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PROCESSES CONTROLLING THE DISSOLVED SILICA DISTRIBUTION IN SAN FRANCISCO BAY

by

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ABSTRACT

Dissolved silica (DS) is supplied to San Francisco Bay primarily by river inflow and, to a lesser extent, by ocean water. Its distribution in the bay differs from that of other micronutrients (e.g., phosphate, nitrate, and ammonia) because man's input to the estuary and recycling by dissolution of siliceous phytoplankton within the estuary appear to be relatively minor sources of DS.

Major variations in the DS distribution are seasonal and are related to the variations in rates of river supply and silica utilization by phytoplankton. When the rate at which river inflow supplies silica to the bay is large compared with the rate of which silica is used within the estuary, the decrease in DS as salinity increases is controlled primarily by mixing of river and ocean waters. When the DS utilization rate increases significantly relative to the supply rate, the DS concentration in the estuary is considerably less than that predicted by simple

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mixing, and is often lower in concentration than **DS** in the near-surface ocean water.

The influence of phytoplankton on DS concentrations in the bay appears to depend on how long the water remains in the estuary. Because river discharge is the fundamental parameter of estuarine circulation as well as the major source of **high** DS concentrations, river discharge modulates both seasonal variations in the estuarine water replacement time and the DS supply. Thus, when river discharge is **high,** even rapid **DS** utilization do not have a significant influence on the **DS** distribution.

INTRODUCTION

Nitrogen and phosphorus distributions in the open ocean have been the object of considerable interest and study since the inception of rapid colorimetric chemical analyses (e.g., *55).* These micronutrient-element studies provide **a** framework for describing and understanding ocean circulation and plankton ecology. In the study of estuarine processes, however, their usefulness **has** not yet been completely exploited because the complex sources and sinks of nitrogen and phosphorus resulting in temporal and spatial distributions are generally difficult to describe.

By contrast, in the San Francisco Bay estuary, dissolved silica (DS) has a relatively simple spatial and temporal distribution. This simple distribution suggests that DS, as a non-conservative property, may provide an excellent reference for comparison with distributions of other less simple, non-conservative properties.

This paper describes major features of the San Francisco Bay estuarine system and demonstrates the relation between the seasonal DS variations and the effects of insolation and river discharge (used as rate terms herein). Particular emphasis is placed on the longitudinal (river to ocean) DS variations which are associated with estuarine circulation.

METHODS

Field and Laboratory Determinations

The San Francisco Bay estuary is defined as the northern reach of the San Francisco Bay system located between Rio Vista and Golden Gate. The southern reach, from Golden Gate to San Jose, has only a small fresh-water source at its southern end.

Water chemistry observations were made within one- to two-day periods at as many as 20 stations in the mid-channel of the estuary between the fresh-water boundary (as far landward as Rio Vista) and the estuary mouth at Golden Gate

(Fig. 1; see McCulloch et al. (46) for station locations). The hydrographic surveys have been repeated on a near-monthly basis from April 1969 to the present.

Most of the analyses were made with a continuous-flow system in which the water was pumped from 2-m depth to the ship through a towable salinity-temperature-depth pumping system (7). On shipboard the water was filtered through a silver membrane filter (0.45 μ pore diameter) and analyzed continuously for dissolved silica, phosphate, nitrate plus nitrite, and ammonia using a Technicon AutoAnalyzer®[1] calibrated at 4-hour intervals. Simultaneous

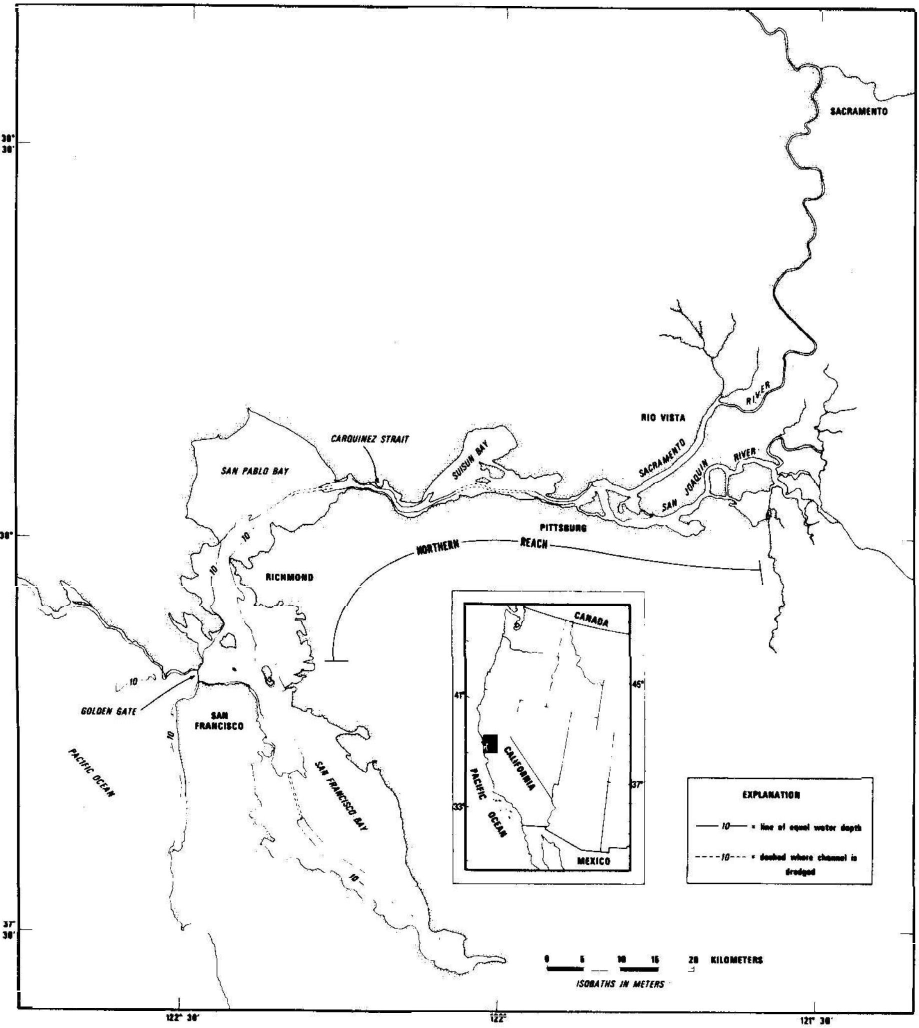

Figure 1. The San Francisco Bay system and environs. The northern reach is the part of the system between Rio Vista and Golden Gate, the entrance to the ocean.

continous determinations of pH, dissolved oxygen, turbidity, and **in** *viuo* chlorophyll a were made. Because the DS analyses were made immediately following collection, special freezing and thawing procedures (13, **37)** were not necessary. The accuracy of our silicomolybdate method *(2)* is estimated to be within ± *2* µ g-atoms SiO_2-Si/liter. Discrete water samples were drawn for studies of phytoplankton cell counts and productivity; the procedures used were similar to those of Strickland (67), Vollenweider (70), and Schindler and Holmgren (57).

Additional Data **Sources**

To extend our data through a longer time base, we used **DS,** phytoplankton, and suspended particulate matter (SPM) data from the investigations of McCarty et al. (45); Storrs et al. ***(65,* 66);** Bain and McCarty (4). Data sources for various parameters are indicated in figure captions. River discharge data from U. S. Geological Survey are published annually in Surface Water Records, California; data used from U. S. Bureau of Reclamation sources are unpublished; insolation data were furnished by the Bay Area Air Pollution Control Board, **San** Francisco, California.

Mathematical Modelling

Because the major **DS** variations can be represented in one dimension, we have modeled the effects of DS advection, diffusion, and biological utilization with an equation for one-dimensional distribution of variables (68 and Doherty, written communication, 21, *22).* In this model, diffusion coefficients were estimated from the salinity distribution during a known river discharge (advection) and the DS utilization rates were assumed.

SAN **FRANCISCO** BAY **ESTUARY**

Sacramento-San Joaquin **River** System

The Sacramento-San Joaquin river system is the dominant feature controlling the major seasonal hydrologic processes in the San Francisco Bay estuary. This river system, which supplies more than 90 percent of the fresh-water discharge to the San Francisco Bay system, is the major source of riverborne dissolved and particulate matter (including DS) and the basic feature controlling nontidal water circulation in the estuary. River discharge influences both the supply rates of substances to the estuary and the removal rates of substances from the estuary.

The combined discharge of the Sacramento and **San** Joaquin rivers vanes annually between approximately 100 m^3/sec and 2,000 m^3/sec. The seasonal cycle (Fig. 2-A) is characterized by a high winter discharge (December-April) and a low summer discharge (June-October). Seasonal riverborne suspended particle concentrations vary with the discharge levels (Fig. 2-C).

Salinity Regime

The salinity values in the estuary respond closely to variations in river discharge (Fig. 2-B); the salinities are depressed in the winter and approach ocean values in the summer. During extremely high river discharge, surface-to-bottom salinity differences in the estuary can exceed 10 ‰, but during normal discharge conditions the estuary is partially mixed or well-mixed by strong tidal currents (69).

During winter, salt water intrudes landward to San Pablo Bay and during summer to Rio Vista on the Sacramento River (Fig. 1). In both seasons the estuarine part of the bay system is long relative to its width. Within this system, sea-bed drifter movements have shown that the near-bottom, landward-flowing, density-driven (salinity) current, a typical feature of estuaries, persists throughout the year (16).

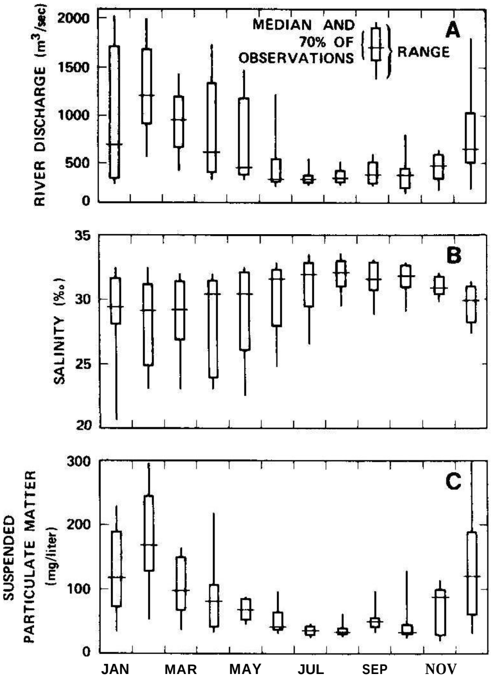

Figure 2. Monthly means 1960-1970. (A) Sacramento River discharge at Sacramento. (B) Surface salinity at Golden Gate. (C) Suspended particulate matter at Sacramento.

Dissolved Silica

Seasonal variations of salinity and DS in the estuary can be illustrated by comparing typical winter and summer longitudinal distributions in the near-surface (2 m) water (Fig. 3). Several features are evident: (a) an inverse relation between salinity and DS concentrations during winter (Fig. 3, **A** and **C);** (b) higher DS concentrations during winter than during summer (Fig. 3, C and D); (c) a rapid decrease in DS concentration with distance in the upper portion of the estuary during summer (Fig. 3-D); and (d) lower DS concentrations during summer within the estuary than at the seaward boundary (Fig. 3-D).

To eliminate the large tidally-caused variations in salinity and DS and to make the above features more apparent, the subsequent discussion relates DS to salinity instead of geographic position (Fig. **4).** Plots of DS as a function of the corresponding salinity define three river-ocean mixing situations within estuaries. **A** linear distribution (Fig. **4-A)** indicates that horizontal mixing rates between river and ocean water dominate non-conservative processes. When DS utilization rates become significant, DS concentrations are less than those produced by a simple mixing process (Fig. **4-C).** In both these instances the concentrations in the estuary are higher than at the ocean boundary, but in the latter instance the estuary is both a sink for river-supplied DS and a DS source to the ocean. When utilization rates are pronounced, the estuary is a sink for both river- and

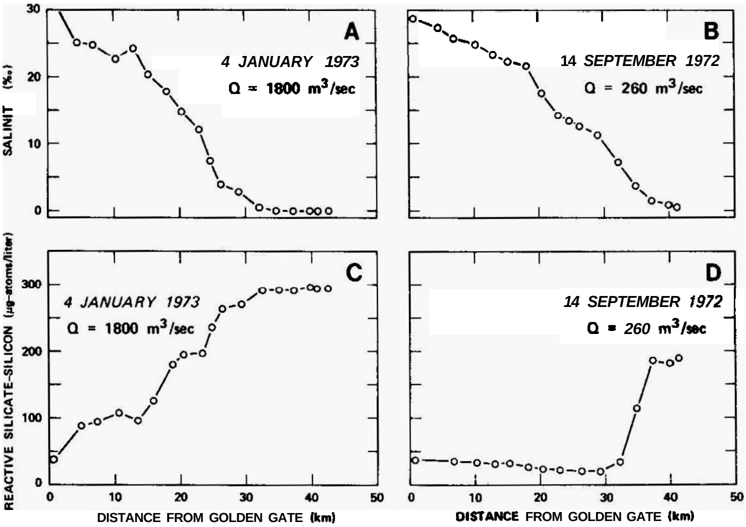

Figure 3. Longitudinal distribution of salinity and silicate-silicon at 2-m depth during typical winter and summer conditions in the northern reach of San Francisco Bay. Q indicates combined mean monthly discharge from the Sacramento and San Joaquin rivers.

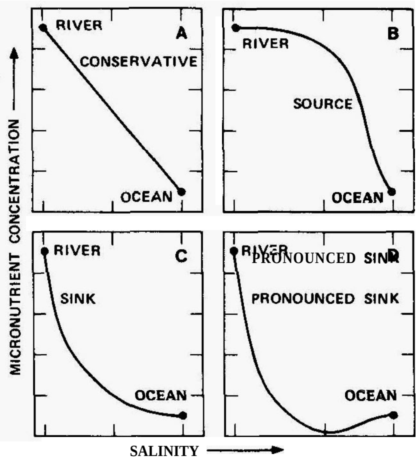

Figure 4. Idealized longitudinal micronutrient-salinity relations showing and mixing of nutrient-rich river water with nutrient-poor sea water in the estuary.

ocean-supplied DS (Fig. 4-D). These three examples typify seasonal DS behavior in the bay (Fig. 3). **A** clear example of a DS distribution corresponding to that shown in Figure 4-B has not been observed in the bay or, to our knowledge, in any other estuary.

Two major temporal features and one major spatial feature can be identified in these DS distributions. The first temporal feature (during 1973) is illustrated by an annually recurring winter and summer variation in the distribution of DS relative to salinity (Fig. 5): the near-linear DS-salinity distribution during winter becomes progressively non-linear towards late summer. The decrease in DS concentrations in the estuary during summer is similar to the decrease observed in coastal waters (3, 18). The second temporal feature is illustrated by comparing a summer of high discharge, 1971, with a summer of lower discharge, 1972 (Fig. 6): the summer level of DS in the estuary in 1971 is demonstrably higher than that in 1972 (Fig. 7).

The two seasonal features above indicate basic processes that are not unique to estuaries. Perhaps more appropriate to the investigation of estuaries, but also more difficult to explain, is the pronounced departure in linearity of the DS-salinity correlations in the inner (landward) part of the estuary (Fig. 7). We believe that in partially-mixed estuaries this non-linear distribution is controlled largely by the hydrodynamics of estuarine circulation, which controls water column residence time, and in turn the turbidity and phytoplankton maxima. For this reason, we will discuss longitudinal variations before seasonal variations.

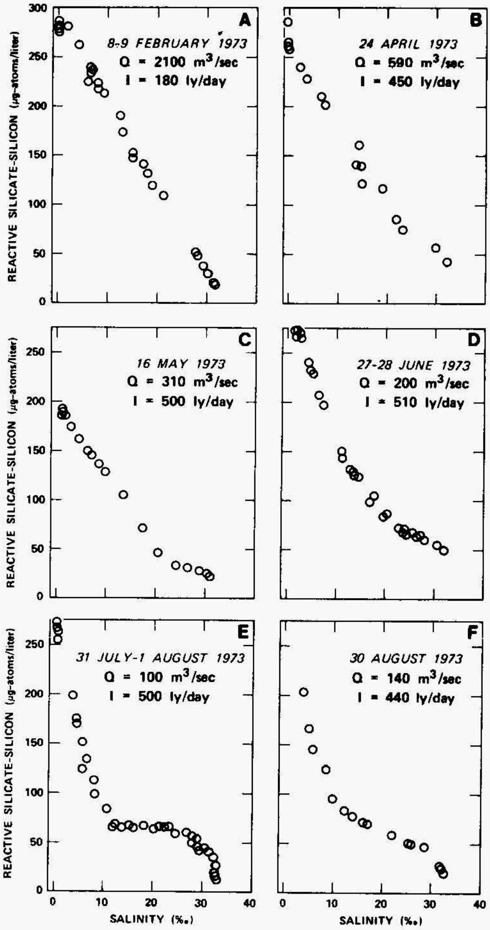

Figure 5. Silicate-salinity relations at 2-m depth in the northern reach of San Francisco Bay, 1973. Q indicates combined mean monthly discharges from the Sacramento and San Joaquin rivers, and I indicates mean monthly insolation at Richmond.

PRIMARY FACTORS AFFECTING DISSOLVED SILICA DISTRIBUTIONS

Longitudinal Variations

In the inner part of the estuary the depression of DS concentrations persists throughout the summer and cannot be explained by the patchy short-term events that are typically associated with phytoplankton blooms. The depression

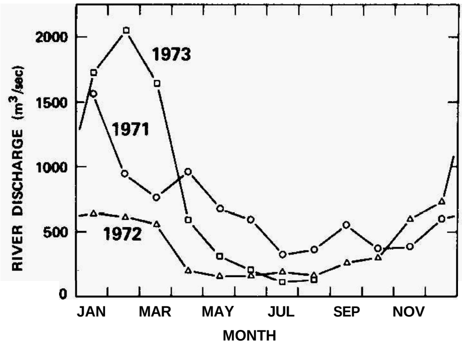

Figure 6. Combined mean monthly discharges from the Sacramento and San Joaquin rivers, 1971-1973.

appears to be best explained by the constant and ordered characteristics of estuarine circulation.

Estuarine circulation and null zone

When measurements of currents in estuaries are averaged over one or more tidal cycles, a nontidal mean flow is commonly observed. This flow may consist of river-, density-, and wind-induced components. The density component, a basic feature of estuaries, is caused by the density difference between river and sea water. It produces a constant net landward bottom flow of dense sea water in opposition to the net seaward flow of less dense river water (Fig, 8, **A** and B) (30). The presence of this landward-flowing current distinguishes an estuary from a tidal river system, in which tidal variations are imposed only on the river-flow regime. The landward-flow regime in an estuary contains a vertical advective component (not indicated in Figure **8-A),** which is also absent from tidal river systems. The geographic area where the landward-flowing density current and the seaward-flowing river current have equal and opposite effect on the nontidal flow is termed the null *zone* (29).

Turbidity maximum

Although the inflow and outflow of water are nearly equal in an estuarine system, the inflow and outflow of suspended particulate matter (SPM) are typically not equal. Riverborne SPM does not necessarily escape to the sea but may settle by gravity from the seaward-flowing surface layer to the landward-flowing bottom layer. This inward advective transport supplies SPM to the null zone and often maintains a higher concentration of SPM there (turbidity maximum) than in either the river or the lower estuary (33, 47, 52, 59, 62).

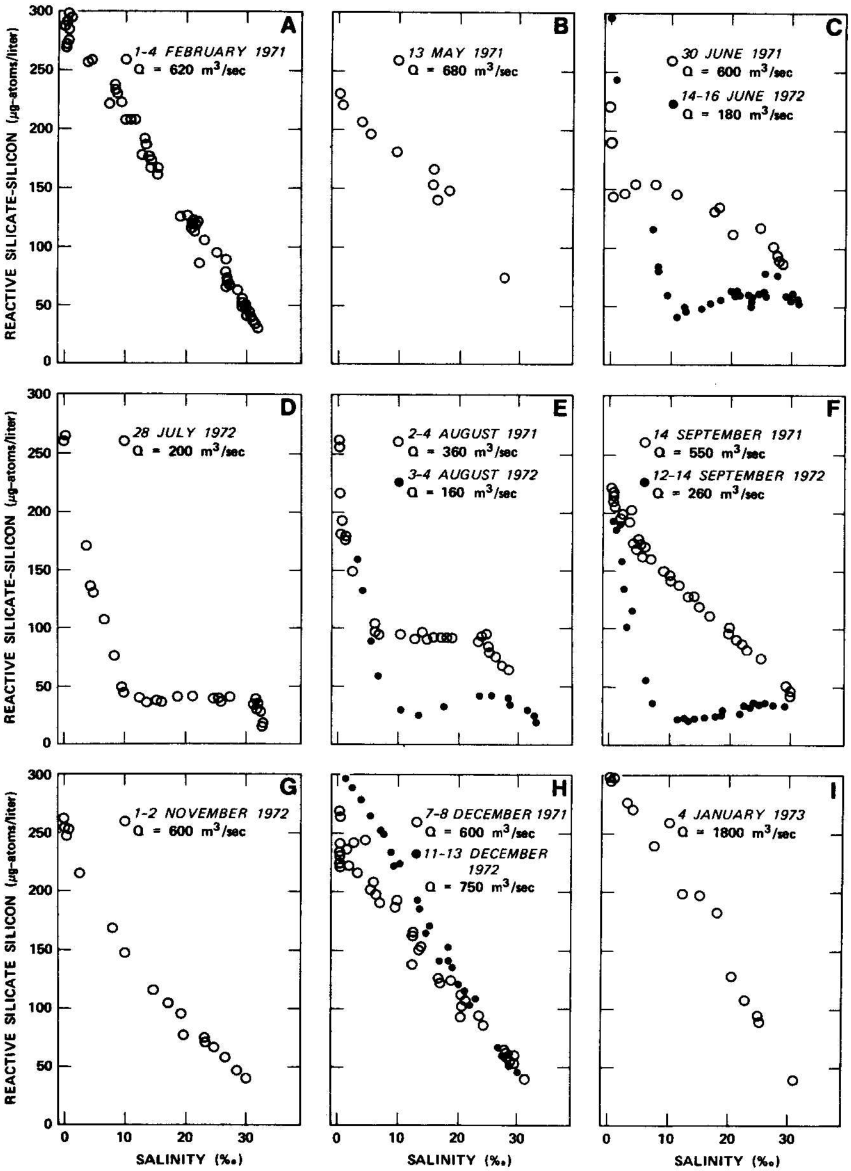

Figure 7. Silicate-salinity relations at 2-m depth in the northern reach of San Francisco Bay as functions of river discharge. Q indicates combined mean monthly discharges from the Sacramento and San Joaquin rivers.

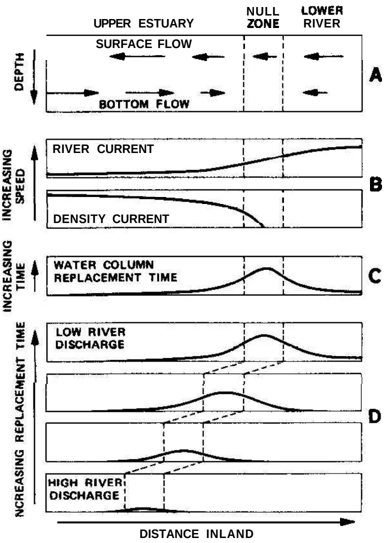

Figure 8. Schematic representation of (A) net drift in vertical section through a river-estuarine system, in which the length of the arrows indicates relative current strength; (B) longitudinal variation in average river and density currents within the river, null zone, and estuary; (C) generalized longitudinal variation in average advective water-column replacement time; and (D) seaward movement of null zone and diminishing water column replacement time with increasing river discharge.

Near-monthly SPM samples taken at I-meter depth in the main channel of the San Francisco Bay estuary show that concentrations are generally highest in winter, apparently in response to the higher concentrations found in the river during that period (Fig. 9, A and B). Also, SPM concentrations are higher in the null zone (Fig. 9-C) than in either the upper or the lower part of the estuary (Fig. 9-A). This existence of a null-zone-associated turbidity maximum in San Francisco Bay demonstrates the typical response of the longitudinal distribution of SPM to estuarine circulation (47). Furthermore, a living photosynthetic fraction of this SPM, the phytoplankton, is also influenced by this circulation.

Phytoplankton maximum

The summer composition of the turbidity maximum suggests that estuarine circulation controls SPM distribution including phytoplankton: the phytoplankton cell concentrations illustrate the same relation with salinity as do the SPM concentrations (51). This pattern of phytoplankton concentration has been observed in several surveys; 1961-1963 (45, 65, 66), 1964 (4), and our

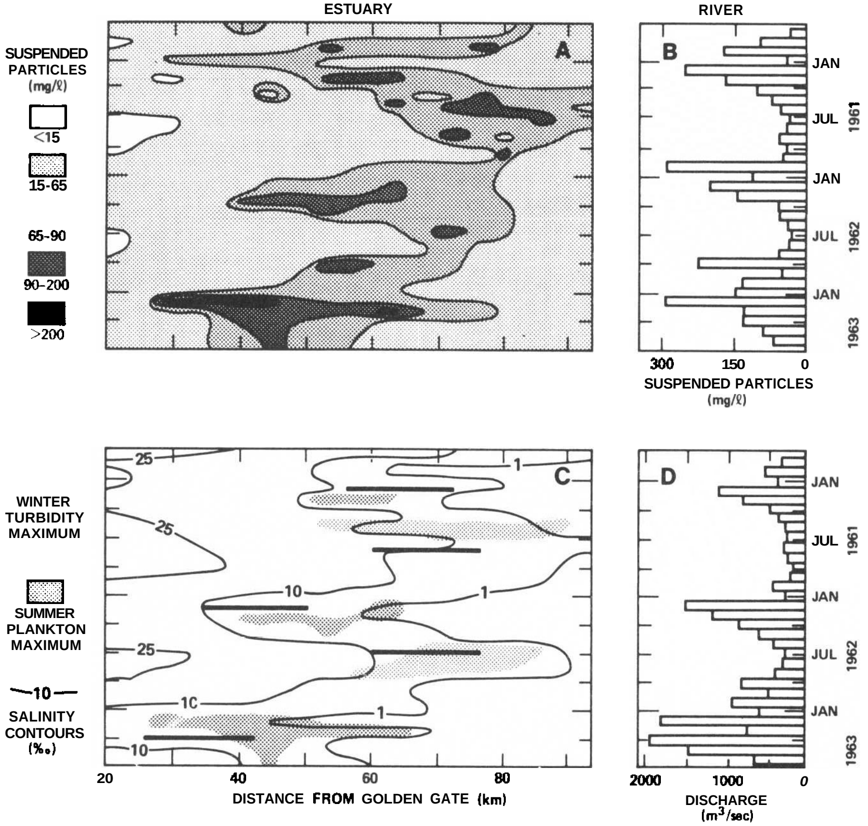

Figure 9. Seasonal distribution of properties in the northern reach of San Francisco Bay, 1961-1963: **(A)** Suspended particle concentration in the estuary; (B) suspended particle concentration in Sacramento River; (C) salinity at 1-m depth in the estuary, compared with location of suspended particle (turbidity) maxima and approximate location of nontidal current null zone (solid black lines); (D) combined discharge from the Sacramento and San Joaquin rivers. Suspended particle and salinity data in estuary from Storrs et al. (65, 66).

studies from 1971 to 1973. In addition, the location of both phytoplankton and SPM maxima correspond with the winter and summer estuarine null zone locations (Fig. 9-C), and, during summer, phytoplankton often comprises a significant weight fraction of the turbidity maximum (17).

Thus, as river discharge and riverborne SPM concentrations decrease during the summer (Fig. 9, B and D), a null-zone-associated phytoplankton maximum appears. This maximum coincides with the null-zone-associated turbidity maximum that typifies partially mixed and well-mixed estuaries.

Residence time and phytoplankton growth

In addition to the advective processes described above, the **SPM** concentrations within estuaries may be increased by ***in situ*** phytoplankton production ***(19,26,*** 71). Significant ***in situ*** production necessitates a minimum period during which the water containing phytoplankton must remain in the estuary ***(6,* 34, *56).*** For this reason a longitudinal variation in abundance of continuously reproducing phytoplankton may reflect the longitudinal variation of water-column residence time as well as of estuarine circulation. To explore the dependence of phytoplankton production on water movements, we have qualitatively evaluated, by inference, the longitudinal variation in water-residence time.

Water replacement, residence, or flushing time of estuaries is generally defined as the average time required for an entering parcel of water to pass through the estuary. The length of this period is controlled by river discharge, density currents, tidal mixing, and wind-induced currents (9). Residence time or water-column replacement time as used in this paper differs from the foregoing. It describes the variation in average longitudinal advective water flow regardless of the flow direction. As such, it can be expressed as the average time required for the water to flow through a unit length of the estuarine system, or

$$\left[\frac{1}{A} \int_{z}^{0} w\,|v|\,dz \right]^{-1},$$

where A is the cross-channel area, w is the depth-variable width of the channel, $|v|$ is the absolute landward or seaward current speed, and z is water depth.

In most estuaries, the river discharge per unit cross-channel area (river current) decreases in a seaward direction owing to the seaward increasing cross-channel area, and the density current must decrease to zero in the landward direction. From purely advective considerations, this circulation pattern and geometry cause the maximum water-column-replacement time to be found within the null zone when the density currents are stronger than the river currents. A typical contribution of river and density currents to average advective replacement time of the water column is illustrated for the river, null zone, and estuary (Fig. **8-C).** In this representation wind effects are assumed to be contributing primarily to turbulent processes, cross-channel variations in current speeds have been averaged, and cross-channel areas are considered to be decreasing in the landward direction. As the river current increases in strength relative to the density current, the replacement time of the water column decreases and the maximum is reduced and shifted in a seaward direction (Fig. **8-D;** 51) At very high river discharges the river component may dominate estuarine circulation throughout the entire estuary. A similar pattern has been described for the Escaut estuary **(73).**

Although this model provides only a simplified description of estuarine circulation in San Francisco Bay, it reflects the flow rates measured by current meters (51) and surface and sea-bed drifters (16). These measurements indicate that estuarine circulation is relatively strong compared with the summer river-discharge component. Strong estuarine circulation is typical of low-flow conditions in many partially- and well-mixed estuaries (9, 10, 54). The advective residence time reaches a miximum in the null zone during low-flow period because both the volume transport and speed of estuarine currents are large relative to river discharge per unit cross-channel area.

A plankton community will be afforded a longer period for growth in the null zone of the estuary than in waters landward or seaward of the null zone. Thus, both landward advective transport to the null zone and longer advective residence time within the null zone are suggested as favorable hydrodynamic conditions for development of the large seasonal phytoplankton community in the upper reaches of the San Francisco Bay estuary. Because the major fraction, both by cell number and biomass, of the phytoplankton community generally consists of diatoms, it follows that highest rates of DS utilization per unit volume occur and are maintained in the upper reaches. These high utilization rates are reflected in the marked departure of DS concentrations from the near-linear river and sea-water mixing relation (compare Fig. 7, A and E). These DS departures closely parallel the average increases in phytoplankton productivity (Fig. 10).

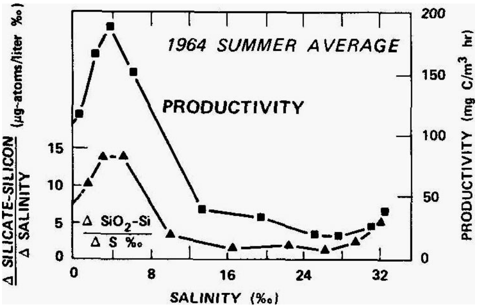

Figure 10. Averaged longitudinal Δ (silicate-silicon) / Δ salinity rate of change and phytoplankton productivity at 1-m depth in summer 1964. Data from Bain and McCarty (4).

Seasonal Variations

Large changes in the DS concentrations in the estuary result from seasonal variations in supply and removal rates. In this section we describe the relation between seasonal DS concentrations and the effects of seasonal variations in insolation and river discharge.

Insolation and primary production

Insolation appears to be the dominant factor limiting phytoplankton productivity in the bay because the nutrient supply seems sufficient throughout most of the year (4). Coincident with increased insolation rates during summer, phytoplankton abundance increases over that during winter (Fig. 11; 4, 5, 45, 65, 66). Our studies indicate that more than 80 percent of these phytoplankton cells are living and that the near-surface productivity of phytoplankton per unit volume of water nearly doubles with a doubling of the cell concentration (Fig. 12). Diatoms comprise a major fraction of the plant cell numbers and biomass; the observed summer depression in DS largely reflects the increase in the size of the phytoplankton population.

Despite the fact that insolation appears to be the dominant factor limiting phytoplankton productivity on a seasonal basis, its control is gross. There is no close correspondence between levels of DS utilization and insolation when considered on shorter time increments during 'the summer months (April-September). For example, during a period of high insolation (Fig. 13-A), the DS distribution for June 1972 (Fig. 14-A) was similar to DS distributions during periods of similar discharge but lower insolation (Figs. 14, B and C and 15-A). This suggests that the difference in insolation rate between June and August 1972 had only a minor influence on the DS distribution. Although the

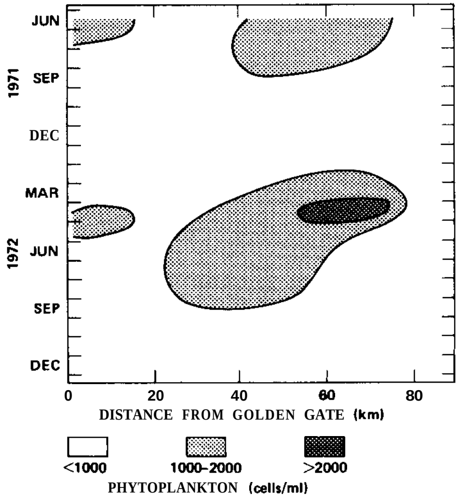

Figure 11. Phytoplankton abundance at 2-m depth in the northern reach of San Francisco Bay, 1971-1972.

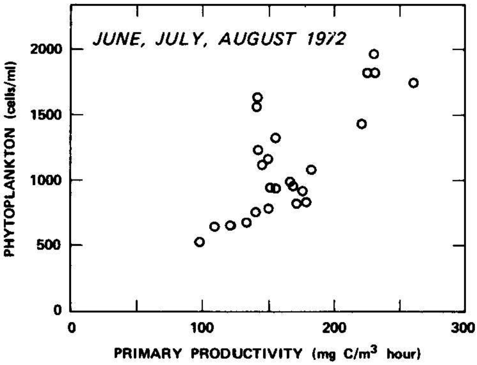

Figure 12. Phytoplankton cell count at 2-m depth as a function of primary productivity in the northern reach of San Francisco Bay, summer 1972.

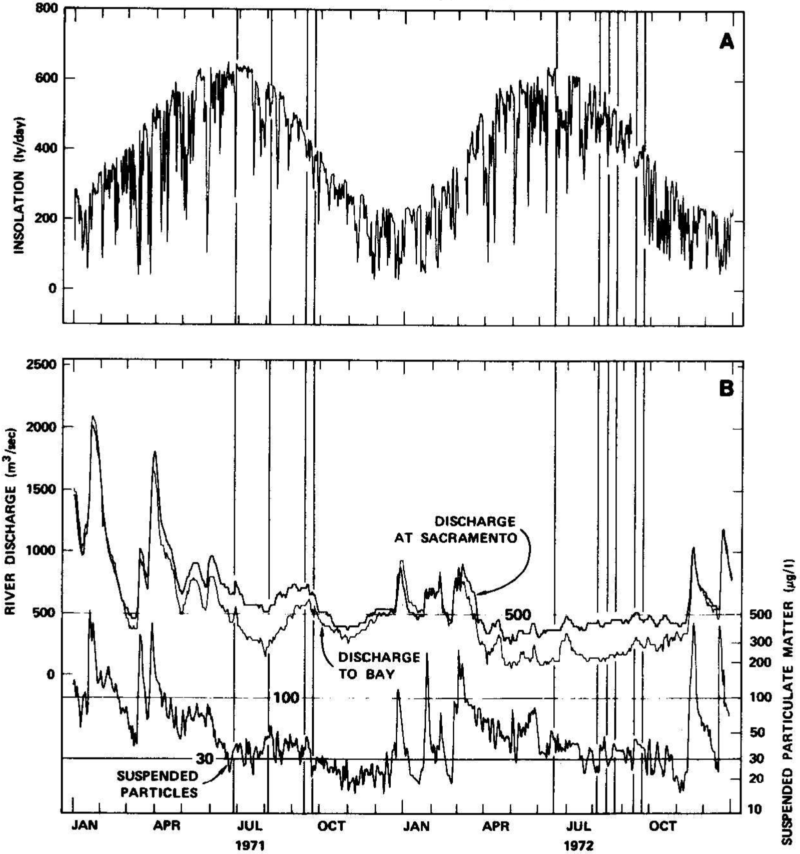

Figure 13. Daily means 1971-1972. (A) Insolation at Richmond; (B) Sacramento River discharge (at Sacramento) compared with combined Sacramento River and San Joaquin River discharges to the bay; suspended particulate matter concentration in Sacramento River at Sacramento. Cruise periods are indicated by vertical lines.

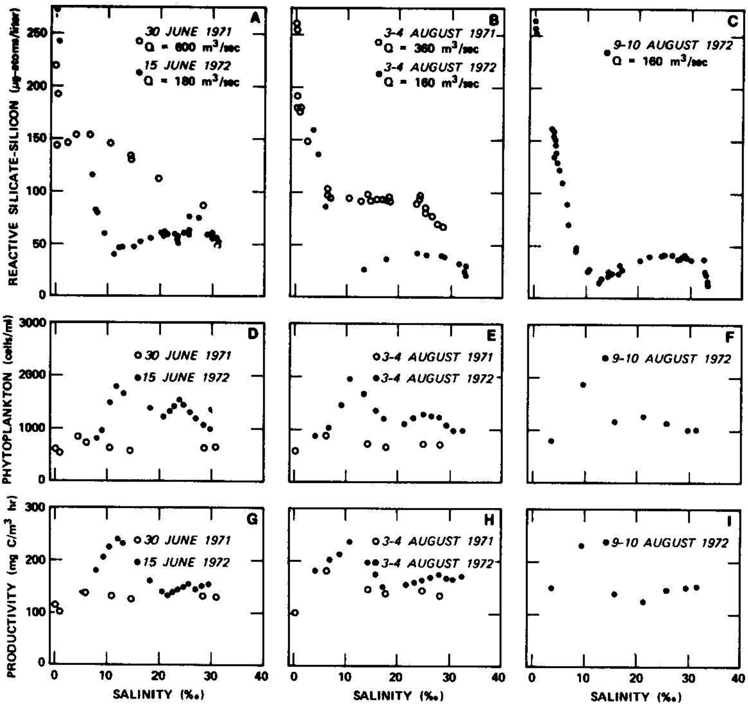

Figure 14. Silicate-, phytoplankton cell count- and productivity-salinity relations at 2-m depth in the northern reach of San Francisco Bay, mid-summer 1971-1972.

discharge was approximately the same in September as in August 1972 (Fig. 13-B), the DS distribution had changed very little (Fig. 15, B and C) despite the lower September insolation rate (Fig. 13-A).

We believe, therefore, that effects of seasonal variations in insolation on DS distributions are less complicated to evaluate than effects of river discharge. The mean monthly insolation rate for a given month of the year may be considered more or less constant from year to year, while the mean monthly river discharge rate is highly variable (Fig. 16).

River discharge and dissolved silica supply

We noted above that insolation is an important factor limiting phytoplankton productivity relative to nutrient availability in the San Francisco Bay system. Because increasing SPM concentrations tend to reduce water-column-light intensity by decreasing water transparency, the potential effects of river discharge variations on turbidity and, hence, on the availability of light in water should be considered (38).

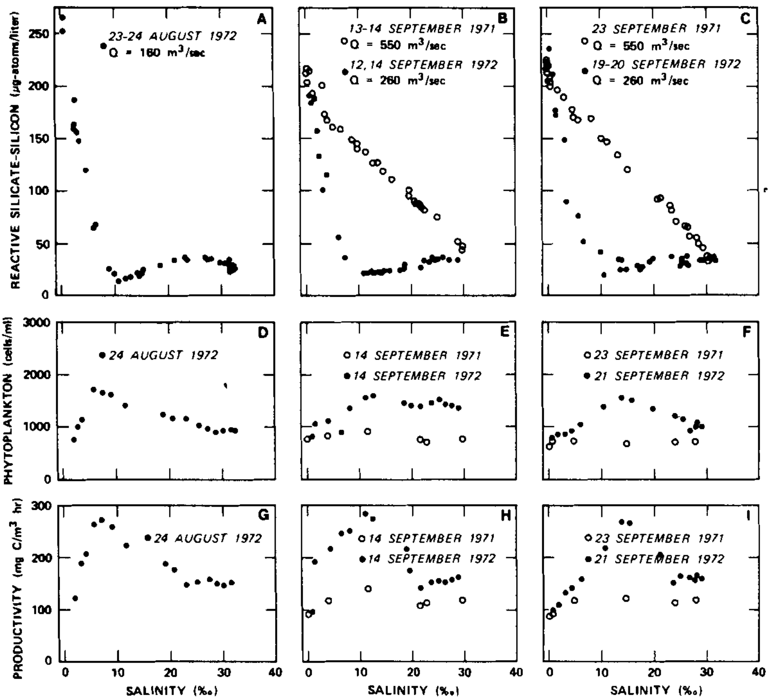

Figure 15. Silicate-, phytoplankton cell count- and productivity-salinity relations at 2-m depth in the northern reach of San Francisco Bay, late summer 1971 and 1972.

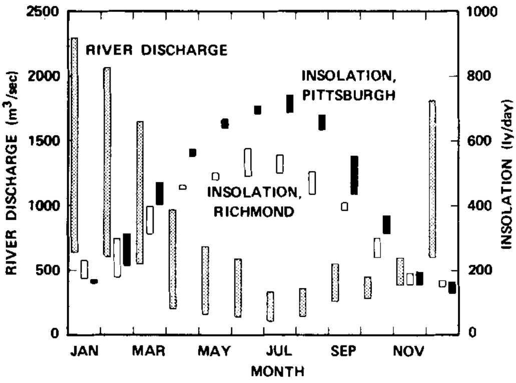

Figure 16. Range of combined mean monthly discharges from the Sacramento and San Joaquin rivers and mean monthly insolation at Richmond and Pittsburg, January 1970-August 1973.

As river discharge increases, both river-current speed and riverborne SPM concentrations generally increase. High SPM concentrations are evident immediately following the first storm-flow conditions if the storms are separated by at least a month (Fig. 13-B). The mean monthly SPM concentrations during three relatively high-discharge summer periods, 1967, 1969, and 1971, were higher than during three low-discharge summer periods, 1964, 1966, and 1968, in the Sacramento River (Fig. 17). However, SPM concentrations during the low flow of late summer were unexpectedly higher than those of high-flow September concentrations (Fig. 17). We suspect that the differences in the effects that riverborne SPM have on the availability of light in the estuary are significant seasonally only when large changes in discharge occur (e.g., in the early summer April 1971 vs. April 1972; Fig. 13). In the general case, turbidity in the estuary must be controlled by a number of factors in addition to river discharge; the effects of a difference in summer discharge on water transparency appear as only a secondary factor in controlling DS distributions.

The influence of the river discharge rate on the DS supply rate and on estuarine water residence time is much more obvious than is its impact on the DS utilization rate. It is relatively simple to estimate the increase in DS supply with increasing discharge, and the decrease in advective water residence time with increasing river discharge is also conceptually simple. Using the estimated river current (river discharge per unit cross-channel area) as a useful approximation of the strength of the river component in the estuary, we have compared the highest (1971) and lowest (1961) rates of summer flow during the period from 1960 to 1973 (Fig. 18). It may be assumed that this seasonally varying river current represents the average advective water transport in the estuary landward of the null zone and is the primary source of DS. If river discharge rate is doubled (and the DS concentration held constant) the DS

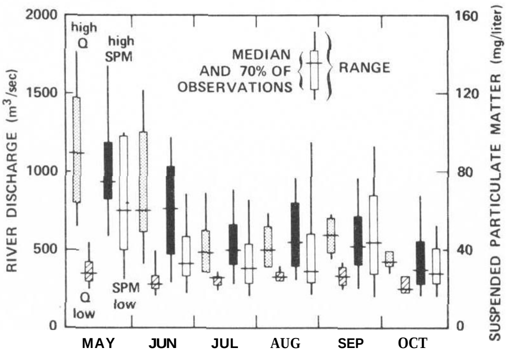

Figure 17. Comparison of daily Sacramento River discharge, Q, and suspended particulate matter concentrations, SPM, during summer months with high discharge (1967, 1969, 1971) and low discharge (1964, 1966, 1968).

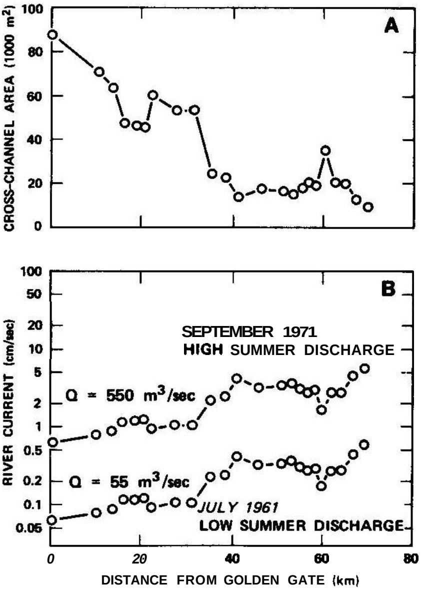

Figure 18. Mean cross-channel area (A) and typical high and low river current speeds during summer (B) in the northern reach of San Francisco Bay. Q indicates combined mean monthly discharges from the Sacramento and San Joaquin rivers. Cross-channel areas from Glenne and Selleck (27).

supply rate is doubled, but the advective residence time is reduced to one-half the initial value. It follows that doubling the discharge rate reduces to one-fourth the time available per unit silica for in *situ* utilization of a DS supply equal to the initial supply. Therefore, river discharge, as a fundamental parameter of estuarine circulation, controls not only the estuarine water-residence time, but also the DS supply rate to the estuary.

Linear and non-linear distributions

The predictable behavior of DS distributions relative to seasonal insolation and river discharge permits us to determine approximately the relative DS supply and removal rates that produce linear or near-linear DS distributions, or that result in apparent phytoplankton growth-limiting DS concentrations. For these estimates we assume that the (a) mean monthly river discharge is a measure of the DS supply rate, (b) month of the year is a measure of the DS utilization rate, and (c) mean monthly insolation for a given month is relatively constant from year to year. The DS distribution that is near-linear for the lowest discharge rate would represent the lowest supply rate for which DS still exhibits conservative behavior (Fig. 19). All DS measurements made during months having a higher

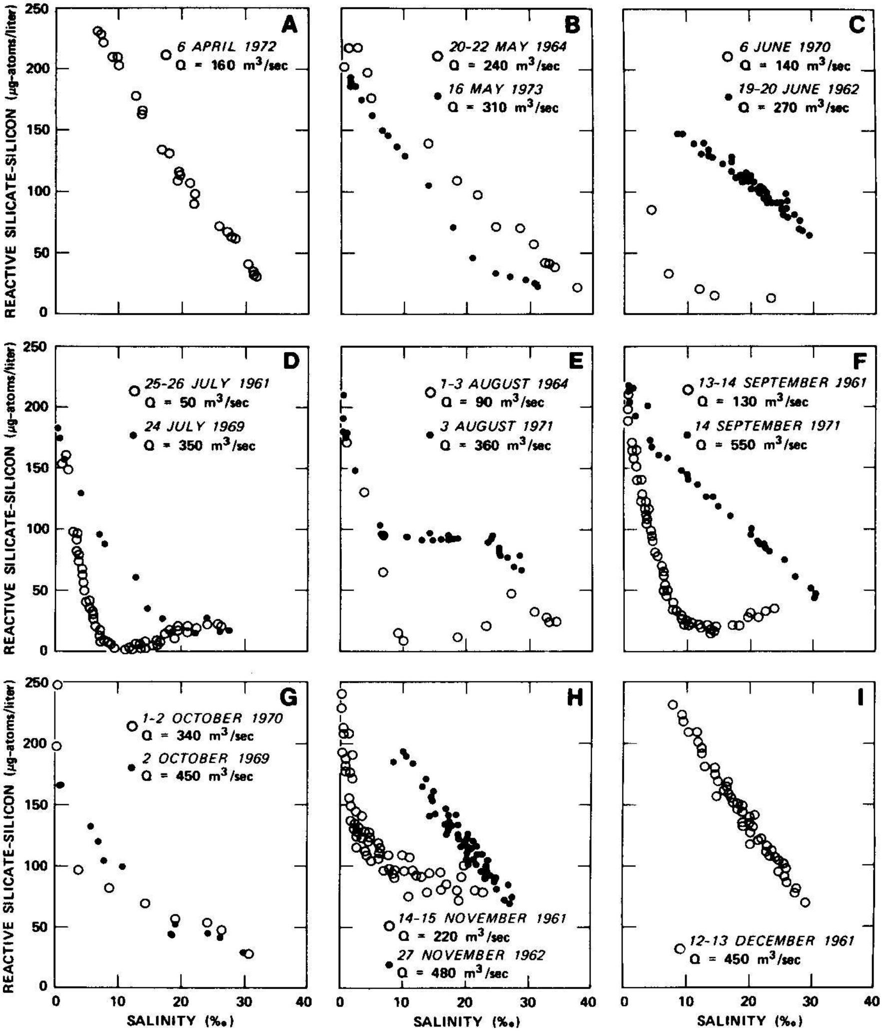

Figure 19. Linear and non-linear silicate-salinity relations at 2-m depth representative of high and low river discharge in the northern reach of San Francisco Bay. Q indicates combined mean monthly discharges from the Sacramento and San Joaquin rivers.

discharge than those given in Figure 19 have described near-linear relations with salinity. Alternatively, with one exception, June 1964, all DS measurements made during the months having the lowest discharge showed DS-salinity distributions that were most non-linear.

DS distributions at particular monthly rates of discharge and insolation are not generally in a steady state. During late summer, the effects of non-conservative processes that occurred during the preceding months may be observed over several months, particularly after a summer of low river discharge. This lag effect during the summer of 1961, which was one of particularly low discharge, may explain the non-linear DS-salinity relation observed in November 1961 (Fig. 19-H). Conversely, the dominance of conservative processes during winter may explain the near-linear relation during April for a low-discharge condition (Fig. 19-A). Persistence of near-linear DS-salinity relations into early summer following near-linear relations between December and April or May is probably a consequence of the difference in timing of the seasonal discharge and insolation cycles. No winter discharge was sufficiently low to allow comparison between the response of DS during low winter insolation and low summer discharge. For lowest discharge levels we have no data to determine how DS-salinity relations vary with insolation. The lowest summer DS concentration occurred during July 1961, the period of maximum insolation as well as minimum discharge (Fig. 19-D).

We have discussed two primary factors that control the seasonal distribution of DS in an estuary. These are (a) the river discharge rate that seasonally modulates both the DS and SPM supplies and the water residence time; and (b) the seasonal variation in insolation that controls phytoplankton DS utilization rates.

Primary factors can be distinguished from such secondary factors as variable DS concentrations in either the river or at the ocean boundary. The importance of one primary factor relative to another is, however, not easily determined. For example, bioligical DS utilization may lower DS concentrations below the levels estimated from conservative mixing, but the particular DS concentration at which this biologically-reduced concentration is maintained may be influenced by varying either the river supply or the phytoplankton **DS** utilization rate.

SECONDARY FACTORS AFFECTING DISSOLVED SILICA DISTRIBUTIONS

DS variations discussed thus far are large-scale temporal and spatial features. There are, however, additional factors that are assumed to be of secondary importance but may relate to some of the minor variations observed in the distribution of DS.

Small-Scale **Variations**

Diurnal variations, which may be large in some estuarine systems, are not notable in San Francisco Bay DS distributions. Data have shown a slight diurnal time dependence, but these effects could explain only the most minor variations in the basic **DS** distribution pattern.

Depth variations in DS utilization rates due to vertical light attenuation have been sought, but have not been observed. The absence of this feature suggests that water-column vertical mixing rates are large relative to the potential effects of the vertical variation in DS utilization rates. How effective mixing is in reducing vertical DS variations can be illustrated. If the average daily DS utilization in the upper meter of a 10-m-deep water column is 10 μM/liter per day and the water column is mixed vertically in less than 24 hours, the average DS utilization in the upper meter would be only 1 μM/liter per day. Such an apparent utilization rate is generally too small to be detected by measuring the DS-salinity relation on two successive days, or by comparing the DS-salinity distribution at the surface with that at the bottom, because random variatiops in DS concentrations are greater than ± 1 μM/liter.

Similar inferences can be made for cross-channel variations. Cross-channel mixing reduces potential differences in the cross-channel DS-salinity distribution. Summer 1964 data (4) indicate that cross-channel variations in phytoplankton cell numbers relative to salinity are nearly similar to the longitudinal variations. These data suggest that carbon uptake rates per unit phytoplankton cell tend to be slightly lower in the shoal areas, but this causes no major differences in the DS-salinity relations.

In summary, only the large-scale longitudinal variations in DS utilization are demonstrable. Vertical and cross-channel variations in DS utilization appear so small relative to vertical and cross-channel mixing that they can be ignored.

Additional Dissolved **Silica** Sources

The paucity of data available from the adjacent ocean (with the exception of CalCOFI stations 60.52 and 60.80; *60*, 61) has prevented elaboration of the potential effects of seasonal variations in DS concentration and exchange rate at the ocean-estuary boundary. Although these boundary effects on the DS distributions are probably small, the total mass transport of ocean-derived DS to San Francisco Bay by the inward-flowing bottom density current may be quite large in comparison to the river supply during low-flow conditions (Table 1).

Wind-induced upwelling (from < 200 m) may produce minor DS variations at the mouth of the estuary during early summer, but at Golden Gate these effects are small in comparison with variations produced by river discharge. During high or low winter discharge conditions or during high summer inflow, DS levels are

TABLE 1

Estimated dissolved silica sources to San Francisco Bay

Source	Winter	Summer
	(metric tons/day)	
River Discharge[1]	2,000	100
Bottom Density Current[2]	400	400
Waste Discharge[3]	30	30

[1] Assumed winter discharge is 1,400 m^3/sec; summer discharge is 80 m^3/sec; and the river DS concentration is 300 µg-atoms/liter.

[2] The average cross-sectional area of the landward flowing current is assumed to be one-half of the total cross-channel area at Golden Gate (area estimated from Glenne and Selleck, 27); the net landward current speed is assumed to be 5 cm/day (Conomos et al., 16) and the average DS concentration is 30 µg-atoms/liter.

[3] Using a waste discharge of 2×10^6 m^3 per day (63) and typical DS concentration of 300 µg-atoms/liter (12).

higher in the seaward-flowing upper layer than in the landward-flowing lower layer. Observations indicate that only after a period of very low summer flow (e.g., September 1972; $Q = 250$ m^3/sec) is San Francisco Bay a net sink for both river- and ocean-supplied DS; during such periods DS concentrations are higher in the inflowing near-bottom (ocean) water than in the outflowing surface (estuary) water.

Estimates of the importance of municipal and industrial sources of DS indicate that sewage effluent is a relatively minor DS source in San Francisco Bay. These effluents supply less than 5 percent of the annual budget (Table 1).

The DS resupply by dissolution of biogenic silica is exceedingly difficult to evaluate because there is no obvious method to obtain reliable estimates of dissolution rates. Studies of DS in the open ocean indicate that silica dissolution of biogenic silica must be considered an important source of DS. Vertical DS gradients in the ocean, which indicate effects of a dissolution process, are developed on a time scale considerably longer than exists in San Francisco Bay (1, 32). An evaluation of silica dissolution in the bay has been attempted with a one-dimensional mathematical model, in which measured values of salinity, river discharge and river and ocean boundary DS concentrations, and assumed values of DS utilization were used to simulate DS concentrations.

The relative effects of eddy diffusivity, K, and river discharge, Q, on the salinity distribution in the model are first illustrated (Fig. 20-A). These distributions can be compared with the similar distributions in Figure 3 by reversing the position of the horizontal (distance) axis. The relative effects of diffusivity, river discharge, and DS utilization, R, are then illustrated (Fig. 20-B) in which both the diffusivity and utilization rates are considered to be constant throughout the estuary. The model is further refined by introducing a variable eddy diffusivity (Fig. 20-C) which represents typical values calculated from the observed salinity. It seems significant that by using a spatially variable utilization rate in the model (Fig. 20-D) a more realistic DS distribution is obtained in the model (Fig. 20-E, distribution VII) than a constant rate (Fig. 20-E, distributions V and VI). This is the case because the observed carbon-production rate is also spatially variable (Fig. 10). With only minor adjustments in the selected DS utilization rates, the resulting DS distribution (Fig. 20E, distribution VII) could duplicate the observed distribution during a river discharge of 50 m^3/sec (Fig. 19-D). In this case, however, such refinement would serve no useful purpose because the values of eddy diffusivity represent a more gross approximation. The fact that distribution VII (Fig. 20-E) is similar to the observed distribution (Fig. 19-D) illustrates that the river DS supply during low summer-flow conditions is an adequate source for support of typical DS utilization rates (20, 31, 48, 49). These results suggest that the DS production rate by silica dissolution is small relative to the DS river supply. It would not be surprising, however, if the biogeneous silica dissolution rates in the estuary proved to be significant, at least during the periods of extremely low DS concentrations.

Biological Factors

Evaluation of temperature and salinity effects on diatom growth rates and related DS utilization rates is beyond the scope of this paper. For two reasons, however, it is clear that seasonal and longitudinal variations in phytoplankton abundance and productivity are not controlled solely by temperature and (or) salinity. First, longitudinal temperature variation in the estuary is influenced by water depth as well as by mixing of river and ocean water; the bay is considerably shallower than the potential depth of vertical mixing. As a result, this longitudinal temperature variation during summer is small in comparison with the observed longitudinal variation in phytoplankton productivity. Second, temperature differences at comparable times of year between 1971 and 1972 were too insignificant to explain the obvious differences in phytoplankton abundance and productivity in 1971 compared with 1972 (e.g., Figs. 14 and 15). These annual differences would also be difficult to explain on the basis of variations in the salinity field.

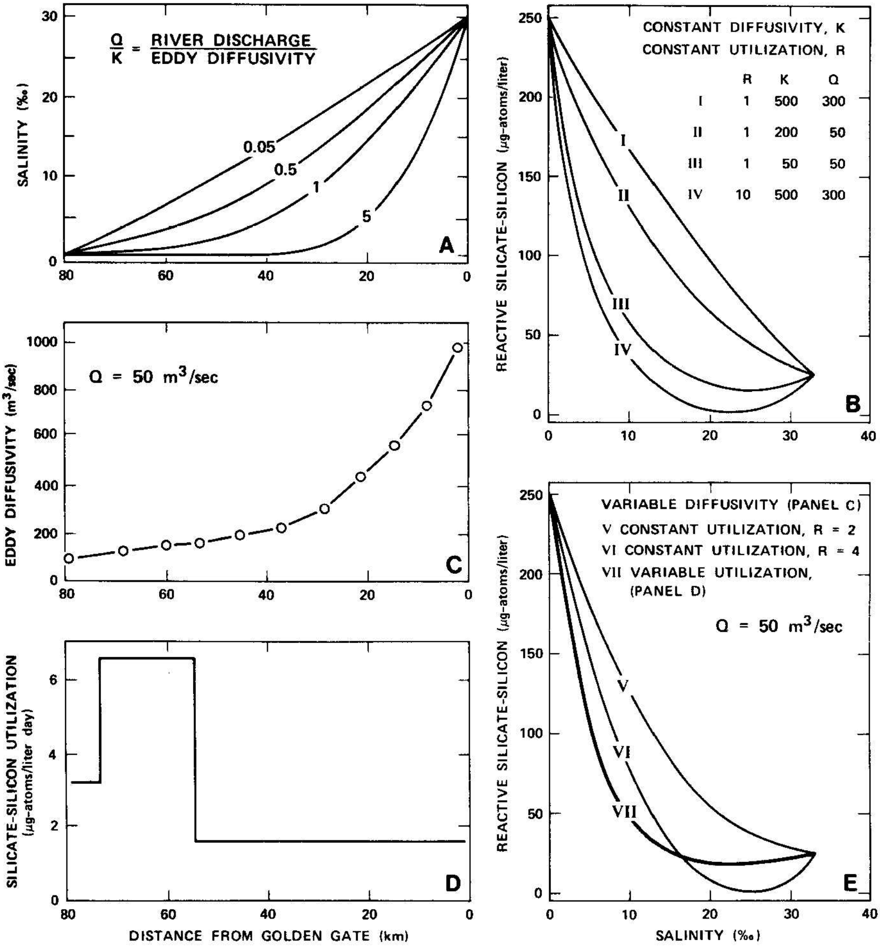

Figure 20. One-dimensional silicate-salinity model in northern reach of San Francisco Bay: (A) Salinity versus distance for various ratios of river discharge, Q, to constant longitudinal eddy diffusivity, K; (B) silicate-salinity relation from the model with constant eddy diffusivity and constant utilization; (C) variation of longitudinal eddy diffusivity from the observed salinity distribution at Q = 50 m^3/sec; (D) parametric representation of variable silicate utilization rate; and (E) silicate-salinity relation from the model with variable diffusivity and silicate utilization rate. R is given in g-atoms Si-SiO_2/liter/day, K in m^2/sec and Q in m^3/sec.

The circulation factors we have discussed emphasize that high DS utilization rates per unit volume exist in the phytoplankton maximum primarily because of an increased phytoplankton abundance per unit volume, rather than because of an increased temperature- or salinity-induced DS utilization rate per unit phytoplankton. The increased turbidity of this maximum further supports our interpretation.

IMPLICATIONS

Ketchum **(34)** emphasized the importance of water-residence time to biological systems in estuaries. Probably the most important feature implied in DS behavior relative to salinity is that physical (conservative) processes in San Francisco Bay have a strong influence on the biological (non-conservative) distributions. River discharge provides a seasonal modulation of residence time in the estuary. Estuarine circulation imposes a spatial variation. Thus the effects of time-dependent biological processes are partly controlled by the physically-controlled variations in water-residence time.

Because the importance of residence time cannot be clearly separated from insolation, we cannot predict what phytoplankton concentrations would develop in the estuary during low winter insolation if the river discharge in winter were as low as in summer. High winter river discharge in addition to the low winter insolation may be an important factor controlling both the near-linear winter DS-salinity relation and the lower winter abundance of plankton in the estuary. Alternatively, if high river discharge prevailed throughout summer, lower phytoplankton concentrations and linear DS distributions might be maintained (i.e., Fig. 9-F). In an extreme case, such as in the Orange River estuary (11), an exceptionally small residence time may result in a paucity of biota.

Longitudinal variations in strength of estuarine circulation imply longitudinal variations in advective residence time, particularly during low river-discharge conditions. The importance of such variations to the distribution of substances in the estuary, however, must depend on wind- and tidally-induced diffusive processes as well. Advective processes are known to have an important influence on zooplanktonic distributions in estuaries **(6,** 8, 28, **44, 53).** The fact that the seasonal DS variations seem to be strongly associated with river discharge implies that advective processes influence the seasonal distributions of substances in the estuary. Similarly, observed longitudinal variations in the non-conservative (non-linear) distributions of **SPM,** phytoplankton, and DS suggest that the effects of advective processes influence the longitudinal distributions of these substances in the estuary. In contrast, diffusive processes may tend to develop uniform distributions.

Cycles of nitrogen and phosphorus and other biologically-reactive substances in estuaries are more complex than that of DS **(15, 35, 36).** San Francisco Bay

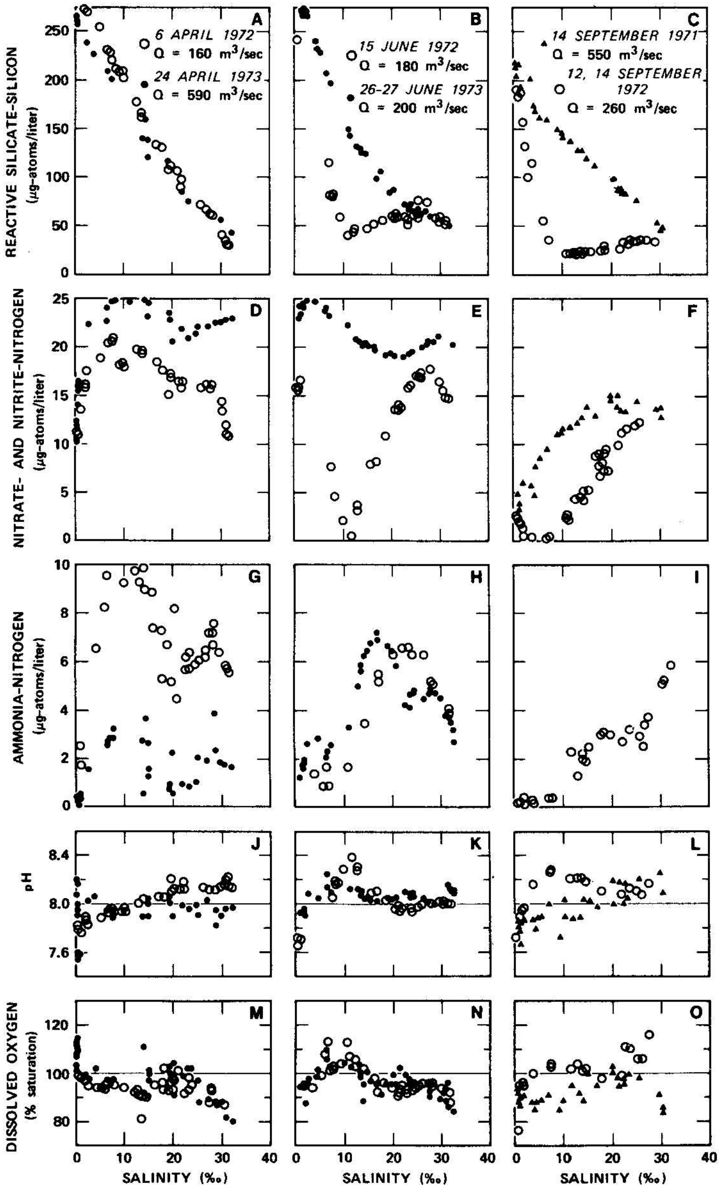

Figure 21. Longitudinal salinity relations with (A-C) silicate-silicon, (D-F) nitrate- and nitrite-nitrogen, (G-I) ammonia-nitrogen, (J-L) pH and (M-O) dissolved oxygen at 2-m depth during summers representing various river discharges. Q indicates combined mean monthly discharges from the Sacramento and San Joaquin rivers.

exhibits similar complexity. Some of the processes controlling the DS distributions apparently control nitrate and ammonia distributions which appear less simple than those of DS (Fig. 21). During early winter (December-March), river discharge is typically a major source of nitrate to the estuary. The relatively high nitrate concentration observed in April 1972 followed a winter of high discharge (Gig. 21-D). In contrast, ammonia concentrations may result largely from sources within the estuary. Thus, higher concentrations are achieved during periods of longer water-residence time, as suggested by the higher levels in April 1972 compared with those in April 1973 (Fig. **21-G).** Such interpretations obviously must be made with caution. Relative to DS, rapid ammonia and nitrate regeneration times would require much smaller residence time scales to clearly influence their seasonal distributions, and factors other than residence time may influence significantly their distributions.

It is apparent then that biological factors are responsible for the non-linear DS-salinity relation during summer in San Francisco Bay; bioligical and physical factors are responsible for its seasonal variation; and physical factors appear primarily responsible for its longitudinal variation. Too few observations have been made to conclude whether the major factors identified in San Francisco Bay apply to most estuaries. The few available observations in other estuaries, however, indicate that DS behavior is not unusually different (14, 24, 25, 37, 39, 40, 41, 42, 43, 50, *58*, ***64,*** 72, 73). Thus, the changes and the rates of changes in the seasonal DS-salinity relation probably can be used as a framework for the initial investigation of other physical and biological processes in many estuaries.

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