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Abstract

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FACTORS INFLUENCING THE ENTRAPMENT OF SUSPENDED MATERIAL IN THE SAN FRANCISCO BAY-DELTA ESTUARY

JAMES F. ARTHUR AND MELVIN D. BALL
U. S. Bureau of Reclamation, 2800 Cottage Way, Sacramento, CA 95825

Inorganic suspended particulate matter, turbidity, particulate nutrients, phytoplankton, *Neomysis mercedis* (Holmes), certain other zooplankton, and juvenile striped bass (young-of-the-year) accumulate in an entrapment zone located in the upper San Francisco Bay-Delta estuary (Sacramento-San Joaquin River System). The location of this entrapment zone is regulated by the magnitude and the pattern of river inflow, as well as the tidal excursion. At Delta outflow indices of 20 $m^3 \cdot s^{-1}$, the zone was located 40-45 km upstream of its location at 1,800 $m^3 \cdot s^{-1}$; tidal movement of the zone is from 3 to 10 km, depending on tidal phase and height. The location of the zone is related to, and can be approximated from, specific conductance values of 2 to 10 millimho$\cdot cm^{-1}$ (1-6 ‰ salinity). The concentration of constituents in the zone varied directly with Delta outflow, water depth, and tidal velocity. Depending on the constitutent and environmental conditions at the time of measurement, the suspended-material concentration varied from as little as twice to as much as several hundred times the upstream or downstream concentration. The most significant environmental aspect of the entrapment zone may be that the quantity of phytoplankton and certain other estuarine biota appear to be enhanced when the zone is located in upper Suisun Bay.

Bureau of Reclamation (USBR) and the California Department of Water Resources (DWR) plans call for large pumped diversions from the southern portion of the Sacramento-San Joaquin Delta and possible construction of a drain (for removal of saline subsurface agricultural water from the San Joaquin Valley) which may discharge in the general vicinity of Suisun Bay.

The USBR is cooperating with the U. S. Fish and Wildlife Service (USFWS), the California Department of Fish and Game (DFG), and DWR in conducting environmental studies ("Interagency Ecological Study Program") to evaluate the potential impact of these projects on the estuary. This chapter describes one aspect of this program: the determination of how changes in Delta outflow and flow patterns, attributable to the operation of the federal and state water projects, might influence the distribution and abundance of estuarine phytoplankton and other particulate material (Ball 1977; Arthur and Ball 1978). Among the factors evaluated thus far, the entrapment zone appears to be a major feature regulating the phytoplankton standing crop in Suisun Bay (Arthur 1975; Arthur and Ball 1978).

BACKGROUND

Phytoplankton are important to the estuarine environment as primary producers, with certain species forming the base of the food web. However, in many aquatic environments, excessive concentrations of phytoplankton cause eutrophication (i.e. reductions in dissolved oxygen concentrations to a point detrimental to higher aquatic organisms), create taste and odor problems in municipal water supplies, clog filters in water treatment plants and/or are aesthetically undesirable for recreationists. However, phytoplankton problems presently appear minor and the maximum desirable concentration and species composition of phytoplankton has yet to be determined

(Arthur and Ball 1978) in the study area (Fig. 1).

The quantity of freshwater flowing through the estuary is important to phytoplankton growth because it regulates nutrient concentration, determines riverborne sediment inflow and influences suspended-particle transport which in turn affects light-penetration (required for algal growth), determines phytoplankton residence time, and directly regulates salinity intrusion and the location of the entrapment zone. These and other factors interact to determine the amount and type of phytoplankton in the estuary (Arthur and Ball 1978). Ball (1977) and Ball and Arthur (1979) have evaluated factors influencing the temporal and spatial distribution and abundance of phytoplankton throughout the San Francisco Bay-Delta estuary.

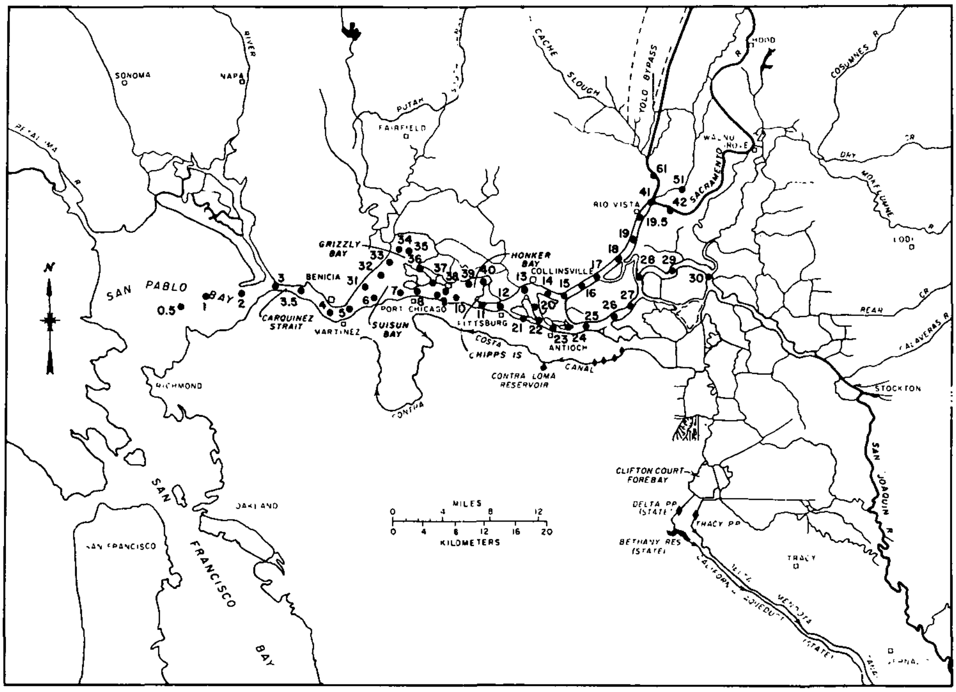

Fig. 1. Sampling sites of entrapment zone study.

Krone (1966, 1979), among others, has speculated that under projected low flow conditions resulting from water development projects the sediment input to the estuary would be greatly reduced, resulting in a greater photic depth in Suisun Bay. This increase in photic depth could potentially increase the phytoplankton standing crop to undesirable concentrations.

In evaluating the probable effects of subsurface agricultural drain discharge to the estuary, Bain (1968) concluded that this discharge would about double the concentration of nitrogen in Suisun Bay which could result in severe algal blooms accompanied by depressions in dissolved oxygen as the blooms decline. As a result, methods were studied for removing nitrogen from drainage water (Brown 1975) and studies were conducted on the potential impact of drain water on the Delta environment (USBR 1972).

In reviewing water quality data and factors controlling phytoplankton growth during the 1968-74 period (Arthur 1975; Ball 1975, 1977), long-term averages of phytoplankton, chlorophyll, particulate organic nitrogen and particulate phosphate, turbidity, and inorganic suspended solids were found to be at higher concentrations in Suisun Bay than in the adjacent upstream or downstream areas. Since phytoplankton concentrations were highest in Suisun Bay, while light penetration was lowest and water temperatures and nutrient concentrations were generally favorable, some other mechanism(s) apparently was responsible for the high phytoplankton concentrations.

Further evaluation of other historical water quality data and review of suspended-materials distribution studies for the area (for example, Simmons 1955; Einstein and Krone 1961; Meade 1972; Peterson and Charnell 1969; Conomos and Peterson 1974, 1977; Peterson et al. 1975a,b) and for other estuaries (Wiley 1977) has led us (Arthur 1975; Ball 1977; Arthur and Ball 1978) to conclude that suspended materials are entrapped and accumulate in the estuary at the upstream end of the fresh-water–salt-water mixing zone. We theorize that the causes of this entrapment are the increased flocculation, aggregation, and/or settling of suspended materials at specific conductances above 1 millimho/cm (0.6 °/oo salinity) and the effects of net two-layered estuarine circulation flow (California DFG et al. 1975, 1976). Terms used by others to describe the area of maximum concentration of suspended materials are the "turbidity maximum," "critical zone," "nutrient trap," "sediment trap" and "null zone" (Arthur and Ball, 1978). We prefer the more descriptive "entrapment zone" (Arthur 1975).

Studies in the San Francisco Bay-Delta Estuary

As early as 1931, Grimm stated there were net upstream bottom currents in the San Francisco Bay Estuary. Since then, studies (Simmons 1955; U. S. Army Corps of Engineers 1967, 1977; Smith 1966; McCulloch et al. 1970; Conomos 1975, 1979; Conomos et al. 1970, 1971; Conomos and Peterson 1974; Peterson et al. 1975a) have demonstrated that a net two-layered flow circulation pattern exists throughout much of the northern reach of the Bay system. This generalized flow is believed to be significantly modified by "trapping" and "pumping" (two forms of tidal dispersion) and wind dispersion (Fischer 1976).

The location of the entrapment zone, the effects of riverflow on its location, and seasonal changes in the abundance and composition of suspended matter in the zone have been described (Conomos and Peterson 1974; Peterson et al. 1975a, b; Arthur 1975; Ball 1977; Arthur and Ball 1978). These and other studies produced a reasonably good understanding of how two-layered flow influences sediment transport in this and other estuaries.

In contrast, very little is known about the effects of two-layered flow on the estuarine biota. Although no specific studies were conducted on the effects of two-layered flow on the plankton and benthos in the entrapment zone, an early conclusion (Kelley 1966) was that of the environmental factors studied, chlorinity (salinity) was most responsible for species distribution of zooplankton and zoobenthos. Recent evaluations (Arthur 1975; Arthur and Ball 1978; Siegfried et al. 1978; Orsi and Knutsen 1979) indicate that zooplankton entrapment occurs. Riverflow and salinity were considered the dominant factors controlling longitudinal distribution of a number of species of fish in the estuary (Turner and Kelley 1966). Furthermore, the maximum concentration of juvenile striped bass (young-of-the-year) are known to occur within specific salinity ranges (Turner and Chadwick 1972; Stevens 1979).

The summer phytoplankton and zooplankton maxima were observed in the entrapment zone (Conomos and Peterson 1974; Peterson et al. 1975a,b; Arthur 1975; Ball 1977; Arthur and Ball 1978).

ESTUARINE HYDRODYNAMICS AND SUSPENDED MATERIAL TRANSPORT

The study area is considered an estuary characterized by two-layered flow with appreciable vertical mixing during most of the year (Conomos 1979). According to Bowden (1967), estuaries having such flow and mixing are generally shallow. The tidal currents are of increasing amplitude and extend throughout the depth mixing the fresher water downwards and the more saline water upwards. Although vertical mixing occurs, there are still two layers of net flow separated by a plane of no-net-motion which is generally above mid-depth (Fig. 2). The salinity continuously increases from the water surface to the bottom with the maximum salt gradient occurring at the plane of no-net-motion.

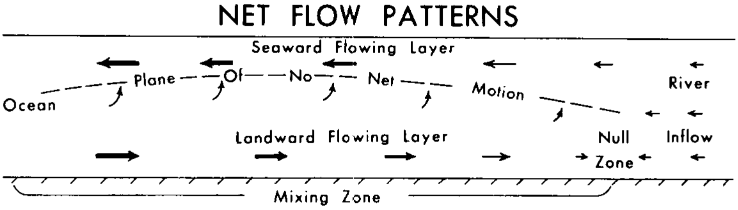

Fig. 2. Theoretical net flow patterns in a two-layered flow with vertical mixing estuary.

A wide range in water stratification exists in this type of estuary and is dependent on the ratio of the amplitude of tidal currents to the riverflow and depth. The increase in salinity from surface to bottom may vary from 1 to 10 °/oo (specific conductance of approximately 1.5 to 15 millimho·cm^{-1}). The net seaward flow of the upper layer may be several times the river inflow (Bowden 1967).

The primary driving force causing the net upstream flow in the lower layer of water is the salt-induced density difference between the surface and bottom waters (Fig. 3). Because of this density difference, freshwater entering the estuary with a greater hydraulic head tends to flow over the denser, more saline water (Simmons 1955; Schultz and Simmons 1957; Helliwell and Bossanyi 1975; Krone 1972). The greater the river inflow, the greater the hydraulic head or vertical gradient and, consequently, the greater the seaward-driving force. High river flows drive the mixing zone of freshwater and seawater farther seaward, increase salinity stratification, and compress the mixing zone (Arthur and Ball 1978; Conomos 1979). The turbulent forces of tides and winds tend to destroy vertical salinity stratifications (Nichols and Poor 1967; Conomos 1979).

The two-layered flow theoretically influences the maximum tidal-current velocities of each layer. Because there is a net downstream flow in the surface layer, surface velocities are greater

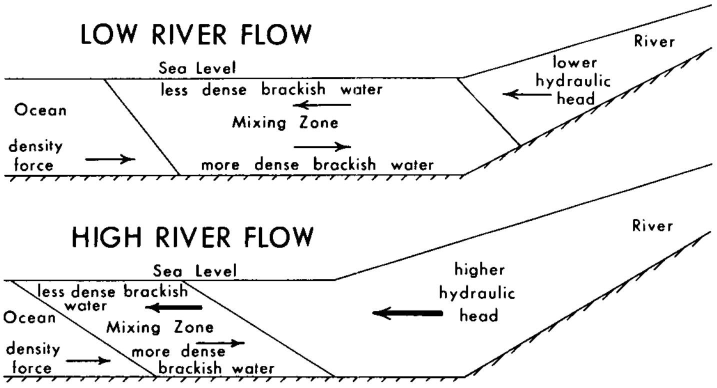

Fig. 3. The primary driving forces controlling two-layered flow circulation in the estuary.

during ebb tides than during flood tides, while in the lower layer, the reverse occurs. Higher velocities occur during flood tides than during ebb tides and increase the net upstream transport of materials along the bottom (Postma 1967).

Several factors influence the transport of suspended materials (Fig. 4). In our laboratory studies we have demonstrated that increasing the salinity of Delta water (starting at about 1.0 millimho/cm specific conductance [0.6 ‰]) enhances flocculation of the suspended inorganic particles (primarily in the 2- to 10-μ size range) into aggregates. These aggregates settle at rates greater than the unaggregated materials and are transported downstream out of the estuary or settle into the lower layer and are returned upstream where they concentrate in the entrapment zone (Simmons 1955; Krone 1966; Meade 1972; Conomos and Peterson 1974, 1977). Larger and denser materials may settle out near slack tides and then be resuspended as tidal velocity increases. The less dense and smallest suspended materials tend to be carried into the upper layer as a result of the net upward vertical flow and are transported seaward. A portion of the suspended material is transported laterally into shallow areas and may be deposited in shoals. Some of the sedimented materials may be resuspended by tidal or wind action and transported back to the channel. Suspended materials in the lower layer may be transported upstream to the entrapment zone where the areas of maximum concentration and maximum water residence time occur. Theoretically the entrapment zone occurs slightly downstream of where the net vertical water velocities are thought to be the greatest. As the aggregates move into the fresher water, partial disaggregation may occur. The materials that enter the upper layer are again transported seaward and theoretically can be recirculated numerous times. Under low riverflows, suspended sediment settles into the lower layer farther upstream in the estuary than during high flows. Conversely, during high riverflows, a larger portion of the fine suspended sediment is transported to the ocean.

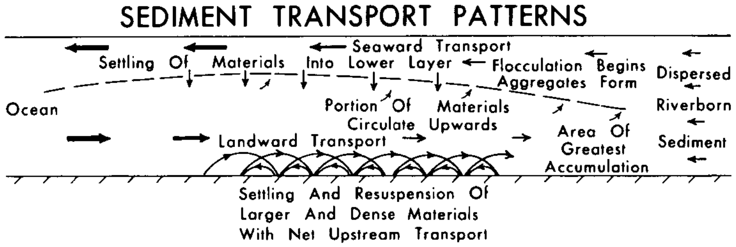

Fig. 4. Theoretical transport patterns of suspended materials in a two-layered flow with vercally mixing estuary.

FIELD OBSERVATIONS

Studies conducted from 1973 through 1977 (Arthur and Ball 1978) and summarized in this chapter were designed to characterize the distribution of suspended materials in the entrapment zone over a range of river discharge in order to determine how the zone influences the water quality and biota (primarily the phytoplankton).

River Discharge

Delta outflow (river discharge past Chipps Island, site 11) was the main variable in the study.

Daily Delta Outflow indices (DOI), calculated by the USBR and DWR, were used in this study. The DOI consists of the Sacramento River discharged at Sacramento plus the San Joaquin River discharge at Vernalis, less the pumped Delta export and the estimated Delta consumptive use (see Conomos 1979, Fig. 11). The consumptive use coefficient estimate varies seasonally but is constant between years. The coefficient is as high as 130 $m^3 \cdot s^{-1}$ in midsummer. Consequently, since crop and weather patterns change between years, under very low flows the DOI lacks precision. This error during typical summer outflow conditions may be as great as ±30 to 60 $m^3 \cdot s^{-1}$. Furthermore, the Yolo Bypass (which has tidally influenced discharge that would be hard to measure) and other peripheral streams also contribute significant discharges to the Delta outflow especially during periods of high runoff (over 1,400 $m^3 \cdot s^{-1}$). Measurements of these additional stream discharges are not included in the DOI but have been incorporated into another calculated outflow (average monthly historical Delta outflow) which still utilizes the consumptive use estimate. The historical Delta outflow, although only a monthly average, is the more accurate of the two for total discharges from the Delta (Fig. 5). Since the DOI is the only daily calculation readily available, the index is usually used when referring to Delta outflow even though it is an underestimate of high flow.

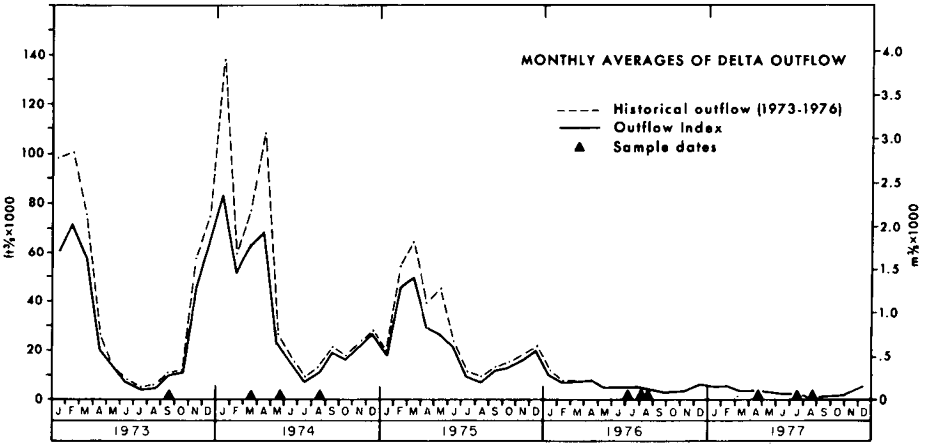

Fig. 5. Comparison of the Delta outflow index and the historical Delta outflow during the study period.

The Delta outflow during the 1973 through 1975 period was above normal, while during 1976 and 1977 it was the lowest since completion of Shasta Reservoir (the main water storage reservoir of the Central Valley Water Project).

Salinity Intrusion

The 2 millimho/cm specific conductance (1 °/oo salinity) isocontour shifted nearly 45 km over the range of DOI studied (23-1,800 $m^3 \cdot s^{-1}$) (Fig. 6).

In addition to the quantity of the riverflow, the pattern of flow also appears to influence the salinity distribution. For example, although the September 1973 and August 1974 surveys were conducted at near identical Delta outflows, there was greater compression of the 2-25 millimho·cm^{-1} (1 to 15 °/oo salinity) water mass in 1973. There had been several months of low flow (the average DOI for July and August was 130 $m^3 \cdot s^{-1}$) prior to September 1973; while prior to the

August 1974 survey the DOI was nearly twice as large (Fig. 5).

Salinity stratification increased with increasing Delta outflow. The isoconductivity contours in March 1974 demonstrated greater vertical stratifications than during the low outflow of August 1977 (Fig. 6). The degree of stratification apparently also influences the distribution patterns of suspended materials.

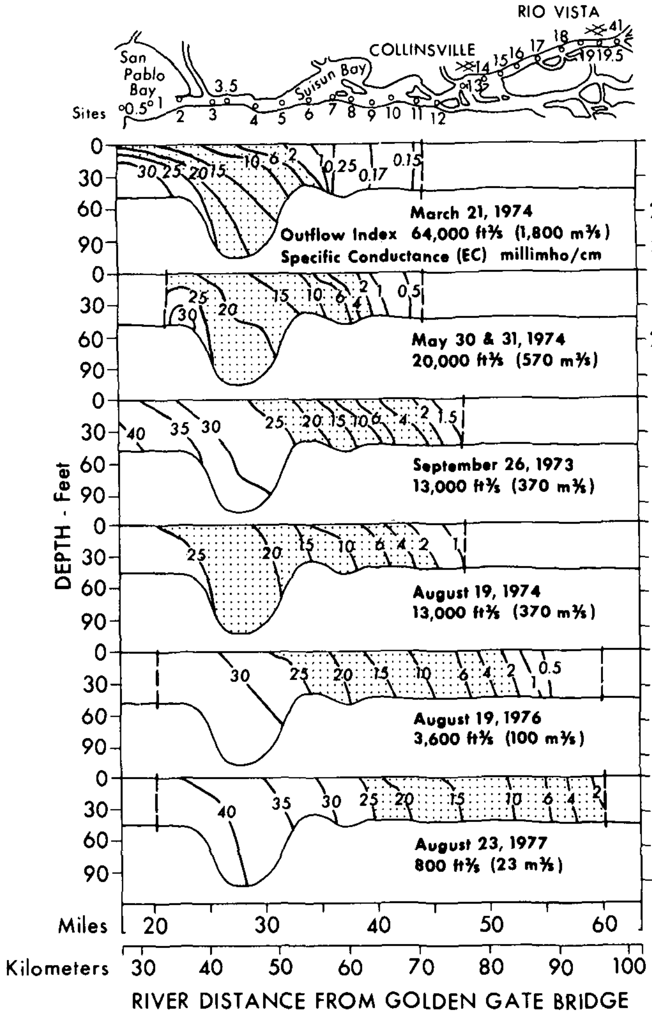

Fig. 6. Isoconductivity (salinity) contours measured on high slack tides at various Delta outflows (the 2-25 millimho/cm EC range has been arbitrarily shaded).

Typical variations in tidal excursion that occur in the study area are demonstrated for the 19-21 August 1974 and the 23 August 1977 data (Figs. 7, 8). The 1974 data were collected on three consecutive days with DOI = 370 $m^3 \cdot s^{-1}$, while the 1977 data were collected on a single day at DOI = 23 $m^3 \cdot s^{-1}$. The tidal excursion measured for the August 1974 run was nearly 10 km and occurred on a greater flood, close to a spring tide (with relatively high tidal velocities). Conversely, the tidal excursion for the August 1977 observations was only about 3 km. The reduced excursion

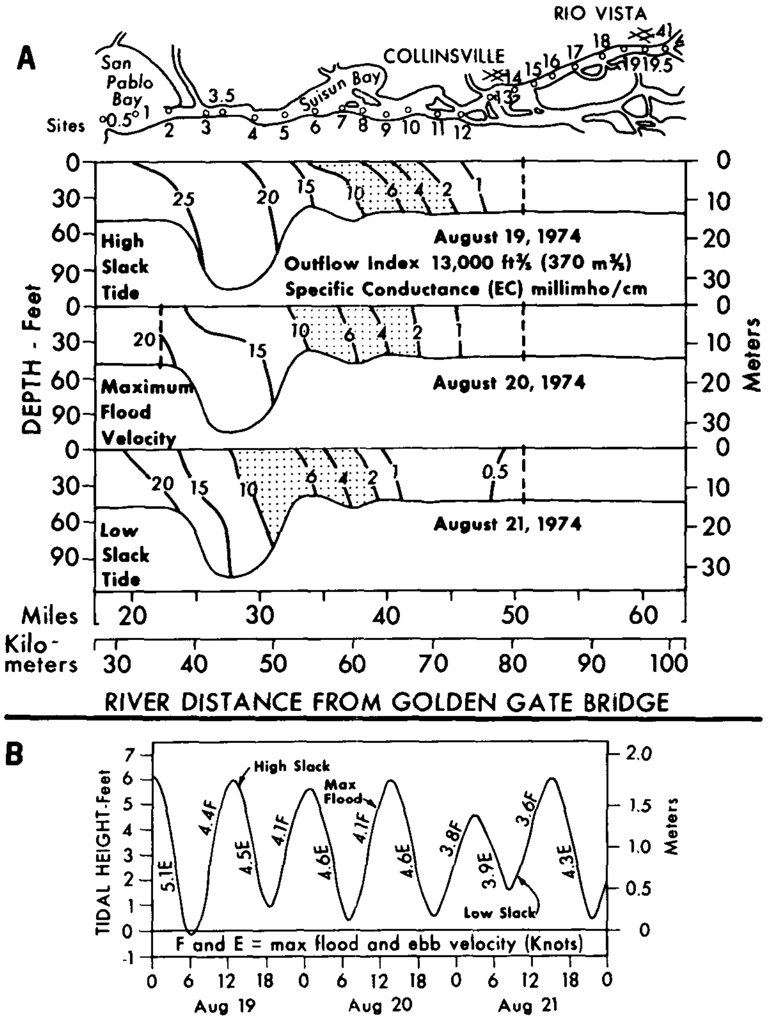

Fig. 7. A. Isoconductivity (salinity) contours measured on three consecutive days during different tidal phases during August 1974. B. Calculated Golden Gate Bridge tidal heights and maximum flood and ebb (F and E) velocities in knots.

resulted from the low tidal velocities and the slight difference in tidal heights occurring on the lesser ebb near a neap tidal period.

Suspended Material Distributions

The distribution patterns of suspended particulate matter and dissolved constituents were characterized in the upper estuary at selected DOI ranging from 23 to 1,800 $m^3 \cdot s^{-1}$ between September 1973 and September 1977 (Arthur and Ball 1978).

Total suspended solids (TSS) correlated well with turbidity, the latter of which was measured more extensively. Areas of maximum turbidity at various Delta outflow were typically located where the surface water was in the 2-10 millimho·cm^{-1} specific conductance (1-6 °/oo salinity) range in both the Sacramento and San Joaquin rivers (Figs. 9 and 10). Because suspended materials accumulated in this salinity range, the 2-10 millimho·cm^{-1} surface specific conductance contour (SUR EC) was added to the illustrations as a reference.

The maximum turbidity in the entrapment zone varied from 2 to 40 times the upstream and downstream levels and increased up to 20 times with depth. The maximum turbidity, over 800 Formazin turbidity units (FTU; USEPA 1971) was centered in Carquinez Strait during the highest Delta outflow studied (1,800 m^3·s^{-1}). In contrast, during 1977 (one of the lowest river discharge years on record), maximum turbidities of about 60 FTU were measured at DOI = 23 m^3·s^{-1} and the entrapment zone was centered about 40 km upstream of Carquinez Strait.

Volatile suspended solids (VSS) also peaked in the entrapment zone and were approximately 10-20% of the TSS.

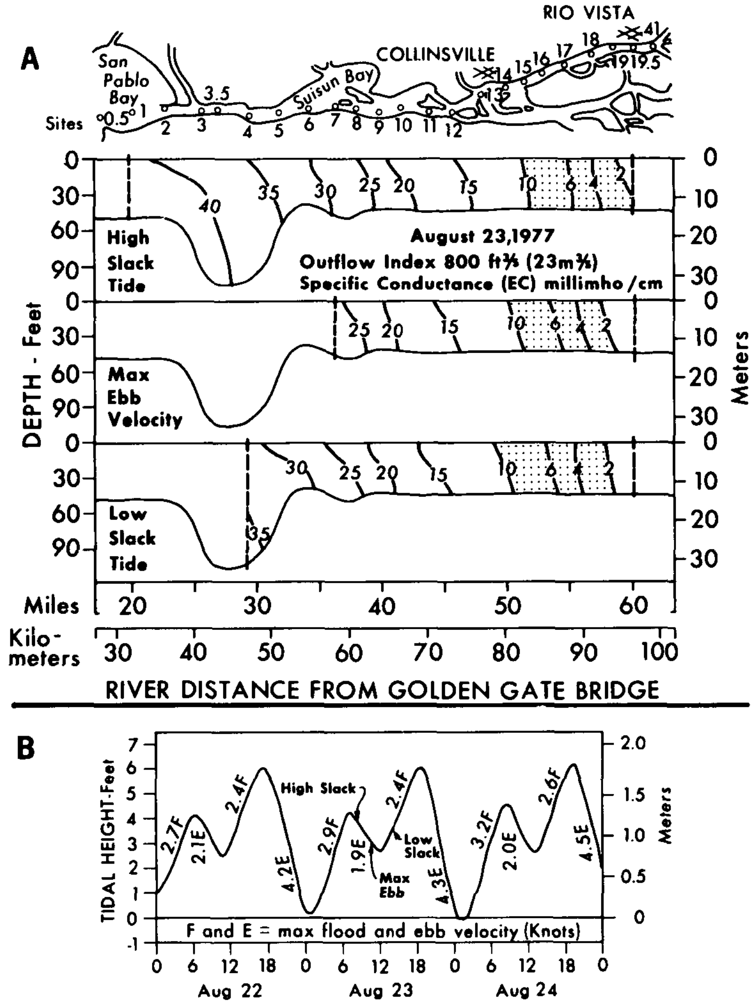

Fig. 8. A. Isoconductivity (salinity) contours measured on three consecutive tidal phases on 23 August 1977. B. Calculated Golden Gate Bridge tidal heights and maximum flood and ebb (F and E) velocities in knots.

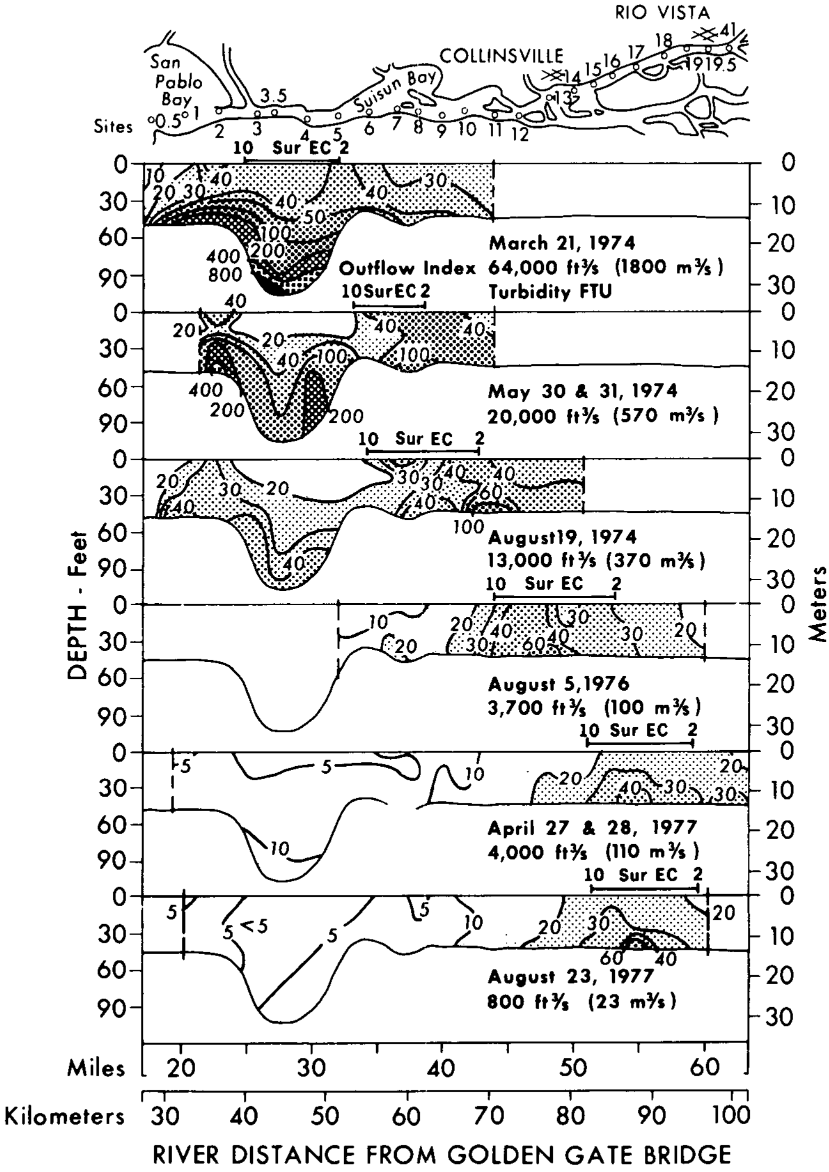

Fig. 9. Turbidity distribution relative to salinity on high slack tides at various Delta outflows.

Differences in the amount of resuspension and settling were observed between the greater and lesser flood and ebb tides (Fig. 11). The greatest resuspension of materials (between slack and maximum tidal velocity) was observed when tidal height differences and maximum velocities were high (Fig. 7) as opposed to when they were low (Fig. 8).

The maximum concentration of particulate organic nitrogen and phosphorus also typically occurred in the same general area as the maximum turbidity.

Distribution of Dissolved Materials

Dissolved constituents, of course, are not subject to entrapment by two-layered flow circulation. The concentration of nitrate+nitrite (Fig. 12), ammonia and orthophosphate generally increased with water depth and peaked downstream of the entrapment zone (see also Peterson 1979; Conomos et al. 1979).

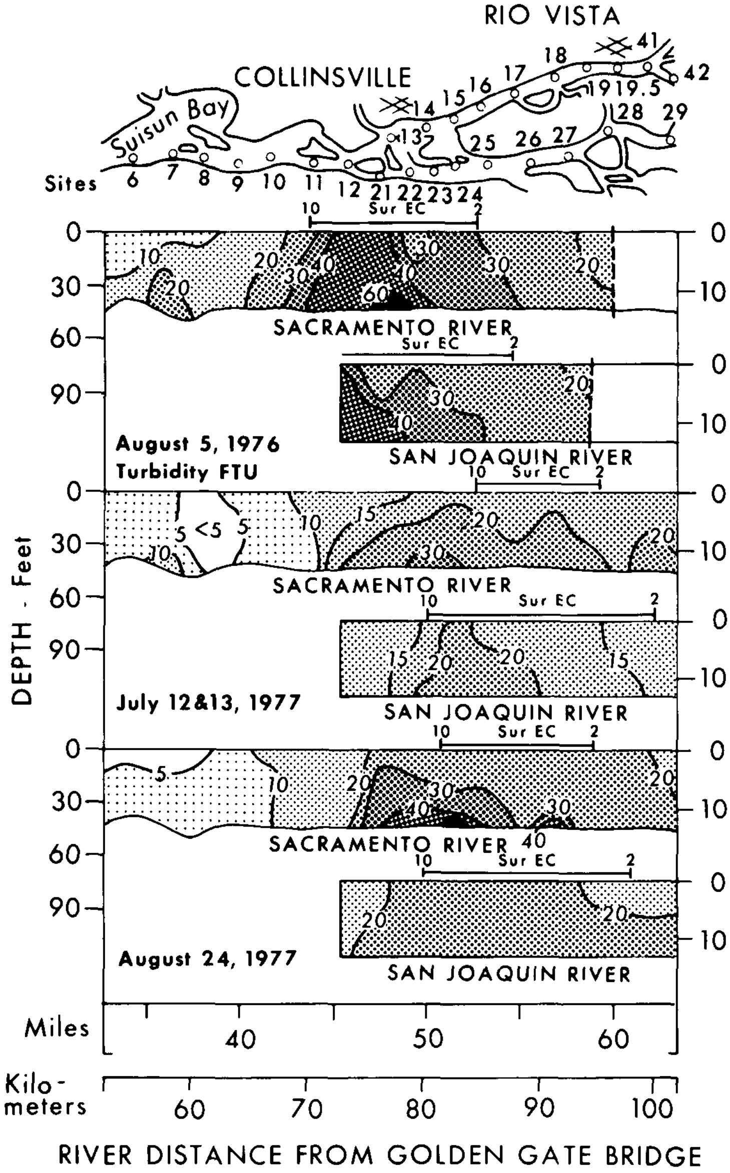

Fig. 10. Turbidity distribution in the Sacramento and San Joaquin rivers relative to salinity on high slack tides during low Delta outflow in 1976 and 1977.

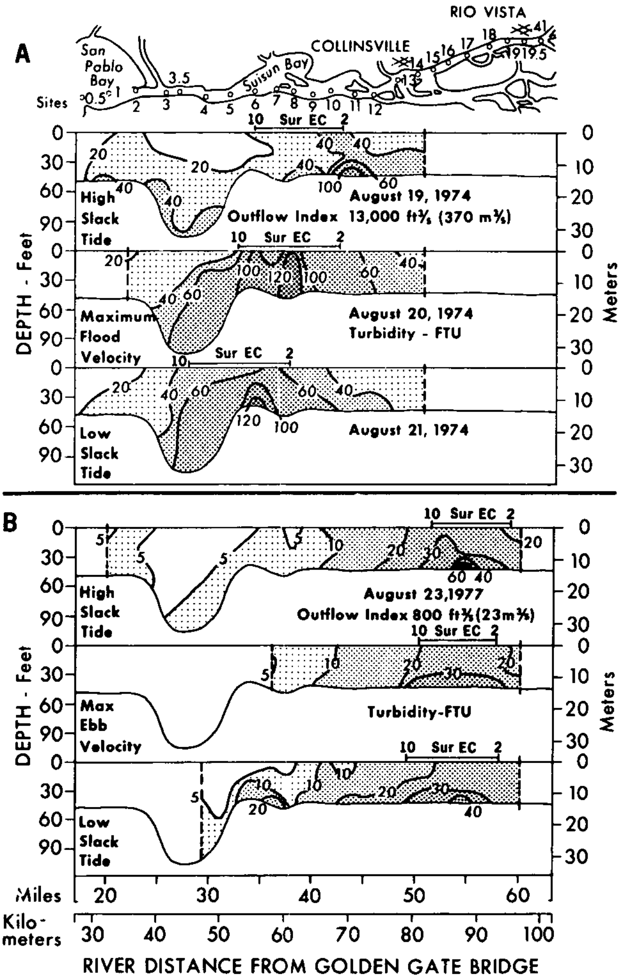

Fig. 11. A. Turbidity distribution relative to salinity measured on three consecutive days during different tidal phases in August 1974. B. Turbidity distribution relative to salinity measured on three consecutive tidal phases on 23 August 1977.

Distribution of Estuarine Biota

The same estuarine-circulation forces that influence the accumulation of suspended solids and particulate nutrients in the entrapment zone also appear to determine the distribution patterns of phytoplankton, certain zooplankton, and juvenile striped bass (young-of-the-year).

The chlorophyll *a* concentration, over a range of Delta outflows (Fig. 13), typically peaked in the entrapment zone at all Delta outflows studied. The peak concentrations in 1976 and 1977 (the two low-flow years) were the lowest ever recorded. The distribution of chlorophyll *a* and the dominant phytoplankton genera were similar throughout the study area and peaked in the 2-10 millimho·cm^{-1} specific conductance (1 to 6 °/oo salinity) range (Fig. 14). The maximum concentration on the surface generally occurred downstream of the maximum concentration on the bottom during bloom periods (see also Ball and Arthur 1979; Conomos et al. 1979).

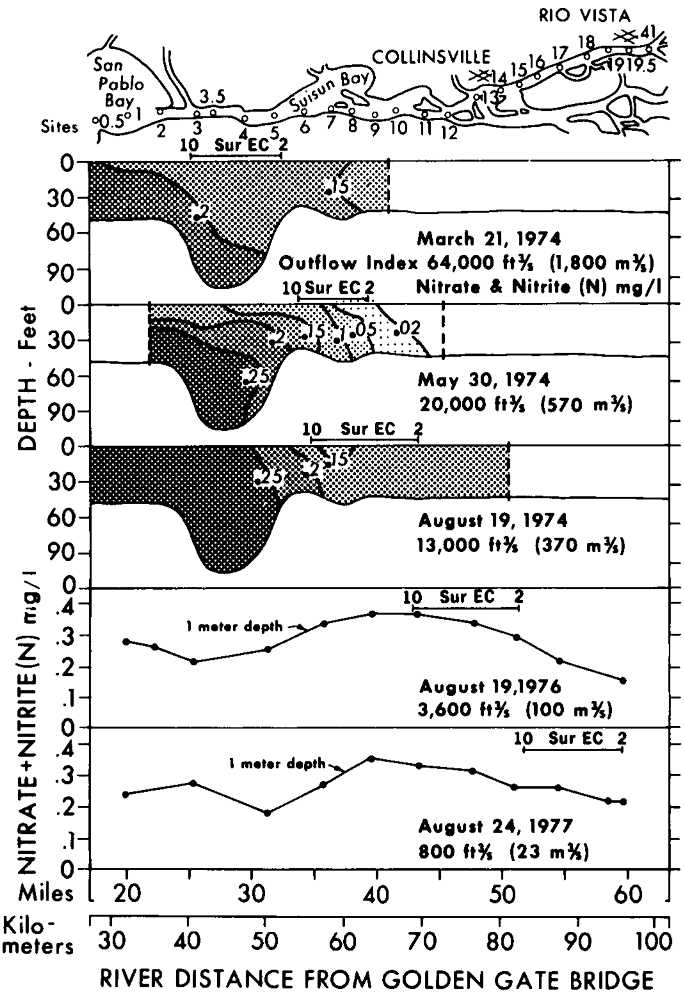

Fig. 12. Nitrate+nitrite distribution relative to salinity during high slack tides at various Delta outflows.

The various factors influencing the distribution of *Neomysis mercedis* and other zooplankton are discussed by Orsi and Knutsen (1979). The maximum abundance of *N. mercedis* and certain other zooplankton occurred in the 2-10 millimho·cm^{-1} specific conductance (1 to 6 °/oo salinity) range. Their distribution pattern relative to salinity (Fig. 15) was similar to that of the other constituents.

The copepod distribution indicated two peaks of abundance (Fig. 16). One peak, composed of *Eurytemora hirundoides*, was centered in the approximate location of maximum suspended solids concentration. The other peak, dominated by *Acartia clausi*, was farther downstream.

The distribution of 50-mm juvenile striped bass (young-of-the-year collected in July, 1973, 1974, 1976, and 1977; Fig. 17) also appears to be related to the distribution of other suspended constituents. The peak concentrations are also related to the surface 2-10 specific conductance (1 to 6 °/oo salinity) range. Similar distribution patterns were noted for other study periods.

DISCUSSION

Entrapment of suspended materials and certain estuarine biota were evident at the entire range of outflows studied in both the Sacramento and San Joaquin rivers. Since the peak concentrations of constituents typically occurred where the surface specific conductivity was approximately in the 2-10 millimho·cm^{-1} (1-6 °/oo salinity) range, this salinity range was selected to estimate the location of the entrapment zone.

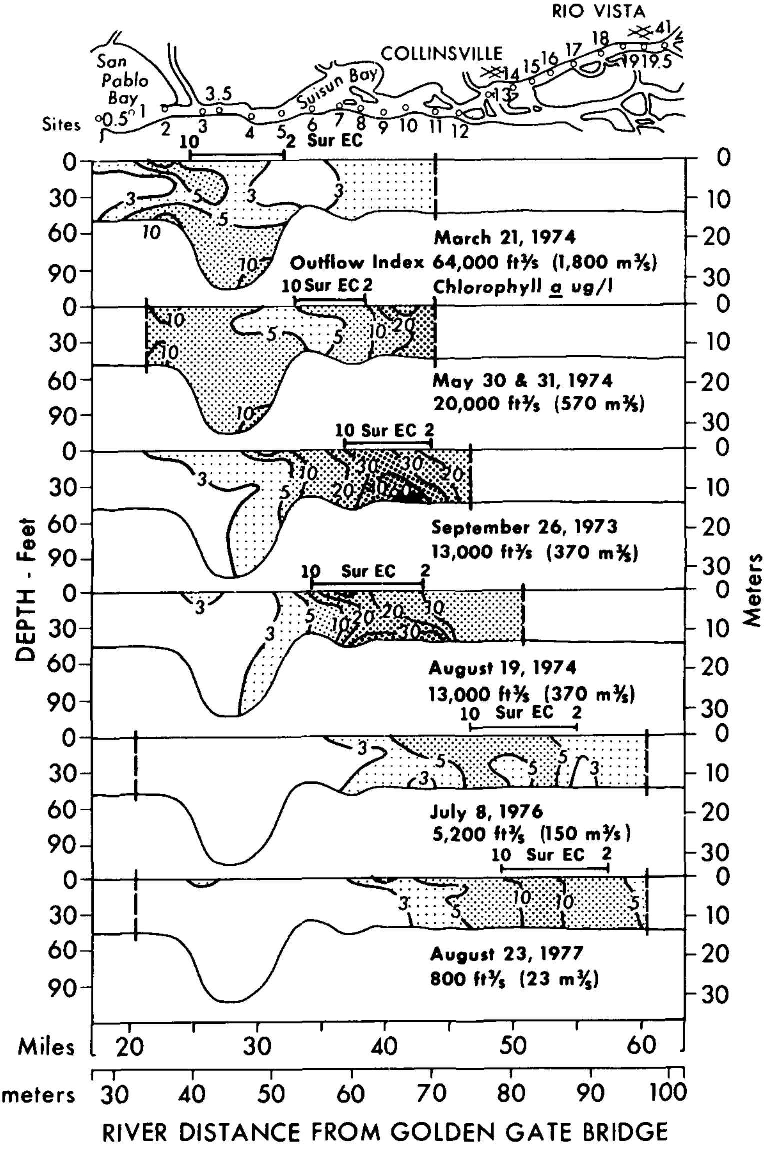

Fig. 13. Chlorophyll *a* distribution relative to salinity during high slack tides at various Delta outflows.

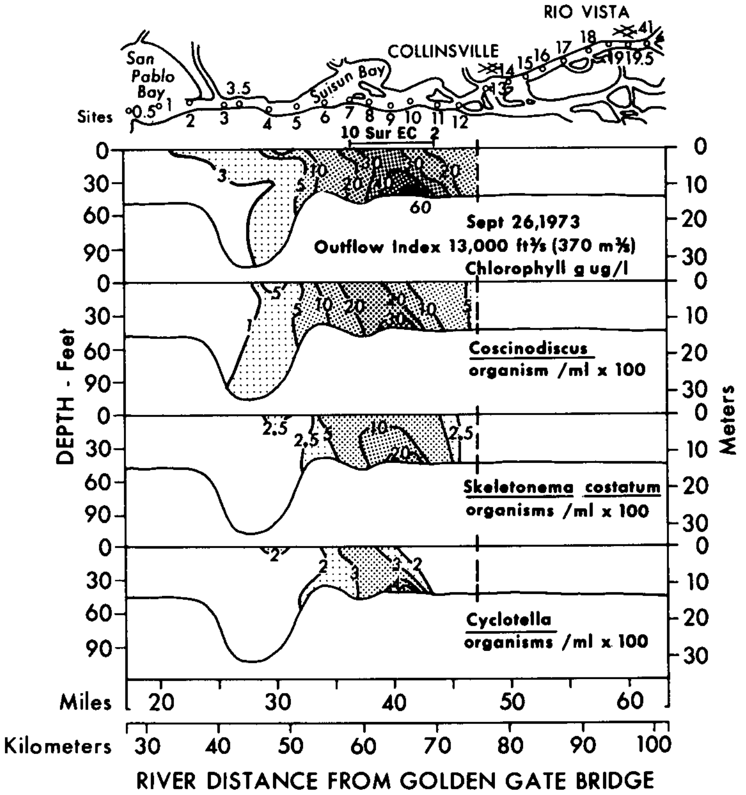

Fig. 14. Distribution of chlorophyll *a* and dominant phytoplankton genera relative to salinity during high slack tides on 26 September 1973.

Factors Influencing Suspended Materials Entrapment

Factors thought to influence the quantity of suspended materials in the entrapment zone include the riverborne suspended sediment load; flocculation, aggregation, and settling rates of particles; tidal- and wind-induced resuspension; bathymetry; dredging activities, and seasonal growth patterns of biota.

High suspended-sediment concentrations and loads to the estuary typically occur with winter floods and to a lesser extent in the late fall and early spring and increase the concentration of suspended materials observed in the entrapment zone.

In recent years, reservoir regulation of riverflows has reduced winter and spring riverflows and increased riverflows throughout the summer and early fall. Releases and drainage return flows have increased suspended sediment loads during the summer. However, flow regulation has resulted in an overall reduction of the total suspended sediment load as a result of settling that occurs in the reservoirs and sediments lost to export.

The Sacramento and San Joaquin rivers are the two main systems discharging suspended sediment to the Delta (Fig. 18). The Sacramento River (including the Yolo Bypass) contributes most (80%) of the total. The combined discharge is an estimate of the total suspended sediment load; however, during the flooding and very high outflows, suspended sediment discharge to the Delta from the Yolo Bypass may be equal to or even greater than that from the Sacramento River.

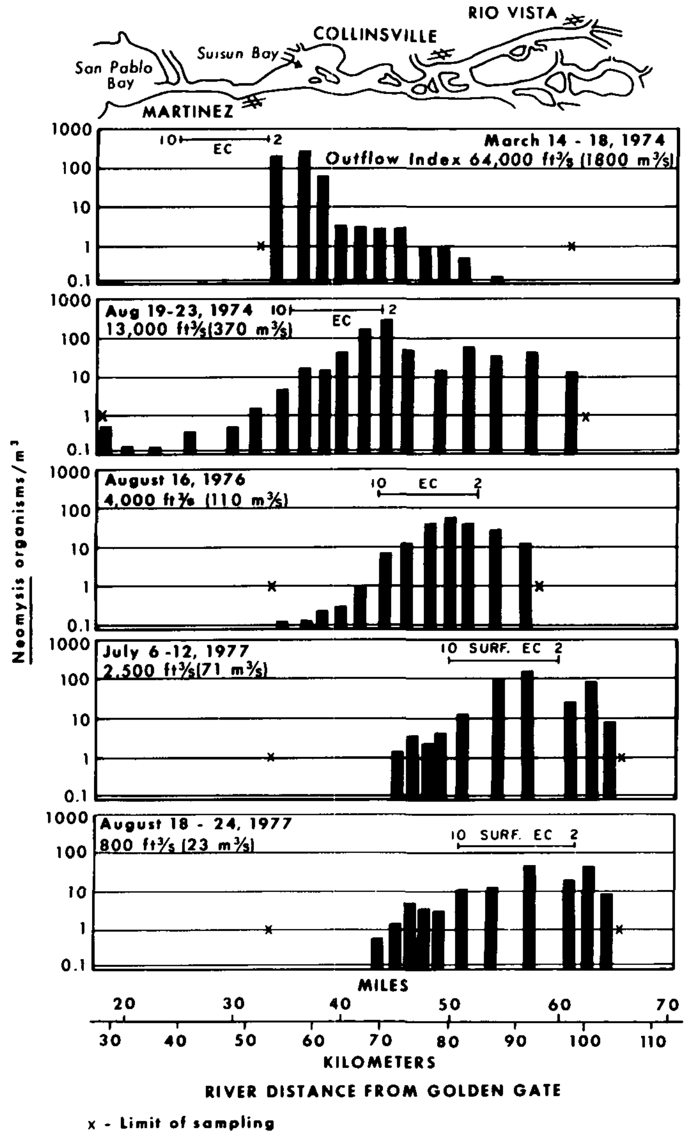

Fig. 15. *Neomysis mercedis* distribution relative to salinity on high slack tides at various Delta outflows (data collected by DFG).

Since the discharge from the Yolo Bypass is not measured, the total discharge to the Delta is often grossly underestimated.

The entrapment zone was located further seaward and with higher suspended-solids concentrations during periods of high suspended sediment discharge as compared to periods of low suspended sediment discharge (Fig. 9). These data support Postma's (1967) belief that the magnitude of the turbidity maximum (entrapment zone) is a direct function of the amount of suspended matter in the river or sea and the strength of the estuarine current.

The maximum suspended solids occurred in higher salinity water during high outflows as compared to low outflows (Fig. 9). This variation may have resulted from seasonal differences in water

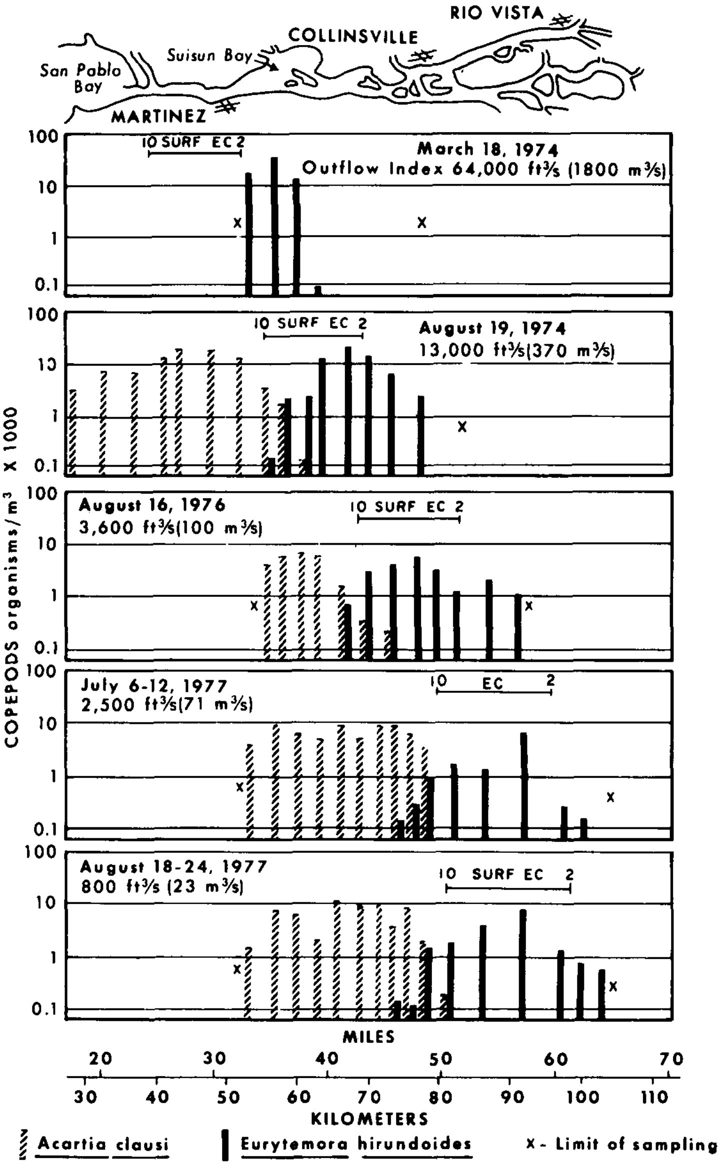

Fig. 16. Distribution of two dominant copepods (*Acartia clausi* and *Eurytemora hirundoides*) relative to salinity on high slack tides at various Delta outflows (data collected by DFG).

velocity or water temperatures. The greater net downstream velocity in the upper layer during high flows may carry the suspended materials further downstream and into more saline water before flocculation, aggregation, and settling of particles occurs. Alternatively, the settling velocity of particles could be decreased during winter by the colder water temperatures increasing the water viscosity.

There are different opinions as to what will happen to the water transparency in Suisun Bay as the amounts of riverborne sediment are decreased by future river diversions. One opinion is the water transparency is inversely correlated to the sediment load entering the estuary during any

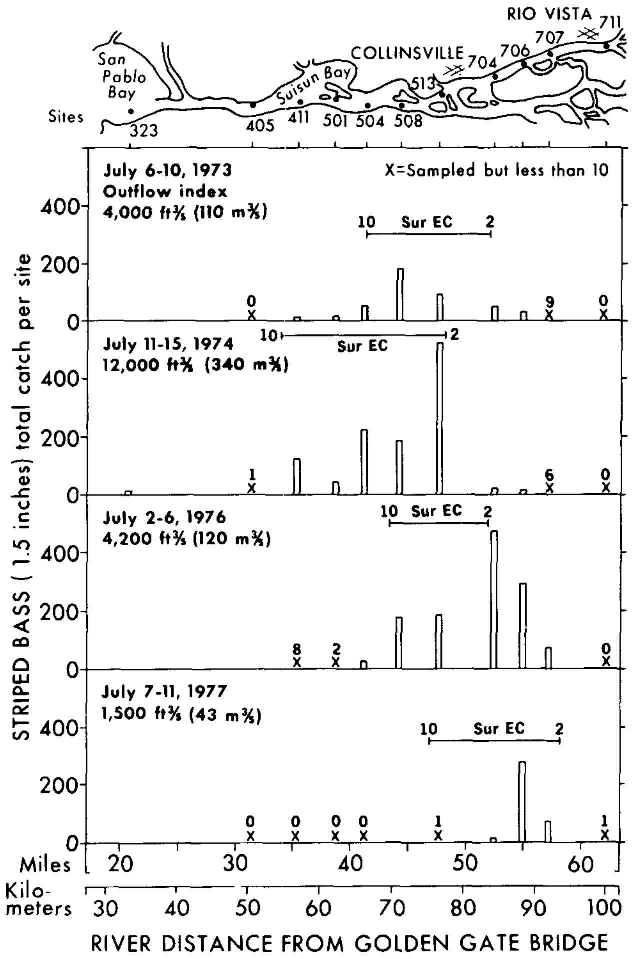

Fig. 17. Distribution of juvenile striped bass (young-of-the-year) relative to salinity on high slack tides during July 1973, 1974, 1976, and 1977 (data collected by DFG).

given year, and therefore, transparencies would increase with decreasing sediment loads. A second opinion is that winds and tidal currents along with tidal dispersion will resuspend large quantities of estuarine sediment and will maintain fairly constant transparency for many years of low river inflow.

Summer Secchi-disc measurements (made monthly during high-slack-tide from 1968-71 and twice monthly from 1972-77 by the DFG), as well as our turbidity measurements, have demonstrated a pronounced increase in water transparencies in Suisun Bay during 1976 and 1977, our two lowest outflow years. An inverse relationship between Suisun Bay water transparency and the summer Delta outflow (Fig. 19) suggests that the summer water transparency in Suisun Bay is strongly influenced by the Delta outflow. This outflow also regulates the entrapment zone location, with the zone moving upstream with the salinity intrusion and the waters of Suisun Bay becoming more transparent. Even though summer wind and tidal resuspension forces were considered to be about equal each summer, considerable transparency variation each year occurred between 1968 and 1977.

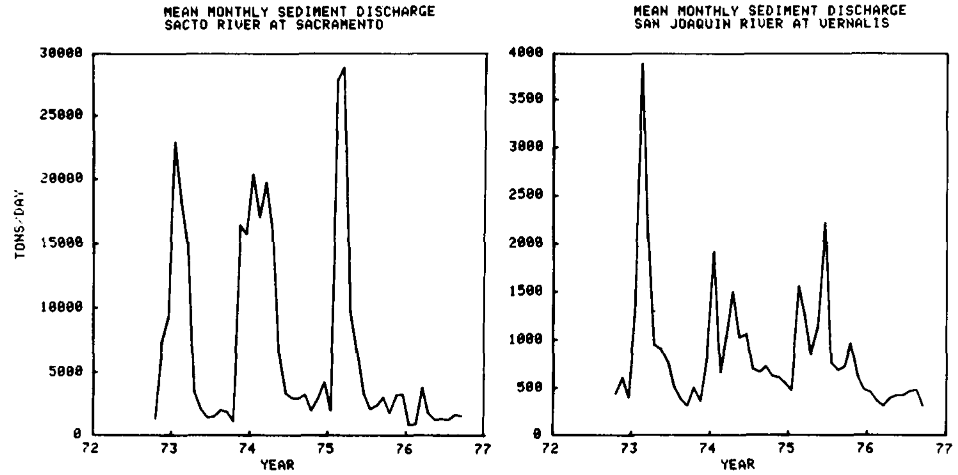

Fig. 18. Suspended sediment loads to the Delta. A. Sacramento River at Sacramento. B. San Joaquin River at Vernalis. Tons·day^{-1} scale differs for the two rivers.

In addition to outflow, both winter and summer sediment loads, the summer inflow sediment concentration and the location of the entrapment zone relative to shallow bays have been thought to influence the summer variation in transparency between 1968 and 1977.

To evaluate the first three factors, the routine Secchi-disc measurements at 14 channel sites between Rio Vista and Martinez (when occurring in water of 2-10 millimho·cm^{-1}) were averaged

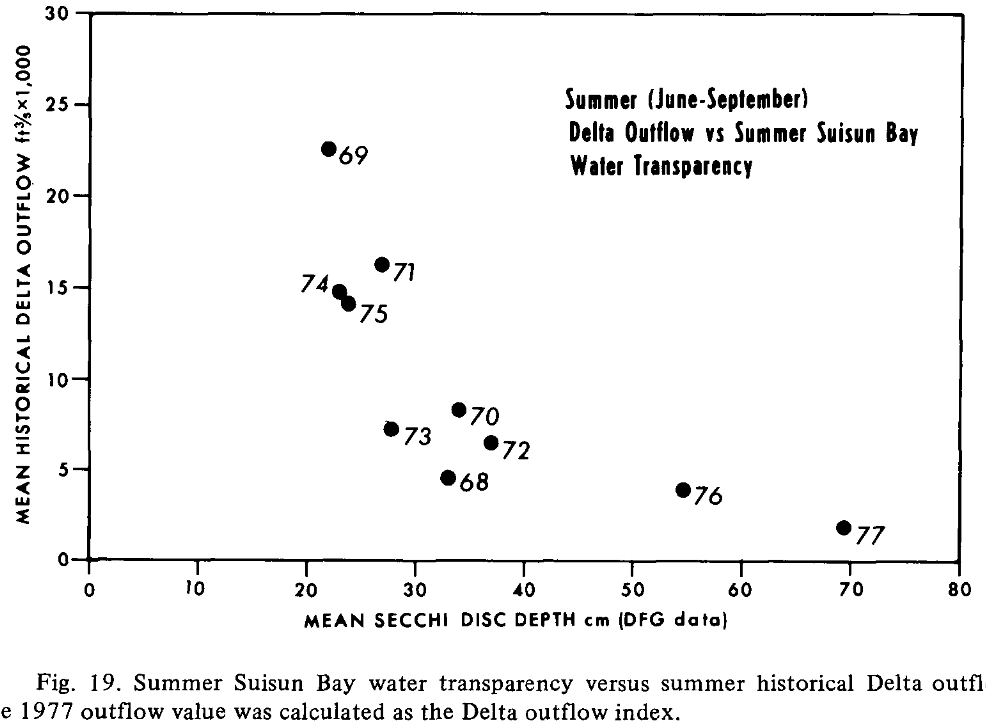

Fig. 19. Summer Suisun Bay water transparency versus summer historical Delta outflow. The 1977 outflow value was calculated as the Delta outflow index.

for each summer (June-September) and compared with the winter suspended sediment load (Fig. 20), summer suspended sediment load (Fig. 21), and summer suspended sediment concentration (Fig. 22). Although there appears to be a slight inverse relationship between the summer water transparency in the entrapment zone and the above factors, the relationships are not conclusive. Furthermore, the summer suspended sediment load as well as concentration were related to the winter load, as summer outflows that followed high outflow winters were usually also high. Since there is also so much variation in water transparency due to wind and tides one must use those evaluations with caution.

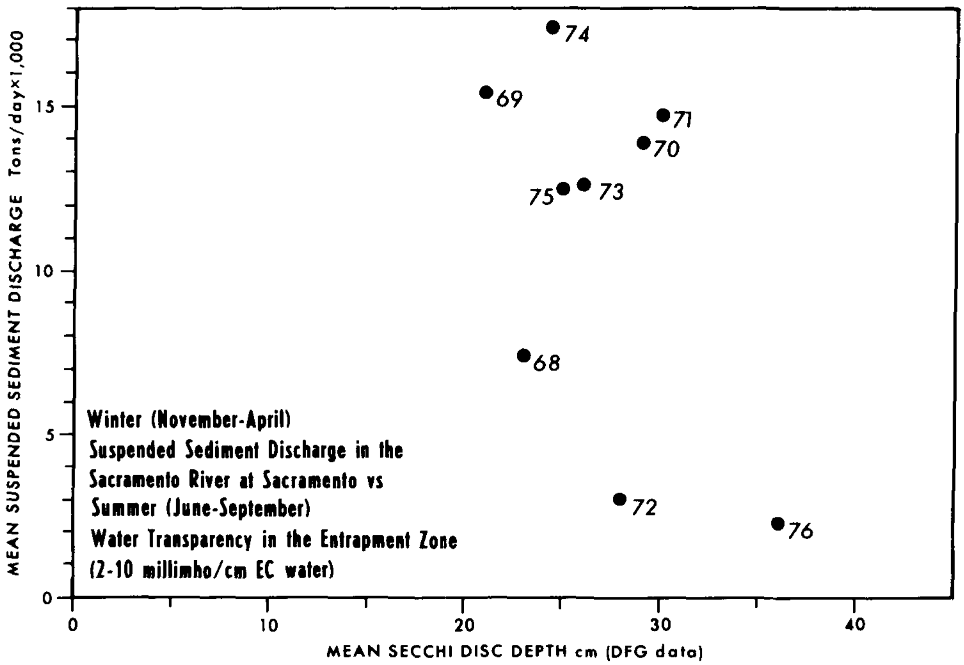

Fig. 20. Summer water transparency in the entrapment zone (2-10 millimho/cm EC range) versus winter suspended sediment load at Sacramento.

Arthur (1975), using Sacramento River water in which the salinity was adjusted with concentrated seawater brine from San Francisco Bay, demonstrated that flocculation, aggregation, and/or settling rates of suspended material increased as the specific conductance of the water samples was increased above 1 millimho·cm^{-1} (0.6 °/oo salinity) (Fig. 23).

We *initiated field measurements in 1975 to obtain particle settling-rate data for verification* of a suspended-solids model (O'Connor and Lung 1977) used by our study program (Arthur and Ball 1978). Particle settling rates were compared using two sampling methods. Samples from the entrapment zone were pumped into the first set of settling chambers, while the second set (special sampling-settling chambers designed by R. Krone, Univ. Calif. Davis) was lowered to the depth of sampling, the ends closed, and the settling chamber returned to the surface. Settling rates for both sets were determined by changes in turbidity at various heights in the chambers. The settling rates of particles collected by the submersible pump were several times less than those collected in settling chambers. These data suggest that the high turbulence caused by pumping disaggregates particles and imply that the particles were flocculated and/or aggregated before collection (USBR

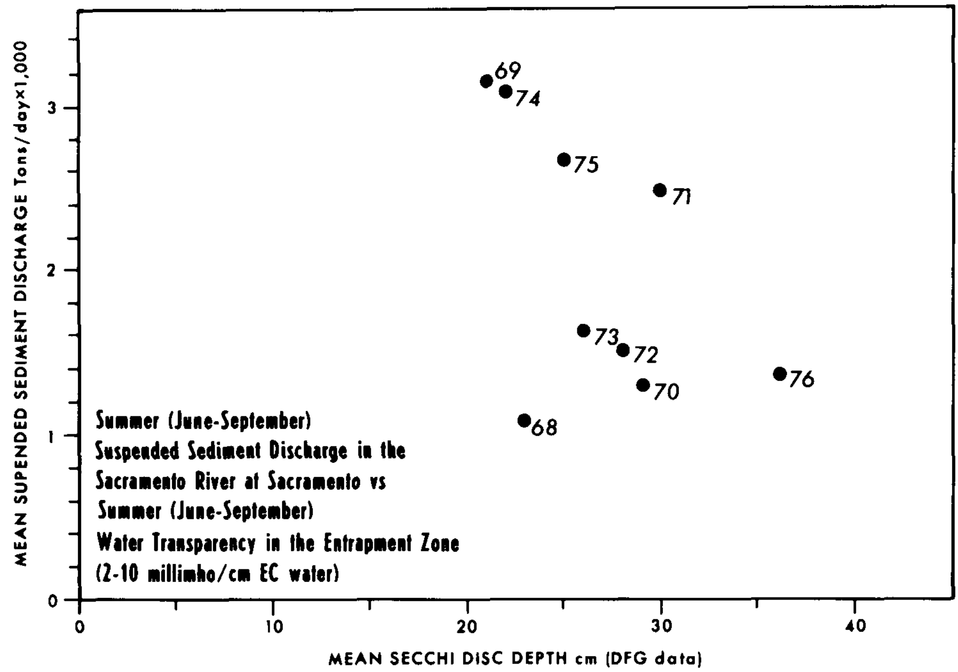

Fig. 21. Summer water transparency in the entrapment zone (2-10 millimho/cm EC range) versus summer suspended sediment load at Sacramento.

unpublished data).

The increased surface-water transparencies with distance downstream of the entrapment zone may be caused by the removal of suspended material with settling velocities greater than the upward vertical water velocity and by increasing dilution with low-turbidity ocean water. These combined effects have not been quantified.

We do not know the extent to which flocculation increases the settling rates of suspended materials and the quantity of suspended materials in the entrapment zone. Our limited data agree with Postma (1967) who suggested that flocculation is an important factor influencing the spatial distribution and entrapment of suspended materials.

Resuspension induced by wind, tide, and dredging activities results in the continual relocation of a portion of the deposited sediments. The TSS concentrations and turbidity in the shallow areas of Suisun and San Pablo bays more than double following periods of high wind (Rumboltz et al. 1976). Increasing tidal current velocities also increase the rate of sediment resuspension, with differences in the amount of resuspension and settling observed between greater and lesser flood or ebb tides. The greatest resuspension was observed when tidal height differences and maximum velocities were highest. During calm days we have often observed highly turbid water masses a few meters in diameter to come billowing to the surface with increasing tidal-current velocities.

Dredging also tends to relocate as well as resuspend sediments. The most intense dredging occurs near Mare Island adjacent to Carquinez Strait, and when the spoils are deposited in San Pablo Bay they increase water turbidity.

The effect of estuarine circulation on suspended sediment distribution in the study area is greatly influenced by bathymetry.

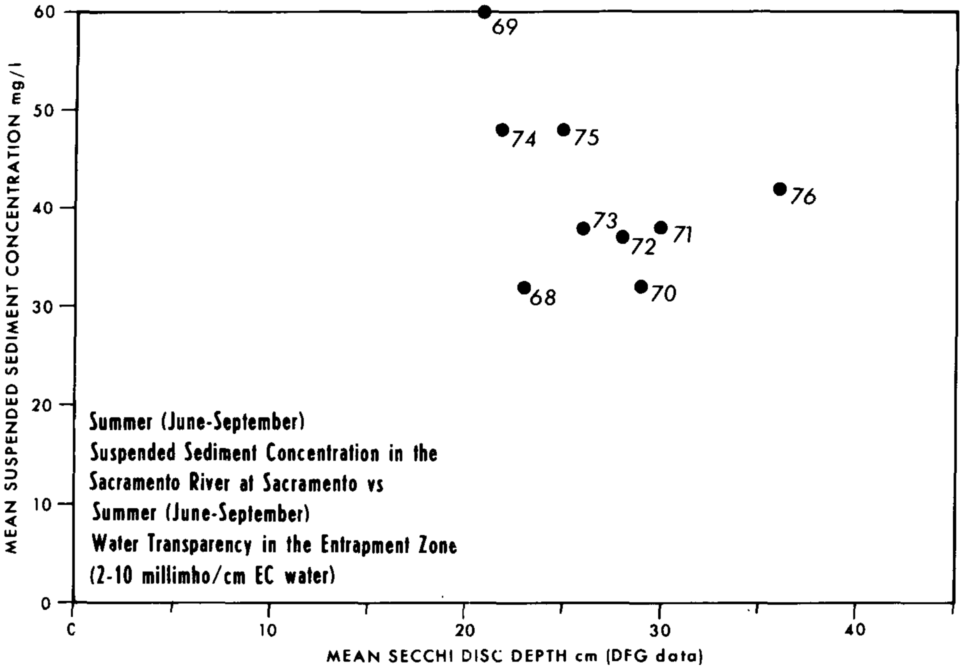

Fig. 22. Summer water transparency in the entrapment zone (2-10 millimho/cm EC range) versus summer suspended sediment concentration at Sacramento.

Distribution of Dissolved Constituents

Dissolved constituents are not directly affected by the entrapment zone. The general increase in nitrate+nitrite (Fig. 12), ammonia, and orthophosphate with depth and distance downstream of the entrapment zone was apparently caused by numerous municipal and industrial waste discharges. Depressions in inorganic nitrogen and dissolved silica concentrations were observed when high phytoplankton standing crops accumulated in the entrapment zone (Arthur and Ball 1978; Peterson et al. 1975b; Peterson 1979).

Dissolved oxygen concentrations (at 1-m depth) in the western Delta-Suisun Bay area were always near saturation values (USBR 1972; Macy 1976) even when chlorophyll *a* concentrations were relatively high (50-100 $\mu g \cdot liter^{-1}$.) Oxygen concentrations one meter from the bottom were generally a few tenths of a $mg \cdot liter^{-1}$ lower than near the surface (these near-bottom oxygen measurements, although made during 1976-77, do not cover periods when high phytoplankton standing crops were present). Presumably, mixing by tidal currents and wind are adequate to maintain near-saturation levels at the present level of eutrophication (Arthur and Ball 1978).

Effects of Entrapment on the Phytoplankton Standing Crop

The location of the entrapment zone adjacent to the Honker Bay area is one of several factors which appears to greatly stimulate phytoplankton growth in the western Delta-Suisun Bay area (Arthur and Ball 1978). In the initial years of our studies (1968-75) when "typical" Delta outflows were present, the standing crop of phytoplankton tended to be highest in the years with the greatest water transparency (Ball 1977; Ball and Arthur 1979).

The unusually low phytoplankton standing crop in Suisun Bay during the recent drought

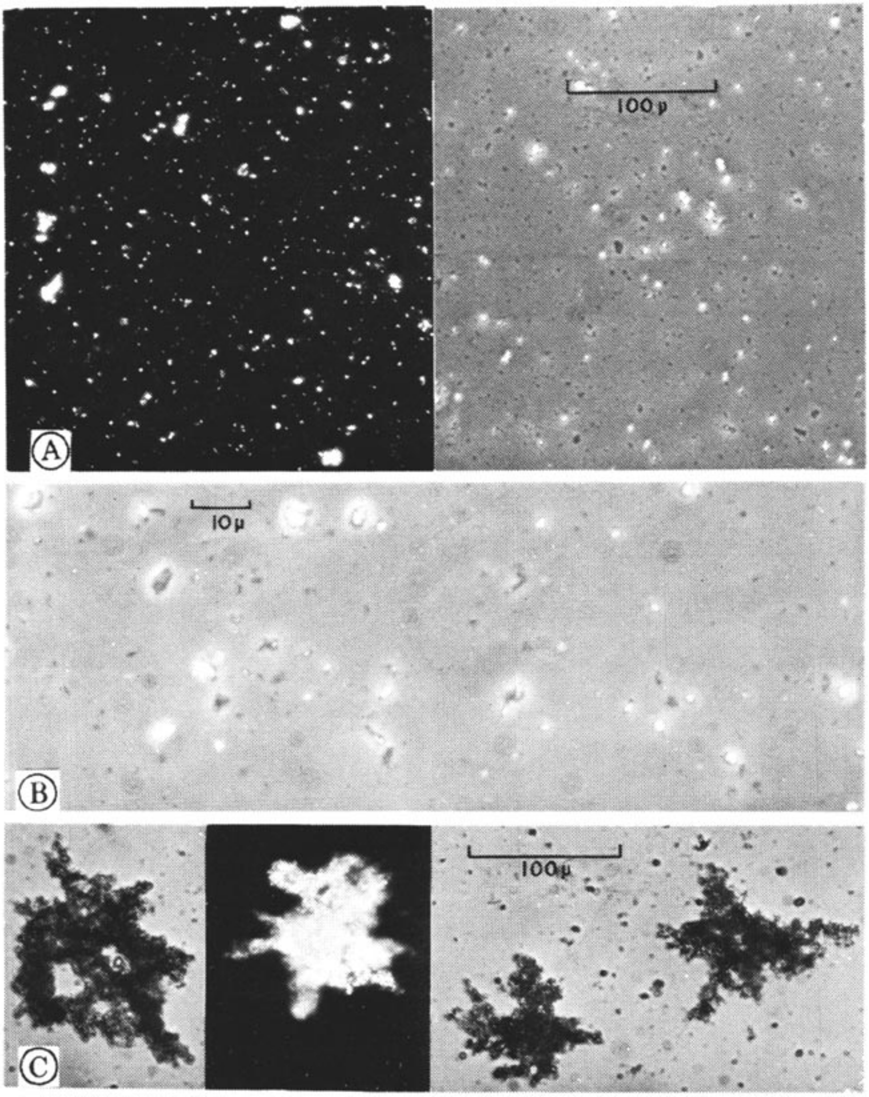

Fig. 23. Photomicrographs illustrating laboratory-induced flocculation of suspended sediments collected from the Sacramento River during flooding conditions on 25 March 1975. A. Control (0.116 millimho/cm EC). B. Control (0.116 millimho/cm EC) (enlarged). C. After addition of concentrated sea brine (2,500 micromhos/cm EC in beaker) and 8 hr of stirring at 30 $r \cdot min^{-1}$.

(summer of 1976 and throughout 1977) was contrary to predictions based on the 1968-75 data period. We conducted a number of field and laboratory studies during 1977 to study the low phytoplankton standing crop associated with low outflow conditions. We evaluated water transparency, water temperature, solar radiation, salinity, nutrient limitation, toxicity, parasitism, zooplankton grazing, filter feeding of benthic organisms, and the location of the entrapment zone and compared them to our previous (1968-75) observations.

The 1976-1977 data indicated that water transparencies in Suisun Bay were approximately double (Fig. 19) that of the previous years of high standing crop while solar radiation (insolation), water temperatures, and algal macro nutrients were within the normal range. Furthermore, the phytoplankton standing crop in the northern and southern Delta during 1976 and 1977 were the highest recorded although climatical conditions in these areas were similar to Suisun Bay.

A number of algal growth potential (AGP) and phytoplankton productivity studies were conducted during 1977 to determine if nutrient depletion, increased salinity, or toxicity might have been responsible for the low phytoplankton standing crop.

The AGP-test results demonstrated that the growth rates of the endemic phytoplankton tend to increase with increasing salinity and suggested that salinity intrusion into Suisun Bay during the low flow years did not directly inhibit the algal growth rates. Furthermore, because the concentration of phytoplankton in the unaltered water of the AGP tests peaked several times higher than in the field, it appeared that neither toxicity nor low concentrations of macro or micro nutrients were limiting algal growth. The primary productivity test results (DO method) in 1977 also supported this contention as the dissolved oxygen production per unit chlorophyll was equal to or higher than that of previous years.

Zooplankton concentrations were lower than normal in 1977, suggesting that grazing rates on phytoplankton should also have been lower than normal.

Although there may have been some movement of marine benthic organisms into Suisun Bay during 1976-77, it was impossible to draw any definite conclusions because there is little previous benthic data with which to compare. Comparison of 1976-77 data with future years of high phytoplankton standing crops may provide further insight into the possible significance of filter feeding of benthic organisms.

Comparison of chlorophyll *a* data in Suisun Bay with Delta outflows (Fig. 24a, b) shows that moderate to high chlorophyll *a* concentrations (above 20 $\mu g \cdot liter^{-1}$) were present when Delta outflows ranged from 110 to 700 $m^3 \cdot s^{-1}$. When the outflows were below 110 $m^3 \cdot s^{-1}$, the standing phytoplankton crop either declined or remained low. This outflow range places the tidally averaged location of the entrapment zone at various positions adjacent to the Suisun-Honker Bay area. The highest chlorophyll concentrations were measured when the outflow varied from 140 to 200 $m^3 \cdot s^{-1}$ in August 1970, 1972, and 1973, and September 1968 when the averaged tidal location of the entrapment zone (based on the 1-6 $^o/_{oo}$ salinity range) was adjacent to the Suisun-Honker Bay area. In February 1976, a substantial algal bloom developed as the entrapment zone moved upstream into the Suisun-Honker Bay area earlier than normal as a result of low river flow. This bloom occurred earliest of any year. Significantly, during the bloom water temperatures were only about 12°C and the photoperiod was short (although water transparencies were high). This bloom declined in March as the water transparency decreased. A second bloom developed in April 1976 and declined as the entrapment zone moved further upstream in June 1976 with decreasing riverflow.

When the entrapment zone was upstream of Honker Bay under low (30 to 110 $m^3 \cdot s^{-1}$) Delta outflows (such as occurred in July and August 1966, July 1970, and June-December 1976), chlorophyll concentrations either remained low or were declining. As the 1976 drought continued into 1977 and Delta outflows remained low, the entrapment zone remained several kilometers upstream of Honker Bay for the entire year. Significantly, 1977 was the first year on record when a phytoplankton bloom did not develop in Suisun Bay. The chlorophyll *a* concentration in Suisun Bay was generally less than 5 $\mu g \cdot liter^{-1}$ with an occasional value of about 10 $\mu g \cdot liter^{-1}$ (see Ball and Arthur 1979).

The highest chlorophyll *a* concentrations (nearly 20 $\mu g \cdot liter^{-1}$) measured west of Antioch during 1977 were in the entrapment zone (at 1 to 6 $^o/_{oo}$ salinity) at locations above Collinsville on the Sacramento River and near Antioch on the San Joaquin River. Summer chlorophyll *a*

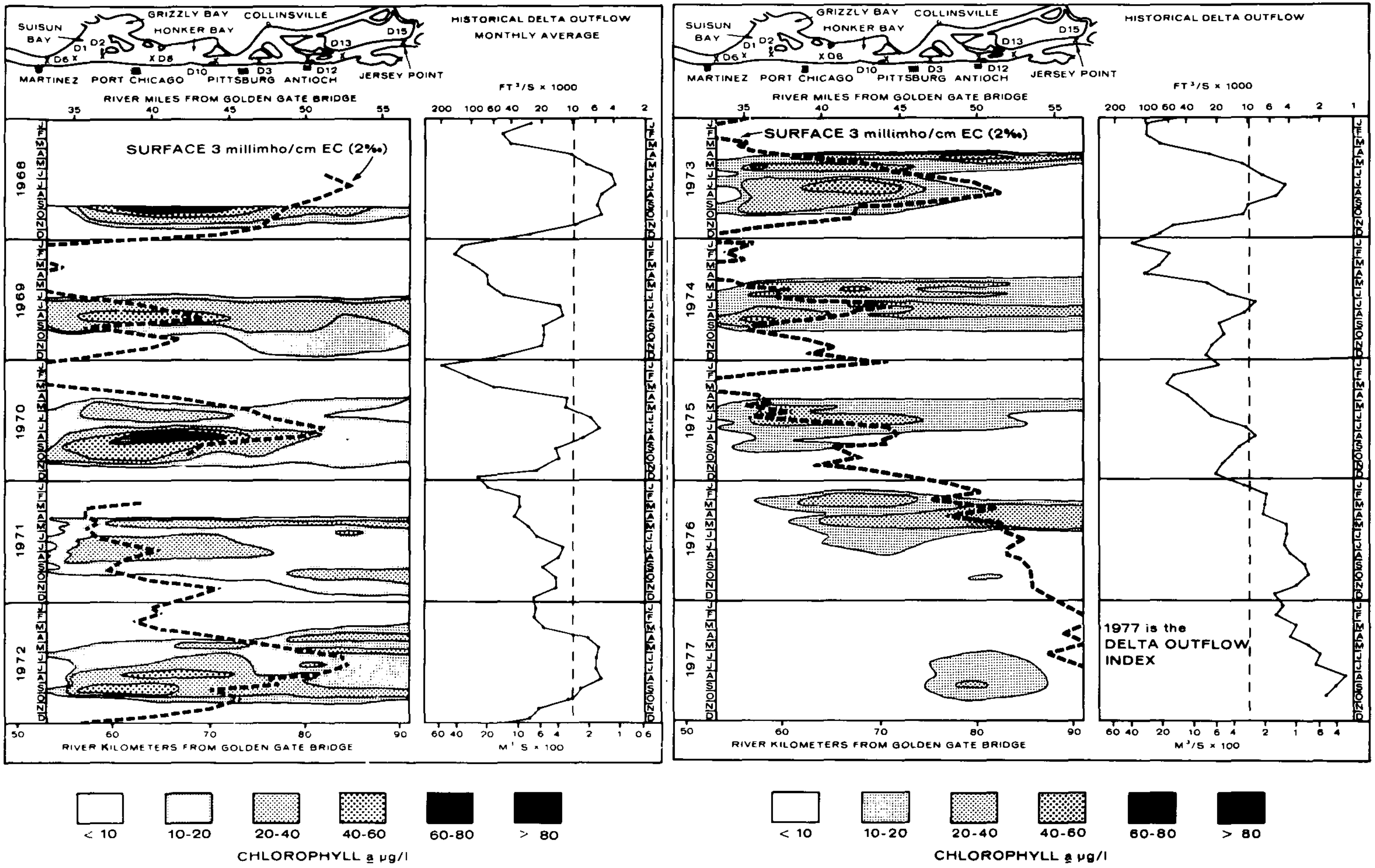

Fig. 24A and B. Chlorophyll *a* distribution on high slack tides from 1968-1977, between Jersey Point and Martinez, as related to salinity intrusion and Delta outflow (from Ball and Arthur 1979). (The 3 millimho/cm EC contour represents the upstream location of the entrapment zone on high slack tides.)

concentrations at the sites where the entrapment zone occurred in 1977, were in the same range as for previous years (1969-75) when the entrapment zone was farther downstream of these sites. Water transparencies at these sites in 1977 were lower than normal, suggesting that the higher phytoplankton standing crop was maintained by entrapment.

An important factor in evaluating algal growth is the residence time of algae in any given location. Whereas the residence time in any stretch of a river can be estimated by knowing the volume of water and the rate of flow, in an estuary where two-layered flow and tidal exchange occur, the residence time of algae (and other suspended materials) can either be greatly increased or reduced over that of the net downstream flow of water. The residence time of phytoplankton in two-layered flow circulation has not been directly measured. In theory, phytoplankton tend to be carried seaward if their settling velocity is less than the net vertical velocity, tend to be recirculated to and about the entrapment zone if their settling velocity is nearly equal to the net vertical velocity, or become entrapped and remain near the bottom if their settling velocity is much greater than the net vertical (upward) water velocity.

Certain algal species of the genus *Coscinodiscus* are consistently associated with the entrapment zone (Arthur and Ball 1978). These organisms have since been identified as belonging to the species *Coscinodiscus decipiens* which is synonymous with *Thalossiosira excentricus.* The organisms have thick cell walls, generally have inorganic particles attached to their exterior, and have been seen to settle rapidly in counting chambers. Their settling velocity relative to the net vertical water velocity presently being studied may provide these organisms with an ecological advantage which allows accumulation in the entrapment zone. In contrast, certain species of the genus *Chaetoceros* have cells much smaller in size which settle very slowly, have high growth rates, and at times become very dominant in the AGP test. *Chaetoceros* probably do not become dominant in the entrapment zone because their settling rates are so low; however, they often are the dominant form downstream of the entrapment zone. In addition to entrapment, the most important aspect of algal residence time related to the algal standing crop is the percent of time algal cells reside in the photic zone.

A substantial phytoplankton bloom (chlorophyll *a* >700 $\mu g \cdot liter^{-1}$ at water surface) occurred in the summer of 1977 in the McAvoy marina (south side of Honker Bay) which consisted almost entirely of *Exuviella,* a motile dinoflagellate. The intensity of the bloom gave the water a reddish-brown cast. This organism was also observed at very low concentrations in Suisun Bay during 1977. Apparently, such areas, although physically connected to the main channel, are isolated from the effects of wind, tidal current mixing and river flushing. The most logical explanation seems to be that the residence time of the algae is longer in these isolated areas than in the main channel and their mobility can maintain them near the water surface.

We do not know exactly how reduced Delta outflow and the location of the entrapment zone influence the phytoplankton standing crop in the Suisun Bay area. We offer, however, several hypotheses which when considered either singularly or in some combination may explain how the upstream movement of the zone could have caused a reduction in the Suisun Bay phytoplankton standing crop during the drought of summer 1976 and throughout 1977 (Arthur and Ball 1978):

1. *Decreased phytoplankton residence time in the Suisun Bay area when the entrapment was located upstream.* The residence time of suspended materials in rivers increases as river flow decreases. The record high phytoplankton crop in 1976 and 1977 in the northern and southern Delta (upstream of the study area) may be attributed to the increase in phytoplankton residence time resulting from lower river flows (Ball and Arthur 1979). However, in the fresh/saltwater mixing zone the water flow and mixing processes are much more complex. The longer residence time in the entrapment zone, relative to the immediate upstream and downstream areas,

may be a major factor regulating the phytoplankton standing crop. We postulate that when the entrapment zone moved upstream in 1976 and 1977, the residence time influencing the phytoplankton standing crop in Suisun Bay (both the shoals and the channel) decreased and resulted in the low phytoplankton standing crop in that area.

2. *Upstream movement of the area of maximum flocculation-aggregation-settling.* Suspended materials are in relatively low concentrations in San Francisco Bay and in the ocean. When Delta outflow were low during 1976 and 1977, the percent of ocean water nearly doubled in Suisun Bay over that of more typical years (1969-75). Furthermore, chlorophyll *a* levels during 1977 in Suisun Bay were similar to those observed in Central San Pablo Bay during the higher flow years.

We are uncertain why phytoplankton standing crops observed in the field were low in high salinity water (over 25 millimho/cm EC water) yet growth rates were highest at similar salinities in our field and laboratory growth rate tests. Perhaps the phytoplankton standing crop is characteristically low in high salinity water in the field because increased flocculation, aggregation, and/or settling of suspended particles occurs in the area downstream of the entrapment zone (the area where the net upward vertical water velocities are assumed to decrease). Phytoplankton may be affected by the increased particle settling and thus are unable to maintain themselves in the photic zone downstream of the entrapment zone. Consequently, as the entrapment zone moved upstream throughout 1976-77, greater settling rates may have occurred in Suisun Bay.

3. *Decreased phytoplankton residence time in the photic zone.* Phytoplankton are concentrated where the entrapment zone is located, with their growth rate directly proportional to the length of time they spend in the photic zone. When the entrapment zone is adjacent to the shallow bays, the average water depth present at the zone is much less than when the zone is located a dozen kilometers upstream in the more confined channels (assuming tidal exchange of the phytoplankton between the channel and the adjacent shallow bays). When the entrapment zone was located upstream in 1977, the contained phytoplankton spent less average time in the photic zone as compared to a downstream location. This hypothesis assumes complete vertical mixing of the water column.

4. *Increased vertical mixing with reduced salinity stratification.* During the low Delta outflows of 1977 the salinity stratification was less and the vertical mixing of the water column was apparently greater than during moderate to high summer outflows. The greater salinity stratification during the higher summer outflows could maintain the algae nearer the water surface and in the photic zone to a greater extent than during low outflows. Consequently, during low outflow, the reduced water stratification results in increased mixing which lowers the growth rate and standing crop of phytoplankton.

5. *Intrusion of marine benthic filter feeders.* We are uncertain whether the upstream movement of marine filter-feeding benthic organisms influenced the phytoplankton crop in 1976 and 1977.

We offer the following hypotheses that may account for the lower suspended materials concentrations observed in the entrapment zone during periods of low flow (as compared to high outflow), but do not know if or how these hypotheses may explain the low phytoplankton standing crop in Suisun Bay during 1976-77.

1. *Reduction of two-layered flow circulation.* The intensity of two-layered flow circulation should decrease as riverflow to the estuary decreases. This reduced circulation could increase the residence time of suspended materials in the entrapment zone while simultaneously reducing the quantity of suspended materials circulated through the zone. The interactions of these factors are unknown, however.

2. *Reduced aggregation and settling.* High concentrations of river-borne suspended materials increase the chances of particle aggregation in the estuary which in turn increases the settling rates of the suspended materials (R. Krone, pers. comm.). This factor may increase the quantity of material entrapped. Conversely, the quantity of suspended material entrapped decreases as the suspended-particle concentration decreases. The suspended-particle concentration entering the estuary usually varies directly with riverflow.

Factors Influencing Entrapment of Zooplankton and Striped Bass

The results of this and other studies suggest that the maximum abundance of *Neomysis mercedis* (Fig. 15) and certain copepods (Fig. 16) relative to salinity is primarily influenced by the interaction of two-layered flow circulation on their instinctive vertical swimming behavior. Cronin and Mansueti (1971), Heubach (1969), and Siegfried et al. (1978) state that certain species of zooplankton migrate upward during the night and downward during the day. In a two-layered flow estuary this movement translates into downstream transport at night and upstream transport during the day, resulting in a roughly circular motion that retains the species near its optimal salinity range. High tidal-current velocities also result in their upstream movement (Heubach 1969; and Siegfried et al. 1978).

The different distribution patterns of *Eurytemora hirundoides* and *Acartia clausi* (Fig. 16) are attributed to differences in the optimal salinity range for these genera (Kelley 1966). The mechanism responsible could be differences in vertical swimming behavior between the two species.

We partially attributed the decrease in the total zooplankton standing crop during 1976 and 1977 to the fact that the center of the populations shifted upstream with movement of the entrapment zone into an area occupied by a smaller surface area and volume of water (Arthur and Ball 1978). The DFG has suggested that *Neomysis* and certain other zooplankton concentrations are directly related to the concentration of phytoplankton in the entrapment zone (see also Orsi and Knutson 1979). It is interesting to note that *Neomysis* (Fig. 15) and zooplankton (Fig. 16) concentrations were relatively high in March of 1974—prior to the development of a phytoplankton bloom. Unfortunately, routine sampling did not extend downstream of Martinez to characterize the distribution of both zooplankton and phytoplankton during higher Delta outflows.

The relatively high concentrations of juvenile striped bass (young-of-the-year) present in the entrapment zone may be caused by (1) the bass tending to swim to where the food supply peaks, or (2) the juvenile bass are concentrated by two-layered flow circulation in the essentially plankton stage in their early life cycles. The latter explanation seems more reasonable. Cronin and Mansueti (1971) have found that the larval forms of many Atlantic Coast fish species that spawn both in freshwater and at the entrance to estuaries are carried to the plankton-rich low salinity area (entrapment zone) where zooplankton are abundant. Stevens (1979) further discusses the factors influencing the striped bass population.

Predicting the Entrapment Zone Location

Evaluation of salinity and suspended materials data over the past 10 years indicates that the location of the entrapment zone can be predicted from salinity gradients and occurs in the upstream portion of the mixing zone where the surface specific conductance is approximately in the 2-10 millimho/cm (1 to 6 °/oo salinity) range. A plot of geographic location of this salinity range versus the DOI (at high slack tide) could be used to estimate the location of the entrapment zone at future outflows within the outflow range presented (Fig. 25). Although the overall relationship between the location of the entrapment zone and the DOI is good, it is less precise at low outflows. This may be due to the lack of precision in calculating the DOI at low outflows, and that the location of the zone is also dependent upon both the history (variation and magnitude) of the previous outflow and on changes in tidal elevation.

Environmental Significance

The most significant environmental aspect of the entrapment zone, other than influencing the location of maximum shoaling (sediment deposition), may be that the quantity of phytoplankton and certain other estuarine biota are enhanced when the zone is located in upper Suisun Bay. The lowest levels of phytoplankton and certain zooplankton recorded in the Suisun Bay area occurred during 1976 and 1977 when the Delta outflow was low and the entrapment zone was located several kilometers upstream of Honker Bay. However, we do not yet know the significance of a long-term low Delta outflow on total estuarine productivity.

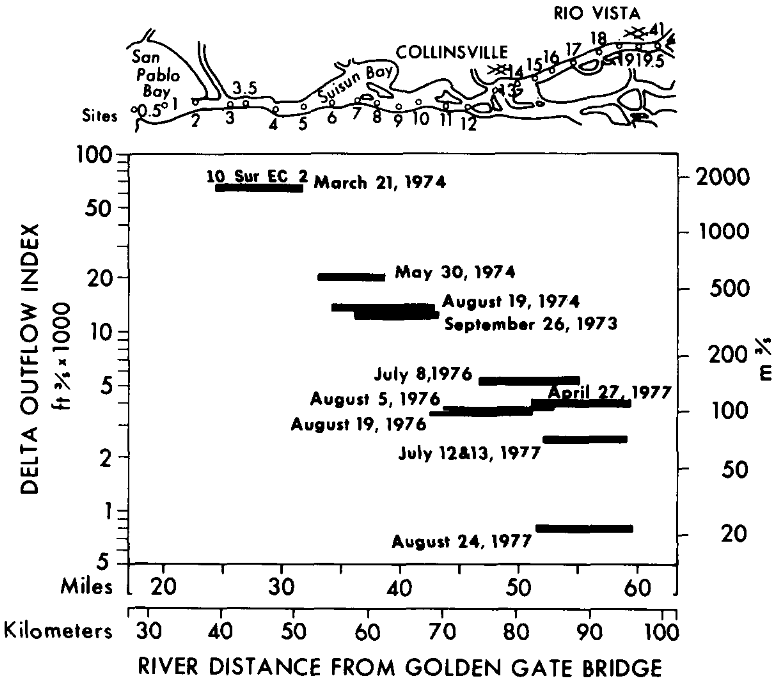

Fig. 25. Estimated high slack tide locations of the entrapment zone, based on the 2-10 millimho/cm EC (1-6 °/oo) range at various Delta outflows.

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