Reduced Phosphate Loading to South San Francisco Bay, California: Detection of Effects in the Water Column.

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ABSTRACT

Dissolved phosphate has been a useful tracer of municipal wastewater in many studies of South San Francisco Bay (South Bay), in part because water column concentrations are higher than background levels even after appreciable dilution. Over the last decade, however, wastewater loading of phosphate to South Bay has been reduced. Our objective was to identify changes in phosphate concentrations in the water column of South Bay that were caused by recent reductions in wastewater loading. The changes proved difficult to detect in this estuary, primarily because of strong effects of interannual and seasonal variability in climate- and weather-dependent processes. This case study for phosphate identified factors that should be considered when attempting to detect effects in the water column for substances that are not completely removed from wastewater discharges and have potentially complex interactions with biogeochemical cycles.

Water-column measurements of phosphate concentrations did not provide clear evidence of a response to the reduced loading. The apparent change in water-column concentrations in recent years could have been caused by dry hydrolgic conditions before 1993 and very wet conditions over 1995-1998. Although interannual and seasonal variations in climate and weather influence water-column properties in many ways, the most apparent was greater effects of dilution by freshwater inflow that persisted for many months during the wet years. During early fall of most years, however, wastewater was the dominant source of freshwater to South Bay, and longitudinal gradients in both salinity and phosphate were directly related to wastewater inflow. At those times, a simple mixing model was effective in estimating average concentrations of phosphate in the wastewater from the longitudinal gradients in the bay. This technique detected a reduction in the phosphate gradient in recent years that was consistent with the decrease in wastewater concentration and the reduced loading.

INTRODUCTION

South San Francisco Bay (South Bay), the largest tributary embayment of the San Francisco Bay estuarine system (fig. 1), is surrounded by densely populated urban areas (Davis and others, 1991). Consequently, South Bay has a long history of water-quality problems related to discharges of municipal wastewater (Nichols and others, 1986), particularly in the reach south of the San Mateo Bridge (defined here as the landward reach). Improvements in waste treatment and discharge strategies have reduced the impact of municipal wastewater on the landward reach over the last few decades, but wastewater remains the major source of many substances found in the water column and bottom sediments (Davis and others, 1991). One of these substances, dissolved reactive phosphate (phosphate), is not of particular concern in bay waters, but it has been a useful tracer of the dispersion of municipal wastewater in studies of South Bay because wastewater concentrations are high and receiving-water concentrations remain higher than natural background levels even after appreciable dilution (McCulloch and others, 1970; Conomos and others, 1979; Schemel and Hager, 1996). Over the last decade, decreasing use of phosphate in detergents and improvements in wastewater treatment have reduced the loading of phosphate to South Bay. Our objective was to detect effects of recent reductions in phosphate

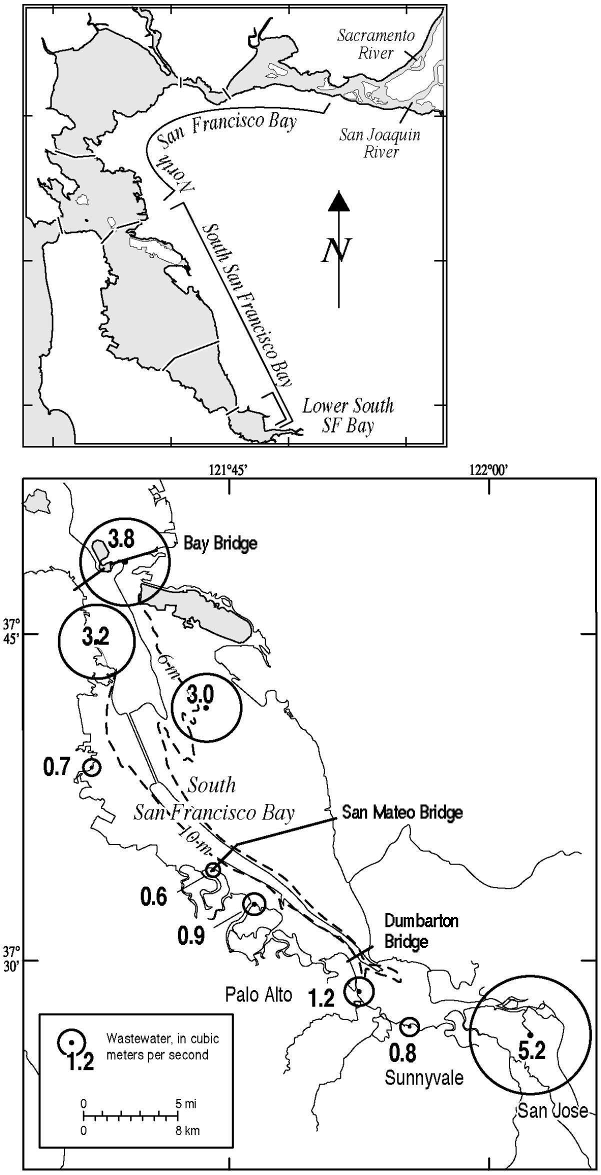

Figure 1. The San Francisco Bay estuarine system and locations and mean discharges for municipal wastewater treatment plants in South San Francisco Bay. Discharge data are from Davis and others, 1991.

loading to the landward reach by examining water-column concentrations and chemical gradients established by wastewater inflow. This case study for phosphate showed that effects in receiving waters can be difficult to identify in hydrologic systems that are influenced by large variations in climate- and weather-dependent processes. Lessons that were learned in the case of phosphate apply to other substances that might not be competely removed from wastewater discharge and have potentially complex interactions with biogeochemical cycles.

Since 1980, most of the major municipal wastewater treatment plants in South Bay have discharged into deep waters adjacent to North San Francisco Bay (North Bay), where the effluents are rapidly diluted and removed from South Bay by mixing processes (fig. 1). However, the San Jose-Santa Clara, Palo Alto, and Sunnyvale treatment plants discharge into the small, shallow basin below Dumbarton Bridge (lower South Bay), where dilution by bay waters is limited and tidally-driven circulation and mixing processes provide relatively slow seaward transport of waste-derived substances during most of the year (Walters and others, 1985). Discharges to lower South Bay from these three plants account for most of the total wastewater discharge to the landward reach (fig. 1). Because of the locations of these discharges and their magnitudes, longitudinal gradients of waste-derived substances are established in the landward reach during much of the year, with lowest concentrations near San Mateo Bridge and highest concentrations below Dumbarton Bridge.

The reduction in phosphate loading was most apparent in the final effluent data from the San Jose-Santa Clara treatment plant (fig. 2). Although mean annual loading varied over a wide range during the 1980's, decreases in the loading and the concentration of phosphate were substantial in 1992-1993. This coincided with improvements in the treatment process to control algal growth that also removed phosphate from the effluent. Phosphate loading for 1993-1997 was reduced to 49 percent of the mean value for 1990-1992 and 37 percent of the mean value for 1980-1989. Small reductions in phosphate loading by the Palo Alto and Sunnyvale treatment plants to 71 percent and 86 percent of their 1990-1992 values, respectively, also occurred over 1992-1993, but specific causes for these reductions were not identified. The combined reductions from these three plants decreased phosphate loading to lower South Bay to 58 percent of the mean value for 1990-1992.

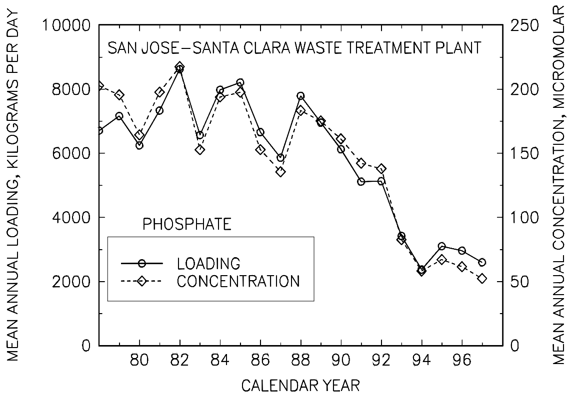

Figure 2. Mean annual loading and concentrations of phosphate in final effluent from the San Jose-Santa Clara waste treatment plant.

Although the reduction in phosphate loading was significant, the supply from wastewater remained greater than removal rates by phytoplankton and estimates of inputs from bottom sediments. Phosphate is not the limiting nutrient for plant growth in South Bay, and phytoplankton blooms typically remove only a small fraction of the water-column phosphate (Hager and Schemel, 1996). Estimated supply rates of phosphate from bottom sediments over the landward reach are equivalent to 8-34 percent of the wastewater supply to lower South Bay, with typical values most likely in the low range (Hammond and others, 1985).

Water-column concentrations of phosphate can be strongly influenced by seasonal inflows of fresh and brackish waters from local streams and North Bay, primarily because they dilute bay waters, thereby reducing concentrations of phosphate (Hager and Schemel, 1996). In addition, strong winds primarily associated with major storms during winter and spring move and mix waters in South Bay, which can rapidly change longitudinal gradients of waste-derived substances (Schemel and Hager, 1996). It is possible, however, to identify periods when freshwater inflows affect water-column concentrations of phosphate because salinity also is reduced in the bay. Dilution by local streamflow to the landward reach is usually limited to late fall through spring, but effects of inflows from North Bay can persist into summer (Schemel, 1998).

MEASUREMENTS IN SOUTH BAY

Interannual and seasonal variations in salinity and phosphate concentrations in South Bay waters between the San Mateo and Dumbarton bridges showed the influence of fresh and brackish water inflows (fig. 3) over the 1990's. Differences among the years primarily were related to the timing, duration, and magnitude of the inflows (Schemel, 1998).

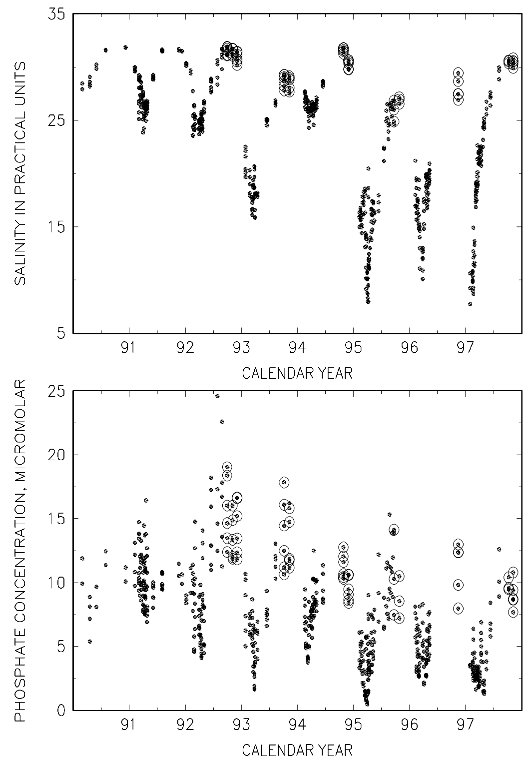

Figure 3. Salinity and phosphate concentrations in South Bay between the San Mateo Bridge and the Dumbarton Bridge. Circled points are measurements from early fall. These data are available from: URL http://sfbay.wr.usgs.gov/access/wqdata/index.htm

Salinity remained high and showed little seasonal variability during 1990-1992, which were drought years with few winter storms and low precipitation in northern California. In contrast, 1993 and 1995-1997 were years with greater-than-normal precipitation and substantial streamflow to the bay system, which caused large seasonal variations in salinity and phosphate concentrations in South Bay. Overall, the dilution of phosphate concentrations and salinity was much greater over the years since the reduction in phosphate loading. Consequently, effects of the reduction in phosphate loading could not be identified in South Bay simply by comparing water-column concentrations among the years.

During early fall of most years, effects of freshwater inflow and storm-related circulation and mixing during the previous winter and spring are at a minimum in South Bay. In general, highest annual values for salinity and concentrations of phosphate were observed during early fall (fig. 3). However, in some years since 1992 salinity during early fall showed residual effects of the previous storm season. Consequently, the apparent decrease in phosphate concentrations during early fall from 1992 to 1997 might have resulted from differences in hydrologic conditions among the years, reduced phosphate loading, or both.

Inflows from local streams are very low and wastewater is usually the major source of freshwater to the landward reach during early fall. Consequently, wastewater discharged into lower South Bay creates a longitudinal gradient in salinity when it mixes with the saline waters of the landward reach. This is analogous to the longitudinal gradient in phosphate caused by the wastewater discharge that was described earlier. Therefore, phosphate concentrations increase as salinity decreases in the direction of Dumbarton Bridge from the San Mateo Bridge (landward). Although mean salinity varied among the years, longitudinal gradients for measurements made during early falls of 1992-1996 showed consistent (inversely proportional) relations between salinity and phosphate concentrations, that in most cases were nearly linear (fig. 4).

The linearity of the relations indicated that the chemical gradients during early fall might be approximated by a simple, two-member mixing model (Liss, 1976). With this model, a linear function describing the relation between salinity and phosphate concentrations can be used to estimate the phosphate concentration of the wastewater mixing member. The zero-salinity intercepts for linear regressions of phosphate concentration as a function of salinity for 1991-1997 provided estimates which were compared to monthly average concentrations of phosphate in

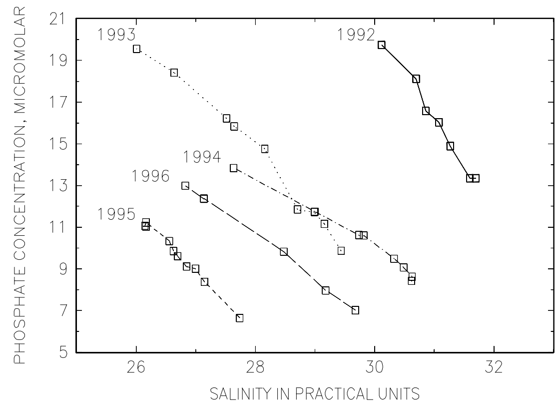

Figure 4. Phosphate-salinity gradients in the landward reach of South Bay from early fall 1992-1996.

the combined wastewater discharge to lower South Bay (fig. 5). Although few field measurements were available the years before the reduction in phosphate loading, the decrease in the wastewater mixing members estimated from the longitudinal distributions was consistent with the decrease in phosphate concentration in the effluent from the three plants both in timing and magnitude.

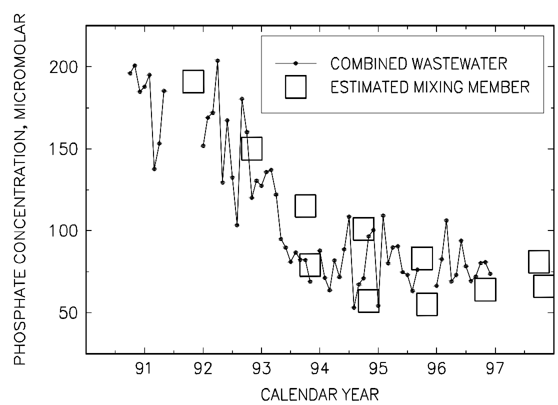

Figure 5. Estimated wastewater mixing-member concentrations during early fall and concentrations of phosphate in the combined wastewater discharge to lower South Bay.

As an additional comparison to recent values, wastewater mixing members were estimated from salinity and phosphate concentrations measured monthly in the landward reach during fall of 1980, a year with normal levels of rainfall and streamflow (Ota and others, 1989). The three estimates for the wastewater mixing member ranged from 161 to 200 micromolar, which is about twice the range measured during 1994-1998. This is consistent with the reduction in phosphate concentration shown by the San Jose-Santa Clara plant since 1980 (fig. 2).

DISCUSSION

Identification of effects of the reduction in phosphate loading in the water column was complicated primarily by large variations in interannual and seasonal climate- and weather-related factors. In addition to dilution by fresh and brackish water, storms and river inflows modulate density- and wind-driven processes that circulate and mix waters in South Bay (Walters and others, 1985; Schemel and Hager, 1996). It was apparent that salinity and phosphate concentrations in the landward reach often reflected current hydrologic conditions and showed residual effects from the previous storm season. Consequently, a response to the reduced loading could not be verified using water-column concentrations alone. Effects of seasonal processes that strongly influence salinity and phosphate concentrations in the landward reach were significantly reduced during early fall, which, in part, made possible the analysis of the longitudinal gradients with a simple mixing model.

An additional factor that made it difficult to detect changes in the water column was that loading and effluent concentrations were reduced to only about one-half of the previous value. Changes in the water column of South Bay were more easily recognized when a major improvement in treatment at the San Jose-Santa Clara plant in 1979 removed nearly all of the ammonium from its effluent (Hager and Schemel, 1996). Prior to this, ammonium had been the most concentrated nitrogen species in the effluent, and its concentration was reduced by more than an order of magnitude. After this large reduction, concentrations of ammonium were substantially lower in the water-column within a few months.

In some ways, the observed reduction in phosphate might be similar to what can be expected for many pollutants in municipal wastewaters that have been regulated in recent years. Concentrations and loadings of pollutants that are potentially harmful to San Francisco Bay, such as trace metals and toxic organic compounds, are typically much lower than for phosphate, but it is unlikely that they can be entirely removed from wastewater discharges (Davis and others, 1991). Consequently, it might be difficult to detect reductions of these more dilute pollutants in the water column, particularly if influences of bottom sediments and biogeochemical cycles are greater than for phosphate.

Although recent improvements in wastewater treatment have reduced the loading of many toxic pollutants to San Francisco Bay, there is concern that water-column concentrations might not be significantly reduced for many years because of sources within the bay that have become increasingly important. For example, pollutants have accumulated in the sediments of South Bay for many decades, and release to the water column through biogeochemical cycles appears to be an important influence on water-column concentrations of some trace metals and perhaps other substances (Flegal and others, 1996). Identification of the processes that control water-column concentrations for these substances is a great challenge. Results of our study indicate that evaluations of climate- and weather-related factors on interannual, seasonal, and perhaps shorter time scales are needed to identify appropriate hydrologic conditions and to select data sets that can be compared.

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