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# A SALINITY STANDARD TO MAXIMIZE PHYTOPLANKTON ABUNDANCE BY POSITIONING THE ENTRAPMENT ZONE IN SUISUN BAY

by

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# I. INTRODUCTION

The San Francisco Bay-Delta Estuary is greatly affected by the amount and timing of freshwater flows from the Sacramento and San Joaquin Rivers. For most of the year, these flows are controlled by large water projects such as the Central Valley Project and State Water Project, which have been operated primarily to provide irrigation, municipal, and industrial water supply as well as power production and flood control. The needs of the San Francisco Bay estuary were not recognized in the design and allocation of water from these projects.

In 1978, the State Water Resources Control Board adopted Decision 1485. D1485 attempted to incorporate environmental standards for water resources management in the Central Valley as it affected the Delta and Suisun Marsh. However, although the impact of water development on the San Francisco Bay-Delta Estuary was recognized, the Board did not include any standards to protect San Francisco Bay in D1485. Instead, the Board required the establishment of a research program and planned reopening the question ten years later.

In 1987, the State Board initiated this review of flow and salinity standards needed to protect beneficial uses in San Francisco Bay and the Delta. In the last ten years, substantial new research has been carried out by the Department of Water Resources (DWR), Bureau of Reclamation (BR), U.S. Geological Survey (USGS), Department of Fish and Game (DFG), and others on the ecology and hydrodynamics of the San Francisco Bay estuary.

The results of this research program can now be used in management decisions concerning the estuary, and specifically, they establish a scientific foundation for the adoption of certain specific flow and salinity standards to protect the estuarine ecosystem.

This report is one of a series recommending four such flow and salinity standards for San Francisco Bay. Each of these standards is complementary, and all are intended to maximize the abundance of phytoplankton, or algae, which now forms the primary basis of the food chain on which the ecosystem depends.

This report describes the rationale for a salinity standard that maximizes phytoplankton abundance in Suisun Bay by positioning the entrapment zone adjacent to the shallows. A separate report, 412-5, also addresses maximizing phytoplankton abundance in Suisun Bay through preventing the establishment of marine benthos on the bottom of Suisun Bay. The two other reports, 412-6 and 412-7, describe standards to maximize phytoplankton abundance in San Pablo and the South Bays respectively.

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## II. CONCLUSIONS

A. Phytoplankton are the base of the estuarine food chain in Suisun Bay, and directly affect the abundance of many other organisms, including shrimp, striped bass, and many resident fish. Maintenance of phytoplankton abundance is critical to maintaining populations of higher-level organisms in Suisun Bay.

B. The abundance and distribution of key zooplankton species, including <u>Neomysis</u> and <u>Eurytemora</u>, are controlled by the phytoplankton abundance in the channels of Suisun Bay.

C. The abundance of phytoplankton, particularly diatoms, in the channels of Suisun Bay is controlled by the positioning of the entrapment zone adjacent to the shallows of Suisun Bay.

D. The abundance of phytoplankton in Suisun Bay is also affected by the intrusion of marine benthos, such as soft-shelled clams, or marine worms during periods of higher salinity.

E. The positioning of the entrapment zone is dependent on the location of the null zone, which is directly affected by Delta outflow.

F. The entrapment zone is located adjacent to the shallows of Suisun Bay when the null zone is located adjacent between Port Chicago and Chipps Island.

G. In order to maximize phytoplankton abundance in Suisun Bay throughout the year, the entrapment zone should be located adjacent to the shallows of Suisun Bay for the period April through September, except when higher flows are required for phytoplankton and for beneficial uses in other parts of the San Francisco Bay-Delta estuary.

H. A tidally averaged bottom salinity standard should be adopted that will locate the entrapment zone adjacent to the shallows of Suisun Bay. The recommended standard is a 28-day tidally averaged mean bottom salinity at Chipps Island, not to exceed 2 ppt. total dissolved solids for the period April through September, except in a one-in-20 dry year.

# 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. Drawings of some typical diatoms found in the San Francisco Bay-Delta Estuary are shown in Figure 1.

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.

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 2.

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 3). 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). An example of the relationship between phytoplankton and the abundance of Neomysis and Eurytemora can be seen by comparing Figures 4a and b with Figure 10.

Neomysis abundance is greater when their population is centered in Suisun Bay rather than in the Delta. Knutson and

Orsi (1983) show that as Neomysis populations are shifted into the Delta during periods of low Delta outflow, abundance drops dramatically (Figure 5). The factors responsible for the decline in Neomysis populations during low Delta outflow are decreased phytoplankton production and abundance in deep Delta channels, which results in less food for adult Neomysis and for the copepod Eurytemora (Knutson and Orsi 1983).

## IV. FACTORS AFFECTING PHYTOPLANKTON ABUNDANCE

The rate at which phytoplankton grows, referred to as the "productivity" and its population, referred to as "biomass" "abundance" or "standing crop," is controlled by a combination of physical, chemical and biological factors.

### A. Sunlight

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 sunlight in summer and least in winter. Figure 6 shows the typical seasonal variation of sunlight at the latitude of San Francisco Bay. Because light is absorbed by water and dissolved substances and absorbed and scattered by particles, irradiance decreases continuously with depth in the water column. At some depth, irradiance is so low that phytoplankton cells cannot gain enough light energy to offset their energy requirements for 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 photosynthesis 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. The compensation intensity varies by species and degrees 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) ranges from 0.2-6.6 meters (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, is determined by the suspended sediment load initially carried into the Bay by the Sacramento River, and subsequently suspended by wind, wave, and tidal action.

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 compensation depth (light too low to survive) and back into the well-lighted upper reaches of the water column in a short period of time. Thus the factor that determines the ability of a population of phytoplankton to grow is the daily mean light history of the population (Figure 7). If the cells in a population, on the average, are exposed to enough light in a day so that the energy trapped by photosynthesis exceeds that expended in respiration, there will be a net energy gain and the population will increase. If, on the other hand, turbulence mixes the water column so deeply that the cells are not able to trap enough light energy to replace energy stores consumed by respiration, the population declines.

A critical mixing depth can be defined where daily population photosynthesis and respiration integrated through the water column to the "critical depth" (Sverdrup 1953) are exactly in balance. If vertical movement due to turbulence is restricted to depths shallower than the critical depth, the phytoplankton population increases. If vertical movement exceeds the critical depth, no net growth occurs and the population declines. Since phytoplankton photosynthesis and respiration are averaged over a daily cycle, day length as well as water turbidity affect the location of the critical depth. Because the waters of San Francisco Bay are highly turbid, the critical depth for San Francisco Bay Delta Estuary phytoplankton populations is on the order of a few meters (Cole and Cloern 1984).

## B. Nutrients

Critical depth theory assumes that no other factors restrict the phytoplankton growth rates. In most temperate aquatic habitats, this is usually only true in spring during the early part of the growing season. The growth of phytoplankton converts dissolved, inorganic salts of nitrogen, phosphorous and silicon (collectively referred to as "nutrients") into plant matter. This depletes the supply of nutrients, which ultimately limits phytoplankton growth rates to the rate at which nutrients are replenished.

Unlike many other aquatic habitats, phytoplankton growth rates in San Francisco Bay are rarely limited by nutrient availability (Smith et al. 1979; Cloern et al. 1983; 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 growth rates in the turbid water of San Francisco Bay. Silicate, an essential nutrient for diatoms but not for most other phytoplankton, is depleted during summer in low flow years, but otherwise it probably does not limit diatom growth. Unlike nitrogen and phosphorus, sewage and waste water are not important sources of silicate.

## C. Grazing

A final factor controlling phytoplankton abundance is the rate at which they are removed by grazers. Grazing can have a profound effect on the composition of phytoplankton communities. Most grazers cannot or will not consume all species of phytoplankton. Some phytoplankton may be too small to be filtered efficiently, or some may be to large. Others may be protected by a casing of slime, or form mats, globs or strings of cells that are too large to handle. Still others may produce chemicals that are toxic to the grazer or impart an unacceptable taste to the cells.

Grazing removes cells from a population without affecting the growth rate of the individual cells. But grazers can reduce the growth rate of a population by eliminating cells, even though environmental factors are optimal 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 related to phytoplankton abundance because the grazer has to work to filter out the cells. When phytoplankton abundance is depleted below a certain concentration, grazers will either stop filtering, leave in search of higher food concentrations, switch to another food item, or starve.

In shallow, turbulent estuaries, grazers living on the bottom, known as benthos, can compete directly with planktonic grazers (zooplankton such as <u>Neomysis</u> and <u>Eurytemora</u>) for phytoplankton. Benthic grazers such as clams are long-lived relative to planktonic grazers, and are frequently larger. Since the ability of an organism to filter water increases with size, larger organisms 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, leaving little behind for planktonic grazers. The reproductive rate of grazers, both planktonic and benthic, is 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. This can have serious implications for organisms such as larval and juvenile fish or planktivorous fish that normally depend on planktonic grazers, such as copepods and shrimp, as their primary food source.

## V. INFLUENCE OF DELTA OUTFLOW ON PHYTOPLANKTON ABUNDANCE IN SUISUN BAY

With the foregoing introduction, we would now like to turn to a specific discussion of phytoplankton population dynamics in Suisun Bay with particular reference to the role of the entrapment zone in phytoplankton distributions in Suisun Bay.

During certain periods in the spring and summer and dependent on Delta outflow, an entrapment zone is located in Suisun Bay. As is described in this report, an entrapment zone is a region of upwelling in the water column sufficient to balance the settling of particles of sediment and also the larger phytoplankton such as diatoms.

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) show that in these conditions no net phytoplankton growth is possible in channels of Suisun Bay where the mixing depth (approximately 10 meters) is greater than the critical depth. However, on the extensive shoals adjacent to the channels, the water depth, of approximately 1 to 2 meters, is less than the critical depth, so there is a considerable net growth or "bloom" of a phytoplankton community composed of diatoms and small flagellates (see Figure 8). These cells are then circulated into the entrapment zone in the main channel by tidal currents (Cloern et al. 1983). Diatoms are concentrated in the entrapment zone because of their higher sinking rates, while the flagellates are carried out of Suisun

Bay by the net outward-flowing surface current. The concentration of diatoms in the entrapment zone greatly facilitates feeding by planktonic grazers, which are found in higher abundances in the channel than on the shoals of Suisun Bay (Ambler et al. 1985, Cloern et al., 1985).

The higher growth rates and abundances of planktonic grazers like Neomysis and Eurytemora in the entrapment zone (Knutson and Orsi, 1983) in turn make it easier for fish to capture an adequate food ration and increase their survival and abundance. This is particularly significant in Suisun Bay because it is a nursery area for many species of fish. The salinity transition that occurs in Suisun Bay may be critical to the the adaptation of migrating young of anadromous fish to salt water such as American shad. These fish need to feed during the adjustment period or they cannot survive the transition.

With low Delta outflows, the entrapment zone moves up into the Delta (as discussed in the following sections), and is uncoupled from phytoplankton production on the shoals of Suisun Bay. This results in a large decrease in phytoplankton biomass, as shown in Figure 9. Diatoms produced on the shoals sink rapidly to the dark depths of channels where they are consumed by benthic organisms or dispersed by tidally-derived turbulence. They do not accumulate to fuel the planktonic foodweb upon which larval and juvenile fish or other plankton predators depend (Nichols 1985).

Figure 10, from Arthur and Ball, 1979, shows the change in chlorophyll concentration, a measure of phytoplankton abundance, in Suisun Bay for different Delta outflows. At very high Delta outflows, flow velocities disperse diatoms downstream. Figure 11 shows the high proportion of diatoms when the entrapment zone is located in Suisun Bay.

# VI. ESTUARINE CIRCULATION

## A. General

The entrapment zone that is critical for achieving high phytoplankton biomass is created by the density-driven water circulation known as the "estuarine circulation." When a river discharges into a saltwater estuary, the fresh water has a tendency to flow over the surface of the salt water because of the difference in density. In some estuaries, a stratified flow can develop with freshwater on the top, with salinity less than 1 ppt., and sea water with salinity of 32 ppt. on the bottom. In many estuaries, including San Francisco Bay, considerable mixing occurs due to tidal action and wave action, and the difference in salinity between the top and bottom is usually small. The northern reach of San Francisco Bay from the Golden Gate Bridge to Rio Vista is generally considered a "partially mixed" estuary, but its character can change with the amount of freshwater flow. In big floods, highly stratified conditions can develop. At low Delta outflows, the estuary can become well-mixed, with only a very small salinity gradient from top to bottom (Conomos 1979).

The salinity differences between fresh and salt water create an estuarine circulation cell that persists even in well-mixed conditions. The fresher seaward-flowing surface current entrains saltwater, causing a landward flowing-current of saltier water to occur at the bottom. A conceptual diagram of the estuarine circulation cell is shown in Figure 12.

As can be seen, there is a point in the estuary where the landward-flowing bottom current is balanced by the seaward-flowing river current. This is known as the "null zone."

During a tidal cycle, the tidal currents are usually much larger than the density-driven currents, so in order to measure the estuarine circulation, the "residual" or non-tidal currents have to be determined by averaging the currents over a tidal cycle. At the null zone (which is actually a stationary point rather than a zone and is sometimes called the "stagnation point"), the horizontal residual current is zero at the bottom by definition.

Downstream of the null zone is a region in which the saltier water is mixed with the fresher water and is called the "mixing zone." In the upstream portion of the mixing zone, downstream from the null zone, the entrainment of salt water creates a small net upward current. This region, in which there are net upward vertical residual velocities, is referred to as the "entrapment zone."

The residual vertical velocities, although small, are sufficient to balance the sinking rate of fine sediment and diatoms. The seaward-flowing river current and the landward-flowing bottom current carry fine sediment into the entrapment zone. Consequently, high concentration of suspended sediment, organic debris, and living organisms occur in the entrapment zone, resulting in high levels of turbidity or light attenuation, which is a measure of turbidity (Festa & Hansen 1978).

## B. Relationship Between Salinity and Location of the Null Zone

Because the salinity distribution is a major determinant of the estuarine circulation, the salinity can be used as a means of determining the location of the null zone (Festa & Hansen 1976). Researchers have analyzed hypothetical uniform estuaries, and have found the null zone where the tidally averaged bottom salinity is in the range 0.15 ppt. to 1.5 ppt. (Festa & Hansen 1976). An example of such research is shown in Figure 13 that illustrates how the location of the "stagnation point" or null zone changes with increasing river discharge. It can be seen that the null zone falls within a narrow range of bottom salinities, even though river discharge and degree of mixing (shown as the K value) varies considerably. When there is a higher degree of horizontal mixing, caused for example by an irregular channel, saltier water and the null zone move further upstream in the estuary. When there is a higher degree of vertical mixing, caused for example by strong tidal or wave action, saltier water and the null zone are pushed downstream.

Variable depths can affect the bottom salinity-null zone location relationship. When there is an appreciable slope in the bed of the estuary downstream, the null zone tends to occur further downstream at a higher salinity.

Generally, for most natural irregular estuaries with tidal and wave action, the null zone is found where the tidally averaged bottom salinity is in the range 2 to 5 ppt. (Dyer 1986).

## C. Effect of Magnitude of Freshwater Flow Rate on Estuarine Circulation

As freshwater inflow to an estuary increases, the estuarine circulation increases in strength and is moved downstream. Figure 13 indicates how the location of the null zone responds to increasing river flow for a hypothetical uniform estuary. It can be seen that initially, small changes in flow cause the null zone to migrate rapidly downstream. However, the further downstream the null zone moves, the greater the increment of outflow required to move it further.

As the estuarine circulation cell increases in strength, the vertical residual velocities increase and the length of the entrapment zone increases. Figure 14 illustrates the change in vertical velocities with increasing outflow for a hypothetical uniform estuary. It can be seen that doubling the river flow will approximately double the vertical residual velocities in the entrapment zone.

Peterson & Festa (1984) have developed a simulation for phytoplankton dynamics in a partially mixed hypothetical uniform estuary that reflects the effect of increasing outflow on vertical residual velocities, suspended sediment concentration, and phytoplankton abundance in the entrapment zone. They demonstrated how high river flows can reduce the phytoplankton concentration even though vertical velocities have increased. This is because the higher flow rates mean higher velocities and lower overall residence times in the water column and phytoplankton are dispersed downstream. There is therefore an optimal flow rate in a particular estuary for phytoplankton abundance at a particular location.

The rate of change of river flow also affects the estuarine circulation and mixing. High flood flows are transitory in nature, and the estuary rarely has time to reach an equilibrium under these conditions. Short-duration high flood flows generally first produce a strong stratification which is then later vertically mixed by tidal and wave action.

# VII. HYDRODYNAMICS OF SUISUN BAY

## A. Circulation in Suisun Bay

Suisun Bay is located at the landward end of the northern reach of the San Francisco Bay estuary. Consequently, it is subject to major changes in its circulation pattern, depending on the amount of Delta outflow. Figure 15 illustrates the estuarine circulation under high, moderate, and low Delta outflows in Suisun Bay (Cloern et al. 1983). At very high Delta outflows, Suisun Bay can become entirely fresh, with the null zone pushed downstream of Martinez. At low Delta outflows, the estuarine circulation is weakened and the null zone can move upstream into the Sacramento River as far as Rio Vista.

Figure 15 also illustrates the tidal mixing whereby water is exchanged from the shallows to the channels. This exchange is increased by wind-driven clockwise gyres in the shallows of Grizzly and Honker Bays (Smith & Cheng 1987).

The degree of tidal mixing is influenced by the 14-day spring/neap tidal cycle. When the tidal range is highest during the spring tides, the estuary becomes more well-mixed vertically. During the lower neap tides, there is less vertical mixing and the estuary is more stratified (Walters & Gartner 1985).

The variation between spring and neap tides in Suisun Bay interacts with the complex bathymetry of Suisun Bay, creating a counter-clockwise horizontal circulation, westwards through the

Suisun Cutoff and eastwards up the ship channel (Walters et al., 1985) (see Figure 16).

It appears that under conditions of moderate Delta outflow (between 10,000 and 20,000 cfs), when the null zone and entrapment zone are located in Suisun Bay, this counter-clockwise circulation is reinforced by the estuarine circulation. Velocity data collected in September 1986 indicate that the simple vertical estuarine circulation cell is distorted into both a horizontal and vertical circulation, with fresher water flowing westwards in the Suisun Cutoff, and saltier water flowing eastwards in the deeper parts of the other two channels. It should be noted that under these conditions, the vertical circulation cell and the entrapment zone remains intact in these two channels.

During periods of lower Delta outflow, the null zone and the weakened estuarine circulation moves upstream into the channel of the Sacramento River east of Chipps Island. When the null zone moves upstream of Pittsburg and the San Joaquin River mouth, part of the landward-flowing residual current is drawn into the San Joaquin River. If there is a net outflow from the San Joaquin River, a second null zone is established at some point upstream.

It should be noted that even when there is a net outflow of San Joaquin River water at Sherman Island, salty water is drawn into the Delta channels by estuarine circulation if the null zone is located above Chipps Island. During the summer, when export pumping occurs, there is both a net landward surface and bottom flow in the San Joaquin. This causes a gradual increase in salinity throughout the Delta until San Joaquin River flows increase and export pumping is curtailed the following winter.

A general description of the tidal hydraulics and circulation in Suisun Bay is contained in Cheng and Smith (1985), Denton (1987), Walters et al. (1985), and Smith and Cheng (1987).

## B. Effect of Delta Outflow on the Location of the Null Zone

There are two methods for identifying the location of the null zone: directly, by measuring bottom currents, and indirectly, by using bottom salinity as an indicator. Obtaining residual current data is laborious and costly. Nevertheless, there are now sufficient data to provide a general idea of the change in null-zone location with change in Delta outflow. Salinity data is more extensive and easily obtainable. It can be used to develop a more precise definition of the null-zone location.

The first definition of the null-zone location using tidally averaged residual bottom velocities was by Peterson et al. (1975), shown in Figure 17. At the time Peterson carried out his work, only approximate estimates of daily Delta outflow were available. More recently, DWR has computed daily Delta outflows back to 1955 in its DAYFLOW program. Although DAYFLOW is the most detailed and comprehensive analysis of Delta outflow to date, it is still subject to uncertainties that may result in errors of several thousand cubic ft./second in computed Delta at large flows but can be significant at low Delta outflows. DAYFLOW estimates of Delta outflow are shown plotted with Peterson et al.'s data on Figure 17. This shows the response of location of the null zone to Delta outflow based on data at that time. It indicates that flows between 5000 and 18,000 cfs would position the null zone at Chipps Island.

In order to define the location of the null zone more precisely, more recent velocity data can be used.

In several periods during 1978, 1979, and 1980, bottom current meters were deployed by USGS in the northern reach of San Francisco Bay. A description of the data collection is contained in USGS Water Resources Investigation 84-4339 by Cheng and Gartner (1984), and overall results are discussed by Denton (1984).

Until now, the current data has not been analyzed for the purpose of locating the null zone. To do this requires examining the specific "Progressive Vector Diagrams" (PVD's) for each bottom current meter station. These are diagrams of the movement of water past a particular point over time. The PVD's are kept on file at the Water Resources Center Archives at UC Berkeley, and examples are shown in Appendix A.

During October and November 1979, sets of current meters were deployed simultaneously at the locations shown in Figure 18, and therefore provide a good indication of the estuarine circulation. Table 1 summarizes the direction of the residual horizontal currents up or down the estuary on the surface and line with changing Delta outflow is shown in Figure 23, and the data set on which it is based is tabulated in Table 3. Figure 21 shows that the 2ppt. bottom salinity/Delta outflow relationship corresponds to the null zone location defined by bottom residual currents. To smooth out daily variations in Delta outflow obtained from DAYFLOW, the 5-day moving average, lagged by one day, was used as the Delta outflow. Appendix B contains a plot of the Delta outflow for the period in which the salinity transects were made.

Figure 23 can be used to predict the location of the null zone, and hence the upstream end of the entrapment zone, for any particular Delta outflow. This means small changes in Delta outflow, when Delta outflow is low, will move the null zone a considerable distance up and down the Sacramento River. When Delta outflows are larger and the null zone is further downstream in Suisun Bay, larger increases in Delta outflow are required to move the null zone a similar distance.

## C. Characteristics of the Entrapment Zone

As Delta outflow decreases, the strength of the estuarine circulation diminishes and the null zone moves upstream. Vertical velocities in the entrapment zone are reduced and its length decreases.

No measurements have been made of vertical residual velocities that would provide a direct measurement of the length of the entrapment zone, and in any event this would be very difficult to do, as the residual vertical velocities are about two orders of magnitude smaller than the tidal velocities.

Instead, the approximate length of the entrapment zone can be determined using turbidity as an indicator. High turbidities occur in the estuarine circulation cell in the zone of upward residual velocities (Festa & Hansen 1978) - which by definition is the entrapment zone.

Arthur and Ball (1979) have plotted the turbidity in the estuary for different Delta outflows. This is shown in Figure 24. A strong turbidity maximum of 2 to 40 times the upstream and downstream turbidity levels migrates downstream with the estuarine circulation with increasing Delta outflow. The higher the Delta outflow, the higher the turbidity level. It should be noted that the turbidity maximum migrates and changes over a tidal cycle. This is illustrated in Figure 25. Arthur and Ball (1979) interpreted the turbidity maxima to identify the entrapment zone as occurring between <u>surface</u> salinities of 1 to 6 ppt. For Suisun Bay, this definition gives length scales for the entrapment zone of between 7 and 10 miles.

Appendix C shows data collected by the USGS and BR in October 1986 for light attenuation, which is a measurement of turbidity, and salinity at different Delta outflows. The length scale of the turbidity maxima in Suisun Bay shown on these transects is approximately 12 miles, with Delta outflows in the 9 to 13,000 cfs range.

With the null zone located at Chipps Island, it appears that the length of the entrapment zone would be roughly of the order of 10 miles, placing it in Suisun Bay. Higher flows up to about 20,000 cfs would still locate the null zone and entrapment zone in Suisun Bay. Flows of about 5,000 cfs would locate the null zone upstream of Collinsville, with the entrapment zone barely extending past Chipps Island.

# X. MANAGEMENT OF DELTA OUTFLOW TO MAXIMIZE PHYTOPLANKTON ABUNDANCE IN SUISUN BAY

The consequences of not adequately managing freshwater inflows into Suisun Bay are severe. Adequately managing freshwater inflows means ensuring that flows are high enough to exclude marine benthos from Suisun Bay (this is discussed separately in Report 412-5), and ensuring that the timing and volume of flow positions the entrapment zone in Suisun Bay.

At present, Delta outflows during the late spring and summer usually position the entrapment zone too far upstream from the shallows in Suisun Bay, causing decreased phytoplankton abundance in most years.

Because estuarine foodwebs are relatively simple and approach a linear foodchain, decreased phytoplankton production will be translated immediately to higher trophic levels. The consequences include: decreased fecundity and growth rates of <u>Neomysis</u> and other zooplankton; decreased growth rate and increased mortality of juvenile and larval fish; and a switch from a planktonic to a benthic dominated foodweb. The switch in energy flow pathways will exacerbate the impact of decreased phytoplankton abundance and growth on planktonic grazers and their predators.

Phytoplankton will respond rapidly to restoration of adequate delta outflows; two or more consecutive years of low flow will not affect their recovery to pre-drought abundances, community structure or productivity. However, higher trophic levels will not recover as rapidly. Species whose life cycles are longer than a few months or whose populations are centered in Suisun Bay or the Delta will be the most heavily impacted, particularly if their populations are composed of only a few year classes.

The goal of managing Delta outflow in Suisun Bay is therefore to provide a stable food source through the spring and summer for zooplankton and organisms that feed on them. This means maximizing phytoplankton abundance in the Suisun Bay channels in the period April through September. The period July through September has been identified as particularly important for Neomysis and Eurytemora (Knutsen and Orsi, 1983). In October it may be beneficial to allow higher salinities in Suisun Bay to prevent establishment of a high biomass of the freshwater clam ,Corbicula .

In order to maximize phytoplankton abundance, sufficient Delta outflow has to be maintained to locate the entrapment zone adjacent to the maximum area of shallows. When this occurs, phytoplankton grown in the shallows will enter the channel on the ebb tide where they will be concentrated by the estuarine circulation. This means that the null zone, which is taken to be the upstream end of the entrapment zone, has to be located at the upstream end of Suisun Bay, so that the length of the entrapment zone is adjacent to maximum area of the shallows.

Delta outflows of approximately 10,000 cfs will position the null zone adjacent to Chipps Island. With flows of 10,000 cfs, the entrapment zone length is about 10 miles, which therefore is positioned adjacent to the maximum area of shallows of Suisun Bay, as is shown in Figure 26.

In order to locate the null zone at Chipps Island, the tidally averaged bottom salinity should be maintained by Delta outflow at 2 ppt. To account for the spring/neap variations, the salinity should be averaged over 28 days.

To enhance phytoplankton abundance throughout the year, the null zone should be located at Chipps Island from April-September, except for those periods in the spring when higher flows are required to maximize phytoplankton abundance in San Pablo Bay (see Report 412-6) and South San Francisco Bay (See Report 412-7), or for other purposes.

Because it is essential to prevent the catastrophic collapse of the ecosystem caused by two successive years of low Delta outflow, as occurred in 1976 and 1977, Delta outflows should be managed to maintain the null zone at Chipps Island in all years except for those with unimpaired Delta outflows less than the 1-in-20 dry year.

# REFERENCES

Ambler, J.W., J.E. Cloern, and A.E. Hutchinson. 1985. Seasonal cycles of zooplankton from San Francisco Bay. Hydrobiologia 129: 177-197.

Arthur, J.F. and M.D. Ball. 1978. Entrapment of suspended materials in the San Francisco Bay-Delta estuary. U.S. Bureau of Reclamation, Sacramento, California. pp. 1-106.

Arthur, J.F. and M.D. Ball. 1979. Factors influencing the entrapment of suspended material in the San Francisco Bay-Delta Estuary. In: Conomos, T.J., ed., San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco. pp. 143-174.

Checkley, D.M. 1980a. Egg production of a marine planktonic copepod in relation to its food supply: Laboratory studies. Limnol. Oceanogr. 25: 430-446.

Checkley, D.M. 1980b. Food limitation of egg production by a marine, planktonic copepod in the sea off southern California. Limnol. Oceanogr. 25: 430-446.

Cheng, Ralph T. and J.W. Gartner. 1984. Tides, tidal and residual currents in San Francisco Bay, California - Results of measurements 1979-1980, U.S. Geol. Surv., Water Resour. Inves. Report 84-4339.

Cheng, Ralph T. and Lawrence H. Smith. 1985. Tidal hydraulics of San Francisco Bay and Estuary. Symposium II, Selenium and Agriculltural Drainage: Implications for San Francisco Bay and the California Environment, March 23, 1985, Berkeley, CA.

Chervin, M.B. 1978. Assimilation of particulate organic carbon by estuarine and coastal copepods. Mar. Biol. 49: 265-275.

Chervin, M.B., T.C. Malone, and P.J. Neale. 1981. Interactions between suspended organic matter and copepod grazing in the plume of the Hudson River. Estuar. Coast. Shelf Sci. 13: 169-183.

Cloern, J.E. and R.T. Cheng. 1981. Simulation model of Skeletonema costatum population dynamics in Northern San Francisco Bay Estuary. Estuarine, Coast. and Shelf Sci. 16: 415-429.

Cloern, J.E., A.E. Alpine, B.E. Cole, R.L.J. Wong, J.F. Arthur, and M.D. Ball. 1983. River discharge controls phytoplankton dynamics in Northern San Franciso Bay Estuary. Estuarine, Coast, and Shelf Sci. 16: 415-429.

Cloern, J.E., B.E. Cole, R.L.J. Wong, and A.E. Alpine. 1985. Temporal dynamics of estuarine phytoplankton: A case study of San Francisco Bay. Hydrobiologia 129: 152-176.

Cole, B.E. and J.E. Cloern. 1984. Significance of biomass and light availability to phytoplankton productivity in San Francisco Bay. Mar. Ecol. Prog. Ser. 17: 15-24.

Conomos, T.J. 1979. Properties and circulation of San Francisco Bay waters. In: Conomos, T.J., ed., San Francisco Bay: The Urbanized Estuary. Pacific Division AAAS, San Francisco. pp. 47-84.

Denton, Richard. 1984. Currents in Suisun Bay. State Water Resources Control Board Report No. UCB/HEL-84/01.

Denton, Richard A. and James R. Hunt. 1986. Currents in San Francisco Bay: Final report. State of CA Water Resources Control Board, Report No. UCB/HEL-86/01. Berkeley, CA.

Dyer, Keith R. 1986. Coastal and estuarine sediment dynamics. John Wiley & Sons. New York.

Festa, John F. and Donald V. Hansen. 1978. Turbidity maxima in partially mixed estuaries: a two-dimensional numerical model. Estuarine and Coastal Marine Science 7, p. 347-359.

Festa, John F. and Donald V. Hansen. 1976. A two-dimensional numerical model of estuarine circulation: the effects of altering depth and river discharge. Estuarine and Coastal Marine Science 4, p. 309-323.

Heinle, D.R., R.P. Harris, J.F. Ustach, and D.A. Flemer. 1977. Detritus as food for estuarine copepods. Mar. Biol. 40: 341-353.

Horne, A.J. and Nonomura. 1976. Drifting macroalgae in estuarine water: interactions with salt marsh and human communities. Univ. California (Berkeley) Sanitary Engineering Res. Lab. Rep. 76-3, 76 pp.

Kirby-Smith, W. 1976. The detritus problem and the feeding and digestion of an estuarine organism. In: Wiley, M., ed., Estuarine Processes, Vol. 1: Uses, stresses, and adaptation to an estuary. Academic Press, New York. pp. 469-479.

Knutson, A.C., Jr., and J.J. Orsi. 1983. Factors regulating abundance and distribution of the shrimp Neomysis mercedis in the Sacramento-San Joaquin Estuary. Trans. Am. Fish Soc. 112: 476-485.

McDowell, D.M. and B.A. O'Connor. 1977. Hydraulic Behaviour of Estuaries. Halsted Press, John Wiley & Sons. New York.

Moyle, P.B., R.A. Daniels, B. Herbold, and D.M. Baltz. 1986. Patterns in distribution and abundance of a non-coevolved assemblage of estuarine fishes in California. Fish. Bull. 84: 105-117.

Nichols, F.H. 1985. Increased benthic grazing: an alternative explanation for low phytoplankton biomass in Northern San Francisco Bay during the 1976-1977 drought. Estuarine Coast. Shelf Sci. 21: 379-388.

Nixon, S.W. 1982. Nutrient dynamics, priiary production and fisheries yield of lagoons. Oceanol. Acta, 1982. Proceedings, International Symposium on Coastal Lagoons SCOR/IABO/UNESCO, Bordeaux, 8-14 September 1981. pp. 357-371.

Peterson, David H. and John F. Festa. 1984. Numerical simulation of phytoplankton productivity in partially mixed estuaries. In: Estuarine, Coastal, and Shelf Science 19: pp. 563-589.

Orsi, J.J. and A.C. Knutson, Jr. 1979. The role of mysid shrimp in the Sacramento-San Joaquin Estuary and factors affecting their abundance and distribution. In: Conomos, T.J., ed., San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, pp. 401-408.

Peterson, D.H., T.J. Conomos, W.W. Broenkow, and P.C. Doherty. 1975. Location of the non-tidal current null zone in Northern San Francisco Bay. Estuarine and Coast. Mar. Sci. 3: 1-11.

Peterson, D.H., R.E. Smith, S.W. Hager, D.D. Harmon, R.E. Herndon, and L.E. Schemel. 1985. Interannual variability in dissolved inorganic nutrients in Northern San Francisco Bay Estuary. Hydrobiologia 129: 37-58.

Smith, R.E., R.E. Herndon, and D.D. Harmon. 1979. Physical and chemical properties of San Francisco Bay waters, 1969-1976. U.S. Geological Survey Open-File Report 79-511. pp. 1-607.

Smith, Lawrence H. and Ralph T. Cheng. 1987. Tidal and tidally averaged circulation characteristics of Suisun Bay, California. Water Resources Research, Vol. 23, No. 1. January 1987. pp. 143-155.

Spiker, E.C. and L.E. Schemel. 1979. Distribution and stable isotope composition of carbon in San Francisco Bay. In: Conomos, T.J., ed., San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, pp. 195-212.

Sverdrup, H.U. 1953. On conditions for the vernal blooming of phytoplankton. J. Cons. Int. Explor. Mer. 18: 287-295.

Thompson, J.K. and F.H. Nichols, in press. Food availability controls the seasonal cycle of growth in the bivalve Macoma balthica. J. Exp. Mar. Biol. Ecol., in press.

Walters, Roy A. and Jeffrey W. Gartner. 1985. Subtidal sea level and current variations in the northern reach of San Francisco Bay. Estuarine, Coastal and Shelf Science (1985) **21**, p. 17-32.

Walters, R.A., R.T. Cheng, and T.J. Conomos. 1985. Time scales of circulation and mixing processes in San Francisco Bay

## Table 1. RESIDUAL CURRENTS IN SUISUN BAY, OCT./NOV. 1979

| Date | | Delta Outflow | Tidal | Horizontal Residual Velocity Direction | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | N25 Martinez | | D239 Port Chicago | | D32 Chipps Island | |
| Calendar | Julian | cfs x 1000 | velocity | upper | lower | upper | lower | upper | lower |
| 10/23 | 296 | 10 | Spring | | | | --> | | |
| 24 | 7 | 6 | | | | | --> | <-- | --> |
| 25 | 8 | 7 | | | | | --> | <-- | --> |
| 26 | 9 | 12 | | | | | --> | <-- | --> |
| 27 | 300 | 14 | Neap | | | --> | --> | <-- | <-- |
| 28 | 1 | 16 | | | | --> | --> | <-- | <-- |
| 29 | 2 | 15 | | | | --> | --> | <-- | <-- |
| 30 | 3 | 13 | | | | --> | --> | <-- | <-- |
| 10/31 | 4 | 7 | | | | <-- | --> | --> | --> |
| 11/ 1 | 5 | 7 | Spring | | | <-- | --> | --> | --> |
| 2 | 6 | 6 | | | | <-- | --> | --> | --> |
| 3 | 7 | 6 | | | | <-- | --> | --> | --> |
| 4 | 8 | 9 | | | | <-- | --> | <-- | --> |
| 5 | 9 | 9 | | | --> | <-- | --> | <-- | --> |
| 6 | 310 | 10 | | | --> | ? | --> | <-- | --> |
| 7 | 1 | 12 | | | --> | --> | --> | <-- | --> |
| 8 | 2 | 13 | | | --> | --> | --> | <-- | <-- |
| 9 | 3 | 10 | Neap | | --> | --> | --> | <-- | <-- |
| 10 | 4 | 11 | | | --> | <-- | --> | <-- | <-- |
| 11 | 5 | 11 | | | --> | --> | --> | <-- | <-- |
| 12 | 6 | 11 | | | --> | <-- | --> | | --> |
| 13 | 7 | 10 | | | --> | <-- | | | --> |
| 14 | 8 | 8 | | | --> | | | | --> |
| 15 | 9 | 8 | | | --> | | | | --> |
| 16 | 320 | 8 | Spring | | --> | | | | |

## TABLE 2
## SUMMARY OF RESIDUAL CURRENT DATA USED IN LOCATING NULL ZONE

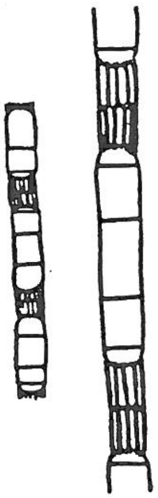
| Year | Date | Identification | Delta Outflow Range (x 1000 cfs) | Location, Miles Above Golden Gate Bridge | Remarks |
|---|---|---|---|---|---|
| 1978 | 8/1 - 9/7 | A | 4 to 13 | Upstream of 48 | |
| 1978 | 9/11 - 10/15 | B | 13 to 8 | Upstream of 48 | |
| 1979 | 3/20 - 4/4 | F | 21 to 45 | Upstream of 28 | |
| 1979 | 4/5 - 4/9 | G | 17 to 20 | Between 46.5 and 58 | |
| 1979 | 4/12 - 4/20 | G | 7 to 10 | Downstream of 46.5 | Spring tide |
| 1979 | 4/21 - 4/24 | G | 6 to 9 | Upstream of 46.5 | Neap tide |
| 1979 | 4/25 - 5/7 | G | 8 to 12 | Downstream of 46.5 | |
| 1979 | 10/24 - 10/26 | K | 6 to 10 | Upstream of 46.5 | |
| 1979 | 10/27 - 10/30 | K | 13 to 16 | Between 42 and 46.5 | |
| 1979 | 10/31 - 10/7 | K | 6 to 12 | Upstream of 46.5 | |
| 1979 | 10/8 - 10/11 | K | 10 to 13 | Between 42 and 46.5 | |
| 1979 | 10/12 - 10/15 | K | 8 to 11 | Upstream of 46.5 | |
| 1979 | 11/6 - 12/4 | L | 8 to 21 | Between 42 and 52 | |
| 1980 | 5/3 - 7/9 | R | 15 to 20 | Between 28 and 46.5 | |
| 1980 | 6/27 - 7/8 | S | 12 to 16 | Downstream of 46.5 | |
| 1980 | 7/9 - 8/22 | S | 9 to 12 | Upstream of 46.5 | |
| 1980 | 10/18 - 10/30 | XA | 4 to 7 | Downstream of 46.5 | Spring tide |
| 1980 | 10/31 - 11/1 | XA | 5 to 6 | Upstream of 46.5 | Neap tide |
| 1980 | 11/2 - 11/13 | XA | 5 to 8 | Downstream of 46.5 | Spring tide |
| 1986 | 9/28 - 10/28 | - | 8 to 14 | Upstream of 41 | |

## TABLE 3
## SUMMARY OF UPRIVER SALINITY TRANSECTS

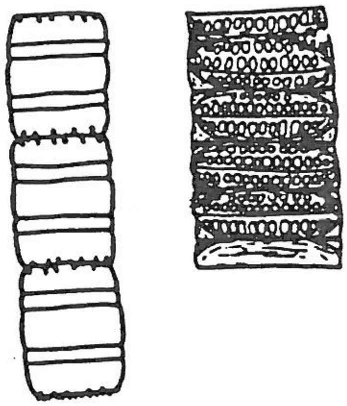
| DATE | TIME | RIVER MILE | 5 DAY AVERAGE DELTA OUTFLOW CFS | SOURCE * |
|---|---|---|---|---|
| 09/26/73 | 1610 | 49.4 | 14075 | GS79511 |
| 09/27/73 | 1050 | 43.5 | 14506 | GS79511 |
| 03/21/74 | 1545 | 39.4 | 70484 | GS79511 |
| 05/30/74 | 1255 | 43.2 | 20264 | GS79511 |
| 08/19/74 | 1905 | 48.6 | 12352 | GS79511 |
| 08/20/74 | 1500 | 45.8 | 12052 | GS79511 |
| 08/21/74 | 1240 | 42.2 | 12843 | GS79511 |
| 07/08/76 | 1230 | 57.7 | 4541 | GS79511 |
| 07/08/76 | 1530 | 59.4 | 4541 | GS79511 |
| 07/08/76 | 1550 | 58.4 | 4541 | GS79511 |
| 07/09/76 | 0935 | 55.7 | 4742 | GS79511 |
| 07/09/76 | 1255 | 57.6 | 4742 | GS79511 |
| 07/09/76 | 1305 | 55.8 | 4742 | GS79511 |
| 08/05/76 | 1035 | 55.1 | 4519 | GS79511 |
| 08/05/76 | 1425 | 56.8 | 4519 | GS79511 |
| 08/05/76 | 1445 | 57.2 | 4519 | GS79511 |
| 08/06/76 | 0900 | 54.1 | 4505 | GS79511 |
| 08/06/76 | 1225 | 57.2 | 4505 | GS79511 |
| 08/18/76 | 1310 | 56.2 | 5964 | GS79511 |
| 08/19/76 | 1335 | 56.4 | 6486 | GS79511 |
| 04/27/77 | 1240 | 61.1 | 3234 | BR |
| 04/28/77 | 1245 | 62.6 | 3262 | BR |
| 07/12/77 | 1745 | 64.6 | 2286 | BR |
| 07/13/77 | 1630 | 62.7 | 2600 | BR |
| 08/23/77 | 1330 | 63.8 | 1542 | BR |
| 08/23/77 | 1520 | 61.9 | 1542 | BR |
| 08/23/77 | 1845 | 61.8 | 1542 | BR |
| 08/24/77 | 1100 | 62.1 | 1502 | BR |
| 08/24/77 | 1545 | 64.7 | 1502 | BR |
| 08/24/77 | 1430 | 63.0 | 1502 | BR |
| 07/12/78 | 1730 | 47.2 | 4256 | BR |
| 07/13/78 | 1225 | 50.0 | 4339 | BR |
| 07/25/78 | 1010 | 53.8 | 4519 | BR |
| 08/02/78 | 1730 | 54.9 | 2594 | BR |
| 08/17/78 | 1835 | 52.5 | 5874 | BR |
| 08/23/78 | 0925 | 53.0 | 5927 | BR |
| 09/07/78 | 0805 | 51.1 | 7792 | BR |
| 09/13/78 | 1420 | 48.2 | 13044 | BR |
| 09/20/78 | 0640 | 46.1 | 12736 | BR |
| 09/20/78 | 1245 | 41.5 | 12736 | BR |
| 10/10/78 | 1220 | 45.8 | 11109 | BR |
| 04/11/69 | 0930 | 39.2 | 84776 | BR79511 |
| 05/22/69 | 0950 | 35.9 | 78308 | GS79511 |
| 09/19/69 | 0830 | 36.8 | 46995 | GS79511 |
| 07/24/69 | 0810 | 40.9 | 10325 | GS79511 |

| DATE | TIME | RIVER MILE | 5 DAY AVERAGE DELTA OUTFLOW CFS | SOURCE |
|---|---|---|---|---|
| 08/28/69 | 0810 | 43.4 | 14978 | GS79511 |
| 10/02/69 | 0900 | 41.1 | 18492 | GS79511 |
| 12/19/69 | 0915 | 43.1 | 28106 | GS79511 |
| 01/27/70 | 0930 | 25.4 | 366339 | GS79511 |
| 02/12/70 | 1315 | 31.0 | 114576 | GS79511 |
| 09/23/71 | 1115 | 38.8 | 19694 | GS79511 |
| 12/08/71 | 1000 | 46.0 | 19166 | GS79511 |
| 04/06/72 | 1745 | 41.6 | 5699 | GS79511 |
| 04/07/72 | 0700 | 47.7 | 6235 | GS79511 |
| 09/14/72 | 0827 | 45.7 | 9880 | GS79511 |
| 11/01/72 | 0745 | 43.9 | 11875 | GS79511 |
| 12/12/72 | 1530 | 40.1 | 20294 | GS79511 |
| 06/27/73 | 1255 | 48.0 | 4146 | GS79511 |
| 04/05/74 | 1200 | 20.0 | 211010 | GS79511 |
| 01/15/75 | 1545 | 42.6 | 2253 | GS79511 |
| 04/24/75 | 1600 | 43.8 | 25337 | GS79511 |
| 09/15/75 | 1445 | 46.0 | 7099 | GS79511 |
| 09/23/75 | 1615 | 44.7 | 13551 | GS79511 |
| 02/06/80 | 1430 | 38.5 | 57029 | GS79511 |
| 11/07/85 | N/A | 61.0 | 1704 | |
| 02/25/86 | 1600 | 17.0 | 466917 | ENV |
| 03/20/86 | N/A | 31.0 | 224500 | ENV |
| 03/25/86 | N/A | 33.0 | 139560 | ENV |
| 03/27/86 | N/A | 28.2 | 120629 | ENV |
| 03/28/86 | N/A | 24.0 | 113333 | ENV |
| 04/02/86 | N/A | 23.5 | 87424 | ENV |
| 04/08/86 | N/A | 36.5 | 67309 | ENV |
| 04/18/86 | N/A | 41.0 | 45092 | ENV |
| 10/17/86 | N/A | 43.5 | 13364 | ENV |
| 10/23/86 | N/A | 51.3 | 9668 | ENV |
| 01/09/80 | 1530 | 45.8 | 36512 | GS82125 |
| 01/24/80 | 1415 | 29.6 | 178700 | GS82125 |
| 02/06/80 | 1430 | 38.5 | 57029 | GS82125 |
| 03/05/80 | 1345 | 28.7 | 156456 | GS82125 |
| 08/05/80 | 1015 | 47.0 | 6663 | GS82125 |
| 09/17/80 | 1400 | 48.2 | 10063 | GS82125 |
| 10/16/80 | 1315 | 48.3 | 8209 | GS82125 |
| 10/29/80 | 1400 | 47.8 | 6672 | GS82125 |
| 11/13/80 | 1400 | 48.7 | 6841 | GS82125 |

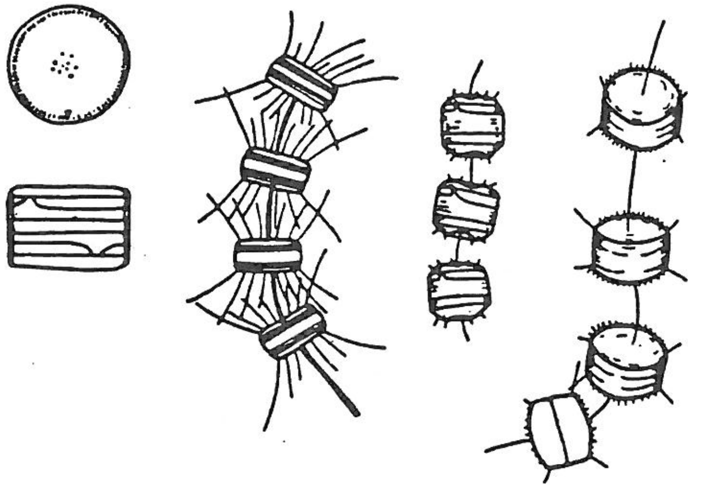
* GS79511: USGS Open File Report 79-511;
BR : Bureau of Reclamation Entrapment Zone Study; San Francisco Bay-Delta Estuary;
ENV : Enviosphere Company, Hydrographic Survey;
GS82125: USGS Open File Report 82-125.



***Skeletonema***



***Melosira***

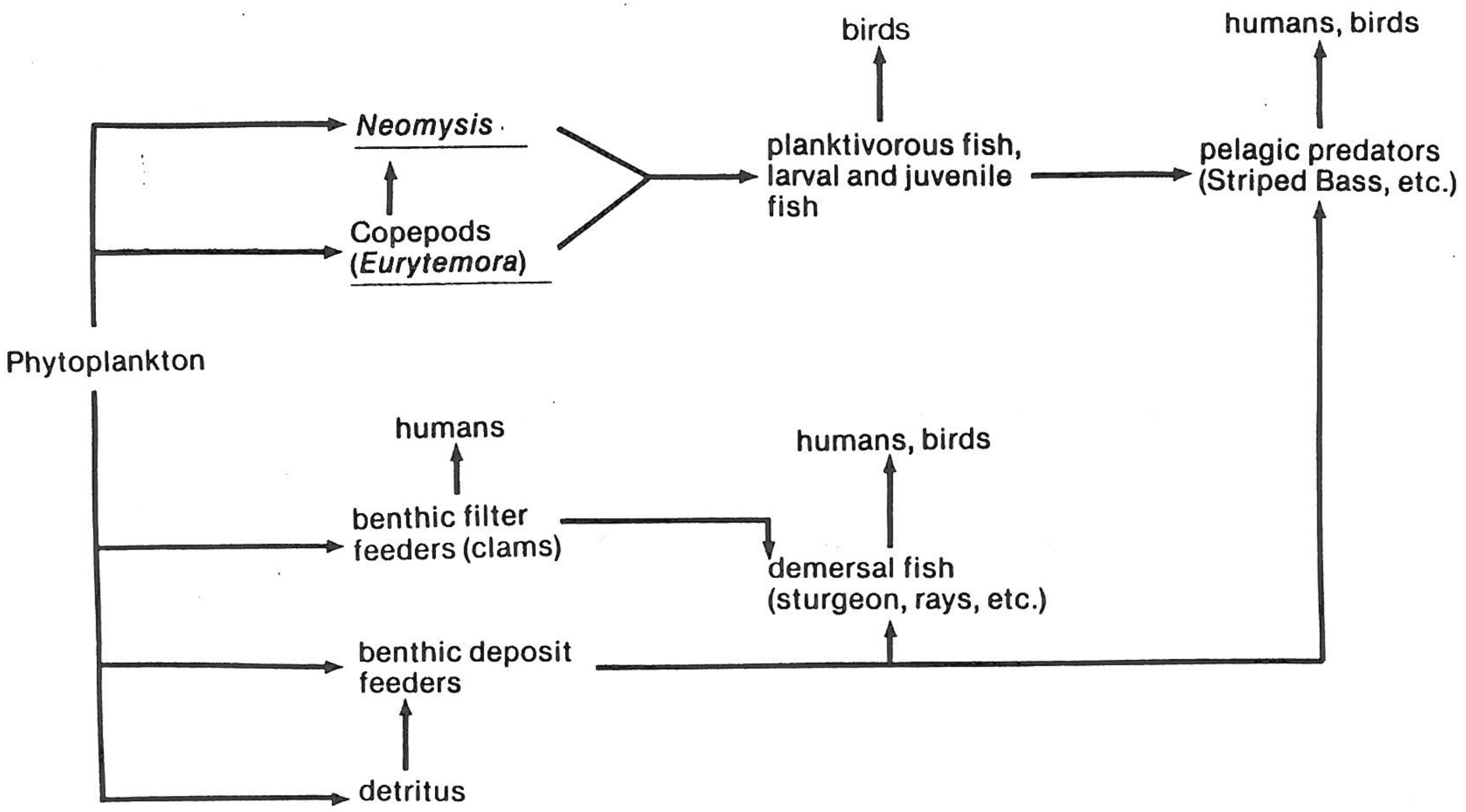


***Thalassiosira***

**Philip Williams & Associates**
Consultants in Hydrology

Typical Diatoms Found in Suisun Bay

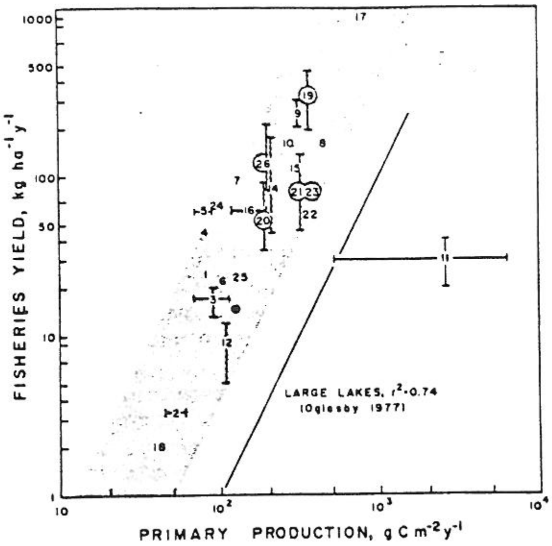
FIGURE
1



**Philip Williams & Associates**
Consultants in Hydrology

Typical Estuarine Foodweb

FIGURE
2



*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)*

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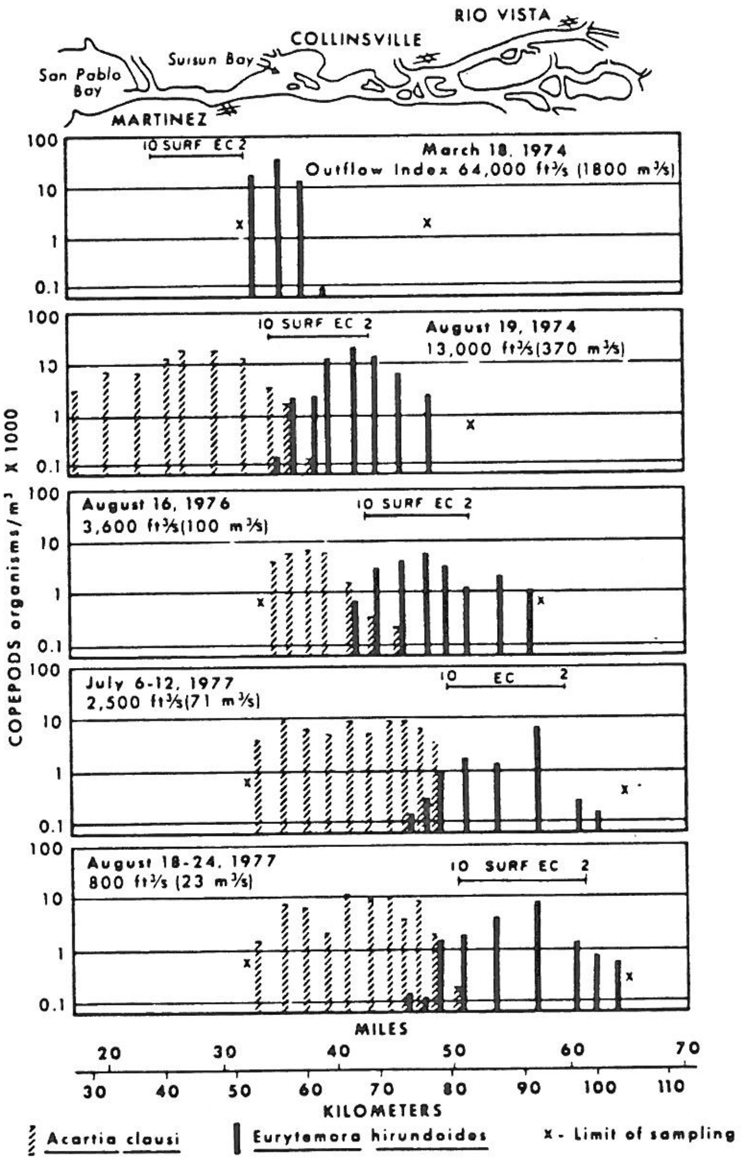
Relationship Between Fishery Yield and Estuarine Productivity

FIGURE
3



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).

*(Arthur & Ball, 1979)*

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Relationship Between *Neomysis* and *Euryemora* Distributions and Phytoplankton Distributions in North San Francisco Bay

FIGURE

4a

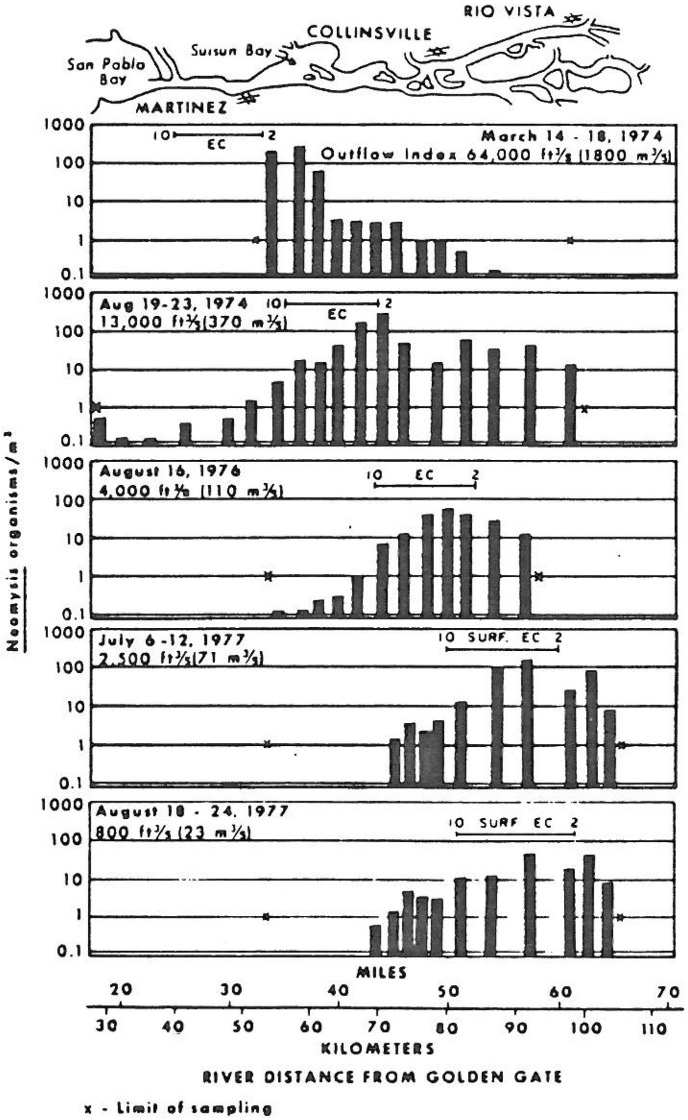

Fig. 15. *Neomysis mercedis* distribution relative to salinity on high slack tides at various Delta outflows (data collected by DFG).

*(Arthur & Ball, 1979)*

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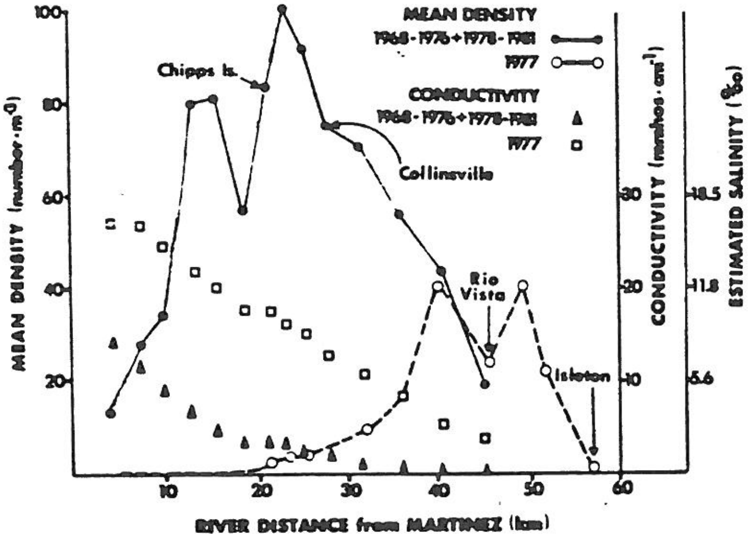
FIGURE
**4b**



—*Mean density of* Neomysis mercedis, *July to October, and electrical conductivity (and estimated salinity) at each channel station from Martinez on Suisun Bay to Isleton on the Sacramento River. The drought year 1977 is isolated from other years.*

(Knutson and Orsi, 1983)

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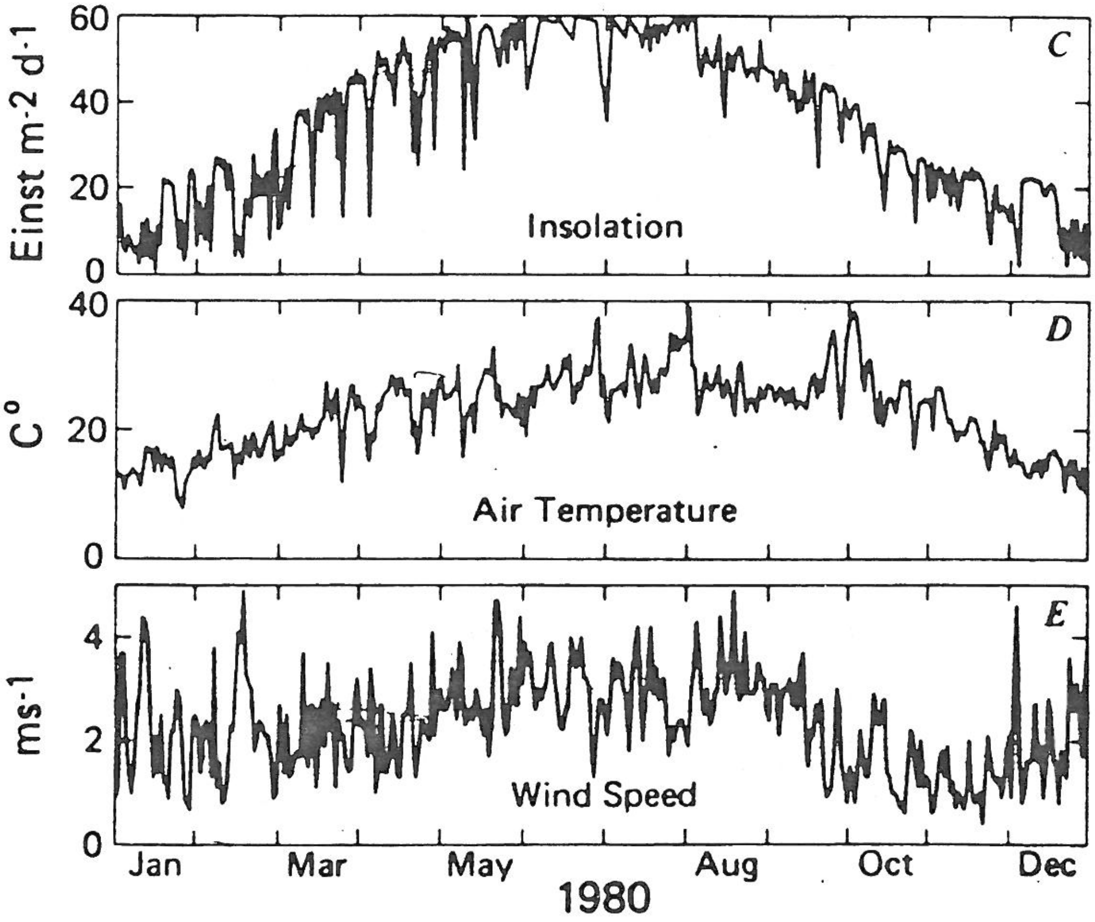
Relation Between *Neomysis* and salinity in Suisun Bay and Delta, July through October.

FIGURE
5



(Cloern, et al, 1985)

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Typical Climatic Variations in S.F. Bay

FIGURE
6

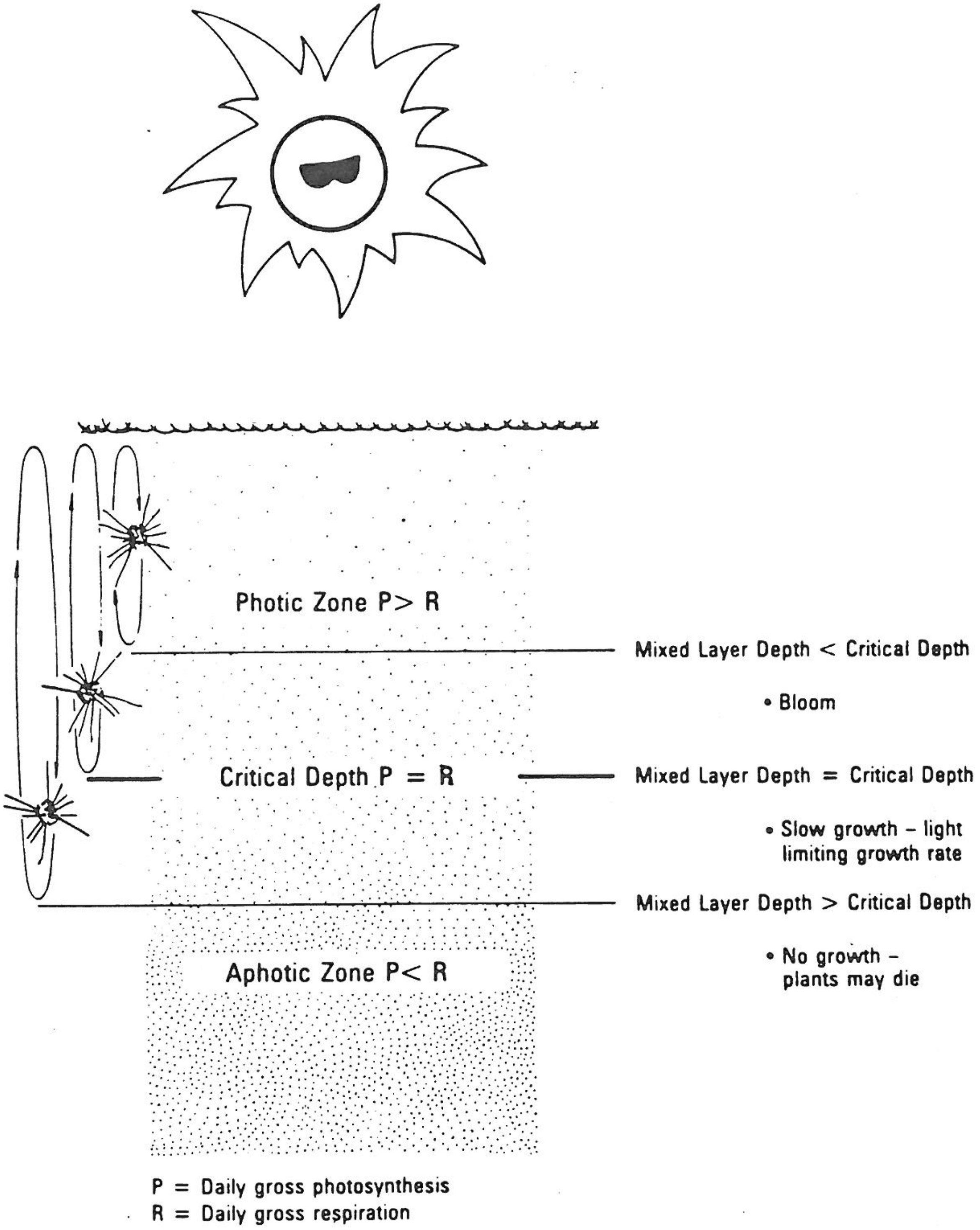
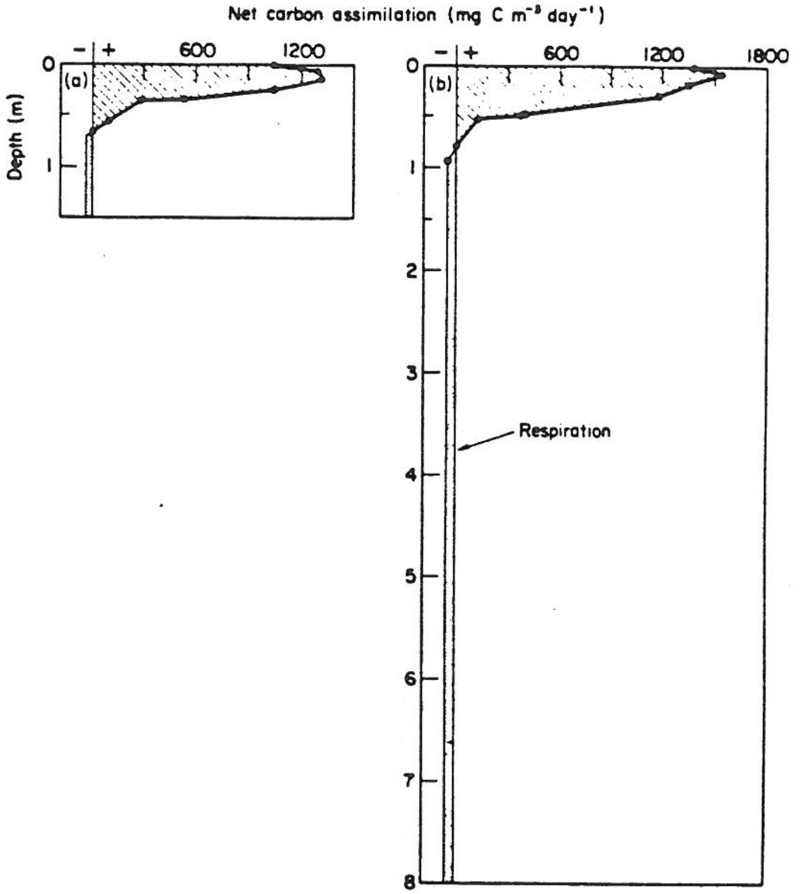


FIGURE 7

Illustration of Critical Depth Theory



Vertical profiles of carbon assimilation at (a) a shoal station (76) and (b) a channel station (3) during a summer diatom bloom (14 August 1979).

| | Shoal | Channel |
|---|---|---|
| Chlorophyll $a$ (mg m$^{-3}$) | 24·9 | 34·3 |
| Phytoplankton C (mg m$^{-3}$) | 996 | 1372 |
| $\epsilon$ (m$^{-1}$) | 8·2 | 6·7 |
| $k_2$ (div. day$^{-1}$) | 0·35 | 0·04 |
| Doubling time (days) | 2·9 | 27 |

*(Cloern, et al, 1983)*

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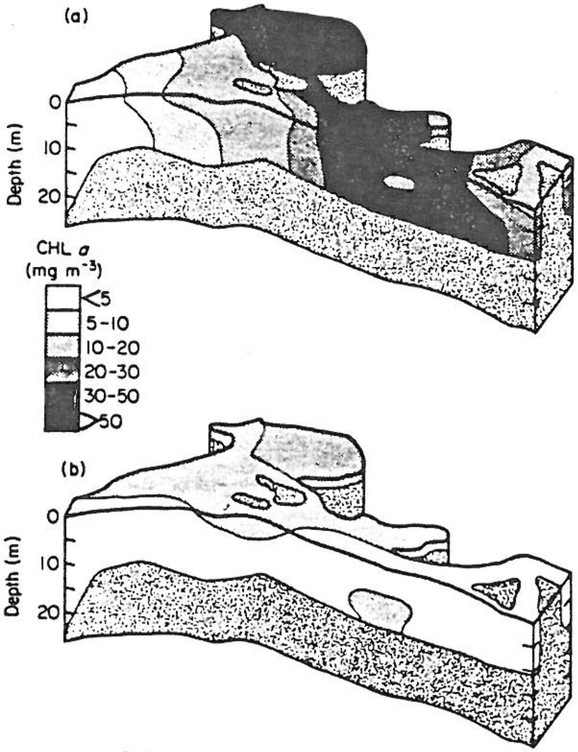
Relationship of Water Depth to Net Phytoplankton Growth

FIGURE
8



Oblique, mid-channel view of Suisun Bay showing chlorophyll *a* distribution during periods of river discharge representative of (a) summer (30 August 1978) and (b) drought (6 August 1976).

*(Cloern, et al, 1983)*

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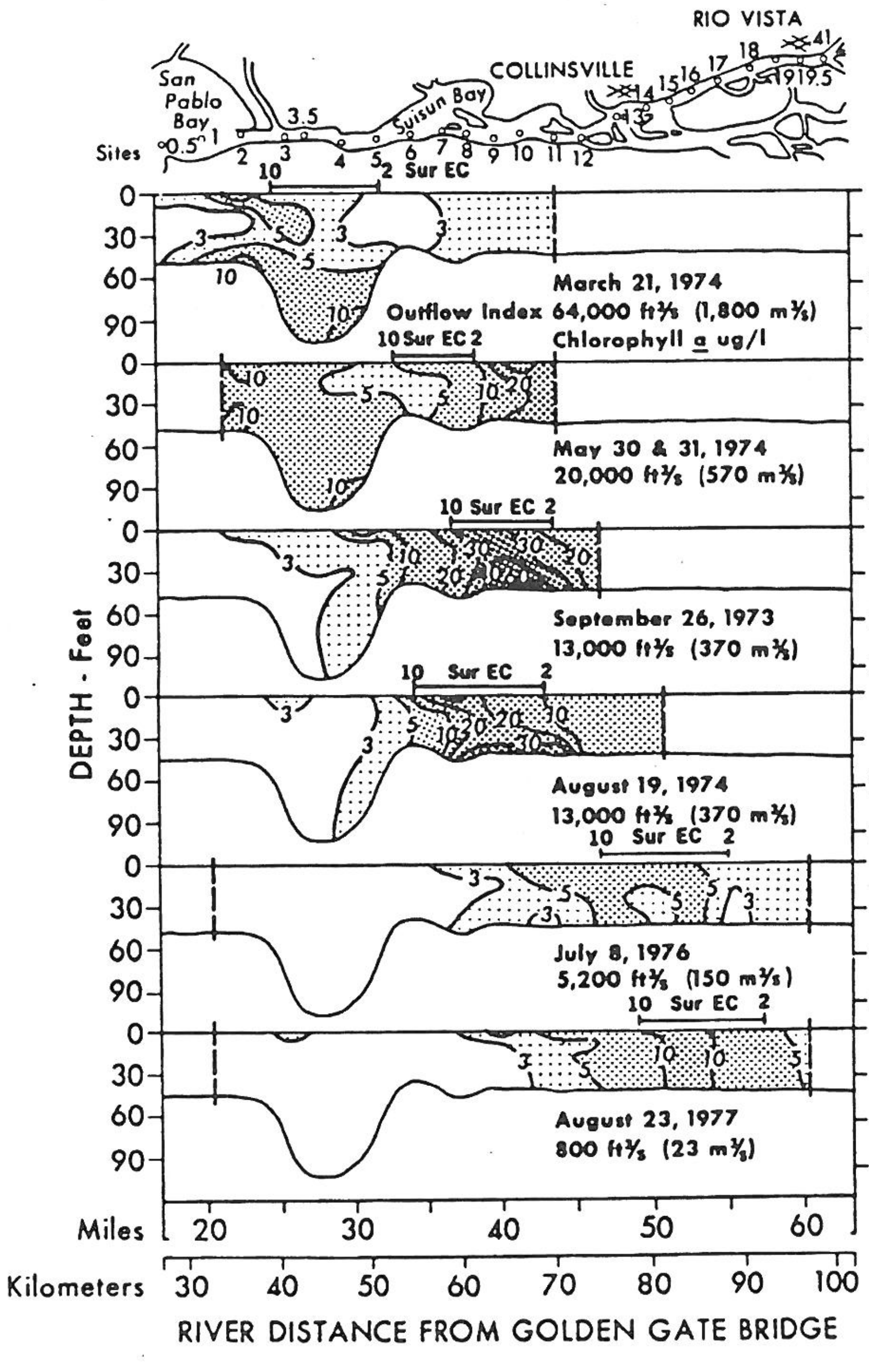
Chlorophyll Distribution at High and Low Delta Outflow (Cloern)

FIGURE
9



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

*(Arthur & Ball, 1979)*

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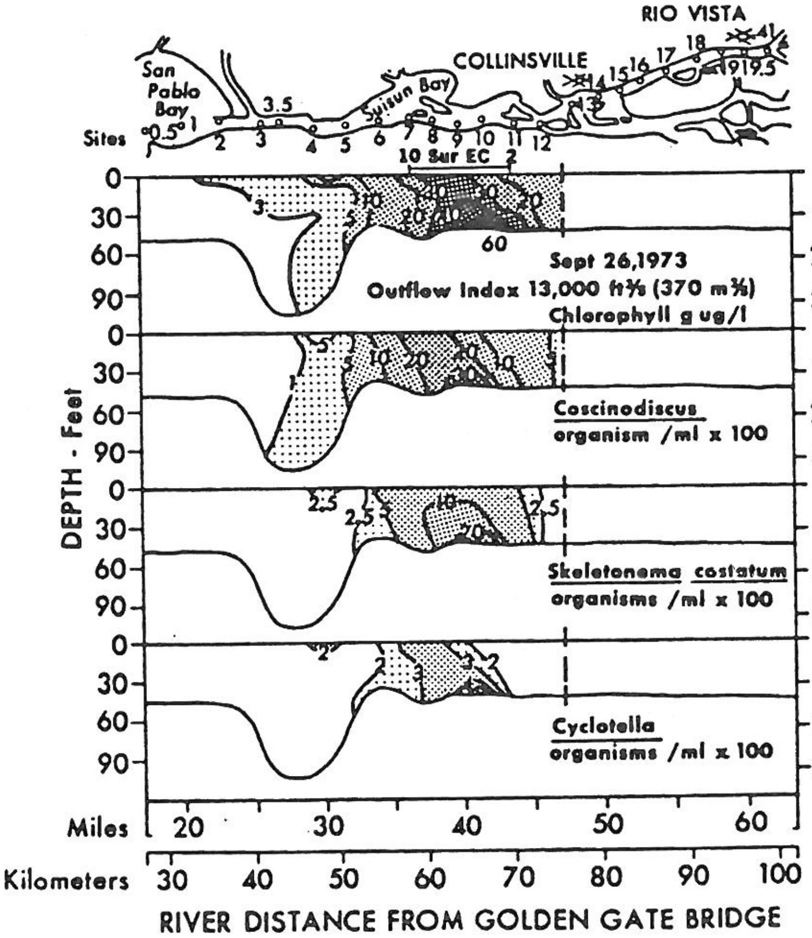
Chlorophyll Distribution Relative to Delta Outflow and Ball)

FIGURE
10



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

*(Arthur & Ball, 1979)*

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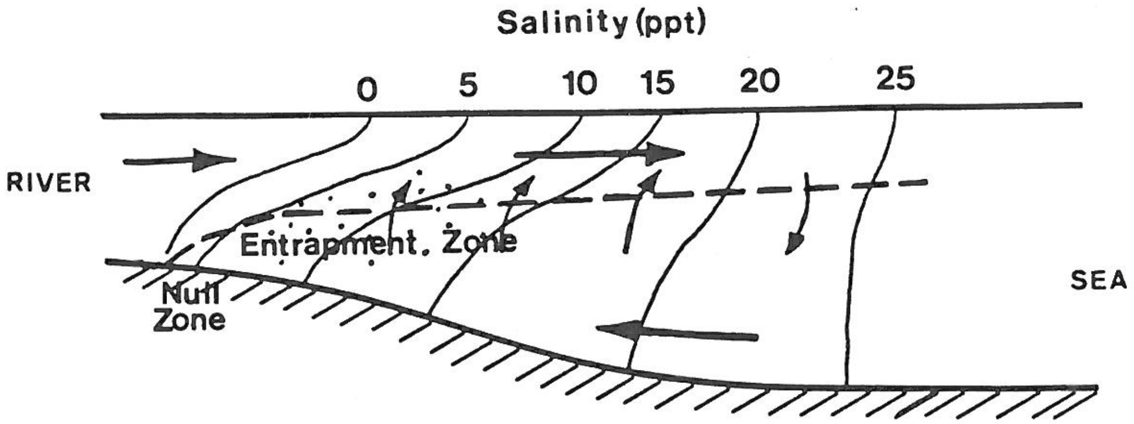
Proportion of Diatoms in Chlorophyll Peak

FIGURE
11



(K. R. Dyer, 1986)

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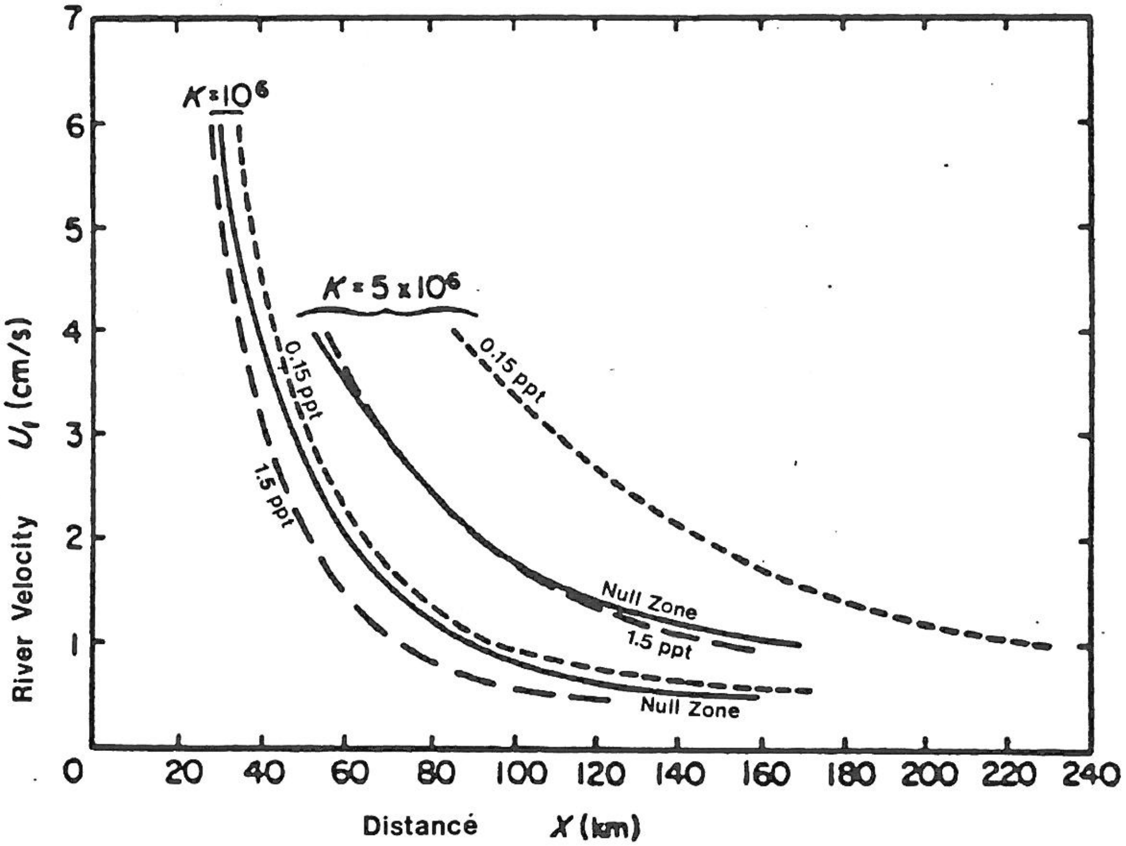
Diagram of Estuarine Circulation for a Partially Mixed Estuary

FIGURE
12



(Festa & Hansen, 1978)

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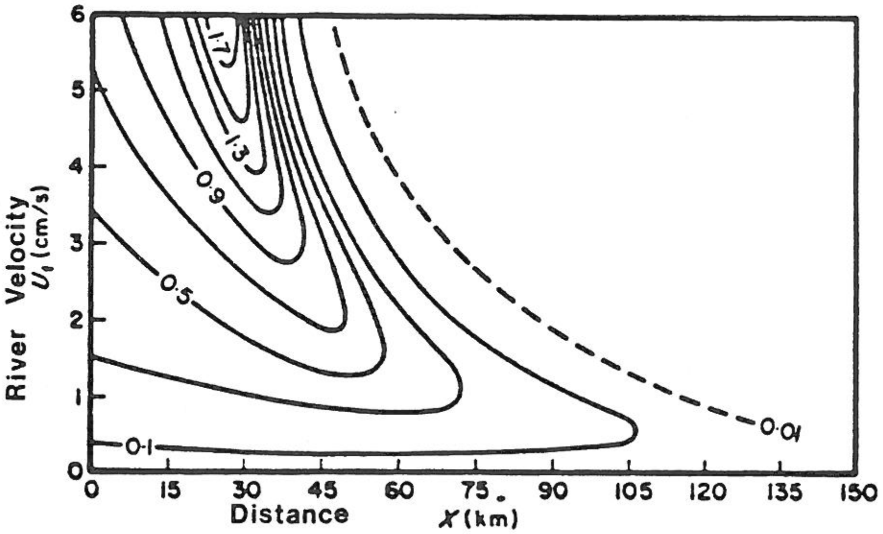
Influence of River Runoff on Salinity Intrusion in a Hypothetical Estuary

FIGURE
13



Vertical velocity contours at mid-depth as function of river discharge, $U_f$. Vertical velocity contours are scaled by $10^{-3}$ cm s$^{-1}$ with a contour interval of 0·2.

*(Festa & Hansen, 1978)*

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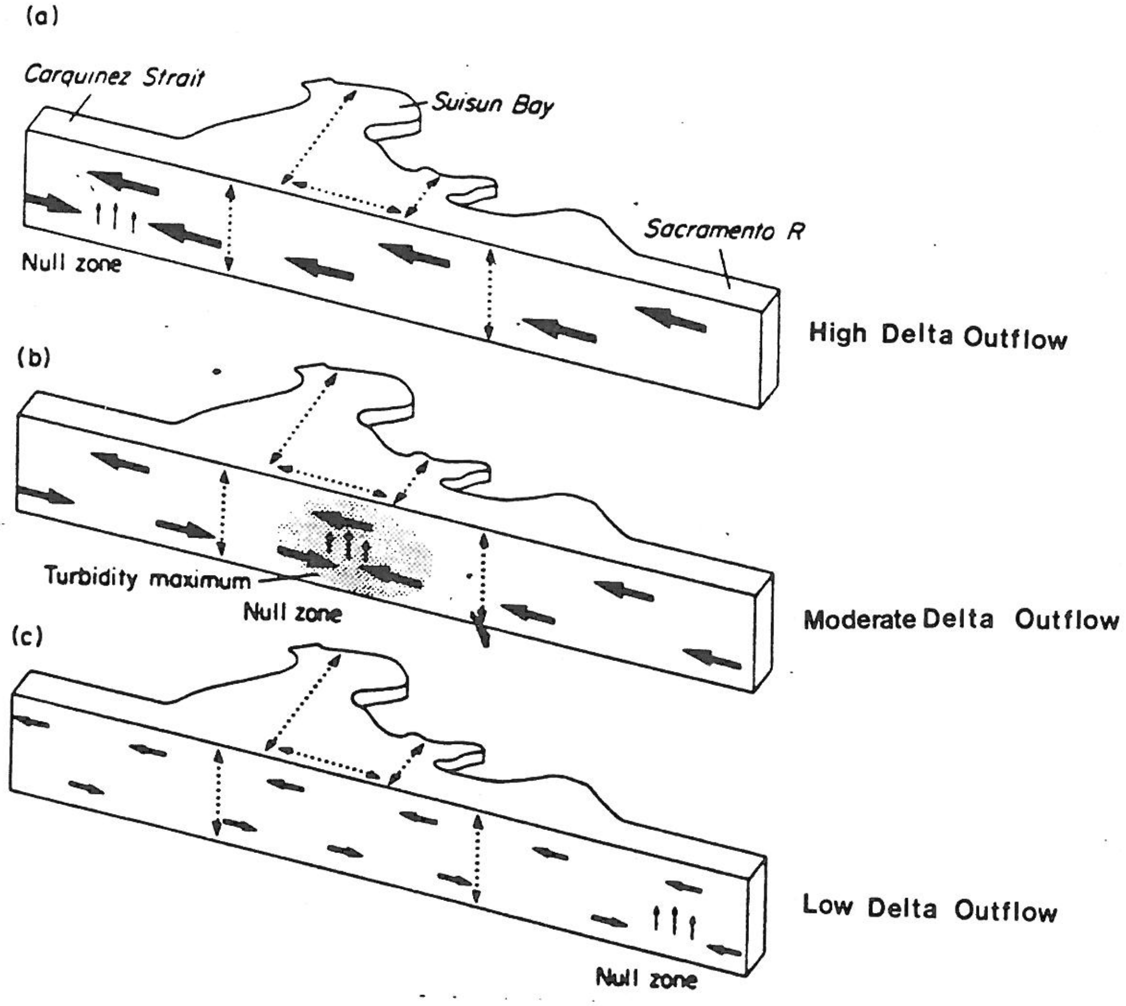
Influence of River Flow on Vertical Velocities in a Hypothetical Estuary

FIGURE
14



Note: Tidal mixing is represented by dotted lines, and non-tidal currents by solid arrows.

(Cloern, et al, 1983)

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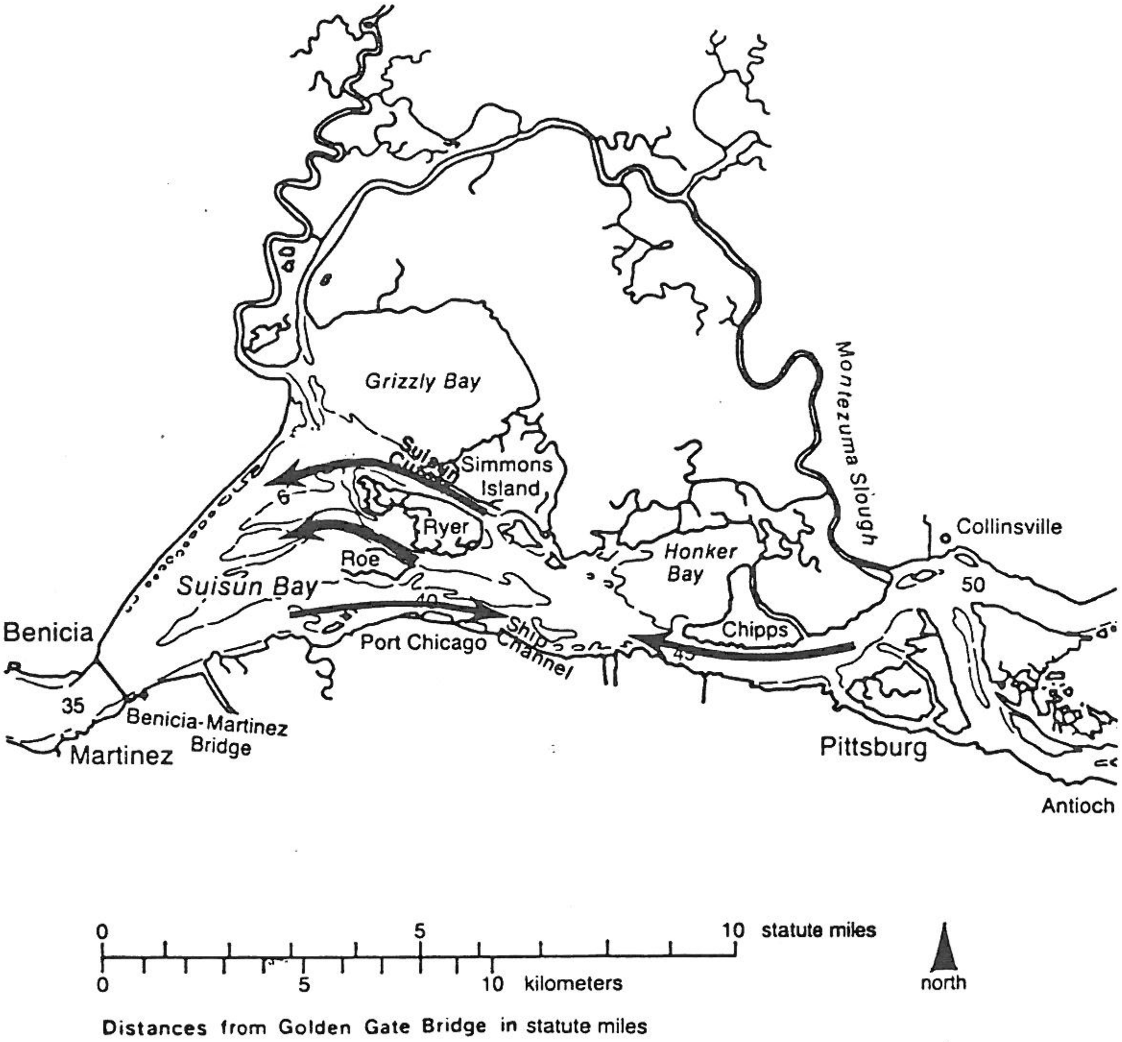
Influence of River Flow on Circulation in Suisun Bay

FIGURE 15



(After Walters, et al, 1985)

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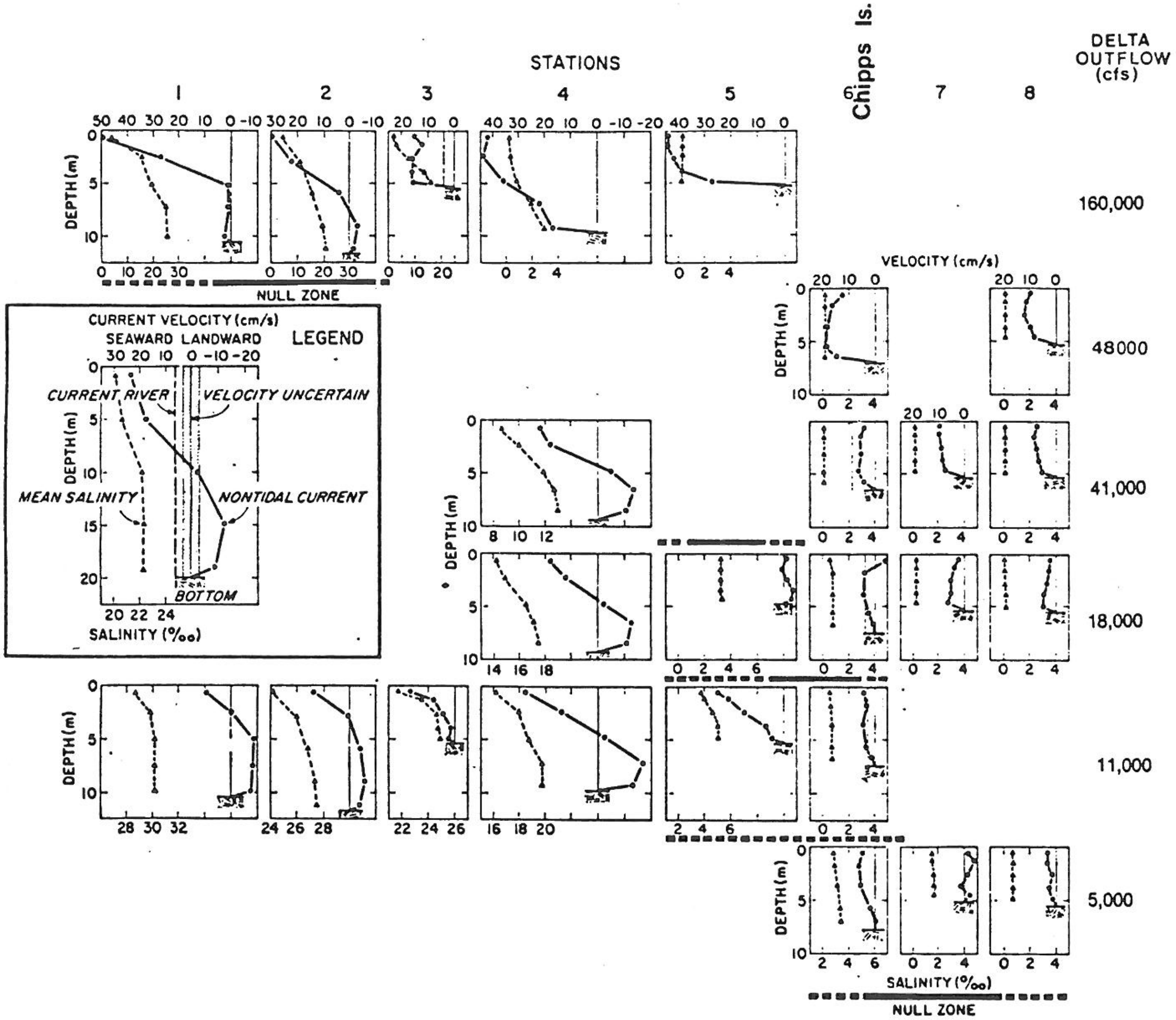
Horizontal Circulation in Suisun Bay

FIGURE 16



Non-tidal currents and mean salinity at Stations 1 through 8 in San Francisco Bay estuary during different river discharge conditions. Profiles are from half-hourly velocity and hourly salinity measurements over a 24·8-h tidal cycle. The location of null zone is indicated by a solid line beneath the velocity profiles where the position is defined by the data and by a dashed line where it is inferred. Blank spaces indicate no measurements were taken.

*(Peterson, et al, 1975)*

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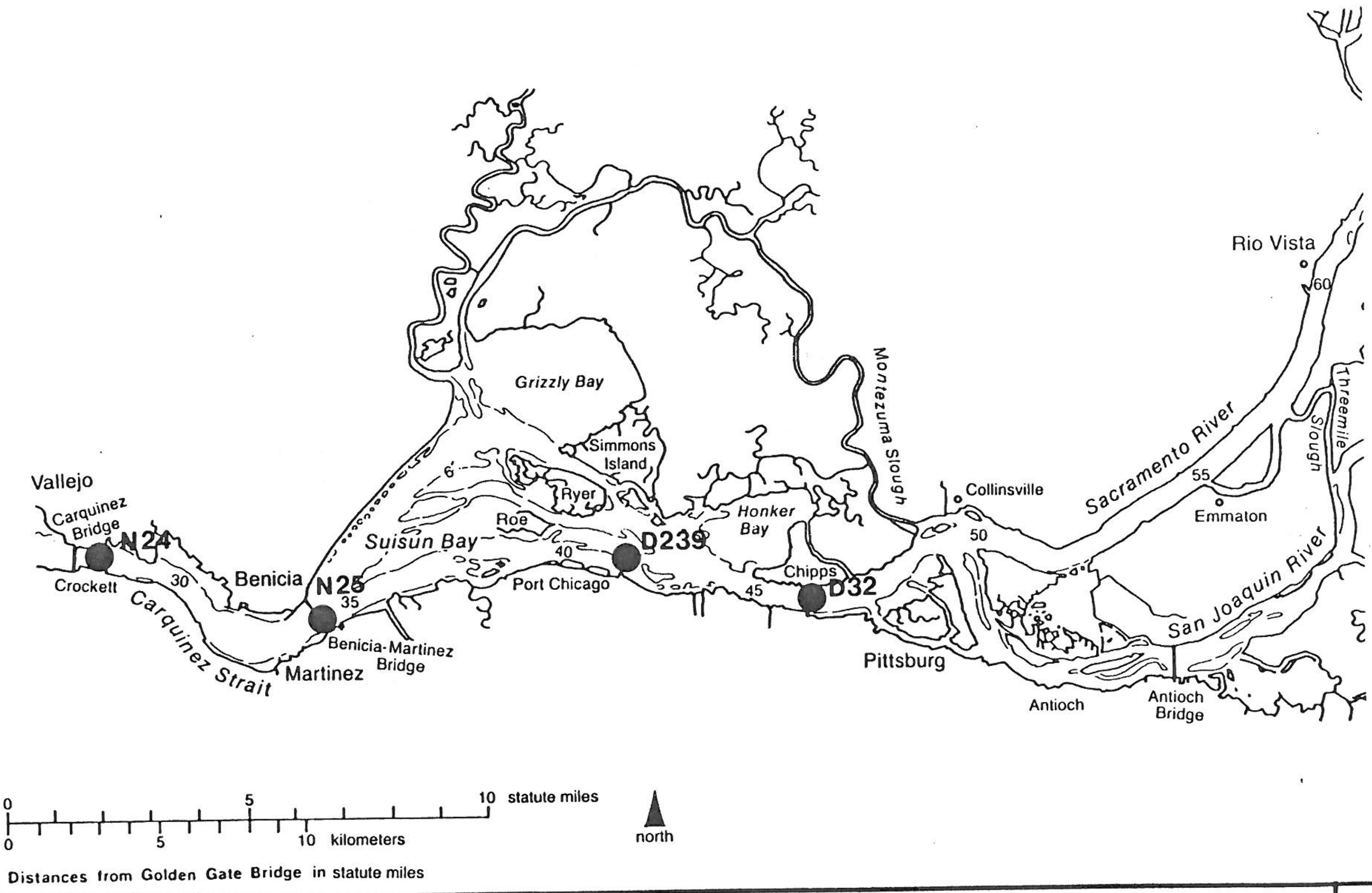
Location of Null Zone (Peterson)

FIGURE
17



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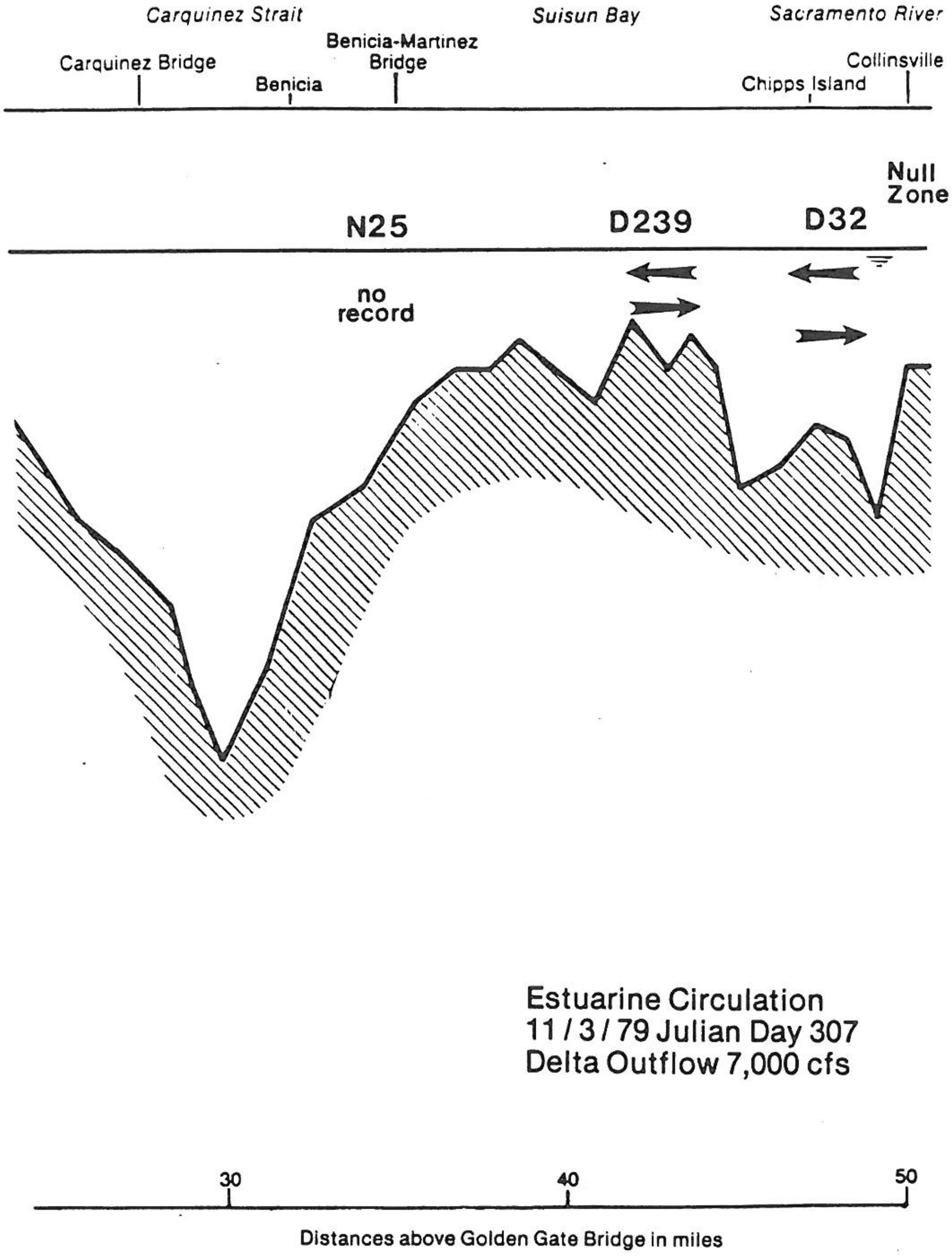
Location of Current Meters — November 3, 1979

FIGURE
18



Estuarine Circulation
11 / 3 / 79 Julian Day 307
Delta Outflow 7,000 cfs

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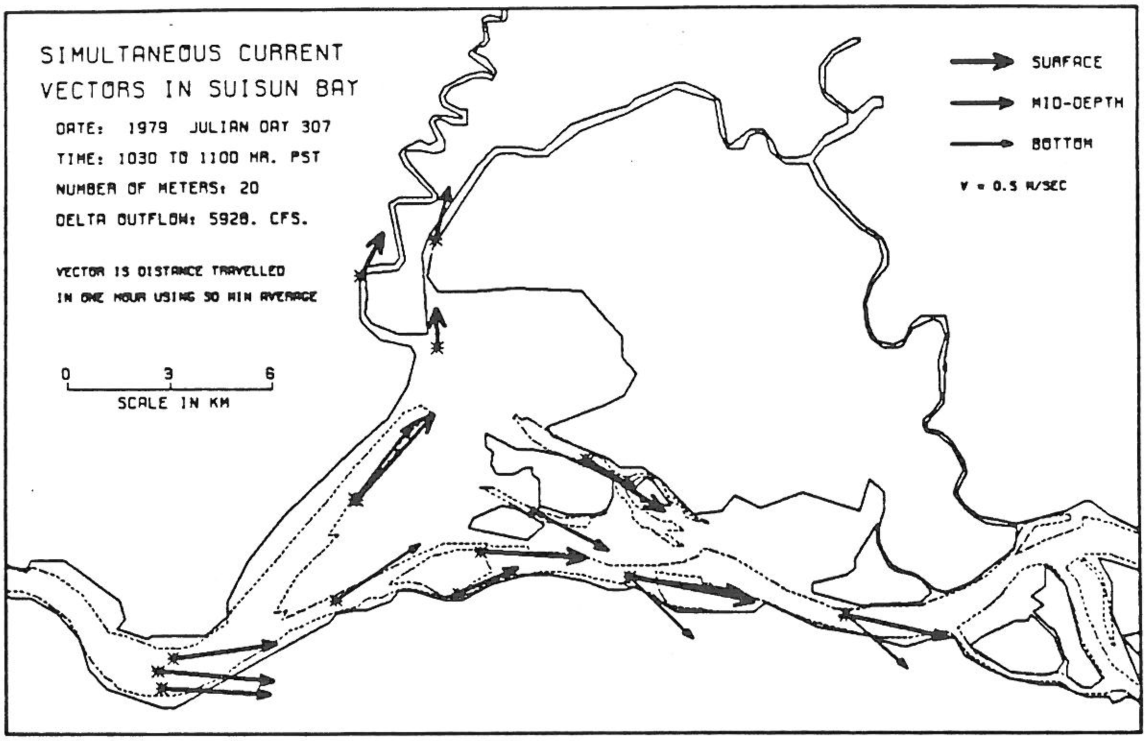
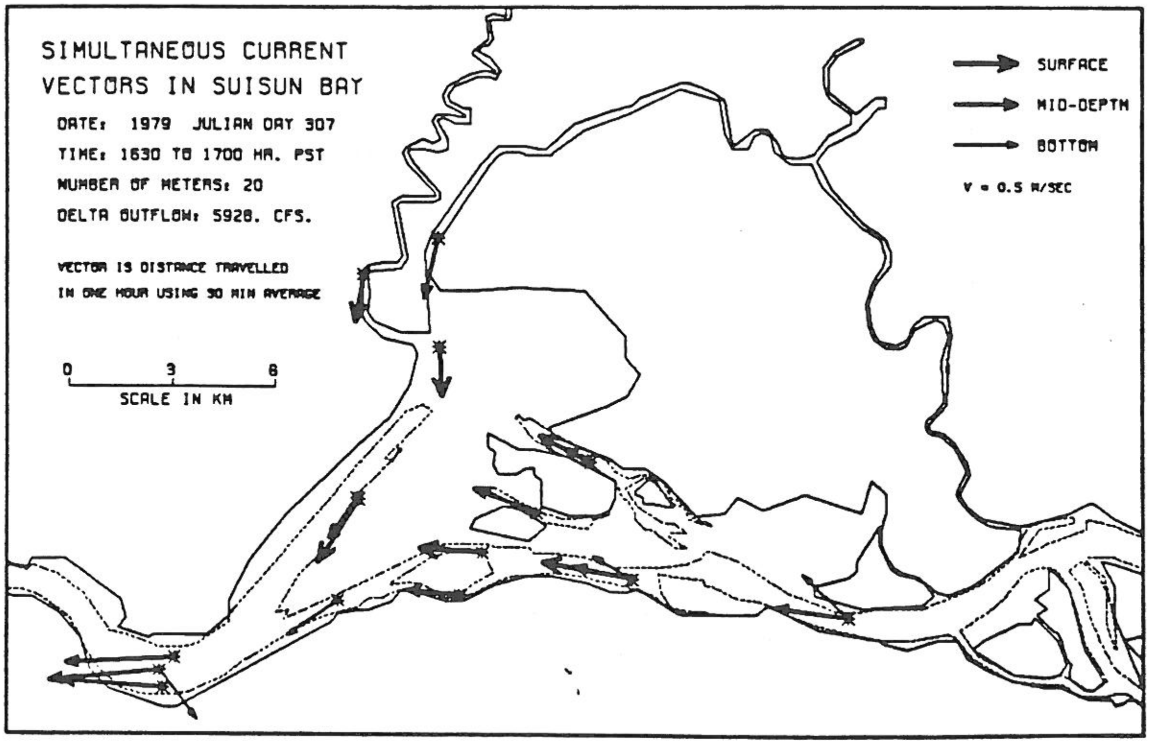
Estuarine Circulation — November 3, 1979

FIGURE 19





*(Denton & Hunt, 1986)*

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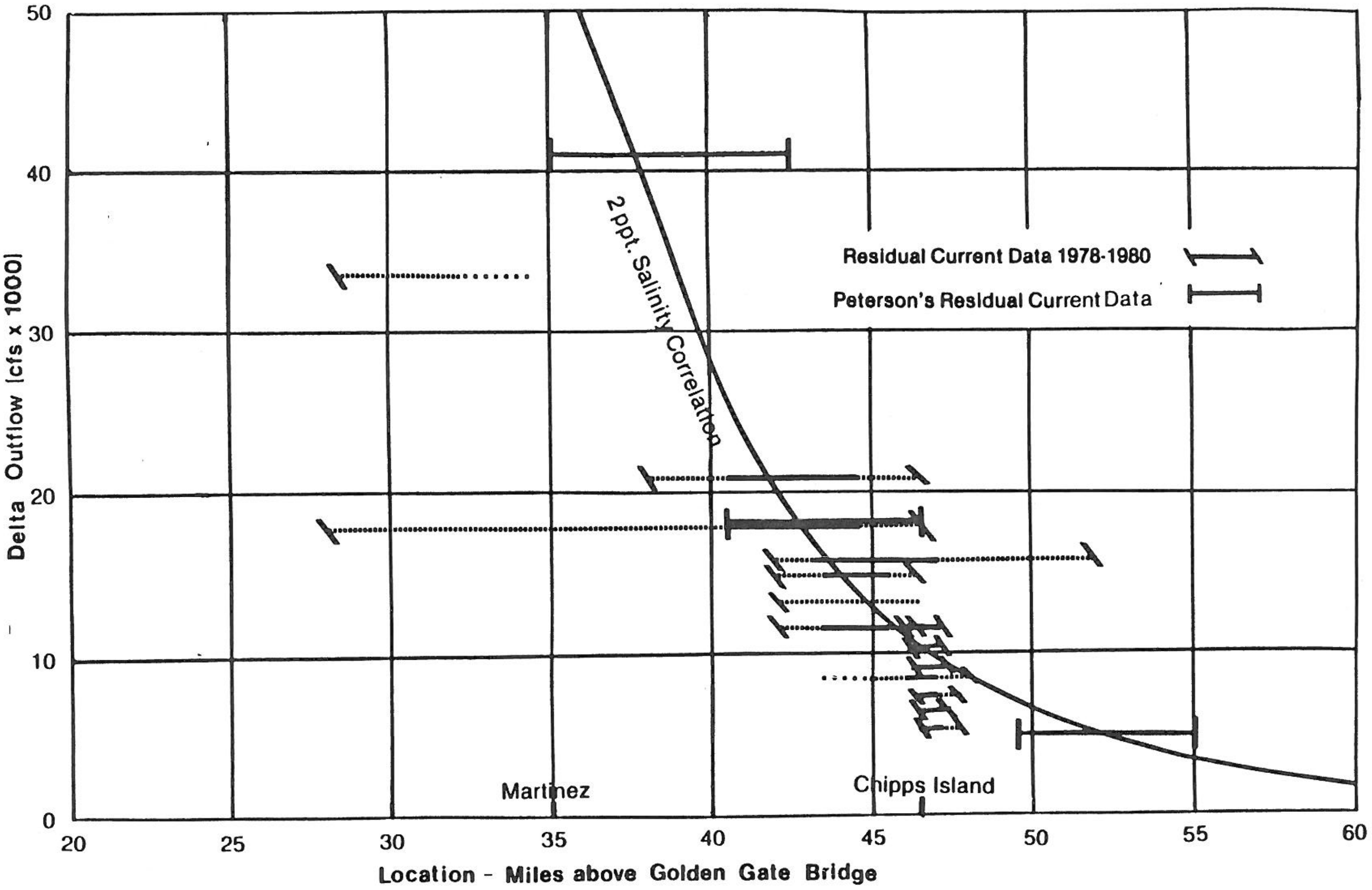
Simultaneous Current Vectors in Suisun Bay

FIGURE 20



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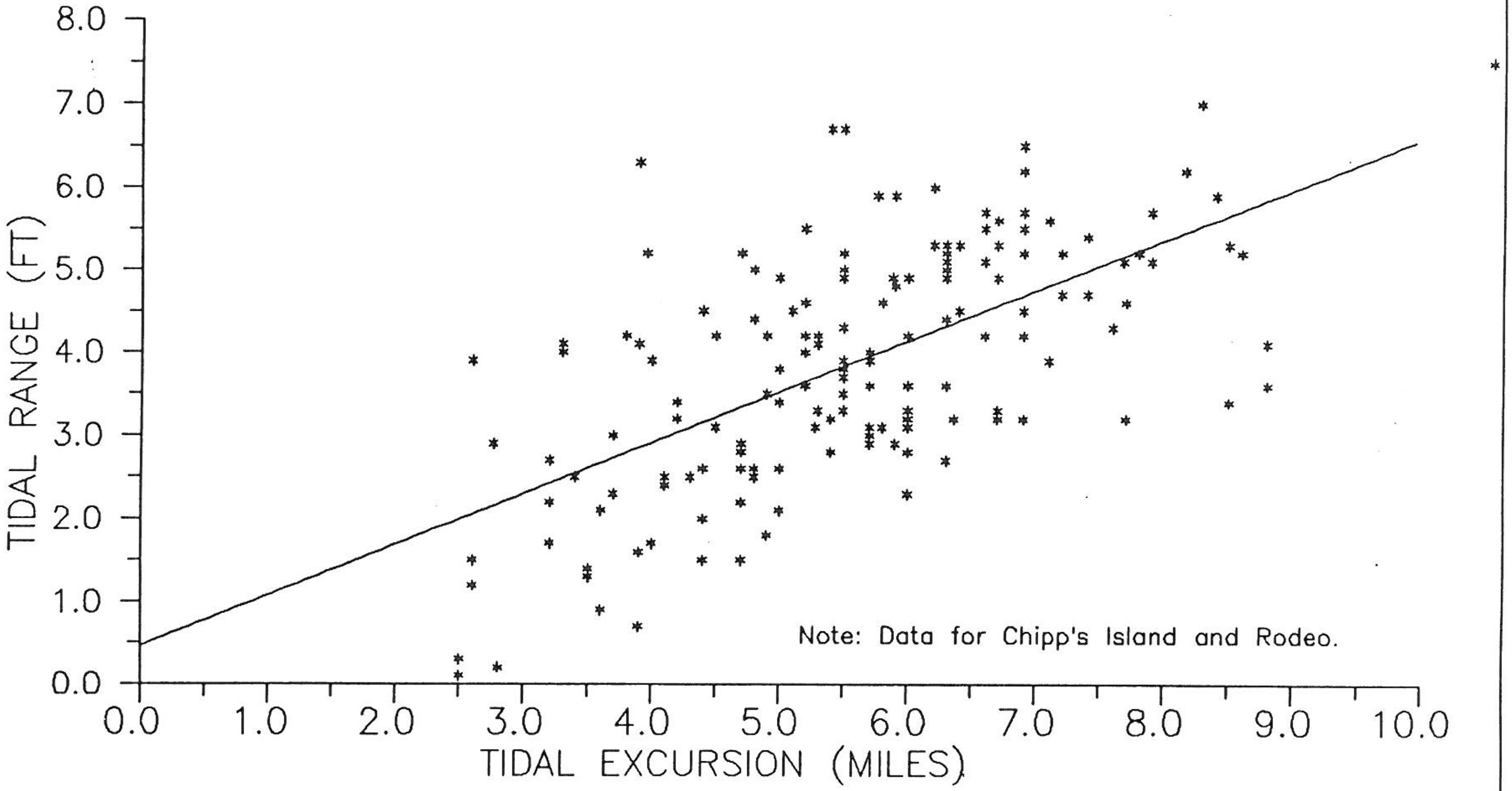
Location of Null Zone Defined by Residual Velocity

FIGURE
21

# TIDAL RANGE VS TIDAL EXCURSION



Note: Data for Chipp's Island and Rodeo.

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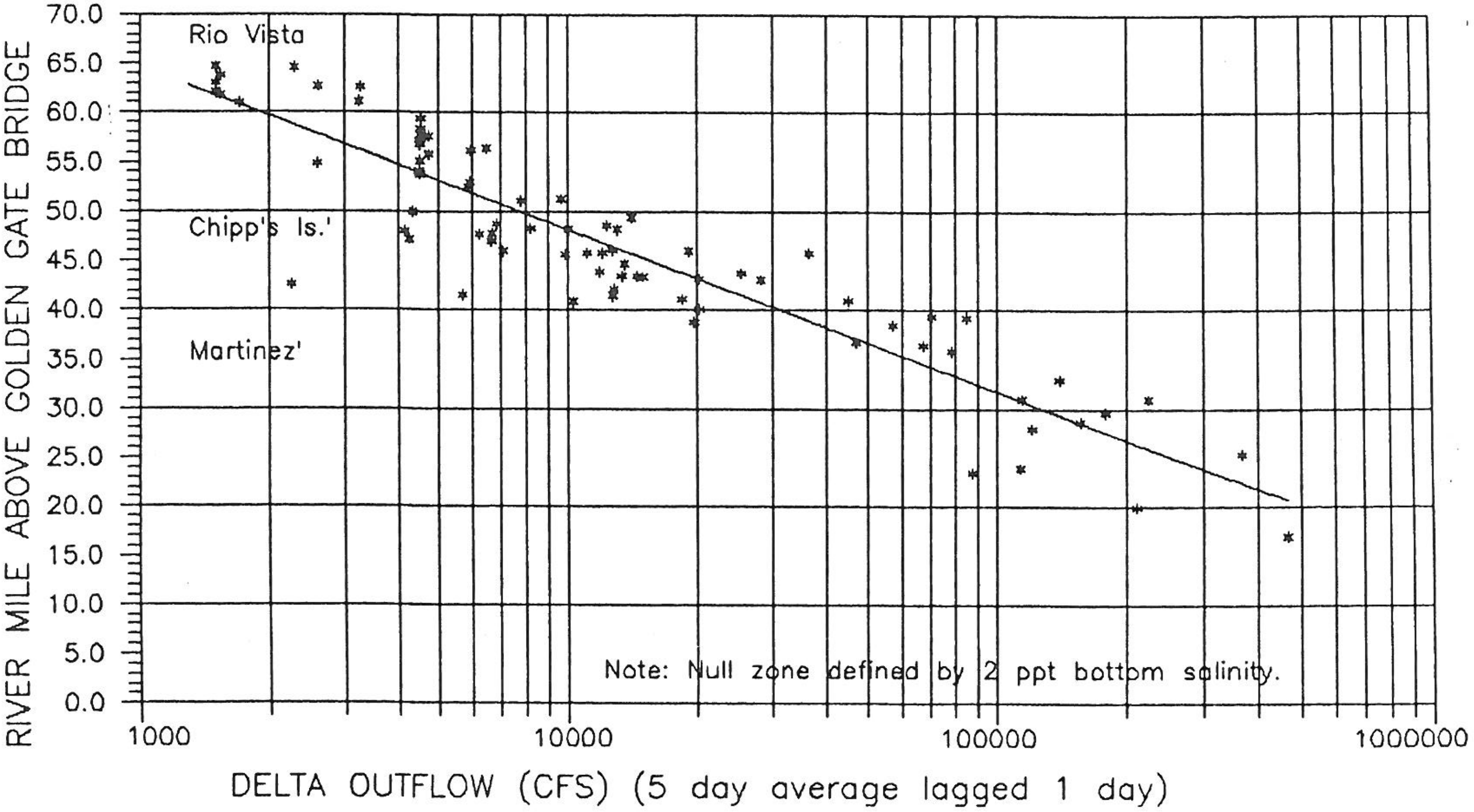
22

# NULL ZONE POSITION VS' DELTA OUTFLOW



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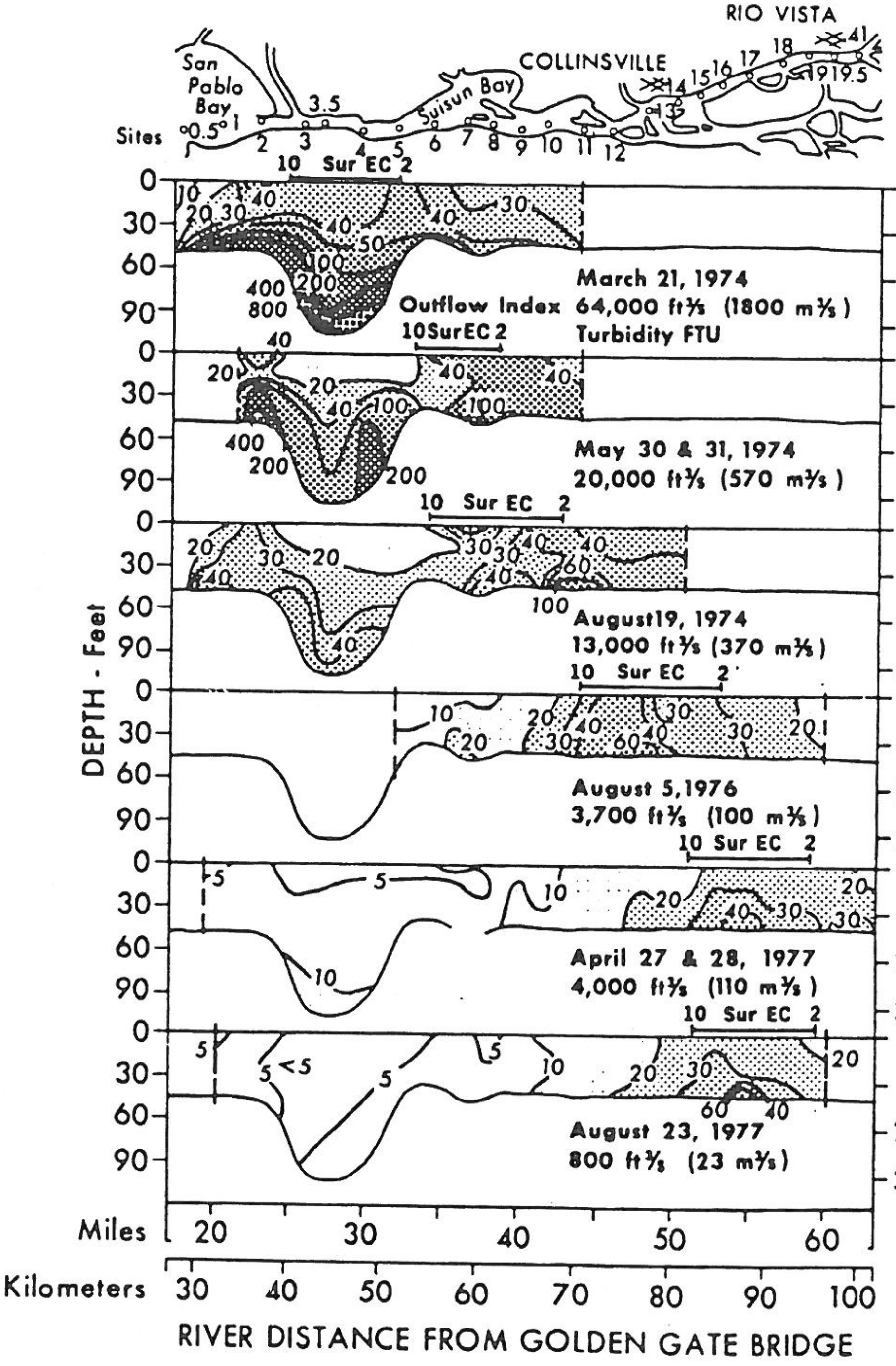
23



*(Arthur & Ball, 1979)*

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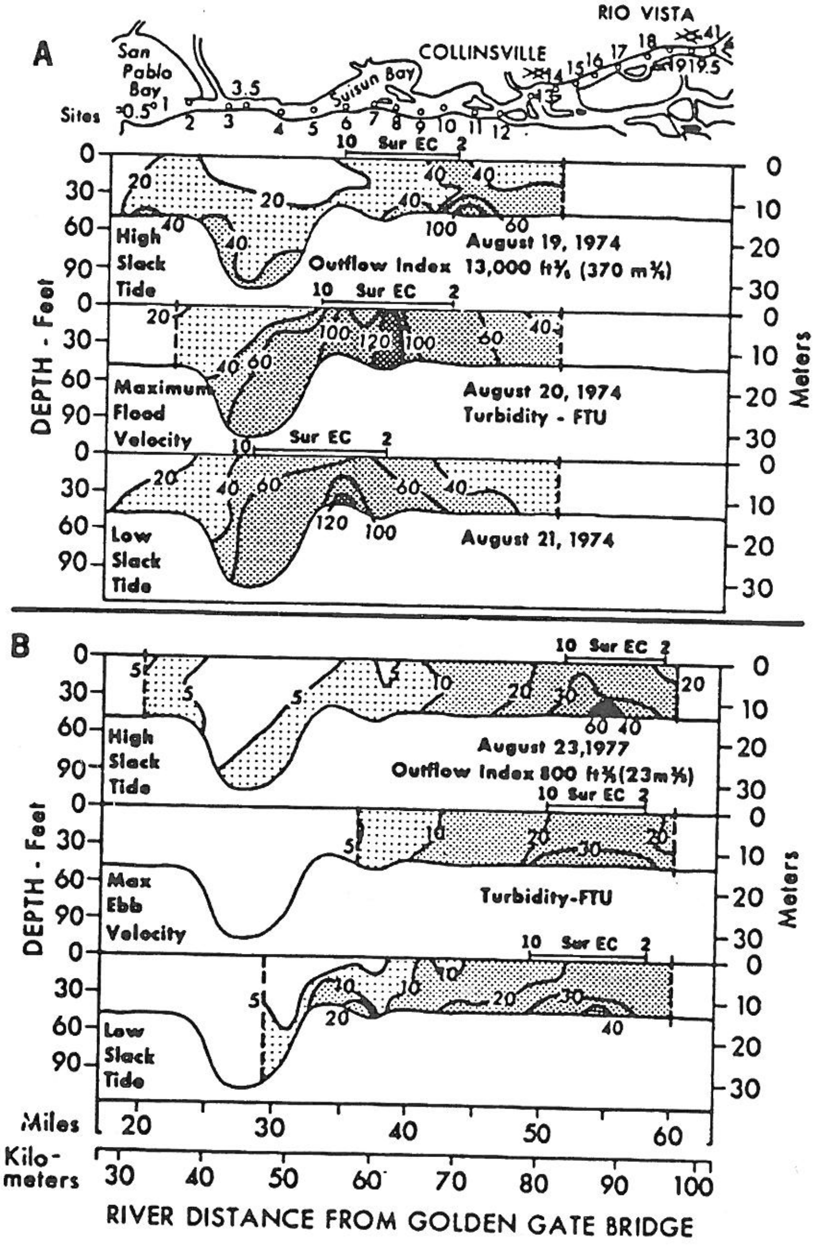
Turbidity Distribution

FIGURE
24

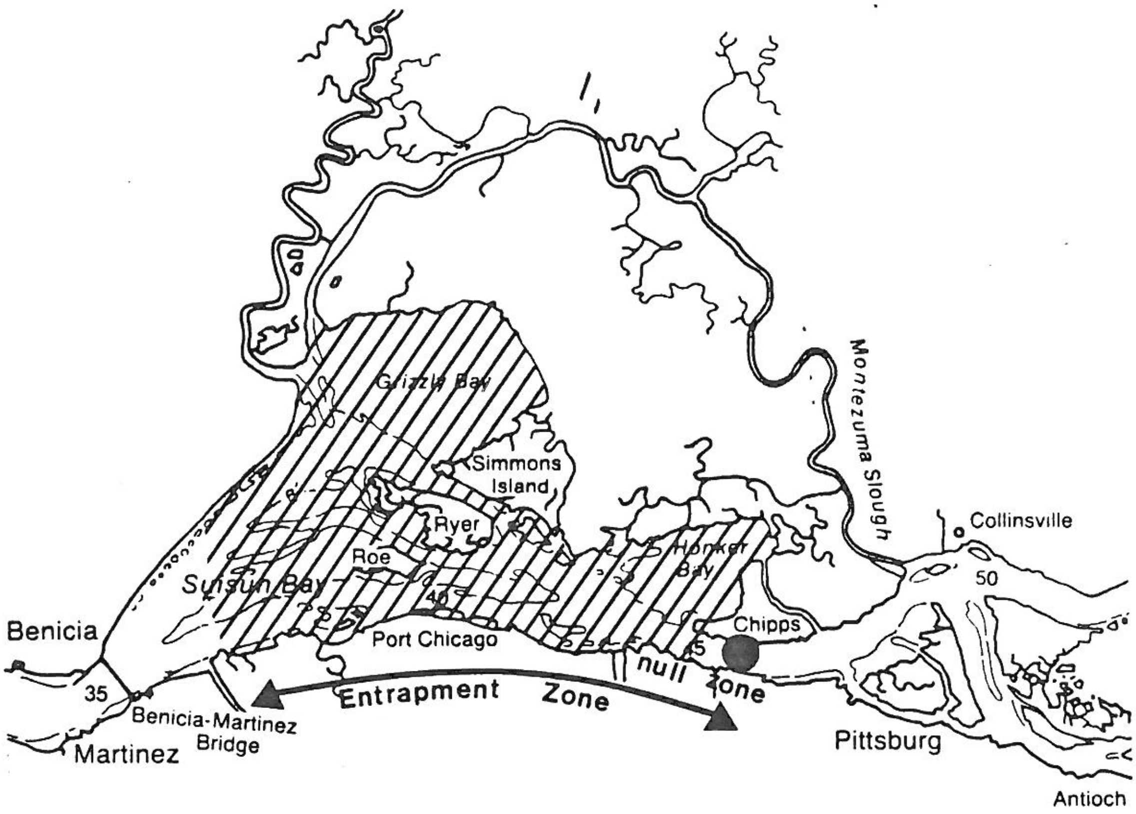


Turbidity distribution relative to salinity measured on three consecutive days during different tidal phases in August 1974. B. Turbidity distribution relative to salinity measured on three consecutive tidal phases on 23 August 1977.

*(Arthur & Ball, 1979)*

Change in Turbidity over a Tidal Cycle

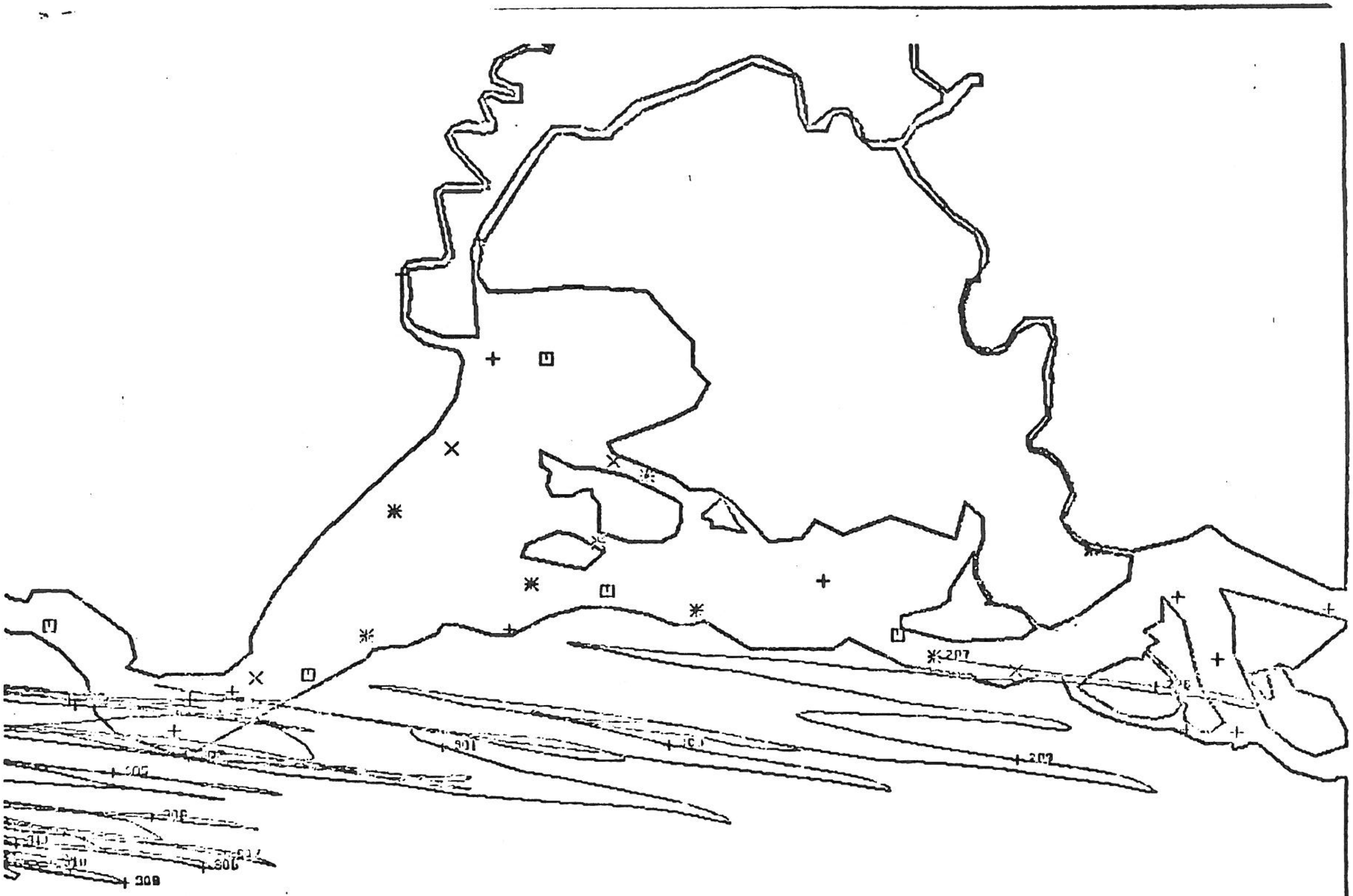
FIGURE
25



Location of Entrapment Zone with Chipps Island Standard of 2 ppt

# APPENDIX A

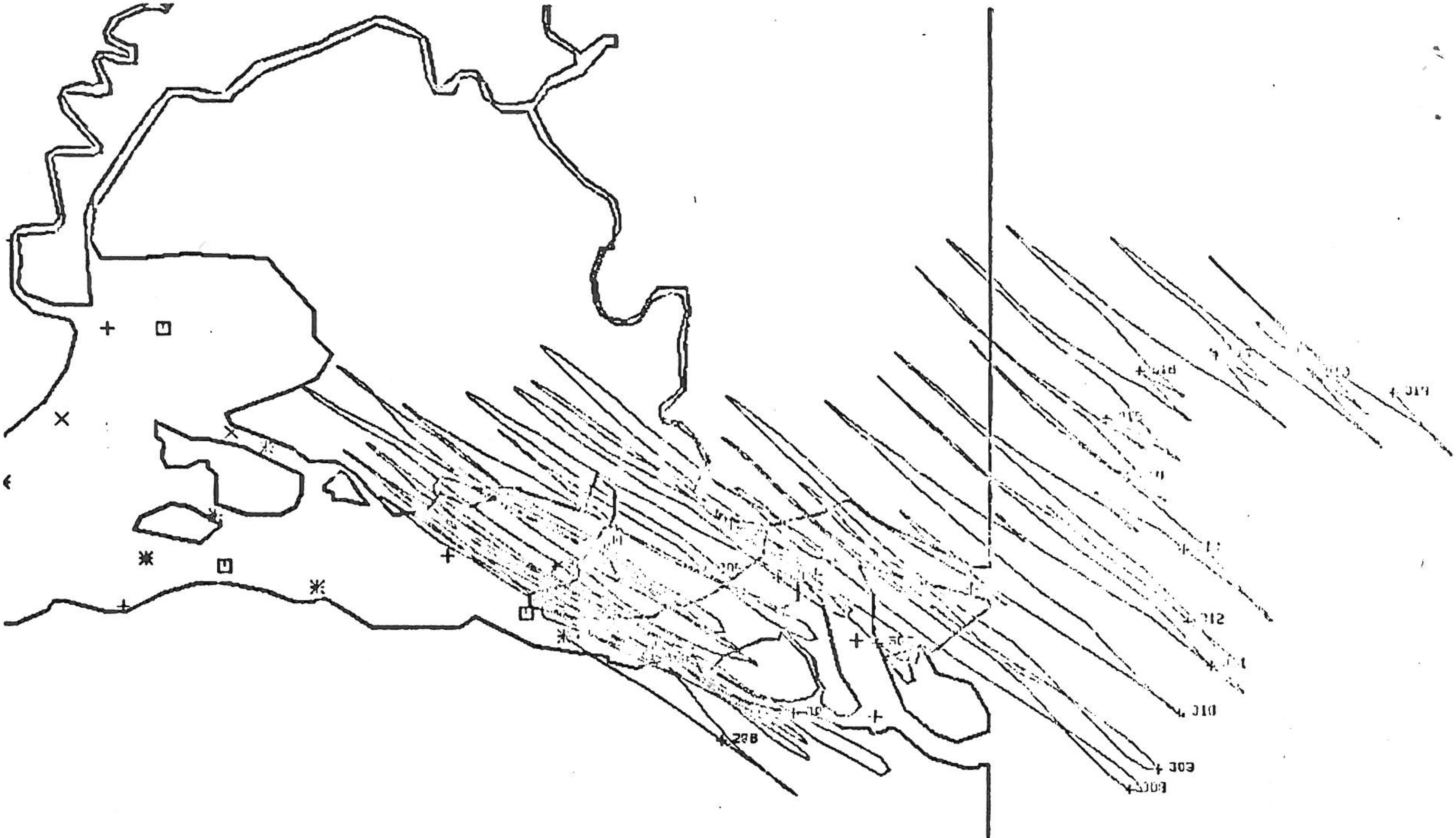
# EXAMPLE OF PROGRESSIVE VECTOR DIAGRAMS USED TO LOCATE NULL ZONE



STATION: D32  FILE: D32K1.30
REMARKS:

POSITION:        38  2 51N  121 55 17W
SENSOR DEPTH :  6.1M
WATER DEPTH  : 12.2M
STARTING DATE: 79297  (10/24/79)
RECOVERY DATE: 79319

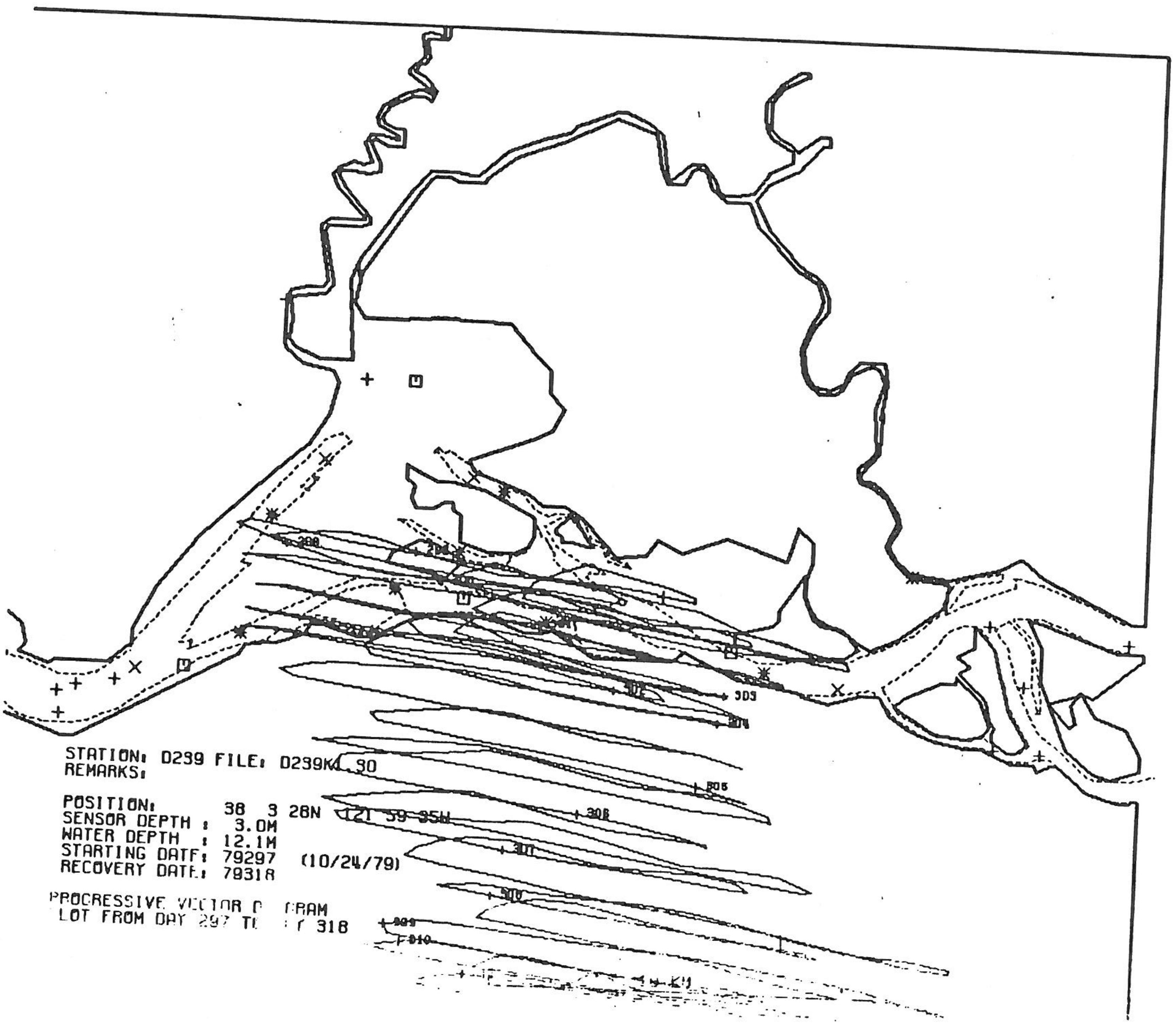
PROGRESSIVE VECTOR DIAGRAM



STATION: D32 FILE: D32K~~2~~3.30
REMARKS:

POSITION: 38 2 51N 121 55 17W
SENSOR DEPTH : 10.4M
WATER DEPTH : 12.2M
STARTING DATE: 79297 (10/24/79)
RECOVERY DATE: 79319

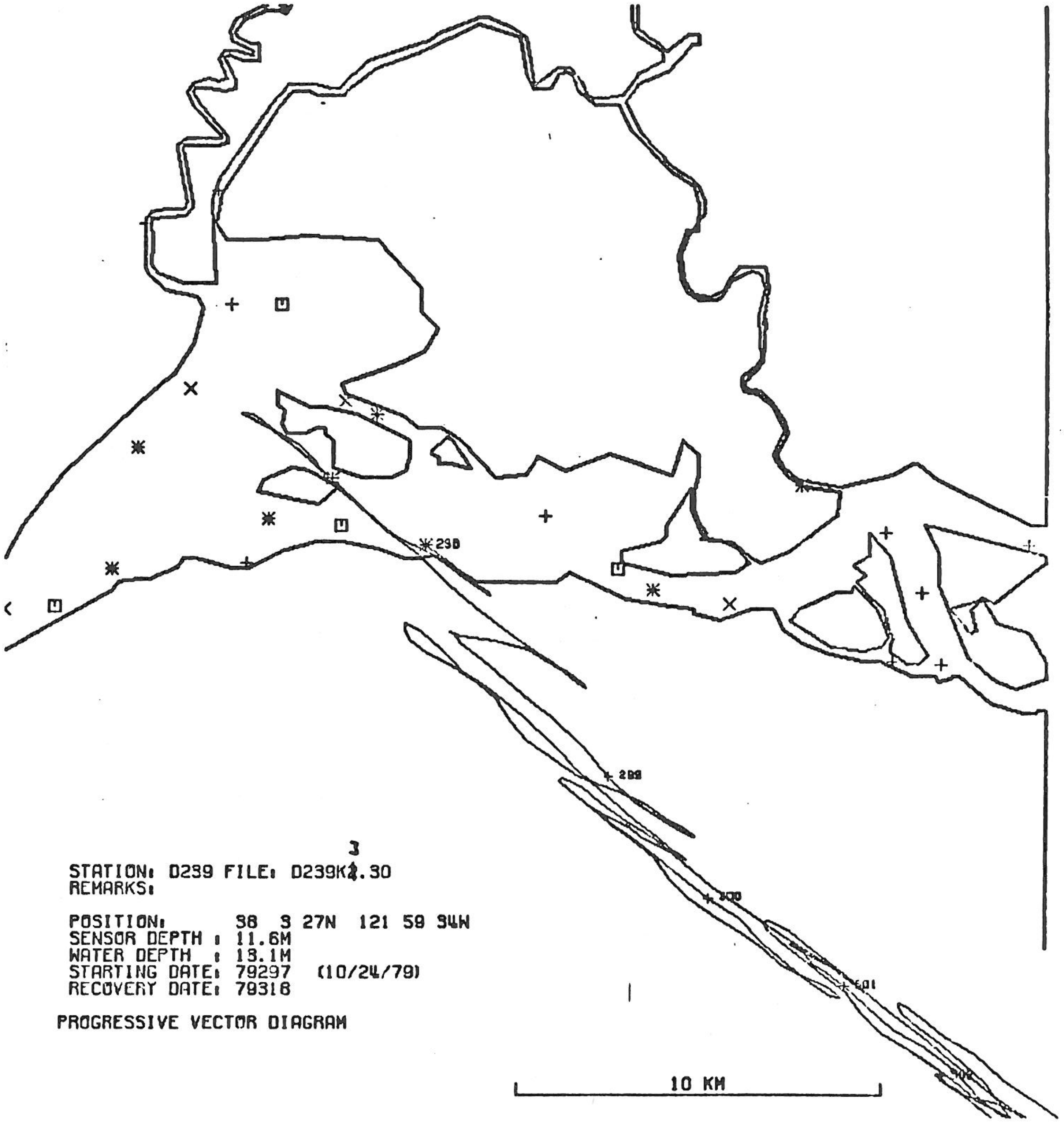
PROGRESSIVE VECTOR DIAGRAM



STATION: D239 FILE: D239K(.30
REMARKS:

POSITION: 38 3 28N 121 59 35W
SENSOR DEPTH : 3.0M
WATER DEPTH : 12.1M
STARTING DATF: 79297 (10/24/79)
RECOVERY DATE: 7931R

PROCRESSIVE VECTOR D GRAM
LOT FROM DAY 297 TC r 318



3

STATION: D239 FILE: D239K3.30
REMARKS:

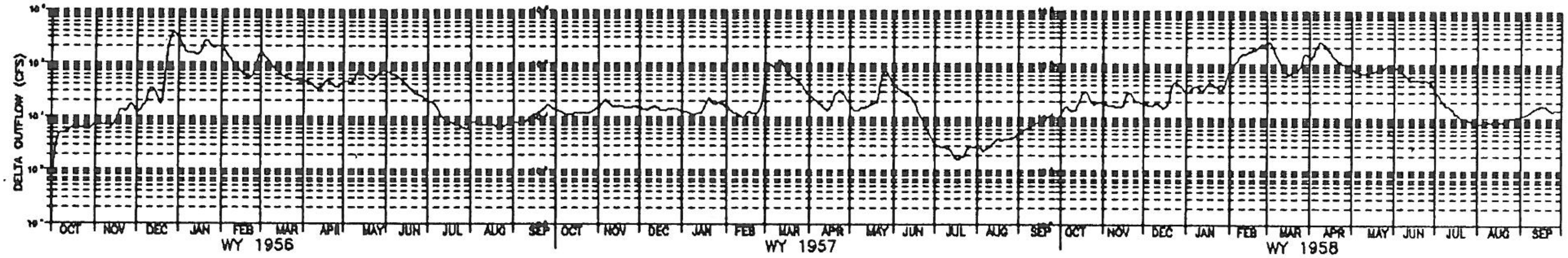
POSITION: 38 3 27N 121 58 34W
SENSOR DEPTH : 11.6M
WATER DEPTH : 13.1M
STARTING DATE: 79297 (10/24/79)
RECOVERY DATE: 79318

PROGRESSIVE VECTOR DIAGRAM

# APPENDIX B

# DELTA OUTFLOW

## DELTA OUTFLOW: 5-DAY RUNNING AVERAGE
1 OCTOBER 1955 – 30 SEPTEMBER 1958



| | |
|---|---|
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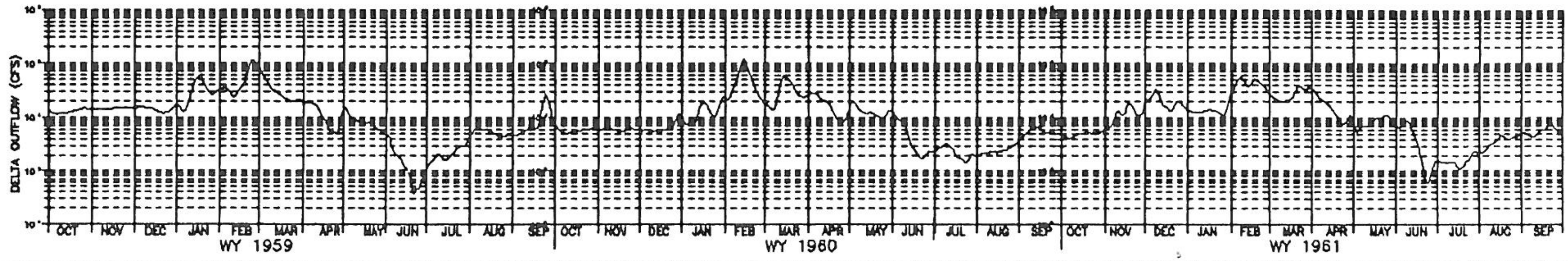
## DELTA OUTFLOW: 5-DAY RUNNING AVERAGE
1 OCTOBER 1958 – 30 SEPTEMBER 1961



| | |
|---|---|
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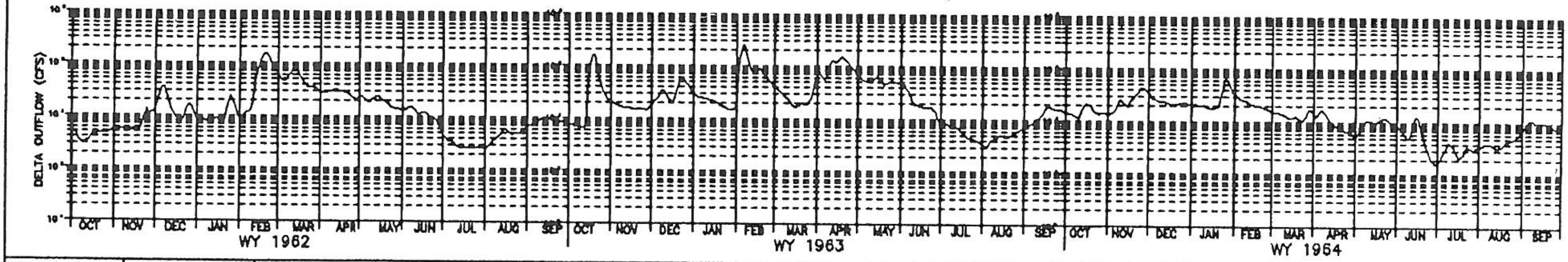
## DELTA OUTFLOW: 5-DAY RUNNING AVERAGE
1 OCTOBER 1961 – 30 SEPTEMBER 1964



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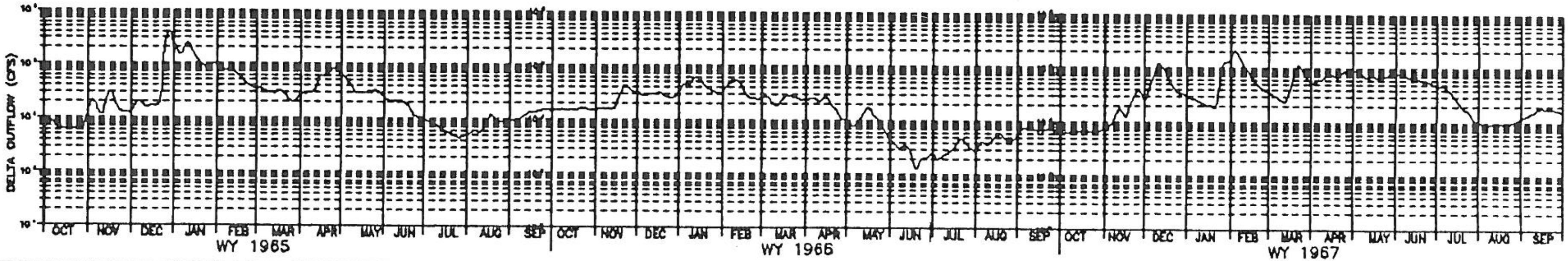
## DELTA OUTFLOW: 5-DAY RUNNING AVERAGE
1 OCTOBER 1964 – 30 SEPTEMBER 1967



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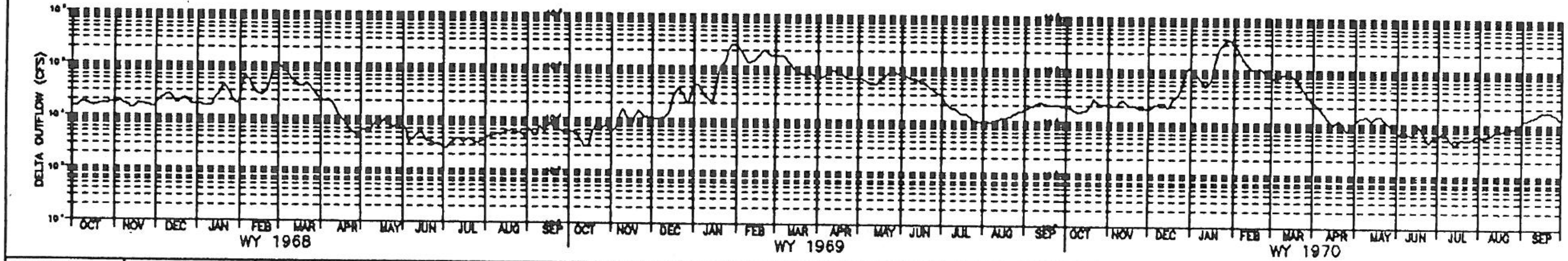
## DELTA OUTFLOW: 5-DAY RUNNING AVERAGE
1 OCTOBER 1967 – 30 SEPTEMBER 1970



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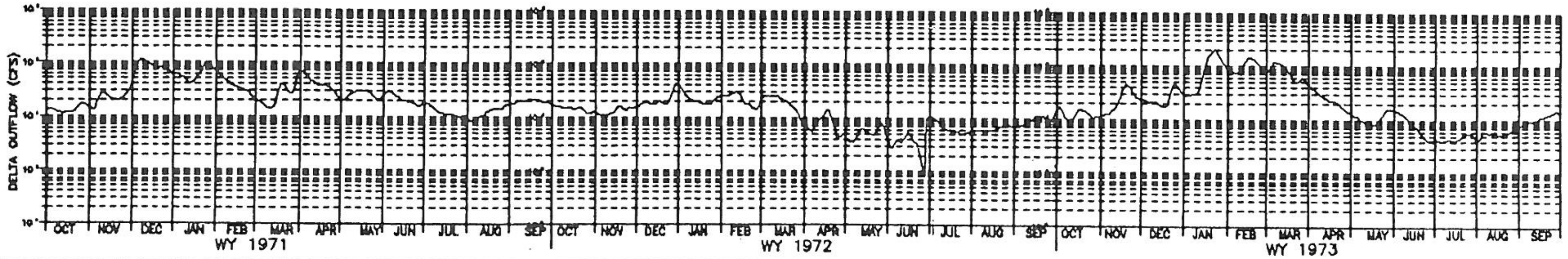
## DELTA OUTFLOW: 5-DAY RUNNING AVERAGE
1 OCTOBER 1970 – 30 SEPTEMBER 1973



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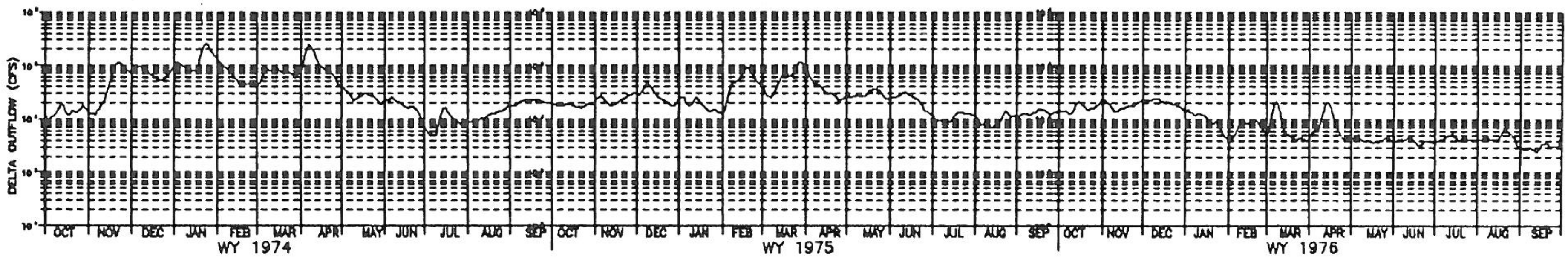
BY: L. FISHBAIN

## DELTA OUTFLOW: 5-DAY RUNNING AVERAGE
1 OCTOBER 1973 – 30 SEPTEMBER 1976



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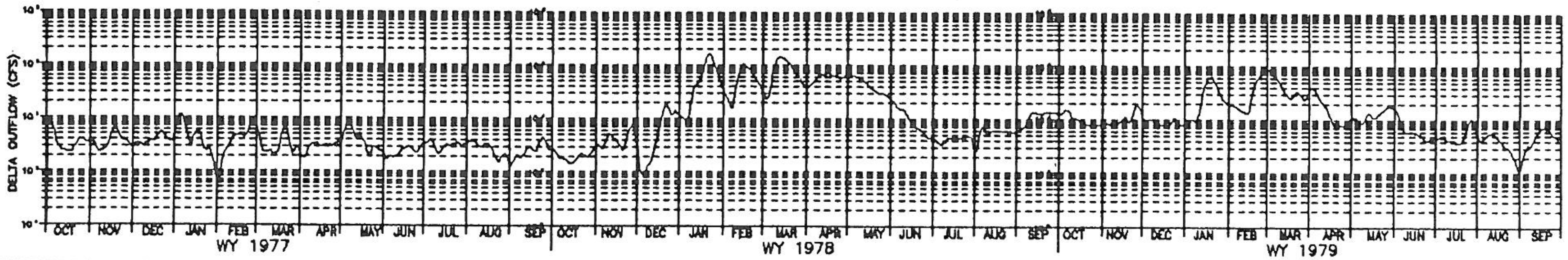
## DELTA OUTFLOW: 5-DAY RUNNING AVERAGE
1 OCTOBER 1976 – 30 SEPTEMBER 1979



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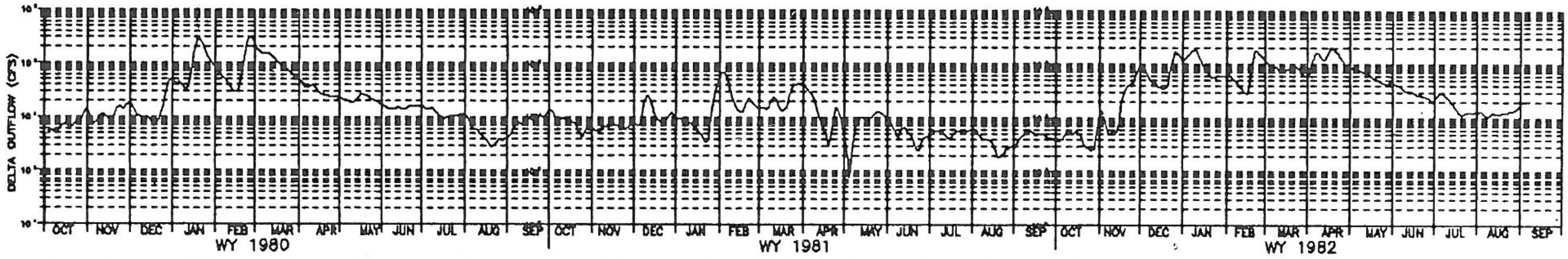
## DELTA OUTFLOW: 5-DAY RUNNING AVERAGE
1 OCTOBER 1979 - 30 SEPTEMBER 1982



| | | |
|---|---|---|
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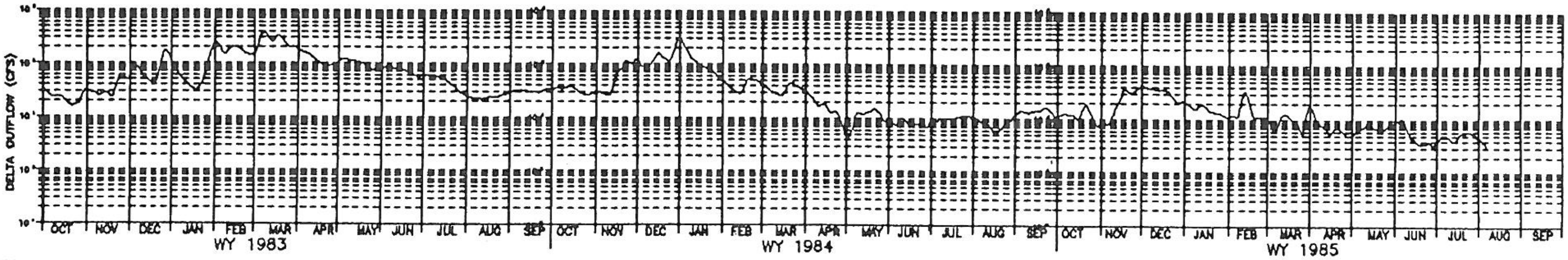
## DELTA OUTFLOW: 5-DAY RUNNING AVERAGE
1 OCTOBER 1982 - 30 SEPTEMBER 1985



| | | |
|---|---|---|
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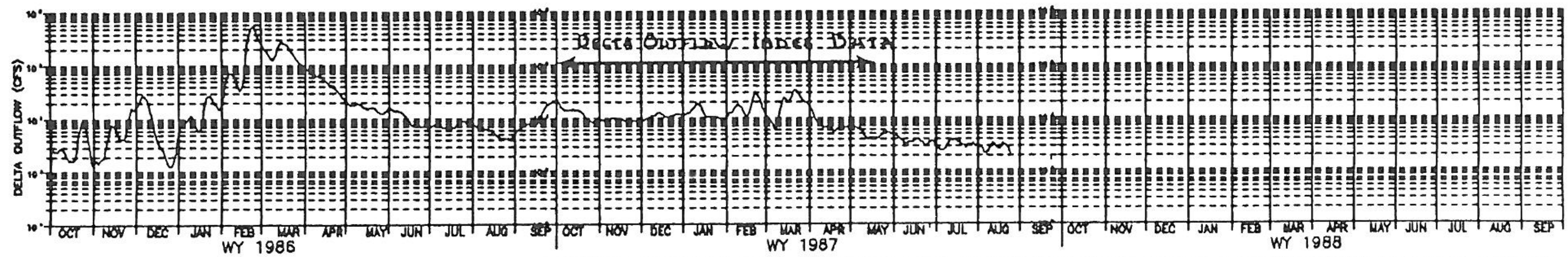
## DELTA OUTFLOW: 5-DAY RUNNING AVERAGE

1 OCTOBER 1985 – 30 SEPTEMBER 1988



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BY: L. FISHBAIN

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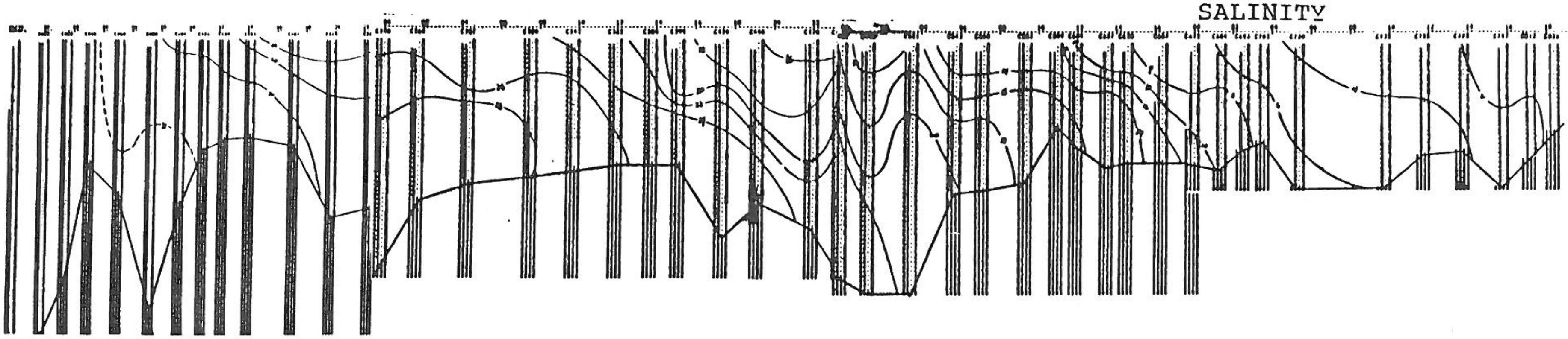
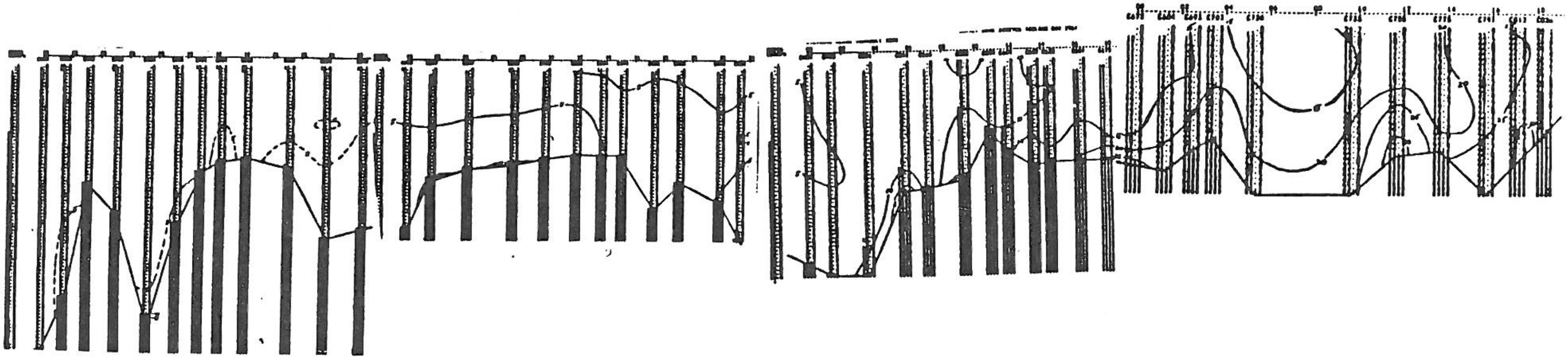
# APPENDIX C

# 1986 SALINITY AND LIGHT ATTENUATION DATA

SALINITY

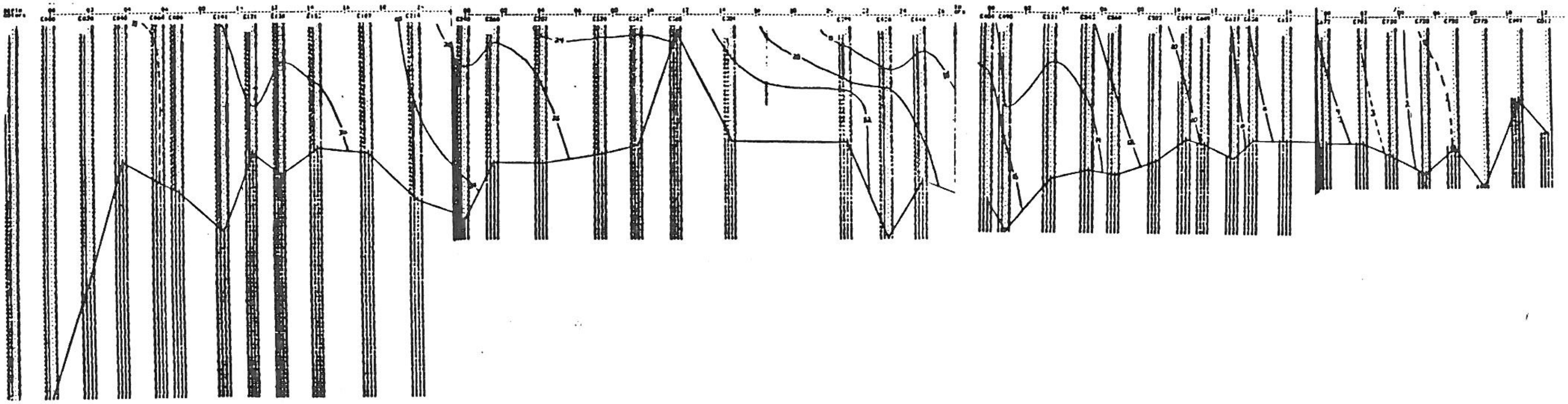


ATTENUATION

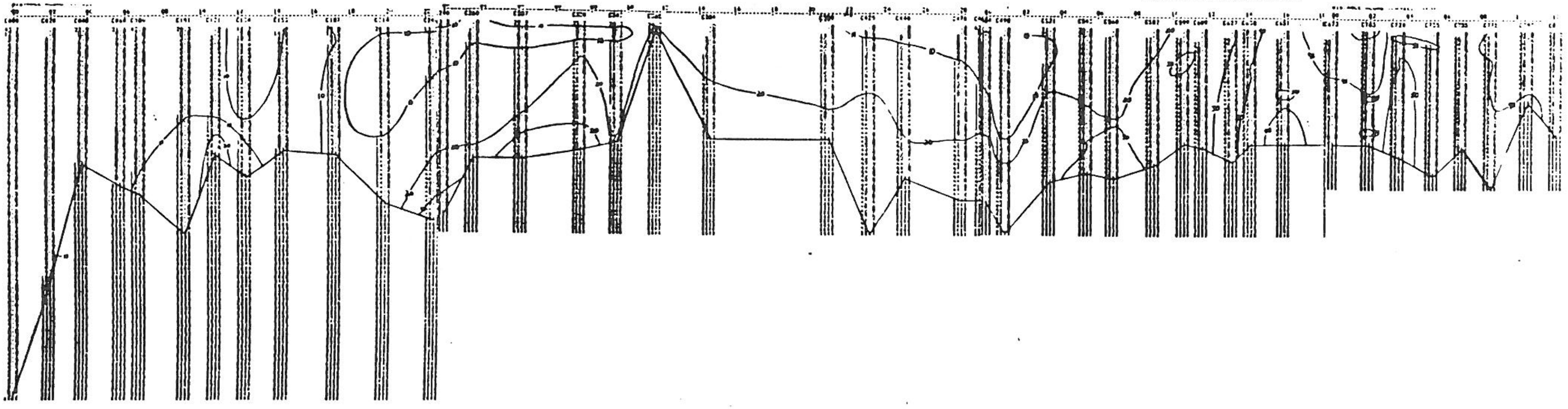


October 23, 1986

## SALINITY



## ATTENUATION



October 17, 1986