate material are complicated by sedimentation and resuspension. We included terms for river flow and other sources in our budget because clearly river flow and STP effluent contribute nutrients to the system, even though they are negligible for salt or (for STP effluent) water budgets. We were unable to estimate groundwater contributions because of lack of data, so it has not been treated explicitly in the budget; however, it is included in the other sources term. Atmospheric deposition presents a similar problem: it may be a significant source of nitrogen to an urbanized estuary like San Francisco Bay (Paerl 2002), but we were unable to obtain estimates of its contribution. Any atmospheric deposition falling on the surface of the estuary would be included in the apparent nonconservative behavior of dissolved nitrogen, and any nitrogen deposited within the catchment that reaches the estuary via runoff is included in other sources in the nitrogen budget as we have constructed it.

ΔY is the sum of the processes affecting water composition other than the hydrographic processes. Thus, at steady state:

$$\Delta Y = -V_Q Y_Q - V_O Y_O - V_R Y_R - V_X (Y_{\text{ocn}} - Y_{\text{syst}}) \quad (5)$$

Using this equation, nonconservative fluxes have been determined for dissolved inorganic phosphorus and dissolved inorganic nitrogen (ΔDIP, ΔDIN) in the two reaches of San Francisco Bay for 11 different periods (five summer, six winter). ΔDIP and ΔDIN are normalized to the areas of each arm of the bay so that rates are expressed per unit area of the budgeted regions for ease of comparison between the two arms and with literature information.

In addition, we have estimated net ecosystem metabolism based on the assumptions made in the LOICZ analysis (Gordon et al. 1996) that the major nonconservative reaction involving DIP is the production or consumption of organic matter and that any organic matter being produced or consumed has a carbon to phosphorus ratio approximating that of phytoplankton (the so called ''Redfield C : P ratio''; in molar units, 106 : 1). Net organic production removes DIP, while net organic consumption (respiration or oxidation of organic matter by bacteria or secondary producers) releases DIP. Net production minus respiration can be denoted as $(p - r)$, so

$$(p - r) = -106 \times \Delta\text{DIP} \quad (6)$$

A system that is net autotrophic $[(p - r) > 1]$ produces organic matter in excess of respiration and requires an input of inorganic nutrients supplied from outside the system in order to support this positive net ecosystem production; a system that is net heterotrophic requires a source of organic matter supplied from outside the system to support this net heterotrophy (Smith and Hollibaugh 1997).

The second stoichiometric calculation involves both nitrogen and phosphorus. Many coastal ecosystems denitrify at relatively rapid rates; a few fix atmospheric nitrogen into organic material (Gordon et al. 1996; Smith and Hollibaugh 1997). Again, ΔDIP is used as a tracer of net organic metabolism. The Redfield N : P ratio (16 : 1) would predict that for each mole of DIP either released or taken up by organic metabolism, 16 moles of DIN will be released or taken up. The difference between the observed and expected ΔDIN is attributed to the difference between nitrogen fixation and denitrification (*nfix* − *denit*):

$$\begin{aligned}(nfix - denit) &= \Delta\text{DIN}_{\text{obs}} - \Delta\text{DIN}_{\text{exp}}\\ &= \Delta\text{DIN}_{\text{obs}} - 16 \times \Delta\text{DIP} \quad (7)\end{aligned}$$

Equations 6 and 7 are thus used to place initial biogeochemical interpretations on ΔDIP and ΔDIN in San Francisco Bay.

Data sources—We have used data from technical reports and unpublished records to perform the analyses presented here. Many of these data are available via the internet. URLs are given where appropriate, and data report citations are given in the bibliography.

North Bay river flow data (Q_{out}) are from the Dayflow web page (http://www.iep.ca.gov/dayflow/), as calculated by the Department of Water Resources (DWR). South bay runoff is approximated from gauged streams (http://nwis.waterdata.usgs.gov/nwis). Runoff coefficients (i.e., measured flow/gauged catchment area) times total catchment areas were used to estimate runoff for the whole South Bay watershed. Bay and river water quality data were provided, as discussed below, by the U.S. Geological Survey (USGS) and DWR. Most of the salinity estimates available for the North Bay were based on DWR measurements of chlorinity. A standard oceanographic assumption is that salinity $\approx 1.806 \times$ chlorinity. Although this conversion factor is most nearly valid at salinities near those of open ocean seawater (i.e., salinity ≈ 35), this factor is sufficiently accurate for use in the North Bay budget because the chlorinity gradients are relatively large. In some cases, data on specific conductance were converted to salinity estimates.

Effluent discharge data were obtained for 12 major municipal sewage treatment plants (STPs) discharging to the bay. These data were provided either by the San Francisco Bay Regional Water Quality Control Board or, in two cases, from treatment plant records. Five of the plants (accounting for about 50% of the STP effluent load into San Francisco Bay) recorded effluent composition with enough detail for dissolved inorganic nitrogen and phosphorus concentrations to be used in the budgets. We assume that these data are representative of effluent composition for other treatment plants for which composition data were not available.

Combined STP effluent discharge rate was assumed to be constant over the 6 yr budgeted here, an assumption that is supported by inspection of the data. Water discharged by the STPs is not significant to the water budget. Storm drains have been separated from sewage lines in the majority of these systems, removing a major source of variation in STP effluent fluxes. Seasonal and interannual variation in nutrient discharge from these plants over the period of record was

Table 1. Hypsographic characteristics of San Francisco Bay. The sectors originally budgeted are labeled. The final budgets combined sectors 1–3 into one budget box, combined sectors 6–9 into a second budget box, and used combined sectors 4 and 5 as the oceanic end member.

Region	Sector	Area (10^6 m^2)	Average depth (m)	Volume (10^6 m^3)
South San Francisco Bay				
South of Dumbarton Bridge	1	30	3	90
Dumbarton Bridge to San Mateo Bridge	2	90	4	360
San Mateo Bridge to San Bruno Shoal	3	140	4	560
Subtotal	1–3	260	3.9	1,010
Central San Francisco Bay				
San Bruno Shoal to Bay Bridge	4	230	7	1,610
Bay Bridge to San Pablo Point	5	200	12	2,620
Subtotal	4–5	430	9.8	4,230
North San Francisco Bay				
San Pablo Bay	6	290	5	1,450
Carquinez Strait	7	20	12	240
Suisun Bay	8	100	5	500
Delta	9	80	2	160
Subtotal	6–9	490	4.8	2,350
Total San Francisco Bay	1–9	1,180	6.4	7,590

judged to be unimportant for the analysis of loadings presented here. Additional information on local inflows of materials from a San Francisco Bay Conservation and Development Commission report (U.S. EPA 1992) were examined, although in the end these data were not used explicitly in the analysis.

Runoff composition data for the South Bay are poorly characterized because there are several small sources, rather than the dominating influence of a single large river system, as is the case for North San Francisco Bay. We were unable to locate a data repository for South Bay runoff composition, although there are undoubtedly individual databases, so we assumed composition to be similar to the Sacramento/San Joaquin river composition. While this estimate is crude, it is sufficient to demonstrate that nutrient discharge to the South Bay is overwhelmingly dominated by STP effluent, a conclusion supported by previous work (Conomos et al. 1985; Hager and Schemel 1996; Schemel and Hager 1996).

Weather data used to calculate runoff and net evaporation were downloaded from the National Oceanographic and Atmospheric Administration web site (http://www.ncdc.noaa.gov/oa/ncdc.html). We used five stations located around South San Francisco Bay because of the obvious dominance of river flow, which is measured directly, in the freshwater budget of the North Bay. Monthly mean rainfall data were used to calculate runoff and net evaporation. Evaporation data for the period were smoothed with an annual sine curve; that is, the seasonal pattern is treated as being the same between years. This approximation is justified because net evaporation is significant only during the summer and there is less interannual variation in summer climatology than there is in winter runoff. San Francisco Bay nutrient data were collected in conjunction with the San Francisco Bay Program of the USGS and were provided by S. W. Hager (USGS). Other San Francisco Bay water quality data used in our analysis (temperature, salinity) were also collected by that program and are posted at http//www.sfbay.wr.usgs.gov/access/wqdata/. These data are also contained in the following technical reports: Wienke et al. (1990), Wienke et al. (1991, 1992); Wienke et al. (1993); Caffrey et al. (1994); Edmunds et al. (1995); and Edmunds et al. (1997). We obtained additional data for North San Francisco Bay and the Sacramento and San Joaquin Rivers from the State of California, Department of Water Resources. Hypsographic data were approximated by planimetry of hydrographic charts of San Francisco Bay.

Results

General—Table 1 summarizes hypsographic information for various sectors of San Francisco Bay. Central San Francisco Bay, which is not budgeted, is the deepest portion of the bay (10 m) and accounts for about 36% (430 km^2) of the bay area. North San Francisco Bay is next in depth (5 m) and accounts for 42% (490 km^2) of the area. South San Francisco Bay is about 4 m deep and covers an area of about 260 km^2 (22% of the area). The overall area of the bay ($\sim$1,200 km^2) makes it the largest estuary on the Pacific coast of the United States and one of the largest estuaries in the country.

Figure 2 presents monthly water inputs to North and South San Francisco Bay. Table 2 gives seasonal averages for these flows. The important points to note are as follows. Freshwater input is dramatically different between the two portions of the bay, with the South Bay being dominated by STP effluent and the North Bay being overwhelmingly dominated by runoff. There is strong seasonality, with the winter months having high and the summer having low freshwater inflow. In the South Bay, this is manifested by net water loss via evaporation during the summer. Finally, note the high interannual variability. The years 1990, 1991, 1992, and

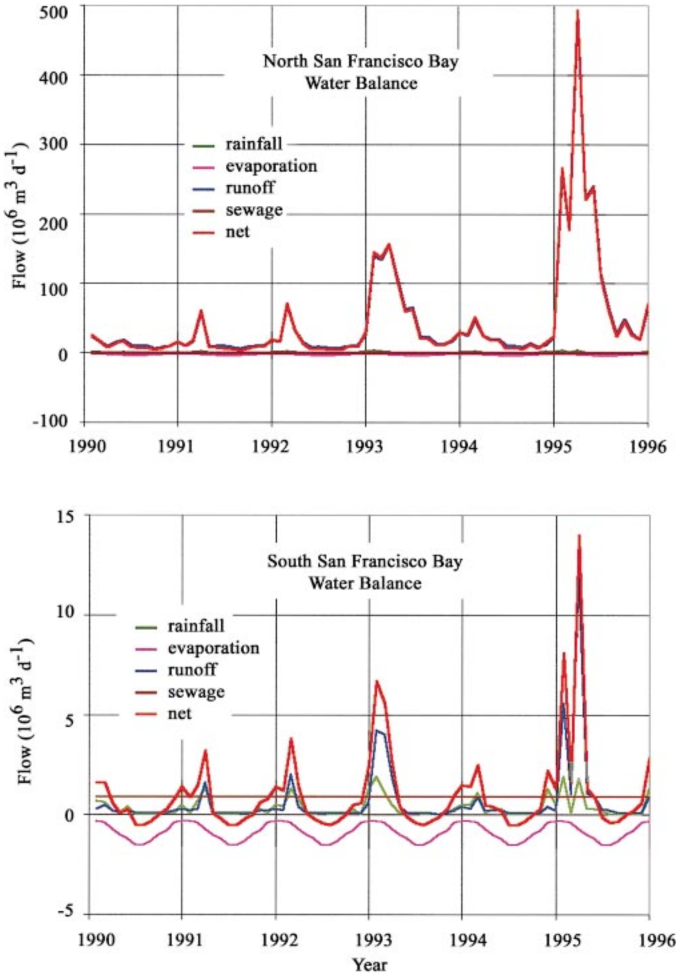

Fig. 2. Freshwater balance for North and South San Francisco Bay. The North Bay freshwater budget is overwhelmingly dominated by river inflow. By contrast, the South Bay budget includes significant amounts of water from rainfall, evaporation, runoff, and especially STP effluent.

1994 are grouped together as dry years; the years 1993 and 1995 are wet years. Comparisons proceed on the basis of this separation.

Water and salt budgets—Tables 2 and 3 summarize data from 1990 through 1995 that were used in the water and salt budgets. Higher precision is maintained on the water flux estimates for the South Bay than for the North Bay because of the small (and similar) magnitudes of each of the freshwater fluxes in the South Bay. During most years, the strong seasonality of rainfall and runoff (wet winters, dry summers) is reflected in the water budgets. There is considerable interannual variability, with 1993 and 1995 being decidedly wetter than the other years represented in the budgets. There are also large differences between the water budgets for the two reaches of the bay.

Of the water budget terms illustrated in Fig. 2 and Table 2, no single term can be ignored for South San Francisco Bay. During the summer, evaporation dominates. The South Bay can become slightly more saline than the Central Bay because evaporation is only partially offset by STP effluent inflow, which is the largest summer freshwater input. Runoff dominates the budget during the winter, but rainfall is significant. The pattern is very different in North San Francisco Bay, where the budget is overwhelmingly dominated by runoff.

Table 4 presents the year-by-year water and salt budgets for the two reaches of the bay. Water quality data were relatively sparse, and the lack of data to develop vertically stratified budgets is a particular shortcoming of the analyses presented here. Because the data are sparse it was impractical to use direct statistical estimates of variability to evaluate sensitivity. Nevertheless, some measure of the uncertainty of the various budget-derived estimates is desired. We have therefore used a simple Monte Carlo analysis (e.g., Laws 1997) with 100 resamplings to estimate mean, median, and standard deviations of V_R and V_X. It was assumed that the errors were uncorrelated and normally distributed and that there was a 25% uncertainty (standard deviation) in the

Table 2. Freshwater fluxes into the sectors of San Francisco Bay. Symbols are V_P, precipitation; V_E, evaporation; V_O estimated (assumed constant) STP effluent influx; V_Q (river flow and runoff). V_Q into the North Bay sectors from sources other than the Delta is small and is assumed to be 0. The bold periods of 1993 and 1995 are wet years; w, winter; s, summer. All fluxes are in units of 10^6 m^3 d^{-1}.

				North San Francisco Bay								
	South San Francisco Bay			San Pablo Bay			Suisun Bay–Carquinez Strait			Delta		
Period	$(V_P - V_E)$	V_O	V_Q	$(V_P - V_E)$	V_O	V_Q	$(V_P - V_E)$	V_O	V_Q	$(V_P - V_E)$	V_O	V_Q
w 1990	−0.4	0.9	0.3	0.0	0.1	0	−0.2	0.2	0	0.0	0.0	14
w 1991	0.0	0.9	0.7	0.0	0.1	0	0.0	0.2	0	0.0	0.0	29
w 1992	0.0	0.9	0.8	0.0	0.1	0	0.0	0.2	0	0.0	0.0	39
w 1993	**−0.1**	**0.9**	**2.1**	**0.0**	**0.1**	**0**	**−0.1**	**0.2**	**0**	**0.0**	**0.0**	**133**
w 1994	−0.2	0.9	0.4	0.0	0.1	0	−0.1	0.2	0	0.0	0.0	32
w 1995	**0.0**	**0.9**	**4.7**	**0.0**	**0.1**	**0**	**0.0**	**0.2**	**0**	**0.0**	**0.0**	**297**
s 1990	−1.0	0.9	0.1	−2.0	0.1	0	−0.5	0.2	0	0.0	0.0	8
s 1991	−0.9	0.9	0.1	−2.0	0.1	0	−0.5	0.2	0	0.0	0.0	8
s 1992	−0.9	0.9	0.1	−2.0	0.1	0	−0.5	0.2	0	0.0	0.0	9
s 1993	−1.0	0.9	0.1	−2.0	0.1	0	−0.5	0.2	0	0.0	0.0	16
s 1994	−1.0	0.9	0.1	−2.0	0.1	0	−0.5	0.2	0	0.0	0.0	10
s 1995	−1.0	0.9	0.1	−2.0	0.1	0	−0.5	0.2	0	0.0	0.0	34

Table 3. Estimated salinity in San Francisco Bay sectors during each sampling period. Central San Francisco Bay is used as the oceanic end member. The bold winter periods (1993 and 1995) are wet years; w, winter; s, summer. Runoff, STP effluent, and (rainfall − evaporation) are assigned salinities of 0.

Period	South Bay	Central Bay	San Pablo Bay	Suisun Bay–Carquinez Strait	Delta
w 1990	28.6	29.6	27.6	9.3	7.5
w 1991	27.1	28.2	23.7	6.6	4.7
w 1992	25.1	27.6	23.1	2.7	1.5
w 1993	**17.9**	**20.3**	**17.3**	**0.2**	**0.2**
w 1994	26.0	27.0	24.7	4.3	2.9
w 1995	**13.6**	**14.3**	**5.6**	**0.1**	**0.1**
s 1990			29.2	9.6	7.6
s 1991	31.8	31.9	29.7	10.0	7.7
s 1992	30.5	31.9	29.4	10.7	8.6
s 1993	27.6	28.8	23.4	4.7	3.2
s 1994	31.4	31.7	29.5	10.6	8.3
s 1995	25.1	27.7	19.0	2.4	0.6

water budget terms and a 1 unit uncertainty in the mean salinity within each box. Note that in some instances the standard deviations became very large as the denominator of Eq. 4 approached 0. Negative values for V_X arise from random error when the signal of the salinity gradient (i.e., $S_{ocn} - S_{syst}$) becomes small and indistinguishable from 0. The condition (negative V_X) has no physical meaning since diffusion cannot be negative. Deviations between the direct budget calculation and the mean Monte Carlo value are largest when the standard deviation is large, reflecting the appearance of a few extreme calculations. This interpretation is supported by the general agreement between the budget

Table 4. Estimates of V_{Q^*} (defined as the sum of the freshwater inputs $\equiv -V_R$, the residual flow) and V_X (tidal mixing exchange) for North and South San Francisco Bay during the budgeted periods. Fluxes in 10^6 m^3 d^{-1}. Values shown are the budget estimates and the mean, standard deviation, and median of 100 Monte Carlo analyses. Bold winter periods (1993, 1995) represent the wet years; w, winter; s, summer. Budgeted flux values marked with an asterisk (*) are not significantly different from 0 according to the uncertainty criterion given in the text.

	$V_{Q^*} \equiv -V_R$				V_X			
Period	Budget	Mean	SD	Median	Budget	Mean	SD	Median
North San Francisco Bay								
w 1990	14	14	4	14	202	161	649	164
w 1991	29	29	8	29	168	203	108	167
w 1992	39	38	9	38	220	232	99	201
w 1993	**133**	**134**	**34**	**132**	**834**	**1,142**	**1,838**	**858**
w 1994	32	31	8	32	361	16	3,449	294
w 1995	**297**	**313**	**86**	**318**	**340**	**365**	**108**	**361**
s 1990	6	6	2	6	—	—	—	—
s 1991	6	6	2	6	85	821	6,988	75
s 1992	7	7	2	7	87	133	353	84
s 1993	14	14	4	14	68	74	31	67
s 1994	8	8	2	9	113	−36	1,223	108
s 1995	32	31	7	30	86	87	26	84
South San Francisco Bay								
w 1990	0.8	0.9	0.4	1.0	23	19	86	12
w 1991	1.6	1.7	0.5	2.0	41	9	550	22
w 1992	1.7	1.8	0.5	2.0	18	39	193	19
w 1993	**2.9**	**2.9**	**0.7**	**3.0**	**23**	**20**	**163**	**20**
w 1994	1.1	1.1	0.3	1.0	29*	23	141	13
w 1995	**5.6**	**5.7**	**1.4**	**6.0**	**113***	**13,331**	**126,885**	**36**
s 1990	0.0	0.0	0.3	0.0	—	—	—	—
s 1991	0.1	0.0	0.4	0.0	30*	7	33	0
s 1992	0.1	0.1	0.5	0.0	2*	15	107	0
s 1993	0.0	0.0	0.4	0.0	0	0	7	0
s 1994	0.0	0.0	0.4	0.0	0	1	23	0
s 1995	0.0	0.0	0.4	0.0	0	−1	11	0

Table 5. Water exchange time τ (days) calculated from data in Table 1 and 4. Calculations are based on the budget values (10^6 m^3 d^{-1}) of $-V_R$ and V_X (mixing exchange). V_{syst}, embayment volume. Bold winter periods (1993, 1995) represent the wet years; w, winter; s, summer. Budgeted flux values marked with an asterisk (*) fail statistical significance criterion given in the text.

Period	$-V_R$	V_X	τ
North San Francisco Bay (V_{syst}=2,350×10^6 m^3)			
w 1990	24	202	10
w 1991	29	168	14
w 1992	39	232	10
w 1993	**133**	**1,142**	**2**
w 1994	32	16	6
w 1995	**297**	**365**	**4**
s 1990	6	—	—
s 1991	6	85	26
s 1992	7	87	26
s 1993	14	68	29
s 1994	8	113	19
s 1995	32	86	20
South San Francisco Bay (V_{syst}=1,010×10^6 m^3)			
w 1990	1	23	42
w 1991	2	41	23
w 1992	2	18	51
w 1993	**3**	**23**	**39**
w 1994	1	29*	34
w 1995	**6**	**113***	**8**
s 1990	0	—	—
s 1991	0	30*	34
s 1992	0	2*	505
s 1993	0	0	∞
s 1994	0	0	∞
s 1995	0	0	∞

value and the Monte Carlo median, which is less sensitive than the mean to extremes. Using more complex estimates of error distributions was deemed unwarranted by the limited amount of data available to test their applicability.

Because of the lack of data from the lower water column, we were unable to evaluate the uncertainties (or errors) in the budgets that resulted from using only surface data and a single-layer box model. Budget-derived estimates for which the median flux estimate (Table 4) differed by more than 50% (i.e., outside the range of 0.5 to 1.5 times the budget flux estimates) were deemed unacceptable. The rule is changed for the very low V_R values in the South Bay during the summer; under those conditions the slight ($<0.5 \times 10^6$ m^3 d^{-1}) differences are all regarded as acceptable. Out of 22 separate budgetary analyses, four estimates of V_X and none of the estimates of V_R (other than the very low summer South Bay values), fell outside the 50% criterion. Two unacceptable values occurred in the South Bay during the winter, and two occurred in the South Bay during the summer. Despite the uncertainties, generalities emerge from the water and salt budgets and are discussed below.

Table 5 summarizes our estimates of water exchange time (τ). As would be expected, water exchange time for both North and South Bay is shorter during the wet season (winter/spring) than the dry season (summer/fall). During the wet season, the North Bay exchange time is typically 1–2 weeks during dry years and less than 1 week during wet years. North bay exchange during the dry season is about 3 weeks. South bay wet season exchange time is typically about 5 weeks. The very wet year of 1995 had an exchange time near 1 week; however, it should be noted that the budgetary calculation of mixing (V_X) was extremely unstable during that period (Table 4). Dry season water exchange in the South Bay is very slow, with all but one year having exchange times that were effectively infinite. That is, within the limitations of the salt and water budget calculations, water exchange in the South Bay during summer is effectively 0. There obviously is water exchange during this period (e.g., by tides), but the resolution of salinity and freshwater fluxes is not adequately constrained to determine the exchange.

Nutrient budgets—Nutrient concentrations are summarized in Table 6, and nutrient loadings are presented in Tables 7 and 8. In the North Bay, the major input of both DIN and DIP is river inflow, while STP effluent input dominates in the South Bay. These conclusions would not be significantly affected by more detailed information on other sources (for example, groundwater or atmospheric deposition) because of the strong dominance of these sources. The river load to the North Bay is, of course, much higher in the winter than in the summer and fluctuates strongly with river flow. During the summer, river and STP effluent delivery of DIN and DIP to the North Bay are of similar magnitude. In contrast, DIN and DIP loadings to the South Bay are always dominated by STP effluent. Table 9 summarizes the nutrient budgets, including both the direct budgetary calculations and the Monte Carlo analysis as discussed above.

The Monte Carlo analysis includes uncertainty in the water and salt budget (same rules as given above) and uncertainty in the nutrients (50% uncertainty [standard deviation] in the mean concentrations within the system; 33% uncertainty in the STP effluent nutrient concentrations). Even with these large uncertainties, there is generally good agreement among the direct budgetary calculations and the means and medians from the Monte Carlo analysis. The one significant exception is during the winter of 1995, when there was a substantial discrepancy between the DIP budget and Monte Carlo calculations of mean fluxes in both the North Bay and South Bay. Because the problem did not carry over to the DIN budget or the salt and water budget, it suggests that the uncertainty lies with the DIP data.

In general, DIP appears to be taken up in North San Francisco Bay in both winter and summer and in South San Francisco Bay during the summer. During the winter, the South Bay usually shows slight DIP release. The conclusion about summer uptake for both North and South Bay seems robust based on both the interannual standard deviations and the standard deviations generated for individual years from the Monte Carlo analysis. Closer inspection of the winter data indicates that the winter uptake in the North Bay needs to be interpreted somewhat cautiously. Both the standard deviations generated by the Monte Carlo analysis and the interannual standard deviations are large. In general, however, the four dry winters (the years with somewhat longer exchange times) all exhibit uptake. The wet years show ap-

Table 6. Estimated inorganic nutrient composition of bay sectors and inflows. Bold winter periods (1993, 1995) represent the wet years; w, winter; s, summer. Note that sewage treatment plant (STP) effluent composition is assumed to be constant, based on weighted averages for five major treatment plants. Runoff composition listed is for runoff (river flow) into the Delta. There are no data available for most of the South Bay streams, so rounded averages of Delta values are used (2 mmol m^{-3} dissolved inorganic phosphorus [DIP]; 30 mmol m^{-3} dissolved inorganic nitrogen [DIN]).

Element	Period	South Bay	Central Bay	San Pablo Bay	Suisun Bay–Carquinez Strait	Delta	STP effluent	Runoff
DIP (mmol m^{-3})	W 1990	8.0	4.2	2.2	2.7	3.1	130	3.1
	W 1991	9.9	5.0	3.1	3.7	3.8	130	3.4
	W 1992	8.5	3.3	2.7	3.1	3.0	130	2.8
	W 1993	**6.0**	**2.0**	**2.0**	**2.0**	**2.2**	**130**	**1.5**
	W 1994	7.6	3.4	2.6	2.7	2.7	130	2.2
	W 1995	**3.9**	**1.6**	**1.6**	**1.4**	**1.5**	**130**	**1.0**
	S 1990			3.2	4.8	4.5	130	3.2
	S 1991	9.9	4.2	2.7	4.4	4.1	130	3.4
	S 1992	18.7	4.6	4.1	4.8	4.7	130	3.3
	S 1993	14.3	3.7	3.1	2.7	2.6	130	1.6
	S 1994	11.8	5.2	3.6	4.0	3.7	130	2.3
	S 1995	10.8	3.2	2.0	1.8	1.3	130	1.4
DIN (mmol m^{-3})	W 1990	28	32	27	39	44	1,300	32
	W 1991	63	38	35	58	53	1,300	54
	W 1992	41	22	24	48	47	1,300	39
	W 1993	**37**	**17**	**25**	**35**	**36**	**1,300**	**25**
	W 1994	42	26	31	45	43	1,300	38
	W 1995	**39**	**19**	**24**	**20**	**22**	**1,300**	**19**
	S 1990			17	33	30	1,300	27
	S 1991	24	21	19	37	34	1,300	31
	S 1992	54	21	21	34	33	1,300	28
	S 1993	51	25	27	27	25	1,300	19
	S 1994	54	30	28	34	28	1,300	22
	S 1995	51	21	14	18	14	1,300	22

parent release, but the release rates are low relative to the loading, so that small errors in the loading estimates could bias the analyses. Nevertheless, overall the bay appears to be a DIP sink, with this conclusion being most robust during the summer and most open to question during high-runoff winters in the North Bay.

When data for the individual years are examined, DIN was apparently taken up during the first three winters and every summer in North San Francisco Bay and is generally taken up in South Bay. During the winters 1993–1995, North Bay appeared to release DIN. These results have to be interpreted very cautiously. In all cases for North San Francisco Bay,

Table 7. Estimated inorganic phosphorus loading into San Francisco Bay, in 10^3 mol d^{-3}. Bold winter periods (1993, 1995) represent the wet years; w, winter; s, summer.

			North San Francisco Bay					
	South San Francisco Bay		San Pablo Bay		Suisun Bay–Carquinez Strait		Delta	
Period	River	Effluent	River	Effluent	River	Effluent	River	Effluent
w 1990	1	117	0	13	0	26	43	0
w 1992	1	117	0	13	0	26	99	0
w 1992	2	117	0	13	0	26	109	0
w 1993	**4**	**117**	**0**	**13**	**0**	**26**	**200**	**0**
w 1994	1	117	0	13	0	26	70	0
w 1995	**9**	**117**	**0**	**13**	**0**	**26**	**297**	**0**
s 1990	0	117	0	13	0	26	26	0
s 1991	0	117	0	13	0	26	27	0
s 1992	0	117	0	13	0	26	30	0
s 1993	0	117	0	13	0	26	26	0
s 1994	0	117	0	13	0	26	23	0
s 1995	0	117	0	13	0	26	48	0

Table 8. Estimated inorganic nitrogen loading into San Francisco Bay, in 10^3 mol d^{-3}. Bold winter periods (1993, 1995) represent the wet years; w, winter; s, summer.

			North San Francisco Bay					
	South San Francisco Bay		San Pablo Bay		Suisun Bay–Carquinez Strait		Delta	
Period	River	Effluent	River	Effluent	River	Effluent	River	Effluent
w 1990	9	1,170	0	130	0	260	438	0
w 1991	21	1,170	0	130	0	260	1,566	0
w 1992	24	1,170	0	130	0	260	1,521	0
w 1993	**63**	**1,170**	**0**	**130**	**0**	**260**	**3,333**	**0**
w 1994	12	1,170	0	130	0	260	1,216	0
w 1995	**141**	**1,170**	**0**	**130**	**0**	**260**	**5,643**	**0**
s 1990	3	1,170	0	130	0	260	224	0
s 1991	3	1,170	0	130	0	260	257	0
s 1992	3	1,170	0	130	0	260	244	0
s 1993	3	1,170	0	130	0	260	310	0
s 1994	3	1,170	0	130	0	260	220	0
s 1995	3	1,170	0	130	0	260	755	0

the standard deviations generated by the Monte Carlo analysis are large relative to the estimates of the nonconservative flux. Because the standard deviations are large, we are forced to conclude that the nonconservative DIN flux is not significantly different from 0 (i.e., DIN behaves conservatively) in North San Francisco Bay. The same conclusion is drawn for South Bay during the winters, but the system is clearly a net DIN sink during the summers.

Discussion

Water exchange—As is true in many estuarine systems, water exchange in San Francisco Bay is strongly influenced by runoff. While the water and salt budgets do not demonstrate the mechanism of enhanced circulation associated with freshwater inflow, it is undoubtedly related to the establishment of estuarine circulation and enhanced entrainment of saltier deep water into the exit flow of river water. The importance of this enhanced flow is emphasized by two features of the water and salt budgets.

First, water exchange during the winter in the North Bay was substantially more rapid during the two wet years than during the four dry years. It does not appear that the relationship is a simple proportionality, however, because water exchange was more rapid during the lower flow wet year (1993) than the higher flow year (1995). There are at least two possible explanations for this observation. It could be an artifact reflecting the insufficiency of the data to resolve vertical stratification of flow and salinity in the system. Alternatively, very high river flow may actually reduce vertical mixing through enhanced stratification and result in a differential discharge of surface water out of the system. That is, the assumption of complete vertical mixing being used in the box model is violated during extreme high flows.

A second feature of water exchange as a function of freshwater inflow is seen in the South Bay. In the absence of significant freshwater inflow during the summer, water exchange is effectively 0. Papers by Walters et al. (1985) and Peterson et al. (1996) are useful for comparison with the exchange times calculated here. These authors concluded that the North Bay has an exchange time (in their paper, the sum of all processes) of the order of days during high flow periods (winter) and months for low flows (summer). These values are consistent with our estimates (Tables 4 and 5). Walters et al. (1985) also experienced problems making summer calculations for the South Bay. After some discussion, they conclude that the exchange time is perhaps as long as 10 weeks, although they did not settle on a particular value. For the winter period, they were also equivocal but suggested that the exchange times could range between 3 d at the northern end to perhaps 2 weeks. Qualitatively, at least, these results and those of Peterson et al. (1996) are consistent with the calculations made here.

Stoichiometric interpretation of nonconservative fluxes—Table 10 summarizes the nonconservative fluxes expressed as daily rates per area and presents the stoichiometric implications drawn from them. Various features emerge. The winter rates of DIP flux in the North Bay are high relative to summer rates and are also high relative to both summer and winter rates in the South Bay. Moreover, when Eq. 6 is used to calculate inferred rates of net ecosystem metabolism ($p - r$), the rates are generally unreasonably high. If we assume a primary production rate of approximately 0.5 g C m^{-2} d^{-1} (Cloern et al. 1985), this would be equivalent to about 40 mmol C m^{-2} d^{-1}. Yet the observed rates of ΔDIP converted to estimates of ($p - r$) are typically of this same magnitude, which implies that $r = 0$. It is unreasonable to expect that none of the primary production is respired. Although uptake by benthic microalgae, which was not included in the budget of Cloern et al. (1985), may be significant (Caffrey et al. 1998), we suspect that much of the DIP uptake in this system is abiotic. Owing to the high turbidity of North San Francisco Bay in particular, this uptake is probably the result of P sorption onto particles (Froelich 1988). DIP was released in the North Bay during the two wet years, again, potentially an abiotic sediment reaction. This conclu-

Table 9. Estimated nonconservative nutrient fluxes for North and South San Francisco Bay. Fluxes in 10^3 mol d^{-1}. Values shown are the budget estimates and the mean, standard deviation, and median of 100 Monte Carlo analyses. Bold winter periods (1993, 1995) were wet years; w, winter; s, summer. Budgeted flux values marked with an asterisk (*) are not statistically significant according to the criterion given in the text. DIP, dissolved inorganic phosphorus; DIN, dissolved inorganic nitrogen.

	ΔDIP				ΔDIN			
Period	Budget	Mean	SD	Median	Budget	Mean	SD	Median
North San Francisco Bay								
w 1990	−443	−466	408	−442	−1,405	−1,511	14,145	−1,103
w 1991	−347	−369	1,712	−356	−1,389	−1,087	19,708	−1,103
w 1992	−152	−157	328	−148	−584*	−79	81,141	358
w 1993	**45***	**137**	**869**	**139**	**5,550**	**5,615**	**20,963**	**6,061**
w 1994	−304	−291	558	−275	1,091	1,272	21,430	869
w 1995	**144**	**−120**	**3,636**	**88**	**2,018**	**1,918**	**12,521**	**2,123**
s 1990	—	—	—	—	—	—	—	—
s 1991	−169	−167	4,131	−131	−693	−689	9,064	−690
s 1992	−82	−82	893	−77	−487	−487	21,254	−432
s 1993	−56	−51	191	−46	−200	−161	7,083	−238
s 1994	−215	−209	288	−195	−594	−665	12,005	−635
s 1995	−104	−103	97	−95	−1,187	−1,304	1,138	−1,378
South San Francisco Bay								
w 1990	−2*	26	113	0	−1,265	−1,195	764	−1,121
w 1991	142	126	156	89	160*	247	1,199	6
w 1992	2*	_t−6	46	0	−732	−750	405	−748
w 1993	**−13**	**−14**	**50**	**−14**	**−672**	**−722**	**454**	**−664**
w 1994	1*	20	65	13	−716	−659	494	−645
w 1995	**167**	**779**	**6,299**	**152**	**1,263**	**1,087**	**4,401**	**1,093**
s 1990	—	—	—	—	—	—	—	—
s 1991	−117	−143	2,208	−111	−1,173	−1,161	661	−1,146
s 1992	−117	−84	148	−107	−1,173	−1,079	469	−1,048
s 1993	−117	−122	136	−118	−1,173	−1,229	552	−1,149
s 1994	−117	110	2,575	−116	−1,173	−1,263	2,590	−1,078
s 1995	−117	−121	46	−123	−1,173	−1,216	370	−1,236

sion about abiotic uptake may also be consistent with the general pattern of DIP flux.

When the estimates of ΔDIP and ΔDIN are converted to estimates of net nitrogen fixation minus denitrification (*nfix − denit*; Eq. 7), San Francisco Bay appears generally to be fixing nitrogen. We were initially perplexed by these observations because they implied that net autotrophic production in San Francisco Bay was so high that nitrogen fixation was required to keep up with the N demand created by organic production. An estuary receiving high nitrogen loads, where DIN is rarely depleted to phytoplankton growth-limiting concentrations (Hager and Schemel 1996), would not be expected to be a net nitrogen fixing system. This conclusion would remain qualitatively the same regardless of the large uncertainty in the nonconservative DIN flux. To resolve this dilemma, we tentatively concluded that there were likely to be additional nitrogen sources that were not being counted in the budget.

Candidates for these sources included dissolved organic nitrogen (DON), which could decompose to liberate N but not P, atmospheric deposition, or non–point source inputs. We cannot evaluate DON loads because of a paucity of data. First-order calculations reveal that the required atmospheric input is simply too high to be plausible. There are some model calculations of non–point source inputs around the periphery of the bay (U.S. EPA 1992). Again, these inputs are insufficient. Further analysis of the data suggests that the problem lies with inferring that the ΔDIP is primarily biotically driven in this system. If we assume, for the sake of argument, that the biotic component of ΔDIP is near 0, then ΔDIN would reflect (*nfix − denit*). That is, if DIP and, by extension, DIN are not being taken up to support net autotrophic production, the ΔDIP term in Eq. 7 goes to 0 and all DIN loss would then be attributable to denitrification. It is unlikely that there is no biological uptake of DIP or DIN in the North Bay; thus, ΔDIN provides a maximum estimate of net denitrification in the bay.

Peterson et al. (1985) used salinity-composition plots of North Bay nutrient data collected during the 1970s to describe nutrient dynamics in this reach. Their results are qualitatively the same as ours, suggesting that the nutrient dynamics of San Francisco Bay have not changed substantially between the 1970s period of their data record and the 1990s period we analyzed. While they did not attempt to model their data or to use it to calculate net fluxes, the shape of the curves they obtained indicates net uptake of nutrients, especially silicate (fig. 6 in Peterson et al. 1985), during the summer. This pattern was most pronounced during drier years. Peterson et al. (1985) interpreted the nonconservative behavior of silicate as an indication of benthic diatom primary production in North San Francisco Bay, an entirely credible hypothesis given the high benthic chlorophyll con-

Table 10. Rates of nonconservative flux normalized per unit area of bay floor (mmol m^{-2} d^{-1}) and stoichiometric estimates of apparent production − respiration ($p - r$) and nitrogen fixation − denitrification (*nfix* − *denit*). Bold winter periods (1993, 1995) are wet years, w, winter; s, summer. DIP, dissolved inorganic phosphorus; DIN, dissolved inorganic nitrogen.

Region				
Period	ΔDIP	ΔDIN	($p - r$)	(*nfix* − *denit*)
North SanFrancisco Bay (area=490 km^2)				
w 1990	−0.91	−2.9	+96	+12
w 1991	−0.71	−2.8	+75	+9
w 1992	−0.31	−1.2	+33	+4
w 1993	**+0.09**	**+11.3**	**−10**	**+10**
w 1994	−0.62	+2.2	+66	+12
w 1995	**+0.29**	**+4.2**	**−31**	**−0**
s 1990	—	—	—	—
s 1991	−0.35	−1.4	+37	+4
s 1992	−0.17	−1.0	+18	+2
s 1993	−0.11	−0.4	+12	+1
s 1994	−0.44	−1.2	+46	+6
s 1995	−0.21	−2.4	+22	+1
South San Francisco Bay (area=260 km^2)				
w 1990	−0.01	−4.9	+1	−5
w 1991	+0.55	+0.6	−58	−8
w 1992	+0.01	−2.8	−1	−3
w 1993	**−0.05**	**−2.6**	**+5**	**−2**
w 1994	+0.00	−2.8	+0	−3
w 1995	**+0.64**	**+4.9**	**−68**	**−5**
s 1990	—	—	—	—
s 1991	−0.45	−4.5	+48	+3
s 1992	−0.45	−4.5	+48	+3
s 1993	−0.45	−4.5	+48	+3
s 1994	−0.45	−4.5	+48	+3
s 1995	−0.45	−4.5	+48	+3

centrations observed in shallow areas of San Pablo and Suisun Bays (J. Thompson pers. comm.). Thus the nonconservative fluxes of DIN and DIP we observed are likely the result of a combination of abiotic processes (P adsorption), primary production, and heterotrophy (denitrification).

Why don't the stoichiometric equations appear to work very well for San Francisco Bay? While there are other systems in which estimates of net ecosystem metabolism based on stoichiometric analyses are not robust, the North San Francisco Bay case seems unusually bad. We suspect that the answer lies with the extremely high nutrient concentrations in the water column (Table 6), probably coupled with high turbidity. Particularly for phosphorus, which is known to be particle reactive (Froelich 1988), these conditions probably result in significant rates of sorption to sediments.

Possible consequences of altered levels of waste treatment—From the perspective of managing eutrophication, it is useful to examine the budgets that have been presented here and consider what management-related lessons can be learned. Taken as a whole, the nutrient loading into San Francisco Bay is presently dominated by STP effluent. During the winter, about half the inorganic nutrient loading to this system is STP effluent; in the summer, the STP effluent contribution to total loading is about 80%. The spatial distribution of this loading (mostly river in North Bay; mostly STP effluent in South Bay) has already been discussed. There is some uncertainty concerning the origin of the nutrients in the river nutrient signal entering the North Bay through the Delta. These nutrients are assumed to originate primarily from agricultural activities in the delta and the Central Valley, yet the urban areas of Sacramento, Davis, Modesto, and Stockton on the periphery of the Delta may contribute significantly to this input via STP effluent discharged into rivers upstream of the Delta. Regardless of the sources, the resultant nutrient concentrations in San Francisco Bay (Table 6) are very high relative to most seawater.

Since STP effluent is such an important nutrient source, it is instructive to ask ''What has the effect of wastewater treatment on nutrient loadings to San Francisco Bay been?'' Unpublished data assembled by the California Regional Water Quality control board between 1955 and 1985 indicate that daily per capita biological oxygen demand (BOD) production by communities discharging waste into San Francisco Bay was about 120 g $person^{-1}$. It should be clarified that this is *production*, not discharge, of BOD. Between 1955 and 1985, it was estimated that the BOD removal efficiency of STPs went from 30% to 95%. The estimated per capita BOD production rate is about 50% higher than standard design criteria reported by Tchobanoglous and Burton (1991), three times values used for widely employed rapid assessment techniques (Economopoulos 1993), and well above the waste load of a variety of published estimates assembled by one of us (S.V.S.). We point out that the San Francisco data seem high to underscore possible uncertainty in these estimates.

Based on this BOD loading estimate (120 g $person^{-1}$ d^{-1}), on typical BOD : nutrient ratios in domestic sewage, and on the nutrient loadings estimated here, we conclude that treatment is currently removing 75–90% of the nutrient load from the waste stream entering STPs. Nutrient loads to the bay and nutrient concentrations in it would be substantially higher in the absence of waste treatment to the present level. However, the low primary production of the bay is not a consequence of nutrient limitation (Cloern 1982; Cole and Cloern 1984; Cloern et al. 1985; Cloern 1987; Alpine and Cloern 1992), so further nutrient loading would probably not increase biotic uptake significantly, though it would increase nutrient export to the coastal ocean.

The more significant role of waste treatment in this system may be with respect to the form of nutrients present and perhaps with respect to pathways of inorganic nutrient uptake. Typically, approximately half of the nutrient load in raw sewage is inorganic. Besides removing nutrients, treatment undoubtedly elevates the proportion of inorganic nutrient. In clear water with low nutrient levels, this might actually enhance biotic nutrient uptake and primary production. In San Francisco Bay, any increase in nutrient removal probably results from abiotic sorption of phosphorus onto particles and perhaps from elevated loss of nitrogen through denitrification.

Prior to implementation of current treatment practices, the organic carbon loading from waste is likely to have been of greater significance to the bay food web and geochemistry than nutrient loading. With the waste production estimates cited above and standard conversion factors, organic carbon discharged to the bay in the untreated STP effluent produced by 6 million people would total about 60×10^6 mol d^{-1} (720×10^6 g C d^{-1}). Spread evenly over the 1,200 km^2 of bay surface, this is equivalent to about 0.6 g C m^{-2} d^{-1}. We can assume that most of this material is relatively reactive and would support heterotrophic activity (respiration and secondary production, broadly defined to include higher organisms as well as bacteria).

Primary production in San Francisco Bay averages about 0.5 g C m^{-2} d^{-1} (Cloern et al. 1985). Phytoplankton biomass is also reactive and supports heterotrophic activity. The conclusion from this simple calculation is that the magnitude of organic matter supplied by waste loading in the absence of treatment could have exceeded the reactive organic matter supplied by primary production. It therefore seems likely that heterotrophic activity might approximately double if that waste load were currently reaching the bay. It should be noted that this simplistic geochemical calculation provides no insight as to where, within the food web of the bay, this elevated heterotrophy would be most strongly felt. Spatially, waste discharge data used in budgetary calculations suggest that the major effect would be in the South Bay. The slow exchange times there, particularly during the summer, would clearly exacerbate any effects from such high organic loading.

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