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A FLOW STANDARD TO MAXIMIZE PHYTOPLANKTON ABUNDANCE BY POSITIONING AN ENTRAPMENT ZONE IN SAN PABLO BAY

by

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I. INTRODUCTION

The purpose of this report is the identification of a practical flow standard that will maximize phytoplankton productivity in San Pablo Bay. Phytoplankton or algae are the basis of the planktonic food chain on which larval and juvenile estuarine fish, adult planktivorous fish, shrimp, and clams depend. The abundance of phytoplankton in the San Pablo Bay channel is increased when there is sufficient Delta outflow to position an entrapment zone in the vicinity of the Pinole Shoal.

This report is one of four complementary studies, each of which is intended to recommend flow or salinity standards to maximize phytoplankton abundance in different parts of the Bay. Two of the other reports, 412-4 and 412-5, deal with Suisun Bay. The other, 412-7, deals with South San Francisco Bay.

These reports have been prepared to assist the State Water Resources Control Board in its current review of flow and salinity standards required to protect beneficial uses in San Francisco Bay and the Delta.

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II. CONCLUSIONS

A. The shallows of San Pablo Bay are seasonally highly productive of phytoplankton, and in particular of diatoms.

B. Phytoplankton produced on the shallows are circulated into the main channel in San Pablo Bay, where they can be concentrated by the estuarine circulation in the vicinity of the Pinole Shoal.

C. An entrapment zone appears to form in the channel in the vicinity of the Pinole Shoal when there is sufficient Delta outflow.

D. The highest concentrations of phytoplankton occur in the channel when Delta outflows are approximately 20,000 cfs.

E. High turbidity in July and August due to wave action on the northern and western shoals appears to inhibit phytoplankton growth in those months.

F. Growth of marine benthos during the year appears to decrease phytoplankton biomass in the fall.

G. Colonization of San Pablo Bay shallows by marine benthos appears to be restricted by low salinities resulting from high winter Delta outflow.

H. In years which do not have sufficiently high winter Delta outflow, it appears that marine benthos can survive through the winter, resulting in high biomass during the following season, which significantly reduces phytoplankton biomass, even though Delta outflows may be sufficient to establish an entrapment zone the following spring.

I. It appears that under present conditions of water development, in approximately the wettest 7 out of 10 years, winter Delta outflow has been sufficient to limit marine benthos in San Pablo Bay.

J. A salinity standard that would optimize phytoplankton abundance in San Pablo Bay is as follows: maintain the 28-day running average of Delta outflow at Chipps Island to be not less than 20,000 cfs during the period April through June. The standard should apply in all years except years when the unimpaired Delta outflow for the prior October through March period is less than the 30 percentile dry year, as determined by the average October-through-March unimpaired Delta outflow.

III. THE ROLE OF PHYTOPLANKTON IN ESTUARINE FOODWEBS AND PRODUCTIVITY

Phytoplankton are tiny, usually microscopic, single-celled members of the group of simple plants called algae. They are closely related to the more familiar macroalgae, or seaweeds. They range in size from 1 - 2 micrometers (um) to cells perhaps 1 millimeter (mm) in greatest dimension. Some forms have one or more flagella or tails which allow them to swim to a limited extent. Others such as diatoms simply drift randomly through the water, sinking slowly.

Phytoplankton are found in virtually every body of water on the surface of the earth. Their growth rate, abundance and community composition are controlled by a number of physical, chemical, and biological factors. The major ones are turbulence, circulation patterns with scales ranging from centimeters to thousands of kilometers, sunlight or irradiance, nutrient concentrations, and consumption by other organisms. Under optimum conditions phytoplankton can grow rapidly. Depending on the species present, the population of phytoplankton in a volume of water can double in a time period ranging from 12 to 120 hours.

Phytoplankton form the basis of most aquatic foodwebs. They use energy from the sun to convert simple inorganic molecules (carbon dioxide, ammonium or nitrate, phosphate, sulfate) into sugars, proteins and fats that are utilized by the grazers or herbivores of the foodweb. Some of the organisms that depend on phytoplankton for sustenance are oysters, clams, worms, barnacles, some shrimp (Neomysis) and tiny shrimp-like zooplankton called copepods. The planktonic larvae of many aquatic invertebrates (meroplankton) also depend on phytoplankton for sustenance (Figure 1).

In some estuarine ecosystems, organic material derived from terrestrial plants or benthic seaweeds and microalgae can augment the food supply provided by phytoplankton. In shallow estuaries, benthic microalgae can be dislodged from the sediment by wind- and current-induced turbulence; they then become part of the phytoplankton. Similarly, phytoplankton (especially diatoms) can sink to the bottom during periods of extended calm and become part of the benthic microalgal population. This is observed in Suisun Bay (Cloern et al. 1985). Seaweeds or macroalgae can become locally abundant (Horne and Nonomura 1976, Josselyn and West 1985), but they are not an important source of organic matter in San Francisco at present.

Another source of organic matter is material from salt marsh plants. Streams can also transport organic material derived from inland forests, fields, and marshes into estuaries or the coastal zone. Waste water and sewage can also increase the organic content of estuarine water.

The importance of this additional organic matter to coastal and estuarine foodwebs depends on the magnitude of the input relative to the production of organic matter by phytoplankton. Much of the material derived from higher plants is difficult to digest and must be at least partially broken down by bacteria before it is available to grazers. Particles of partially decomposed organic material and the bacteria and other microorganisms associated with them are called detritus. Grazers harvest detritus particles the same way they harvest phytoplankton. Some grazers consume the detritus and phytoplankton in water indiscriminately, but most selectively graze on phytoplankton or the more nutritious detritus particles. Detritus particles that have low food quality are rejected by the grazers. A number of investigators have found negative correlations between the percentage of detritus in the diet of grazers and their growth rates (Kirby-Smith 1976; Heinle et al. 1977; Chervin 1978; Chervin et al. 1981). Thus, although detritus particles may dominate the suspended particulate load in an estuary, phytoplankton may dominate the nutrition of grazers and provide the basis of the food chain. A schematic diagram of a typical estuarine food web is shown in Figure 1.

In the San Francisco Bay-Delta ecosystem, phytoplankton are a much more important source of particulate organic carbon than detritus. Weinke and Cloern (1987) determined the contribution of phytoplankton to the particulate organic carbon load (POC, POC = phytoplankton + bacteria + detritus) in San Francisco Bay waters over a seasonal cycle. Phytoplankton accounted for an average of 95% of the POC during blooms and over 30%
most of the rest of the year. Spiker and Schemel (1979) analyzed the carbon stable isotope composition of POC in San Francisco Bay. Their data show that salt marsh grass is not a significant source of POC in San Francisco Bay.

Moreover, phytoplankton biomass increases because of growth (Cloern _et_ _al_. 1985), while detritus is dead material being decomposed by bacteria and associated microbes.

Phytoplankton production or availability is critical to the growth or productivity of many other organisms in estuaries. Nixon (1982) compiled phytoplankton production and fisheries yield data from a number of estuaries and coastal waters from around the world. He found a consistent, direct relationship between fishery yield and phytoplankton productivity (Figure 2). In San Francisco Bay, Thompson and Nichols (in press) have shown that growth and reproductive rates of a common clam varies with seasonal and interannual phytoplankton productivity.

Similarly, it has been documented that the abundance of the opossum shrimp _Neomysis_ _mercedis_, depends on phytoplankton abundance (Orsi and Knutson 1979; Knutson and Orsi 1983). Since _Neomysis_ and other zooplankton such as _Eurytemora_ are major items in the diet of many of the fish in the San Francisco Bay - Delta, phytoplankton productivity is a critical factor affecting the Bay's fisheries (Orsi and Knutson 1979, Moyle _et_ _al_. 1986, Arthur & Ball 1979).

IV. FACTORS CONTROLLING PHYTOPLANKTON GROWTH

A. Light

As mentioned above, phytoplankton productivity is controlled by a combination of physical, chemical and biological factors. The dominant physical factor is light intensity or irradiance. Light penetration into the water column is controlled by the elevation of the sun above the horizon and by turbidity. Sun elevation and day length vary seasonally at a given location in a highly predictable manner, with most insolation occurring in the period April through September.

Because light is absorbed by water and dissolved substances and absorbed and scattered by particles in the water column, irradiance decreases continuously with depth. At some depth, irradiance is so low that phytoplankton cells cannot trap enough light energy to replace energy used to maintain basic cellular functions. Respiration exceeds photosynthesis and the cell effectively starves to death if it remains at that irradiance too long. The light intensity at which photosythesis and respiration are balanced is called the compensation intensity and the depth in the water column at which it occurs is called the photic zone depth. It varies by species and degree of adaptation to low light, but is generally at an irradiance of 1 to 0.1 % of the irradiance just below the surface. In the highly turbid waters of San Francisco Bay, the photic zone depth (= 1% of surface irradiance) is on the order of 0.2 - 6.6 m. (calculated from the range of extinction coefficients given in Cole and Cloern 1984, Table 2).

Water column turbidity, and hence photic zone depth in San Francisco Bay, are determined by the suspended load initially carried into the Bay by the Sacramento-San Joaquin River, and subsequently resuspended by wind and currents.

This simple picture is complicated by water column turbulence, which ensures that a phytoplankton cell will not remain at a given depth (or light level) for very long. Turbulence can move phytoplankton cells to depths below the photic zone depth (light too low to survive) and back into the well-lighted upper reaches of the water column in a short period of time. The effect of vertical movement due to turbulence on phytoplankton survival and growth is described by the critical depth theory (Sverdrup 1953) and is discussed in more detail in Report 412-4 of this series.

B. Nutrients

In addition to light, phytoplankton growth rates can also be limited by the availability of inorganic nutrients. However, this occurs only rarely, if at all, in San Francisco Bay (Cole and Cloern 1984; Peterson et al. 1985). Nutrient supply rates from river inflow, sewage and other waste water, and release from Bay sediments exceed phytoplankton removal rates which are constrained by light-limited phytoplankton growth rates in the turbid waters of the Bay.

C. Grazing

A final factor controlling phytoplankton abundance is consumption by herbivores or grazers. Grazing removes cells from a population without affecting the growth rate of individual cells in the population. Thus, grazers can reduce population growth rate even though physical and chemical environmental factors are optimum for the growth of individual cells. If grazing pressure is sufficiently heavy, the net population growth rate (births minus deaths) can be negative and the standing crop or biomass of phytoplankton will decline. Grazing efficiency is affected by phytoplankton abundance because the grazer has to work to filter out the cells. When phytoplankton abundance is depleted below a certain level, grazers will either stop filtering, leave in search of higher food concentrations, switch to another food item, or starve.

D. Benthic Versus Planktonic Grazers

In shallow, turbulent estuaries, benthic invertebrate grazers such as clams compete directly with planktonic invertebrate grazers such as copepods (Eurytemora) or shrimp (Neomysis) for phytoplankton (see Figure 1). Benthic invertebrates like clams are long-lived relative to planktonic invertebrates and are frequently larger. Since the ability of an organism to filter water increases with size, larger organisms can remove phytoplankton faster. If the abundance of large benthic grazers is high enough, they can consume most of the food in the water flowing over them, significantly reducing food sources for planktonic grazers. The reproductive rate of grazers, both planktonic and benthic, is often tied to food availability (Checkley 1980a, b; Thompson and Nichols, in press). A well-established benthic grazer population can depress the reproductive potential of planktonic grazers in addition to limiting their growth rate. Deprived of food, larval and juvenile fish, planktivorous fish like smelt, and other organisms that depend on planktonic grazers starve.

E. Distribution and Abundance of Benthic Grazers

The distribution of benthic invertebrate grazers is controlled by environmental factors that affect their dispersal and subsequent survival in the new habitat. Dispersal can be accomplished by motile adults or, as occurs most frequently, by motile larval or juvenile stages. Most aquatic species produce larvae that are planktonic for some period of their development. Often eggs and sperm are simply shed into the water where fertilization occurs. The embryos formed develop into planktonic larvae that drift until settling and metamorphosing into adults. Abalone, sea urchins, and many clams and worms disperse this way. In other cases, the eggs are fertilized and develop in or on the female. The larvae that emerge may or may not be planktonic. Some oysters, the clam *Gemma gemma* and most shrimp and crabs disperse this way.

The dispersion of planktonic larvae is controlled by water movements and modified by the behavior of the larvae. Larvae that migrate up and down through a water column in which there is current shear will be distributed differently from larvae that stay more or less at one depth. In estuaries with well-developed estuarine circulation, larvae staying in the surface layer will be carried out to sea while larvae remaining in the bottom layer will be carried inland. When residual currents are small, larvae will experience little net transport although they may oscillate about their point of release. Localized larval dispersion will depend on turbulent diffusion and on the dimensions of the tidal ellipse.

The second factor controlling the distribution of adults is the survival of larvae or adults in the colonized habitat. Survival is dictated by a host of factors including physical and chemical variables such as water temperature, salinity, current velocities, sedimentation rates, elevation and substrate type. Biological variables include the availability of adequate quantities of nutritious food, the presence of predators, competition with other species for food or for space..

Many of these variables have a seasonal cycle so that a habitat that is acceptable at one time of the year (e.g., when the larvae settle) may prove to be lethal at another. For example, the distribution of limpets in rocky intertidal zones is strongly influenced by mortality during exposure to high temperatures and desiccation at a few key low tides during the spring.

Another example of a key seasonal event determining distributions is the effect of seasonally variable salinity on marine species in estuaries. Marine larvae settling in a high salinity environment during the summer may be killed during winter when increased runoff decreases the salinity. Mortality is a function of both the magnitude of the decrease in salinity and the duration of the period of depressed salinity. Organisms such as clams that live buried deep in the bottom are more resistant to decreased salinity because the sediment slows the exchange of water around the animal's body. Many species tolerate short periods (a few days to a week) of depressed salinity by withdrawing into burrows or shells and "holding their breaths", since pumping low salinity water through their bodies for respiration and feeding would kill them. Motile organisms such as the amphipod _Ampelisca_ _abdita_ which is abundant in San Francisco Bay may migrate down-estuary or into deeper, more saline water in the channels (Storrs _et_ _al._).

Water column stratification may limit mortality to shoals or to the intertidal zone where organisms are subjected to the lowest salinity for the longest time (Figure 3). The intrusion of high salinity water onto the deeper portions of shoals or into channels at high tide may permit organisms that would otherwise expire to ventilate and feed briefly, until the turning tide again submerges them in low salinity water.

At the upper end of the estuary, fresh or brackish water organisms unable to tolerate elevated salinities may be killed by the intrusion of salt water during the summer. Because of these stresses, the distribution of species and biomass of benthic invertebrates in estuaries typically has a minimum at around 5 ppt. salinity (Figure 4).

V. CONTROL OF PHYTOPLANKTON ABUNDANCE IN SAN PABLO BAY

To achieve high biomass of phytoplankton and in particular diatoms in the channel of San Pablo Bay requires both a hydrodynamic mechanism for concentrating phytoplankton - an entrapment zone - and at the same time, high productivity in the shallows.

A. The Entrapment Zone and Phytoplankton Abundance in San Pablo Bay

As is discussed in later sections, sufficient Delta outflow can create an entrapment zone in the vicinity of the Pinole Shoal. When this happens, a chlorophyll maximum coincides with the turbidity maximum.

Phytoplankton growth in the entrapment zone is severely limited by light as a result of the high turbidity of the water (Cloern et al. 1983, Cloern and Cheng 1981). Analysis of phytoplankton growth models for Northern San Francisco Bay channels by Cloern and Cheng (1981) show that no net phytoplankton growth is possible in the channels because the mixing depth is much greater than the critical depth.

On shoals surrounding channels, water depth is less than the critical depth so there is net growth of a phytoplankton community composed of diatoms and small flagellates. These cells are then carried into the entrapment zone by residual currents. The diatoms are concentrated and retained in the entrapment zone by virtue of their higher sinking rates, while the flagellates (which do not sink) are carried out of the system by the net outward-flowing surface current. The accumulation of diatoms in the entrapment zone facilitates the feeding of planktonic grazers. Higher growth rates and abundances of planktonic grazers like Neomysis and Eurytemora (Arthur and Ball 1979; Ambler et al. 1985; Cloern et al. 1985) make it easier for larval and juvenile fish or planktivorous fish to capture an adequate food ration and increases foodweb efficiency. While benthic grazers like clams and worms that are abundant on the shoals of San Pablo Bay (Cloern et al. 1985) are eaten by birds and bottom-feeding adult fish like sturgeon, flounder, sharks or rays, they are not available as food for larval or juvenile fish.

The relationship between the extensive shoals of San Pablo Bay and the position of the entrapment zone is thus critical to concentration of phytoplankton biomass in the entrapment zone. Cloern (1979) and Cloern et al. (1985) discuss the importance of increased residence time on the northern San Pablo Bay shoals to attaining high phytoplankton biomass. Because of the net clockwise circulation in San Pablo Bay (Walters et al. 1985), phytoplankton produced there are introduced into the entrapment zone at its upstream end.

Early in the season in a typical year (January through March), productivity is curtailed by low light levels due to short daylength, low sun angle, clouds, and high turbidity resulting from river-borne sediment associated with winter floods. Later in the season, (July through August), productivity is curtailed by increasing turbidity and decreasing residence time during the summer in response to increased wind-induced wave action. This is especially noticeable on the expansive northern and western shoals (Cloern _et al_. 1985) and less so on the smaller southern and eastern shoals (Josselyn and West 1985). This means that the April-through-June period is particularly important for phytoplankton production in San Pablo Bay.

B. Role of Benthic Grazing

As discussed above and in Report 412-5 of this series, benthic filter feeders can consume most of the phytoplankton produced in the water column of shallow estuaries. This appears to be possible in Northern San Francisco Bay (Nichols 1985, Cloern et al. 1985) including on the shoals of San Pablo Bay (Cloern et al. 1985). Benthic biomass in Suisun Bay is strongly affected by seasonal flushing with fresh water during periods of high Delta outflow (Nichols 1985). Although it has not been examined as closely, the same process probably controls benthic biomass, and thus benthic grazing pressure, on the shoals of San Pablo Bay.

During periods of high Delta outflow, a layer of low salinity water spreads over the San Pablo Bay Shoals. When this layer of low salinity water persists for a sufficient period, it can eliminate most of the marine filter feeders from the shoals. This significantly decreases benthic biomass, and thus reduces benthic grazing pressure, at the begining of the phytoplankton growing season. Decreased benthic grazing pressure means that more phytoplankton is available to planktonic grazers. Smaller zooplankton such as copepods have high reproductive rates in the presence of adequate food (Checkley 1980a, b) and bloom in response to elevated food levels. Eventually, benthic grazers probably recolonize the shoals and benthic grazing accounts for an increasing portion of phytoplankton consumption.

V. RELATIONSHIP BETWEEN PHYTOPLANKTON ABUNDANCE AND DELTA OUTFLOW

There is a good correlation between peaks in phytoplankton biomass in the channel in spring and summer and Delta outflow, for those years in which the peak winter Delta outflow was larger than 100,000 cfs. Figure 5 shows data, collected by DWR and the Bureau of Reclamation for the 1971-1985 period, correlated with 5-day average Delta outflow, lagged by one day for years in which the previous winter Delta outflow exceeded 100,000 cfs. Figure 6, by contrast, shows the same plot for years with winter flows less than 100,000 cfs. The data used in Figures 5 and 6 is shown in Table 1. The difference in chlorophyll-a concentration for similar spring and summer Delta outflows shown in these two plots can be attributed to the increased benthic grazing in dry years.

With flows above 100,000 cfs, salinities in San Pablo Bay are significantly reduced, probably killing or displacing marine benthos from the shoals. Unfortunately, at present a detailed analysis of salinity/Delta outflow relationship has not yet been made available. Preliminary analysis (SWRCB Exhibit 10) indicates that even in the dry 1924-35 period, salinities at Rodeo were reduced below 5 ppt. in 50% of the years. 5 ppt. is the survival limit for most marine benthos (see Report 412-5).

Until 1980, data on channel chlorophyll-a concentration (which is used as an indicator of phytoplankton biomass) was collected at Station D42 adjacent to Rodeo. After 1980, the monitoring station was moved to upstream of Point Pinole to Station D41 (see Figure 7). It appears that D42 may have somewhat higher concentrations than D41 but generally has a similar response to Delta outflow as shown in Figure 8. This is also indicated in Ball and Arthur's (1979) data plots for San Pablo Bay.

It appears from Figure 5 that at flows higher than about 70,000 cfs, velocities are too high to allow high concentrations of phytoplankton to accumulate in San Pablo Bay. After June, high turbidity tends to limit phytoplankton productivity, and so the abundance is reduced (Cloern et al. 1985).

VII. HYDRODYNAMICS OF SAN PABLO BAY

The northern reach of San Francisco Bay, from the Central Bay to the Sacramento River, is a partially-mixed estuary whose circulation is affected by the amount of fresh water inflow, tidal action, wave action, and also by the geomorphology of the estuary itself. The wide shallow San Pablo Bay, with average depths of approximately 6 ft., is separated from the wide shallow Suisun Bay by the deep narrow Carquinez Straits (see Figure 7).

San Pablo Bay has been described as "a seaward embayment of a partially mixed estuary" (Cloern et al. 1985). Within San Pablo Bay itself, a natural deeper channel, now dredged to about 35 ft., runs from the Carquinez Straits to the San Pablo Straits. Between Point Pinole and Mare Island, the Pinole Shoal constricts the flow of water from Carquinez Straits into San Pablo Bay.

Circulation and salinities in San Pablo Bay are strongly influenced by the amount of Delta outflow. Vertical salinity transects taken by USGS during 1980, shown in Appendix A, illustrate the changes in estuarine circulation in San Pablo Bay for different Delta outflows and the important role the Pinole Shoal has in affecting salinity distribution.

At very high Delta outflows (e.g., 1/23 or 3/4 transects of Appendix A), the null zone is pushed into Carquinez Straits or San Pablo Bay from Suisun Bay and a strongly stratified estuarine circulation forms in San Pablo Bay, extending to beyond the Golden Gate Bridge. As the flow decreases, the null zone moves back into Suisun Bay. In Suisun Bay, the salinity becomes well-mixed vertically (e.g., 4/8 transect). However, a stratified flow is formed over the Pinole Shoal with a strong horizontal salinity gradient (indicated by closely spaced salinity contours in the transects shown in Appendix A). These conditions are generally associated with an entrapment zone - an area of vertical upwelling in the estuarine circulation.

At flows of about 20,000 cfs, the zone of stratification and strong horizontal salinity gradient is located over the Pinole Shoal (e.g., 5/7, 5/21 transects). When the flow drops below about 10,000 cfs, the strong horizontal salinity gradient weakens (e.g., 7/16, 9/16 transects). At low Delta outflows, the salinity distribution becomes almost uniform (e.g., 8/18 transect).

Based on these salinity gradients, it appears that an entrapment zone forms in San Pablo Bay at Delta outflows greater than approximately 10,000 cfs. The strength of the entrapment zone increases as the Delta outflow increases.

An entrapment zone is a region in the estuarine mixing zone in which there are positive residual vertical velocities. These upward vertical velocities trap suspended sediment and phytoplankton, creating areas of high turbidity and biomass. (A more complete description of the entrapment zone is contained in Report 412-4 of this series.)

In an estuary with simple geometry, the entrapment zone is located immediately downstream of the null zone. However, where the geometry is more complex, such as in San Francisco Bay, other entrapment zones and even null zones can develop. Walters et al. (1985) have suggested that the Pinole Shoal weakens or limits the estuarine circulation. This means that under some circumstances, two estuarine circulation cells can exist at the same time, one between the Pinole Shoal and the Delta, and the other downstream of the Pinole Shoal. The Delta outflow and tidal mixing conditions that create this situation are uncertain. Two cells appear to occur at flows above about 30,000 cfs, as is shown by the direction of residual horizontal currents measured on the Pinole Shoal during March 1979. Table 2 and Figure 9 show the direction of these residual currents. However, current data taken in October 1980 shows the same phenomena at Delta outflows of about 10,000 cfs.

Whether or not two estuarine circulation cells occur with a second "null" zone forming on the Pinole Shoal, the important physical process for phytoplankton production is the existence of an entrapment zone with positive residual vertical velocities. There are two sources of data that verify the existence of an entrapment zone over Pinole Shoal.

First, high turbidity levels occur in the vicinity of the Pinole Shoal where Delta outflows are higher than about 10,000 cfs. In particular, the maxima is very noticeable at flows of approximately 20,000 cfs as is shown by data analyzed by Ball and Arthur (see Figure 10), and is also noticeable in vertical transect data taken in 1986 (see Appendix B).

Second, another method of determining the approximate location of an entrapment zone is calculating vertical velocities from the salinity distribution data. This can be done using a "box" model. The use of box models to define the two-dimensional estuarine circulation pattern is described by Officer (1980a).

The upper and lower part of the flow is divided into boxes, as shown in Figure 11. The vertical velocity Q_{vm} is determined by the equation:

$$Q_{vm} = \frac{S_m S^1_m - S_{m-1} S^1_{m-1}}{(S^1_{m-1} - S_1)\ (S^1_m - S_{m-1})} \quad x \quad R\ (1-V)$$

where S denotes salinity, the prime (^{1}) denotes values in the bottom layer, R is the river discharge, and V the estuary classification index.

Box models have also been used to characterize the entrapment zone (Officer 1980b). For the purposes of defining the entrapment zone, we are only concerned whether the vertical velocity is positive or negative, in other words, whether

$$S_m S^1_m > S_{m-1} S^1_{m-1}$$

This computation has been carried out for two detailed vertical salinity transects made by the Bureau of Reclamation and USGS in 1986, with Delta outflow of 45,000 cfs on April 18th and 13,000 cfs on October 17th. The analysis is shown in Appendix B. As can be seen, the zone of upward velocity correlates fairly well with the turbidity maximum and indicates an entrapment zone located over the Pinole Shoal at lengths on the order of 10 miles.

The estuarine circulation within San Pablo Bay is affected by the spring/neap tidal cycle (Walters et al. 1985). Neap tides tend to increase stratification, pushing salt water up the estuary, and spring tides tend to cause increased mixing. The time scale of these changes is 14 days. Superimposed on these changes are the fluctuations in Delta outflow, which may change rapidly within a few days during high flow peaks. Consequently, the circulation in San Pablo Bay is rarely in a state of equilibrium during high flows.

The non-estuarine, wind- and tide-driven circulation in San Pablo may also be significant. It appears that a net clockwise circulation current may exist that circulates water from the shallows into the channel in the vicinity of the Pinole Shoal (Denton 1985).

Local runoff to San Pablo Bay is small, less than 10% of Delta outflow (SWRCB, Exhibit 3) and occurs almost entirely in the winter. Nevertheless, runoff from the Petaluma River and Sonoma Creek may contribute to reducing salinities in the shallows of the Bay during the winter in wet years.

VIII. A PROPOSED FLOW STANDARD TO MAXIMIZE PHYTOPLANKTON ABUNDANCE IN SAN PABLO BAY DURING THE SPRING

To maximize phytoplankton abundance, and in particular the concentration of diatoms, the Delta outflow has to be managed to ensure the maintenance of an entrapment zone over the Pinole Shoal. This has been observed to occur at Delta outflows greater than 10,000 cfs. The entrapment zone appears to be created by the estuarine circulation interacting with the bottom topography of the shoal and occurs simultaneously with a separate entrapment zone in Suisun Bay. In the absence of a detailed understanding of the character and salinity distribution of the entrapment zone in San Pablo Bay, the Delta outflow is used to define optimal conditions for phytoplankton. This occurs when the Delta outflow is approximately 20,000 cfs, as is shown in Figure 5.

Phytoplankton abundance is also dependent on the benthic filter feeder population in San Pablo Bay, which appears to be limited by lower salinities in the winter, when Delta outflows exceed about 100,000 cfs. In drier winters, higher salinities occur, and the population of benthos will probably be much larger the following spring. In these circumstances, the supply of phytoplankton from the shoals to the channel will be limited, and concentrations will remain low in the channel whether or not an entrapment zone is present. In the last 32 years, 70% of the years have had peak winter outflows greater than 100,000 cfs.

Therefore, pending further analysis of the hydrodynamics of San Pablo Bay, the following standard is recommended:

To maximize the phytoplankton abundance in San Pablo Bay, the 28-day averaged Delta outflow at Chipps Island should exceed 20,000 cfs during the months of April, May, and June. The standard is to be applied in all years where the October-through March unimpaired Delta outflow is greater than the 3 in 10 dry year.

It should be noted that the development of this standard is based on the frequency of historic winter flows rather than unimpaired or natural flows. It therefore attempts to maintain the historic frequency of years with high enough winter flows to limit benthic growth rather than restore the frequency to what occurred naturally. At present, there is insufficient data to correlate San Pablo salinity with benthic biomass, as has been done for Suisun Bay. With further research, it should be possible to establish a winter maximum salinity standard for San Pablo Bay, as has been recommended for Suisun Bay (see Report 412-5).

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TABLE 1

CHLOROPHYLL DATA IN THE CHANNEL OF SAN PABLO BAY

DATE	CHLOROPHYLL (MG/CU. M)	5 DAY AVERAGE DELTA OUTFLOW (CFS)	SOURCE	STATION
03/--/71	6	22000	Arthur & Ball, 1979	D42
04/--/71	9	38000	"	D42
05/--/71	2	30000	"	D42
06/--/71	29	20000	"	D42
07/--/71	3	11500	"	D42
08/--/71	13	12500	"	D42
03/--/72	3	24000	"	D42
04/--/72	1	12000	"	D42
05/--/72	4	3750	"	D42
06/--/72	1	5000	"	D42
07/--/72	4	6000	"	D42
08/--/72	1	6000	"	D42
04/--/73	2	4000	"	D42
05/--/73	8	7500	"	D42
06/--/73	10	7500	"	D42
07/--/73	5	4200	"	D42
08/--/73	4	6000	"	D42
03/26/76	6.18	4336	IAMP	D42
04/22/76	7.88	5654	"	D42
05/11/76	1.86	3982	"	D42
05/25/76	2.94	4411	"	D42
06/24/76	1.09	3299	"	D42
06/08/76	1.55	4118	"	D42
07/09/76	1.24	4742	"	D42
07/22/76	1.86	4331	"	D42
08/04/76	1.86	4454	"	D42
08/31/76	1.39	3074	"	D42
03/30/77	5.25	2836	"	D42
03/16/77	4.33	2275	"	D42
04/14/77	5.41	3149	"	D42
04/28/77	2.78	3262	"	D42
05/27/77	1.24	2819	"	D42
05/12/77	2.63	4123	"	D42
06/10/77	1.24	1942	"	D42
06/29/77	1.86	3063	"	D42
07/14/77	0.62	2810	"	D42
07/25/77	2.47	3441	"	D42
08/11/77	1.09	3009	"	D42
08/26/77	0.78	1924	"	D42
03/07/78	8.65	63904	"	D42
04/20/78	24.71	64774	"	D42
04/06/78	8.34	49058	"	D42
05/18/78	7.57	37517	"	D42
05/04/78	13.13	63935	"	D42
06/30/78	8.65	4468	"	D42

DATE	CHLOROPHYLL (MG/CU. M)	5 DAY AVERAGE DELTA OUTFLOW (CFS)	SOURCE	STATION
06/15/78	11.12	9150	IAMP	D42
07/27/78	5.81	4678	"	D42
07/13/78	5.56	4339	"	D42
08/24/78	3.09	5777	"	D42
08/11/78	2.97	5533	"	D42
03/08/79	2.35	56811	"	D42
03/22/79	14.82	33287	"	D42
04/20/79	4.14	8591	"	D42
04/05/79	3.28	33815	"	D42
05/24/79	3.34	15735	"	D42
05/04/79	4.57	10859	"	D42
07/19/79	3.09	3912	"	D42
07/06/79	3.96	4539	"	D42
08/17/79	3.96	4246	"	D42
03/27/80	2.01	61161	"	D41
04/11/80	3.25	38513	"	D41
04/25/80	4.17	23444	"	D41
05/08/80	6.80	18751	"	D41
05/22/80	15.60	22774	"	D41
06/20/80	9.58	14961	"	D41
07/15/80	1.86	9688	"	D41
08/07/80	3.22	5976	"	D41
08/21/80	3.22	2946	"	D41
04/30/81	3.25	5080	"	D41
04/15/81	3.71	6206	"	D41
05/29/81	3.09	11020	"	D41
05/14/81	5.41	10150	"	D41
06/11/81	2.17	6065	"	D41
06/26/81	0.62	3854	"	D41
07/09/81	1.24	5412	"	D41
08/51/81	0.78	5133	"	D41
03/04/82	3.40	97284	"	D41
03/18/82	2.32	82653	"	D41
04/15/82	2.78	170645	"	D41
06/15/82	8.96	29251	"	D41
06/29/82	15.29	21246	"	D41
07/29/82	3.25	12386	"	D41
07/15/82	4.64	15993	"	D41
08/26/82	17.3	13433	"	D41
08/18/82	9.73	23776	"	D41
08/12/82	4.33	12539	"	D41
03/24/83	1.24	220353	"	D41
04/07/83	1.09	160906	"	D41
05/05/83	3.09	124612	"	D41
06/17/83	1.70	76660	"	D41
06/07/83	8.30	7494	"	D41
07/20/83	3.40	43229	"	D41
03/14/84	0.60	25997	"	D41
04/12/84	4.80	16982	"	D41

05/10/84	4.30	12400	"	D41

DATE	CHLOROPHYLL (MG/CU. M)	5 DAY AVERAGE DELTA OUTFLOW (CFS)	SOURCE	STATION
07/10/84	4.90	10104	IAMP	D41
07/20/84	15.10	10299	"	D41
08/21/84	3.70	6307	"	D41
08/06/84	2.80	9321	"	D41
03/15/85	5.10	12881	"	D41
04/17/85	3.20	5519	"	D41
04/02/85	2.90	18250	"	D41
05/02/85	6.00	4991	"	D41
05/15/85	1.10	8285	"	D41
06/13/85	2.90	4387	"	D41

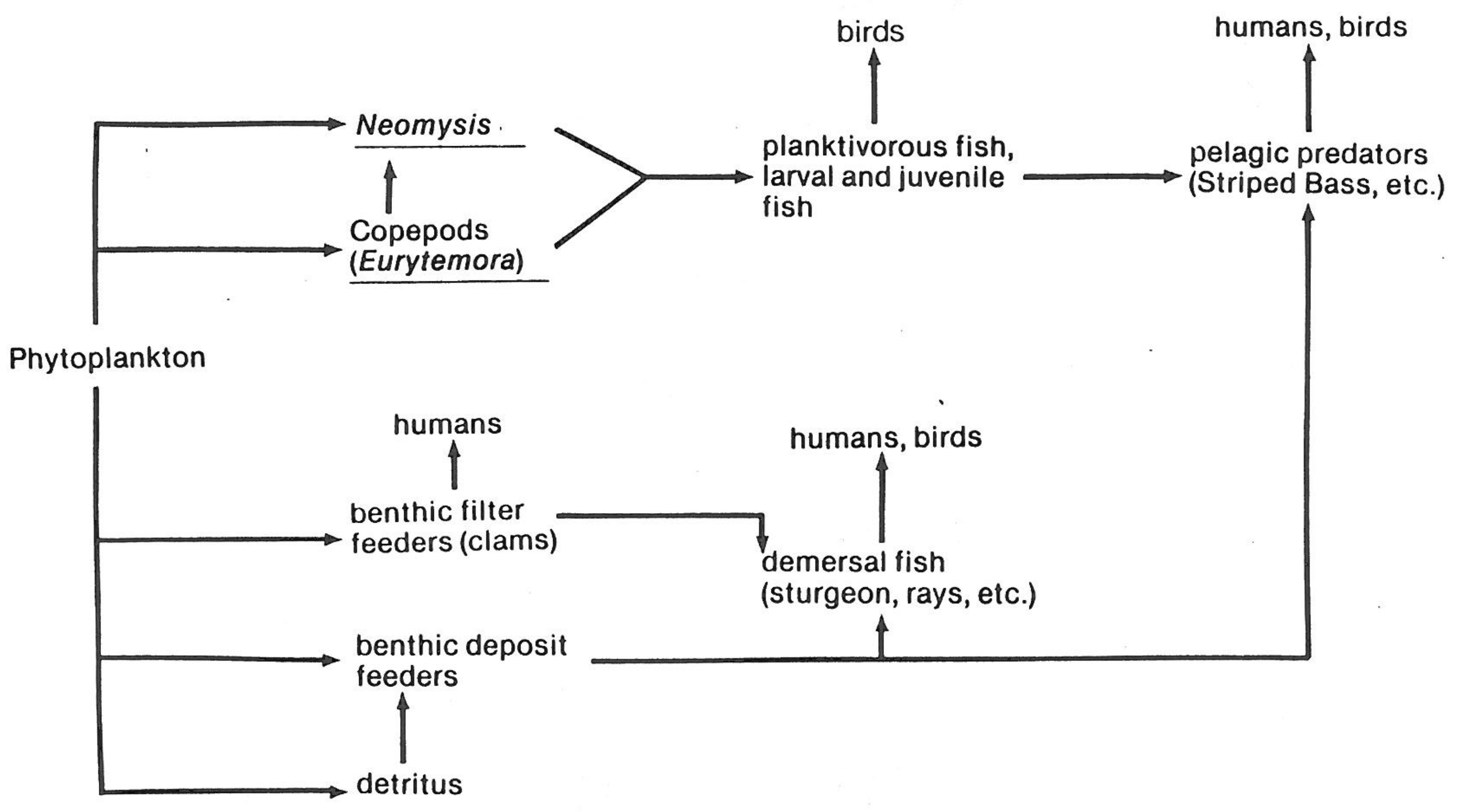
*IAMP: Interagency Monitoring Programs

TABLE 2

RESIDUAL CURRENTS IN SAN PABLO BAY, 1979

Date		Delta* Outflow cfs x 1000	Tidal Velocity	D18 Pt. San Pablo		D22 Pinole Shoal		N24 Carquinez	
Calendar	Julian			Upper	Lower	Upper	Lower	Upper	Lower
3/20	79	30	neap					<--	
21	80	32						<--	-->
22	81	33	spring		-->			<--	-->
23	82	33			-->			?	-->
24	83	32			-->			?	-->
25	84	30			-->		-->	?	-->
26	85	28			-->		-->	?	-->
27	86	25			-->		-->	?	-->
28	87	24			-->		-->	-->	-->
29	88	25			-->		<--	?	-->
30	89	28			-->		<--	?	-->
31	90	33			-->		<--	<--	-->
4/ 1	91	37	neap		-->		<--	<--	-->
2	92	40			-->		<--	<--	-->
3	93	40			-->		?	<--	-->
4	94	37			-->		?	<--	-->
5	95	34					-->	?	
6	96	30					<--	?	
7	97	27					-->	?	
8	95	25					-->	?	
9	99	23					-->	?	
10	100	21					<--	?	

* 5-Day Moving Average, lagged one day



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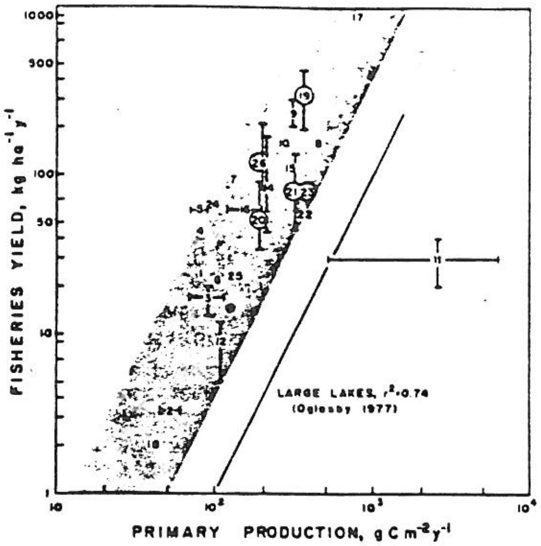
Schematic Diagram of a Typical Estuarine Foodweb

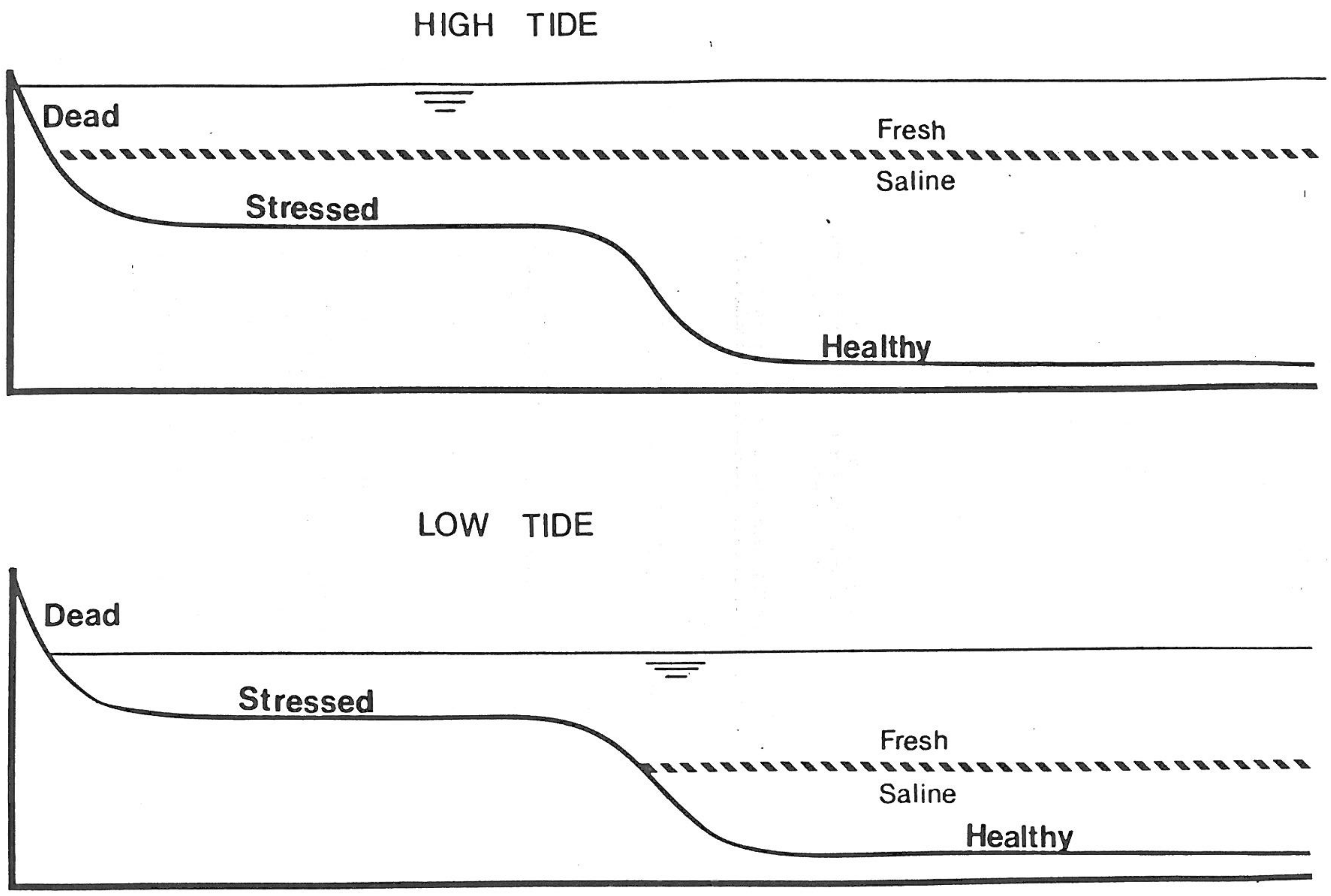
FIGURE 1



The relationship between fisheries yield (first reference) and the primary production (second reference) of a variety of marine systems (points in shaded area) compared with the regression line developed by Oglesby (1977) for similar data from large fresh water systems. Range bars have been added to the marine data where practical and lagoon systems have been circled. Point 11 represents general ranges for coral reef systems reviewed by Marshall (1979) and DeVooys (1979). Other marine systems include : 1) Gulf of Finland (Thurow, 1980 ; Lassig et al., 1978), 2) Gulf of Bothnia (Thurow, 1980 ; Ackefors et al., 1978 and Lassig et al., 1978), 3) Adriatic Sea (General Fisheries Council for the Mediterranean, 1980 ; Kveder et al., 1971 and Pucher-Petkovic et al., 1971), 4) South Baltic Sea (Thurow, 1980 ; Lassig et al., 1978), 5) North Sea (Steele, 1974), 6) Scotian Shelf and 7) Scotian slope, NW Atlantic (Mills, 1980), 8) Georges Bank, NW Atlantic (Olsen and Saila, 1976 — ICNAF Zone 5 ZE, US and foreign fleet ; Sherman et al., 1978, 9) Peru Upwelling (Paulik, 1971 - 1969-1970 catch), 10) Louisiana near-shore shelf, USA (Bahr et al., 1979 ; Sklar, 1976), 11) coral reefs (Marshall, 1979 ; DeVooys, 1979), 12) Black Sea, USSR (GFCM, 1980 ; Sorokin, 1964), 14) Long Island Sound, USA (upper bound = 1880 catch from Goode et al., 1887, lower 1975 catch from NMFS area 611 ; Riley, 1956), 15) Nearshore Rhode Island, USA (NMFS area 539 for 1975 ; Riley 1952 and Furnas et al., 1976), 16) Mid-Atlantic Bight (USA) — Cape Hatteras, NC to Nantucket Shoals, MA to 100 m isobath (McHugh, 1979-US catch only, data from early 1960's before foreign fleet was important ; Emery and Uchupi, 1972), 17) Gulf of Cariaco, Venezuela (Margalef, 1971), 18) Caribbean and Gulf of Mexico (Margalef, 1971), 19) Barataria Bay, LA, USA (Day et al., 1973, production includes macrophytes), 20) Peconic Bay, LI, USA (upper bound = 1880 catch from Mather 1887, lower 1975 N.M.F.S. landings ; Bruno et al., 1980), 21) Charlestown Pond, USA (upper bound when bay scallops abundant, lower without scallops from R. Crawford, pers, comm. ; Nixon and Lee, in press and Thorne-Miller et al., 1981, production includes macrophytes), 22) North Carolina Sounds, USA (Taylor 1951 ; Thayer, 1971 and Dillon, 1971, production includes macrophytes), 23) Apalachicola Bay, FL, USA (National Estuary Study, 1970, Estabrook, 1973), 24) Sagami Bay, Japan (Hogetsu, 1979), 25) Seto Inland Sea, Japan (Hogetsu, 1979), 26) Wadden Sea, Netherlands, W. Germany (Postma and Rauck, 1979 ; cadée and Hegeman 1974 a and b). The heavy point represents the world ocean catch if it is assigned to the total world shelf and slope area (Moiseev, 1973 ; Platt and Subba Rao, 1976).

(Nixon, 1982)

Philip Williams & Associates Consultants in Hydrology	Relationship Between Fishery Yield and Phytoplankton Productivity	FIGURE 2



Philip Williams & Associates
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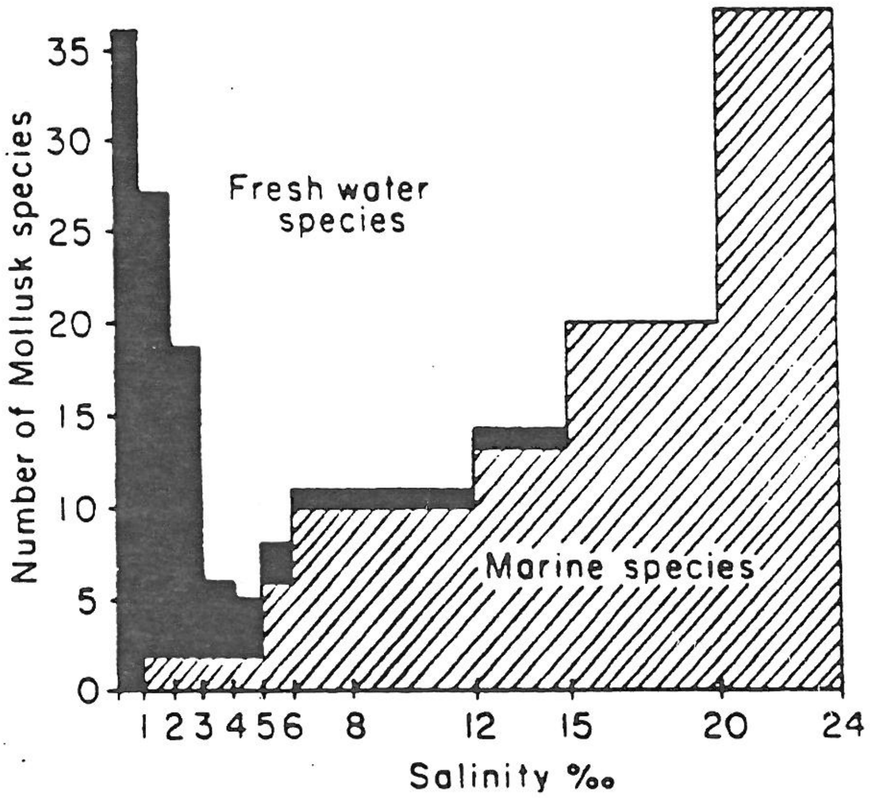
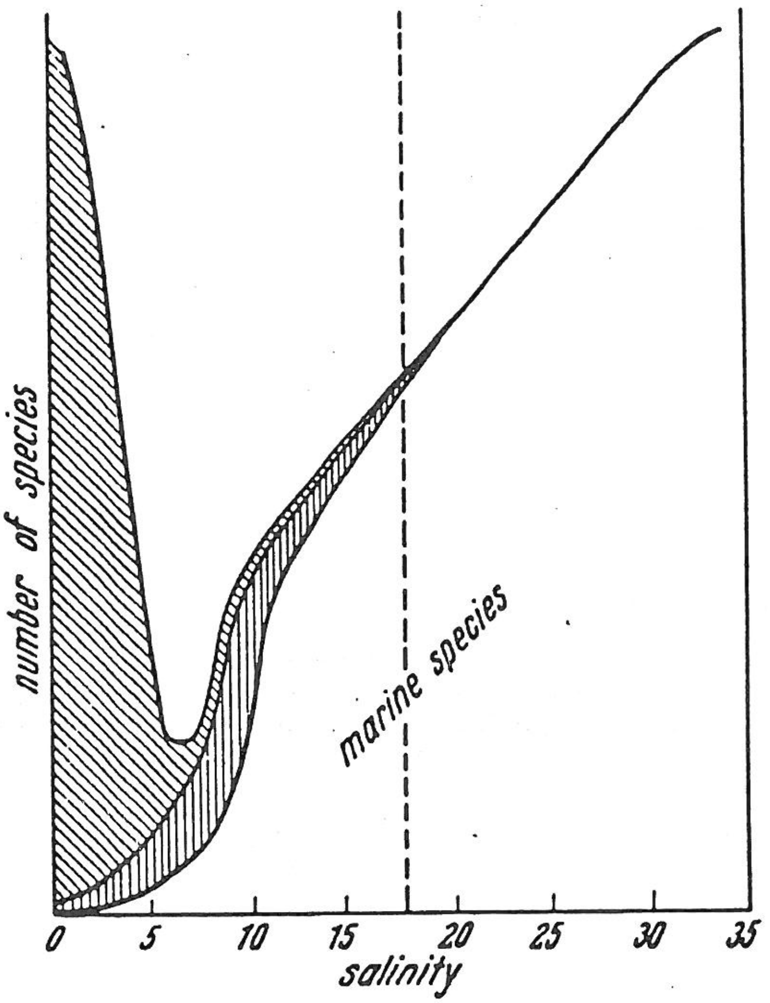
Effect of Stratification on Distribution of Marine Benthos

FIGURE
3



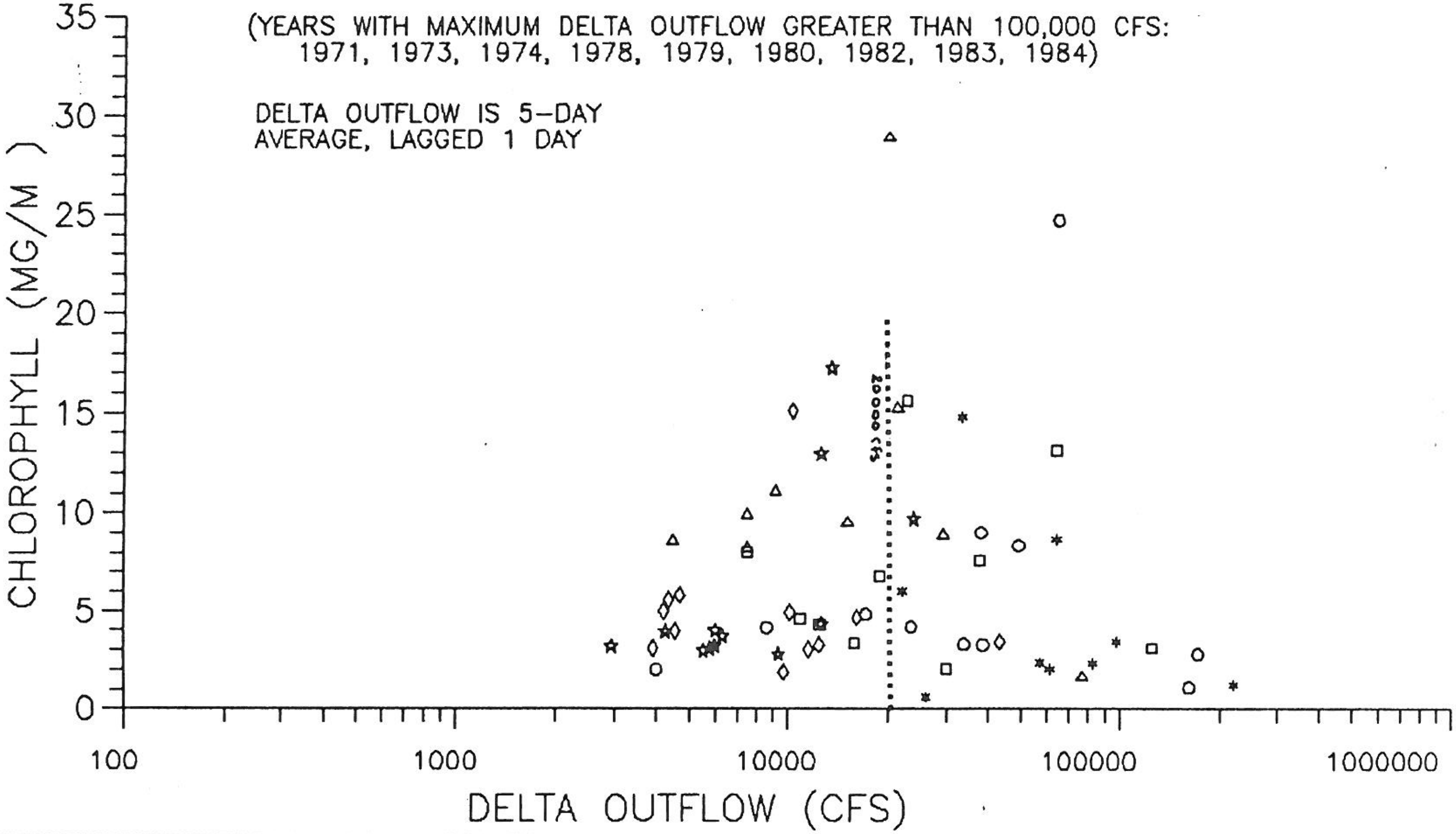
Species richness along the estuarine gradient of the Randersfjord, Denmark. (After Remane and Schlieper, 1971)



Number of species in relation to salinity. The graph has been based on numerous single records. Obliquely hatched: Proportion of fresh-water species. Vertical hatching: Proportion of specific brackish-water species. Light: marine species. Black (at base): holeuryhaline species. In each case the number of species corresponds to the vertical extent of the respective area. After REMANE 1934.

DELTA OUTFLOW AND CHLOROPHYLL CONCENTRATION
SAN PABLO BAY

MARCH, APRIL, MAY, JUNE, JULY, AUGUST



(YEARS WITH MAXIMUM DELTA OUTFLOW GREATER THAN 100,000 CFS:
1971, 1973, 1974, 1978, 1979, 1980, 1982, 1983, 1984)

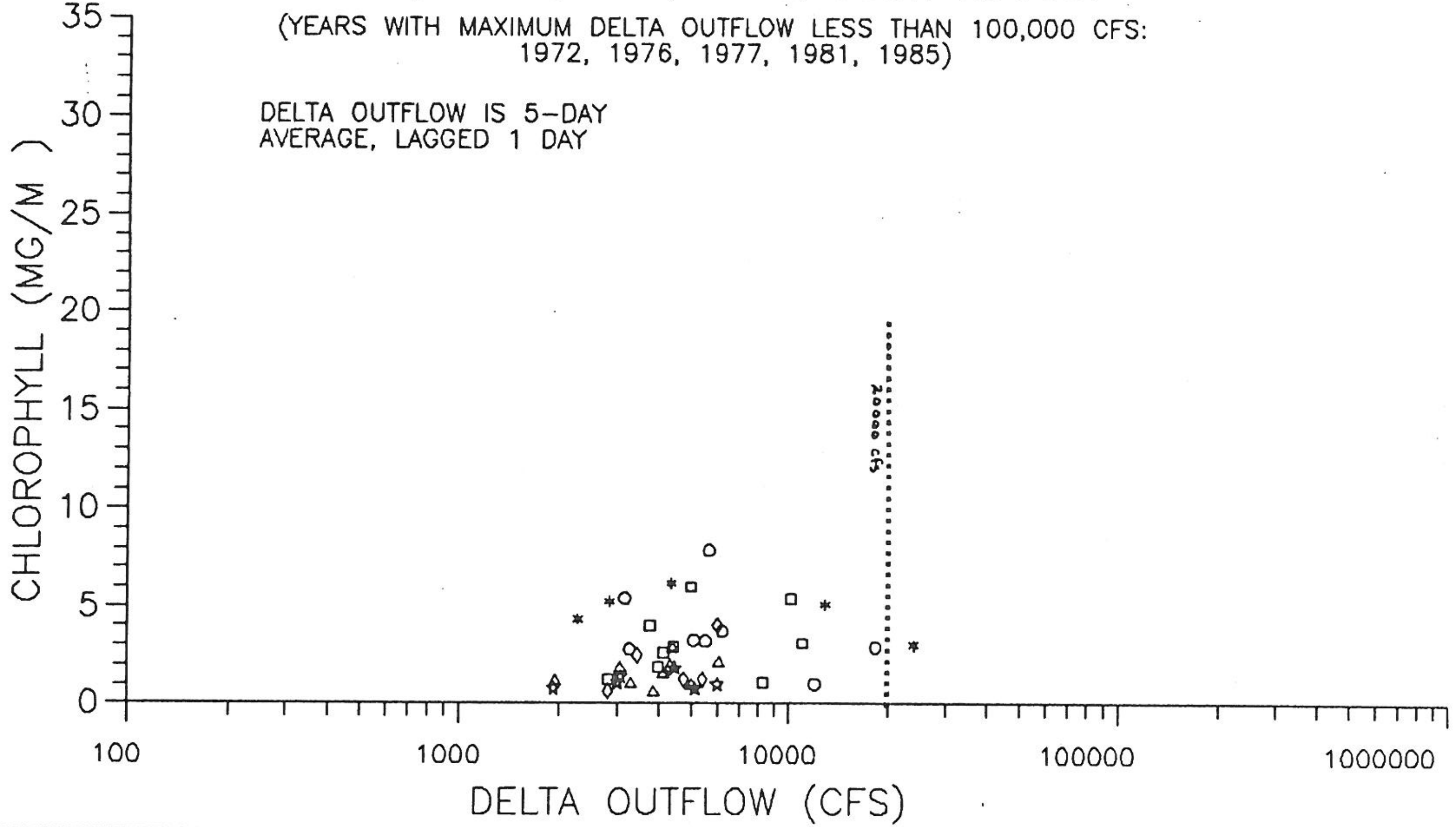
DELTA OUTFLOW IS 5-DAY
AVERAGE, LAGGED 1 DAY

DATE: 09/14/87 BY: L. FISHBAIN	* MARCH ○ APRIL □ MAY	△ JUNE ◇ JULY ☆ AUGUST	Philip Williams & Associates Pier 35, The Embarcadero San Francisco, California 94133	5

DELTA OUTFLOW AND CHLOROPHYLL CONCENTRATION
SAN PABLO BAY

MARCH, APRIL, MAY, JUNE, JULY, AUGUST

(YEARS WITH MAXIMUM DELTA OUTFLOW LESS THAN 100,000 CFS:
1972, 1976, 1977, 1981, 1985)



DELTA OUTFLOW IS 5-DAY
AVERAGE, LAGGED 1 DAY

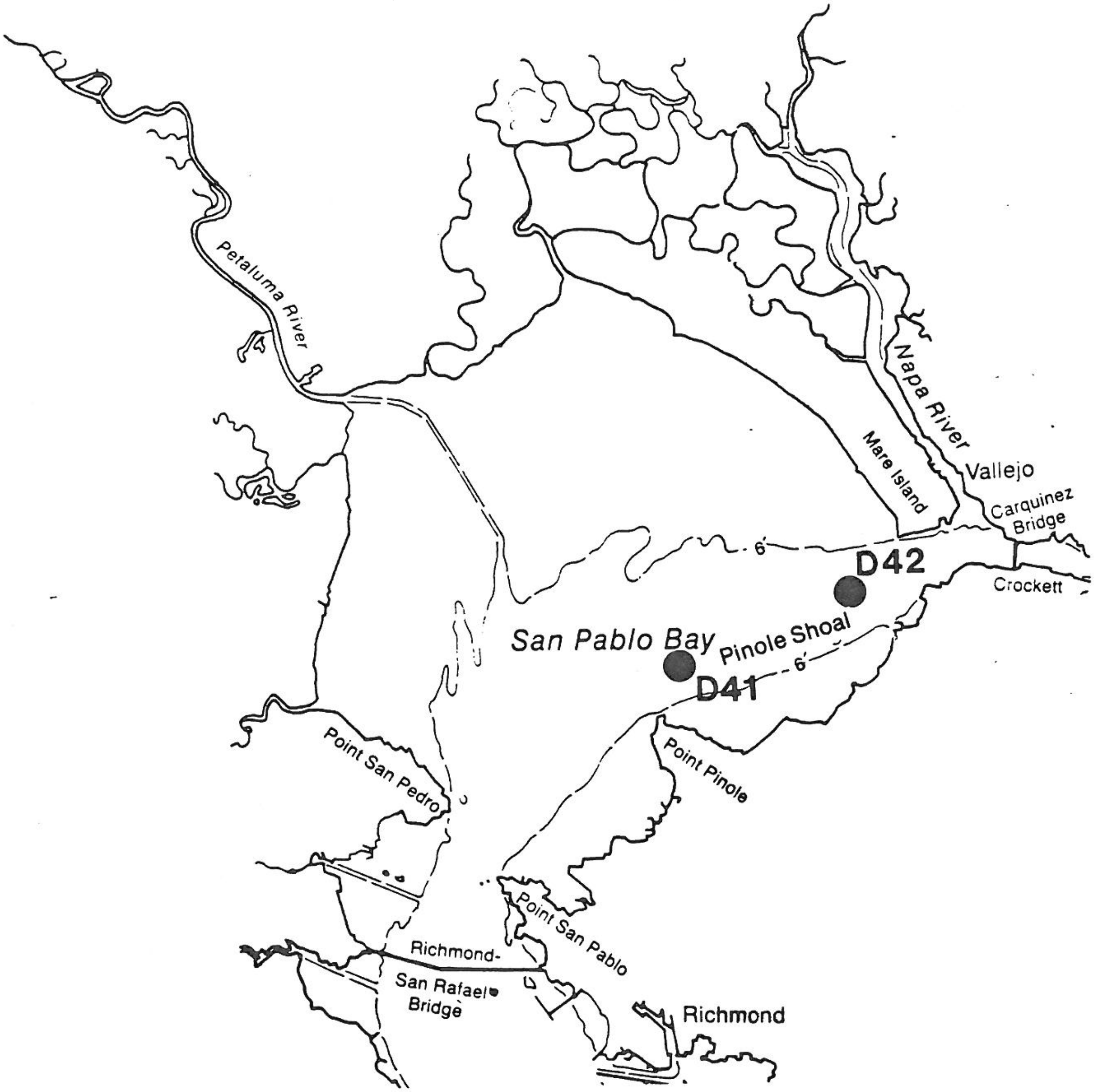
DATE: 09/14/87.

BY: L. FISHBAIN

* MARCH
○ APRIL
□ MAY
△ JUNE
◇ JULY
☆ AUGUST

Philip Williams & Associates
Pier 35, The Embarcadero
San Francisco, California 94133

6



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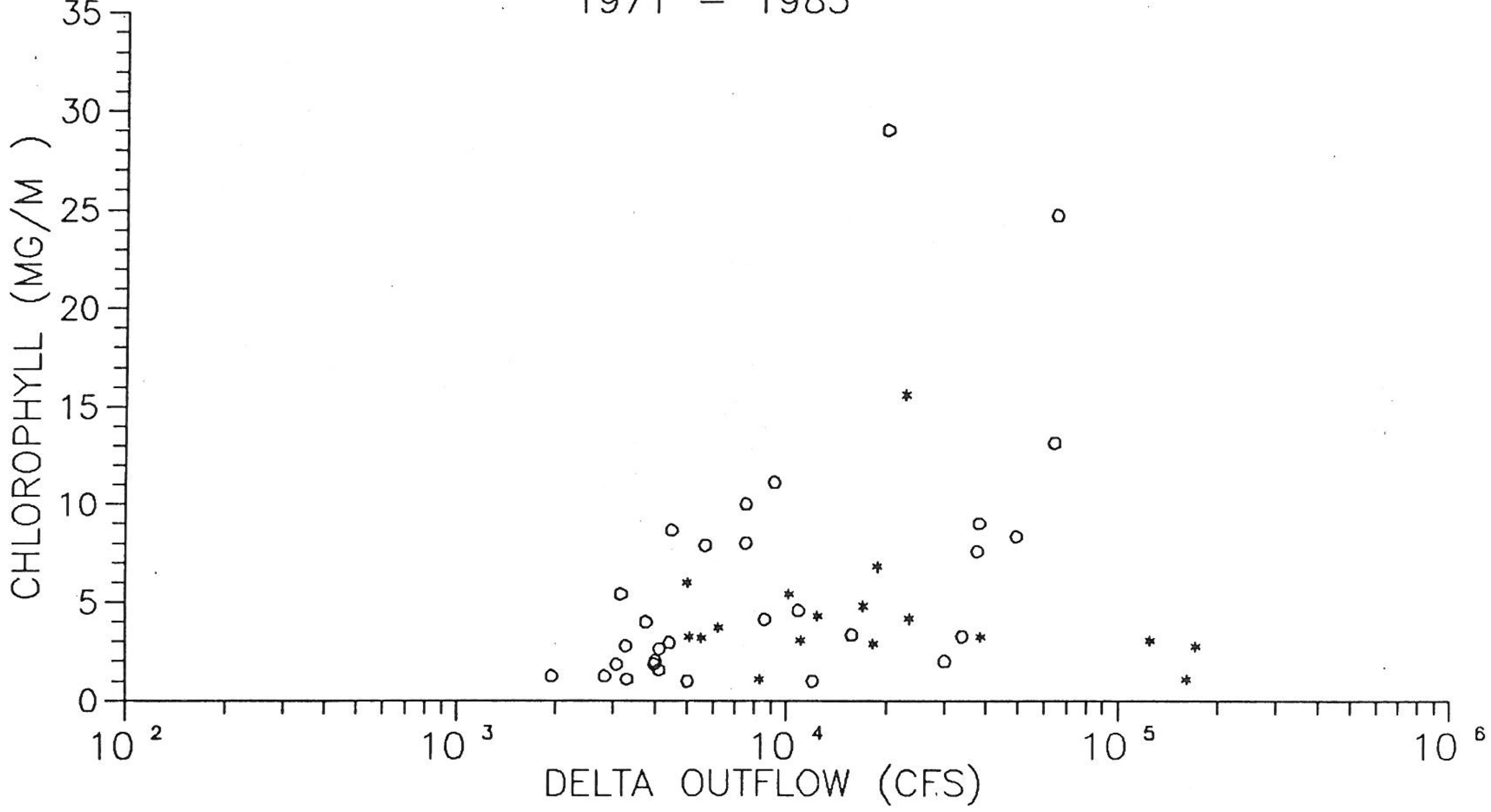
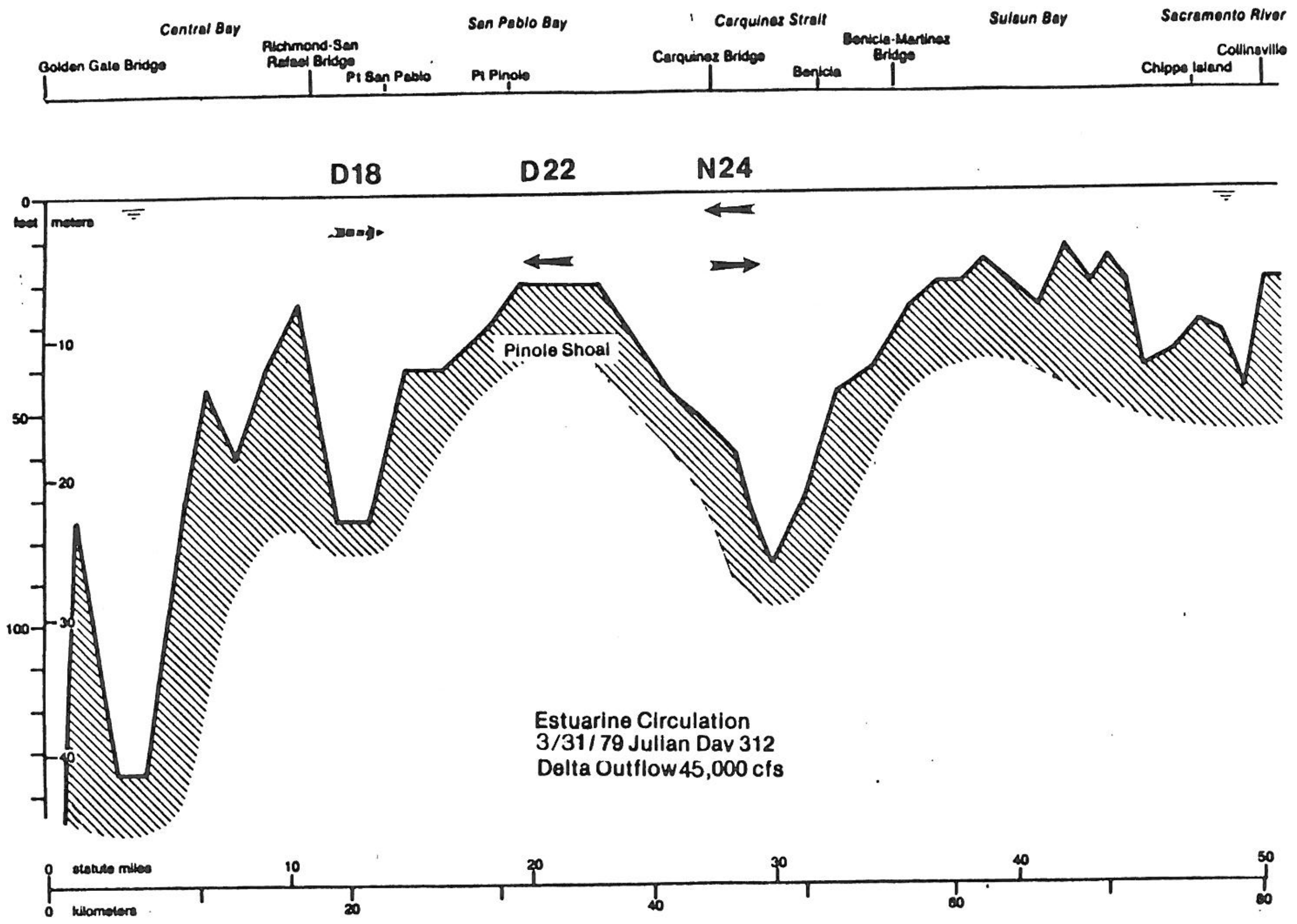
Monitoring Stations in San Pablo Bay

FIGURE 7

DELTA OUTFLOW (5-DAY AVERAGE; LAGGED 1 DAY) AND CHLOROPHYLL CONCENTRATION IN SAN PABLO BAY
APRIL, MAY, JUNE
1971 – 1985



DATE: 09/10/87 BY: L. FISHBAIN	* STATION D41 ○ STATION D42	Philip Williams & Associates Pier 35, The Embarcadero San Francisco, California 94133	8



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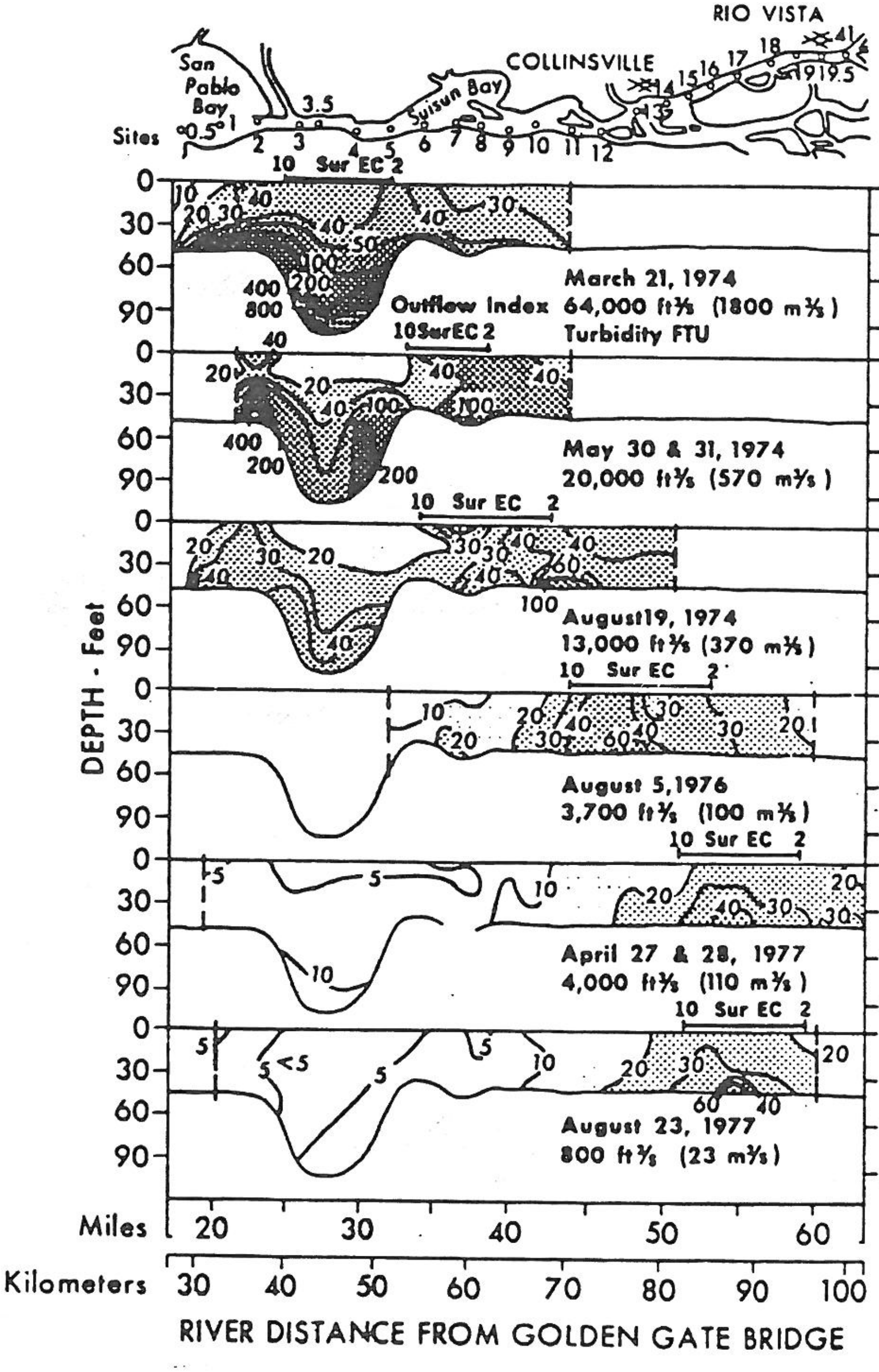
Direction of Residual Currents: March 1979

FIGURE
9



(Arthur & Ball, 1979)

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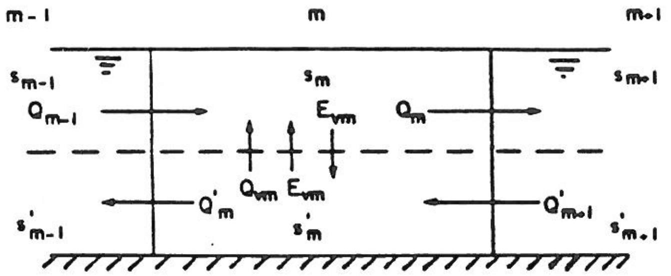
Turbidity Maxima For Different Delta Outflows

FIGURE

10



- Nomenclature and exchange coefficients for two dimensional box models with negligible longitudinal tidal exchange.

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Schematic Diagram of Box Model

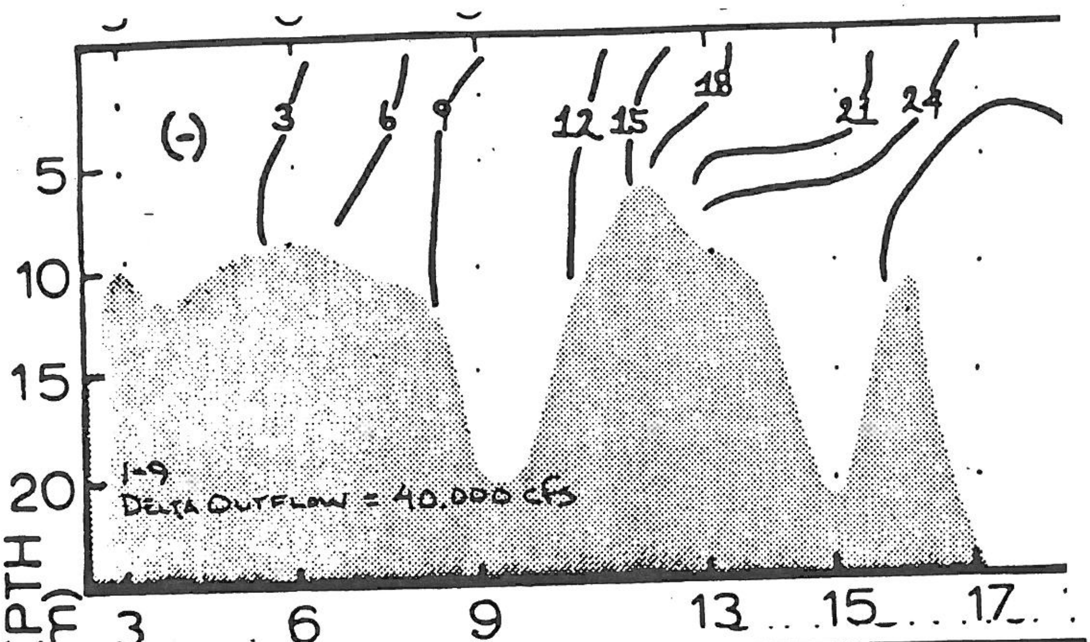
FIGURE
11

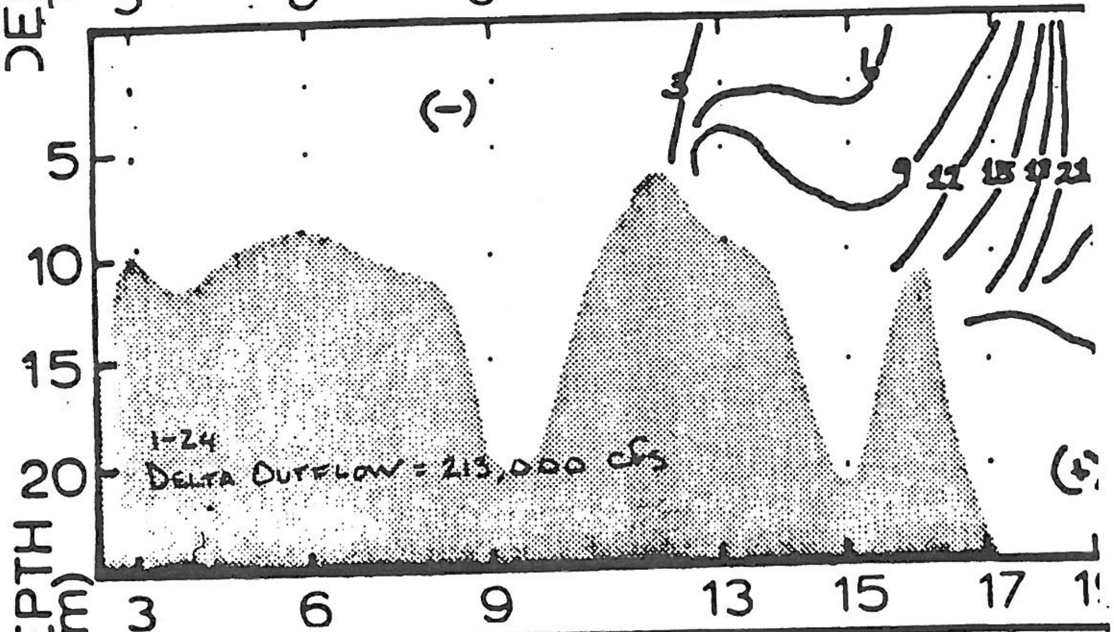
APPENDIX A

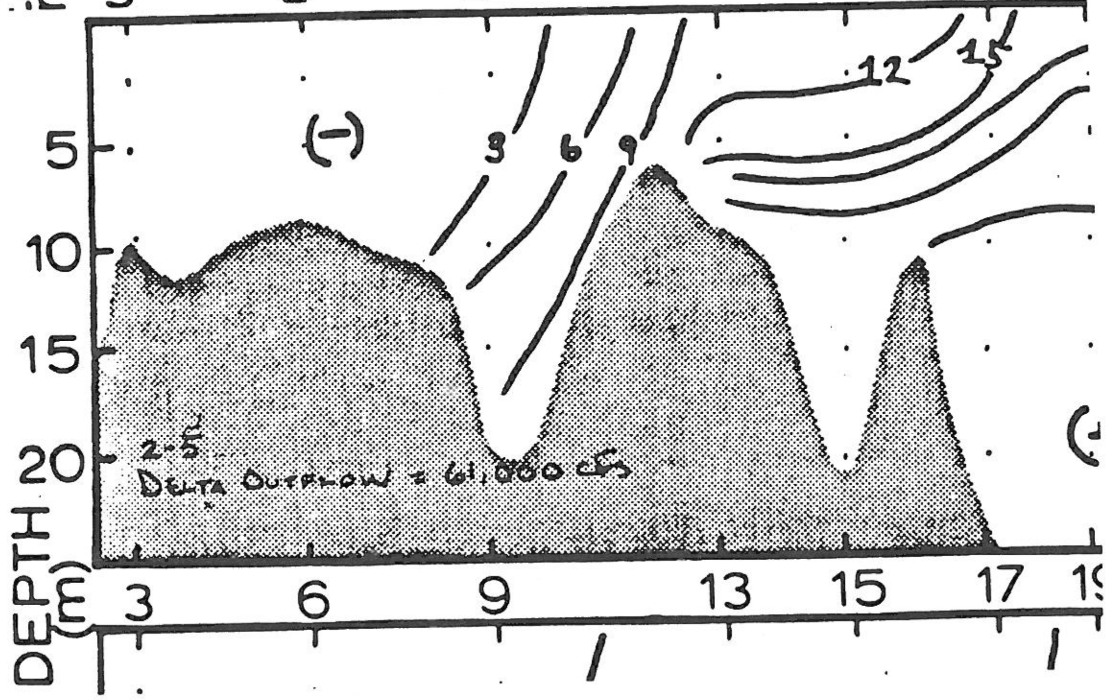
VERTICAL SALINITY TRANSECTS
IN SAN PABLO BAY, 1980

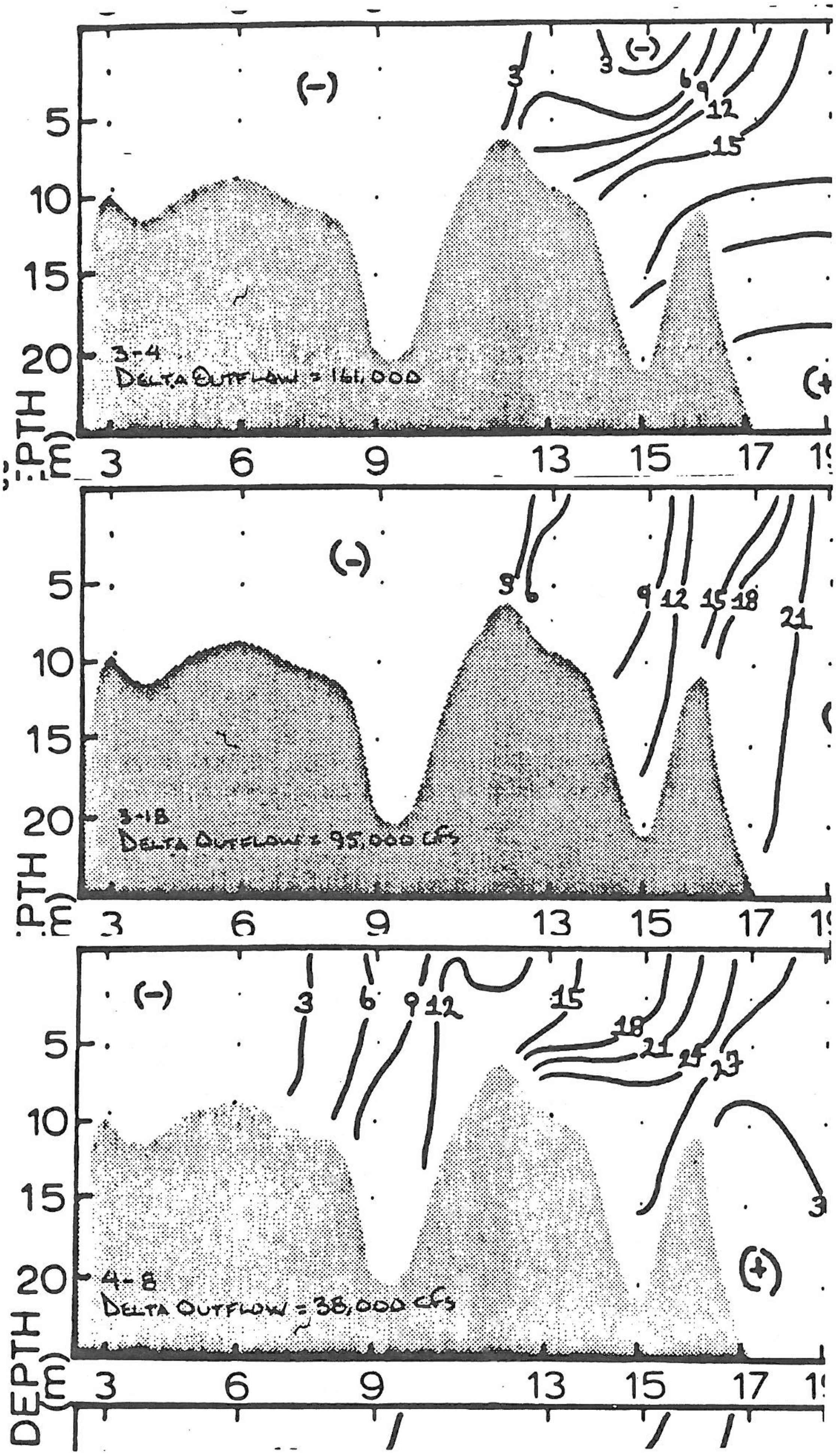
Philip Williams & Associates
Consultants in Hydrology

Report 412-6


(-)
3
6
9
12
15
18
21
24
5
10
15
20
DEPTH (m)
1-9
DELTA OUTFLOW = 40,000 cfs
3
6
9
13
15
17


(-)
3
6
9
12
15
17
21
(+)
5
10
15
20
DEPTH (m)
1-24
DELTA OUTFLOW = 215,000 cfs
3
6
9
13
15
17

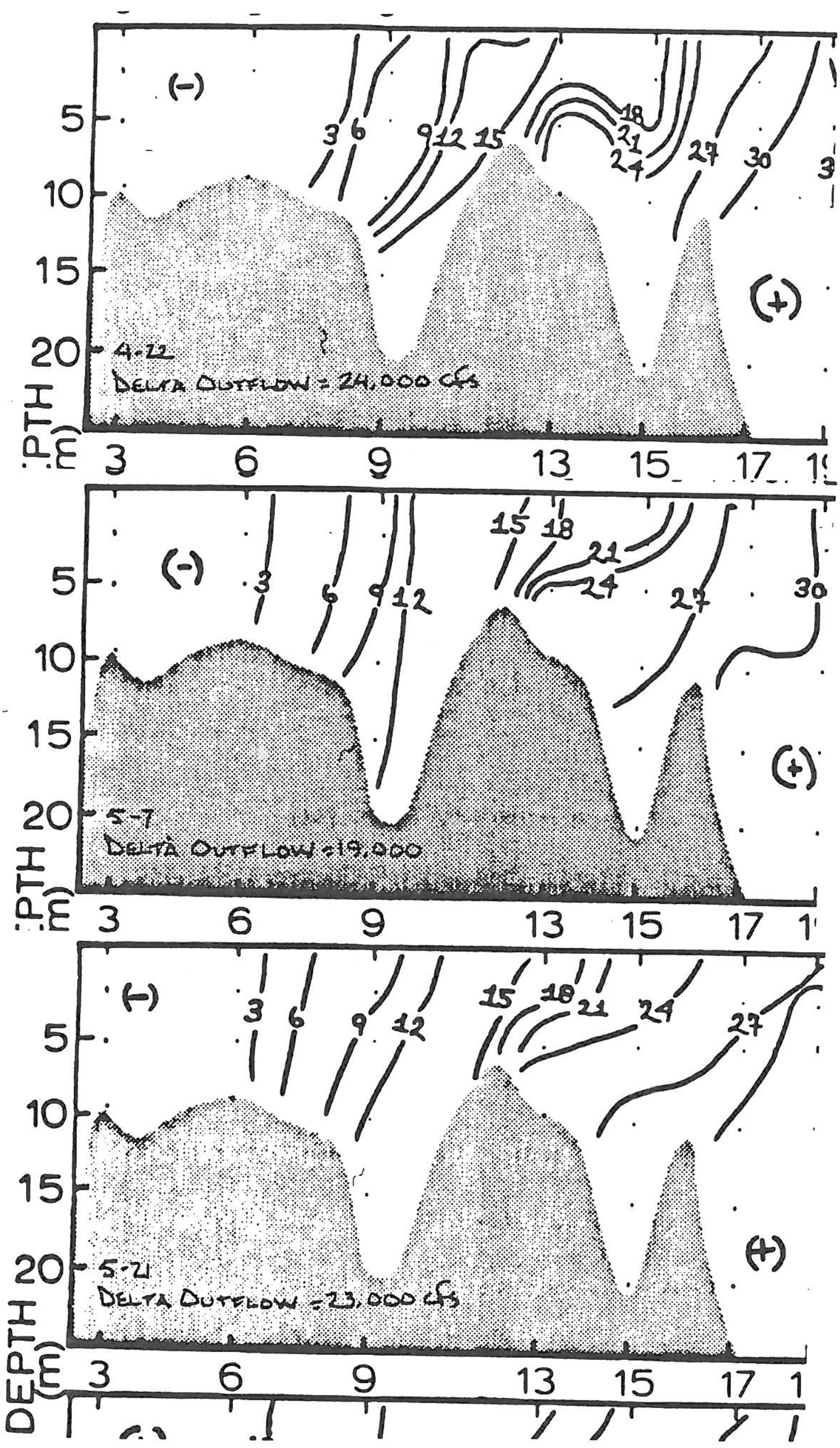

(-)
3
6
9
12
15
5
10
15
20
DEPTH (m)
2-5
DELTA OUTFLOW = 61,000 cfs
3
6
9
13
15
17

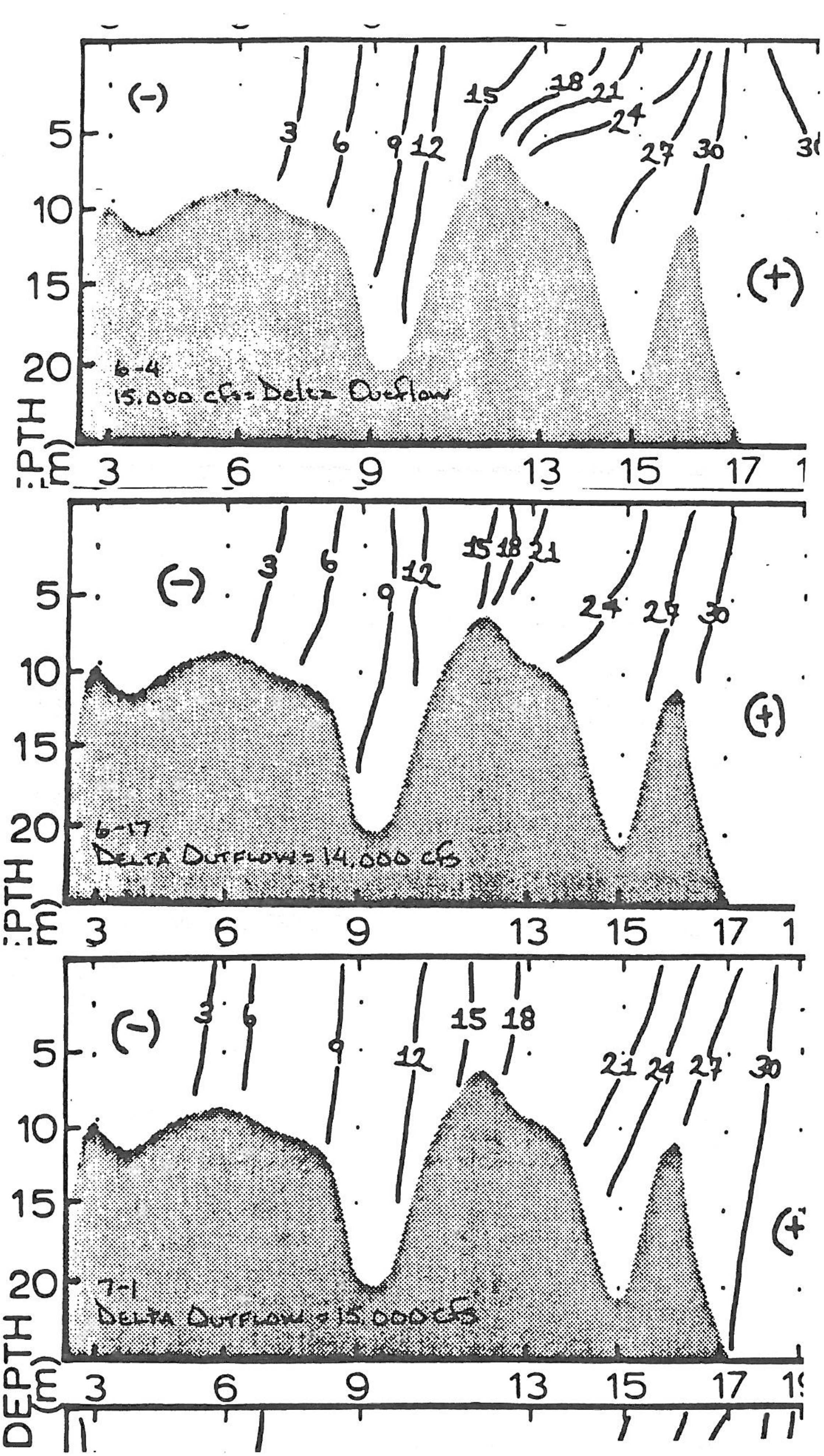


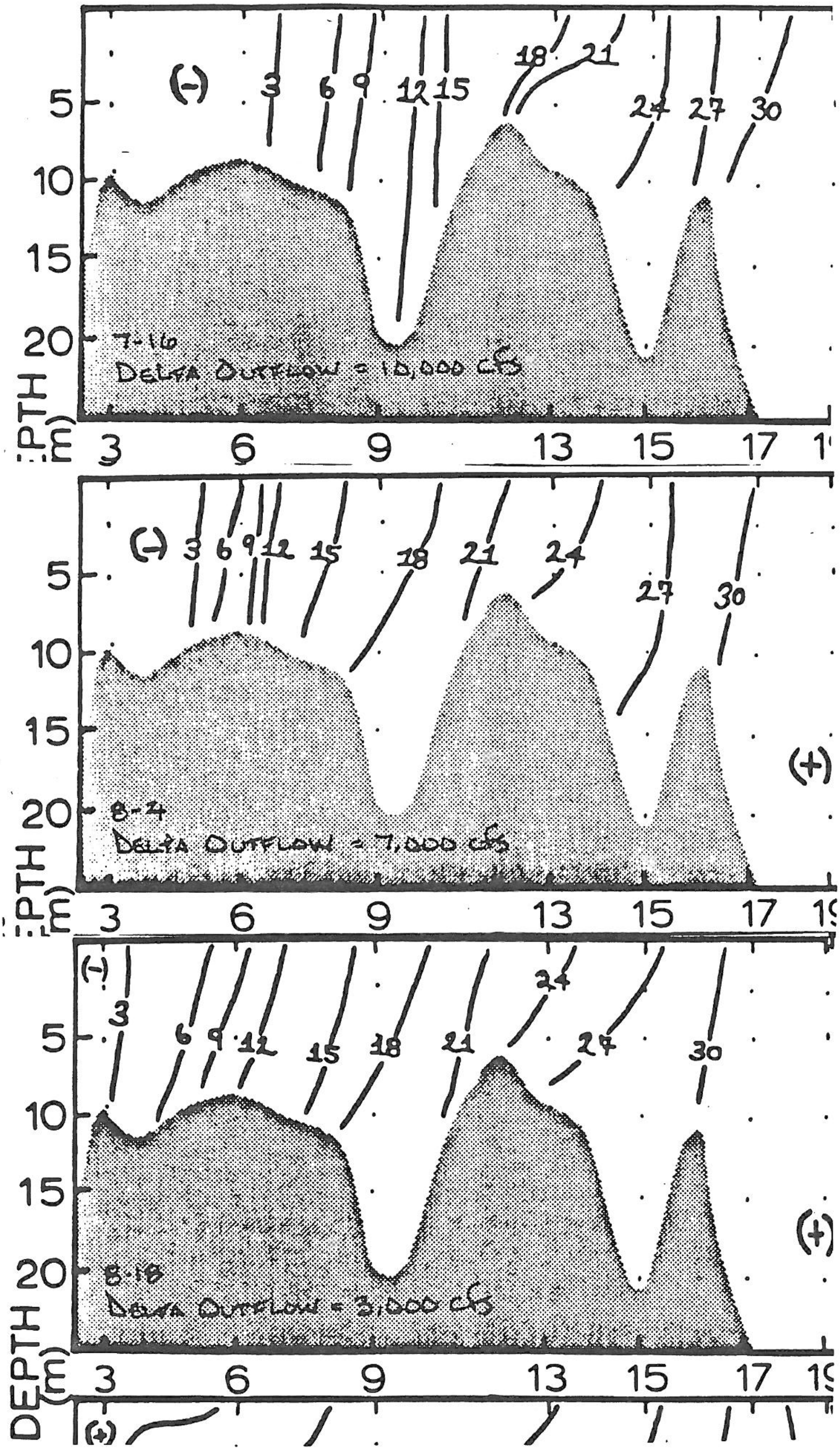
3-4
Delta Outflow = 161,000

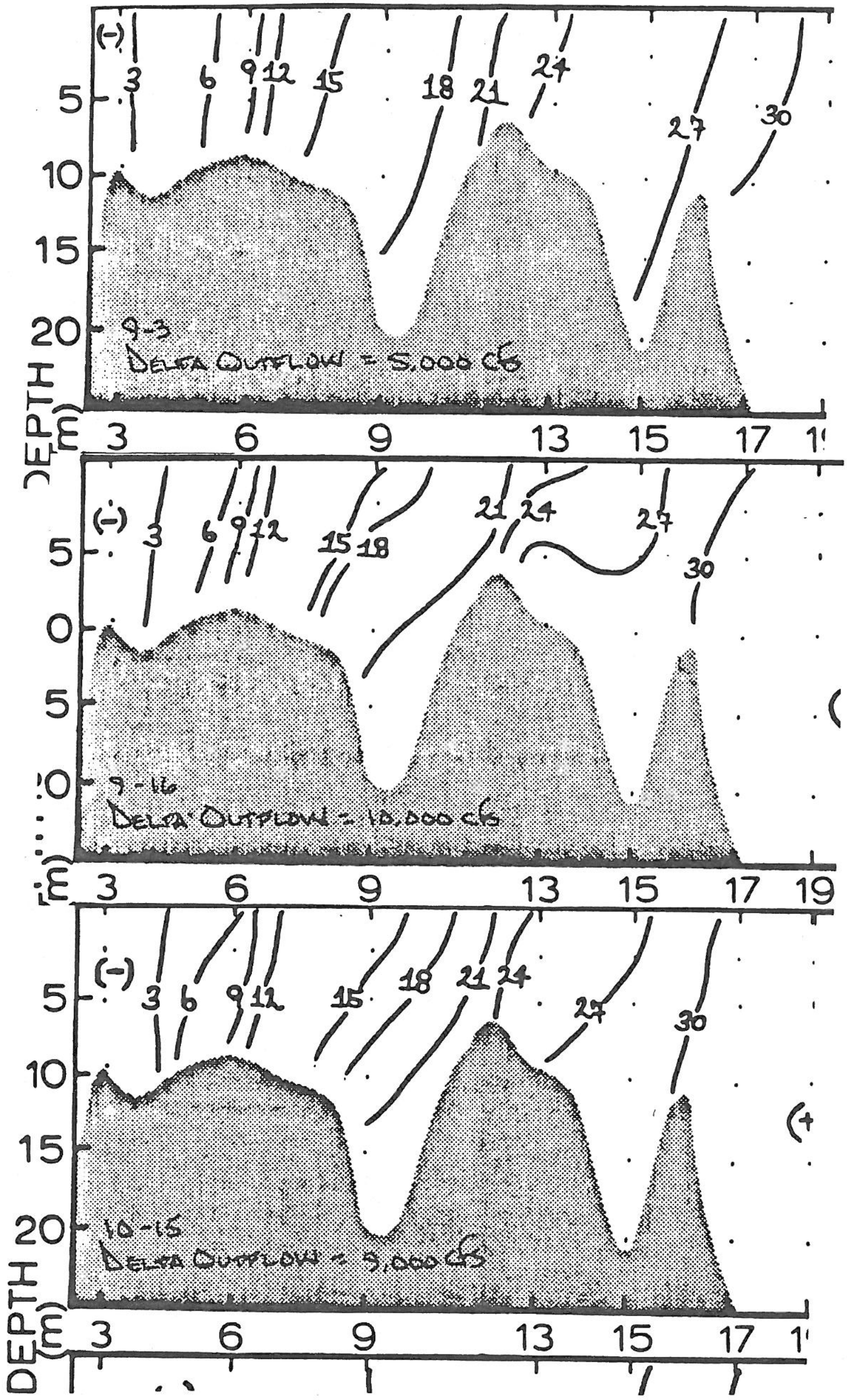
3-18
Delta Outflow ≈ 95,000 cfs

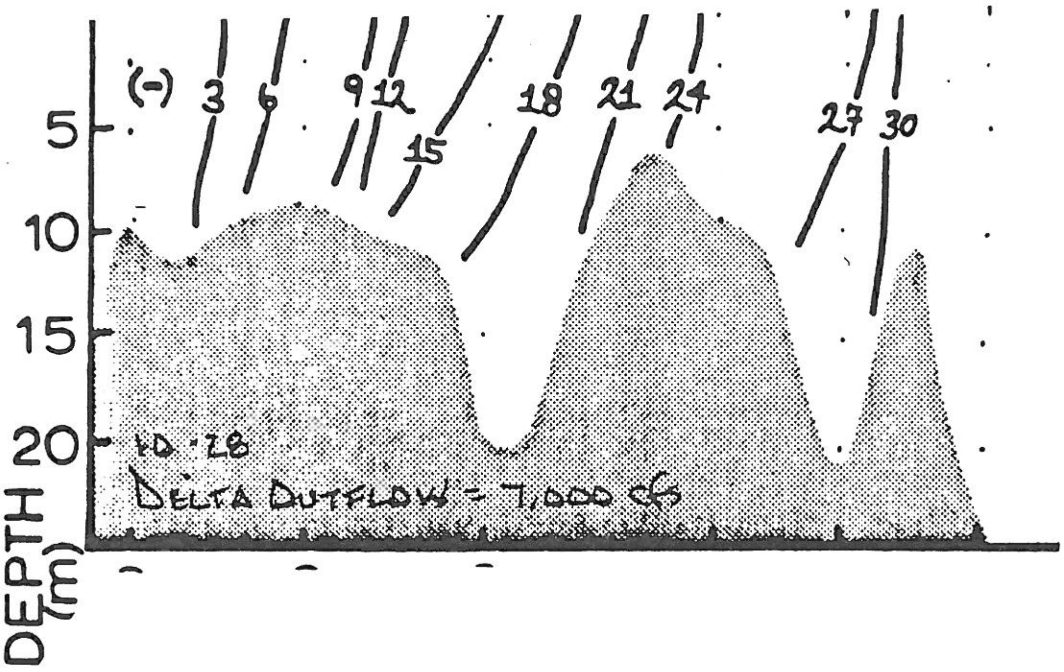
4-8
Delta Outflow = 38,000 cfs

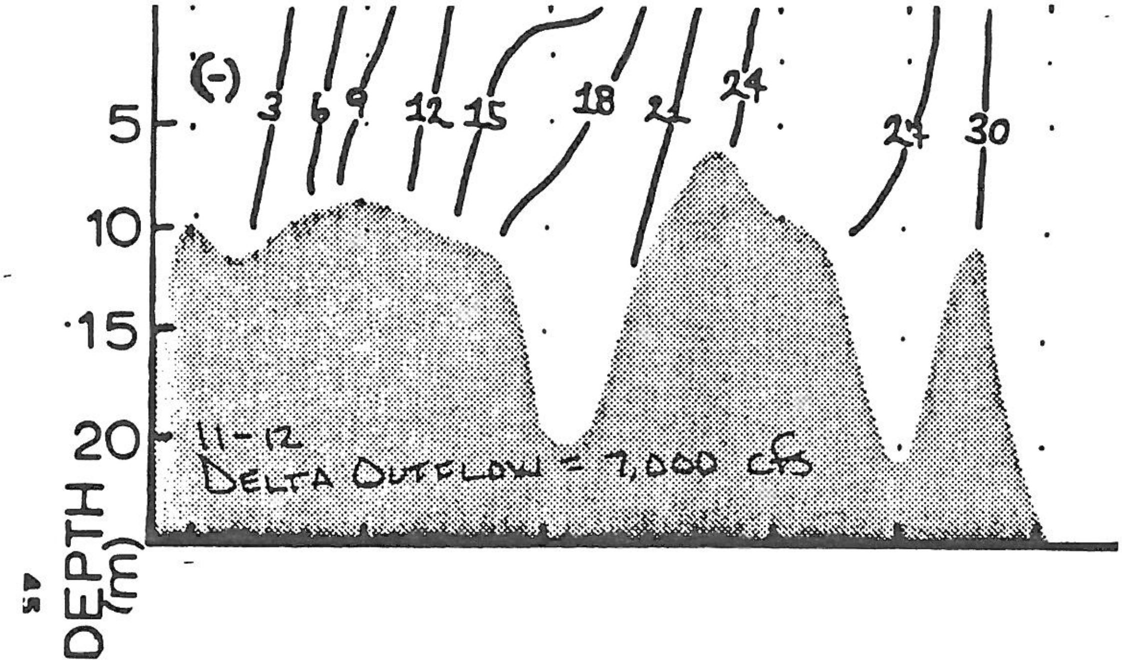

(-)
3
6
9
12
15
18
21
24
27
30
(+)
4-22
Delta Outflow = 24,000 cfs
(-)
3
6
9
12
15
18
21
24
27
30
(+)
5-7
Delta Outflow = 19,000
(-)
3
6
9
12
15
18
21
24
27
(+)
5-21
Delta Outflow = 23,000 cfs
5
10
15
20
DEPTH (m)
3
6
9
13
15
17

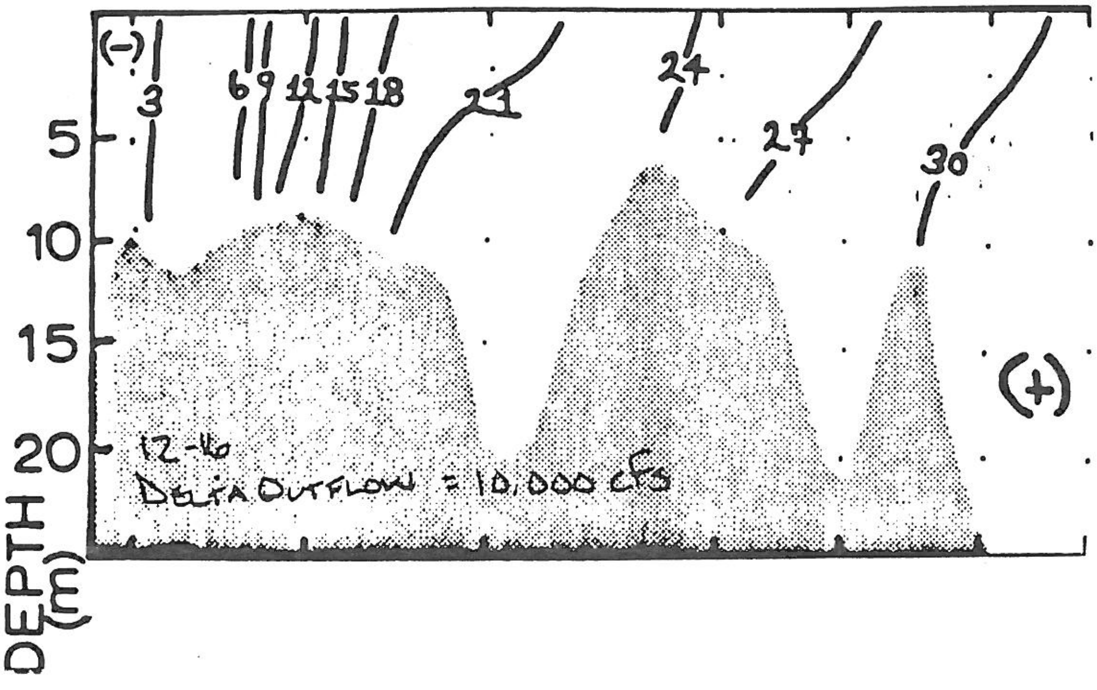

(-)
(+)
3
6
9
12
15
18
21
24
27
30
6-4
15,000 cfs = Delta Outflow
DEPTH (m)
5
10
15
20
3
6
9
13
15
17
(-)
(+)
3
6
9
12
15
18
21
24
27
30
6-17
Delta Outflow = 14,000 cfs
DEPTH (m)
3
6
9
13
15
17
(-)
(+
3
6
9
12
15
18
21
24
27
30
7-1
Delta Outflow = 15,000 cfs
DEPTH (m)
3
6
9
13
15
17


(-)
3
6
9
12
15
18
21
24
27
30
5
10
15
20
7-16
Delta Outflow = 10,000 cfs
DEPTH (m)
3
6
9
13
15
17
(-)
3
6
9
12
15
18
21
24
27
30
(+)
5
10
15
20
8-4
Delta Outflow = 7,000 cfs
DEPTH (m)
3
6
9
13
15
17
(-)
3
6
9
12
15
18
21
24
27
30
(+)
5
10
15
20
8-18
Delta Outflow = 3,000 cfs
DEPTH (m)
3
6
9
13
15
17
(+)


(-)
3
6
9
12
15
18
21
24
27
30
5
10
15
20
9-3
DELTA OUTFLOW = 5,000 CFS
DEPTH (m)
3
6
9
13
15
17
1
(-)
3
6
9
12
15
18
21
24
27
30
5
0
5
20
9-16
DELTA OUTFLOW = 10,000 cfs
3
6
9
13
15
17
19
(
(-)
3
6
9
12
15
18
21
24
27
30
5
10
15
20
10-15
DELTA OUTFLOW = 9,000 CFS
DEPTH (m)
3
6
9
13
15
17
1
(+


(-)
3
6
9
12
15
18
21
24
27
30
5
10
15
20
DEPTH (m)
10-28
Delta Outflow = 7,000 cfs


(-)
3
6
9
12
15
18
21
24
27
30
5
10
15
20
DEPTH (m)
11-12
Delta Outflow = 7,000 cfs


(-)
3
6
9
12
15
18
21
24
27
30
5
10
15
20
(+)
DEPTH (m)
12-16
Delta Outflow = 10,000 cfs

APPENDIX B

BOX MODEL ANALYSIS
OF SALINITY DATA IN SAN PABLO BAY

1/5

Box Model Analysis of Residual Vertical Velocity Distribution

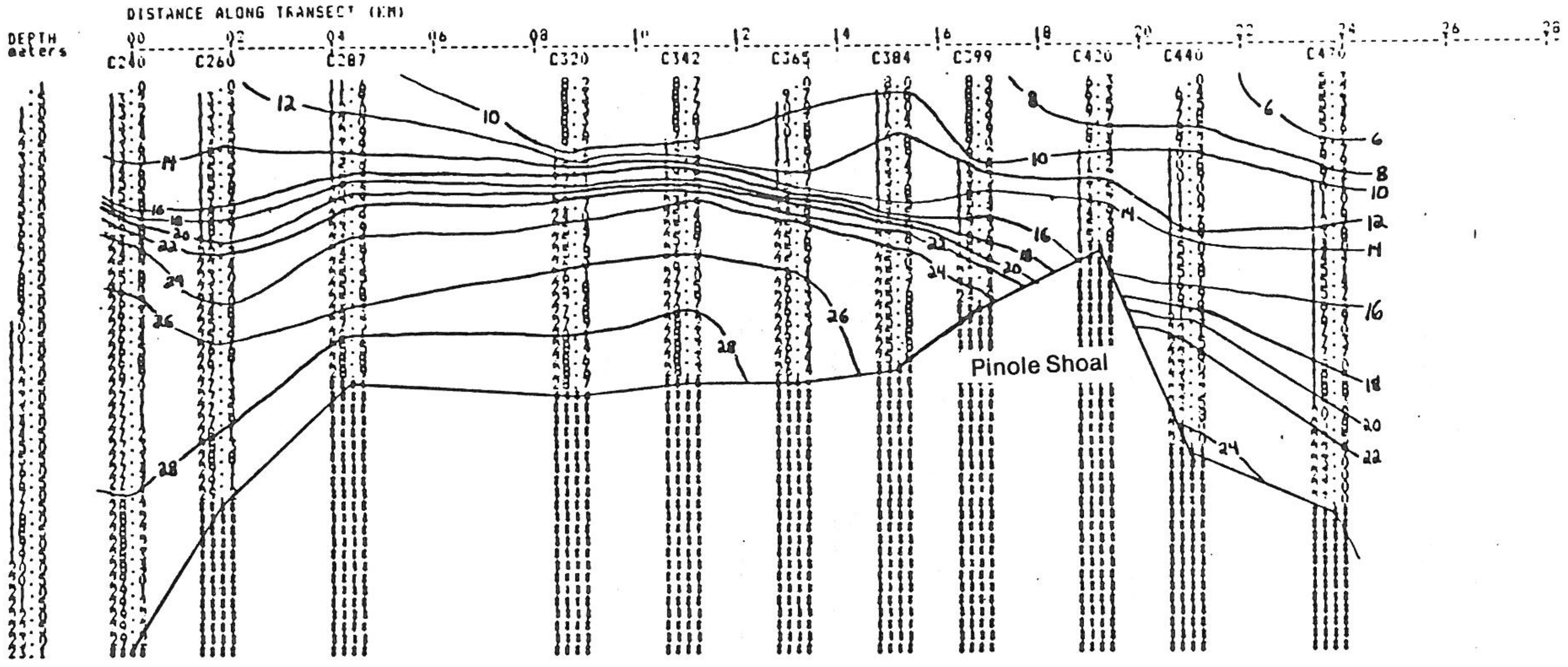
Distance (km) from Golden Gate Bridge — Pt. San Pablo — Pinole Shoal — Carquinez Bridge

	DELTA OUTFLOW (CFS)		12-14	14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30	30-32	32-34	34-36	36-38	38-40	40-42	42-44	44-46	46-48	48-50	
4-18-86	45902																					
Sm			18	18.5	18	18	16.5	16	15.5	15	14.5	13.5	12	12	10.4	10.6	10.5	11	10.5	10	5.5	6
Sm'		30.3	30.3	28	28	28	27	27	26.5	26	24.5	24	24.5	24	23.5	23	21	15.5	19	18	20	
SmSm'			545	518	504	504	446	432	411	390	355	324	294	288	244	244	221	171	200	180	110	
Sm-1Sm'+1			560.5	636	504	462	448	419	405	384	351	294	288	255	278	247	253	221	155	152	108	
R.V.V.*			▽	▽	○	▲	▲	▲	▲	▲	▲	▲	▲	▲	▽	▽	▽	▽	▲	▲	▲	
Turbidity	Maxima						▨	▨	▨				▨	▨							▨	
10-17-86	13364																					
Sm									26	26	25.7	24.5	24.5	24	23.5	22	21	19.5	18.5	18	18	
Sm'								27.4	27	26.5	26	25.6	24.7	24.5	24.2	23.5	23	22.5	22	21.4	20	16.5
SmSm'									702	689	668	627	605	588	569	517	483	439	407	385	360	
Sm-1Sm'+1									712	694	649	637	614	591	539	508	458	426	405	396	375	
R.V.V.*									▽	▽	▲	▽	▽	▲	▲	▲	▲	▲	▲	▲	▽	
Turbidity	Maxima								▨	▨	▨			▨	▨	▨	▨	▨	▨	▨	▨	

* Residual Vertical Velocity

FILE: 18APR86.VKT SAN FRANCISCO BAY CIRCULATION STUDY

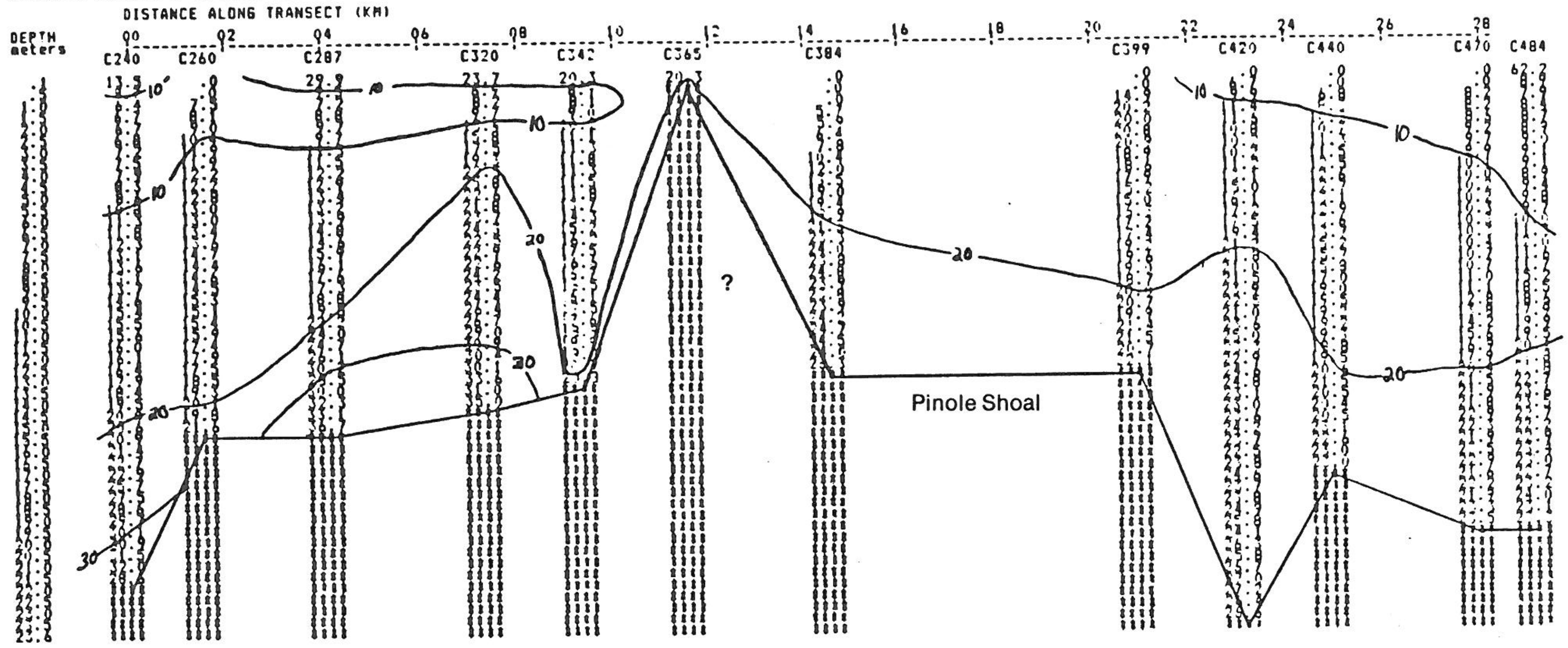
VERTICAL SECTION OF SALINITY (0/00) FOR TRANSECT SC2 ON SURVEY DATE 18APR86 (JULIAN DAY 109)



CONTOURED BY: DR DATE: 4-21-87 CHECKED BY: JWL DATE: 4/21/87

FILE: 17OCT86C.VRT SAN FRANCISCO BAY CIRCULATION STUDY

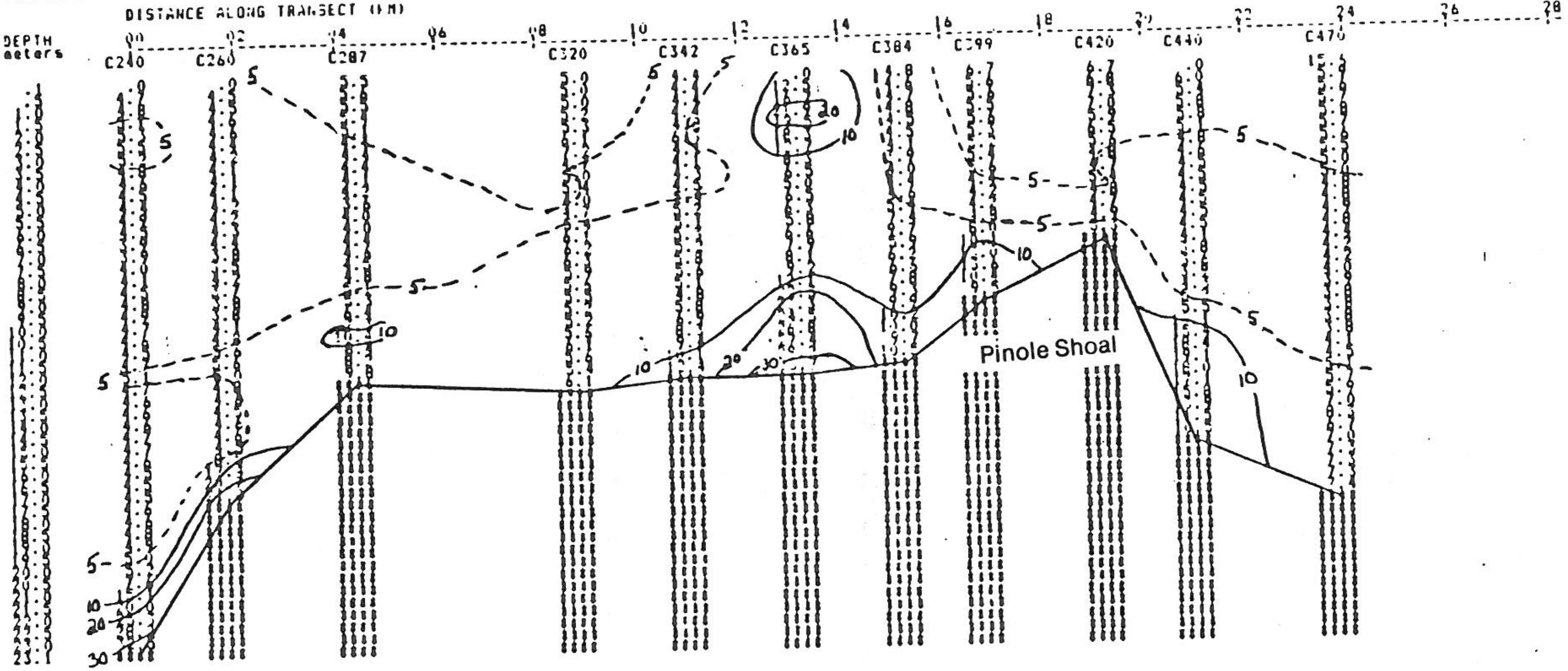
VERTICAL SECTION OF ATTENUATION (1/m) FOR TRANSECT SC2 ON SURVEY DATE 17OCT85 (JULIAN DAY 290)



CONTOURED BY: DR DATE: 4-24-87 CHECKED BY: DATE: 4/28/87

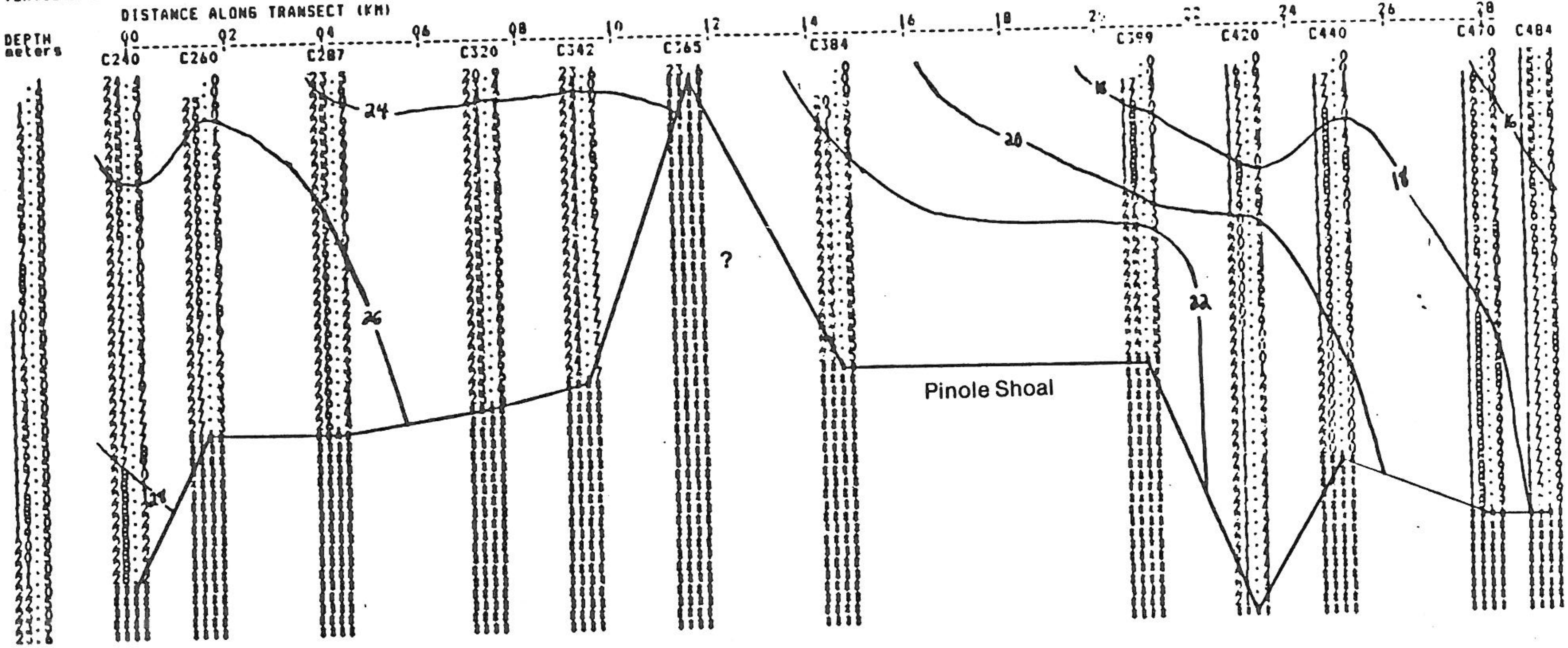
FILE: 16AFR86.VRT SAN FRANCISCO BAY CIRCULATION STUDY

VERTICAL SECTION OF ATTENUATION (1/m) FOR TRANSECT SC2 ON SURVEY DATE 16AFR86 (JULIAN DAY 108)



CONTOURED BY: DR DATE: 4-21-86 CHECKED BY: VWJ DATE: 4/12/87

FILE: 17OCT86C.VRT SAN FRANCISCO BAY CIRCULATION STUDY
VERTICAL SECTION OF SALINITY (0/00) FOR TRANSECT 5:2 ON SURVEY DATE 17OCT86 (JULIAN DAY 29?)



CONTOURED BY: DR DATE: 4-23-87 CHECKED BY: VWJ DATE: 4/28/87