title Planktonic Chlorophyll Dynamics in the Northern San Francisco Bay and Delta

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Subject algae, ecology, biological resources, aquatic invertebrates

Description THE STUDY AREA, Environmental Factors, METHODS, DOMINANT PHYTOPLANKTON GROUPS, Northern Delta, Southern Delta, Eastern Delta, Western Delta, Suisun Marsh, San Pablo Bay, CHLOROPHYLL - PHEO-PIGMENT RELATIONSHIPS, DISCUSSION, ACKNOWLEDGMENTS, LITERATURE CITED

Coverage San Francisco Bay, Sacramento-San Joaquin River Estuary

Temporal 1970-1980

Source Fifty-eighth Annual Meting of the Pacific Division of the American Association for the Advancement of Science, San Francisco State University, San Francisco, California, June 12-16, 1977

Date 1977-06-12

IsPartOf SAN FRANCISCO BAY: THE URBANIZED ESTUARY Investigations into the Natural History of San Francisco Bay and Delta With Reference to the Influence of Man (265-286)

Publisher Pacific Division of the American Association for the Advancement of Science c/o California Academy of Sciences Golden Gate Park San Francisco, California 94118

Issued 1979

Type text

Format 8-1/2" x 11" bound document

Identifier ISBN 0-934394-01-6

Language English

Abstract

Diatoms were the dominant phytoplankters throughout the Sacramento-San Joaquin Delta into San Pablo Bay during 1969 through 1977. Green algae seldom exceeded 20% of the total. Chlorophyll α concentrations seldom exceeded $\mu g \cdot liter^{-1}$ at the most upstream station in the Sacramento River, the major water source to the Delta, except during the 1977 drought when 40 $\mu g \cdot liter^{-1}$ was measured. Conversely, peak summer chlorophyll concentrations entering the Delta from the San Joaquin River were the highest (100-350 $\mu g \cdot liter^{-1}$ and were inversely related to riverflow. During spring through fall, export pumping from the southern Delta caused a net flow reversal in the lower San Joaquin River, drawing Sacramento River water across the central Delta to the export pumps. The relatively deep channels and short water residence time apparently resulted in the chlorophyll concentrations remaining low from the northern Delta and in the cross-Delta flow to the pumps. Chlorophyll concentrations in the shallower eastern Delta sloughs and channels were often quite high and variable. Western Delta spring blooms reached concentrations of 25-50 $\mu g \cdot liter^{-1}$. Spring blooms of 30-40 and summer blooms of 40-100 $\mu g \cdot liter^{-1}$ were observed in Suisun Bay. The entrapment zone location adjacent to the shallows of Suisun and Honker bays appears to increase the Suisun Bay phytoplankton standing crop. Chlorophyll a concentrations in Suisun Marsh generally peaked to 40-100 $\mu g \cdot liter^{-1}$ in the late spring except during 1977. Chlorophyll levels in central San Pablo Bay seldom exceeded $\mu g \cdot liter^{-1}$, although blooms as high as 40 $\mu g \cdot liter^{-1}$ were observed in the northern shallow portion of the Bay.

Percent chlorophyll a (of the total chlorophyll α plus the pheo-pigments) in near-surface water generally varied from 50-80% during the spring-fall months throughout most of the study area. Upstream of the entrapment zone, percent chlorophyll α near the bottom averaged about 5% lower than that near the surface. Downstream of the entrapment zone, percent chlorophyll α was as much as 40% lower near the bottom.

PLANKTONIC CHLOROPHYLL DYNAMICS IN THE NORTHERN SAN FRANCISCO BAY AND DELTA

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Diatoms were the dominant phytoplankters throughout the Sacramento-San Joaquin Delta into San Pablo Bay during 1969 through 1977. Green algae seldom exceeded 20% of the total. Chlorophyll *a* concentrations seldom exceeded 6 $\mu g \cdot liter^{-1}$ at the most upstream station in the Sacramento River, the major water source to the Delta, except during the 1977 drought when 40 $\mu g \cdot liter^{-1}$ was measured. Conversely, peak summer chlorophyll concentrations entering the Delta from the San Joaquin River were the highest (100-350 $\mu g \cdot liter^{-1}$ and were inversely related to riverflow. During spring through fall, export pumping from the southern Delta caused a net flow reversal in the lower San Joaquin River, drawing Sacramento River water across the central Delta to the export pumps. The relatively deep channels and short water residence time apparently resulted in the chlorophyll concentrations remaining low from the northern Delta and in the cross-Delta flow to the pumps. Chlorophyll concentrations in the shallower eastern Delta sloughs and channels were often quite high and variable. Western Delta spring blooms reached concentrations of 25-50 $\mu g \cdot liter^{-1}$. Spring blooms of 30-40 and summer blooms of 40-100 $\mu g \cdot liter^{-1}$ were observed in Suisun Bay. The entrapment zone location adjacent to the shallows of Suisun and Honker bays appears to increase the Suisun Bay phytoplankton standing crop. Chlorophyll *a* concentrations in Suisun Marsh generally peaked to 40-100 $\mu g \cdot liter^{-1}$ in the late spring except during 1977. Chlorophyll levels in central San Pablo Bay seldom exceeded 6 $\mu g \cdot liter^{-1}$, although blooms as high as 40 $\mu g \cdot liter^{-1}$ were observed in the northern shallow portion of the Bay.

Percent chlorophyll *a* (of the total chlorophyll *a* plus the pheo-pigments) in near-surface water generally varied from 50-80% during the spring-fall months throughout most of the study area. Upstream of the entrapment zone, percent chlorophyll *a* near the bottom averaged about 5% lower than that near the surface. Downstream of the entrapment zone, percent chlorophyll *a* was as much as 40% lower near the bottom.

Phytoplankton are important primary producers in the estuarine environment since they form the base of the water-column food web. However, in many aquatic environments, high phytoplankton concentrations can cause oxygen concentration reductions to a point detrimental to higher aquatic organisms. High phytoplankton levels can also adversely affect water supplies, or create aesthetically undesirable environments. In the study area, phytoplankton problems have been negligible, with the exception of the southern and eastern Delta.

In this chapter we summarize results of a cooperative multiagency study of phytoplankton biomass, measured as chlorophyll, in the Sacramento-San Joaquin Delta, Suisun Bay, Suisun Marsh, and San Pablo Bay during 1969 through 1977. We discuss, in particular, factors influencing phytoplankton biomass distributions, occurrence and distribution of dominant phytoplankton classes, and the chlorophyll - pheo-pigment relationships.

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This coordinated monitoring program is one of two major studies involving routine chlorophyll measurements in the Sacramento-San Joaquin Delta Suisun Bay area (Arthur and Ball 1979). The other study was conducted during 1966 and 1967 by California Departments of Water Resources (DWR) and Fish and Game (DFG) at 10 stations throughout the Delta and Suisun Bay. Only total chlorophyll (chlorophyll *a+b+c* not corrected for pheo-pigments) measurements were reported (California DWR and DFG 1972).

Previous water quality studies in the system were prepared by the U. S. Bureau of Reclamation (USBR 1972, 1974) for 1968-70 data. The 1969-74 chlorophyll data were evaluated by Ball (1975, 1977).

Phytoplankton chlorophyll analysis, a relatively rapid and quantitatively accurate method of determining the total phytoplankton standing crop, can be directly related to total phytoplankton carbon with conversion factors determined in any given study (Strickland and Parsons 1968).

THE STUDY AREA

The Delta, with over 1,100 km of waterways, is formed by the confluence of the Sacramento and San Joaquin rivers (Fig. 1). The Sacramento River system contributes approximately 80% of the freshwater entering the Delta, and the smaller San Joaquin River system contributes about 15%. The remaining flow (5%) is primarily from the smaller streams entering the eastern Delta.

During spring through fall, southern Delta pumping by the USBR and DWR for export in the Delta-Mendota Canal and California State Aqueduct generally exceed the San Joaquin River flow, drawing most of this water to the pumps. This combination of low flow and export pumping

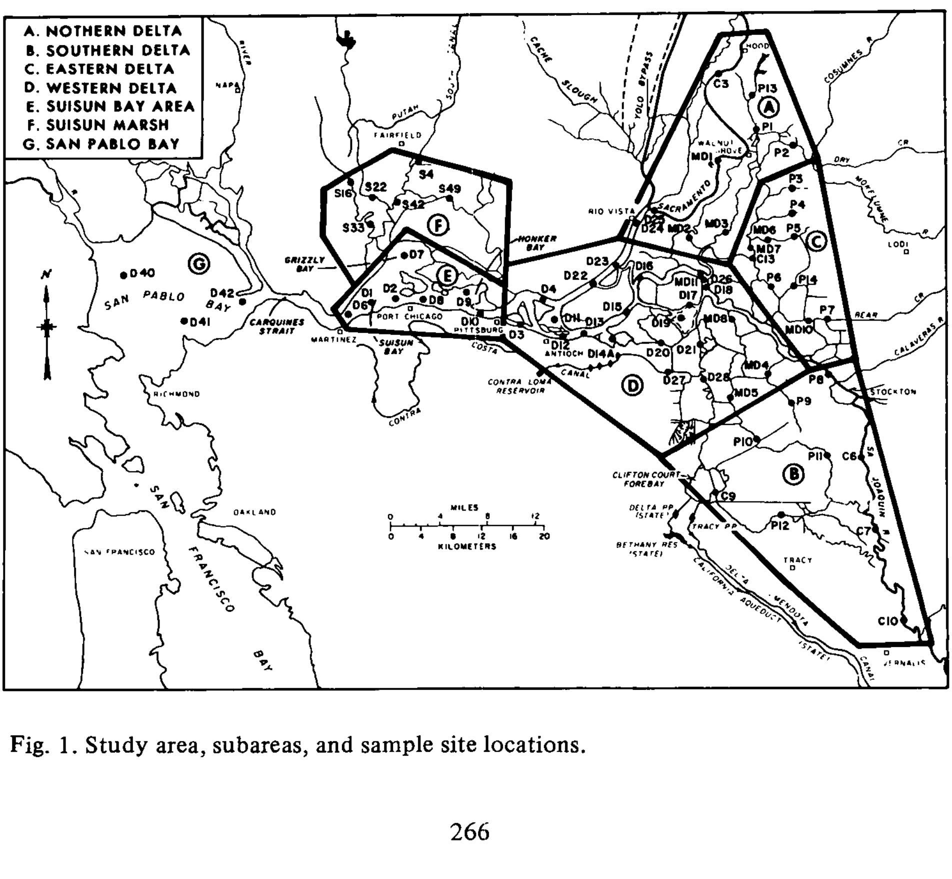

Fig. 1. Study area, subareas, and sample site locations.

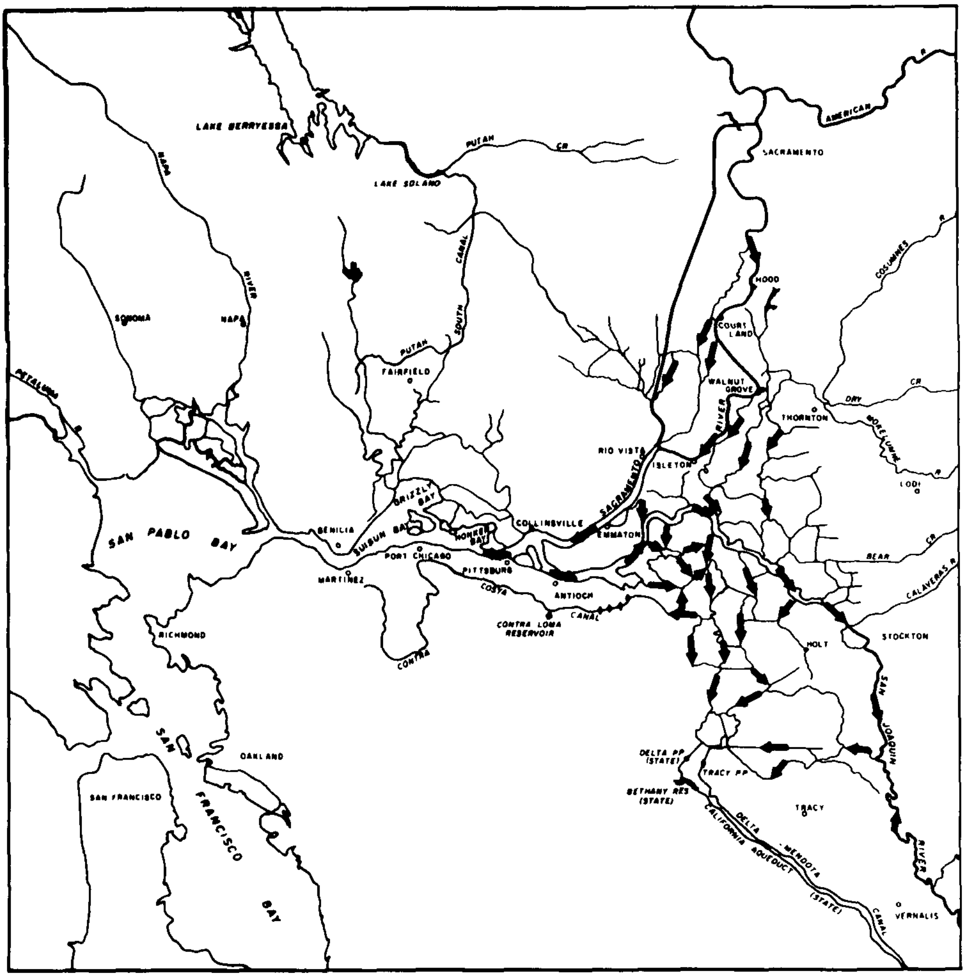

Fig. 2. Typical Delta summer net flow patterns. Note the reverse flow in the San Joaquin River system toward the export pumps. (From Ball 1977).

causes a net flow reversal in the lower San Joaquin River and draws Sacramento River water across the central Delta to the export pumps (Fig. 2). The water residence time from the northern Delta to the export pumps during periods of high summer export is only a few days.

Because of unmeasured inflow in several minor streams, consumptive water use within the Delta, and tidal current action, the net inflow to San Francisco Bay has not accurately been measured (Conomos 1979). Instead, an estimate termed the Delta Outflow Index (Sacramento and San Joaquin River flow less export and consumptive use [see Arthur and Ball 1979] is computed daily for operations of the state and federal water projects. This error during typical summer outflow conditions may be as great as ±30 to 60 $m^3 \cdot sec^{-1}$.

The quantity of river inflow to the Delta is important to phytoplankton growth in that it regulates nutrient concentrations, affects water transparency, determines water and phytoplankton residence times, and regulates the extent of salinity intrusion and the location of the entrapment zone. These and other factors all interact to determine the quantity and quality of the phytoplankton.

Environmental Factors

Water and/or phytoplankton residence time, nutrients, temperature, and light are the main factors interacting and influencing the algal standing crop. Other factors such as toxic materials, zooplankton, zoobenthos and algal parasites may also have inhibiting effects on the algal growth rate but are not discussed.

The residence time of water varies greatly throughout the study area. During winter, high river inflow rates greatly shorten residence times as compared to the summer, when export effects are more significant. Geographic effects also modulate water residence time. For example, eastern Delta dead-end sloughs have very long water-residence times, whereas major tributaries have short residence times. Currents generated by tidal and wind action also influence residence times.

Water residence time and degree of vertical and horizontal mixing are very influential on the algal growth rate, standing crop, and the bloom development. High algal growth rates occur where there is sufficient light penetration relative to the water depth. Assuming other growth factors equal, the longer the phytoplankton remain in areas of high relative light penetration, the greater the standing crop that will develop.

Certain species of phytoplankton tend to accumulate in the entrapment zone as a result of two-layered flow (see also Arthur and Ball 1979). This phenomenon increases their residence time over that of the water.

There are great seasonal and spatial variations in the nutrient concentrations (USBR 1972, 1974). During summer, highest concentrations of inorganic nitrogen typically occur in dead-end sloughs and near agricultural drains and sewage effluents. Lower concentrations tend to occur in the western Delta and San Pablo Bay. During winter, river inflow largely controls concentrations of inorganic nitrogen, phosphorus, silica, and other nutrients required for algal growth (see also Peterson 1979; Conomos et al. 1979).

Results of past studies have demonstrated that nitrogen typically was the most limiting nutrient and was often depleted during algal blooms. Phosphorus and the micronutrients were always present at sufficient levels to cause higher algal growth concentrations when additional nitrogen was supplied to the water in laboratory test (USBR 1972).

Seasonal increases in incident solar radiation (insolation) and water transparency greatly increase algal growth rates. Incident sunlight in the Delta is approximately five times greater in the summer than in winter (Fig. 3A). As the water transparency is generally greater during the summer low-flow period than during the winter high-flow period (see Arthur and Ball 1979), the covariance of these parameters increase in the summer algal growth rate severalfold.

The temperature increase from winter to summer (Fig. 3B) also has a profound effect on algal growth rates. The growth rate of most planktonic algal species can increase 2 to 4 times with each 10°C temperature increase, until the optimum temperature (about 20 to 25° C; Fogg 1965) is reached. Additional increases above optimum cause rapid growth rate decline.

METHODS

The sampling sites in our study area are grouped into various subareas (northern Delta, southern Delta, eastern Delta, western Delta, Suisun Bay, Suisun Marsh, and San Pablo Bay) to simplify discussion (Fig. 1). The boundaries are based on geographical location and on similarity in seasonal phytoplankton growth patterns. Sampling frequency typically varied from twice monthly and data for nearly 70 sites studied through 1974.

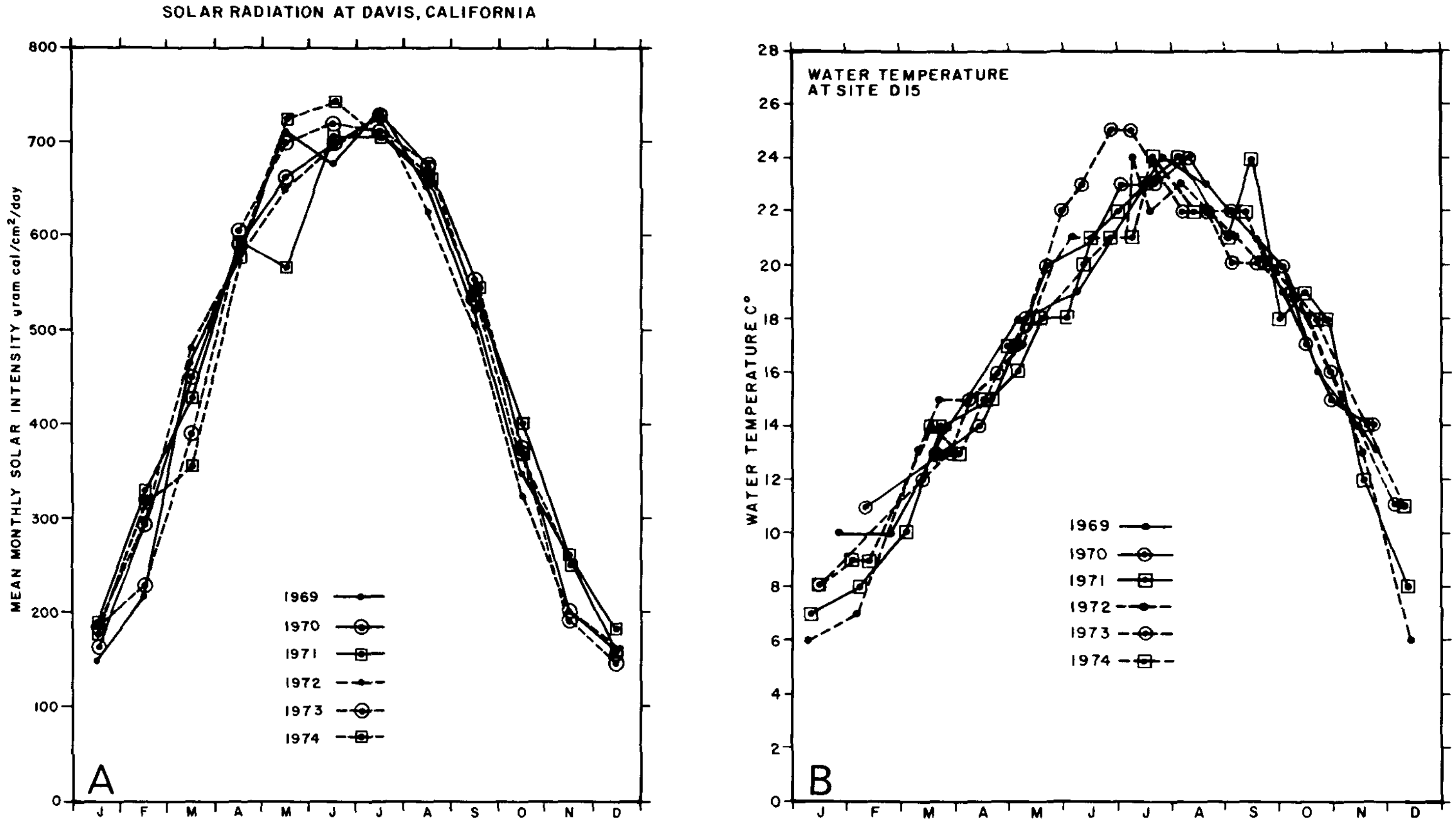

Fig. 3. A. Mean monthly solar intensity (insolation) measured at Davis, California for the years 1969-1974. B. Water temperature at Jersey Point (site D14) for the years 1969-1974. Data from the routine monitoring program. (From Ball 1977).

SAN FRANCISCO BAY

All samples, unless otherwise stated, were collected using submersible pumps or Van Dorn-type water bottles within approximately 1 hour of the time of high slack tides (except in the eastern and southern Delta) and approximately 1 m below the water surface. Chlorophyll *a* and pheopigment sample volumes ranged from 0.1 to 1 liter. Sample handling and filtrations were according to the methods of Strickland and Parsons (1968) with modifications described by Ball (1977).

The accuracy of the chlorophyll *a* measurements following May 1970 is probably within ±10% while the accuracy of the measurements made prior to that date is slightly lower.

Phytoplankton samples for identification and counting were stored in glass bottles containing 1% Lugol's solution, and at times, stored up to two years before analysis. The samples were identified and counted by several persons using inverted microscopes and various types of settling chambers, including 3.2-mm deep specially designed chambers and the standard Utermohl chamber. The organisms were identified and enumerated to genus except for a few easily recognized species.

DOMINANT PHYTOPLANKTON GROUPS

The dominant genera varied with time of year and location in the estuary. The diatoms (class Bacillarophyceae) dominated (cell number) the spring through fall algal community (Table 1; the green algae (class Chlorophyceae) were the second most numerous group, and generally constituted less than 20% of the total count. In the dead-end sloughs of the eastern Delta, however, the green algae percentage was often higher. Cryptomonads (class Cryptophyceae) were occasionally dominant at some sites during winter. Cryptomonads, dinoflagellates, and other flagellates also were in high concentrations in low water velocity areas such as marinas and the Stockon Ship Channel turning basin.

TABLE 1. DOMINANT GENERA OF PHYTOPLANKTON AND AREAS OF OCCURRENCE DURING SPRING THROUGH FALL, 1969-1974[1]

Area	Dominant genera
Northern Delta	*Coscinodiscus, Cyclotella, Melosira*
Western Delta	*Coscinodiscus, Cyclotella, Melosira, Skeletonema, Stephanodiscus, Microsiphona*
Suisun Bay	*Chaetoceros, Coscinodiscus, Cyclotella, Melosira, Skeletonema, Stephanodiscus*
San Pablo Bay	*Chaetoceros, Coscinodiscus, Cyclotella, Skeletonema*
Suisun Marsh	*Coscinodiscus, Cyclotella, Stephanodiscus*
Eastern Delta	*Coscinodiscus, Cyclotella, Stephanodiscus, Melosira*
Southern Delta	*Coscinodiscus, Cyclotella, Stephanodiscus, Melosira*

[1] From Ball 1977.

GEOGRAPHIC AND SEASONAL CHLOROPHYLL DISTRIBUTIONS

The phytoplankton standing crop, defined by averaged chlorophyll *a* concentration, indicates that the major rivers contribute vastly differing amounts of chlorophyll *a* to the Delta (Fig. 4). Very low chlorophyll concentrations occurred in the Sacramento River water entering the Delta whereas very high concentrations occurred in the shallower and smaller San Joaquin River. We present these separately as each area has differing and complicating characteristics.

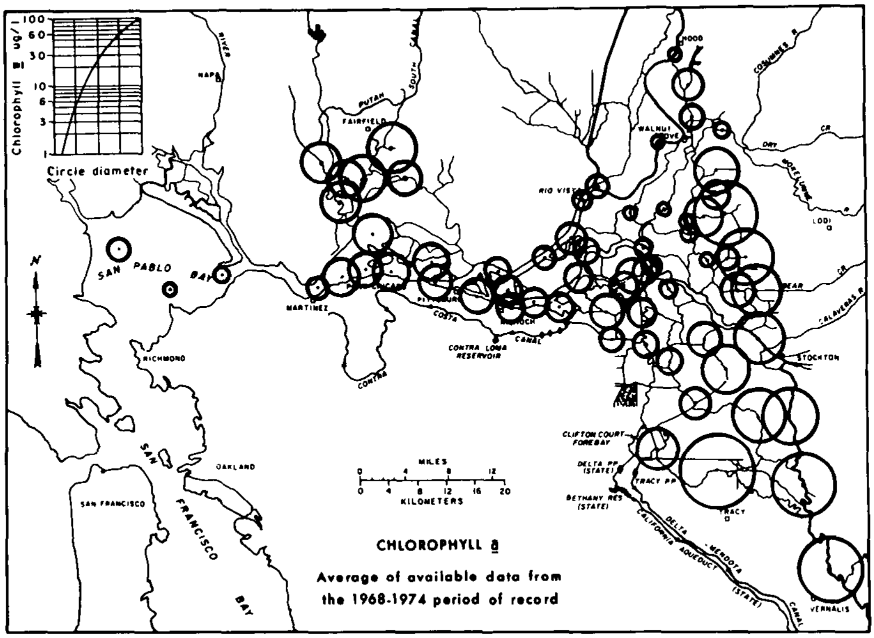

Fig. 4. Average chlorophyll *a* concentration from September 1968-1974. The area of each circle is proportional to the concentration.

Northern Delta

Phytoplankton primarily enter the northern Delta from the Sacramento River. The Yolo Bypass, containing mostly Sacramento River overflow, may contribute the greatest water discharge to the Delta during high flow and flood periods (see also Conomos 1979).

Chlorophyll concentrations at Hood (C3), representing Sacramento River inputs, were uniformly low and seldom exceeded 6 $\mu g \cdot liter^{-1}$ during the spring through fall months (Fig. 5). An important exception was the occurrence of a high phytoplankton standing crop during the 1977 drought year (spring and summer flow was less than one-half normal), which we think is the result of longer water residence time.

At Rio Vista (D24) the chlorophyll *a* concentrations seldom exceed 12 $\mu g \cdot liter^{-1}$ (Fig. 5). During typical summer low flow conditions the chlorophyll levels increased nearly twofold between sites C3 and D24.

Chlorophyll *a* concentrations below the confluence of the Mokelumne and Cosumnes rivers (P2) were usually less than 3 $\mu g \cdot liter^{-1}$ excepting years of very low or no flow (1972, 1976, 1977).

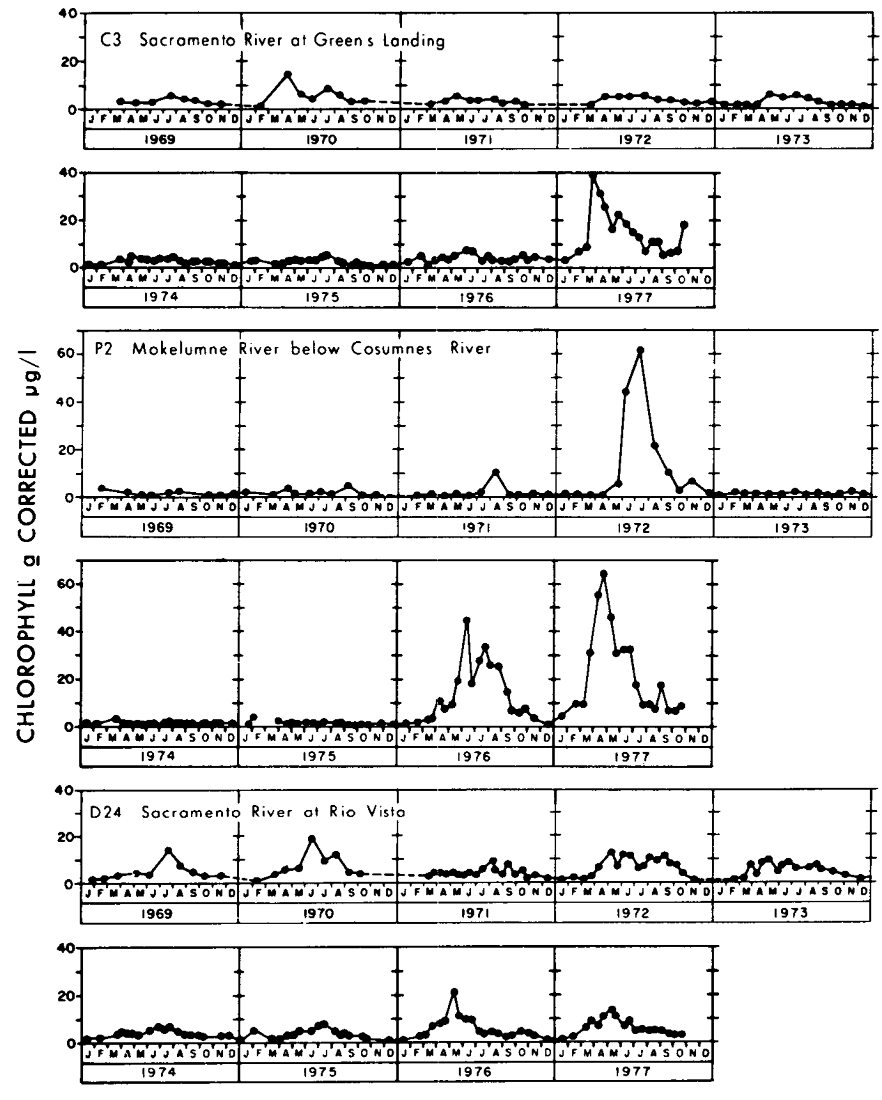

Fig. 5. Typical chlorophyll *a* concentrations in the northern Delta.

Southern Delta

In contrast to the Sacramento-derived low chlorophyll concentrations, the levels in the San Joaquin River (consisting largely of agricultural and municipal waste water) entering the Delta from the south were extremely high (Figs. 6A, B). The winter chlorophyll *a* concentrations were typically between 10 and 20 $\mu g \cdot liter^{-1}$, whereas during summer, the concentrations were an order of magnitude higher. The June and July (1969-77) chlorophyll *a* concentrations at Vernalis in the San Joaquin River (C10) were inversely related to riverflow ($r = -0.75$; Fig. 7).

The standing crop of phytoplankton at site P8 (Fig. 6A) typically declined following spring blooms. Since average water depth at this site is the greatest of the southern Delta sites,the higher concentrations during the spring (100 $\mu g \cdot liter^{-1}$) prior to flow reversal in the San Joaquin River

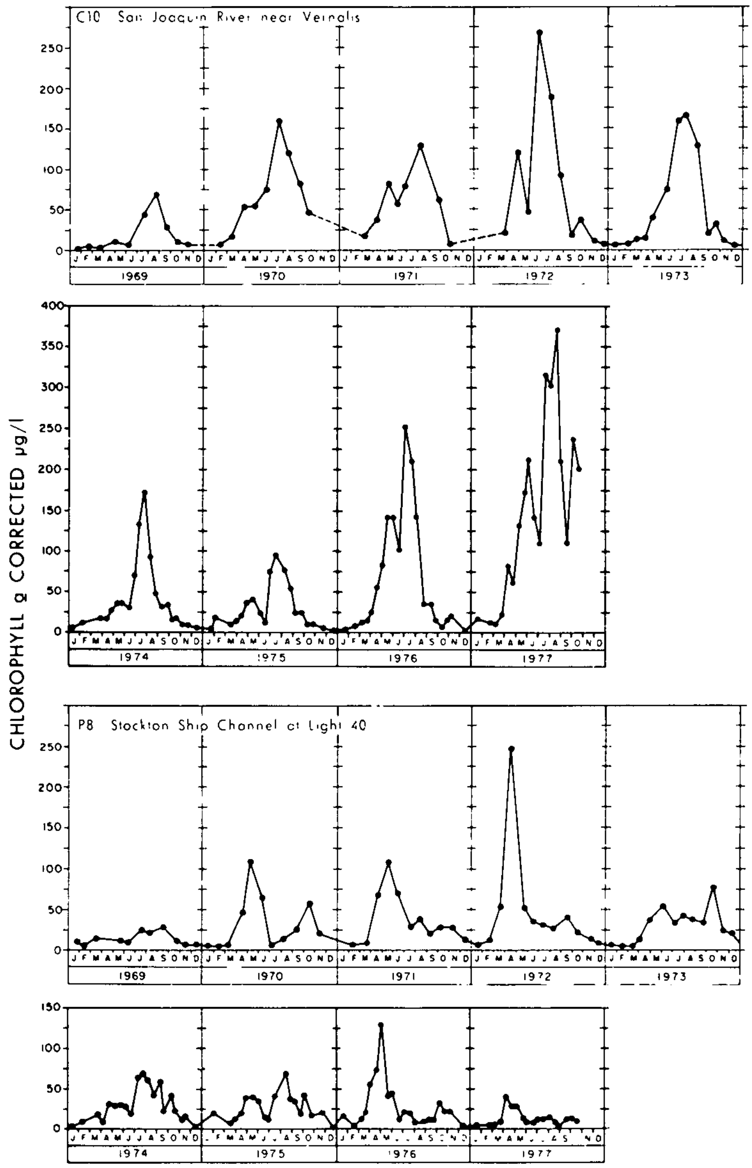

Fig. 6A. Typical chlorophyll *a* concentration in the southern Delta.

suggest that phytoplankton produced in the shallow upstream portion of the San Joaquin River may be transported to the site. Phytoplankton contained in the Stockton wastewater treatment plant effluent and other discharges may also influence the distribution.

Site P12 on the shallow and nutrient-laden Old River had consistently higher chlorophyll concentrations than any other Delta site (Fig. 6B). High phytoplankton levels (chlorophyll *a* µ 200 µg·liter^{-1} occurred in spring, reached peak levels during late spring or summer, and did not subside until fall. Concentrations reached 350 µg·liter^{-1} in the spring of dry years (1976-77). Most of this highly productive, algae-laden San Joaquin River water is pumped into the Delta-Mendota Canal

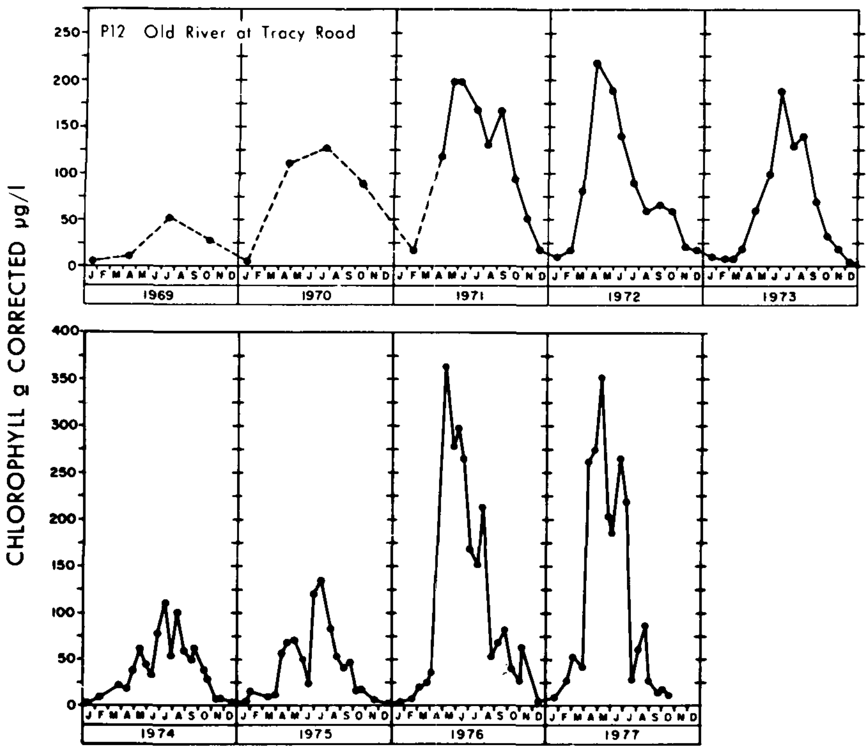

Fig. 6B. Typical chlorophyll *a* concentrations in the southern Delta (continued).

during low tides and is returned to the San Joaquin Valley instead of flowing into the Delta.

Eastern Delta

Initially the eastern Delta sites were chosen because of their close alignment with the proposed Peripheral Canal (a canal to convey Sacramento River water from the northern Delta to the export pumps in the southern Delta for transport southward). Most of the sites are located on dead-end sloughs and have high chlorophyll concentrations.

The timing of maximum chlorophyll concentration was variable at these and other sites in the eastern Delta and did not tend to follow seasonal patterns (Fig. 8). Of the dead-end sloughs studied, Sycamore Slough (P5) had the highest summer chlorophyll *a* concentrations (50-150 $\mu g \cdot liter^{-1}$) and Hog Slough (P4), the lowest (35 $\mu g \cdot liter^{-1}$).

Western Delta

Most of the western Delta sites are on the lower San Joaquin River system (Fig. 1) and had similar chlorophyll concentration patterns. Typically spring blooms peaking at 20-50 $\mu g \cdot liter^{-1}$ were followed by summer declines (Fig. 9). In some years a second peak occurred during the fall. Spring blooms were not measured in 1969 and 1977 (years with extreme variations in river flow; see Fig. 16A, B).

Vertical chlorophyll *a* measurements made in 1973 were quite uniform between surface (1-m depth) and bottom (0.5 m above the bottom) because of tidal mixing. The surface sample concentrations averaged 1% higher.

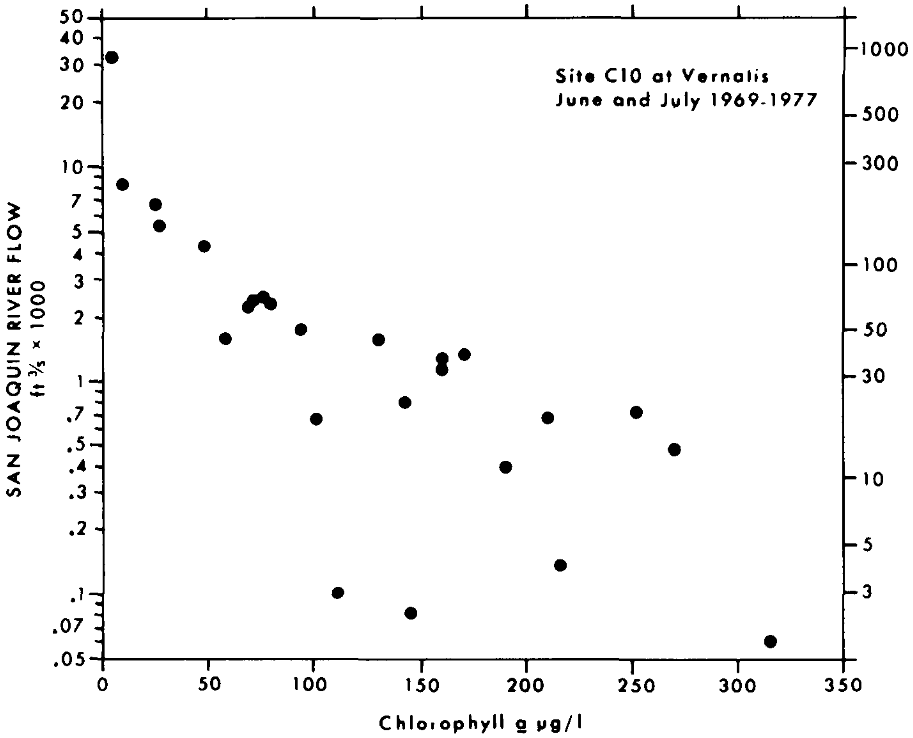

Fig. 7. Relationship of chlorophyll *a* concentration at site C10 to the San Joaquin River flow.

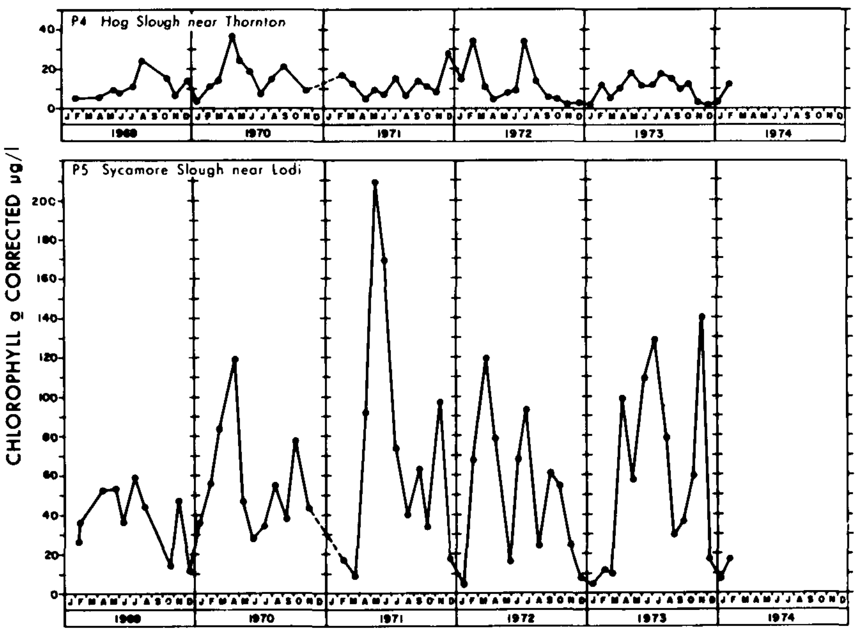

Fig. 8. Typical chlorophyll *a* concentration in the eastern Delta.

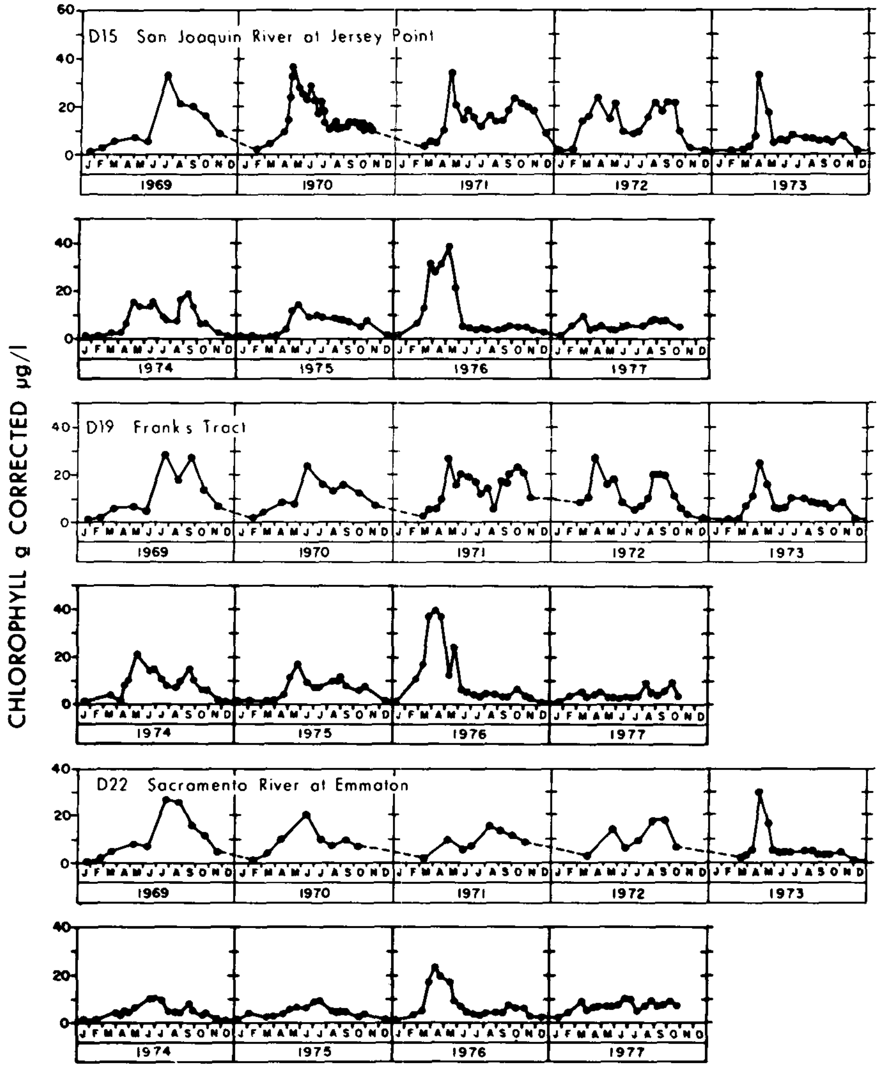

Fig. 9. Typical chlorophyll *a* concentrations in the western Delta.

Suisun Bay

The timing of phytoplankton blooms and the level of standing crops in Suisun, Grizzly and Honker bays were highly variable (Fig. 10). The blooms were generally associated with different dominant phytoplankton species than those found in the western Delta, and usually peaked in the two areas at different times.

All sites in Suisun Bay had similar concentration patterns, with maximum values (50 to 100 $\mu g \cdot liter^{-1}$) generally measured in August. During an extremely wet year (1969) only one summer peak was observed, whereas during 1976, a dry year, a late winter and a spring peak appeared but no summer bloom occurred. No bloom was detected during the 1977 drought.

During phytoplankton blooms, the highest chlorophyll concentrations in the river channel

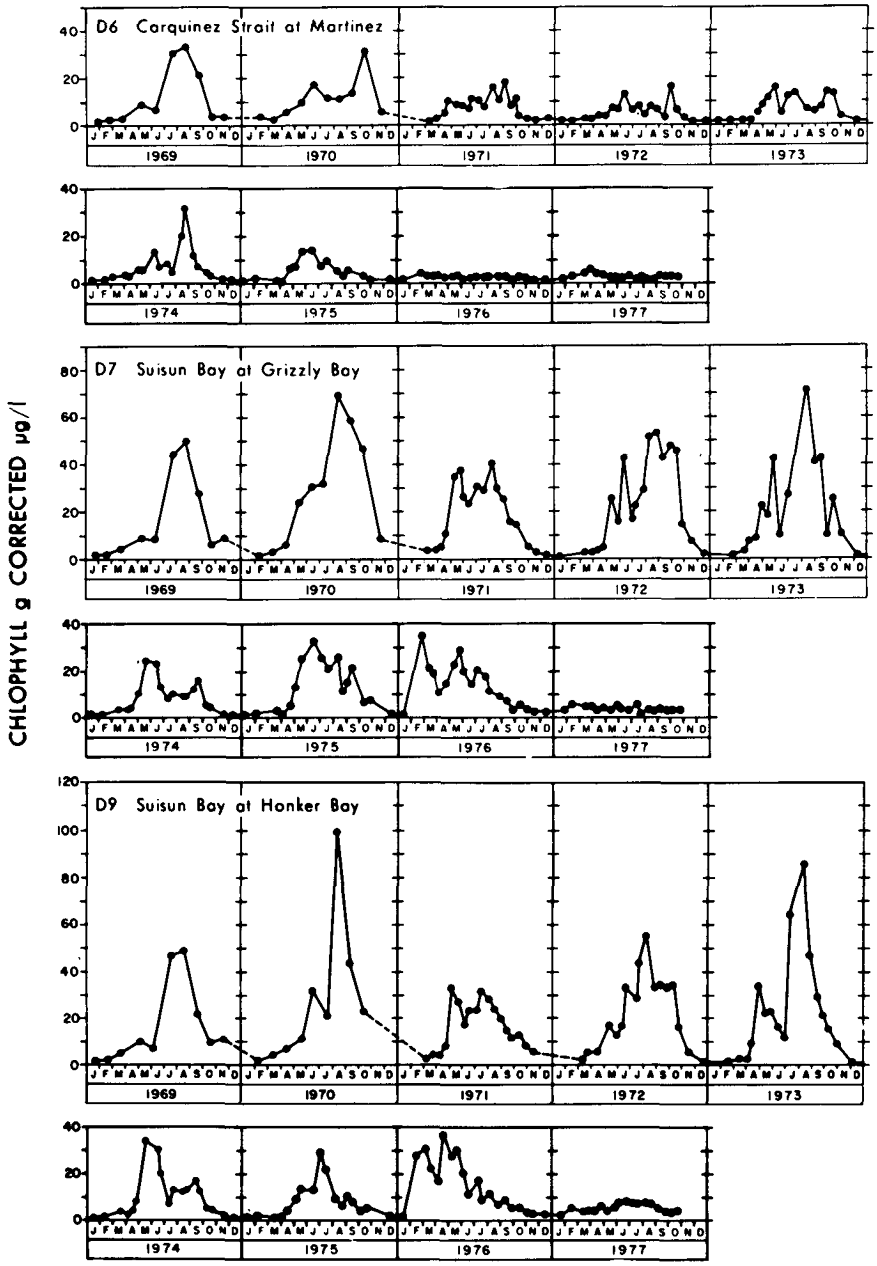

Fig. 10. Typical chlorophyll *a* concentrations in Suisun Bay.

typically occurred in waters having specific conductances of approximately 2-10 millimho/cm (1 to 6 °/oo salinity) or slightly higher (see also Arthur and Ball 1979). Intensified sampling starting in September 1973 demonstrated that there were often severalfold differences between the chlorophyll *a* concentration at surface and bottom (Fig. 11). Highest surface concentrations frequently

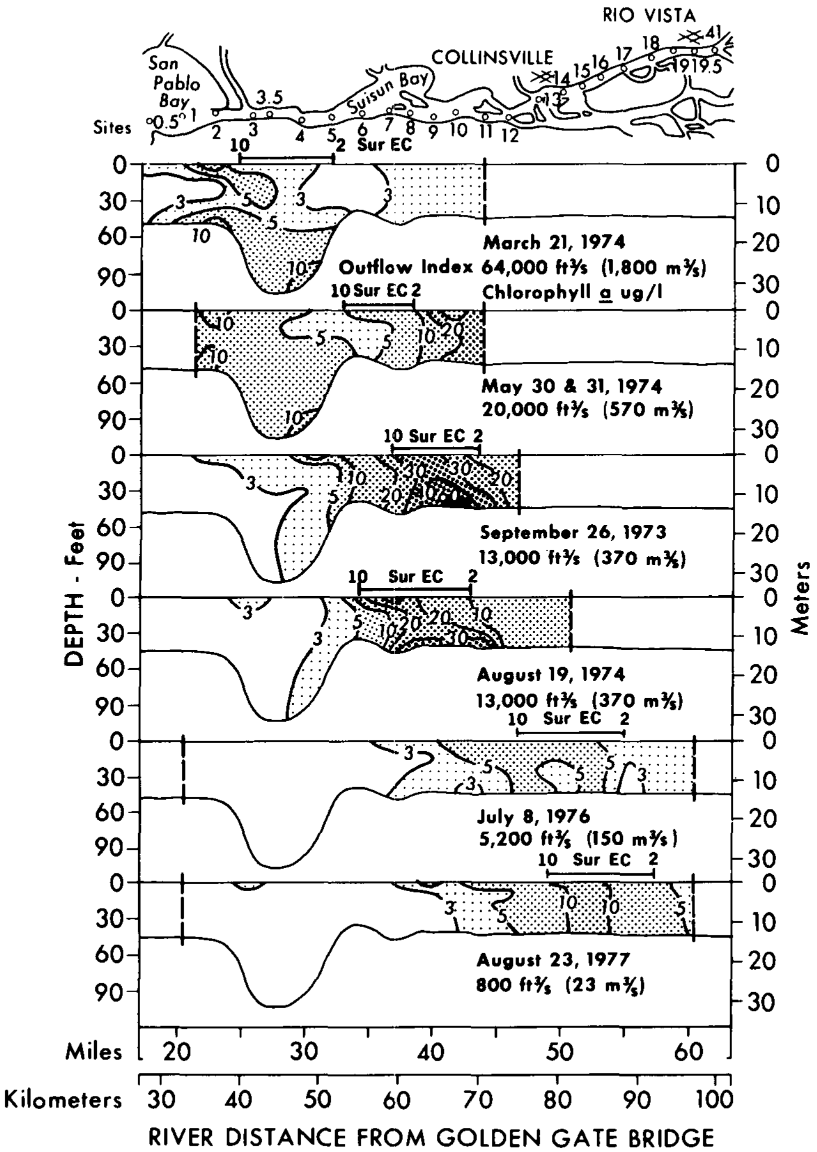

Fig. 11. Chlorophyll *a* distribution in the Sacramento River Channel relative to surface salinity (2-10 millimho/cm specific conductance is approximately 1 - 6 °/oo salinity) on high slack tides at various Delta outflow indices. (From Arthur and Ball 1978).

occurred downstream of the maximum in bottom waters.

Suisun Marsh

Maximum chlorophyll *a* concentrations generally occurred during spring and summer, seldom exceeding 60-80 $\mu g \cdot liter^{-1}$. The seasonal concentration patterns were similar throughout the marsh. As for Suisun Bay, chlorophyll concentrations in Suisun Slough were unusually low during 1977 (Fig. 12).

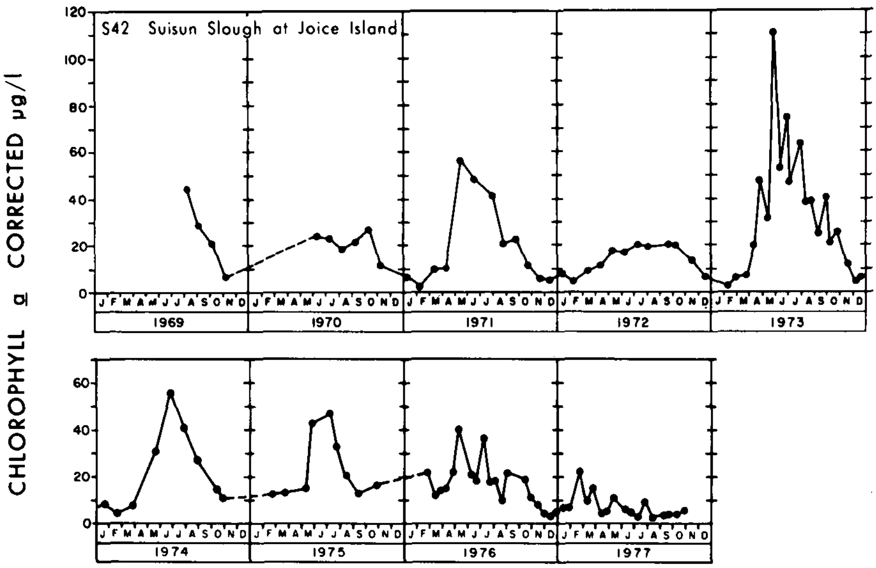

Fig. 12. Typical chlorophyll *a* concentrations in Suisun Marsh.

San Pablo Bay

The three sites in San Pablo Bay demonstrated significant yearly variations in chlorophyll concentrations; however, both the temporal and spatial sampling frequency has been less than for the other areas (Fig. 13). The greatest variation in chlorophyll levels among years sampled occurred at shallow-water site D40. The highest concentration (38 $\mu g{\cdot}liter^{-1}$) was measured during spring 1973 and occurred two months earlier than a similar concentration in Suisun Bay. Central San Pablo Bay (D41) consistently had the lowest chlorophyll concentrations (seldom exceeding 7 $\mu g{\cdot}liter^{-1}$) for the entire study area.

CHLOROPHYLL - PHEO-PIGMENT RELATIONSHIPS

The percent chlorophyll *a* (of the total chlorophyll *a* plus pheo-pigments) was generally in the range reported by Yentsch (1965a, b) and Spence and Steven (1974) for other productive major water bodies. Typical levels were 50 to 80% (20 to 50% pheo-pigments) between spring and fall for most areas except in some of the dead-end sloughs, where at times the percentages were quite low. Winter levels in much of the study area often dropped below 50%.

Furthermore, the percent chlorophyll *a* appeared to be highest during the algal bloom periods and usually dropped 10 to 20% during the weeks immediately following the bloom peaks.

Surface and near-bottom sampling in the channels indicated the percent chlorophyll *a* levels were approximately 5% lower near the bottom upstream of the entrapment zone (Fig. 14). In the channels of Suisun and San Pablo bays, where salinity stratification occurred, the percent chlorophyll *a* levels were generally 10 to 40% lower near the bottom than the surface.

DISCUSSION

The phytoplankton standing crop in the northern and southern Delta is greatly influenced by chlorophyll concentrations in river inflow (Fig. 4). Summer insolation and water temperatures maxima largely determine the timing of the blooms (Figs. 5, 6A,B). The low chlorophyll levels in the Sacramento River entering the Delta combined with the relatively short residence time result in low levels in the northern Delta. In contrast, the very high concentrations in the southern Delta are promoted by the high concentrations entering the Delta in the San Joaquin River, the shallowness of this portion of the Delta, and the high levels of agricultural and municipal wastewater rich in inorganic nitrogen and phosphorus.

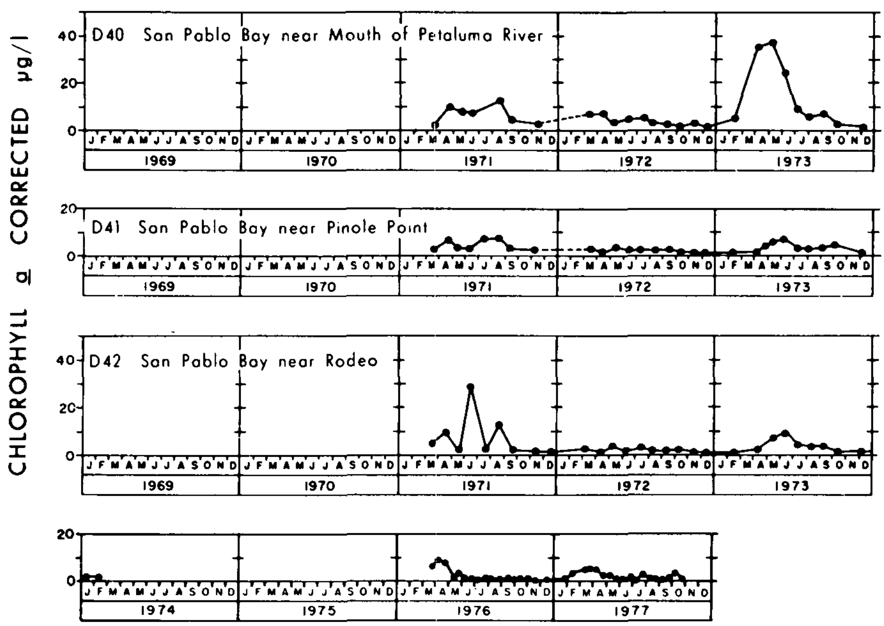

Fig. 13. Typical chlorophyll *a* concentrations in San Pablo Bay.

In the central portion of the Delta, the relatively deep channels and short residence time created by reverse flow in the San Joaquin River (Fig. 2) apparently are primarily responsible for the low chlorophyll concentrations. The central and western Delta would probably be much more productive during the summer if the San Joaquin River water were not drawn to the export pumps but allowed to flow seaward.

The high concentrations in the eastern Delta reflect the long water residence time due to the sluggish circulation patterns, the high agricultural and municipal waste inflows, and the shallow water depths.

In the western Delta and Suisun Bay a more complicated series of interactions occur. These two areas typically were dominated by different algal species and experienced peak chlorophyll concentrations at different times of the year (Figs. 9, 10; Ball 1977). Also, the growth patterns for each area varied considerably from year to year. Summer insolation and temperature maxima did not correspond to peak bloom periods in all years, such as in the southern Delta. However, blooms did not occur in midwinter. We believe the following factors primarily influence the differences in phytoplankton abundance between years in these two distinct areas (Ball 1975, 1977; Arthur and Ball 1979): (1) average length of time phytoplankton spend in the photic zone as influenced by the water transparency, (2) entrapment zone location (including several possible

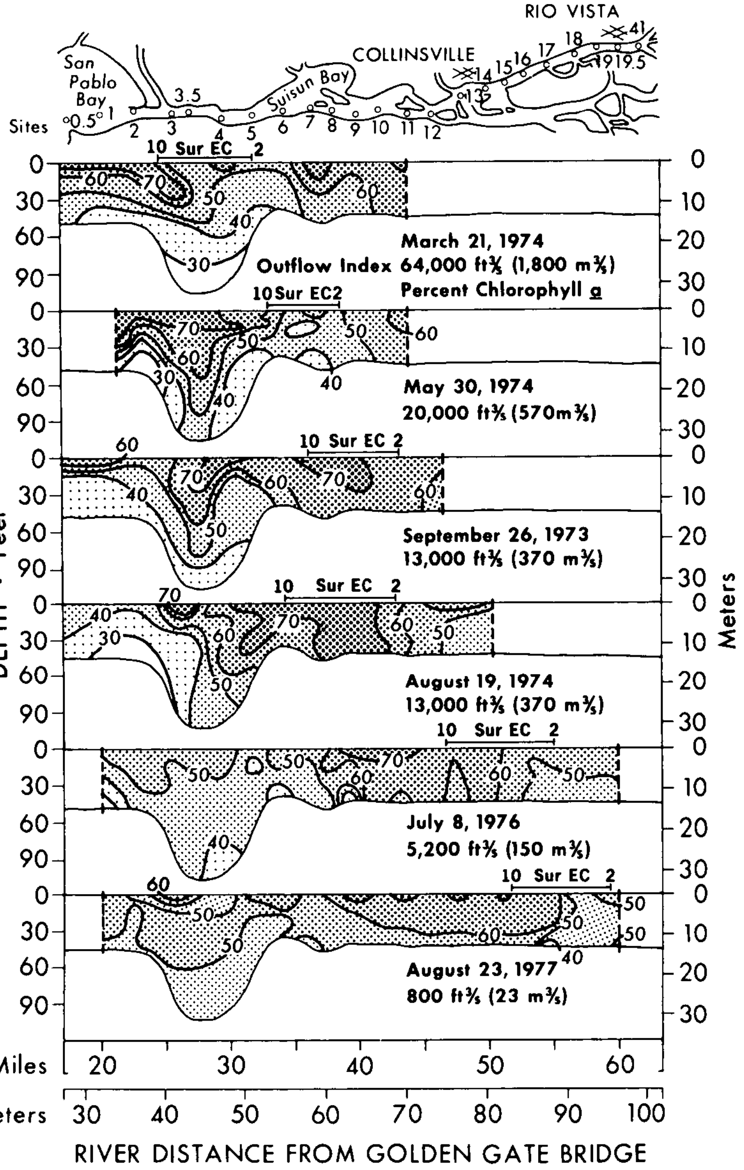

Fig. 14. Percent chlorophyll *a* (of chlorophyll *a* plus pheo-pigments) in the Sacramento River Channel relative to surface salinity (2-10 millimho/cm specific conductance is approximately 1-6 °/oo salinity) on high slack tides at various Delta outflow indices. (From Arthur and Ball 1978).

effects), (3) nutrient concentrations, and (4) transport of phytoplankton into the area.

In a well-mixed system such as the western Delta, the proportion of time phytoplankton are in the photic zone depends on the water depth and transparency. In addition, these factors control their growth rate which influences the standing crop. The water transparency varies greatly from year to year and appears to have directly influenced the phytoplankton growth rate and standing crop.

Several environmental factors influence the water transparency: suspended particle concentrations in the water entering the Delta, particle flocculation and settling, waste discharges within the Delta, location of the entrapment zone (see also Arthur and Ball 1979), tidal current- and wind-induced sediment resuspension, and possibly the resuspension and upstream transport of a portion of the winter sediment load deposited in the bays downstream. We do not understand fully the interaction of these factors.

The water transparency in the western Delta varies with river flow. During the winter and spring flood-prone periods the transparency tends to be lowest and inversely related to the amount of Delta outflow. During the spring months the outflow decreases and the water transparency increases. The variation in water transparency during spring from 1969 to 1977 appeared to be influential on the development of the spring phytoplankton blooms. Earlier spring bloom development and relatively higher chlorophyll *a* concentrations occurred during years of greater water transparency (Fig. 15; Ball 1977). During summer months, the transparency in the western Delta tends to be directly related to the amount of outflow as the entrapment zone moves upstream into

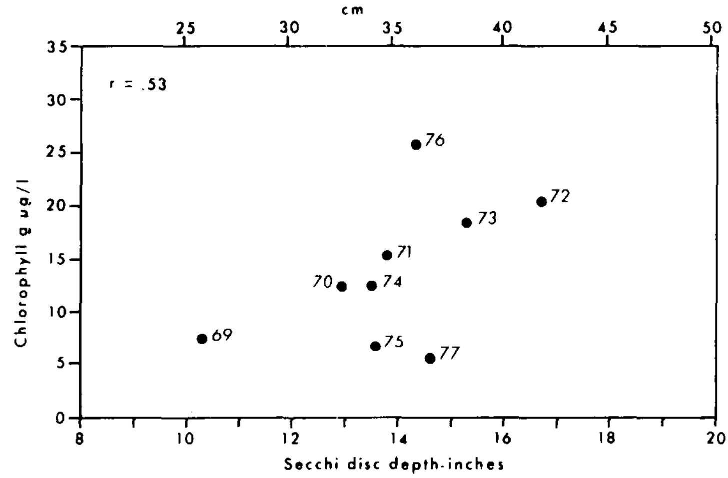

Fig. 15. Relationship of the average April and May chlorophyll *a* concentrations to water transparency in the western Delta. Averages are for sites D11, D12, D14A, D15, and D19.

this area and wind velocities are at their peak. The phytoplankton populations also decline during summer. Although water transparency values may be representative for the time of measurement, the great reductions in transparency due to tidal current- and wind-induced sediment resuspension may make these averages questionable.

Water source and algal residence time may also influence phytoplankton standing crops. The water source during late spring through early fall is primarily the Sacramento River which typically has low chlorophyll concentrations. In contrast, San Joaquin River water with several times the chlorophyll concentration is drawn to the export pumps in the southern Delta. During high flows of the San Joaquin River in 1969 the flow reversal did not occur until midsummer, and the highest midsummer chlorophyll concentrations ever measured in the western Delta may have partially originated in the southern Delta.

Inorganic nitrogen normally is the nutrient that at times limits algal growth in the study area (USBR 1972). Measurements in the western Delta and Suisun Bay indicated prior to the spring blooms sufficient nitrogen was available to support higher algal concentrations than were observed. In most years during spring blooms, nitrogen was depleted to limiting ($\leqslant$ 0.02 mg·liter^{-1}) or

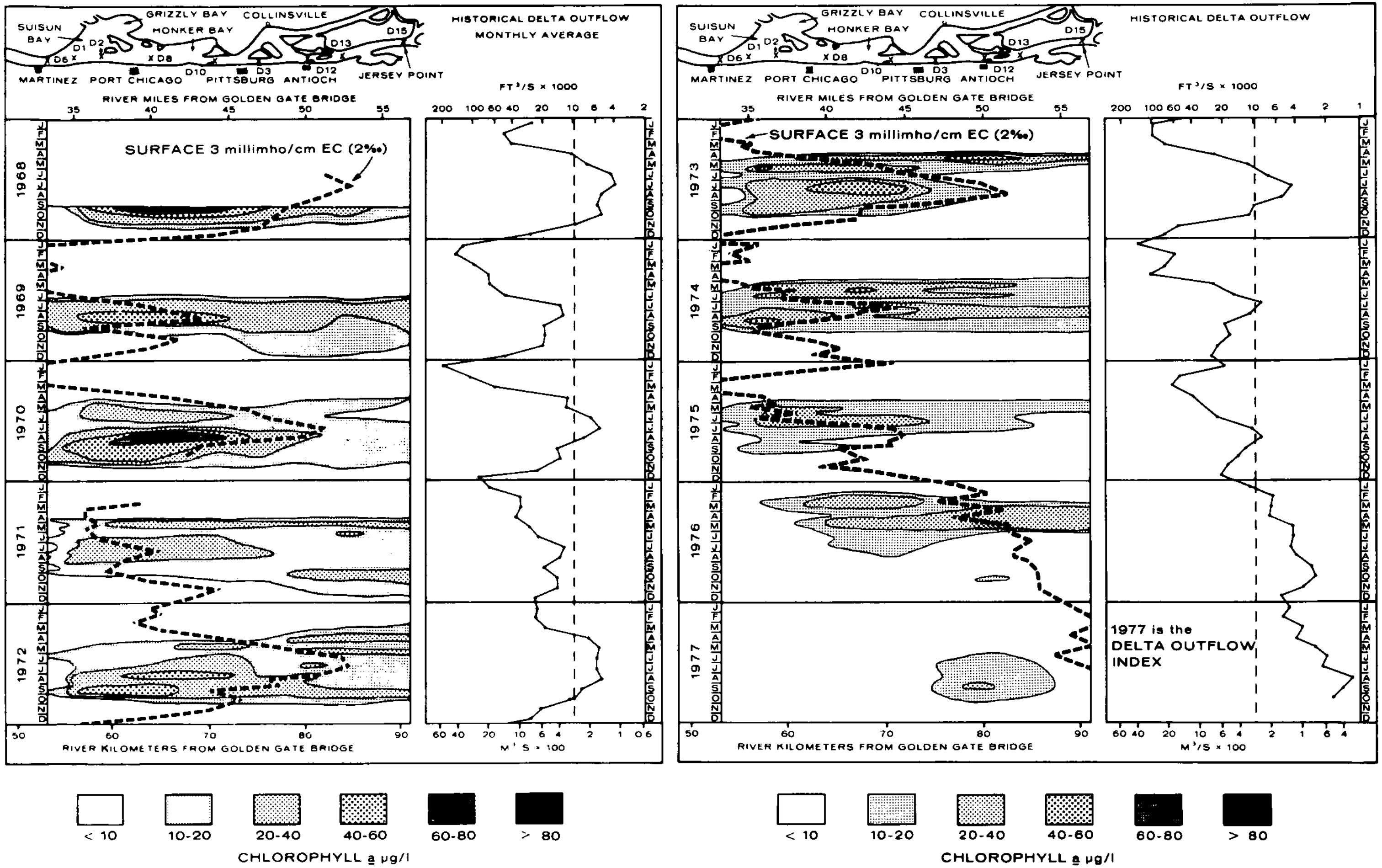

Fig. 16A, B. Chlorophyll *a* distribution from 1968-77, between Jersey Point and Martinez, as related to salinity intrusion and Delta outflow. The 3 millimho/cm specific conductance contour represents the approximate location of the upstream edge of the entrapment zone at high slack tides. The tidally averaged center location of the entrapment zone would be nearly 10 km downstream.

near-limiting levels at many sites. The greatest nitrogen limitation was observed in 1971, a year with high water transparency. In 1971 the spring blooms in these two areas generally depleted the nitrogen to limiting levels and subsequent phytoplankton growth depleted nitrogen from the inflowing water until fall. Chlorophyll concentrations were at lowest recorded levels during 1977, except near Antioch (D12) and Emmaton (D22), the approximate center of the entrapment zone during that time. Also, inorganic nitrogen concentrations remained near winter high levels.

It is difficult to determine which are the dominant factors that develop and maintain phytoplankton blooms in the Suisun Bay area (Ball 1977). The highest chlorophyll peaks between 1969 and 1977 were measured during the period of maximum water temperature (23 to 25°C) and slightly after the period of maximum insolation. These data suggest that high water temperatures and solar radiation levels stimulate the phytoplankton growth rate to produce high level standing crops. However, low standing crops occurred during July-September of 1974, 1975, 1976, and throughout 1977. These differences indicate that high standing crops will occur only if factors in addition to insolation, water temperature, and available nutrients are favorable for growth.

Prior to 1976 we believed that the Suisun Bay phytoplankton standing crop was directly related to the water transparency and indirectly related to Delta outflow (Ball 1975). But, while the 1976 and 1977 summer water transparencies were nearly double those of the previous seven years and the outflows were at record lows, only a late winter and a spring bloom developed in 1976 and no bloom occurred in 1977. This pronounced inconsistency with preceding trends prompted special studies in 1977 which evaluated all possible factors influencing phytoplankton standing crop (see also Arthur and Ball 1979).

It became apparent that chlorophyll *a* concentrations above 20 $\mu g \cdot liter^{-1}$ (Figs. 16A,B) developed only when the Delta outflow was between about 700 (25,000) and 110 $m^3 \cdot s^{-1}$ (4,000 $ft^3 \cdot s^{-1}$). Below about 110 $m^3 \cdot s^{-1}$ (4,000 $ft^3 \cdot s^{-1}$), the standing crop either declined or remained low.

The tidally-averaged location of the entrapment zone is adjacent to the shallows of the Suisun-Honker Bay area when the outflow varies between 110 and 700 $m^3 \cdot s^{-1}$. Such a location appears to provide the potential for a high phytoplankton standing crop if other environmental factors are favorable (hypotheses are discussed by Arthur and Ball 1979).

The shallowness of Suisun Marsh may promote relatively high chlorophyll concentrations and minimize the growth-limiting effects of high water turbidity. Because the salinity distribution is similar to that of Suisun Bay, many of the factors influencing growth there are probably present in Suisun Marsh. The few available nutrient data indicate that inorganic nitrogen is depleted to limiting conditions during periods of high phytoplankton standing crops.

We do not know which factors most control phytoplankton growth in San Pablo Bay. As in Suisun Bay, estuarine circulation and nutrient limitation undoubtedly influence growth (see also Cloern 1979).

The 1977 drought year has provided us with interesting but puzzling findings. Areas of the southern and northern Delta experienced two- to six-fold increases in summer chlorophyll concentrations, respectively, whereas the western Delta, Suisun Bay and Marsh experienced two- to four-fold reductions. The increases are apparently due to increased water residence time and nutrient buildup during that period. The decreases in the western Delta and Suisun Bay are apparently caused by the landward migration of the entrapment zone (Arthur and Ball 1979). The cause of the chlorophyll *a* decrease in Suisun Marsh is unknown, but may also relate to salinity intrusion.

ACKNOWLEDGMENTS

These data were obtained from a coordinated monitoring program involving USBR and DWR and are stored in the Environmental Protection Agency's (EPA) national data storage and retrieval system (STORET).

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